

ENHANCED SURFACE FINISHING OF BEARING RACEWAYS

by

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the requirements for the degree of**



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Abstract

ENHANCED SURFACE FINISHING OF BEARING RACEWAYS

Bearing surfaces are highly engineered and high precision parts in regard to surface finish, waviness, form and dimensional size. Surface finishing techniques will not only affect the surface finish and texture but the mechanical properties of the surface and subsurface including surface stress state and hardness as well as chemical properties. The bearing surface is a functional surface influencing fatigue, wear, and friction, noise and lubrication regime. Bearings are low cost, high volume commodity products, which adds additional constraints to any manufacturing process of low cost, fast cycle time and automation.

This thesis documents the development route for a superfinishing technique for bearing raceways. Initially work was performed on electrochemical machining (ECM) of raceways, but this was found to improve the surface finish too slowly and gave poor waviness as a result of non-conductive MnS inclusions becoming exposed on the bearing surface during ECM. Abrasive honing stones or superfinishing tapes were then combined with the ECM, a process called electrofinishing to remove these MnS peaks. A beneficial interaction between the ECM and the abrasive resulted in reduced loading of the abrasive and therefore more aggressive cutting and for longer.

Using a fine grit (3- 4 μm) CBN vitreous bonded honing stone the surface finish of a ground ring (0.3 $\mu\text{m Ra}$) or a turned surface (1.2 $\mu\text{m Ra}$) could be improved to <0.02 $\mu\text{m Ra}$ in around 6 seconds. These new surfaces showed low R_{tm} and Δq (slope), but also acceptable or very good levels of waviness. The material removal is dominated by the ECM process while the rate of surface finishing is controlled by the abrasive process.

The process of electrofinishing gives the possibility of fast, high and controlled material removal capability combined with fine surface finishing, which presently must be achieved by throughfeed honing or two stage honing. The main difficulty to overcome is achieving a stable consistent honing needed for a production process. These difficulties arise from the incompatibility of the ECM electrolyte and honing fluid (usually an oil). Improvements were made by using a water soluble synthetic metalworking fluid mixed with the NaNO_3 electrolyte. Further improvements are possible by better choice of honing stone, better application of stones, while for superfinishing tapes, the use of tape feed and oscillation will give further improvements.

Acknowledgement

I wish to thank SKF for their support of this project giving me the opportunity to continue my education while increasing my industrial experience. Studying and living in the Netherlands for the last three years has opened my eyes to new experiences and ideas. I would like to thank the people at SKF's Engineering & Research Centre (ERC) for their friendliness and openness during discussions. In particular, I wish to thank Paul Shore for his guidance especially during the first year of the project and Rene van Breemen for continual support and interest in the work. Many thanks also to John van de Sanden and Robert Smalley for their assistance and support particularly with working within ERC procedures.

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Finally I have made many new friends while in Holland, people from all over Europe with different backgrounds and beliefs. They have certainly influenced and changed me, and likewise I hope that I have had a beneficial influence on them. I would like to thank them for making this an enjoyable period in my life.

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1. Introduction

The bearing manufacturer SKF to further evaluate a finishing method for bearing raceways initiated this Ph.D. study. Preliminary testing at SKF's Engineering & Research Centre (ERC) in The Netherlands demonstrated a technique for improved surface finishing, producing smooth highly reflective surfaces in short cycle times. The process developed from research on electrochemical machining of bearing raceways, which was later combined with honing. This combined process was called electrofinishing. The technique had a number of problems, which needed to be solved before the process could become a production technique.

Since this work was performed fully in industry at ERC, emphasis is placed on the industry requirements for a manufacturing process suitable for surface finishing of bearing raceways. The Ph.D. study was initiated to gain a better understanding of the surface finishing mechanisms as well as the influence of process parameters on the rate of surface finishing and the surface finish achievable. The bearing surface is a highly functional surface influencing fatigue, lubrication, wear, friction and noise and is manufactured to strict specifications usually regarding surface roughness parameters including arithmetic mean roughness R_a , peak to valley height R_{tm} , slope Δq , and skewness R_{sk} , but also circumferential waviness. In addition geometric form such as cross track profile and dimensional size are important. These parameters were used to evaluate the process.

As background to this work an introduction to SKF is presented below and the important role bearings play in our everyday lives and within industry is discussed, and finally an overview of a typical manufacturing route for the inner ring of a cylindrical roller bearing, the workpiece used in this study.

1.1 SKF The Company

SKF started in 1907 in Gothenburg, Sweden and has grown to be the largest bearing manufacturer in the world with operations in over 150 countries and over 44,000 employees. SKF is truly a multinational company with over 80 manufacturing sites all over the world including China, Malaysia, Poland, USA, and Argentina, however most production is still at European sites in Sweden, Germany, France and Italy.

For more information¹ www.skf.com

1.2 SKF Research and Development

SKF's centre for product and process R&D is based in the Netherlands at SKF Engineering and Research Centre (ERC) in Nieuwegein (near Utrecht). Research activities include heat treatment, steels, ceramics, coatings, lubrication, new technologies, mechatronics, noise & vibration, FEM and other customized bearing simulation software.

Research & development funding within SKF is divided up into corporate (group technology development GTD), divisional and individual factories. Long term R&D is mostly funded by Group Technology Development and the divisions, while short term development is funded more by the division or factories benefiting most. The structure is designed to ensure research is better focused on the requirements and needs of the factories. As a central resource for these research activities, technical development centres (TDC) figure 1.1, have been formed which focus on specific bearing technologies. The main manufacturing sites also have their own process and product development teams, although they mainly deal with short-term development and improvements.

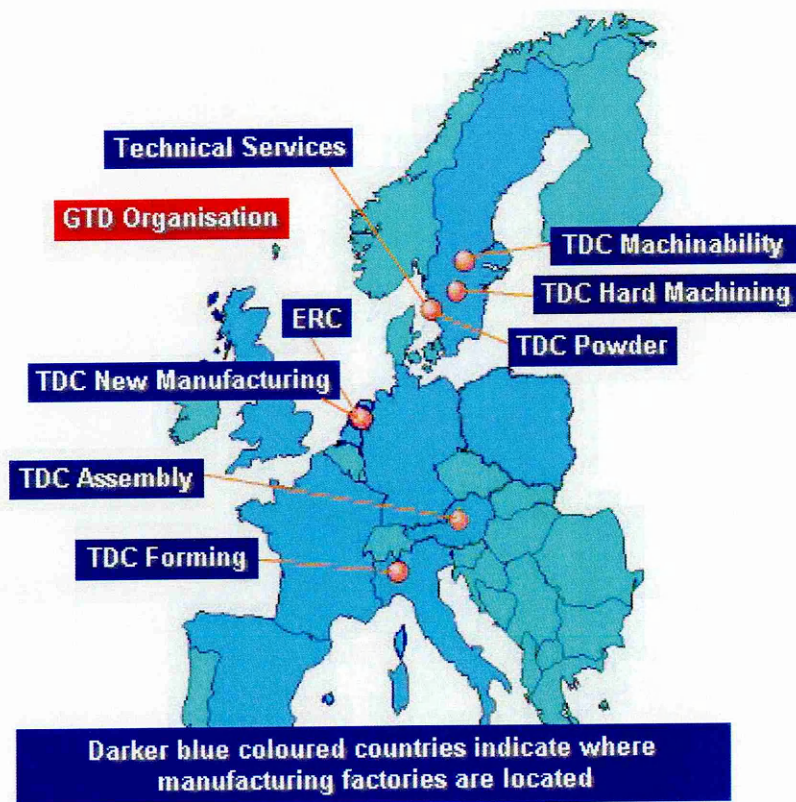


Figure 1.1: SKF manufacturing sites in Europe and location of technical development centres

1.3 Bearing Applications

Bearings impact all aspects of our daily lives from travelling using automobiles, trains, bicycles, inline skates, and airplanes. In the workplace bearings can be found in lifts and air conditioning systems. At home bearings are used in domestic appliances such as washing machines, dishwashers, vacuum cleaners, hand drills and lawn mowers.

Bearings are very important in other industries; they are essential for extraction of raw materials and manufacturing. Industries including mining, metal rolling, textiles and machine tools (supplying spindles for grinding, milling, and turning machines) rely on bearings. Power generation or any rotary machinery requires bearings such as electrical motors, dynamos and windmills.

1.4 The bearing industry

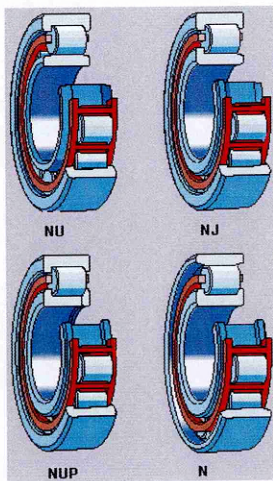
Standard bearing types are produced in high volume in automated production lines. Parts are made with very fast cycle times to very high precision in regard to dimensional size and surface finish. The technology for producing bearings is now readily available and competition within the marketplace is very high. This requires bearing manufacturers to differentiate their products through lower cost, higher quality, enhanced performance, added value by greater integration of component function particularly with electronics (mechatronics). In the future the ability to respond fast to customer requests to produce smaller lot sizes that may be more and more customized will be important. Service in the after market is also seen as a way of achieving customer loyalty and added value, by supplying a complete package for example to a large steel mill which may include the bearings, but also maintenance and condition monitoring which allows the customer to predict damage or failure of the bearing, who can subsequently plan in maintenance, avoiding any unplanned breakdowns which can be very expensive.

Manufacturing meets these requirements through continuous improvement. They also employ new technologies and processes to reduce manufacturing cost by decreasing process cycle times at bottleneck operations. This is achieved using cheaper processes and combining machining operations in one machine to reduce capital machine costs. Important is reducing non-value adding operations such as measuring and inspection; this requires processes, which are capable (consistent and stable). Resetting a production line to change from one product to another also needs to be fast to minimize production downtime and fast response to customer needs.

1.5 Standard bearing types

Roller and ball bearings generally consist of an inner ring, outer ring, rolling elements (balls or rollers) and a cage. In addition some have seals and are greased for life. The actual bearing is chosen depending on the application, which includes considerations such as speed, load and direction of loading. The common types of bearings are presented below:

Cylindrical roller bearings (CRB)

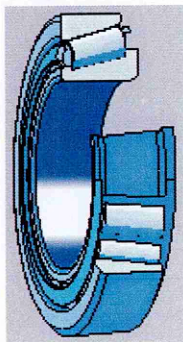


CRBs are mainly used for high radial loads. Axial loads can be accommodated depending on exact bearing design e.g. flanged inner ring. Their main applications are in car and truck gearboxes, compressors, fans, and pumps but also in heavy industrial applications such as metalworking, mining and construction equipment.

This project used the inner ring of a NU type CRB because of its simple geometry.

Figure 1.2: CRB bearing

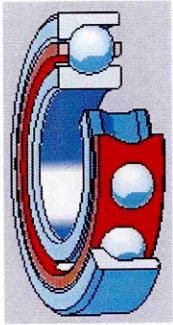
Taper roller bearings (TRB)



TRBs can accommodate combined axial and radial loads. Main applications include truck HUB units and gearboxes.

Figure 1.3: TRB bearing

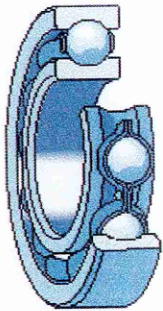
Angular contact ball bearings (ACBB)



ACBBs are often used in machine tools; they can accommodate radial and axial loads.

Figure 1.4: ACBB bearing configuration

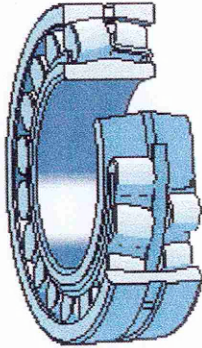
Deep Groove ball bearing (DGBB)



DGBBs can accommodate some combined load, but their main attribute is high rotation speeds. DGBBs are used in electric motors and fans

Figure 1.5: Deep groove ball bearing

Spherical roller bearings (SRB)



Can accommodate high radial loads but also a degree of misalignment. SRB are used in the pulp and paper and mining industries.

Figure 1.6: Double row spherical roller bearing

SKF's product range also includes thrust bearings, plain bearings, seals, other automotive special products, and linear motion systems to name a few.

1.6 Manufacturing route for bearings

Bearings are made up of a number of components including rings, rolling elements, and cage, but there are also a wide range of product shapes and sizes and even different bearing materials are used. This requires a wide range of manufacturing processes to be utilised in bearing production. Methods commonly used include pressing, stamping, forging, soft turning, cold rolling, injection moulding, casting, powder metallurgy, heat treatment, hard turning, grinding, honing, vibrofinishing, tumbling, lapping, and coating techniques such as phosphating and CVD.

The bearing component used for this work was a NU207 inner ring (cylindrical roller bearing) and the diagram below shows in more detail its production route.

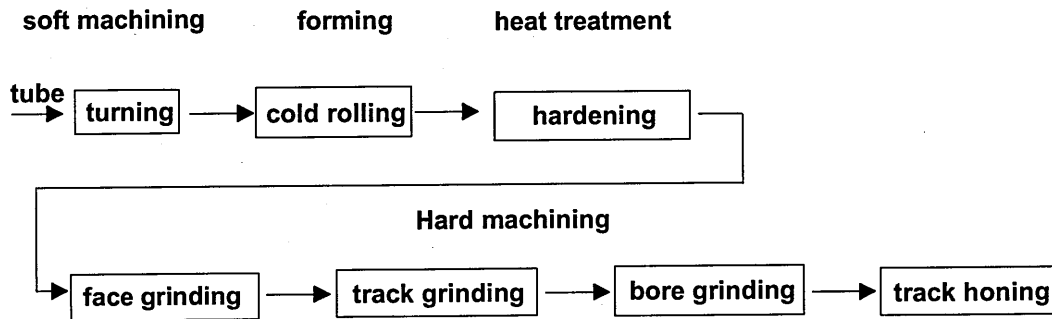


Figure 1.7: Manufacturing route for inner ring of CRB

Starting from tube, a blank is made by soft turning the part into approximately the correct volume for the cold rolling operation. Cold rolling can be considered a type of extrusion where the ring is rolled between two shaped mandrels to give approximately the correct ring dimensions, this operation reduces the number of tube sizes needed in stock since one tube can make a number of different ring sizes, it also work hardens the material and alters the microstructure through material flow. The ring is then hardened by heat treatment. The hard machining operations provide the final dimension accuracy and surface finish.

All these processes are linked and can influence following operations, optimisation of the process route therefore requires knowledge of the total process. For example grinding is often the bottleneck operation and much research is performed to make stiffer and faster grinding machines to remove material more quickly, while part of the problem is the distortion introduced by heat treatment which increases the machining allowances. While the grinding operation also has a significant impact on the honing operation, a rough surface requires more material to be removed by the honing to achieve the desired surface finish, and waviness produced by grinding must be removed by honing. Input ring roughness, also influences honing stone selection and stone wear.

The manufacturing process not only influences the product dimensions including shape, roundness and tolerances but also physical, chemical and mechanical properties of the surfaces, such as stress state, hardness, microstructure and surface topography which all have an influence on the bearing functionality.

2. Literature Review

This PhD study on surface finishing of bearing raceways combines both traditional and non-traditional machining methods in the form of honing and electrochemical machining (ECM) respectively, to improve the surface finish of a bearing raceway. This combined process called electrofinishing had preliminarily been investigated by SKF and had shown promising results in regard to improved surface finishing with fast cycle times. This literature survey will firstly discuss traditional bearing finishing techniques, which is followed by an introduction to electrochemical machining with emphasis on surface finishing. Honing was found to dominate the electrofinishing process so a more in-depth view of honing is presented next to demonstrate the complexity and often empirical nature of the process. The following section looks at other surface finishing techniques including hybrid machining processes. Finally a brief look at how the tribology of a bearing surface can influence the bearing performance citing developments by bearing manufacturers on new surface finishes and reported enhanced bearing performance as a result.

2.1 Traditional surface finishing techniques used in the bearing industry

Most traditional surface finishing techniques apply abrasives onto the workpiece surface to remove a small amount of material by abrasion. The abrasive can be applied as

1. Bonded abrasive, e.g. grinding wheel or honing stone
2. Coated abrasive e.g. superfinishing tapes or belts
3. Free abrasive e.g. lapping slurry

2.1.1 Bonded abrasives

Bonded abrasives comprise abrasive grits (hard and sharp particles) held in a bond (matrix) material, often with fillers and additives to act as lubrication aids or to induce porosity. The different components of the bonded abrasive are critical to its correct operation and are selected for the specific machining operation taking into account the workpiece material, material removal, surface finish needed and process parameters.

Bonded abrasives are used in grinding wheels and honing stones. While they are designed to work in different ways, for example grinding wheels frequently must be redressed while honing stones are self dressing, the underlining material removal and wear mechanisms are similar.

2.1.1.1 Grinding

Although grinding is not strictly a finishing technique within the bearing industry, there are a few cases where the ground surface is adequate for the bearing running surface like the outer ring of a spherical roller bearing where the roughness and texture are used to control friction between the roller and outer ring to prevent skewing of the roller. There is also a close link with honing, as mentioned, the output quality from grinding has a large influence on the honing operation.

Main characteristics of grinding:

- a) Generally feed controlled
- b) Line contact between grinding wheel and workpiece
- c) Grinding fluid used to cool, lubricate and remove grinding chips

Grinding can be performed on centres or centreless in plunge or throughfeed mode.

Grinding is used to remove material fast, produce workpiece form and dimensional size. The grinding wheel must be trued to give the required shape and reduce run-out followed by a dressing or conditioning operation to provide the correct cutting surface.

The quality of the grinding depends very much on the grinding machine characteristics. Stiffness, vibration sources, the dressing system employed as well as the selection of the grinding wheel and process parameters such as feed rate, wheel speed, workpiece speed, clamping method, workpiece, type of grinding fluid and method of applying fluid etc. all affect the ground quality.

2.1.1.2 Honing

Honing is an abrasive machining process used primarily to improve the surface characteristics of a functional surface. Although considered a minimal material removal process, it is increasingly used as a final machining step to achieve or correct part shape and dimensional accuracy.

Honing can be divided into short and long stroke honing. Short stroke honing is used for bearing raceway finishing, however long stroke honing which is used for finishing of bores such as cylinder liners is a good example of how the functional properties of the surface can be improved by the finishing operation to give enhanced performance during operation.

When honing is applied to produce very smooth surfaces the process is often called superfinishing to differentiate it from honing which has comparatively a higher stock removal capability and rougher surface finishing, which is generally the result of coarser abrasive grit sizes employed.

2.1.1.2.1 Short stroke honing

The superfinishing stone is shaped to conform to the workpiece. The stone is then applied with an oscillation motion onto the rotating workpiece, figure 2.1. The main characteristics of the superfinishing process include:

- a) Large contact area
- b) Short stroke oscillation of superfinishing stone
- c) Low workpiece speed
- d) Moderate pressures (under force control)

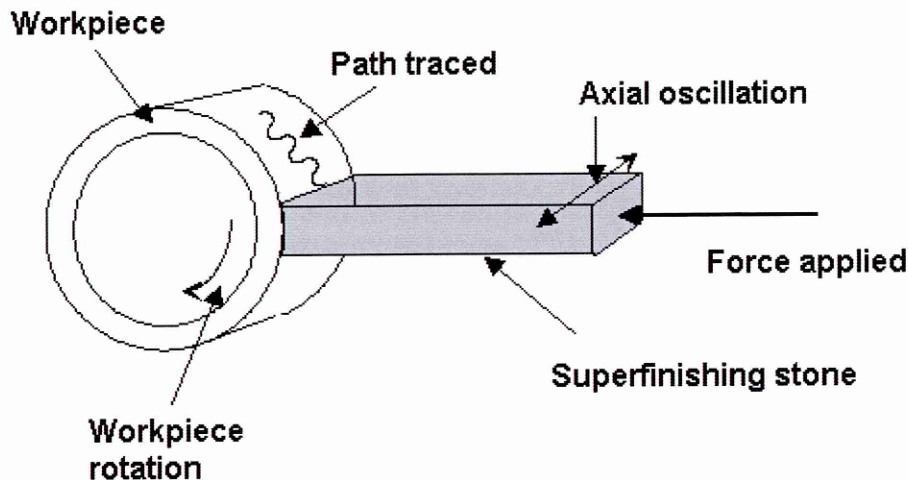
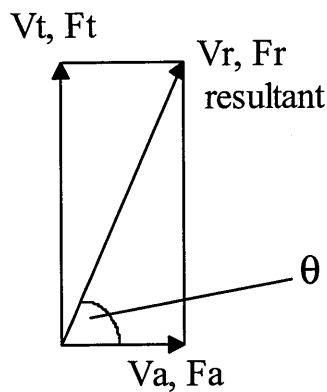


Figure 2.1: Schematic of stone superfinishing

Usually superfinishing is performed using neat honing oils supplied into the working area via nozzles. The oil has two main objectives 1) provides lubrication over the large contact length to reduce stone wear, and 2) flush away any adherent chips which can cause stone loading. To this end the neat oil often has extreme pressure (EP) additives to prevent welding of chips to the stone surface. In some high precision applications the lubricant also helps control the workpiece temperature, which gives better dimensional size control. Filtering of the metalworking fluid is needed to prevent entrained debris from causing deep scratches. The superfinishing stone is often treated by impregnating with a lubricant additive directly into the stone structure so that it is directly available at the stone / workpiece interface. Additives include sulphur and wax that activate at defined temperatures occurring in the cutting zone.

The oscillation of the superfinishing stone reduces loading and increases the rate of material removal. The oscillation speed can be controlled to produce a certain surface pattern i.e. crosshatched pattern. The motion of the honing stone as a result of the stone oscillation and workpiece rotating, traces a sinusoidal path around the workpiece. The resultant stone velocity (V_r) relative to the workpiece is the vector sum of the circumferential velocity (V_t) and the axial oscillation velocity (V_a), figure 2.2. The crosshatch angle thus produced being dependent on the relative speed of the workpiece and oscillation.



Where

d_w workpiece diameter

n_w the rotation speed of workpiece

$2A$ oscillation amplitude

f_s oscillation frequency

t time (V_a depends on time i.e. at top and bottom of stroke V_a is zero)

Figure 2.2: Vector diagram showing resultant stone velocity and force

The tangential velocity depends on the workpiece rotation speed and diameter.

$$V_t = \pi d_w n_w$$

While the axial oscillation velocity varies as a sine function with time such that at the top and bottom of the stroke, V_a is zero and is a maximum in the middle of the stroke.

$$V_a = 2\pi A f_s \cos(2\pi f_s t)$$

The resultant stone velocity is given by

$$V_r = \sqrt{(V_a)^2 + (V_t)^2}$$

The resultant stone velocity is at an angle

$$\theta = \tan^{-1}\left(\frac{V_a}{V_t}\right)$$

which has a maximum value when $\cos(2\pi f_s t) = 1$ therefore

$$\theta_{\max} = \tan^{-1}\left(\frac{2A f_s}{d_w n_w}\right)$$

and the maximum resultant velocity

$$V_{r_{\max}} = \left[(2\pi A f_s)^2 + (\pi d_w n_w)^2\right]^{\frac{1}{2}}$$

Under typical superfinishing condition, the V_a term is much smaller than the V_t term so

$$V_{r_{\max}} = \pi d_w n_w \approx v_t$$

A similar analysis can be carried out for the force components of superfinishing. A normal force F_n is applied to the ring, which results in a cutting force F_r in the direction V_r which is the vector sum of the force components in the circumferential direction F_t and the axial direction F_a .

$$F_r = (F_t^2 + F_a^2)^{\frac{1}{2}}$$

Again F_a is much smaller than F_t so

$$F_r \approx F_t$$

The power expended during superfinishing given by the axial component can also be neglected so that

$$P \approx F_t V_t$$

Using the power required and the material removed, it is possible to obtain the specific energies for the superfinishing operation, which can be used to analyse stone behaviour. As shown by Malkin² using theory developed for grinding, it is then possible to differentiate between the energy expended for actually cutting (material removal) and ploughing. This work has shown that the prevailing material removal mechanism for superfinishing are similar to grinding.

The most common ways to apply honing to bearings include: plunge honing and through feed honing, see figure 2.3 below.

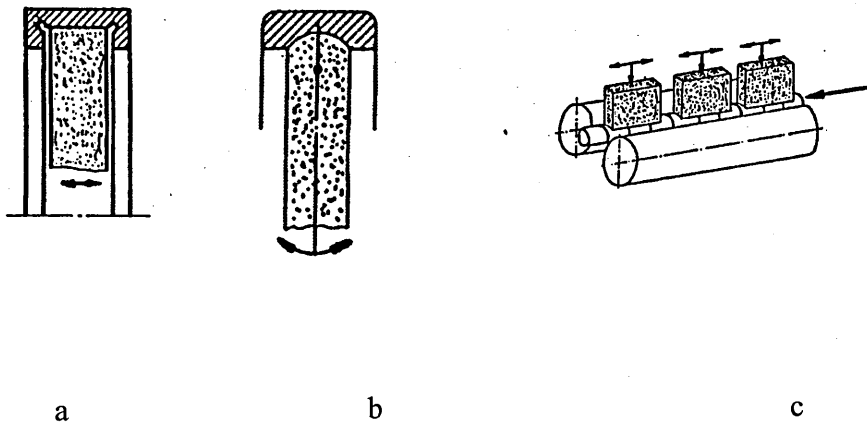


Figure 2.3: Common ways to apply honing stones, a & b) plunge and c) throughfeed (from SKF hard machining course)

Figure a & b show plunge honing where the oscillating honing stone with the correct form is plunged onto the surface of the rotating ring. Case a) is for a CRB outer ring with a linear oscillation of the stone, case b) is for a DGBB, which because of the groove shaped raceway, the oscillation motion must be through a swivel pivot. Plunge honing can be used for rough and fine finishing using the same stone by changing the process parameters. For example rough honing can be accomplished by slow rotation of workpiece with fast stone oscillation and finishing can be achieved by the reverse, high workpiece speed and slow oscillation. However ultimately the surface finish and material removal depend on grit size so often, double stage honing is used employing two different hone specifications, for rough and fine surface finishing. Double stage honing can be performed either on the same machine or using two machines depending on productivity requirements.

Figure c) demonstrates the throughfeed system that is typically used for bearing rollers. The workpieces are rotated and fed to the different honing stations by drive rolls, which are set at a slight angle to produce the feeding motion. Throughfeed systems can have many honing stations and the honing stones can be varied between stations so that a course grit stone can be used initially to achieved material removal and fine grit stones are used at the end for surface finishing.

Standard honing attachments are available on the market, which can be fixed onto the tool holder of a lathe, or another frame such as shown below in figure 2.4. These offer simple to use and low cost superfinishing capability.

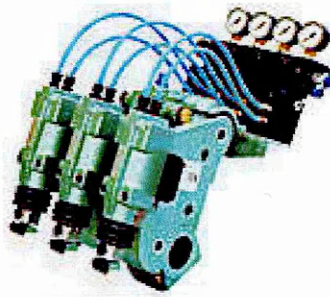


Figure 2.4: Stone superfinishing attachment from Supfina³

There are also a number of companies such as Supfina and Thielenhaus⁴ who produce tape and stone superfinishing machines dedicated to bearing raceway finishing, but also for other applications such as fuel injectors, camshaft, crankshaft and valve tappets.

Honing was first introduced into the bearing industry to prevent a problem known as false brinelling, which occurred when assembled bearings were transported by rail. The motion of the trains resulted in transmission of vibrations between the bearing rings and rolling elements, which lead to damage on the bearing raceway. The damage resulted because after grinding a thin white layer of poor integrity material remained.

The gentler action of the superfinishing stones results in low heat generation and therefore no thermal damage, and its detrimental effects. These effects introduce tensile stress, microstructural changes and poor surface integrity. Today with improvements in grinding the main benefits that honing imparts to a bearing surface include:

1. Introducing compressive surface stresses beneficial for fatigue life

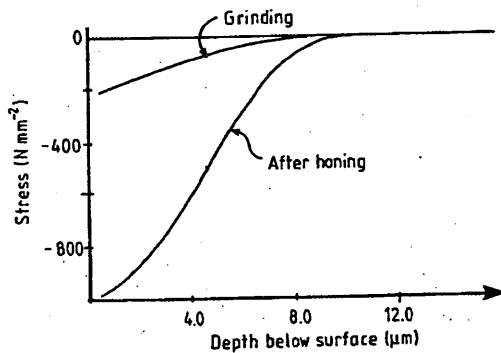


Figure 2.5: Stresses left after honing and grinding⁵

Generally when grinding is performed correctly it will produce a small compressive stress in the top surface of the workpiece. When grinding parameters are set incorrectly however, workpiece burn can occur from high grinding temperatures. This can result in tensile stresses being formed on the surface and possible softening and microstructural changes to the workpiece. Honing on the other hand is a gentler process that introduces higher levels of compressive stresses, deeper into the surface. Typically compressive stresses range from 600 - 850 MPa to a depth of 5-10 μm.

2. Creating desired surface texture and roughness

The surface roughness as well as texture is critical to a bearing's performance in regards to friction, wear, lubrication and fatigue, as will be discussed later. Textures typically produced by honing include crosshatch and plateau patterns.

A cross hatch pattern can be produced by changing the workpiece speed and/or stone oscillation frequency, the cross hatched angle will depend on the operating parameters, it is also possible to produce predominately circumferential grooving. The crosshatch pattern is believed to aid in lubricating film build-up by forming a barrier to lubricant flow and leakage from the contact.

On rotating sealing surfaces it is claimed⁶ that a crosshatch pattern can improve the wiping action, reducing the risk of ingress of debris and dirt past the seal. A low angle crosshatch is found to decrease the friction while larger angles increase the surface ability to trap and retain lubricant.

Plateau honing employs a two stage honing operation, firstly a coarse grit stone is used to generate deep grooves and then a finer grit stone to remove the peaks giving a surface with plateaus of low roughness for load bearing and deep valleys acting as lubricant reservoirs.

3. Improving geometric form such as roundness, waviness and raceway cross track profile

A round part after grinding is never perfect as it has roundness errors and waviness generated by the grinding process resulting from vibrations transmitted across the line contact between grinding wheel and workpiece. The large conforming contact associated with honing allows for improvement of roundness and waviness. The stone width has a large influence on reducing roundness and waviness. See figure 2.6 below, which shows a ring with exaggerated waviness. The honing stone acts under force control and the dynamic response of the honing attachment and stone will influence which frequency waves on the surface will be cut and which are passed over. Also the self dressing characteristics of honing stones means that high points are cut faster combined with a higher real contact pressure at the peaks.

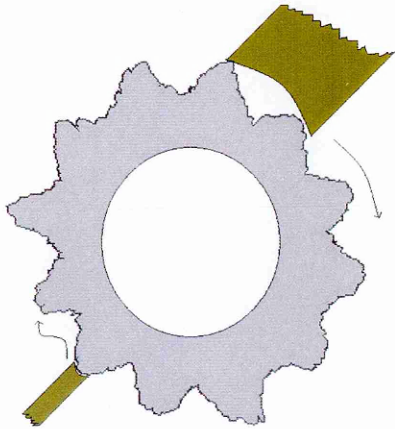
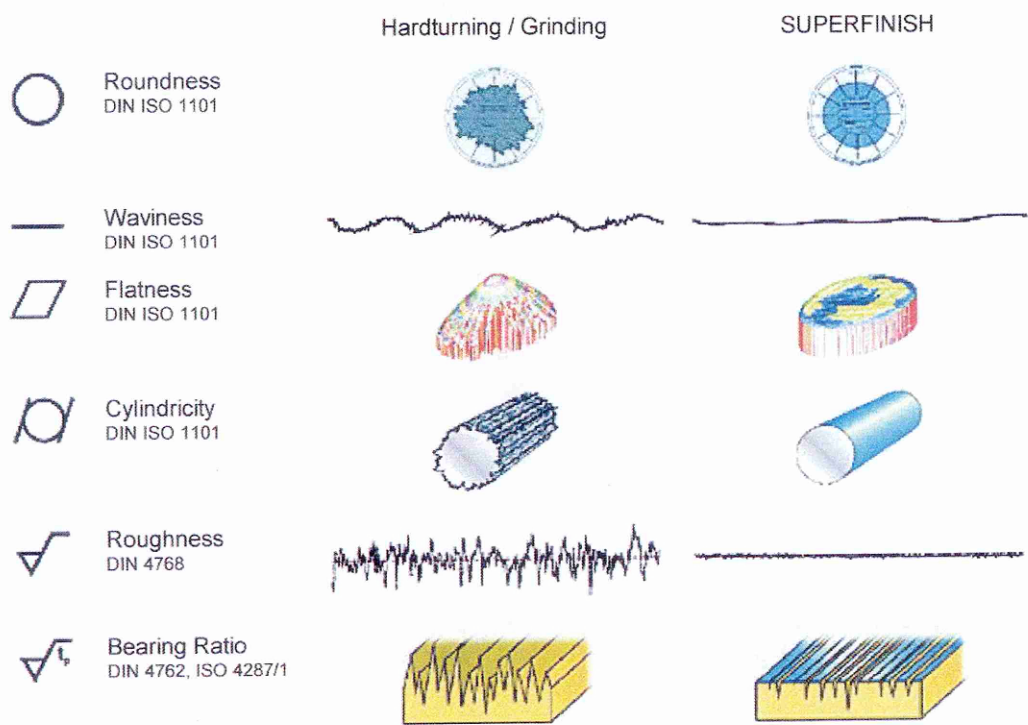


Figure 2.6: Schematic showing influence of stone width on waviness reduction

In addition it is possible to add waviness to the workpiece when operating at half ratios of axial oscillation frequency to rotation speed. Although in reality this is not seen due to uncontrolled variations in rotation speed⁷.

Figure 2.7 is taken from Supfina's web page, which pictorially summarizes the key benefits of superfinishing of parts which had been ground or hard turned.



SUPERFINISHING - Benefits

- | | | |
|------------------------|--------------------------|--------------------|
| • short operating time | • lower tooling costs | • low noise level |
| • lower friction | • low initial investment | • safe operation |
| • less wear | • low operating costs | • high flexibility |

Figure 2.7: The benefits associated with superfinishing³

2.1.1.2.2 Long stroke honing

Long stroke honing is used for the finishing of bores of bushings, hydraulic cylinders, connecting rods and cylinder liners. It is mentioned here because considerable research has been performed on relating the honed surface topography with the functional properties and performance of cylinder liners.

Long stroke honing^{8,9,10} applies the honing head to the bore of the workpiece. The expandable honing head rotates and is reciprocated (stroked) through the bore. The rotating and axial reciprocation motion provide for a crosshatch pattern as described for short stroke honing.

The honing head can have one, two, four or more hones. Selection of honing stone¹¹ (abrasive type, grit size, bond) and operating parameters influence the roundness, cylindricity, roughness and material removal from the bore. Long stroke honing can improve bore form errors¹² such as out of roundness, waviness, taper, and barrelling introduced from previous processing such as heat treatment and machining. Incorrect selection of stone length and stroke length can however, introduce such errors. Modern honing machines with greater in-process measuring capability can control the stroke position⁸ to ensure cylindricity of parts, this is particularly important for blind holes where the hone must remain at the bottom of the hole for longer to prevent tapering.

Single stroke honing^{13,14} using diamond or CBN plated tools can also be applied to bores. Here the tool has an electroplated sleeve, which is expandable to compensate for tool wear, however no expansion occurs during operation. The tool is designed to pass through the hole and remove a desired amount of material to give the hole to size with correct surface finish in a single pass. The grit size is chosen to achieve the material removal rate and surface finish.

An internal combustion engine has many moving parts, for long life and efficient operation many studies have been performed to optimise the surfaces of these moving parts to minimize wear, friction and to improve engine performance. For the case of the cylinder - piston ring the surface topography of the cylinder has been claimed to influence friction, anti-wear, anti-scuffing, blow-by and oil consumption¹⁵. The initial surface finish also greatly affects the running-in characteristics of the cylinder¹⁶.

Running-in is the beneficial wear by removal of surface peaks for improved conformance between the surfaces during first operation. The surface produced has truncated peaks and deep valleys. It is found that a very smooth surface has high wear resistance during running in but more inclined to scuffing. A rough surface wears quickly during running, promoting quick conformance. Rough surfaces however, also have increased oil consumption and show increase wear of the Cr plated piston ring. Engine manufacturers would like to reduce the running-in period. One proposed method is to produce an equivalent run-in surface during the machining process¹⁷. This plateau surface texture can be produce by a two stage honing operation, firstly by using a coarse grit honing stone to produce deep valleys, followed by a fine grit stone to remove the surface peaks to produce a low roughness plateaus. A surface produced in this way has high load bearing plateau region and deep

valleys for oil retention and as a depository for wear debris¹⁸ and containments. The volume of space available for lubricant storage or real oil capacity V_{OR} is an important specification for cylinder liners¹⁶. The plateau structure¹⁷ shows fast run-in, and lower friction and oil consumption. This plateau surface shows high wear initially but drops off to a low level compared to a cross hatched surface of similar roughness so that the overall wear is lower. This work additionally showed that the friction of the plateau surface was lower under mixed lubrication conditions compared to a normal honed surface with the same R_z . If the deep valleys are not considered, the plateau structure has a lower roughness and hence less asperity contact. Under hydrodynamic lubrication the deep valleys do not influence the friction and so the friction for the two surfaces is the same. Other studies¹⁹ also show that a crosshatch angle of less than 45° i.e. transverse roughness restricts lubricant side flow and enhances squeeze film action, which maintains a lubricating film for lower friction.

A more recent machining method²¹ for cylinder bores by Gehring is designed to produce a plateau structure by using laser machining to produce deep valleys ($5\text{ }\mu\text{m}$ deep x $30\text{ }\mu\text{m}$ wide with a $600\text{ }\mu\text{m}$ separation, and cross hatch angle 30°) followed by honing to give the low surface roughness ($1\text{ }\mu\text{m}$ R_z). The method can also laser machine a pattern of slots or pits. This new laser honing method was reported to reduce oil consumption, lower contamination of the catalyser, reduced emission, reduced wear, lower friction and fuel consumption.

The metallurgy of the surfaces²⁰ in addition can be important, i.e. as for a grey cast iron cylinder, for which exposed soft graphite flakes can act as a lubricant or can allow hard particles to become embedded reducing wear. Machining methods investigated to prevent smearing and covering up of these flakes include ECM and superfinishing tapes.

The above example shows that considerable improvements can be made to the performance of a functional surface by correctly engineering the surface topography.

2.1.2 Coated abrasives (Tape superfinishing)

Coated abrasive products and their applications have developed considerably over the last two decades. Conventional coated abrasives include belts for grinding and paper and fibre backed tape such as sandpaper. Modern coated abrasives used for superfinishing make use of thin polyester backing, which is smooth, and abrasive grains. The abrasive grains have a controlled size distribution, giving a much more uniform product. Developments in abrasive types and micro replication techniques have allowed coated abrasives to become more engineered and consistent.

Traditionally superfinishing is accomplished using honing stones or superfinishing stones known as bonded abrasives. The problems with honing stones are their lack of consistency and controllability. Stones have a tendency to glaze/dull or become loaded giving material removal and surface finish variations. Stone properties vary between stones and through

individual stones, which can give an inconsistent process. Such problems then rely heavily on the operator to correct these problems. Coated abrasives are designed to present a controlled open and aggressive cutting surface to the workpiece which when combined with continuous or step feed and oscillation gives consistent and predictable high quality surface finishes. A tape superfinishing attachment is shown below figure 2.8. These attachments provide tape feed either stepwise or continuous and also tape oscillation.



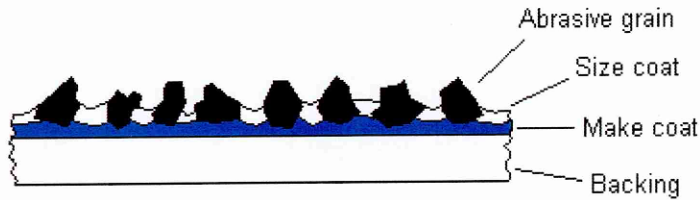
Figure 2.8: Superfinishing attachment

2.1.2.1 Coated Abrasives Basics

The structure of a coated abrasive^{22,23} is shown in figure 2.9. It consists of a thin strong **backing** material onto which an adhesive **make coat** is applied. A monolayer of **abrasive** is then electrostatically coated so that their sharp cutting edges are exposed perpendicular to surface. A second layer of adhesive a **size coat** is then applied to anchor the abrasive to the backing. Often fillers or grinding aids are added to the make coat to improve performance. For very fine grit abrasives, a slurry coating is used which means the grits are covered and some wear is needed for effective working.

Backing Material

There is a range of backing materials are available depending on the application including paper, cloth, fibre and polyester films. For microfinishing applications polyester films are important. The backing (or substrate) strongly influences the distribution of abrasive heights (i.e. tape topography) and so therefore greatly influence the uniformity and consistency of the achievable surface finishes. The ultimate in backing uniformity is achieved with polyester and reinforced polyester films that show high uniformity, quality, smoothness combined with high strength results in a uniform abrasive topography less likely to cause deep scratches.



Typical coated abrasive

Figure 2.9: Schematic of superfinishing tape

Abrasives

The abrasive type and grain size has a major influence on the surface finish but also on the removal rate. A coarse grain will have high material removal capability but poor surface finishing while finer grains remove less but give a finer finish. Grains are more precisely graded with a narrower distribution of grain sizes so that when coated onto backing they give a more uniform abrasive height above the tape thereby reducing deep scratches. The fine abrasive grain sizes used for finishing applications are extremely small so are not classified by the usual mesh number or grade number but rather by the actual grain size in microns.

Types of abrasives ^{24,25} used are described later but include fused alumina, sintered alumina, sol gel abrasives and superabrasives like diamond and CBN.

Grinding aid + fillers

Fillers ^{26,27,28} are intended to produce porosity, promoting cooler grinding or enhanced grinding. Fillers include hollow alumina bubbles, cryolite and pyrite.

Alumina bubbles are hollow spheres of aluminium oxide to control porosity and inhibit loading.

Cryolite (sodium hexafluoroaluminate) used in resin bonds and is found to melt when the temperature reaches 950 °C and the reaction provides a cooling effect but is less effect on carbon steel. Pyrite (iron sulphide) is intended to react with the metal surface and enhance grinding. Sulphide fillers like Pyrite perform better on stainless and carbon steels.

2.1.2.2 Types of tapes

Belt grinding

Belt grinding^{29,30,31,32} for high stock removal has always been a limitation for conventional coated abrasives, though important advancements have been made over the past decade, including new stronger backing materials, pressure resistant adhesives and improved tougher abrasives like the ceramic alumina and Zr toughened alumina.

Another development has been structured abrasives, which are designed for a degree of abrasive wear.

Monolayer tape

Conventional monolayer³³ coated abrasives are coated such that the sharp abrasives are oriented perpendicular to the tape surface by an electrostatic coating technique, giving a sharper more aggressive product which grinds at lower specific energies. Wear of the abrasive however results in an initial break-in period (can be ~30 % of belt life) where surface finish and aggressiveness varies. A used belt produces a finer surface finish this inconsistency in finishing is usually undesirable. New structured coated abrasives have been developed which are capable of maintaining consistent material removal rate and surface finish by self dressing which provides new sharp cutting points in an analogous way to superfinishing stones.

Structured tapes

^{34,35,36,37}Clustered coated abrasives (e.g. 3M Multicut) consist of fine abrasive grains bonded together. These larger particles are coated onto the backing. The clusters are very aggressive and extend the life of the abrasive tape.

Apex was developed by 3M using micro replication technologies. A three dimensional structure is produced on the tape. The tape surface structure can be made of any shape (pyramids, cones, cubes etc.). Within these shapes is an abrasive composite of bond and fine abrasive grains. These shapes wear uniformly exposing fresh unused abrasive giving a more consistent surface finish and maintaining a high rate of cut for extended periods of time while generating less heat associated with dull grains because of sharper and cooler cutting action. The open structure allows chips and lubricant to flow out of the contact.

2.1.2.3 Superfinishing or microfinishing

If only surface finishing with minimal material removal is required as in the finishing of bearing raceways then a monolayer coated abrasives with fine abrasive grains can be used. 3M produce microfinishing films where the abrasive is electrostatically coated onto a 5 mil polyester backing giving highly oriented sharp cutting points for more aggressive cutting.

Lapping film is slurry coated onto a 3 mil polyester backing so that the very fine abrasive is covered by the adhesive resin coating, therefore a degree of bond wear is needed to initiate cutting. Usually a sequence of superfinishing tapes is used with gradually decreasing grain size. Development work on roll finishing^{38,39,40} provides information on how process parameters affect the process.

Influence of tape finishing parameters

1) Roll direction

The rotation direction of the roll (workpiece) shows little influence on the surface finish although care is needed to prevent the tape being pulled out when the tape and the workpiece rotate in the same direction.

2) Contact force

Higher contact forces give higher rates of surface finishing.

3) Workspeed

Higher workspeed reduces finishing time and produces slightly finer surface roughness.

4) Tape feed rate

Continuous or indexed tape feed presents fresh abrasive in the cutting zone. A lower tape feed rate gives better surface finish as the abrasive can breakdown giving finer finishes although too low a speed can result in tape loading. Typical tape feed rates are between 8 - 10 cm / minute.

5) Oscillation frequency

Higher oscillation frequency gives increased rate of surface finishing or material removal as a result of crosshatch abrasion. By controlling the workspeed and the oscillation speed it is possible to produce crosshatched patterns similar to stone honing. Patterns from linear to slight crosshatch to high angle crosshatch angle can be produced. These patterns can add certain functionality to a surface like oil retention.

6) Forming roll/backup

Hard backing rolls are designed to mirror part geometry or semi hard roll that conforms to the part being finished. Hard backup rolls give deeper penetration of the grits and rougher surface finishes.

7) Abrasive grain size and sequence

Finer mineral grain size gives lower surface roughness, however it is found that a fine tape is not able to remove deep scratches (likely because of lower material removal). A sequence of tapes is therefore recommended starting with the aggressive microfinishing tapes and passing through a sequence of finer grit sizes through to lapping films. The exact sequence and number of steps depends on the application and surface finish desired.

2.1.3 Free abrasive: Lapping

In the bearing industry lapping is commonly used for finishing of steel and ceramic balls.

Lapping is a free abrasive process, where the abrasive, often fine grit diamond is applied as a slurry or paste in water, grease or oil. For ball lapping the balls are placed between laps, which can be made from cast iron. The laps have circular grooves machined onto them to control the movement of the balls. Rotation of one of the laps results in circular movement of the balls around the lap onto which is superimposed a spinning motion of the balls ensuring complete coverage of the balls. The hard abrasive becomes embedded into the soft lap and acts as a cutting point.

Material removal is very slow and hence its use is primarily to improve the surface finish. The surfaces produced depend on the material removal mechanism but are generally isotropic. Lapping is also used to produce smooth flat parts such as gauge blocks or sealing surfaces.

2.1.4 Mass finishing

Mass finishing^{41,42,43,44} includes vibrofinishing, tumbling, and centrifugal finishing. These techniques are generally batch processes, where the workpieces are placed in a container with an abrasive media. Motion between the abrasive media and the workpieces result in abrasion and burnishing. The force between the abrasive media and workpieces can be provided by gravity, centrifugal or vibratory action.

The abrasive media are much larger ($> \text{mm}$) than in other superfinishing techniques and can have a range of different shapes e.g. cones and pyramidal. The media is often made from metal or a ceramic. The process is usually performed wet with water and other wetting agents, lubricant, rust inhibitors, anti foaming agents.

The technique is used in the bearing industry for deburring, blending of sharp corners and surface finishing of components such as cages and rollers. Mass finishing techniques are simple to run and cheap requiring little operator intervention. There are however disadvantages, principally relating to it being a batch process whereas most bearings are produced with an in-line channel concept. Processing time can be of the order of hours and the cost of disposal of the waste effluent from mass finishing can also be important, although dry mass finishing techniques are becoming available. Chemical accelerated vibrofinishing, to speed up the surface finishing rate, and continuous or through-feed systems are also becoming available.

2.2 Electrochemical machining

2.2.1 Introduction

Electrochemical machining (ECM) is classified as a non-traditional machining method used for shaping, deburring, forming and finishing of parts. With the exception of the aerospace industry and deburring, ECM has had limited impact on manufacturing industry.

ECM is an anodic dissolution process where the workpiece is made the anode and the tool the cathode in an electrochemical cell. The passage of current between the electrodes results in anodic dissolution. High current densities ($10 - 300 \text{ A/cm}^2$) can be used giving high material removal rates ($25 - 30 \text{ cm}^3/\text{min}$ are commonly achieved). An electrolyte must be used to complete the electrical circuit between the anode and the cathode. The electrolyte also has the function of removing dissolution products and heat generated in the gap by Joule heating effects. The combination of heat and reaction by-products can lead to sparking in the gap leading to electrode damage, therefore high electrolyte flow rates are required to remove the heat. Small inter-electrode gaps ($0.1 - 1 \text{ mm}$) are used to give greater fidelity to the contours of the cathode tool and greater dimensional control, this results in the use of high pumping pressures. An ECM system then consists of i) power supply, ii) an electrolyte system including pump, filters, electrolyte storage tanks, and recycling and iii) electrochemical cell incorporating tooling and electrodes.

ECM has many advantages over traditional machining methods such as grinding and honing. The ECM process is independent of material strength and hardness explaining its applicability to the aerospace industries^{45,46,47}. The general trend in aerospace material development is for stronger and harder materials to withstand the operating conditions found in a turbine engine. To machine these harder and harder materials, cutting tools have also developed from using carbon tool steel, high-speed tool steels, tungsten carbide tools, and ceramic cutting tools. For very hard materials, grinding with abrasive wheels made from alumina, CBN, SiC and diamond can be used. Such cutting tools become expensive and when coupled with small cutting depths, longer cycle times and tool wear, ECM becomes very attractive.

When machining comparatively softer materials like bearing steels, the advantages are not so clear when competing with conventional grinding and honing. ECM is a newer process and is perceived as risky and untested, while conventional machining has a longer history and a proven track record within the bearing industry.

Electrochemical deburring has found greater use in the automotive industry, where sheet metal forming and stampings leave burrs and sharp edges, which can be dangerous. A pulsed ECM current can concentrate removal at these points removing burrs or rounding them off. Deburring of holes, in particular cross-holes inside components such as diesel injectors⁴⁸ has also been a successful application of ECM deburring. Table 2.1 shows a list of advantages and disadvantages of the ECM process.

Table 2.1: Advantages and disadvantages of the ECM process as a surface finishing technique

Advantages of ECM	Disadvantages of ECM
Fast material removal rate	Cost of power supply and tooling
Good surface finishing	Corrosive electrolytes (fixtures need to be made of stainless steel etc.)
Independent of material hardness and strength	Hydrogen gas evolution at cathode
No tool wear	Workpiece needs to be conductive
Low stresses	Some dedicated tooling
No burrs	
Low noise machines	
Automation	
Machine large area in one operation	
Relatively clean, safe process (no oils),	

2.2.2 Electrochemistry for ECM

Electrochemical machining is an electrolytic material removal process with similarities to electroplating, electroforming and electropolishing. A simple ECM cell, figure 2.10 consists of an anode (the workpiece), a cathode (the tool), a conductive media (electrolyte) and a voltage source. The application of a voltage results in the anodic dissolution of the workpiece and a flow of current through the cell.

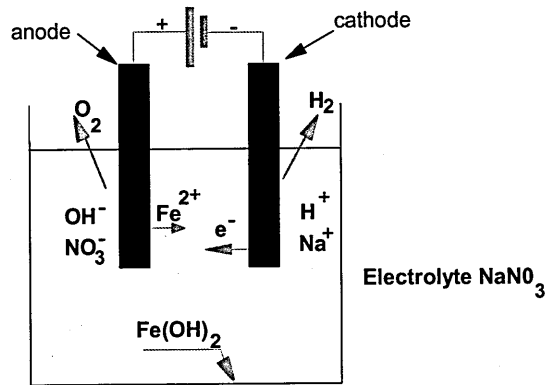


Figure 2.10: Schematic of electrochemical cell

When an electrode is placed in an electrolyte a dynamic equilibrium is formed between the metal atoms entering into solution and the discharge of ions from the solution.

$M \leftrightarrow M^{z+} + ze^-$ z is the valency of metal M

The electrons left contribute to the formation of an electrical double layer, transfer of ions will cease when the energy required to dissolve is less than the work necessary to pass the ion across the double layer.

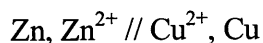
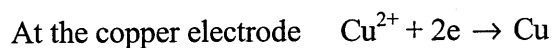
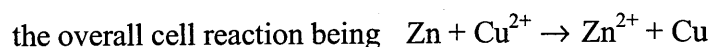
The Nernst equation is used to calculate the electrode potential difference between a metal and its ions in solution.



$$E = E_0 + \frac{RT}{zF} \ln \frac{[M^{z+}]}{[M]}$$

where E_0 is the standard electrode potential, R is the Gas Constant, T is the temperature and z the number of electrons involved in the reaction.

The Daniell cell is often given as an example of an electrochemical system. Convention means that the cell is written so that current flows from left to right



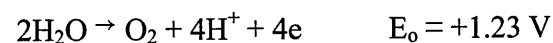
The emf of the Daniell cell is found from subtracting the electrode potential of the left hand electrode from the right hand electrode.

so $E = V_{\text{right electrode}} - V_{\text{left electrode}}$

$$E = +0.34 - (-0.76) = +1.1 \text{ V}$$

In ECM usually two different materials are used for the anode and cathode. An emf will be produced either in the direction of or opposed to the external power supply. For the ECM of iron with a copper cathode, the emf of the cell is +0.78 V and so Fe should preferentially dissolve, however the emf is so low that the dissolution rate is low. By applying an external potential across the cell the metal removal rate can be increased depending on direction of applied potential.

The above calculations were made using standard electrode potentials where all the concentrations were taken as unity. The emf of a cell is actually concentration (and temperature) dependent, which the Nernst equation takes into consideration. This is particularly important when reactions involving hydrogen or hydroxyl ions exist since the concentration of these species is determined by the pH. For example the reaction for the evolution of oxygen:



The electrode potential is given by Nernst equation:

$$E = E_o + \frac{2.303RT}{zF} \log_{10} [O_2][H^+]^4$$

$$= 1.23 + \frac{2.303RT}{zF} \log_{10} [H^+]^4 + \frac{2.303RT}{zF} \log_{10} [PO_2]$$

definition of pH = - log $[H^+]$

It can be seen that the electrode potential is affected by pH and oxygen partial pressure. Similarly machining of many metals in alkaline or neutral electrolytes results in the formation of hydroxides of low solubility, which precipitate out. Consequentially the metal ion concentration in the electrolyte remains low and the electrode potential made less positive. Conversely in acidic solutions the ion concentration in the electrolyte will continue to increase and the potential becomes more positive.

Pourbaix diagrams are useful aids in ascertaining the possible reactions and how likely they are to occur in a range of potentials and pH. There are several chemical species that can form from the reaction of iron with water. The reaction most likely will result in the largest decrease in free energy i.e. thermodynamically favourable, but tells nothing about the kinetics of the reactions i.e. the rate of the reaction.

The Pourbaix diagram can show the stable equilibrium phases on a potential/pH plot. For the iron-water system, figure 2.11, the various reaction products under different pH and potential conditions are shown. The domains where iron is immune, passive or active can also be seen, at least from a thermodynamic point of view.

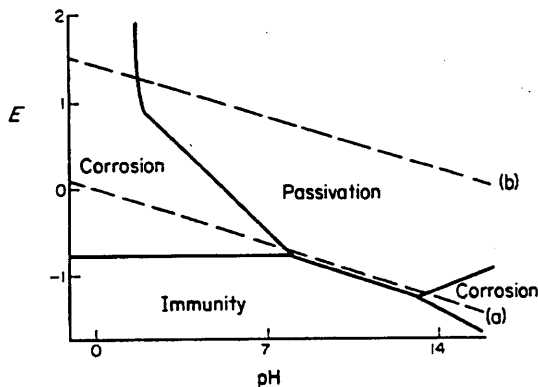
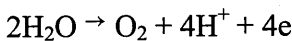
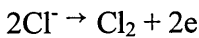


Figure 2.11: Simplified Pourbaix diagram for iron - water system, where dashed lines a) and b) are the pH dependencies of E for hydrogen and oxygen electrodes respectively⁴⁹

The electrolytes used for ECM are usually water based salt solutions instead of the pure water commonly used in the determination of Pourbaix diagrams. Caution is therefore needed when interpreting such diagrams but nevertheless information can be obtained about the type of films likely to form.

2.2.2.1 Polarization and overvoltage

When a current of appreciable magnitude is passed through a cell the actual electrode potential observed may be considerably different from the reversible standard electrode potential. The difference is called the overvoltage. This overvoltage is a measure of the energy required to make the reaction proceed more rapidly than the exchange reaction rate, which occurs at the reversible electrode potential. When the electrode reactions become irreversible, the electrodes are said to be polarised. Generally the higher the current flow the greater will be the departure from equilibrium and the higher the overvoltage observed. In ECM a very large current is made to flow and consequently the overpotentials can be very large. It is then possible for other reactions to occur (from thermodynamic considerations) at the electrodes. For example the evolution of oxygen, figure 2.12 and chlorine from the anode depending on the electrolyte used:



Or at the cathode the plate out of iron: $\text{Fe}^{2+} + 2\text{e}^- \rightarrow \text{Fe}$

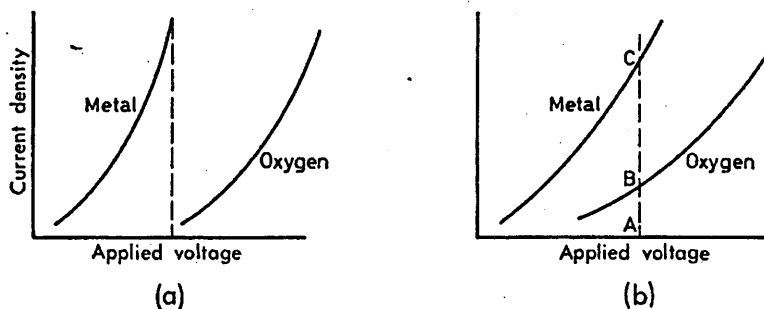


Figure 2.12: Illustrating that at higher overvoltages oxygen can be produced as well as metal dissolution resulting in a lower efficiency⁵⁰

There are several types of polarisation and the observed overvoltage is the sum of overvoltages associated with each polarisation effect.

1) Activation polarisation

At equilibrium few ions in solution have enough energy to overcome the energy barrier to deposit onto the electrode surface. In equilibrium atoms in the electrode have to overcome the same energy barrier to pass into solution to maintain the dynamic equilibrium. The rate at which ions and atoms transfer in equilibrium is called the exchange current. In order to pass a larger current, the atoms in the electrode have to be given an increase in energy to overcome this barrier, such that the rate of ions dissolving is greater than those depositing. This energy is supplied by applying an overpotential to the cell called the activation overpotential. This overpotential will depend on the chemical composition of electrode, the state of the surface, the current density, temperature, pressure and the concentration of ions in the solution.

2) Concentration overpotential

If the rate of dissolution of a species is faster than the rate at which they can be transported away into the bulk electrolyte, a diffusion layer will form where ions will accumulate. From the Nernst equation a change in the concentration near the electrode will result in a change in the potential of the electrode, the concentration overpotential.

The transport of ions from the electrode/electrolyte is controlled by three processes:

- i) migration of charged ions under the influence of an electric field
- ii) diffusion resulting from concentration gradients introduced by the dissolution
- iii) convection e.g. by the movement of the electrolyte causing agitation

3) Resistance overpotential

Anodic dissolution can result in a build up of ions in the vicinity of the electrode, which can lead to film formation. Movement of ions through this layer will be restrictive, so a greater potential is needed to maintain the flowing current. This additional potential is called the ohmic overvoltage. This overvoltage will depend on the film properties such as

structure and conductivity. A film which prevents dissolution is called passivating. The electrolyte composition can also affect film formation for example;

- iron is easily passivated in the presence of NO_3^-
- halides such as Cl^- reduces film forming ability and can breakdown films.

If the surface film strongly prevents anodic dissolution the overpotential can become very high and other anodic reactions are likely to occur such as oxygen evolution.

From the above, the voltage required to maintain a current flowing in a cell is:

$$V = (E_c - E_a) + \eta_a + \eta_{conc} + \eta_r + IR$$

Where E_c and E_a are the reversible potentials at the cathode and anode

η_a is the activation overvoltage

η_{conc} is the concentration overvoltage

η_r is the resistance overvoltage

IR is the ohmic drop across the electrolyte in the inter-electrode gap where R is the resistance between the electrodes. The IR drop will depend on current density, gap width and electrolyte conductivity. Figure 2.13 shows schematically the potential distribution across the gap.

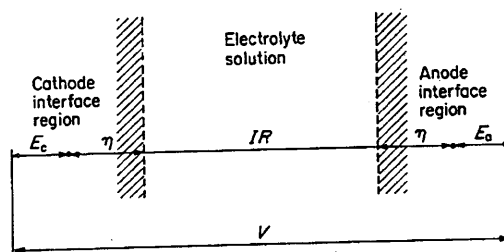


Figure 2.13: Potential distribution in machining gap⁵¹

2.2.2.2 Polarisation Curves

Potential versus current plots give information about the anodic behaviour of metals. The shape gives information on the mechanisms and an indication of the surface finish.

There are three general regions in a current density versus potential curve; the actual shape depends on many factors including electrolyte, temperature and flow conditions.

At low potentials the current density increases according to Tafel's equation and active dissolution of the metal occurs (region I). In potential region II an oxide film forms on the surface, which reduces the dissolution rate, called the passive state. Region III is at much higher potentials and is called the transpassive region associated with passive film breakdown and an increase in dissolution rate.

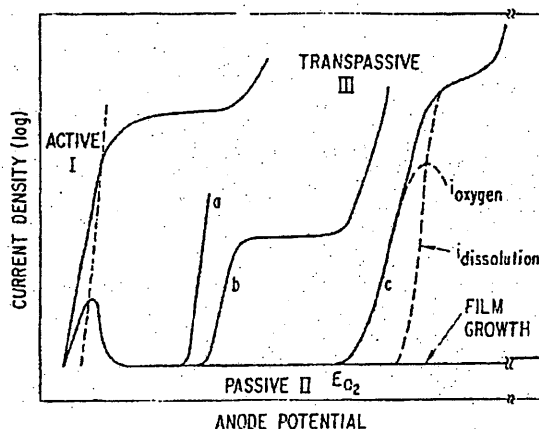


Figure 2.14: Schematic representation of different types of anodic polarisation behaviour, showing active (I), passive (II), and transpassive (III) regions. Curve IIIa: localised breakdown by pitting; curve IIIb: electropolishing in concentrated acids; curve IIIc: transpassive oxygen evolution followed by metal dissolution at high rates in ECM electrolytes. E_{O_2} is the potential for oxygen evolution⁵².

I) Active dissolution

Active dissolution involves the removal of atoms from favourable sites on the surface direct into the electrolyte in a hydrated or complexed form. Grain boundaries^{53,54,55,56}, dislocations and other lattice defects are favourable sites for dissolution as the bonding is not as strong. In these areas there is a lower energy of activation which results in an 'etched' dull surface appearance. Studies have shown a strong correlation between dissolution kinetics and atomistic morphology. Kinks on the surface are preferential sites as the hydrating species

have greater access; it is then possible for a step to propagate across the surface forming facets. The surface concentration of steps is found to be pH dependent⁵⁷.

II) Passivation

⁵⁸In the passive region the anode is covered with a surface film, which acts as a barrier to ionic transport and protects the surface from high rate dissolution. The dissolution rate will then be controlled by the dissolution of the passive film, which in turn depends on the ionic conductivity of the film and its solubility in the electrolyte. The dissolution process then becomes limited by i) movement of cations from the metal into the oxide, ii) movement of cations and/or oxide anions (to maintain electroneutrality) through the oxide film and iii) movement of cations from the oxide film into the solution.

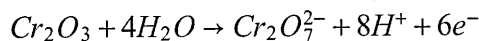
In the passive region the passive current density is of the order of a few $\mu\text{A}/\text{cm}^2$ and is independent of the applied voltage. The thickness, composition and electrical properties of the passive film depend on the metal involved, the solution and the applied voltage.

Oxide films only one atomic layer thick can dramatically alter the surface properties, and the film thickness are known to increase as the applied voltage increases. Anodic films on iron have been studied extensively from the point of view of corrosion resistance. Nagayama and Cohen^{59,60} proposed a sandwich model consisting of an inner layer of Fe_3O_4 and an outer layer of $\gamma\text{-Fe}_2\text{O}_3$. Fe_3O_4 is a good electronic conductor, while $\gamma\text{-Fe}_2\text{O}_3$ is stable only if it contains a minimum concentration of hydrogen ions and there are further indications that the outer layer contains hydrogen in the form of hydroxyl or water⁶¹.

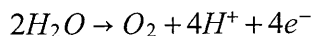
III) Transpassivity

If the potential is raised into the transpassive region an increase in dissolution rate is observed. The breakdown of the surface passive film results in exposing fresh bare metal surface to be dissolved at the higher potential. There are many proposed mechanism for the film breakdown including:

1. Pitting in the presence of an aggressive anion, the pits can then grow and coalesce.
2. Mechanical damage from induced stresses from film thickening leading to pit initiation.
3. At high overvoltages anions can penetrate the film creating ionic defects and increasing the ionic conductivity of the film.
4. Oxidation of film to a soluble product e.g. the trivalent Cr oxide film that protects the metal is oxidised to a soluble hexavalent form:



In metal-electrolyte systems where solution oxidation results in oxygen evolution and an increase in current, transpassive metal dissolution sets in at higher potentials than the potential for oxygen evolution.



Mao⁶² has concluded that the film dissolved under conditions of low pH as a result of oxygen evolution. Hoare⁵⁸ considered an ion exchange model where anions would exchange positions with oxygen ions in the film lattice, thus facilitating film dissolution.

Besides the above three regions other behaviours need to be considered:

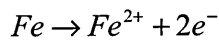
- 1) Secondary passivity: here when the potential of certain transpassive anodes are raised further a new sparingly soluble precipitate is formed and consequently a drop in anode current is observed.
- 2) Solution oxidation: as the potential of a passive anode is raised it is possible for other species within the electrolyte to be oxidized depending on the conductivity of the oxide film. Usually the electrolysis of water producing oxygen occurs and an increase in current flow.
- 3) Film thickening: for films with low conductivity the film can thicken by high field conduction and then the film is able to carry a large part of the applied potential.
- 4) Re-activation: if the potential of an anode with a passive film is lowered, the surface is re-activated at a potential just below that for passivation, this potential is called the Fade potential, the passive film is removed by cathodic reduction.

2.2.2.3 Electrochemical reactions

Possible reactions at the anode include:

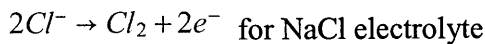
- 1) $M \rightarrow M^{z+} + ze^{-}$ where z is valency of dissolved species, M^{z+} is the dissolved ion.

Metals with variable valency can show a change in dissolution valency depending on overpotential, e.g. iron usually dissolves as Fe^{2+} but can dissolve as Fe^{3+} under the right conditions.



- 2) $2H_2O \rightarrow O_2 + 4H^{+} + 4e^{-}$ oxygen evolution

- 3) Electrolyte anion oxidation, depending on electrolyte and conditions for Cl^{-} .

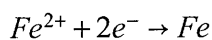


Reactions at the cathode include:

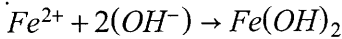
- 1) $2H^{+} + 2e^{-} \rightarrow H_2$ acidic environment

- 2) $2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-}$ in neutral or alkaline electrolytes

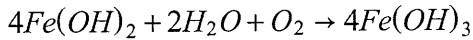
- 3) Metal plate out



Metal plate out is unlikely in neutral or alkaline electrolytes as metal ion reacts with OH^{-} ions forming a precipitate



The ferrous hydroxide is then oxidised into a reddish colour ferric hydroxide although this reaction is not part of the electrochemical reaction.



2.2.2.4 Electrolytes for ECM

The theoretical material removal rate will depend on the valency of the dissolving ions and the applied current. As shown earlier the voltage drop across two electrodes is divided up into standard electrode potentials, polarisation overvoltages and the ohmic drop through the electrolyte IR. At high current levels as used in ECM, the voltage needed to pass current through the electrolyte becomes large.

$V=IR$ where R is resistance and I current

$$R = \frac{\rho l}{A}$$

ρ is the resistivity of the electrolyte, l is the length (gap) and A is the cross sectional area.

Resistivity is the reciprocal of conductivity κ , so rewriting the above but using current density $J=I/A$

$$J = \frac{I}{A} = \frac{\kappa V}{l}$$

Therefore to maintain a high current density, a high conductivity electrolyte, a high voltage and a small inter-electrode gap is needed. Power requirements generally mean voltages of 10 - 30V are used.

Electrolytes are usually aqueous salt solutions or acids and therefore they must be strong acids or bases to fully dissociate. The conductivity of an electrolyte is related to the ion concentration and temperature. Because heat is generated by Joule heating the electrolytes must have; a high thermal conductivity, a high specific heat capacity and high boiling point in order to prevent bubbling and sparking. The use of high current densities means that the

products and the heat generated within the gap must be removed by the flowing electrolyte. An electrolyte with low viscosity is therefore favourable, because the pressure needed to achieve the required flow will be lower and less demanding on the pumping system. The cost of waste disposal and life of electrolyte must also be considered. The electrolyte for a particular application is then chosen on machining rate (efficiency), power consumption and desirable surface finish and accuracy.

The theoretical material removal rate is obtained from Faraday's laws of electrolysis:

- i) The amount of metal dissolved or deposited is directly proportional to the amount of electricity that has flowed and
- ii) The amounts of different substance deposited or dissolved by the same quantity of electricity is proportional to their chemical equivalent weights.

These two laws yield:

$$m = \frac{AI t}{zF}$$

where m is the mass deposited or dissolved by a current of I for a time t . The reacting ions have atomic weight A and valency z . The chemical equivalent is A/z and F is Faraday's constant 96,500 C.

The removal rate is given by $\dot{m} = \frac{AI}{zF}$

and the volumetric removal rate is then

$$\dot{V} = \frac{AI}{z\rho_a F}$$

where ρ_a is the density of the metal

From the above equations it can be seen that the theoretical removal rate of a certain metal is controlled by the local current density such that a linear relationship exists, if the current is increased the removal rate increases.

Even for calculating theoretical removal rates an understanding of the electrochemical reactions occurring is needed. Much confusion arises concerning what valency level (z) the metal is dissolving. Observations have shown that the valency state can change or a mixture of valency ions can form during ECM.

The current is found to be a very important parameter. Other processing parameters and the metal/electrolyte combination are also important. The mode of metal removal has been shown to depend on current density. The interaction of metal and electrolyte is closely linked to the formation of surface films, which play a dominant role in determining dissolution rates, dimensional control and surface finish.

Determining the chemical equivalent for an alloy is more difficult than that for individual elements. Again knowledge of the dissolution valency states must be assumed and a method of combining the alloy's constituent elements together to give a single chemical equivalent. One method 'Percentage by weight' uses the chemical equivalents of the individual elements, i and their weights X_i as a weighing factor.

$$\left(\frac{A}{z}\right)_{\text{alloy}} = \frac{1}{100} \left[X_A \left(\frac{A_A}{z_A} \right) + X_B \left(\frac{A_B}{z_B} \right) + X_C \left(\frac{A_C}{z_C} \right) + \dots \right]$$

Then the removal rate for an alloy becomes

$$\dot{m} = \left(\frac{A}{z}\right)_{\text{alloy}} \frac{I}{F}$$

Again the equation does not account for process variables like flow rate, temperature, and current density.

2.2.2.5 Current efficiency

The difference between the theoretical removal rate and experimental removal rate is expressed by the current efficiency, which is the ratio of the observed mass dissolved and the theoretical mass dissolved under same specified conditions of chemical equivalent and current.

$$\text{current efficiency} = \frac{\dot{m}}{\left(\frac{A}{zF}\right) I}$$

where $\dot{m}$ is the observed mass removal rate

For 100% efficiency all the current is used for metal dissolution. The current efficiency can be affected by incorrect choice of valency or alloy chemical equivalent. Passivation will also reduce the dissolution rate. Other electrochemical reactions can occur at the anode like gas evolution e.g. oxygen using up part of the applied current. Intergranular attack at grain boundaries can result in grains falling out of surface and giving a current efficiency greater than 100 %. So current efficiency will be affected by the process parameters and the electrolyte/metal combination.

A discussion of how current efficiency is affected by process parameters will be looked at for the various types of electrolytes commonly encountered for use in ECM.

2.2.3 Electrolytes

There are a range of ECM electrolytes in use depending often on the workpiece and the application:

i) Mineral acids have high conductivity due to the very mobile hydrogen ion. The cathodic reaction is the discharge of hydrogen gas although metal plate-out can occur. The loss of hydrogen ions during ECM increases the pH and lowers the conductivity of electrolyte increasing the possibility of plate-out, which is highly undesirable. If the metal plates out on the cathode the tool shape will change affecting machining accuracy. Applying a reverse polarity making the cathode the anode for a short time, a low voltage can be applied to remove the plated-out metal without affecting the tool material itself. Acid electrolytes are more corrosive and need handling with care, the ECM machine needs to be made from expensive materials and costs of disposal of acid need consideration. The main application for acid electrolytes is for small (0.1 - 4 mm) deep (aspect ratio 300:1) hole drilling⁶³ in turbine blades where if a precipitate formed could block the hole so the dissolution products are desired to remain in solution.

ii) Neutral and alkaline salt solutions are divided into two classes a) passivating (NO_3^- , ClO_3^-) and b) non-passivating (NaCl). Although other electrolytes exist they are usually for specific applications like ECM for Ti.

In neutral and alkaline electrolytes the cathodic reaction is the electrolysis of water giving hydrogen gas and hydroxyl ions. The dissolving metal ions can then react with the hydroxyl ions forming an insoluble precipitate preventing plate-out of metal ions at the cathode. The electrolyte must then however be filtered and the sludge dried and disposed of.

Each workpiece/electrolyte combination works differently, and the hope of an universal electrolyte for the machining of a wide range of metals and alloys would appear unlikely as the chemistry of each system is different.

1) Sodium Chlorate (NaClO_3) electrolyte

Sodium chlorate is used for more accurate machining. For passivating electrolyte as the current density is increased the mode of dissolution changes from active dissolution (not always seen) to a passive film formation. At higher current densities corresponding to ECM, film breakdown occurs leading to transpassive dissolution. From the polarisation curve, figure 2.15 & 2.16, it can be seen that the transition from no machining to machining is sharp allowing good dimensional control. Chlorates are used for ECM of steels, oxygen evolution reduces efficiency at lower current densities but at higher current densities efficiencies over 100% can be reached as a result of grain fall out.

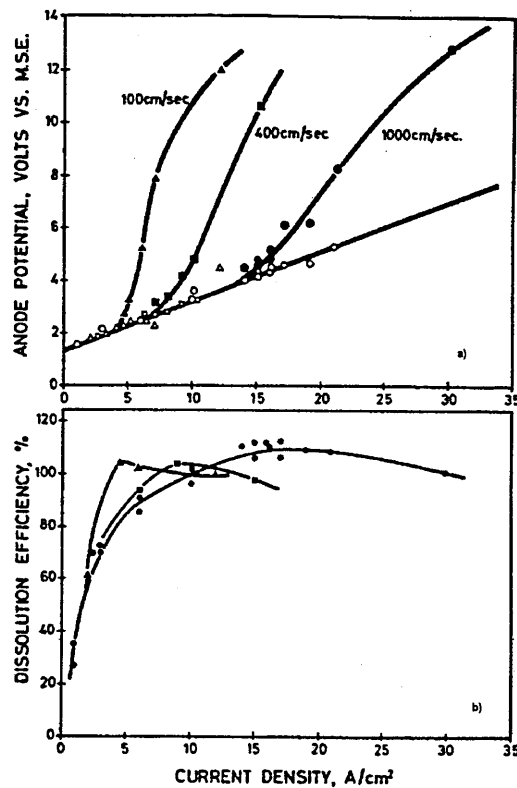


Figure 2.15: Polarisation curve and efficiency curve for ECM on nickel in chlorate electrolyte, showing influence of electrolyte flow rate.

Figure (2.15)⁶⁴ shows how for Ni the efficiency depends on current density but also on flow rate, a possible reason being that film breakdown and hence anodic dissolution in the transpassive region is favoured by high anion concentration at the surface. For electroneutrality the anion concentration at the surface is greater than the bulk electrolyte and will depend on current density and hydrodynamic conditions. The current efficiency for

iron in chlorate electrolyte, also figure (2.15)⁶⁴ is not affected as much by flow rate because of adherent hydroxide layers. The figure 2.16 for iron shows their polarisation curves and their dependence on flow. Figure (2.16)⁶⁴ also shows that the onset of surface brightening relates to the formation of salt films on the surface and mass transport control.

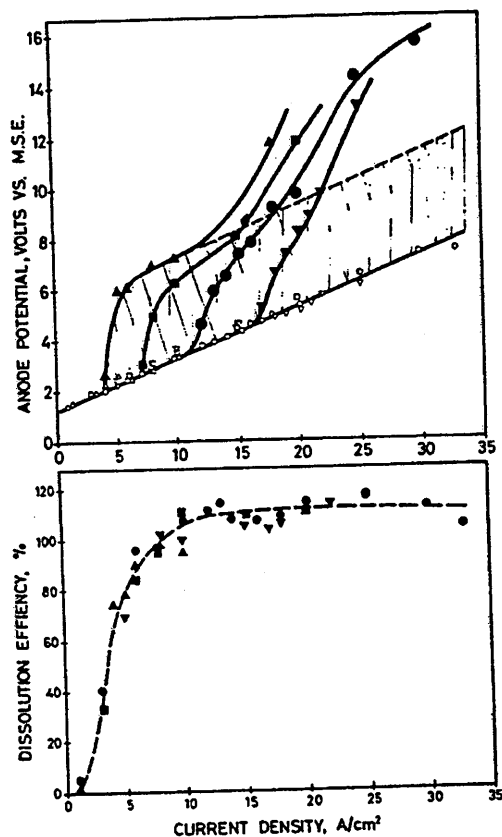


Figure 2.16: Influence of current density on surface fraction appearing bright for iron dissolution in 5 M NaClO_3 at different flow rates⁶⁴, flow rates 100cm/s ($\blacktriangle$), 400cm/s ($\blacksquare$), 1000cm/s ($\bullet$), and 1760 cm/s ($\blacktriangledown$)

2) Sodium Nitrate (NaNO_3) electrolyte

Sodium nitrate is another common electrolyte for machining of steels. The transition from machining to non-machining is not as sharp as for chlorate, dimensional control is therefore not as good. The transpassive potential for NaNO_3 is more noble than NaClO_3 so the machining rate under the same conditions is not as high and the efficiency is lower because of oxygen generation, figure 2.17. For nitrates the efficiency is found to increase with current density⁶⁴, up to around 80% depending on flow rate and current density. At low current densities the efficiency can be as low as 12% for metal dissolution. There is also

literature on anodic dissolution of Ni in nitrate electrolyte also indicating that mass transport control is needed for surface brightening^{65,66}.

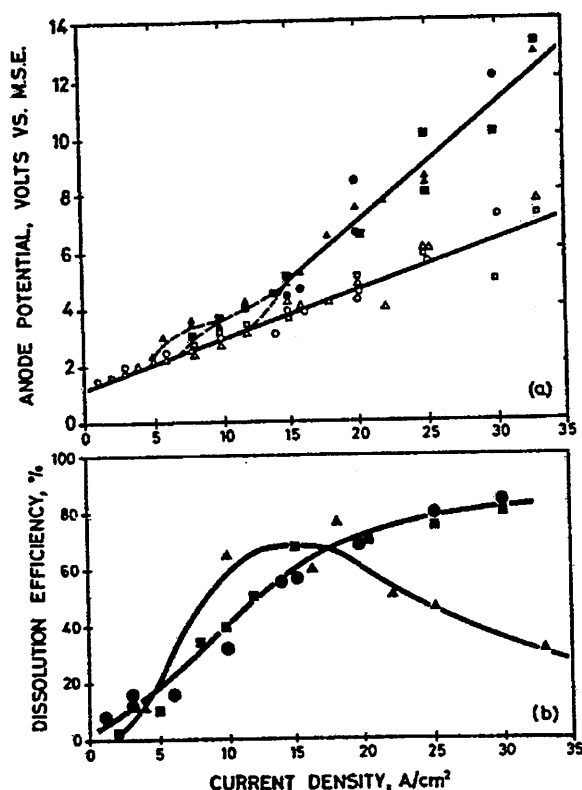
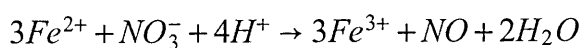


Figure 2.17: ECM on iron in nitrate electrolyte, showing polarization and efficiency curves, flow rates 100cm/s (Δ), 400cm/s ($\blacksquare$), 1000cm/s ($\bullet$)

Figures 2.17, shows the dissolution of iron in nitrate electrolytes again indicating that the onset of surface brightening coincide with salt film formation and transport control. The onset of brightening is delayed by higher flow rates.

At low flow rates (100cm/s) the efficiency goes through a maximum at about 60% efficiency. This has been related to a temperature rise in the electrolyte, which encourages the reduction of nitrate ions⁶⁴.



This reaction is faster at higher temperatures and has the effect of reducing the anion concentration at the anode surface needed for film breakdown in the transpassive region.

This reduces efficiency but also delays the onset of a salt layer formation needed for surface brightening.

3) Sodium Chloride (NaCl) electrolyte

NaCl is non-passivating and can therefore be used at higher current densities but at lower potentials. At such high current densities stray currents are possible which lead to poor dimensional control, however ECM can be used with wider electrode gaps. The onset of surface brightening correlates again to mass transport control⁶⁷ believed to result from the precipitation of insoluble $\text{Fe}(\text{OH})_2$. The thick unprotective porous film restricts dissolution and the random diffusion through the film results in a smooth surface finish. Reports suggest that during transpassive dissolution Fe^{2+} and Fe^{3+} ions are produced. High machining rates are achievable with NaCl and a current efficiency of 100%.

2.2.4 Surface finish

Surface finish as well as form during ECM is influenced by a number of factors given below:

i) Mass transport control

Research, mainly by Datta and Landolt, has shown that the onset of surface brightening corresponds to mass transport control. The onset of brightening was shifted to higher and higher current densities as the flow rate was increased. A certain concentration of dissolved ions is required for the precipitation of a salt film on the surface; dissolution through this salt film will suppress favourable sites such as grain boundaries resulting in a more uniform removal and brightening.

ii) Conductivity variation

The local dissolution rate at the surface will depend on the local current density, so any variation in current density will result in non-uniform removal. Possible reasons for conductivity variations are given below:

a) Flow variation: For the simple case of two parallel plates with an electrolyte flowing between them, the plate surface will retard the electrolyte near the boundaries, this results in a flow rate variation. A diffusion layer is formed at the surface and this diffusion layer

grows in the downstream direction causing a variation in flow. The flow can also be turbulent and the surface roughness will also affect the flow.

b) Temperature: ECM involves the passage of current so Joule heating effects will cause the electrolyte's temperature to rise. Conductivity is very dependent on temperature, as the charge is carried by mobile ions, which can move faster at higher temperatures. The electrolyte will get hotter and hotter as it passes through the gap, which can lead to plane parallel plates diverging downstream as a result of conductivity changes. If the electrolyte is recycled for re-use its temperature will gradually increase so temperature control (cooling system) is required for reproducibility.

c) Hydrogen bubbles: are generated at the cathode. These bubbles will then accumulate downstream and cause conductivity variations.

e) Reaction products: reaction products (hydroxides) will accumulate downstream. The amount of hydroxides in electrolyte will affect the conductivity of the electrolyte.

iii) Stray currents: If the workpiece and tool are not sufficiently insulated, machining will not be confined to the electrode gap. Stray currents will machine unprotected parts of workpiece or continue dissolving parts, which had already be ECM to the required dimension and will also affect the surface finish. The greatest potential will be between the electrodes. However there will be a potential distribution which can result in the potential falling into the passive (risk of pitting) or etching regions of polarisation diagram both affecting surface finish and accuracy, figure (2.14).

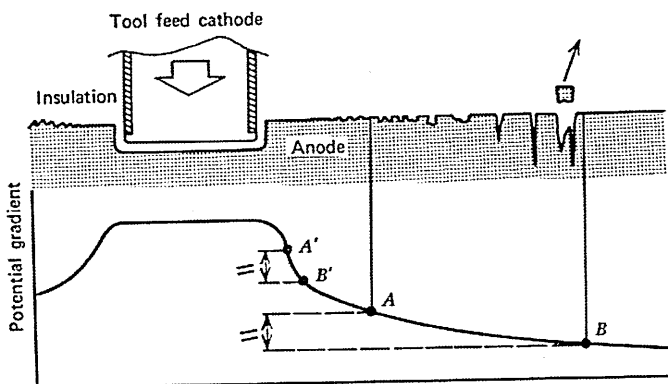


Figure 2.18: showing the effect of stray current on surface finish and dimensional accuracy⁶⁸

Figure 2.18, shows a hypothetical potential distribution, for a tool close to the workpiece surface. The highest potential gradient is between the workpiece and tool. However the distribution tails off outside the gap. Different phases or constituents of the surface will have different dissolution potentials, so as the potential gradient falls, different phases will stop machining and form plateaus. Between A and B in the figure 2.18, as the distance gets further away from the tool, successive phases will fall below their dissolution potential resulting in etching and pitting of the surface. Points A' and B' show the effect of using an electrolyte, which introduces a higher overvoltage for the dissolution of the constituents into solution, thereby decreasing the etching region.

iv) Microstructure and inhomogeneity within the material can lead to differing machining rates and selective dissolution of alloys. Most materials are not pure but a mixture of elements either deliberately added, to improve some material property (strength, corrosion resistance, machinability, etc.) or present as an impurity from extraction, but they will have different electrochemical properties and will be machined differently. Grain boundaries and other defects^{53,54,55,56} can act as preferential sites for dissolution. Inclusions such as MnS in steels are known to be pit initiation sites for corrosion and will have a different potential for dissolution. Figure 2.19 shows the effect of an inclusion on the surface. If the inclusion is a poor conductor, the current must be displaced around it increasing the removal in adjacent areas.

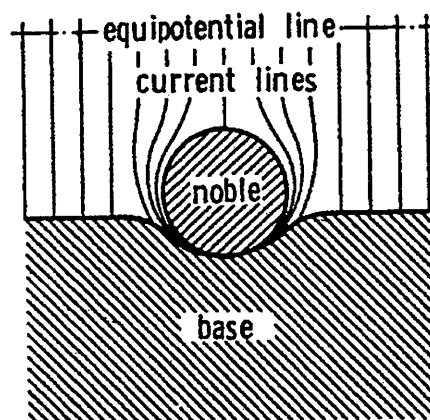


Figure 2.19: Effect on material variation of workpiece⁵⁶

Segregation of carbides during the initial processing of highly alloyed components to be ECM can lead to material regions high in carbides and other regions low in carbides. Such differentials lead to selective dissolution. The microstructure of a part is very much

controlled by pre-processing e.g. rolling, forging, or extruding, which can align grains. Heat treatment will also affect the phases present, morphology and grain size.

Generally the surface finish improves with current density as the mode of dissolution changes from etching to transpassive, however the roughness can pass through a minima whereupon surface pit formation and flow streaks form at very high current densities. Ideally material removal should be in the transpassive region under mass control to give a surface smoothing and brightening.

2.2.5 ECM Machine Design Considerations

2.2.5.1 Material considerations

Materials need to be corrosion resistant from both chemical attack caused by the corrosive electrolyte and also electrochemical attack. If fixtures and pipes are made from materials that corrode, they must be easy to replace and accessible. Materials used in an ECM machine must also be strong and rigid. This may be unexpected as one of the advantages of ECM is that it is non contact machining, however high electrolyte pressure and flow rates can result in deflections and worse initiate tool oscillations leading to water hammer i.e. pulsing of electrolyte. Materials considered for use in ECM machines will depend on the required stiffness and cost but include: plastics, monel, copper, stainless steels, bronzes or brasses, even reinforced plastics and fibre bonded resins are in use. Stainless steels are susceptible to corrosion by stray currents if not insulated. Titanium, which forms a compact adherent oxide film, can resist this type of corrosion but is very expensive. Generally it is best to bring the current directly to component and insulate the remaining metal parts of the machine.

For the cathode stainless steel and copper are the main choices: copper has a high electrical conductivity and thermal conductivity, which gives uniform current distribution and sparking is limited. Electroplating can repair damaged cathodes. One difficulty is the application of insulating coatings, as bonding to the copper surface is difficult. Stainless steel is often used because it has good corrosion resistance.

Insulating coatings are an intricate part of tool design preventing stray currents, which can affect machining accuracy as well as initiate unwanted corrosion. Rubber coatings have been used as well as epoxy resins.

The basic requirements for ECM systems are explained below.

2.2.5.2 Electrical supply

A power supply is required with smooth dc and low ripple content. The size of the power supply will depend on the application. The greater the current, the higher the cost of the power supply, so a compromise must be met with respect to the present application and the expected future requirements. Fast switch on and off times are required and many systems have a spark detection circuit to prevent the electrode from excess damage. Pulsing the current is nowadays a frequent requirement particularly for high precision applications.

Usually because of the large currents employed during ECM, copper power cables are used to bring the current to the machine. Copper has very high electrical and thermal conductivity combined with good corrosion resistance. If the cables are cooled then thinner cables can be used. Good electrical joints require small contact areas to reduce power losses although the total connector needs to be bigger to allow for the dissipation of heat. The contact area needs to be clean and to obtain a good electrical contact a high clamping force should be used to plastically deform the mating surfaces.

2.2.5.3 Electrolyte system

Using neutral or alkaline electrolytes results in the precipitation of insoluble products, which must be removed from the electrolyte by filtration. For large volumes of sludge a centrifugal filter or filter press is used to remove as much water as possible to reduce the weight before disposal. Sludge is usually disposed of by landfill. A second filter is usually used as a safety measure before the electrolyte enters the gap. An electrolyte system will have storage tanks and settling tanks with a capacity for continual running of the ECM machine. Since the electrolyte is corrosive the pump and pipes have to be made from a corrosive resistant material. The electrolyte should not be pulsing therefore centrifugal pumps are often used.

2.2.5.4 Working area

The working area includes the electrodes, electrolyte flow nozzle or channels in tooling, and mountings. As mentioned before the mountings and locating fixtures must be made from non-corrosive materials and metals should be electrically insulated to prevent dissolution. The electrode and tooling and flow must be looked at together and have a large effect on successful operation.

When ECM is used for forming operations such as turbine blade shaping the flow and control of the flow through the tooling is very important and some 'rules of thumb' have been developed from practical experience⁶⁸.

From the flow point of view, tooling must be checked to ensure there are no stagnant places or areas, which are deficient of electrolyte. The use of flow restrictors and dams can be used to channel the flow and provide backpressure reducing cavitations. Insulating coatings can be used to minimize stray currents. These coatings must withstand high electrolyte flow rates and must be held firmly. There are some techniques to predict the approximate shape of the tool. However, experimentation is still often required. Computer simulations can cut the cost of tooling development and also speed up development time with less dependence on a 'trial and error' approach. A number of approaches have been documented from: FEM⁶⁹, boundary element method⁷⁰ or using the simpler $\cos \theta$ rule⁴⁶. Most of this work is for die sinking.

2.3 Honing and superfinishing

Stone honing and tape superfinishing have been introduced earlier. This section will discuss honing stones in more detail including stone specifications and general behaviour of honing stones in relation to bearing raceway finishing.

2.3.1 Introduction

Bonded abrasives include grinding wheels and abrasive (honing) stones.

They consist of:

- 1) Hard abrasive grits for cutting
- 2) Weaker bonding matrix

Often fillers such as fibre reinforcement and grinding aids are added

A superfinishing stone has a composite type structure consisting of abrasive grains, bond material, porosity, fillers and lubrication aids. The consistency of this mixture is important both from stone to stone but also within each stone to give more consistent and predictable performance.

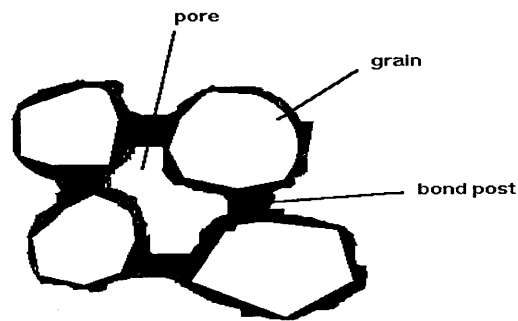


Figure 2.20: Showing structure of honing stone

The properties and performance of a honing stones depends on

- i) Type of abrasive material
- ii) Grit size
- iii) Bond material and composition
- iv) Porosity
- v) Interactions between bond, grit and workpiece
- vi) Metal working fluid
- vii) Material removal and abrasive wear mechanisms
- viii) Machining conditions

2.3.2 Stone Specifications

There is a standard specification for bonded abrasives. The specifications incorporate key information to aid the manufacturing engineer in the selection of the correct abrasive for the application. Honing stones are grouped into two classes: conventional abrasives and superabrasives

2.3.2.1 Conventional abrasive stone specification

0	1	2	3	4	5	6
Prefix	abrasive type	grain size	grade	structure	bond type	Manufacturers
record						

0 Prefix is an optional manufacturers symbol identifying the exact abrasive used. Differing chemical composition and structural characteristics can affect mechanical and physical properties of the cutting grits.

1 Abrasive type: A - Al₂O₃ and C - SiC

2 Grain size: represented by a grit number, which is related to the screen used to sort the grains. Usually sieving is used for larger grit sizes and sedimentation for finer grits. The grit number represents a distribution of grit sizes characterized by an average grit size. The larger the grit number the finer the grit size.

Table 2.2: Showing abrasive grit sizes

Coarse	Medium	Fine	Very fine
8	30	70	220
10	36	80	240
12	46	90	280
14	54	100	320
16	60	120	400
20		150	500
24		180	600
			800
			1000
			1200

Sometimes manufacturers use a range of grit sizes to facilitate closer packing densities.

3 Grade or hardness: indicates stone strength, the degree to which the abrasive is held by the binder. A harder stone will have less porosity and more binder, however the numbering system is not universal between manufacturers.

Soft	Medium	Hard
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z X		

4 Structure: represents the volumetric concentration of abrasive grains. A higher number indicates less abrasive or a more open structure.

An upper limit on grain concentration is opposed by packing density, which is affected by grain size and shape; higher packing densities can be obtained by using a range of grit sizes. For vitrified bonds a lower limiting volumetric packing density is imposed to maintain grit to grit contact to minimize shrinkage and distortion on vitrification.

5 Bond type: there are a range of different bond types however for conventional abrasives vitreous or resinoid bonds are most common. Changing the bond's compositions or adding additives can alter the properties of the bond.

V- vitrified

B- resinoid

6 is optional and is for the manufacturers record

2.3.2.2 Superabrasive stone specification

Superabrasives have a slightly different specification system

0	1	2	3	4	5	6	7	8
Prefix type	abrasive type	grain size	grade	concentration	bond type	bond modification	depth of abrasive	manufacturer record

0 Prefix manufacturers symbol

1 Abrasive grit type D - diamond, B - CBN

2 Grain size

3 Grade hardness level

4 Concentration: refers to the amount of abrasive in the stone, originally used for diamonds a proportional scale where concentration number/4 = volumetric percentage of grit

i.e. 100 concentration has an abrasive content of 4.4 carats/cm³ or 25% volume

The density of CBN is similar to diamond so 100 concentration of CBN is 24%

Typical concentrations vary between 50 - 150 (12.5 - 37.5 Vol. % for diamond); vitrified wheels need a higher concentration and therefore are more expensive.

5 & 6 Bond: B- resinoid, V-vitrified and M- metal bonds are used. Resin and metal bonded wheels have virtually no porosity. Changing bond formulations and fillers can change the

hardness, e.g. combustible sawdust filler can be added to resin bonded stones, which burn off during curing resulting in increased porosity.

7 Depth of abrasive: since superabrasives are very expensive, it would be very expensive for a whole grinding wheel or abrasive segment to be made for diamond. Instead only a layer of bonded abrasive is attached to the outer rim of a metal/plastic hub. The depth of the abrasive layer is indicated on the specifications. Electroplated wheels are often used to minimize the amount of abrasive needed.

2.3.3 Abrasive types

There are a range of abrasive types, divided into conventional abrasives and superabrasives. Within each type a wide range of cutting properties can be obtained by using different compositions and manufacturing routes allowing the development of certain types of grains for particular grinding operations such as rough or fine grinding. These abrasives can be evaluated using mechanical properties such as hardness, abrasion resistance, toughness and compressive strength and grain morphology.

Abrasives need to be harder than the material being cut. Diamond is the hardest known substance. Toughness is also an important parameter as a high toughness abrasive is likely to fracture on impact with surface. Harder grains are generally more friable and are applied to precision grinding and surface finishing since the higher friability helps regenerate sharp cutting edges (self sharpening or dressing) as grains dull. Tougher grains are used for heavy grinding operations.

a) Conventional abrasives include alumina Al_2O_3 (natural and synthetic) and SiC (synthetic) and their behaviour will depend on their composition, crystal structure, fabrication method and grain size.

Al_2O_3

Al_2O_3 is available in its natural state corundum and emery, however virtually all Al_2O_3 and SiC used are synthetic. The hard α - Al_2O_3 phase has a hexagonal structure, which exists in, various states of purity and degrees of crystallization. Al_2O_3 also contains metallic oxides as additives or as impurities. The range of compositional and structural variables affects the abrasives cutting properties and grain morphology, allowing the development of certain types of grains for particular grinding operations. Below is a list of some of the forms of alumina in use:

1) Regular (brown) Al_2O_3 produced by fusing calcinated bauxite with coke and iron giving a brownish product with $\sim 2.7\%$ TiO_2 which dispersed as a softer phase $\beta\text{-Al}_2\text{O}_3$. TiO_2 is responsible for its lower hardness or increased toughness. Grains tend to be irregular shaped featureless surfaces; they are semi friable and are used in heavy duty, roughing and semi finishing operations.

2) Microcrystalline Al_2O_3 is produced by rapid cooling into smaller ingots. The finer crystal sizes produced are tougher.

3) Monocrystalline Al_2O_3 is produced by a similar route as regular Al_2O_3 except FeS and alkaline compounds are added to remove titanium compounds with the other oxides. The alumina formed has only minor impurities. The grains are produced without high crushing forces. The grains appear faceted which can act as cutting points. Monocrystalline Al_2O_3 is used in finishing operations.

4) White and modified Al_2O_3 have very high purity, nearly 100%, except for additives used in modified Al_2O_3 . Additives include soluble metal oxides, which provide solid solution strengthening enhancing hardness and toughness. White alumina has sharp fracture facets, which are not present on the modified form. White and modified Al_2O_3 are used in finish grinding.

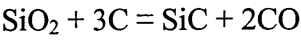
5) Sintered Al_2O_3 is made via a sintering route resulting in a very fine crystal structure and extremely high toughness. Grains have rounded edges and are used in heavy duty grinding.

6) Mixed Al_2O_3 - ZrO_2 has limited solubility forming eutectic at 42 wt.% ZrO_2 . ZrO_2 has hardness, which is half that of Al_2O_3 but forms a eutectic structure which is very tough and prevents crack propagation. It is believed that the ZrO_2 is trapped in a high-pressure form, which reverts to a low-pressure form with an increase in volume as a crack approaches making crack propagation more difficult. By varying the amount of ZrO_2 different mechanical properties can be achieved. Increasing the amount of ZrO_2 up to the eutectic point gives higher toughness and lower friability.

7) Sol-gel abrasives⁷¹ are converted from colloidal dispersions of hydrosol containing goethite ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$) to a semi-solid gel, drying the gel to a glassy state and crushing to the required grain size followed by firing at 1300°C . Grains have a randomly orientated microcrystalline structure.

Silicon carbide

Two types of SiC are used, black and green and are prepared by reducing sand (SiO₂) with excess coke (C) in an electric furnace at temperatures > 2000 °C.



Hexagonal form of SiC is green to black colour which must be separated from unreacted coke. The green SiC is harder and is a semiconductor, while black SiC is less expensive. The high hardness and friability of SiC makes it good for fine grinding.

SiC is often used for surface finishing of hardened steels because of its higher friability so it can regenerate fine cutting points. Grinding of ferrous materials can give low grinding ratios due to iron reacting chemically with SiC. This reaction leads to poor attrition resistance. However it can be used for grinding high carbon cast irons, which minimizes reactivity.

Table 2.3: Showing properties of typical abrasive grain types⁷²

Grain type	Knoop hardness Kg/mm ³	Friability index
Alumina Al₂O₃		
modified (3% Cr)	2,260	65
White	2,120	57
Monocrystalline	2,280	48
Regular	2,040	36
Microcrystalline	1,950	11
10% ZrO ₂	1,960	11
40% ZrO ₂	1,460	8
Sintered	1,370	7
Silicon Carbide SiC		
Green	2,840	63
Black	2,680	57
Diamond	8,000	
Cubic Boron Nitride (CBN)	4,700	

b) Superabrasives include diamond (natural + synthetic) and cubic boron nitride (CBN) (synthetic). These abrasives are extremely hard, diamond being the hardest substance known to man. Synthetic diamonds are made by converting hexagonal graphite into its cubic form at high temperature and pressure with a catalyst. Diamond is however not generally used with low carbon steels since diamond is an unstable form of carbon. The carbon has a tendency to diffuse into the steel at the high temperatures and pressures that arise during grinding, which gives excessive abrasive wear. To machine steels therefore

CBN was developed by a similar reaction converting hexagonal boron nitride to its cubic form at high temperature and pressure. CBN is more expensive compared to diamond. Although CBN is not as hard as diamond it is still much harder than the other abrasives.

The main types of diamond grades available from GE⁷³ include:

- i) RVG elongated friable crystals with rounded edges for resin/vitrified bonds
- ii) MBG (Metal Bond Grinding) are tough block-shaped diamonds, which are not as friable.
- iii) MBS (Metal Bond Sawing) blocky extremely tough grains with smooth regular surface used for cutting concrete/stone.

For finishing operations the RVG diamonds are important. The polycrystalline grains are agglomerates of tightly bonded diamond grits. This gives good friability. Controlled breakdown by micro chipping ensures dull grits break off leaving new cutting points. This permits smooth surface finishing. There are a number of RVG type grits depending on grinding system, coolant, temperature (cutting rate), and workpiece material. Better grit retention can be achieved when using resin bond by using a special Ni coating, which can better adhere into grit crevices and surface. The controlled roughness of Ni layer is better at adhering to the resin bond. The higher thermal conductivity improves the conductivity of wheel and reduces thermal deterioration of bond. Ni coated RVG is called RVG-W available in 56 or 30 wt.% Ni coating i.e. 56 or 30 % of weight of grain. Cu coatings can also be used for better thermal conductivity in high removal rate grinding, or dry grinding.

CBN grits are available as monocrystalline and polycrystalline grits. The monocrystalline CBN grits are blocky with sharp edges and smooth faces making bonding difficult so a Ni coating is used to give better adhesive when a resin bond is used.

2.3.4 Grit size

Grit size has a profound influence on the superfinishing process affecting surface finish, material removal rate, cutting force required and loading attributes. Often the superfinishing operation is divided into a roughing (large grits) and a finishing (fine grit) operation.

Conventional abrasive grit size is indicated by a grit number related to a mesh number (US) where a larger number indicates a smaller grit size, table 2.4. Superabrasives are slightly different, they are designated by two mesh numbers indicating the mesh most grits past and the mesh where most grits are retained.

Table 2.4: Showing average grit size for the different grit size systems

Comparison of grit sizes		
Microns	Mesh	Grit number
60	325	180
45	500	240
30	700	320
15	1100	500
9	1800	800
6	3000	1000
3	8000	1200
1	14000	2000

2.3.5 Bond type

There are a number of bonds types in use, the three main ones are:

i) vitrified bonds are made from glass or ceramic materials, they combine the freeness of cutting of a resin bond with the wear resistance of metallic bonds,

ii) resin bonded stones show higher removal rate, freer cutting and are easier to use. The weaker bond system leads to faster wear of abrasive. Lower cutting forces permits their used on less stiff machines. The resin bond can be weakened by heat therefore metalworking fluids are used where possible. The hardness of the bond is affected by grit type, concentration, resin type, fillers, and solid lubricants present.

iii) metal bonds are strong and can hold blocky mono crystalline grits. These are usually modified bronze or iron. Metal bonds are used to give excellent grit retention which when combined with the wear resistance of the metal bond provides good abrasive life. Metal bonds are used to machine brittle materials such as glasses and ceramics, often where geometric accuracy and not removal is of importance.

The bond has a large influence on the stone behaviour. Resin bonds are softer so generally have higher wear rates. The damping behaviour of resin has lead to the belief that it can give better surfaces finishes from reduced vibrations transmitted. Metal bonded stones are extremely hard and very difficult to “true” the correct stone profile. Often a large number of workpieces must be wasted before the stone is bedded in correctly. The main benefit is that the stone will last for a long time. Vitrified bonds have intermediate behaviour, acceptable wear rate but with the ability to self dress and maintain cutting without loading.

2.3.6 Stone Treatments

Lubrication is very important in honing because of the large contact area and also because of the very fine abrasive grits employed means there is a very small gap between the workpiece and the bonding of the stone. As will be discussed later abrasive wear and bond wear play an important role in consistent surface finishing but also on stone life, which is highly influenced by lubrication. Lubrication can be provided by flooding the honing stone with a metalworking fluid or by directly impregnating the stone with the lubricant.

The stones themselves can also be impregnated with lubricity agents such as sulphur^{74,75} or wax to provide lubrication directly at the cutting zone. These additives are found to re-enforce the bond giving improved stone life as well as improved surface finishes and reducing stone loading. For reinforcement the sulphur needs to be a solid in the cutting zone and can act as an extreme pressure additive. The articles showed that if the temperature is high enough for the wax to melt then the stone life is not improved although surface finish is still enhanced i.e. the grit re-enforcement is lost.

2.3.7 Metal working fluid

Honing fluids can have a major influence on the superfinishing performance affecting the material removal rate, surface finish and stone wear. The costs of honing fluids are generally small and are often overlooked when seeking ways to enhance productivity or surface quality.

Superfinishing uses high/moderate pressures and low speeds so therefore require honing fluids with greater lubricity, compared to grinding fluids (where coolant is a major purpose of applying a fluid). Most honing operations use neat honing oils and when attempts have been made to change to a more environmentally friendly water based substitute generally results in a loss in performance. For superabrasives water based fluids are in greater use since the higher material removal rates and the accompanying heat generation requires the better coolant properties of the fluid.

Increased interest in the use of water-based substitutes however, persists mainly as a result of environmentalists and new regulatory laws concerning usage, disposal and recycling of hazardous waste. This means the costs to use such oils in the future is likely to increase. Together with fire hazards and health problems from skin irritation and breathing problems means that alternatives are being sought.

Function of metal working fluid⁷⁶

The main functions of the metal working fluid are:

- 1) Lubricant, abrasive/workpiece interface to reduce friction and heat generation
- 2) Flush away fines out of contact zone to reduce stone loading or galling and deep scratches
- 3) Corrosion protection
- 4) Provide cooling, particular in high precision applications, the lubricant helps keep a constant workpiece temperature for better size control
- 5) Lubricate non-abrasive components such as support shoes

The lubricant therefore influences the abrasive wear, the surface finish, grinding forces and heat generation which influence the economics of the process, output quality and surface integrity i.e. subsurface stress generated and possible white layer formation.

Types of fluid

Honing fluids^{76, 77, 78} are divided into 4 types, table 2.5.

Neat honing oils are petroleum-based and undiluted with water; they include paraffinic oils and kerosene. Neat honing oils provide a boundary film for excellent lubricity separating the interfaces so that only the cutting points make contact. The lubricant often has extreme pressure additives especially when using high honing pressures, to prevent chip welding to the honing stone resulting in clogging or galling.

Water-based fluids are considered better for the environment. They can dissipate heat better; have good wettability, low viscosity and are easier to handle. Water-based fluids are more often used with superabrasives because the higher material removal obtained with superabrasives results in greater heat generation^{79, 80, 81}.

Table 2.5: Comparison of metalworking fluids for grinding⁷⁸

GRINDING FLUID CHARACTERISTICS				
	1 = POOR		4 = BEST	
	SYNTHETICS	SEMI-SYNTHETICS	SOLUBLE OIL	STRAIGHT OIL
HEAT REMOVAL	4	3	2	1
LUBRICITY	1	2	3	4
MAINTENANCE	3	2	1	4
FILTERABILITY	4	3	2	1
ENVIRONMENTAL	4	3	2	1
COST	4	3	2	1
WHEEL LIFE	1	2	3	4

There are three groups of water-based fluids⁸²:

a) Oil emulsions use emulsifiers to form a suspension of oil droplets in water. The oil emulsion will often incorporate EP additives and show good lubrication, cooling and rust protection. Emulsions are potential feeding grounds for bacteria so biocides are often required.

b) Semi synthetics are a complex mixture of emulsions and water solutions, with mineral oil and other components. Again they are vulnerable to biological attack from bacteria. Semi synthetics offer good wettability and detergency however generally have inferior lubricity.

c) Synthetics are true water-based solution containing no oil. Synthetics offer better cooling, easier filtration, bioresistance and the ease to clean the workpiece. Synthetics are usually formulated with lubricant properties and rust inhibitors. Typical ingredients are organic acids, amines, surfactants and soaps.

One type of synthetic fluid⁸³ is based on poly alkylene glycols (PAG). PAG provides lubricity as a consequence of its inverse solubility above their cloud point and form a thin lubricating film, but under high pressure, extreme pressure additives must be added to prevent the formation of spot weld. Water-soluble EP additives include fatty acids and phosphate-based acids.

Synthetics are generally cheaper than neat oils depending on the dilution level. For synthetic grinding fluids, often 2 - 15 % concentrate is needed.

Additives often used with lubricating fluids include:

- i) Anti-oxidizing agents to prevent oxidation of the oil.
- ii) Wetting agents to help the oil coat the workpiece, abrasive and chips (fines) which prevent micro welding and improve lubrication, chip removal and cooling.
- iii) Extreme-pressure (EP) additives like sulphur, chlorine and phosphorus compounds that assist in lubrication under high pressure and temperature. These compounds work in different ways i.e. the heat generated by the cutting is used to form oxides⁷⁷ on the work's surface to which anti-weld and anti-wear additives attach preventing galling and micro-welding of chips. These temperature activated compounds can alternatively decompose into free radicals, which react or adsorb quickly with the exposed clean surface forming metal salts or low shear strength films. The different EP additives often active at different temperatures, so matching lubricant to application becomes important. Chlorinated paraffins and sulfurized hydrocarbons⁸⁴ are believed to work by forming ferric chloride or ferric sulphide on the ferrous workpiece. These metal salts form a barrier to metal to metal contact and welding. Jain⁸⁵ also investigated the EP activity of some inorganic metallic salts of chloride, sulphates and phosphates in aqueous cutting fluids and found that phosphate salts showed improved anti-seizure properties believed a result of a transfer layer formed providing lubricity. Chips that become clogged onto the stone can cause scratches and poorer surface finishes.
- iv) Corrosion inhibitors prevent corrosion by forming a thin compact protective film on the metal surface. These corrosion inhibitors consist of long narrow molecules with a polar head, which is attracted to the metal surface. Chemicals include organic compounds like amines and fatty acids. Alternatively passive film can be formed on the unprotected surface by using inorganic compounds containing oxygen, which reacts with the surface to produce different oxides, these chemicals include borates, phosphates and silicates. Nitrite has been used in the past but is being phased out due to health concerns.
- v) Biocides are designed to protect fluid from bacterial attack, which can result in a change in performance and also bad odours, table 2.6.

Table 2.6: Problems associated with bacterial attack on metalworking fluids⁸⁶

PRIMARY SYMPTOMS OF MICROBIAL SPOILAGE
IN METALWORKING FLUIDS

<ul style="list-style-type: none">• Odor development• Decrease in pH• Changes in emulsion stability• Increase in corrosion rates• Increased incidence of dermatitis and skin irritations• Surface-finish blemishes	<ul style="list-style-type: none">• Clogged filters, screens and lines• Increased work piece rejection rates• Decreased tool life• Unpredictable changes in coolant chemistry
---	--

vi) Antifoam. Excessive foaming from agitation of the metal working fluid can cause problems for filtering

Good maintenance of metal working fluids is needed for consistent performance. Maintenance and disposal costs⁸⁷ should also be a consideration when selecting a metalworking fluid. Neat honing oil can last indefinitely with proper care. While careful chemical control of synthetic fluids is needed for consistent performance, issues include water quality^{88,89}, concentration of additives, pH and removal (filtering) of fines.

2.3.8 Wear and cutting behaviour of stones

A honing stone is engineered to remove material, improve surface finish and improve roundness in a short cycle time. This is achieved by a gentle abrasive action, which introduces less heat into the surface. Critical for successful operation, when using honing stones, is the self-sharpening or self-dressing effect.

The honing stone surface consists of protruding abrasive grits distributed over the surface with a distribution of heights and cutting geometries (i.e. rake angles). These grits are held within a bond. Honing stone wear is divided into two groups⁹⁰, grit wear and bond wear. It is important that the bond wear closely matches the abrasive wear to prevent premature loss of abrasive grits. When the wear of grit and bond is well matched good grit protrusion is ensured while maintaining a long stone life. This self-sharpening will influence the surface finish achievable, the material removal capability and the predictable or consistency of the process, which would otherwise be adversely affected by clogging or loading of the honing stone.

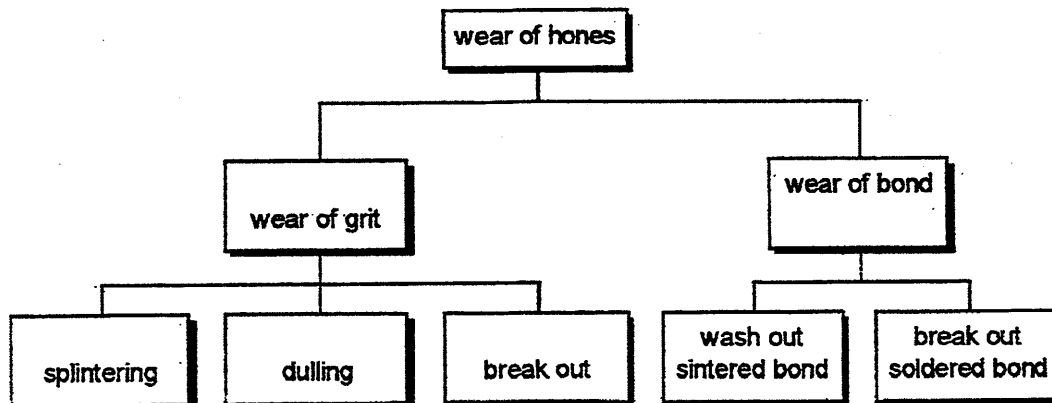


Figure 2.21: Overview of honing stick wear mechanisms⁹⁰

Figure 2.21 show wear mechanisms for metal bonded diamond and CBN honing sticks used in long stroke honing. For such stones grit protrusion is $\sim 1/3$ the grit size and is retained by self-sharpening.

2.3.8.1 Grit wear

Grit wear is mainly caused by i) mechanical friction between the cutting edge and the work piece (dulling) producing wear flats, ii) grit splintering producing new sharp cutting edges and iii) breakout of complete grits.

Grit breakout may result from advanced bond wear adjacent to the grit weakening the bond. Grit wear can lead to blunting of the cutting edges and formation of wear flats which increases the local cutting forces on the grit and possible mechanical overload of the bond which can result in grit pullout.

The abrasive grit type, morphology and mechanical properties will influence its wear behaviour. Monocrystalline grits are less likely to fracture and when they do it results in a large cleavage of the abrasive and a high grit wear. SiC is friable so fractures easily forming new small sharp cutting edges. New microcrystalline abrasive consists of an agglomeration of fine micron grains tightly bonded together. As the cutting force increases on the grit, instead of wear by cleavage fracture or grit pullout, these microcrystalline abrasive show controlled breakdown by micro chipping. This micro chipping ensures dull cutting edges break off leaving new cutting points.

In addition, chemical wear of the abrasive grits should be considered. As previously mentioned carbon steels are not usually ground with diamond as under the high temperature and pressure in the grinding contact, carbon can diffuse into the workpiece giving increased grit wear.

2.3.8.2 Bond wear

Contact between the bond and the workpiece combined with their relative motion results in frictional wear of the bond. This relative motion between the stone and the workpiece determines the cutting direction and chip flow. As a chip is formed it runs off the cutting surface and impacts the bond, which serves as a chip guide and reroutes the chip flow. The region in front of the cutting grit experiences intense wear from the impact of the chip forming a wear crater^{90,91}. The flow of the chip around the cutting grit also results in wear of a trench allowing the chip to exit at the rear of the stone. The oscillation of the stone results in chip flow occurring on both sides of the cutting point so a V shaped groove is formed, figure 2.22.



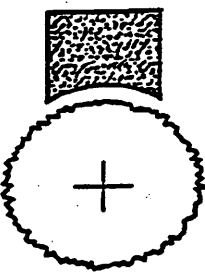
Figure 2.22: Showing crater wear ahead of cutting grit and side trench as a result of chip flow⁹⁰

To allow the chip to escape the cutting zone, it is recommended to use a thinner honing stone when applying diamond or CBN superabrasives. The distance the chip must travel is then less and it is less likely for the chip to become loaded, which would give occasional deep scratches and inconsistent surface finishing. Using thinner stones is more critical with superabrasives because they are much harder and wear less than conventional abrasives. For maximum usage of the superabrasive, harder bonds are used such as metal or a harder grade vitreous bond. The use of harder bonds reduces the bond wear and prevents premature loss of the superabrasive. Superabrasives are much more expensive than conventional abrasives so economically it is important to maximize the abrasive usage. Depending on the application G ratios (volume of material removal from workpiece / volume of stone wear) for superfinishing⁹² with CBN are of the order of ~ 10 - 20 compared to conventional stones of ~1- 0.5 which are considered the lower limits of practical use.

The higher stone wear allowable when using conventional stones leads to a slightly different self-dressing cycle, see figure 2.23. The application of the honing stone onto the rough surface results in self-dressing or sharpening, which gives aggressive cutting and material removal. The majority of the material removal is in this phase as well as the stone wear. As the stone continues to cut, the workpiece becomes smoother as well as the honing

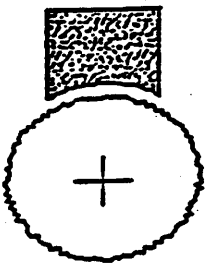
stone. Stone wear then decreases and the cutting grits can become duller resulting in reduced free cutting ability⁹⁴ and surface finishing commences. The smooth honing stone must then be re-dressed by the next rough incoming part.

ABRASIVE SELF-SHARPENING CYCLE



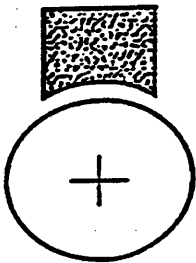
Cycle 1

The smooth abrasive tool surface contacts the rough surface of the part to be superfinished. The rough surface dresses the bonded abrasive tool and aggressive cutting begins.



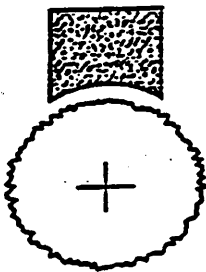
Cycle 2

The rough abrasive tool surface continues to cut and wear. As the finish of the workpiece improves, the abrasive surface also becomes smoother. This results in a slower cut rate and decreased wear.



Cycle 3

Finally, the workpiece and abrasive tool surface are both smooth. The ability to cut is minimal and final finish is achieved.



Cycle 1

NEXT PIECE: The smooth abrasive tool surface contacts the next rough workpiece and the cycles repeat themselves.

Figure 2.23: Self dressing cycle for conventional stones⁹³

The self sharpening attributes of the honing stone will be influenced by the incoming part quality⁹³, so it is important to have a consistent incoming part quality, including component metallurgy and heat treatment as well as surface finish and part geometry i.e. roundness. If the surface roughness of the incoming part is too rough it can lead to excessive stone wear, diametric variations and a rough surface finish. These problems are caused by excessive self-sharpening and aggressive cutting during the superfinishing cycle. Similarly if the incoming part is too smooth it delays the self-sharpening and can lead to stone loading. Excessive out-of-roundness can also disrupt the self-sharpening causing it to cut more aggressively and increase the stone wear.

2.3.8.3 Material removal mechanisms

Malkin and Puthanangady² applied theory developed for grinding⁹⁷ to superfinishing, investigating the abrasive-workpiece interactions from energy and power requirements. Any superfinishing mechanism must be able to account for the magnitude of specific energies and patterns in the behaviour. Malkin investigated sintered and fused alumina stones and a clear difference in their behaviour was found. Since this work introduces some theory into superfinishing which is more often considered an art than a science, more details will be given about this paper, since it gives an insight into the material removal mechanisms.

Analysis of the honing stone cutting behaviour is shown below:

The forces and corresponding energies consist of a cutting and sliding component.

$$F_t = F_{t,c} + F_{t,sl}$$

and

$$F_n = F_{n,c} + F_{n,sl}$$

Assuming that the normal ($F_{n,c}$) and tangential ($F_{t,c}$) cutting forces are proportional to the removal rate then

$$F_{t,c} = k_1 Q_w$$

$$F_{n,c} = k_2 Q_w$$

where k_1 and k_2 are constants, the cutting force ratio is then defined as

$$\eta = \frac{k_1}{k_2} = \frac{F_{t,c}}{F_{n,c}}$$

so that

$$F_t = k_1 Q_w + \mu F_{n,sl}$$

and

$$F_n = \frac{k_1}{\eta} Q_w + F_{n,sl}$$

The overall force ratio is defined by

$$f \equiv \frac{F_t}{F_n}$$

Therefore as the removal rate Q_w approaches zero the force ratio should approach the sliding friction coefficient μ

$$f = \frac{F_t}{F_n} \rightarrow \frac{F_{t,sl}}{F_{n,sl}} = \mu \quad (Q_w \rightarrow 0)$$

And at higher Q_w the sliding components become negligible and the force ratio should approach the cutting ratio

$$f = \frac{F_t}{F_n} \rightarrow \frac{F_{t,c}}{F_{n,c}} = \eta \quad (Q_w \text{ large})$$

The force ratio plotted against the removal Q_w showed two regimes. As Q_w approaches zero $f \sim 0.08$ implying a sliding friction coefficient of 0.08 this value is much lower than found in grinding or honing and has attributed to the wax treatment given to stones. At higher Q_w the force ratio tends towards 0.35, which implies the cutting force ratio is 0.35.

It is now possible to determine the magnitudes of the cutting and sliding forces and associated specific energies.

$$\left(\frac{f}{\mu} - 1\right)F_n = \beta Q_w$$

$$\text{where } \beta = k_1 \left(\frac{1}{\mu} - \frac{1}{\eta}\right)$$

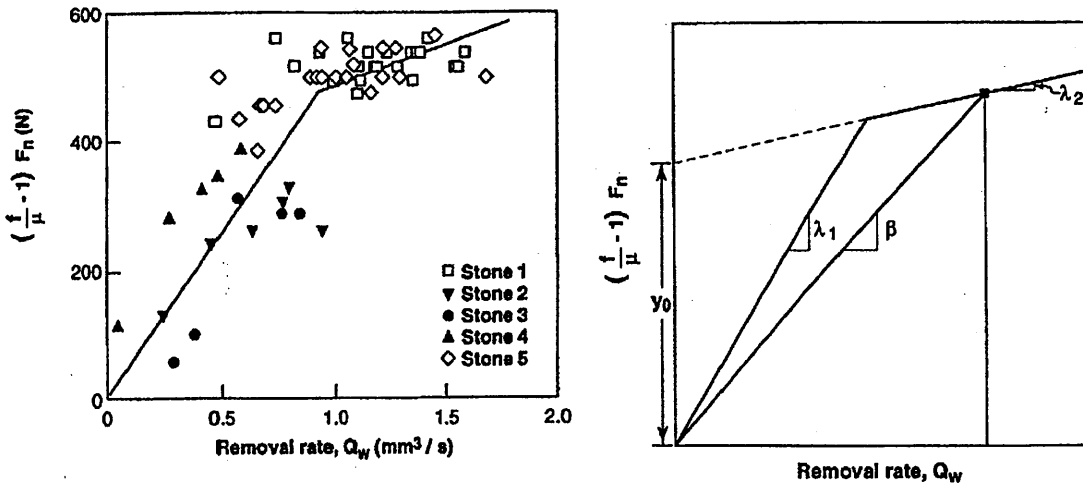


Figure 2.24: plot of $\left(\frac{f}{\mu} - 1\right) F_n$ versus removal rate, stones 2 & 3 are sintered while 1,4 & 5 are fused alumina, 500 grit with wax treatment

A graph of such a plot should be a straight line of slope β passing through origin. The graph is however; better described by two lines, of slope λ_1 at lower Q_w regime and λ_2 at higher Q_w , figure 2.24.

At Q_w below $0.9 \text{ mm}^3 \text{ s}^{-1}$ the straight line passes through origin implies constant specific cutting energy component β is found to be 567 Nmm^{-3} and using $\mu = 0.08$ and $f = 0.35$ gives $k_1 = 58.8 \text{ Nmm}^{-3}$ from which the specific cutting energy is obtained

$$u_c = \frac{P_c}{Q_w} = \frac{F_{t,c} v_r}{Q_w} = k_1 v_r$$

the specific cutting energy in first regime using $v_r = 1.35 \text{ ms}^{-1}$ was $u_c = 79.6 \text{ Jmm}^{-3}$

A similar analysis can be applied to the second regime except β depends on the material removal.

$$\beta = \frac{y(Q_w)}{Q_w}$$

The above analysis assumed the total specific energy consists of a cutting and a sliding component. The energy used for cutting can actually be separated into a chip formation component u_{ch} and a ploughing component u_{pl}

$$u_c = u_{ch} + u_{pl}$$

Chip formation energy refers to the energy required for actual material removal, typically in grinding $u_{ch} = 13.8 \text{ Jmm}^{-3}$, this is related to the melting energy for iron. The ploughing energy does not actually remove material but is expended by side flow of material and plastic deformation under grit.

$$u_c = u_{ch} + u_{pl} = 79.6 \text{ Jmm}^{-3}$$

In the first regime $Q_w < 0.9 \text{ mm}^3 \text{ s}^{-1}$ a constant specific cutting energy independent of removal rate indicates that if $u_{ch} = 13.8 \text{ Jmm}^{-3}$ then the specific energy for ploughing $u_{pl} = 65.8 \text{ Jmm}^{-3}$. This is 83% of the total cutting energy with only 17% associated with actual chip formation. The insensitivity to removal rate suggests critical rake angle controlled ploughing, where only grits with a rake angle in excess of a critical value are involved in material removal by chip formation, other cutting points ploughing material aside.

In the second regime the specific cutting energy is given by:

$$u_c = u_{ch} + u_{pl} = 13.2 + \frac{59.5}{Q_w}$$

13.2 is considered to be the energy for chip formation u_{ch} , the second term u_{pl} is found to vary inversely with removal rate. This is consistent with critical depth controlled ploughing

where ploughing becomes less likely at bigger uncut chip thicknesses i.e. larger removal rates. Critical depth controlled ploughing is characterized by a nearly constant ploughing force thereby the specific ploughing force would vary inversely with removal rate.

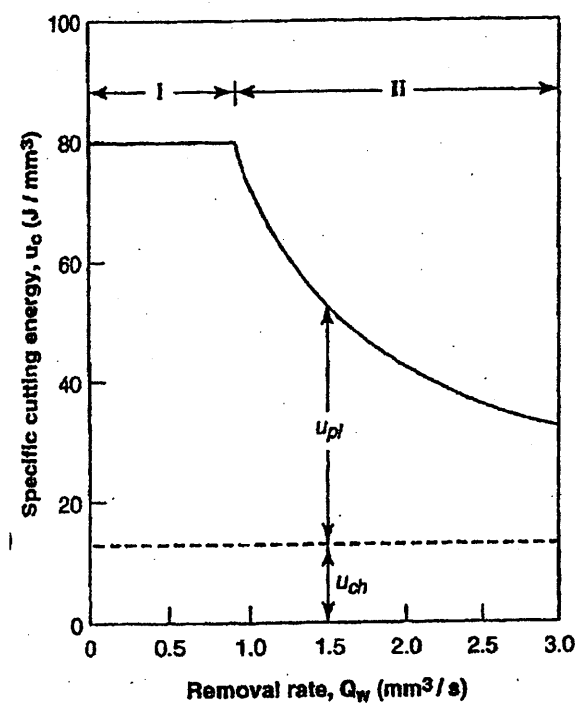


Figure 2.25: Specific cutting energy vs material removal illustrating chip formation and ploughing components

The above analysis shows that mechanisms applied to grinding are also prevailing with superfinishing. Chip formation and ploughing components depend on removal rate, which in turn is related to the sliding component. Sliding forces result from rubbing of worn abrasive (dull flatten areas on grits) and loaded metal against the workpiece. A sharper abrasive with less adherent metal will therefore show less sliding and more of the applied force can be used for material removal.

One way for stones to remain sharp and clean is through stone bulk wear, where worn grits are continually being replaced by sharper fresh grits. Often it is found that a stone with low wear rates has poor cutting ability. From observing the sliding component of the normal force with the stone wear give an indication of stone dullness or sharpness. The analysis carried out for the above situation clearly showed differing behaviour between the fused stone and sintered stones. The fused stones are behaving as expected, i.e. the stone wear rates increased the sliding component of the normal force decreases. The sintered stones show the opposite behaviour where the stones become duller at higher stone wear rates. The difference may be related to the way the stones break down, involving grain fracture, whole grain dislodgement, or bond wear. The analysis shown above clearly is able to differentiate between stone behaviour.

The other two important results found by experimentation were; if the input roughness dropped below a certain value then the cutting action would stop, and the removal was insensitive to input roughness above this critical value. The removal is sensitive to tracking by the stone i.e. if the workspeed and axial oscillation are an integer ratio then the stone will travel along the same path and the removal rate is reduced.

2.3.9 Practical behaviour of superfinishing stone

When superabrasives are used to replace conventional stones it is recommended to reduce the stone width⁹⁸ by 1/2 to 1/3. The possibility to use lower pressures is also needed with superabrasives. Usually CBN stones are used with neat oils or soluble oils. The bond material is important because superabrasives cut the workpiece rather than erode the surface so the bond is under greater stress. As a general rule for hard brittle materials, softer bonds are needed, as they break down the abrasive faster, therefore greater bond wear is needed to replenish the supply of cutting edges. For lower hardness materials, greater bond strength is needed since the abrasive penetrates the workpiece deeper generating higher stresses on the bond. Higher abrasive concentrations will give a longer stone wear life but too high a concentration can impair the cutting speed leading to loading and glazing.

Work by Matsumori^{99,100,101} on CBN superfinishing of bearing raceways shows that CBN has better cutting performance, more consistent surface finishing and lower stone wear. The key to successful application of any superfinishing process is to optimise stone selection and machining parameters. The process is very sensitive to machine conditions and stone structure, improper conditions can lead to an increase in stone wear from loading and glazing of cutting grits and an increase in cost.

The high cost of CBN abrasive tools must be justified by much better stone wear and higher performance. The structure of the stone becomes very important; the cutting grits must be held strongly and space available for easy chip flow provided.

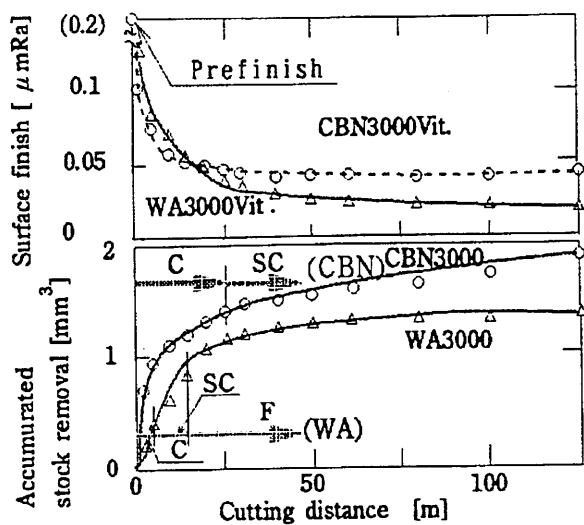
Chip removal for conventional stones is associated with bulk wear of the stone due to erosion by the cutting chips. The chip produces a wear pocket at the base of the cutting grit which if sufficient will allow for easier chip flow out of the contact. For a CBN stone however, which experiences relatively little stone wear, space must be provided within the stone to allow stable chip flow out of the cutting zone. If this space is not available, excessive loading will occur and result in abnormal forms of stone wear such as spalling which, ultimately results in higher stone cost and poorer surface finishing. In general as the abrasive grits become finer the formation of this chip pocket or the self-dressability/sharpening becomes more difficult; therefore engineering a stone with a more open structure for chip flow becomes essential. Porous CBN stones have been shown to give higher material removal capability with more consistent surface finishing^{100,101}.

The lower stone wear associated with CBN stones does give significant benefits particularly for high volume production including: less frequent stone changes, higher quality and consistent quality surfaces as well as more consistent stone shape.

Three typical superfinishing characteristics have been described¹⁰⁰.

- i) Cutting (C) high stock removal and rough surface finish
- ii) Mirror finishing (MF) low stock removal and fine mirror finish
- iii) Semi-cutting (SC) intermediate behaviour

Figure 2.26 shows these regimes for superfinishing with CBN and alumina.



Comparative performance of CBN and aluminum oxide superfinishing stones. [SAE52100, HRc60/62, BB, $\alpha = 15^\circ$, $f = 400\text{cpm}$ $D = 22.3\text{mm}$ $N = 3000\text{rpm}$ $P_n = 1.7\text{MPa}$, $\Theta = 1.1^\circ$, $V = 210\text{m/min}$]

Figure 2.26: Showing superfinishing regimes¹⁰⁰

The higher stone wear rate associated with conventional abrasives is critical in their usage. When a soft abrasive is applied onto a rough workpiece, the stone is redressed by the incoming part generating a fresh cutting surface. The material removal rate and the stone wear are greatest at this stage (C), however as material is removed, the stone wears and the workpiece becomes smoother such that the material removal rate begins to decrease (SC). The final stage shows very little or no material removal as the stone becomes worn or loaded at which point surface finishing (MF) begins by burnishing the surface.

CBN fine grit stones tend to perform in C or SC regimes with higher finishing ratios compared to conventional stones. The high stock removal or vigorous cutting action of CBN grits inevitably gives a rougher surface finish. To achieve the same finish achievable with a conventional alumina stone generally a finer grit size CBN stone is required, figure 2.26.

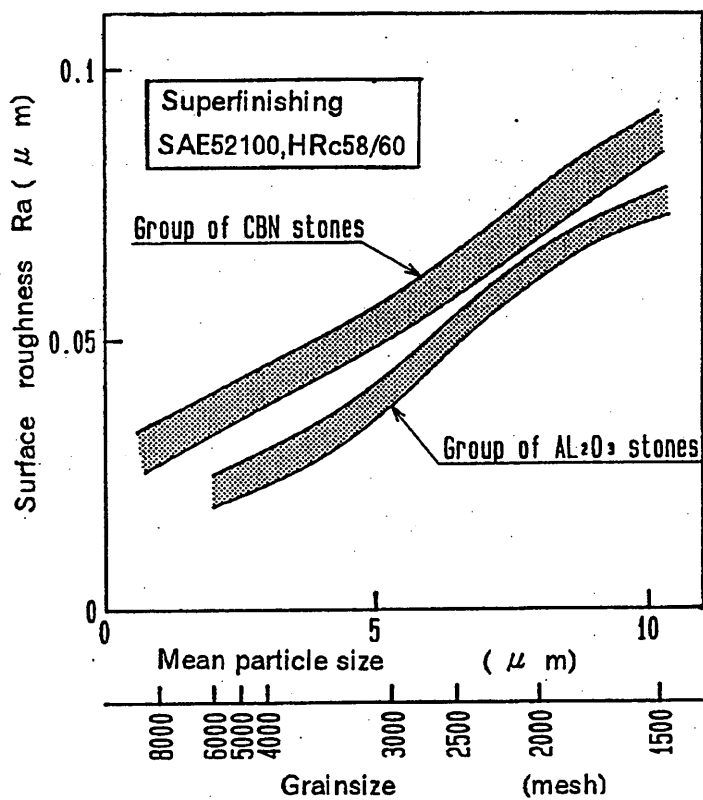


Figure 2.27: Graph comparing surface finishing achievable by using different grit size CBN and alumina stones

Examination of chip morphology formed by superfinishing with CBN showed the following trends: thinner and longer chips for higher workpiece velocities, short chips for larger cross hatch angle, finer chips for finer grit sizes and thicker chips for higher stone pressures^{99,100}.

A surface finish of 0.03 μm R_a can be reached with a #4000 or finer CBN stone, although finer stones e.g. #6000 CBN stone will have lower stock removal so a two stage superfinishing operation using fine grit followed by a very fine grit CBN stone is preferred in practice.

A characteristic stone parameter is P_c , a critical pressure at which the stone shows a change in properties such as stone wear, removal rate and surface finish.

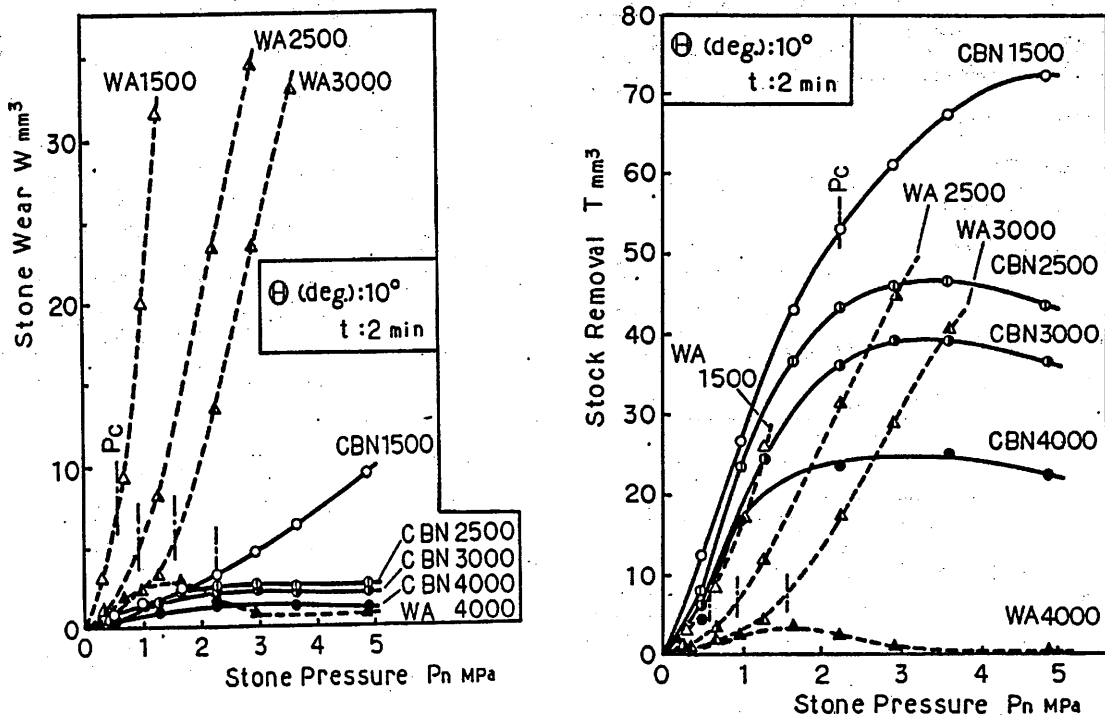


Figure 2.28: Comparing material removal and stone wear for different CBN and alumina superfinishing stones. Indicated on the graphs are the critical pressures P_c ⁹²

For Alumina with 1500, 2500 and 3000 grits, stone wear and removal rate increases at P_c , this is also found to happen with CBN 1500. The actual magnitudes of stone wear for 1500 CBN is however, very much smaller than for alumina, so the finishing ratio is much better. For WA 4000 at P_c the stone loads up and stock removal drops, figure 2.28.

CBN 2500, 3000, and 4000 appear to have a similar stone wear behaviour as the loaded and glazed WA 4000 but they remain cutting so have a much better finishing ratio. Finer grit stones will not show grit fracture as much, and therefore 4000 WA will glaze. CBN will maintain its sharp cutting points longer so will continue removing material. CBN generates no decrease in stock removal by glazing even if the maximum cross hatch angle is decreased significantly. The surface finish is however improved with much improved finishing ratios, as the crosshatch angle is decreased or working distance is increased.

The general superfinishing behaviour when using CBN stones include⁹⁹:

- 1) Increasing pressure will increase the material removal. At P_c the stock removal continues to increase but at a much faster rate. This occurs with a large increase in stone wear so the G ratio decreases substantially. Above P_c the R_a is also found to increase. The actual material removal and surface finish depend on the grit size employed.
- 2) Higher cross hatch angles result in greater material removal but also a slight drop in G ratio. The surface finish also increases with cross hatch angle.
- 3) Increasing peripheral speed gives an increase in material removal, but again a drop in G ratio.

The recommended superfinishing conditions are a low stone pressure, high peripheral speed and a certain optimal crosshatch angle.

Cycles are not mentioned except for a few tens of seconds¹⁰¹. Using conditions⁹⁹ of 1.5 MPa, cross hatch angle 5° , workspeed 60 m/min and a working distance of 100 m, a CBN stone #2500 gave a surface finish of $\sim 0.03 \mu\text{m } R_a$ with a material removal of $\sim 6 \text{ mm}^3/\text{mm}^2$. The stone wear rate was less than $1 \mu\text{m}$ per workpiece. Special porous CBN stones had very high finishing ratio 20 times that of alumina with G ratios of 10 - 20.

Work by Bordeianu and Marinescu^{102,103} investigated conventional stones of 1000 grit alumina and SiC. They concluded that; alumina should be used for the rough superfinishing stage, due to its high material removal capability; while the SiC is recommended for the fine superfinishing stage, because of its better surface finishing ability. Cycle times of 8 - 10 seconds were recommended. The material removal using alumina increases with stone pressure, workspeed and oscillation frequency, while the SiC was not affected as significantly. For alumina the stone wear was found to increase with pressure, workspeed and oscillation frequency, but again the SiC was not affected so drastically. The higher material removal capability and stone wear of alumina honing stones resulted in a G-ratio of ~ 1.5 while for SiC the G-ratio was ~ 3 . It should be noted these tests were done on DGBB inner rings (outer diameter 14.7 mm, input $R_a \sim 0.1 \mu\text{m}$) and the lowest workspeed used was 3000 rpm. With SiC, a surface finish of $0.025 \mu\text{m } R_a$ could be achieved in 6 seconds.

Comparing the conventional stones with CBN¹⁰⁴ of similar grit size showed the CBN had a much higher material removal capability, which further increased with increasing stone pressure, workspeed, oscillation frequency and cycle time. At the same time the CBN showed the lowest stone wear rate. This gave G-ratios for the CBN stone of 25 - 30, whereas the conventional stones had G - ratios of 1 - 4. The CBN stone however, gave a higher surface roughness. Higher stone pressure, workspeed and longer cycle times gave an improvement in R_a for the alumina, SiC and CBN stones, while an increase in oscillation frequency increased the roughness for the CBN stone. A R_a of $\sim 0.02 \mu\text{m}$ was achievable using the highest workspeed 7000 rpm. This work suggests CBN for the roughening operation and SiC for the fine finishing. Low oscillation frequency is recommended for fine finishing when using CBN.

Puthanangady¹⁰⁵ also investigated superfinishing of DGBB inner rings using alumina and SiC with different hardness grades and grit sizes. It was found that for alumina, increasing the contact pressure increased the material removal, although the softest grade showed only a slight increase in material removal. The soft grade did show the greatest stone wear which was very high even at low pressures. The soft grade stone also gave the highest roughness. Larger stone oscillation amplitude was also found to increase stone wear. The material removal rate using SiC showed insensitivity to contact pressure; therefore harder grade stones are needed to minimize stone wear to ensure long stone life. Sulphur treated stones gave improvements in stone life and surface finish with only a marginal drop in material removal.

As a guide to trouble shooting, figure 2.29, some general rules can be used as a starting point to optimise a superfinishing process⁹³.

CONDITION	INCREASE	DECREASE	OTHER
EXCESSIVE STONE WEAR	SPINDLE RPM	STONE/WHEEL PRESSURE	USE HARDER ABRASIVE PRODUCT
INSUFFICIENT STOCK REMOVAL	ABRASIVE PRESSURE RECIPROCATION/OSCILLATION RATE	SPINDLE RPM	USE SOFTER ABRASIVE PRODUCT USE COASER GRIT ABRASIVE
ROUGH FINISH	SPINDLE RPM	STONE/WHEEL PRESSURE RECIPROCATION/OSCILLATION RATE	USE FINER AND/OR HARDER ABRASIVE PROD.
UNDESIRABLE SMOOTH FINISH	RECIPROCATION/OSCILLATION RATE ABRASIVE PRESSURE	SPINDLE RPM	USE COARSER AND/OR SOFTER ABRASIVE PROD.
EXCESSIVE HEAT GENERATED	COOLANT FLOW RATE	STONE/WHEEL PRESSURE	USE SOFTER ABRASIVE PRODUCT
OUT-OF-ROUND PARTS	RECIPROCATION/OSCILLATION RATE	STONE/WHEEL PRESSURE SPINDLE RPM	USE SOFTER ABRASIVE PRODUCT
GLAZING OF ABRASIVE SURFACE	RECIPROCATION/OSCILLATION RATE ABRASIVE PRESSURE	SPINDLE RPM	USE COARSER AND/OR SOFTER ABRASIVE PROD.
LOADING OF ABRASIVE SURFACE	RECIPROCATION/OSCILLATION RATE	SPINDLE RPM	USE FINER AND/OR SOFTER ABRASIVE PRODUCT

Figure 2.29: Trouble shooting list for superfinishing⁹³

2.3.10 Developments in abrasives

i) Open pores

Work in Japan by N. Matsumori¹⁰⁰ has been conducted using superfinishing stones, which have been engineered to have a structure with a two pore size distribution to aid with chip flow and removal. The small and very large pores (20~50 x grit size) allows chips to flow stably preventing excessive wear and loading of the stone. This new stone structure maintains a clean cutting surface, which allows greater removal and less stone wear with greater consistency in finish.

ii) Electrolytic in-process dressing (ELID) dressing

A Japanese Paper¹⁶⁴ by Ueda applies conventional ELID technology to superfinishing using a rotary honing stone (grinding wheel). The process differs from ELID grinding since an oscillation unit has been added to the grinding wheel. Using a water based coolant and a metal bonded diamond #4000 mesh wheel the cuttability of the wheel could be controlled by varying the electrolytic dressing on-off time. By making the electrolytic dressing stronger the cuttability increased as well as the removal rate although the surface finish became worse. Using less strong dressing parameters gave better surface finishing. This work also showed that a wheel that had lost its cuttability could be regenerated by strong electrolytic dressing.

iii) Corundum hollow spheres are presently being added to grinding wheels to give increased porosity to aid chip flow and to allow adequate coolant into the contact zone.

iv) The superfinishing process is beginning to be investigated in more detail using test machines with sensors added to monitor stone wear, removal rate, cutting forces and spindle power¹⁰⁶. This information is then used to determine stone behaviour i.e. specific energies. Piezoelectric force transducers are being used allowing the average force as well as the oscillatory forces to be determined to within 10 mN.

v) The use of slotted grinding wheels for easy removal of chips and coolant flow are now being applied to superfinishing stones¹⁰⁷. The larger the contact area between the stone and workpiece the greater the chance of loading and increased stone wear. Reducing the distance a chip must travel to be removed from the cutting zone will reduce the risk of loading.

vi) Ultrasonic assisted honing^{107,108,109} has been investigated to reduce stone loading by using ultrasonic vibrations acting perpendicular to the honing stone. These vibrations promote stone wear to ensure self-sharpening.

vii) Microcrystalline (sintered aluminum oxide¹¹⁰) abrasives. Microcrystalline abrasives are already being applied to grinding wheels to increase material removal and to lower wheel wear. They are also being introduced to honing stones to improve the self-sharpening, by a controlled micro-chipping breakdown mechanism to maintain sharp cutting edges. These stones are mainly for rough honing operations and are not readily available in the fine grit sizes needed for fine superfinishing.

2.4 Non conventional surface finishing methods

There is a range of additional machining and finishing methods see table 2.7, based on chemical, thermal, electrical, and mechanical methods as well as hybrid combinations^{111,112} thereof. For example figure 2.30 shows possible hybrid machining methods using ECM.

Some of these techniques are not suitable for bearing finishing because of surface quality or speed. For example, electric discharge machining (EDM) removes material thermally, which can produce poor surface integrity, cracks, white layers and tensile stresses that are not acceptable for a bearing running surface.

Any surface finishing process will affect not only the surface but also subsurface, influencing surface texture, surface integrity, hardness and stress state. Surface modification techniques such as ion implantation or coatings, which often come under the category of surface engineering are not included.

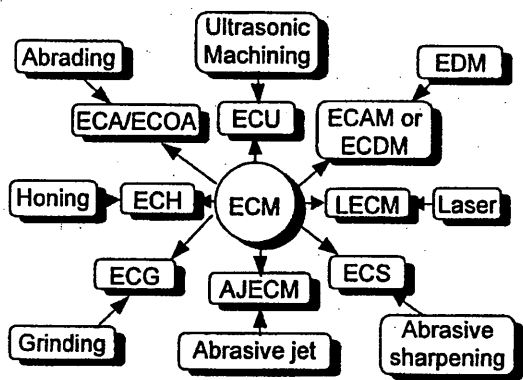


Figure 2.30: Hybrid machining processes based on ECM technology¹¹¹

There is considerable evidence in the literature that the machining characteristics can be significantly altered with the assistance of thermal, chemical or electrochemical reactions. One way this is accomplished is by changing the material properties of the surface, for example forming an oxide or soft shearable layers, which are more easily removed, or by material removal without mechanical abrasion. The benefits of such interactions can include higher material removal rates, improved surface finish, reduced surface damage, lower abrasive tool wear, lower machining forces and alternative surface textures. However there can also be adverse effects such as lower compressive stresses, lower surface hardness and lower fatigue life from reduced mechanical working of the surface.

Chemical and electrochemical finishing techniques can give surface smoothing but are relatively slow and for efficient smoothing and brightening material removal needs to be under mass transport control. Combining these with an abrasive process can accelerate the smoothing.

Table 2.7: Showing some of the different finishing techniques available including some hybrid processes

	Processes
Mechanical	Honing, abrasive brushes, finish hard turning Lapping, mass finishing Abrasive flow machining Burnishing Magnetic abrasive finishing Peening
Chemical	Chemical finishing Chemical milling Photochemical milling
Chemical assisted	Chemical mechanical polishing Chemical accelerated vibrofinishing Chemical assisted machining Mechanochemical polishing
Electrochemical	ECM Electropolishing
Electrochemical assisted	Electrochemical honing/polishing Electrolytic grinding Electrochemical assisted machining Electrolytic In-process Dressing (ELID)
Electrical	EDM EDM texturing, EDM alloying
Electrical assisted	Electric discharge grinding Abrasive electric discharge machining AEDG Electrochemical discharge machining
Thermal assisted	Laser assisted Plasma assisted

This project investigated an electrolytically assisted abrasive finishing process and from the literature there is evidence of related techniques in research articles and patents. In these cases the general mechanism for the enhanced surface finishing was attributed to forming a weak oxide layer which is preferentially removed at surface peaks by the abrasive, further electrolytic attack is then concentrated more on the exposed peaks than the valleys increasing the selectivity for peak removal. The research articles generally use a low current density and low abrasive pressure, although the rate of finishing was found to improve at higher pressure and higher workpiece speed indicating the importance of the abrasive mechanism on surface finishing. The cycle times for these processes were also very slow (minutes) compared to conventional bearing finishing techniques (seconds).

2.4.1 Mechanical

The conventional mechanical abrasive finishing techniques have already been discussed: however there are other possible mechanical surface finishing techniques.

A) Hard turning¹¹³ is essential turning in the hardened condition. Developments in machine tool design and in hard cutting tool materials such as ceramic inserts have meant machining of hardened steel for particular applications can be economic. This has considerable advantages in regard to flexibility and machine cost. A turning machine can perform a number of machining operations in one setting, reducing the number of machines needed, increasing flexibility and improving part precision. Surface finishes¹¹⁴ 0.025 μm Ra can be achieved in finish hard turning. Hard turning can also introduce high levels of compressive stress deep into the surface, but can also give tensile surface stresses particular when using worn inserts.

B) Abrasive flow machining (AFM)¹¹⁵ uses abrasive grits held in a putty type medium whose viscosity changes with shear rate. The process is used for finishing, deburring, blending of holes such as in extrusion dies. By using constrictions the abrasive action can be made more selective. Orbital AFM is a variant for finishing complex cavities in moulds.

C) Burnishing¹¹⁶ results in plastic deformation of the surface using a ball or roller, which is pressed onto the surface. The process introduces high levels of compressive stresses deep into the surface.

D) Peening is another plastic deformation process where shot of steel balls or glass beads are bombarded at the surface which introduces high compressive stresses to improve fatigue life but can also be used to produce a surface texture of pits.

E) Magnetic abrasive finishing (MAF)¹¹⁷ using magnetic abrasive particles to form an abrasive tool in a magnetic field. The workpiece is rotated between the two direct current

electromagnets with a small gap filled with the magnetic abrasive particles. The magnetic field holds the abrasive within the gap and higher material removal can be achieved by using higher rotation speeds. The material removal and surface finish depend on the abrasive grit size used and the magnetic force. When applied to bearing surfaces an improvement in Ra from 0.5-0.6 μm to 0.05 - 0.06 μm in 30 - 60 seconds has been reported¹¹⁷. The process has also been applied to ceramic roller and balls¹¹⁸.

2.4.2 Chemical Finishing

Chemical polishing has been used for thinning and polishing of metallographic specimens; it is also used for chemical deburring of parts such as used in the textile industry.

Chemical polishing¹¹⁹, like electropolishing, is believed to involve diffusion of atoms dissolving from the workpiece through a continually replenished surface layer. Atoms from protruding parts are removed quicker since they have a shorter diffusion path resulting in macro smoothing and micro smoothing. Polishing solutions generally contain three components, an oxidizing agent to oxidize the surface, a depassivator to prevent the passive oxide film building up which would stop further chemical attack, and a viscous component to promote formation of a thick viscous surface layer needed for macro smoothing. The alternating oxidation and removal of the oxide is also postulated as a possible finishing mechanism. Chemicals such as nitric acid and hydrogen peroxide can be used for the oxidizing agent, while orthophosphoric acid, sulphuric acid or glycerol can be added to dissolve the oxide layer and form a viscous layer. Some chemical polishing compositions for iron include

1. 5 % H_2SO_4 saturated with oxalic acid, 45 % water and 50 % H_2O_2
2. 60% H_3PO_4 and 40 % H_2O_2
3. 30 % HNO_3 , 15% HCl , 10 % HF , and 45 % water

Kim and Suh¹²⁰ investigated chemical smoothing of 440 stainless steel using FeCl_3 . They showed that using a rotating disk electrode for efficient smoothing, the process had to be under diffusion control, but also that the diffusion layer thickness influenced the smoothing rate. An 80 μm R_{max} surface produced by EDM could be improved to 10 μm , although the surface finish was influenced by microscopic etch pits of 3 μm . FeCl_3 is also used for photochemical milling.

2.4.3 Chemical assisted

2.4.3.1 Chemical mechanical polishing CMP

CMP combines simultaneously chemical action with a mechanical action for planarisation and polishing without causing surface damage. CMP has found extensive use in the electronic industry for manufacture of wafers, flat panel display and thin film magnetic heads.

The process consists of a rotating polishing pad, which is pressed against the workpiece. The polishing pad is soaked with slurry, which is a chemically active liquid with abrasive particles. The active chemicals can include chemicals such as hydrogen peroxide¹²¹ and ammonium hydroxide¹²², while the abrasive could be fine grained alumina or diamond.

Surface finishing is achieved by cyclic formation of a metal passivation layer, which is subsequently removed by the abrasive action. A balance must be achieved between high oxidation rate needed for rapid material removal and etching rate, which can lead to selective etching of different phases or components within the workpiece. For example planarisation of metallisation structures on Si wafers may consist of insulating SiO₂, and conductive Cu tracks, which can be etched at different rates.

2.4.3.2 Chemically assisted mass finishing

This process combines vibrofinishing (although other mass finishing techniques are applicable) with active chemicals for increase rate of surface finishing and improve surface finish. US patent 4491500¹²³ by REM Chemicals Inc. discloses a chemically accelerated vibratory mass finishing technique with active chemicals which is combined with mechanical abrasion generated by the vibrofinishing equipment.

The workpieces react with the chemical liquid forming a soft conversion coating, which then acts as a barrier for further attack. Agitation of the workpieces results in continuous wetting by the chemical liquid. The mechanical abrasion results in the removal of the coating predominantly at the surface peaks revealing fresh metal, which is subsequently attacked by the chemical liquid reforming a protective coating. This combined chemical and mechanical removal from the surface peaks results in a more rapid rate of surface finishing.

The chemicals employed by REM form an aqueous solution with a pH of 1.5 - 3: the preferred embodiment uses water, oxalic acid, sodium nitrate, and hydrogen peroxide. The hydrogen peroxide increases the activity of the solution for faster finishing. However in high concentrations it results in excessive material removal and at low concentration it can lead to unacceptable pitting on the surface. The nitrate ions are believed to contribute not only to the process speed but also the weight of the conversion coating produced.

An important point is that it takes time for the coating to form, i.e. an incubation period. For the solution above approximately 1 minute is needed before a film is first observed and approximately 4 minutes before a continuous film is seen.

In a patent US5503481 ¹²⁴, the bearing company Timken describes the REM process for the finishing of bearings. This patent discusses the benefits imparted to a bearing finished by this process. The process described was used on the raceways and rollers of taper rolling bearings. In the process, the REM chemicals flow at 1.5 gal/hr through the vibrofinishing tank until the surface roughness was removed producing an isotropic surface with shallow pits. Then a burnishing fluid flowing at 20 - 40 gal/hr also provided by REM is added to neutralise the previous chemicals and remove the protective coating. The low material removal of the process prevents any change to geometry of the processed parts. The isotropic surface with small pits was also claimed to reduce running-in, demonstrated by lower temperatures and torque during running-in trials plus lower operating temperature and torque once the bearing was run-in, compared to a honed / superfinished surface. The fatigue life was also claimed to have been improved. The reason for this much improved performance was attributed to better lubrication from an isotropic surface compared to the circumferential textured roughness resulting from a grinding or honing process. But also the slope Δq of the surface and consequently the plasticity index were lower for the new surfaces, which could explain the improvement in running in.

In the patent typical surfaces produced by grinding, honing and REM are given in table 2.8.

Table 2.8: Comparison of surface finish from ground, honed and REM vibrofinished

	Grinding	Honing	REM
Ra μm	0.3	0.1	0.06
Rp μm	1.3	0.55	0.2
Δq slope	9	6.2	1.8
Ψ Plasticity index	2.25	1.54	0.44

In a separate patent ¹²⁵ Timken covered material removal and surface finishing rates. The input surface texture consisted of circumferential lines with an initial roughness 0.28 μm Ra that was gradually reduced with processing time. After 30 minutes the roughness had decreased to 0.06 μm Ra although some circumferential grooving was still evident. After 45 minutes the roughness was at its limit of 0.06 μm Ra characteristic of the vibratory finishing process, but the circumferential marks from grinding had been removed. So depending on the input surface an optimum cycle time is available to form an isotropic surface, with low material removal reducing any geometric form errors plus lower liquid usage and hence cost.

2.4.3.3 Chemical assisted machining of ceramics

The machining of ceramic parts can be an appreciable part of the cost of the final component up to 50 - 80 %. The requirements for a ceramic machining process are high material removal with good surface finish and good surface integrity (no cracks). It is found that for hard brittle ceramics, high material removal is accomplished by brittle fracture which results in a rough surface with cracks, while ductile grinding of ceramics gives good surface finish but a lower material removal rate. Wang and Hsu¹²⁶ postulated that to achieve high material removal and finishing together, a way was needed to by-pass the hardness and brittleness of ceramics. This was done by adding active chemicals into the cutting fluid and using the temperatures and stresses generated by the grinding process to initiate tribochemical reactions, which assisted the grinding process. Wang and Hsu tested a range of liquids and found that halogenated hydrocarbons gave improved material removal rates and by combining CCl₄ with HF acid, high material removal with good surface finish of 0.07 µm Ra without cracks could be achieved. Possible chemical mechanical reactions that were postulated included disruption by abrasion of the surface bonds resulting in dangling Si bonds. These can then react with oxygen or water forming oxides, which further react with the halogen forming easily shearable layers.

2.4.3.4 Mechanochemical polishing

Mechanochemical polishing uses abrasive powders, which are mechanically softer than the workpiece but can chemically react with them. Example is BaCO₃ powder for the polishing of Si wafers¹²⁷ or Cr₂O₃ oxide for polishing SiC and Si₃N₄. This process has advantages in low mechanical damage and no scratch marks; also the process can be performed dry, improving cleanliness in the production environment. Surface finishing of < 1nm Ra are reported.

2.4.4 Electrochemical processes

2.4.4.1 Electropolishing

Electropolishing is a process that smoothes and brightens a surface by a) macro smoothing as a result of greater material removal from the surface peaks than the valleys and b) micro smoothing, which suppresses crystallographic features, and surface defects.

Electropolishing is accomplished by making the workpiece the anode and using concentrated acids or mixtures of acids such as phosphoric acid, sulphuric acid as the electrolyte. Most electropolishing electrolytes are proprietary but often have other additions such as glycerol (to increase the viscosity), water, or methanol and work at set temperatures and electrochemical conditions. The workpiece is placed between one or two cathodes, which can be sheets or rods with a large inter-electrode gap and by applying a certain current density, smoothing and polishing takes place. The workpiece is often agitated.

Electropolishing has been studied extensively and a number of theories and mechanisms exist for the smoothing action¹²⁸.

1) The macro smoothing results from preferential attack on the surface peaks and can be modelled using the primary current distribution, which depends on the geometry, electrochemical parameters and hydrodynamic condition. McGeough⁵¹ showed that longer wavelengths of roughness are levelled at a slower rate than short wavelengths. This model doesn't incorporate effects resulting from activation and concentration over voltages, which give secondary and tertiary current distributions. Wagner applied the Nernst diffusion layer model to the current distribution under mass transport control. If the diffusion layer is uniform over the surface then only geometric levelling should occur. Unfortunately in practice perturbation in hydrodynamic conditions results in a non-uniform diffusion layer thickness.

2) Micro smoothing

For micro smoothing the dissolution must be under mass transport control. There are a number of possible mechanisms but the salt precipitation mechanism appears to be better recognized. In this mechanism the rate-determining step is the diffusion of dissolved metal ions from the anode entering the bulk electrolyte. At the limiting current the concentration of the metal ions reaches saturation and a salt film precipitates at the surface. The current density then depends on the concentration gradient between the metal ions on the anode surface and in the bulk electrolyte. Evidence for this mechanism include:

- 1) A decrease in limiting current if the metal ion concentration in the electrolyte is increased
- 2) Increase in limiting current when using a rotating electrode at higher speeds indicating mass transport control.

There is also evidence that for brightening a thin compact conductive surface film is needed. The composition of such films is still in question. However removal of metal through the “oxide” film is a random process governed by cation vacancies so is not influenced by the crystallography of the surface unlike metal removal in the active potential region; therefore etching does not occur. There is clear evidence for the existence of an oxide film when electropolishing Ti, which then requires a higher voltage to break down this film. Experiments on the transpassive dissolution of Fe and Ni show that the breakdown of a passive film leads to pitting but not necessarily brightening which needs mass transport control occurring at or above the limiting current. At high potentials an increase in pit nucleation rate and growth leads to merging of the pits which when combined with dissolution under mass transport control can result in smooth bright surfaces. Pitting can also arise due to gas bubbles and non-conductive inclusions which perturbate the hydrodynamic flow.

Surfaces produced by electropolishing

The surface finish produced depends very much on the electropolishing conditions and also on the workpiece material. Homogeneous material can be electropolished fairly easily, but heterogeneous materials, which may have a number of different phases, can be more difficult due to potential differences existing between the phases. Macro smoothing will reduce the surface roughness ($<0.1\ \mu\text{m}$) while micro smoothing results in brightening and a highly reflective isotropic surface due to lower surface slopes.

The properties of the surfaces are different from mechanical produced surfaces as a result of no work hardening and stress free surface finishing.

The electropolished surface can be considered equi-potentialised¹²⁹ as there are few or no local corrosion cells, which can be caused by local galvanic differences within the surface from induced stresses. The presence of a thin transparent oxide layer, which can result from electropolishing particularly for stainless steel and aluminium, also gives a degree of corrosion resistance. It has been claimed that electropolished carbon steel parts can be stored at 60 - 70 % relative humidity for over 6 months without visible signs of rust. The surface produced is cleaner¹³⁰ with none of the smearing of metal often seen on ground surfaces. One disadvantage of electropolishing is a reduction in fatigue life (possibly by 10 - 30 % that of a mechanical polished surface) resulting from lower compressive stresses or no compressive stresses (depending on amount material removed) unlike mechanical finishing methods, which generate a thin surface compressive stressed region.

2.4.4.2 Electrochemical machining

Electropolishing is closely related to electrochemical machining. The main differences lie in their application. ECM is used as a forming technique with high material removal rates, using neutral electrolytes while electropolishing is purely a surface finishing and brightening technique using acidic electrolytes. Acidic electrolytes can be used for ECM, for example ECM drilling of very small holes in turbine blades to avoid precipitates blocking the hole, but the material removal rates are lower.

Electrochemical machining has been discussed earlier with its main applications in deburring, blending of corners, and shaping particularly for hard aerospace materials.

The surface finish achievable is influenced by the microstructure, grain size and inclusions. ECM can influence short order waviness, and it has been found that a larger grain size reduces the power of the short wavelength irregularities¹³¹. Increasing the electrolyte flow also reduces short order waviness¹³² but, in addition, increases the initial rate of surface finishing. Longer machining times are found to improve the surface finish¹³³.

As with electropolished workpieces, ECM on cast and wrought steels¹³⁴ was found to reduce the fatigue life of the ECMed component. The reduction in life (~ 14%) is attributed to removal of compressive stresses, but also, at lower ECM currents, because of inferior surface finish. The life of components after ECM can be substantially improved by shot peening to re-introduce compressive stresses. The fatigue lives after ECM on cobalt-chromium alloy and stainless steel¹³⁵ have also been found to be reduced after electrochemical machining. It was considered that the reduction in life for the Co-Cr alloys was due to surface defects while for the stainless steel the elimination of a work hardened and residual compressively stressed layer contributed to the reduction in life.

ECM has been considered for bearing machining and finishing¹³⁶; US patent 3730861 describes a technique for electrochemical machining to form surfaces of revolution with a feeding electrode. High current densities of 6000 amperes per square inch (930 A/cm²) are used to achieve high material removal rates. Once the workpiece has been machined to final dimensions the current is reduced to 1500 - 3000 A/square inch (230 - 460 A/cm²) for one revolution to obtain a bright surface finish. The idea was considered for taper roller bearings where ECM could replace rough and fine grinding operations, as well as the honing step. The gap at the end of machining was 37.5 µm with a voltage of 15 volts. The workpiece could be machined to within a dimension of 2.5 µm and an out-of-roundness of 2.5 µm with a surface finish of less than 0.125 µm Ra.

Patent US4456516 also demonstrates a further possible advantage of the ECM process to improve the roundness of shafts¹³⁷. The technique uses a bracket to make a two point sliding contact with the shaft. This bracket has a measuring device, which sends a signal as a feedback to the ECM current, which gives the possibility to correct out-of-roundness.

2.4.5 Electrochemical assisted processes

2.4.5.1 Electrochemical honing ECH

ECH combines electrochemical machining with an abrasive material removal process. This introduces a number of problems mainly related to optimising two processes, which have different requirements at the same time.

An article ¹³⁸ in 1965 announced that electrolytically assisted honing was approaching reality, claiming the process resulted in a sharp increase in abrasive efficiency and rapid finishing for hard materials. It was claimed that the abrasive removed the surface oxide produced by the ECM process and prevented the formation of polarisation layers. The method applies both processes (ECM and honing) initially and finishes with only honing to give conventional surface finishes and geometric tolerances. A conventional honing cycle for the bore of a transmission gear took 160 seconds, which was decreased to 30 seconds by electrolytic honing with a stock removal of 0.2 mm and tolerances maintained to 0.05 mm.

A patent ¹³⁹ by the superfinishing machine builder Supfina in 1968 described an electrolytic honing technique for short stroke plunge honing or throughfeed honing. In this patent, the grinding tool (honing stone) was made the positive electrical connection to the workpiece. The honing stone was made electrically conductive by impregnation with metallic powder or graphite. The ECM operation occurred before or simultaneously with the machining, but the final step was pure abrasive machining at which point the workpiece could be rotated at a higher speed. The patent also detailed the possibility of improving diametrical fluctuations (roundness errors) on the workpiece by using constant voltage, so that changes in the inter-electrode gap between the cathode and workpiece resulted in an increase or decrease of the ECM current to control the material removal and improve rounding up.

A Polish article ¹⁴⁰ on optimisation of electrochemical honing (ECH) applied to cylinder bores considered material removal capability more than surface finish. The parameters most effecting machining output was time, honing pressure and current. The tribological properties of the surfaces also indicated that ECH surfaces showed greater wear but this was attributed to uneven dissolution of particular components in the machined material. This disadvantage can be utilised to expose hard Si crystals on the surface such as in aluminium alloyed cylinders used in internal combustion engines, which have a high Si content. An earlier article ¹⁴¹ by the same author also suggested a decrease in stress state due to ECH by 20 - 30 % compared to conventional honing. Usually ECH surfaces are finished by honing only, to remove any oxides, however the surface stress properties are still not as good as conventional honing.

Computer integrated field controlled electrochemical honing ¹⁴² is a technique developed in China giving the ability to give good surface finishes but also providing the possibility to correct form errors by a using displacement sensor with a feedback to a computer to control the current and hence material removal. In this case low current densities are employed with an oscillating honing stone, which acts as a scrub to remove oxides formed on the surface, ensuring current efficiency is mainly controlled by the current density and not

polarisation effects. The process has been investigated for gear honing and also rollers used for sheet metal rolling. The process can then be considered an alternative to CNC grinding but would be cheaper and provide a better surface finish. However the process is slow; 67 minutes were required to machine a profiled roller of length 200 mm and diameter 32 mm to a surface finish of $0.038 \mu\text{m Ra}$. Once again the final operation uses only the honing stone to remove remaining oxide.

Patent US4483755¹⁴³ discusses a combined process for treating cast iron workpieces in relation to cylinders for internal combustion engine. It makes mention of the problems associated with electrochemical honing of bores which include reference to:

- 1) The tool design must incorporate honing stones and cathodes in a small space, which makes the tool complex and expensive.
- 2) The small bore size imposes restrictions on the process parameters.
- 3) Metallic bonds cannot be used since they would be subjected to anodic attack.
- 4) The electrolyte cannot be optimised simultaneously for mechanical and electrochemical material removal. Honing usually requires neat honing oils to lubricate, minimize stone wear, prevent stone clogging and corrosion protection of machine and workpiece, while ECM uses electrically conductive salt solutions, which are highly corrosive. Also the motion of the honing stone disturbs the electrolyte flow conditions which influences surface finish and stock removal.

There are reports of other abrasive-assisted ECM processes for surface finishing which employ abrasives in different forms including cloth and free abrasives thereby avoiding the problems associated with honing stones. One patent EP0452501¹⁴⁴ on super-mirror finishing with electrolytic grinding for small diameter tubes improves the surface in two steps. Firstly a cathode rod is insulated by a porous elastic urethane sheet, which allows the electrolyte (20 wt.% NaNO_3) to pass. Then a non-woven nylon sheet comprising abrasive grains is wrapped on the urethane. A sequence of abrasive grain sizes can be used, but the final preferable size is #10000. A small electrolytic current ($0.1 - 0.4 \text{ A/cm}^2$) is passed between the cathode rod and the anodic tube to be finished. Motion is generated between the tube and cathode rod by rotating the rod and oscillating the rod or tube. A low pressure of 5 - 100 kPa is generated between the abrasive and the inside of the tube. The finishing mechanism is described as the forming of a passive oxide film, which is abraded at the peaks and, the freshly exposed metal is electrolytically attacked forming an oxide again. This removal of the film by the abrasive grains is repeated such that the time-averaged current density on the high peaks is greater than in the surface depressions resulting in rapid smoothing. The second stage of the finishing technique uses free abrasives ($\sim 1 \mu\text{m}$ alumina), which does not result in deep scratches associated with fixed abrasives. Here the cathode rod with the insulating porous urethane provides the electrolytic action and the free abrasive is mixed with the electrolyte. The method applied to stainless steel tubes improved the surface from $3 \mu\text{m Rmax}$ to $0.05 \mu\text{m Rmax}$ in less than 8 minutes.

In another patent US4294673¹⁴⁵ a similar electrolytic mirror finishing technique was disclosed for treating cylindrical workpieces. The cathode had a layer of water-permeable abrasive matter (cloth, buff or free abrasive) with a thickness of 0.5 mm or greater, Abrasive grain size employed was #600 to #800. The cathode was fed onto the rotating (> 2 m/s) cylindrical workpiece. This feed controlled the pressure ($> 0.5\text{kgf/cm}^2$) exerted by the abrasive and the inter-electrode gap (1 - 3 mm). 20 wt.% NaNO_3 electrolyte is supplied through holes in the cathode or by a separate nozzle. Electrolytic action results by applying a voltage of a few volts to 15 volts and a current density of $\sim 10\text{ A/cm}^2$ or less. The surface finishing mechanism is again by the formation of passive anodic films, which are abraded at the peaks, resulting in greater selective removal from the surface peaks. The patent also allows for auxiliary electrodes (without abrasives), working at lower voltages, to be used for larger cylindrical parts to allow sufficient time for the passive film to form. The process also claims to improve roundness since the abrasive pressure and current efficiency depend on the inter-electrode gap, so that a lobe on the surface will decrease the gap and hence result in greater abrasive and electrolytic material removal from the lobe. A cylindrical part 20 μm R_{max} and roundness of 4 - 7 μm was finished by the said technique (using a current of 14 A and voltage of 9 V, abrasive pressure 1kgf/cm^2 , rotating speed 500 rpm, feed rate 8mm/min) to an R_{max} of 0.05 - 0.1 μm and roundness of 1.5 - 3 μm with a material removal from diameter of 0.04 - 0.06 mm. The cycle time for these operations was not mentioned but the mass removal rate is briefly reported at approximately 80 mg/min. The surface finishing rate was improved at higher speeds and greater pressures.

2.4.5.2 ECM polishing

Patent US5911841 describes a method to increase the corrosion resistance of stainless steel parts by using electrochemical buffing followed by a heat treatment¹⁴⁶. It claims that the electrochemical buffing results in a "Beilby layer" or a chemically active work strained layer consisting of fine crystals at the surface. This strained layer provides diffusion routes via grain boundaries for Cr so that during heat treatment in a weakly oxidizing atmosphere, a Cr_2O_3 layer is formed which has better corrosion resistance than an iron oxide or mixed oxide layer. A sample of SUS 316L having an initial roughness R_{max} 20 - 50 μm was improved by a sequence of electrochemical buffing using SiC abrasives #120 - #1500 and 20 wt.% NaNO_3 at a current of 0 - 6 A/cm^2 to give a surface 0.1 μm R_{max} .

Kimoto et al.^{147,148} described an electrolytic mirror polishing technique for stainless steel, which could produce better surface finishes than electropolishing or mechanical buffing. This improved surface finish had applications for reducing fouling or adhesion in large stainless steel vessels used in chemical reactors. The method used a rotating tool, which had cathodic and abrasive areas, and the electrolyte (NaNO_3) passed through the centre. The abrasive used was a non-woven nylon abrasive cloth (alumina grit size #600), a light pressure 0.2 Kgf/cm^2 and a tool rotation speed of 400 rpm. A potential of 8.2 V improved a surface of 6 μm R_{max} to 0.2 - 0.3 μm R_{max} after 2 - 3 minutes. By applying a second operation where free abrasive (alumina #1500) was used, this 0.2 - 0.3 μm surface could be further improved to 0.05 - 0.01 μm R_{max} in another 2-3 minutes.

Tam et al¹⁴⁹ describe a similar ECM-abrasive polishing technique using a vitrified CBN tool or a bonded Al₂O₃ pad, grit size #320, again using an NaNO₃ electrolyte. Machining parameters were evaluated using an experimental design, and they found that for CBN the main factors were d.c. voltage and pressure while for alumina, the electrical parameters had a greater influence such as d.c. voltage and electrolyte conductivity. The best surface finish achieved was 0.4 µm R_{tm} with a processing time of around 30 minutes.

Patent US4839005 describes an electrolytic-abrasive polishing technique for aluminium surfaces¹⁵⁰. This patent details a finishing technique for soft aluminium surfaces to avoid scratch marks. The electrolytic process is performed using low concentrations of NaNO₃ electrolyte (3 - 10 %) at 15 °C. A low voltage (-0.3 V to 2.1 V) is used with a low current density of 5-30 mA/cm² so that a passivating film forms on the Al surface. Abrasive (<1 µm size) and a lapping (pressure 0.5 kgf/cm²) using non-woven cloth from ultra fine fibres removed this passive layer at protruding peaks. The use of a low concentration and low temperature electrolyte reduces electrolytic dissolution or leaching, which can result in selective dissolution and pitting of the surface. A surface finish of 0.015 µm R_{max} could be produced by this method although processing time was not mentioned.

Takahata et al presented a technique for surface finishing of 3-dimensional microstructures produced by micro EDM¹⁵¹. The technique used the EDM electrode with an electrolyte, consisting of a water-based colloidal solution mixed with Al₂O₃. A high voltage ~ 80 V is needed due to the low conductivity. They found that positive electrification of the Al₂O₃ particles in the low conductivity electrolyte resulted in accumulation of the abrasive particles at the cathode (EDM electrode) by electrophoresis. Rotation of the electrode with these Al₂O₃ agglomerates resulted in increased mechanical polishing, removing metal hydroxides from the surface and allowing more even metal dissolution and a better surface finish. A surface finish of 0.032 µm R_{max} was produced after 120 seconds from an EDM surface of ~ 0.35 µm R_{max}.

2.4.5.3 Electrochemical grinding

Electrochemical or electrolytic grinding^{152,153,154} combines grinding with electrochemical material removal. Most of the material removal is performed by the ECM action and ideally only 5- 10 % of the stock removal is done by the abrasive. The set-up uses a conductive grinding wheel as the cathode. The grinding wheel consists of non-conductive abrasive grits (60 - 320) such as SiC, Al₂O₃, diamond or CBN and is made conductive by using a metal bond or a conductive resin bond. The resin is usually made conductive by filling with a metal such as copper powder. The workpiece is made the anode and an electrolyte such as NaNO₃ or a mixture of salts is directed into the working gap through a nozzle. The passage of current results in metal dissolution and the formation of soft surface metal hydroxides and oxides. The abrasive action serves to remove these oxide layers permitting efficient ECM. The non-conductive abrasive acts as a spacer maintaining an inter-electrode gap¹⁵⁵ of ~ 0.025 mm. The process uses low voltages (0-24V) and high currents. The process has

found particular use for grinding tungsten carbide cutting tools, honeycomb structures and hard alloys. The main benefits for electrolytic grinding are associated with the low grinding force, less mechanical damage, less heat generation, burr free machining and lower grinding wheel wear. This means that expensive grinding wheels are not redressed so frequently. The accuracy achieved is not as good as grinding due to the ECM producing an overcut, but 0.125 mm can be readily achieved and 0.013 mm is possible¹⁵⁶. The surfaces produced can be from Ra 0.1 μm - 1 μm , but have a matte surface appearance consisting of minute slightly oval mounds.

At high grinding wheel in-feed and high currents the possibility of arcing exists between the metal bond and the workpiece or grinding chips, which places a limit on the material removal capability¹⁵⁷. However this electric discharging can be beneficial since it can redress the grinding wheel removing loaded metal and bond material to expose sharp cutting abrasives and maintaining low grinding forces¹⁵⁸.

Patent US5045161 discusses an electrolytically assisted machining technique applied to cutting tools¹⁵⁹ using a localized ECM action, which is believed to lead to structural weakening or loosening of the surface of a conductive workpiece allowing easier material removal. The process uses the conductive tool shank as the cathode and a non-conductive cutting tool. An electrolyte is directed to flood the gap (can be via the bore in tool shank) in front of the cutting tool and the anodic workpiece. A low voltage and a d.c. current of 10 - 100 amps is applied which electrolytically weakens the workpiece, which is subsequently removed by the cutting tool in discrete particulate form and washed away by the electrolyte. The weakening is highly localized, so the depth of cut is very shallow, but the material removal rate by cutting/wiping is high because the electrolytic structural weakening is almost instantaneous so high surface speeds can be used.

A similar patent (US5976347) describes micro cutting of a metal surface¹⁶⁰. Electrochemical machining is used to form an oxide layer of known thickness; this layer is weaker than the base material and can be readily peeled off by a cutting tool. The oxide that is formed has a greater volume and so generates tensile stresses in the oxide layer, lowering its mechanical strength. One advantage claimed is that since the oxide is not as elastic as the base material better accuracy can be achieved.

The articles above show that the surface can be weakened by surface chemical reactions; it is well known that the mechanical behaviour of solids is influenced by surface physical-chemical phenomena caused by the surrounding media. One example is hydrogen embrittlement or liquid metal embrittlement. Electrical polarisation also plays a role in surface physicochemical phenomena and can lead to a drop in hardness. Stress corrosion cracking is another example of where stress and chemical (electrochemical) interaction alter mechanical properties. Vidensky looked at a process called electro-chemo-mechanical treatment for grinding steels¹⁶¹. This work investigated the effect on grinding carbon steel by the reduction of certain ions Zn^{2+} , Cd^{2+} and H^{+} onto the workpiece. Here the workpiece is the cathode and the effect determined by grinding at constant force and measuring the weight of material removed. As the current density is increased the mass removed increases up to a limit and then falls, showing a possible adsorption-induced plasticification.

2.4.5.4 Electrolytic in-process dressing (ELID)

Electrolytic in-process dressing ^{162,163} (ELID) is applied to fine grit grinding wheels and more recently to fine grit honing wheels ¹⁶⁴ (i.e. constant pressure with oscillation). ELID grinding prevents loading of the wheel surface by forming an oxide layer on the wheel surface by an electrolytic action. The technique allows fine grit abrasive wheels to maintain stable fine finishing without the problems of loading and clogging often associated with higher material removal using fine grit abrasives. The process was developed at RIKEN in Japan by Ohmori and can be applied to any conventional grinder e.g. face grinder, cylindrical grinder, although best results are obtained from high precision machines with lower machine vibrations. The metal bonded or conductive resin bonded grinding wheels use diamond or CBN (for ferrous materials) abrasive grits. The wheel is the anode and a secondary electrode acts as the cathode usually stainless steel or copper. A small gap 0.1 mm is maintained between the electrodes. A suitable grinding fluid (essentially water with a rust inhibitor) is supplied by a nozzle into the gap and a current is applied which results in electrolysis of the metal bond material. The friable oxide formed prevents grinding chips from sticking to the wheel. As the cutting grains are worn, the insulating oxide layer is also worn resulting in further oxidation of the wheel in a self regulating manner and provides continual exposure of fresh cutting points so that the grinding force remains low.

Correct application of ELID depends very much on controlling the etch layer and oxide layer thickness. Research has shown that this can be influenced by the metal bond, power supply, and grinding fluid ¹⁶⁵. The abrasive grit size has a large influence on the achievable surface finish, and the ELID dressing must be optimised with regard to depth of insulating oxide layer and grit size.

Work on Si shows that surface finishes of:

#4000 (2 - 4 μm grits) CIFB-D: Rmax 48 nm Ra 8 nm

#8000 (0.5 - 3 μm grits) CIFB-D: Rmax 36 nm Ra 5 nm

#10000 (0.0 - 3 μm grits) CIFB-D: Rmax 22 nm Ra 4 nm

where CIFB-D is a cast iron fibre bonded diamond grinding wheel. While work ¹⁶² using ultra fine abrasive (<0.5 μm grits) on Si with a lapping type arrangement (constant force) gave surfaces of Rmax 8.92 nm and Ra 1.21 nm. Here the insulating layer thickness is of the order of the grit size and a free abrasive lapping mechanism is believed to work.

Most work on ELID is for ceramics^{166,167} and optical materials¹⁶⁸, although recently a paper ¹⁶⁹ discussed ELID for bearing steel. Surface finishes obtained were 0.011 - 0.036 μm Ra and 0.08 - 0.18 μm Rz. One influence of the process was that it generated lower compressive stresses (150 - 400 MPa) compared to a honed surface (600 - 800 MPa). The cycle time for ELID grinding was also longer at 20 seconds.

2.4.6 Electric and electrically assisted machining

Electric discharge machining¹⁷⁰ removes material electrically by applying a high frequency pulsed, ac or d.c current between an electrode and the conductive workpiece through an insulating dielectric fluid (oil or de-ionised water). Under high voltage and small gap an intense electromagnetic flux is formed which eventually breaks down the insulating properties of the dielectric, and leads to a single spark which melts and vaporizes the metal leaving a crater. Surfaces produced in such a way can have a recast layer with cracks and a higher concentration of carbon from the vaporized dielectric, as well as a heat affected zone (HAZ). This results in a surface of poor integrity, a hard and brittle top surface, and tensile stresses. Often a secondary finishing operation is needed such as ECM, hand polishing or abrasive flow machining. One of the main applications for EDM is die and mould manufacture. The surface finishing and integrity of EDM has been much improved by better control of power supplies. Also additions of conductive powders¹⁷¹ to the dielectric can give greater control of the discharges, which minimizes the recast layer thickness.

EDM is also used for random texturing of surfaces for example rollers for sheet metal rolling and also surface alloying or coating¹⁷² by using an electrode made of the alloying elements, which are then transferred to the workpiece during discharging. It is even possible to EDM non-conductive materials by utilizing conductive films formed on the surface during EDM.

Other applications using EDM or hybrid EDM processes include electric discharge grinding (EDG), abrasive electric discharge grinding (AEDG), and EDM dressing of grinding wheels.

2.4.7 Thermal assisted machining

These include laser assisted machining and plasma assisted machining. The added heat can give increased ductility or cause chemical reactions forming softer reaction products such as oxides. One example is plasma assisted machining of ceramics for improved surface finish.

2.5 The functional bearing surface

The running surface of a ball, roller or plain bearing is a highly functional surface often critical to successful utilisation of a bearing in a particular application. A great amount of research is performed to ensure the surfaces are engineered for optimum performance, and monitoring and control during manufacture ensures these surfaces are realized.

The field of tribology, which looks at the interaction of surfaces, is beyond the scope of this Ph.D. study but some basic concepts will be presented here only to emphasize the importance of the bearing surface. The bearing surface influences:

- a) fatigue life
- b) friction
- c) wear
- d) lubrication regime
- e) corrosion
- f) noise and vibrations

It is important to realize that a bearing surface involves the physical, chemical and mechanical attributes of the surface but also of the subsurface region. Properties include surface finish (texture), stress state, hardness, ductility, and surface integrity (cracks, white layers).

Every manufacturing process has a direct influence on these properties¹⁷³. To illustrate; if grinding is performed incorrectly resulting in workpiece burn known as abusive grinding, this can lead to the formation of tensile stresses. Also the high temperature from abusive grinding can result in a change of the metallurgical structure and softening of the material.

There are also economical justifications for a better understanding of a bearing surface. High friction requires greater power consumption, while wear of bearings results in their earlier replacement and consequently lost production time as well as shorter maintenance periods. There is also a manufacturing cost occurred to produce smoother and smoother surfaces. A common way to improve the surface finish is double stone honing using a course grit stone followed by a fine grit stone. This makes the honing machines more complicated and expensive and can also increase machining cycle times.

2.5.1 Metallic surfaces

The surface after manufacture consists of regions

1. Bulk material: unaffected by the machining process
2. Deformed layer: which has undergone plastic deformation and has often work hardened and has a different stress state and hardness to the bulk material. It is also believed likely that cutting fluids can be trapped in this deformed layer from the machining process.
3. Oxide layer: a clean surface will spontaneously react with its environment, in the case of air an oxide layer will form. This layer has a critical effect on the friction and wear of metals.
4. The oxide layer will be covered with contaminants such as condensed oil vapour, dust and smoke particles

2.5.2 Friction and wear

Friction and wear^{174,175,176} result from contact of asperities on opposite faces of two bodies in motion. The general procedure to determine the degree of contact requires knowledge of the apparent contact area, the pressure distribution, topographic details of surface, the real area of contact and whether the peaks are deforming elastically or plastically. This approach requires many assumptions and usually can only be solved numerically using computer simulations.

A) The apparent area of contact (footprint) and pressure distribution are found from Hertzian theory for non-conforming contacts. Plastic deformation occurs when the shear stress reaches a critical value k . The important points are that:

- 1) The maximum shear stress is reached $0.79a$ below surface, where a is the semi-contact width.
- 2) The onset of plastic deformation occurs when the maximum pressure P_{max} reaches $3.3k$ at the centre of the footprint, i.e. higher loads than expected can be supported elastically in non conforming contacts and when subsurface yielding occurs little plastic deformation occurs due to constraint by surrounding elastic material
- 3) As the load is increased the plastic zone increases in size until it spreads to the surface when plastic indentation can occur. This happens when the mean pressure is $\sim 6k$ or the indentation hardness H of the material. For metals $H \sim 6k \sim 3\sigma_y$ where σ_y is the uniaxial tensile yield strength.

4) When a tangential force (friction) is combined with the normal load it is found that the shear stress distribution is altered such that the maximum shear stress moves closer to the surface which means plastic deformation becomes easier in the presence of frictional forces.

The above illustrate why the subsurface properties such as residual stress have a large influence on bearing performance particularly in fatigue.

B) Hertzian theory is again used to calculate the real area of contact, the load and the number of contact spots for two rough surfaces in contact. The problem is reduced to one rough surface in contact with a smooth surface, where the asperities are treated as sectors of a sphere and there are no interactions between asperities¹⁷⁵.

C) Plastic/elastic criteria

Greenwood and Williamson developed the plasticity index ψ as an indication of the degree of plasticity.

$$\psi = \left(\frac{E^*}{H} \right) \cdot \left(\frac{\sigma}{\beta} \right)^{\frac{1}{2}}$$

This is a useful parameter as it combines surface topographic features with mechanical properties. When the plasticity index is greater than 1 the surface is largely plastic while when the plasticity index is less than 0.6 the deformations are largely elastic.

In most situations on first contact the surfaces will deform elastically and plastically, the outer most peaks being plastic, as the load is increased the amount of plastic deformation will increase. Both friction and wear are very dependent on the degree of plastic deformation.

2.5.2.1 Friction

Amonton's Laws of friction:

1. Friction is independent of apparent area
2. Friction force is proportional to load W , the proportionality constant is the coefficient of friction μ

$$F = \mu W$$

The real area of contact is proportional to load when the contact is fully plastic or for elastic contacts, which have Gaussian or near Gaussian height distributions.

The coefficient of friction of a particular material is meaningless; instead the friction coefficient must be quoted for a particular pair of materials sliding under specific set of surface and environmental conditions. No theory can predict the coefficient of friction for the wide range of material pairs and running conditions so μ must be found experimentally, although general rules for choosing frictional pairs are available.

Friction arises due to adhesion and plastic deformation of the sliding surfaces.

Adhesion

Thermodynamically when two solids are brought together they can reduce their energy states by forming an interface, which lowers the total energy of the system. To break this interfacial bond/junction requires energy or a force. Depending on the strength of this junction, failure may occur at the original interface or in the softer of the two original materials resulting transfer of material to the harder surface.

When two surfaces come into contact, the high pressure at the peaks results in plastic deformation of the softer material. Plastic flow results in growth of the junctions and formation of new contacts until the load can be supported elastically. For ideally elastic-plastic materials this occurs when $W = AP_0$, where P_0 is the yield stress of the weaker material and A the real contact area. P_0 is approximately H the indentation hardness of the softer material, so $W = AH$. Severe plastic deformation results in cold welding of the junctions and a frictional force is then required to shear these junctions. $F = As$ where s is the specific friction force.

Thus $F/W = \mu = s/H$

This result gave good agreement with Amonton's laws that friction is independent of apparent contact area and proportional to load. The friction coefficient was slightly less than found for metals pairs in normal atmospheres, also that friction was only dependent on the softer material, and didn't explain why friction was much higher for clean surfaces.

Modifications to this theory allowed for greater contact area by increased junction growth resulting for a shear stress component to the previous normal load.

Friction is found to be higher on surfaces produced in a vacuum. The lower friction found on normal surfaces can be explained by considering a thin contaminant film on the surface of low shear strength τ_s where $\tau_s = ck$. This film could be an oxide usually present in normal atmosphere.

$$\mu = \frac{\tau_s}{p} = \frac{c}{[a(1-c^2)]^{\frac{1}{2}}}$$

As c tends to 1 the friction tends to infinity in agreement for clean surface (i.e. produced in a vacuum), for lower values of c corresponding to a weakening of the interface by a thin film the friction drops very quickly. It is clear that containment films have a large influence on friction and is the bases of boundary lubricants technology.

Deformation

Resistance to motion can arise from deformation and displacement of material during motion, either from interlocking asperities or by ploughing of hard asperities into the softer material. Additionally hard wear particles can cause ploughing. The extent to which deformation contributes to friction will depend on the surface roughness, hardness of the two surfaces and the size, shape and hardness of any wear debris.

Most frictional energy is dissipated in the form of heat, which has an impact on the microstructure, oxide formation rate and type. It also changes the lubricant viscosity. The heat generated must be dissipated at the asperities, which can lead to high flash temperature.

2.5.2.2 Wear

There are many classifications of wear but are often grouped into two main categories; mechanical and chemical.

1. Mechanical

a) Adhesive wear

Similar to adhesion theory of friction, adhesion wear results when cold weld junctions form at asperities. If the junction is sheared at the original interface no wear occurs but if the shear occurs at the softer asperity then material is transferred to the harder surface and can later be rubbed off, resulting in wear debris. Archard suggested three laws of adhesive wear

I) the volume of material worn is proportional to the sliding distance

II) the volume of worn material is proportional to load

III) the volume of worn material is inversely proportional to the hardness of the softer material

This theory was modified to include a factor k to take into account that not every asperity contact will produce a wear particle

$$Q = \frac{kW}{3H} \text{ or } Q = \frac{KW}{H}$$

where K is the wear coefficient found experimentally. The hardness H is found to change during experiments as a result of work hardening but also variation in hardness due to the microstructure. Therefore the wear rate is often written as:

$$Q = CW$$

Where C is the wear constant

b) Abrasive wear

Abrasive wear results from ploughing of a rough surface into a softer surface. Two situations arise; two-body abrasion where a rough hard surface slides against a softer surface and three-body abrasion resulting from hard particles trapped between two sliding surfaces.

It is found that most material is displaced by an abrasive particle and not removed. It is clear that abrasive wear is more severe if one surface is harder and has sharp asperities (high asperities slope). Most manufacturing finishing processes will produce a smooth surface which produces fine wear marks instead of a few deep marks.

In lubricated contacts abrasive wear is largely eliminated by correct design of surface roughness and material properties. However under high loads or low speed when the lubricating film cannot build up then adhesive wear can result in roughening up of the surfaces followed by work hardening leading to significant problems. Three body abrasive wear is still an issue particularly during running in where wear particles can form or from contamination of hard particles from outside. Here filtering and flushing of the lubricating oil is used to remove the particles.

c) Fatigue wear

Even when the surfaces are completely separated by a lubrication film the surfaces experience stress cycling transmitted through the lubricant, which can lead to wear throughout the bearing's life. Rolling contact fatigue or macroscopic fatigue will be mentioned later. However another form of wear affecting sliding contacts is microscopic fatigue occurring between sliding asperities. When two surfaces approach each other under

a normal force the asperities deform plastically until the surface can accommodate the load elastically. Similarly with sliding the surface must support both normal and tangential forces elastically, the contact stresses on the asperities will vary from very low elastic stresses up to yield stress of the weaker of the two contacting materials. The higher stresses on the asperities can be below the elastic limit but still above the fatigue limit so wear by fatigue can occur. The accumulation of such fatigue cycles can result in the formation of wear particles by local surface fatigue fracture.

The plasticity index $\psi = \left(\frac{E}{H}\right) \cdot \left(\frac{\sigma}{\beta}\right)^{\frac{1}{2}}$ can be used to estimate the number of contacting asperities stressed above the fatigue limit. Table 2.9 shows the ratio between plastic and elastic contacts for different plasticity indexes and pressures. For realistic loads the deformation of the surfaces is elastic when ψ is less than 0.6 and at least partial plastic when ψ is significantly greater than 1.

Table 2.9: Showing the ratio R between plastic and elastic contact area, for different plasticity W and different normalized pressure p/H¹⁷⁴

$\bar{p} = 10^{-4}$		$\bar{p} = 5 \cdot 10^{-4}$		$\bar{p} = 10^{-3}$		$\bar{p} = 5 \cdot 10^{-3}$		$\bar{p} = 10^{-2}$	
ψ	R	ψ	R	ψ	R	ψ	R	ψ	R
2	0	2.3	5.3	5	200				
		1.3	0	1.5	2	5	500		
				1.2	0.5	1.3	3.6	1.8	13
				1.1	0	1	0	1.2	3
								1	2
								0.6	0

Most engineered surfaces have ψ greater than one; so on first contact the deformation will be predominately plastic, which is further exacerbated by tangential traction. Running-in will reduce ψ to a point were deformations become elastic, but as long as the stresses are still above the fatigue limit, cyclic fatigue of the asperities will occur. Even with fine surface finishes where ψ could be below one, the elastic stresses on the asperities can still be above the fatigue limit and fatigue wear is still likely.

d) Delamination wear

Delamination wear is a severe form of fatigue, where the surface undergoes cyclic shear loading, which nucleates void and cracks below the surface. Under further cyclic loading these voids and cracks grow and link up, until some critical length at which point the crack tip breaks through the surface forming large thin plate-like wear particles.

2. Chemical wear

Chemical wear refers to wear in the presence of a corrosive medium, which may be liquid or gaseous. One example is oxidation wear in the presence of air. The degree of wear depends on a number of factors including the rate of oxide film growth, the stresses developed in the film, the adhesive strength of the oxide to the substrate, the hardness of substrate, load, temperature and speed.

The oxide film can be beneficial since it prevents metal to metal contact reducing severe adhesive wear.

Lubricants used in roller bearings not only separate the surfaces, reducing adhesive wear and removing wear particles, which can cause three body abrasive wear but can also contain extreme pressure (EP) additives. These EP additives react with the surface at the flash temperatures generated in the contact. The reaction products form a barrier to metal-to-metal contact. EP additives are often used in heavily loaded contacts where scuffing can occur. EP additives result in mild wear preventing the roughening of the surfaces, which can lead to scuffing.

The other classifications for wear types include fretting and erosion

2.5.3 Lubrication regime

The dimensionless film parameter Λ is commonly used in literature to describe the lubrication condition or regime see figure 2.31.

$$\Lambda = \frac{h_{\min}}{(R_{q,a}^2 + R_{q,b}^2)^{\frac{1}{2}}}$$

where $h_{\min}$ is the minimum film thickness

$R_{q,a}$ is the rms roughness of surface a

$R_{q,b}$ is the rms roughness of surface b

The denominator is the combined rms roughness of the two contacting surfaces.

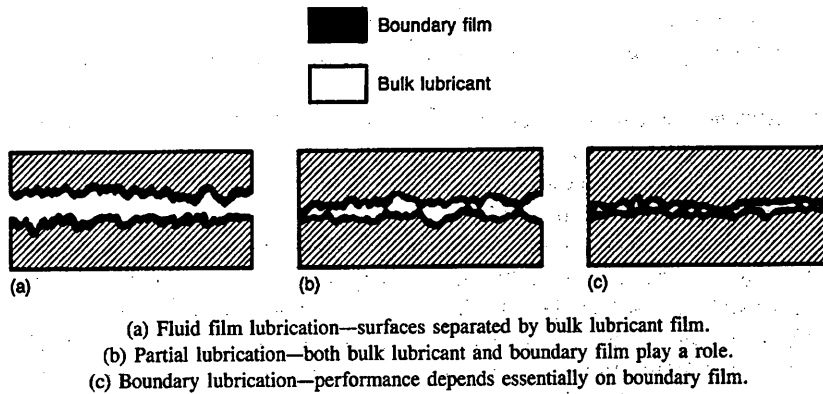


Figure 2.31: Lubrication regimes¹⁷⁷

Λ defines four important lubrication regimes

1) Hydrodynamic lubrication $5 \leq \Lambda < 100$, the film thickness ($>1\mu\text{m}$) is sufficient to completely separate the surfaces. The lubrication is governed by the physical properties of the lubricant such as viscosity, so the frictional characteristics arise purely from shearing the viscous lubricant. Hydrodynamic lubrication is generally applicable to oil lubricated bearings operating at sufficient speed, where a pressure (usually less than 5 MPa) develops because of the converging film thickness, relative motion and viscosity of the fluid.

2) Elastohydrodynamic lubrication $3 \leq \Lambda < 10$ is typified in non conforming rolling contacts where the pressure generated can be 0.5 - 3 GPa with a film thickness of $> 0.1 \mu\text{m}$. At these pressures the elastic deformation of the contacting surfaces becomes significant and results in flattening of the asperities giving thicker film thickness that would be expected from the initial rms roughness values.

The above situations are characterized by a lubricating film fully separating the surfaces which results in low wear and low friction, which is considered the ideal condition for running a bearing.

3) Partial or mixed lubrication $1 \leq \Lambda < 5$. This situation can arise in bearings operating with too high a load or too low a running speed such that the film thickness decreases and the highest asperities can penetrate the film making contact. The film thickness is less than $1 \mu\text{m}$ but greater than $0.01 \mu\text{m}$. The load is transmitted via a few contacting asperities and the lubricating film formed in spaces between the surfaces. As the load increases the load carried by asperities increases. Friction is then controlled by a thin boundary lubricating film at the contacting asperities and the partial fluid lubricating film.

4) Boundary lubrication $\Lambda < 1$. In this regime the surfaces are not separated by a lubricating film and there is considerable asperity contact. Behaviour is then governed by thin molecular films (1 - 10 nm) and the properties of the surfaces. This situation is highly undesirable and results from high load and low speeds where a lubricating film is difficult to attain or from starved lubrication conditions. This leads to higher friction, wear and the possibility of scuffing. Applications include heavily loaded gear teeth and low speed bearings. In such circumstances the lubricant is formulated with EP additives or solid lubricants.

Figure 2.32 shows the different lubricating regimes and their influence on friction and wear.

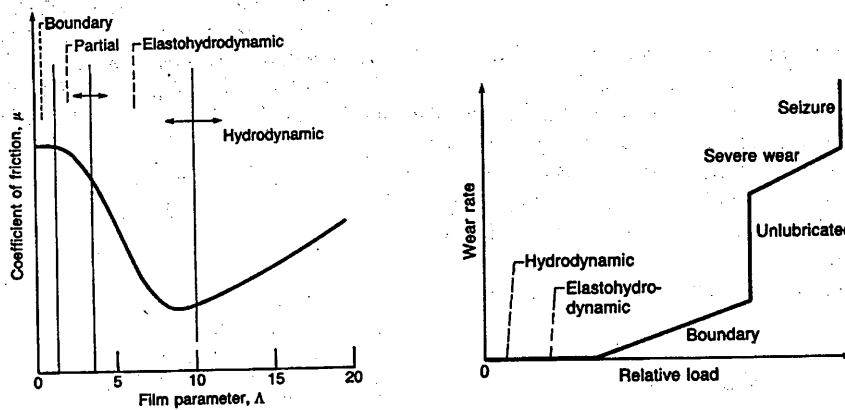


Figure 2.32: Indications of friction and wear rates for the different lubricating regimes¹⁷⁷

The surface finish has a significant influence on the film built-up and collapse¹⁷⁸. The contact must be looked at on two scales, the macro Hertzian contact and the size of asperities on the surface. Surface roughness introduces high pressure spikes and pressure gradients within the contact, which introduces shear stresses into lubricant, which depends on the pressure gradients and film thickness for pure rolling. The lubricant properties are important, the chemistry of the lubricant affects its viscosity, viscosity - pressure coefficient and viscosity- temperature coefficient. If a small amount of sliding is introduced then high stresses in the sliding direction are also formed.

In heavily loaded contacts the lubricant can act as a plastic solid or highly viscous liquid particularly when considering the high shear stresses experienced in the contact and the short time scale of interaction. This can result in the lubricant showing non-Newtonian behaviour i.e. shear stress is no longer proportional to shear strain rate but exhibits a limiting shear strength, which depends on the type of lubricant, the pressure and temperature. If the limiting shear strength in the lubricant is reached side flow of lubricant perpendicular to the relative sliding velocity will reduce the oil film thickness produced. The pressure gradients resulting from surface roughness (a function of surface heights and

slopes) can lead to side flow and the collapse of the micro contact and re-emergence of the asperity depending also on the surface velocity (time factor).

Under pure rolling conditions the shear stress generated will be lower than the limiting shear stress so lubricant behaves Newtonian and the local pressure spikes flatten the surface roughness so very small oil films can effectively lubricate the contact. If a slight amount of sliding is introduced the shear strength in the sliding direction is used up and the lubricant can flow perpendicular to the sliding direction and the asperities can re-merge.

Investigation has shown that the viscosity had to be increased by 8.5 - 14 times for a smooth surface and 32 - 24 times for a rough surface to prevent metal-metal contact when sliding was superimposed onto the pure squeeze motion.

The interaction between the surface asperities and the lubricant rheology determines the state of lubrication. The surface finish and texture becomes more significant at low Λ .

2.5.4 Fatigue

If the bearing is mounted correctly and fully lubricated without contamination, good bearing life can be achieved. The life of bearings can be predicted with sufficient accuracy when the bearing is correctly selected for the particular application taking into account the load, lubricant and operating conditions. This is a result of higher purity steel with controlled inclusion size and distribution, better control of the manufacturing processes to give correct part dimensions, geometry and surface finish. Difficulties arise from demands to use smaller and smaller bearing sizes for the same load to reduce weight, or when operated under more severe conditions such as heavier loads, higher speeds, higher temperatures, interrupted lubricant supply and contaminated environments.

Bearing fatigue life is based on statistical fatigue models, which assumes that a fatigue crack is initiated below the surface at the position of maximum orthogonal shear stress and at the weakest point. The weakest point is assumed to be stochastically distributed. With a better understanding of the stresses generated during over rolling and improved computer modelling these models have been improved to incorporate additional factors influencing bearing life.

When selecting a bearing an adjusted rating life equation¹⁷⁹ is used.

$$L_{na} = a_1 a_2 a_3 (C/P)^p$$

where L_{na} is the adjusted rating life in millions of revolutions. So L_{10a} would be 90 % reliability or L_{1a} is 99% reliability. C is the basic dynamic load rating (at elevated temperatures a reduction factor is needed) and P the equivalent dynamic bearing load. The exponent p is taken as 3 for ball bearing and 10/3 for roller bearings. Adjustment factors

a_1 life adjustment factor is used to determine lives other than L_{10} ($a_1=1$)

a_2 takes into account the bearing material quality

a_3 is determined by the efficiency of lubrication (provided temperatures are not too excessive), which is primarily determined by the degree of metal to metal contact between the surfaces. For adequate lubrication the lubricant must have a minimum viscosity at the operating temperature, so a_3 is based on the viscosity ratio defined as the ratio of actual viscosity v to the viscosity required v_1 for good lubrication at the operating temperature.

The SKF new fatigue life model¹⁸⁰ introduces a fatigue limit below which the bearing has infinite life; adjustment factors are included to take account of the material quality, lubrication conditions, temperature and contamination¹⁸¹. Here the adjusted rating life equation becomes:

$$L_{na} = a_1 a_{SKF} (C/P)^p$$

a_1 is as before, but a_{SKF} is the new life adjustment factor related to viscosity ratio $\kappa = v_1/v$, and the function $\eta_c(P_u/P)$, where P_u is the fatigue load limit and η_c is an adjustment factor for the degree of contamination. The influence of surface finish is intrinsically included in v_1 the viscosity needed for efficient lubricating. The viscosity ratio is related to the dimensionless film parameter Λ .

The two main modes of metal fatigue failure in bearings are spalling and surface distress¹⁸². Spalling results from cracks nucleating below the surface often at interfaces between non-metallic inclusions and the matrix. Alternatively spalling can be surface initiated from large dents or damage on the raceway, which upon successive over rolling can create a surface crack usually at a spot behind the indent. Spalling leads to a large piece of material breaking away from the raceway, which will result in a large increase in bearing noise. Surface distress is a result of micro-plastic deformation resulting from cyclic stressing.

Work by Zhou¹⁸³ demonstrated the beneficial effect of surface finish and cross track form on fatigue life for a standard bearing (rough) and an enhanced finished bearing which was smoother and had an improved cross track form. This work calculated from real surface measurements the contact pressures and stresses in the surface under high and low film thickness. The work showed that with low film thickness the rougher surface demonstrated high pressure spikes, which introduced higher levels of shear stress into the subsurface, compared to the smooth enhanced surface, which had a relatively uniform stress field at a lower maximum octahedral shear stress. This resulted in an improved fatigue life for the enhanced surface. For conditions where the surfaces are completely separated by a lubricating film the maximum octahedral stresses are not significantly different and fatigue life was not affected. Large film thickness dampens the effect of pressure spikes. Hoeprich¹⁸⁴ also demonstrated the importance of raceway contact geometry and designing the cross track form to optimise fatigue life for a range of loading conditions.

Ali¹⁸⁵ also investigated how the fatigue life is influenced by the surface finish from contact pressure variations and the corresponding variations in the interior stress field. A comparison of three different manufacturing processes (not described) showed the surface roughness had a significant impact on stress variations in the near-surface, which is

responsible for the life reduction. Processes B and C had an improved fatigue life compared to process A.

Table: 2.10: Showing surface finish parameters for the three different surfaces and the corresponding life reduction factor¹⁸⁵.

Surface type	Ra (micron)	Rq	Average asperity slope x 10 ⁻²	Life reduction factor
Process A	0.104	0.131	1.144	0.418
Process B	0.037	0.047	0.604	0.982
Process C	0.035	0.044	0.423	0.94

Trip and Ioannides¹⁸⁶ modelled the influence of some surface finish parameters on the fatigue life in dry unlubricated contacts with the aim of identifying roughness parameters for specifying functional surface topography, which could be used to control production processes. This work showed that lower surface slopes and more negative skewness gave an improvement in bearing life. From the surface finishing parameters modelled, slope had the biggest influence then skewness and lastly Ra.

Patir and Cheng¹⁸⁷ have modelled the influence of surface roughness orientation on central film thickness in EHD contacts. This work showed that the lubricating film forming ability increases as the surface roughness pattern changes from longitudinally oriented to isotropic to transverse oriented pattern, see figure 2.33.

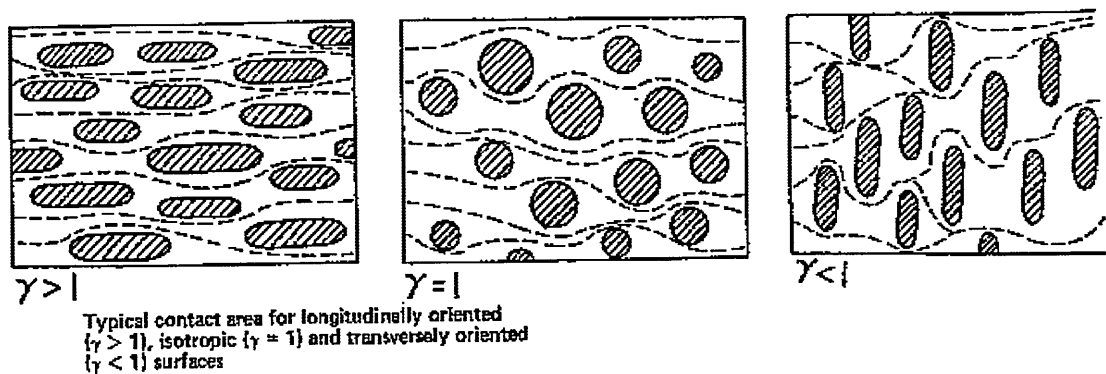


Figure 2.33: Influence on lubricant flow with different surface roughness patterns

Horn¹⁸⁸ et al investigated the tribological behaviour of steel rollers under rolling-sliding contact. This work looked at different roughness patterns, and asperity heights under different applied loads and rotational speeds. A transversely oriented pattern gave lower friction coefficients than longitudinally oriented. The influence of speed on the friction

coefficient depended on the lubrication mode. For EHL, increasing the speed increases the friction coefficient while for mixed lubrication, increasing the speed decreases the friction coefficient. For mixed lubrication the oil temperature is related to the roughness pattern, the transverse pattern gave lower temperatures. Wear is also influenced by the surface pattern and surface roughness. The smooth roller surface gave the lowest wear rate, while the transversely oriented pattern gave the highest wear rate. Increasing wear rate was associated with increased asperity height, increased load and reduction in rotating speed.

Jeng¹⁸⁹ also studied the effect of surface roughness on friction. It was found that lower roughness heights yielded lower friction, and that transverse roughness has lower friction than longitudinal roughness. Surface roughness effects become increasingly significant at lower film thickness.

The bearing company NTN, have published a number of articles on improving bearing fatigue life particularly under low oil film thickness. Under low values of Λ (oil film parameter) or under contaminated lubrication conditions surface damage by peeling can occur. Rolling contact fatigue can be prolonged by promoting oil film formation to preclude metallic contact between the surface asperities. Akamatsu (1990) demonstrates that transversely oriented surface roughness texture produced by grinding can provide better oil film formation compared to longitudinally oriented roughness, as a result of resistance to lubricant flow¹⁹⁰. Akamatsu (1991) also investigated the improvement in fatigue life under mixed or boundary lubrication for a smooth isotropic surface with a random distribution of small indentations (pits)¹⁹¹. Akamatsu (1992)¹⁹² described that the life of rolling bearings can be divided into two categories, service life determined by 1) sub-surface originated flaking and 2) surface initiated flaking. The sub-surface flaking is a result of cyclic stressing but does not usually appear in high purity steels under loads that do not cause plastic deformation. The surface initiated flaking or surface distress originates at sites of smearing on the bearing raceway, at the sites of dents left by rolled over hard particles and at sites of pitting or peeling that develop due to fatigue or plastic deformation of the asperities during contact. Improvement in surface originated flaking can be achieved by establishing better lubrication conditions, contamination control, heat treatment and by improving the quality of machining. Bearings with isotropic surfaces with small recesses was found to improve the oil film formation and improve the fatigue life, figure 2.34, particularly for low Λ film parameter.

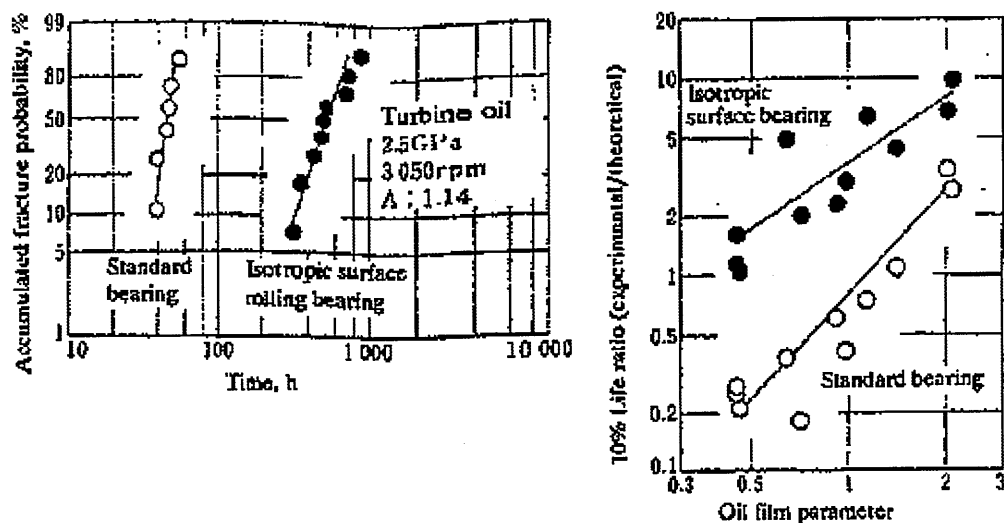


Figure 2.34: Showing the improvement in fatigue life of the isotropic surface particularly at low oil film parameters. Note: accelerated fatigue tests¹⁹²

NTN also demonstrated the influence of skewness of these isotropic surfaces on rolling contact fatigue life¹⁹³. An improvement in fatigue life and lubrication film build-up was found for surfaces with a more negative skewness. These isotropic surfaces are produced by barrelling, using different abrasive sizes to change the indents' size and shape. Bearings running under more severe lubrication conditions such as increased speed, temperature or load where the oil film parameter is low can show an improvement in the fatigue life by enhanced lubrication provided by improved surface texture.

Other work also by NTN produces micro indentations by a non-mechanical process, electrochemical jet machining. Grinding to make a transverse roughness on a raceway is difficult, while barrelling can introduce residual stresses, microcracks and sharp asperities, which can lead to spall nucleation. After barrelling the surface is polished to remove the ridges generated at the indents¹⁹⁴. Electrochemical jet machining has been used to produce micro indents (diameter $\sim 200 \mu\text{m}$ and depth of $\sim 4 \mu\text{m}$) with different patterns¹⁹⁴. The patterns were produced on superfinished surfaces ($R_{\text{max}} < 0.2 \mu\text{m}$) in staggered or aligned configuration and compared to a superfinished surface. It was found that the surfaces with patterns showed less metal to metal contact and that the staggered configuration showed the best performance. The amount of peeling damage was reduced with the patterned surfaces indicating better lubrication. The fatigue life of the surfaces was not presented. The electrochemical jet machining does not introduce compressive stresses associated with barrelling so the improvement in lubrication and reduced surface damage is a result of enhanced lubrication from the surface pits.

Patent US5397188 gave further information on these isotropic surfaces with recesses for improved lubrication and fatigue life¹⁹⁵. The improvement is given by a combination of surface finish but also heat treatment. The manufacture route disclosed included:

- 1) heat treatment and nitriding to increase the amount of retained austenite and introduce compressive stresses.
- 2) roughening to form recesses and increase compressive stress to greater than 600 MPa
- 3) barrel tumbling to improve surface finish to give $R_q < 0.1 \mu\text{m}$ and $R_{sk} < -1.6$

Such surfaces give less peeling, reduce wear while the fatigue life is prolonged as a result of increased surface strength of rolling elements and improved film forming ability.

In another patent US5642947 for balls, grinding is used to form multiple microscopic needle-shaped recesses extending in random directions for improved lubrication, which gave less metal to metal contact¹⁹⁶.

As mentioned earlier Timken also claimed to have improved bearing performance by changing the bearing surface texture. Timken used a chemical vibrofinishing technique¹²⁴, which produces a smooth isotropic surface. The surface produced is typically characterised by a $R_a 0.06 \mu\text{m}$, $R_p 0.24 \mu\text{m}$, $\Delta q 1.8^\circ$ and plasticity index 0.44. This new surface is claimed to have no running in. Usually new bearing surfaces must run-in, where the surfaces begin to conform to each other, this is generally indicated by a period of higher wear, but also the surface roughness changes and mechanical properties change i.e. work hardening and plastic deformation until a stable surface texture results. The plasticity index can be used to describe the elastic-plastic deformation properties of a rough surface and this new isotropic surface has a very low plasticity index. The new surfaces showed lower temperatures and torque during running-in trials plus lower operating temperatures and torque once the bearing was run-in, compared to a honed / superfinished surface. The plasticity index remained more constant and surface roughness R_a also showed less variation during run-in, compared to a superfinished surface. This new surface also gives improved bearing life since the contact stress distribution is more uniform, with less pressure fluctuations, which are lower in magnitude¹⁹⁷.

The bearing manufacturer Koyo also describes the manufacture of a surface with many small independent recesses¹⁹⁸, which act as lubricant reservoirs formed by shot blasting followed by barrel finishing. The patent uses carbonitriding to introduce high residual compressive stress deeper into surface and a microstructure with $> 8\%$ retained austenite. The surface has an R_{max} of $< 3 \mu\text{m}$, $R_q < 0.3 \mu\text{m}$ and $R_{sk} < -3$. The open area of the minute depressions is between 5 - 20 % of the bearing surface.

NSK disclosed a surface for controlling the friction and relative movement between the raceway and rolling elements¹⁹⁹, by a plateau type surface structure produced by honing using first coarse grit stone followed by a finer grit stone. This results in a surface with groove shaped recess portions with a cross hatch pattern and a depth of 0.5 - 8 μm and a smooth surface portions with $R_a < 0.08 \mu\text{m}$.

The literature above emphasizes the importance of the bearing surface, not only the surface roughness (R_a , R_{sk} slope etc.), but also the surface texture (transverse, isotropic etc.) and cross track form, which influence the lubrication regime and stress distribution in the loaded contact. The surface texture also influences friction and wear. The subsurface stresses have been shown to be important and can be introduced by heat treatment or mechanically e.g. by honing. The purity of the bearing steel has a large influence on macroscopic fatigue. A wide range of hardness and microstructures can be produced by suitable heat treatments effecting the bulk mechanical properties and surface hardness influencing wear and fatigue behaviour. The literature also indicates that most work on bearing surfaces is related to bearing running under conditions with low Λ ratio where the surface texture has the biggest influence.

3. Experimental

3.1 Test rig

The test rig had been developed for pure electrochemical machining of bearing raceways. The test rig known as ELMARI (electrochemical machining of rings) consists of a control cabinet, power supply, electrolyte handling system, and machining area. Figure 3.1 below shows an overall view.

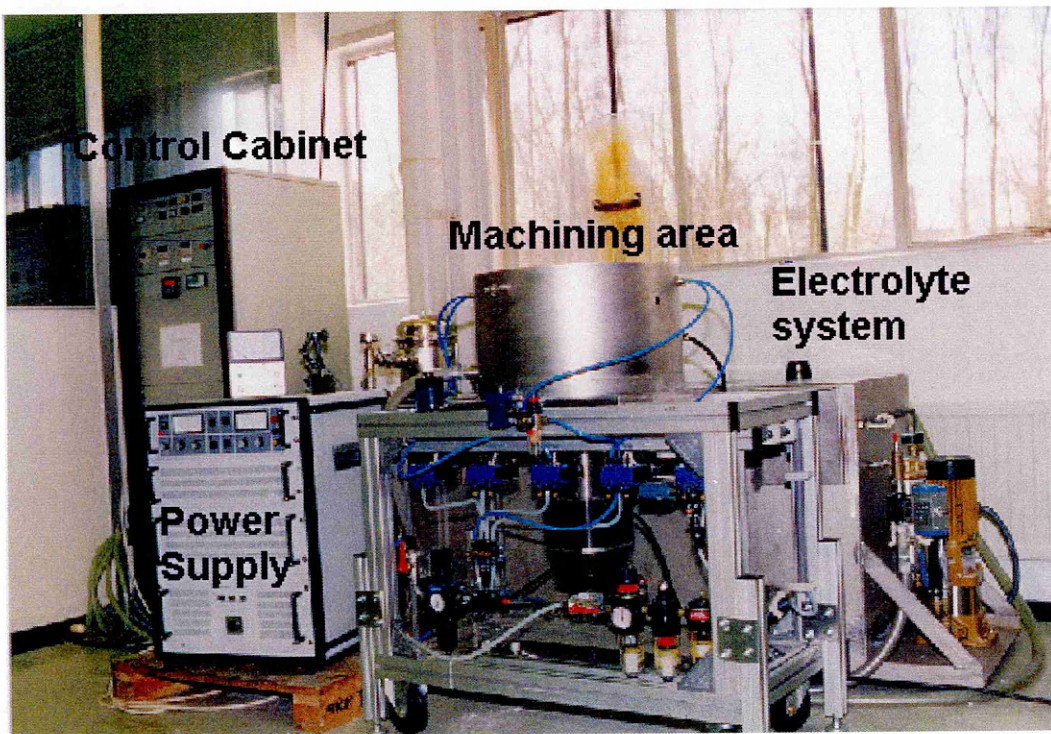


Figure 3.1: Overview of ELMARI test rig

The control cabinet controls the spindle speed, electrolyte pumps and the time the current is applied. It also monitors the electrolyte flow rate and pressure. When honing is combined with ECM the control cabinet also controls the honing time and the stone oscillation frequency.

The d.c. power supply is an EP-PS5065-130 by AE, which can give a maximum of 130 amps and 60 volts. The current level can be preset and the voltage responses to maintain constant current or the power supply can be run in constant voltage mode. Tests were performed under constant current.

The electrolyte handling system figure 3.2, consists of one 600 litre tank which is divided into three equally sized compartments (only two are used) one is a settling compartment for dirty electrolyte and the other for clean electrolyte.

The system consists of two circulation systems. The first system draws dirty electrolyte and clean electrolyte and passes them through a filter before returning to the clean electrolyte compartment. The second system pumps the clean electrolyte through a cloth filter to the machining area. Before the electrolyte enters the machining area it passes through a 5 μm filter as a secondary precautionary measure to prevent large particles entering the inter-electrode gap, which could initiate sparking. The pump delivering the electrolyte to the test head can generate a maximum of 5 bar pressure and can deliver up to 60 l/min.

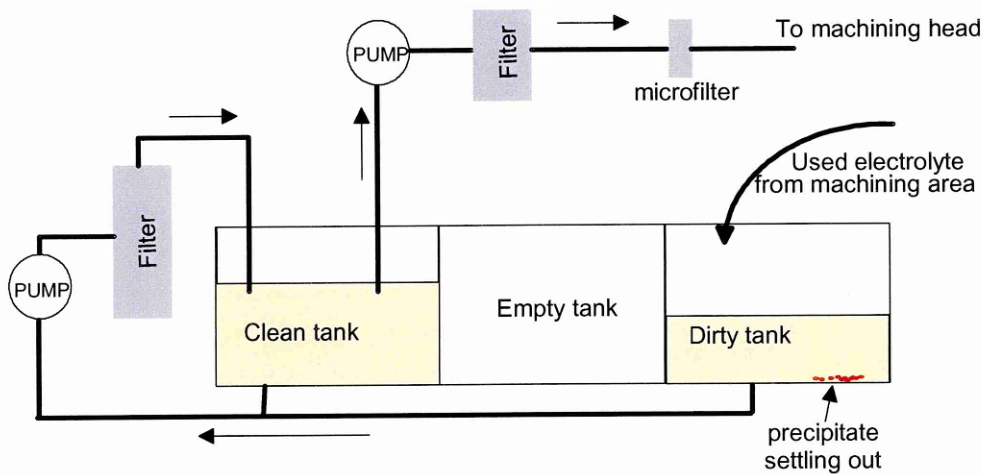


Figure 3.2: Showing schematic of electrolyte system

The electrolyte used was 30 wt.% NaNO_3 (sodium nitrate). The concentration was controlled by measurement of the density and adjustment was made to 1.2 g/cm^3 ($1.2 \times 10^3 \text{ Kg m}^{-3}$). No temperature compensation was employed, since early work on electrochemical machining of rings had shown no significant influence of temperature in the range 23 - 33 $^\circ\text{C}$ on material removal.

The machining area consisted of a corrosion resistant air-bearing spindle especially designed for the application by Loadpoint Ltd (UK). This spindle was directly coupled to a 16-pole A.C. Infranor motor. Specifications of spindle were:

Max. speed	2000 rpm
Radial stiffness	12 N/ μ m
Max. Radial load	222 N
Axial stiffness	35 N/ μ m
Max. Axial load	300 N
Air supply pressure	5.5. bar

Electrical current could be passed through the spindle to the workpiece by a copper rod running through the centre of the air bearing. Positive electrical connection was made via four silver graphite slip rings positioned between the motor and the spindle shaft. The spindle housing was electrically insulated from the copper rod. At the top of the spindle is a clamping plate onto which the clamping device is positioned. The rings are clamped using a six point expandable collet designed for the ring size to be tested. The figure 3.3 below shows the clamping fixture on top of the air bearing spindle. The spindle is surrounded by a stiff stainless steel circular platform for fixing the electrode attachment and the honing attachment.

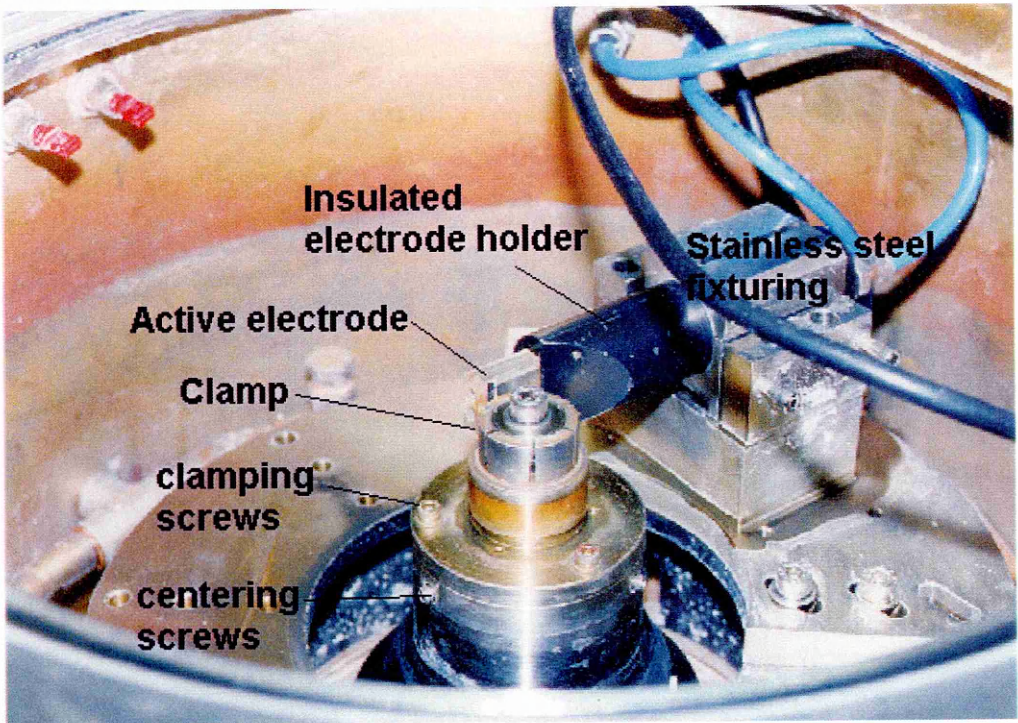


Figure 3.3: Showing machining area, including top of air-bearing spindle, clamping fixture and electrode holder.

The spindle including the clamping fixture had previously been balanced by the spindle manufacturer. Centering of the workpiece could be performed by measuring the out of roundness of a clamped ring with a linear variable displacement transducer (LVDT). The out of roundness was corrected by three side screws which pushed the top clamping fixture. Three perpendicular screws were then used to clamp the fixture to the spindle. With practice a round out of less than 2 μm could be achieved, while the workpiece's out of roundness is usually less than 1 μm .

The early electrode design is shown in the figure 3.3 above. It is held in a stiff stainless steel fixture, which allows positioning of the electrode to ensure that it is parallel to the ring face and the centre of the electrode is at the centre of the ring. The figure 3.4 below shows the alignment of the cathode relative to the ring (workpiece). A small inter-electrode gap (100 - 200 μm) is set between the electrode and ring using plastic shims. The electrolyte passes through the electrode holder and exists via a rectangular nozzle, which directs the electrolyte jet parallel to the active electrode area into the gap. The early electrode holder was machined from stainless steel and coated in a polymer insulating coating, but was found to de-bond particularly at the exit of the nozzle.

Electrical connection to the cathode was made by passing the current through the electrode holder to the electrode. It was found that short circuits could occur between the electrode holder and the stainless steel fixturing as a result of breakdown in the insulating coating.

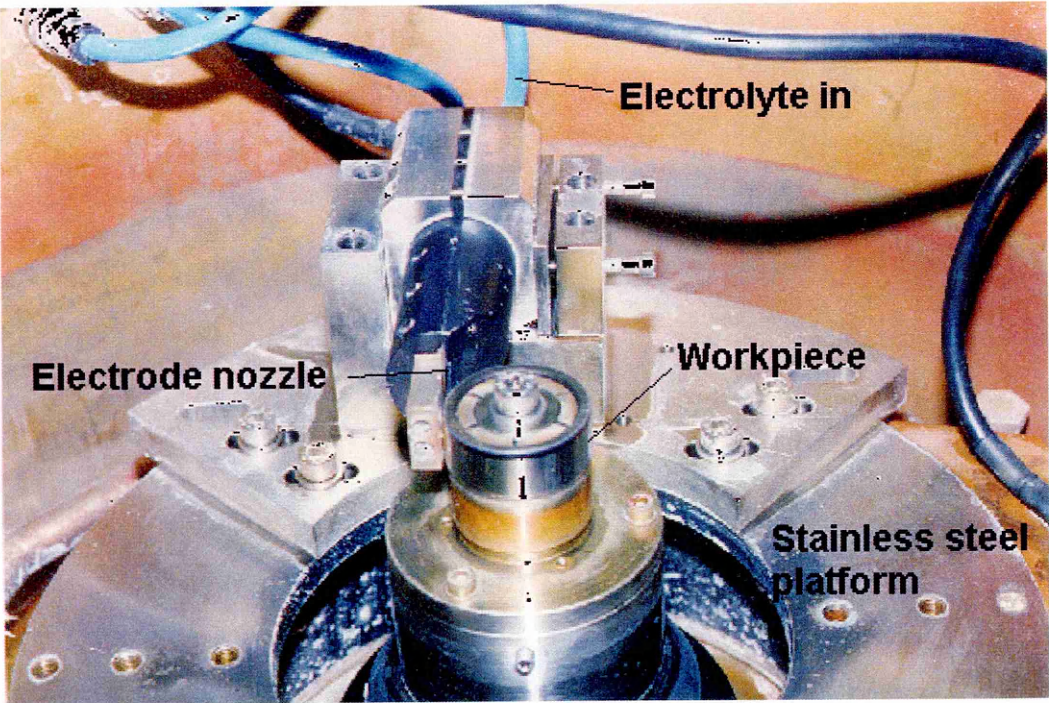


Figure 3.4: Early electrode design

A new electrode was designed which isolated the electric current to only the electrode area to minimize stray currents. The electrode was made from stainless steel and was then moulded in insulating epoxy resin. Later a standard metallographic sample preparation method was used for moulding the electrode, which was found to be simpler and gave better edge definition and adhesion.

For the metallographic method a Struers ProntoPress 20 was used with Isofast mounting resin (green coloured). A 50 mm diameter die was used. The moulded electrode was then ground to final dimensions. The moulded electrode was screwed onto a Perspex rectangular block, which was then ground flat again to give better electrolyte flow across the interface. Electrical connection was made directly to the electrode, which is insulated from the rest of the machine.

The new design also attempted to achieve a more uniform electrolyte flow by giving a longer distance within the nozzle for a laminar type flow to develop. Also the width of the moulded electrode was widened to obtain better electrolyte flow within the gap. The distance between the nozzle exit and the gap was also kept to a minimum.

As the ECM process was used to only to remove material uniformly from the workpiece no shaping was required. The electrode was then made rectangular with different electrode thicknesses 1, 2, 4 mm. The electrode was 14 mm wide, see figure 3.5.

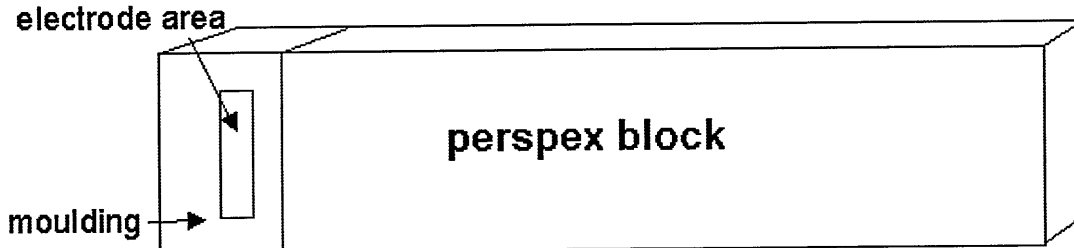


Figure 3.5: New electrode arrangement

The nozzle width could be controlled by using a plastic low compressible shim, which sets the gap between the Perspex block and the electrode holder. The shim was cut to give a nozzle width of 20 mm so the electrolyte flow completely covers the electrode.

The figure 3.6 shows the new electrode design with the electrical connection directly onto the electrode. A black plastic shim 0.5 mm thick was used to set nozzle thickness. The figure also shows the honing attachment used for the combined electrofinishing process.

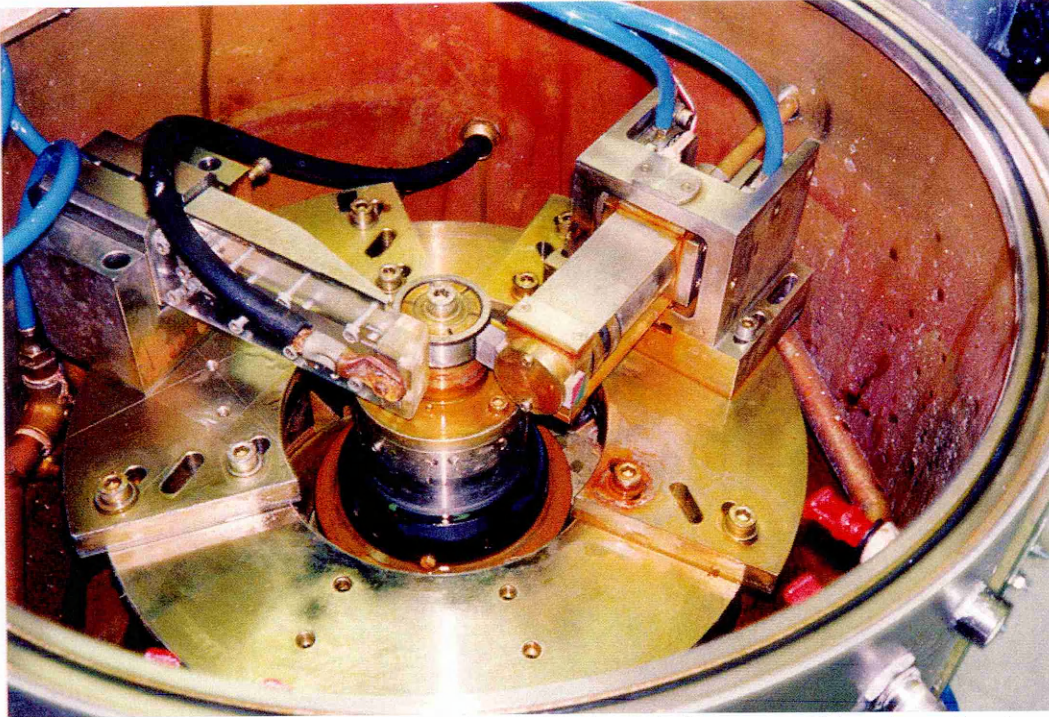


Figure 3.6: Showing new electrode (cathode) design and honing attachment

The honing attachment presses and removes the honing stone from the workpiece by pneumatic cylindrical pressure pads. Oscillation of the honing stone is achieved by an eccentric motion driven by an electric motor from outside of the machining area. The attachment is made stiff in the radial direction by two stainless steel plates. The honing stone is clamped at the end of the attachment. Different types of honing stones were investigated; SiC and CBN stones but also different stone sizes. Later experimental work also tested the influence of synthetic metalworking fluids supplied by Cimcool.

Honing stone wear was also considered in the latter work. Stone wear was evaluated by measuring the displacement of the end of the honing stone at the start of the test and at the end of the test using a LVDT. The measurement was taken from the same point on the ring. A small v-groove was glued onto the end of the honing stone to allow repeatable positioning of the measuring arm connected to the LVDT. Knowing the displacement of the stone and the material removed from the ring gave an estimate of the stone wear for comparative analysis.

Some tests were also performed using superfinishing tapes. The set-up is shown below in figure 3.7 for superfinishing tapes applied statically.

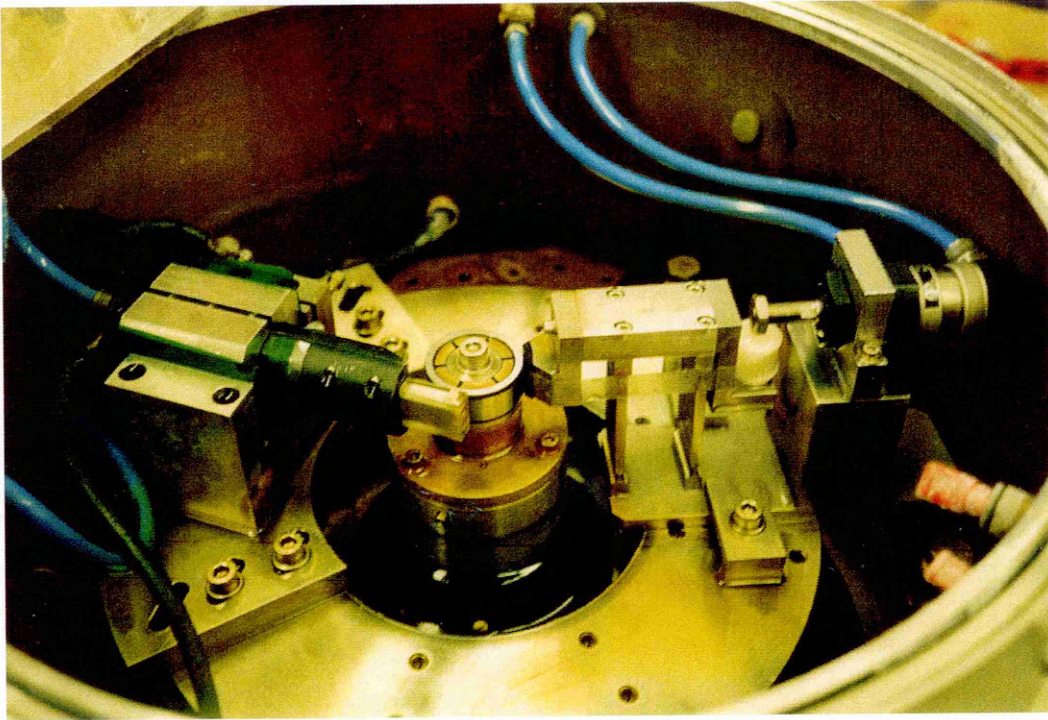


Figure 3.7: Static superfinishing attachment used during electrofinishing trials

The very simple set-up uses a pneumatic cylinder to push the tape onto the workpiece. Different tapes were tested and different hardness backings.

For the electrolytic dressing work, the honing stone was made the anode by electrically connecting the positive terminal to the honing stone. Good electrical connection was made by drilling a hole at the back of the stone and brazing or soldering the electrical cable to it. For the metal bonded stones the support was very hard and edm had to be used to form the hole. For the aluminium resin bonded stones the cable was mechanically connected to the stone, as it was difficult to solder. The same honing attachment was used during electrolytic dressing trials, so the stone is electrical insulated from the attachment by a plastic sleeve. Although some stray machining of the clamping fixture was observed, because during operation the clamping fixture becomes covered in the electrolyte resulting in conductive paths for stray currents between the stone and the clamping fixture.

3.2 Measured parameters

Diameter measurements

The diameter of the rings before and after processing was measured using a UD gauge, which could give an accuracy of 0.5 μm . The measurements were performed in a temperature controlled metrology room 20 °C $\pm$ 0.1 and the rings were left a day before measurements to allow the temperature to equilibrate.

Weight measurements

The weight of the ring before and after processing was measured as an accurate way to determining the material removed.

Scanning electron microscope (SEM)

A Philips 525M SEM with an EDAX system was used for characterization of the surfaces produced. SEM's have good depth of focus and high resolution making them a vital tool for evaluating surfaces. The energy dispersive X-ray (EDAX) was also used for qualitative and semi-quantitative chemical analysis of constituents on the surface.

Waviness measurements

The MWA is a piece of equipment designed by SKF for measuring workpiece roundness and waviness, figure 3.8. The basic principle of operation involves placing the workpiece onto the chuck of the air-bearing spindle, which is rotated at low speed by a motor drive. The rotational position of the workpiece is monitored by an encoder. A LVDT measures the circumference displacement on 1024 points per revolution as the workpiece makes a number of revolutions. The software then can calculate the difference between the best fitting circle and the real data and presents the waviness of the object. This gives information on the roundness and waviness eliminating the run-out of the spindle. The software can also perform Fast Fourier Transformation (FFT) to give more details on harmonics.

Measurements can be performed in a single-track mode or multi-track mode, which is a collection of individual tracks separated by an equal distance in the cross track direction of the bearing.

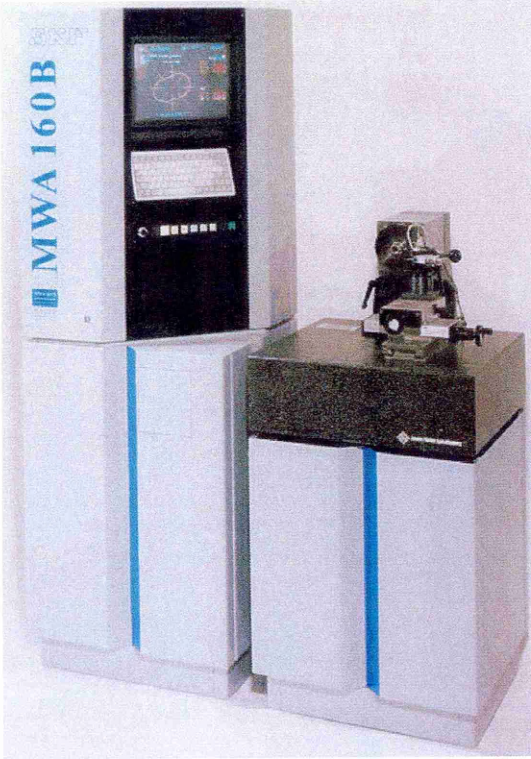


Figure 3.8: Picture of roundness and waviness measurement equipment developed by SKF

Roughness measurements using Talysurf

Roughness and form measurements were performed using a mechanical stylus profilometer by Taylor Hobson. The method works by sliding a stylus of 0.002 mm radius, across the surface and the vertical displacement of the probe is measured by a laser.

Roughness measurements were made using a 0.8 mm cut-off length and an ISO filter, while the form measurements were made generally over a length of 12 mm with a straight reference surface.

Surface finishing parameters of interest include

Ra - Average Roughness

The average roughness is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length; mathematically expressed as:

$$R_a = \frac{1}{N} \sum_{n=1}^N |r_n|$$
$$R_a = \frac{1}{L} \int_0^L |r(x)| dx$$

The roughness trace is divided up into 5 sampling lengths in each sample length i , the max peak height R_{pi} and max valley depth R_{vi} can be found. The max peak to valley height R_{ti} in each sample length can be then be found.

$$R_{ti} = R_{pi} + R_{vi}$$

R_{tm} or R_z(DIN) is the average of these five max peak to valley heights.

$$R_{tm} = \frac{\sum_{i=1}^5 R_{ti}}{5}$$

R_t is the sum of the max peak height (R_p) and deepest valley (R_v) over the whole measurement length. It is more sensitive to extreme values.

$$R_t = R_p + R_v$$

R_{pm} is the mean peak height taken as the average of the maximum peak height from each of the 5 sampling lengths

R_{sk} is the skewness, which is a measure of the asymmetry of the profile. A surface with many peaks has a positive skewness while a surface with lots of valleys has a negative skewness, see figure 3.9.

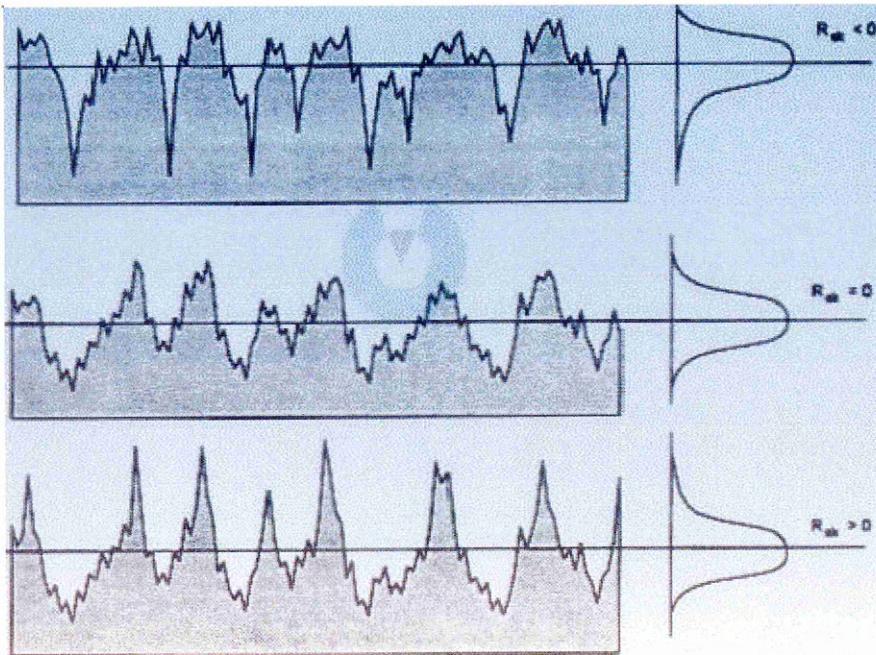


Figure 3.9: Pictorial representation of skewness

Δq is rms slope of the roughness profile

3.3 General experimental procedure

1. Rings labelled by spark eroding
2. Rings cleaned to remove preservative
3. Rings weighed
4. Diameter of rings measured after given time to equilibrate in metrology
5. Input quality of representative number of rings assessed for roughness, cross track form, waviness and SEM.
6. Machining with ECM only
 - a) Positioning and centering of ring was performed as described previously using a LVDT.
 - b) Electrode was positioned parallel and centred on the workpiece. The gap is set using shims. Once set the electrode does not need to be moved during a series of tests as the incoming rings have a diameter spread of less than a few microns.
 - c) Preset current and set voltage to maximum to ensure sufficient voltage to maintain current.
 - d) Set spindle speed and start spindle. It was also possible to computer control the spindle speed.
 - e) Start electrolyte pump, the electrolyte flow could be changed by a valve but tests were performed at the maximum flow rate achievable determined by the pump pressure and the exit nozzle size.

- f) Set current on time
- g) Start machining cycle
- 7. Machining with ECM and honing
 - a) The honing stone is rigidly clamped perpendicular to ring. The honing stone must first be trued to give the correct shape. A diamond plated dresser was used to get approximately the correct profile and then bedded in to the exact shape by running a few tests until the stone was cutting over its full area.
 - b) Set stone oscillation frequency. Most tests performed at maximum oscillation speed to give best self-dressing
 - c) Set stone pressure using an air pressure valve
 - d) Set ECM conditions as above
 - e) Run test
- 8. Wash machined ring in hot water and dry
- 9. Measure weight and diameter
- 10. Measure roughness
- 11. Certain samples' waviness and SEM were also taken

4. Results

4.1 Previous work

At ERC work had been performed on ECM finishing of bearing rings NU308 as an alternative to honing. The set-up is shown below in figure 4.1

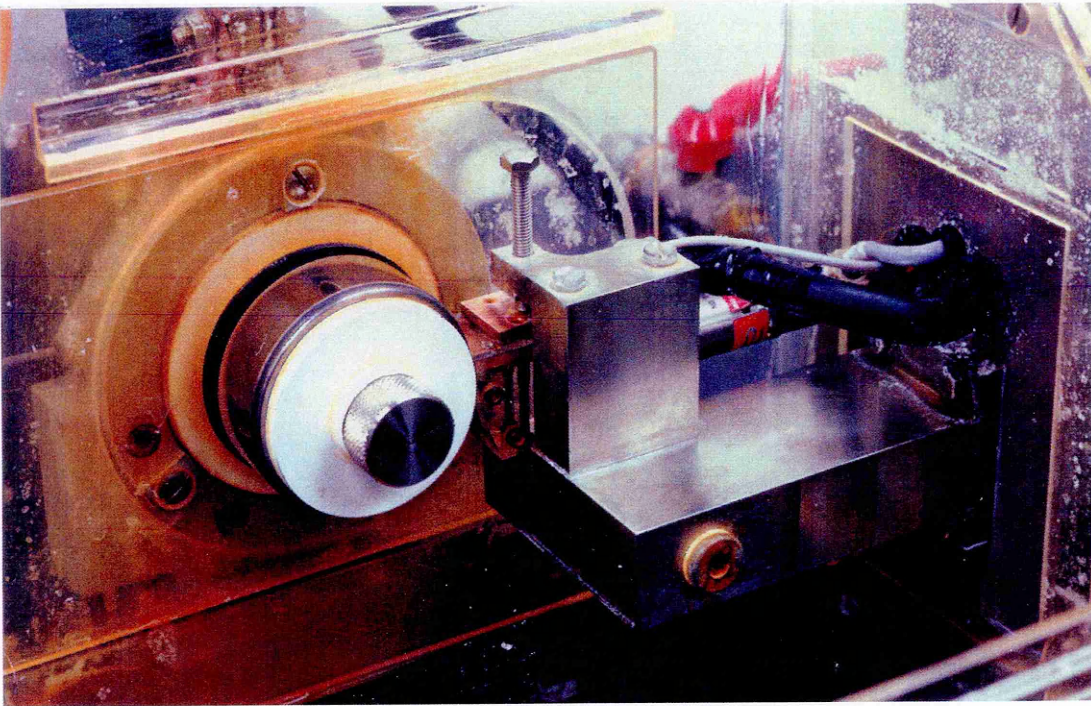


Figure 4.1: Electropolishing test set-up used in previous studies

The technique called electropolishing demonstrated the high material removal capability of ECM for a finishing operation; $78\text{ }\mu\text{m}$ could be removed in 60 seconds, although the rate of improvement in surface finish was low. A ground surface of $0.3\text{ }\mu\text{m Ra}$ could be improved to $\sim 0.1\text{ }\mu\text{m Ra}$ in 55 seconds. This cycle time is far too long for a production technique and the corresponding material removed is too much and unnecessary. The surface produced had a low slope and low peak - valley but the skewness was close to zero. The surface exhibited long order waviness of $\sim 1\text{ mm}$ attributed to electrolyte flow variations. This work also investigated the influence of current, workspeed, electrolyte flow rate, gap, electrolyte concentration, electrolyte temperature and pH on the material removal rate. The

significant factor influencing material removal was the current, while the other factors had a small or negligible effect, which can easily be controlled.

The cross track profile of an electropolished surface was poor, particularly when the electrolyte was pressure fed perpendicular to the surface. Improvements were made by using a jet of electrolyte flowing parallel to the workpiece surface. Roundness and waviness from grinding were not improved by electropolishing. The compressive surface stresses were found to be lower than honed workpieces; 180 MPa compared to 600 MPa. However fatigue data showed no detrimental effect on bearing life. Although this was based on a comparison between a honed surface of 0.072 μm Ra and 1.4° slope and an electropolished ring 0.052 μm Ra and slope 0.6°. The improved surface finish more than offset the benefits associated with higher compressive stresses.

Additional work applied a light polishing action to improve the waviness and to increase compressive residual stresses, the idea being that the ECM would remove ~ 90 % of material leaving only ~ 10 % to be removed by the abrasive polishing. This process was called electrofinishing and the test rig "Electrochemical machining of rings (ELMARI)" was developed for this work (see chapter 3). This process used a 1200 grit SiC honing stone and showed a very fast rate of surface finishing. The rate of surface finishing depended on the input roughness; a 0.5 μm Ra surface was improved to 0.02 μm Ra in 8 seconds. Other roughness parameters were slope 0.28 °, Rt 0.365 μm , Rsk -3.9, and the surface was clean and free from micro burrs. The work also indicated a beneficial interaction between the ECM operation and the honing stone, allowing the honing stone to maintain cutting.

The work was abruptly ended by the departure of the previous researcher. However the results had been promising enough that further work was needed to gain a better understanding of the process. The work presented below continues this development since not enough data were collected from the previous work, particularly with reference to the electrofinishing process. Also a number of possible benefits including fast surface finishing, honing stone/ECM interaction and size control aspects had not be fully demonstrated.

4.2 Input quality of rings

4.2.1 Workpiece

The workpiece chosen for this work was an inner ring (NU207) of a cylindrical roller bearing (CRB), figure 4.2. It was chosen because of its simple geometry.

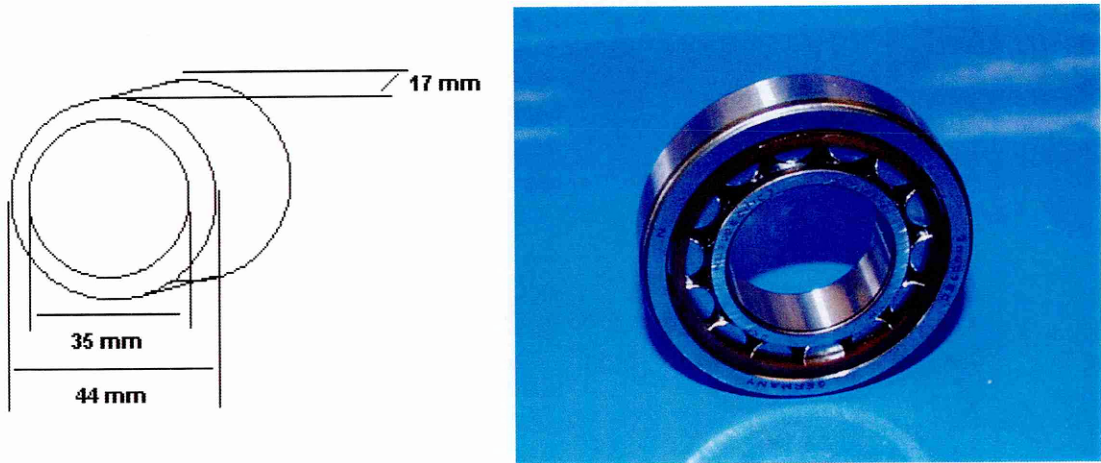


Figure 4.2: Dimensions of workpiece and photograph of actual complete bearing

This inner ring has a bore size of 35 mm and an outer diameter of 44 mm. The ring width is 17 mm, but the track width is approximately 12 mm.

The rings are based on standard bearing steel SAE 52100 also known as 100 Cr6. The material composition is shown below in table 4.1.

Table 4.1: Composition of bearing steel

Element	Fe	C	Si	Mn	P	S	Cr	Ni	
min.	Bal.	0.95	0.15	0.25	-	-	1.35	-	(%)
max.	~97	1.1	0.35	0.45	0.03	0.01	1.65	0.25	
	Mo	Cu	As	Sn	Sb	Pb	Al		(%)
min.	-	-	-	-	-	-	0.01		
max.	0.1	0.3	0.04	0.03	0	0	0.05		
	O	Ti	Ca						(ppm)
min.	-	-	-						
max.	15	30	10						

The rings have been through hardened to a hardness of 60 -63 Rockwell C with a martensitic microstructure with some retained austenite.

Ground and honed rings were electrochemically machined during trials.

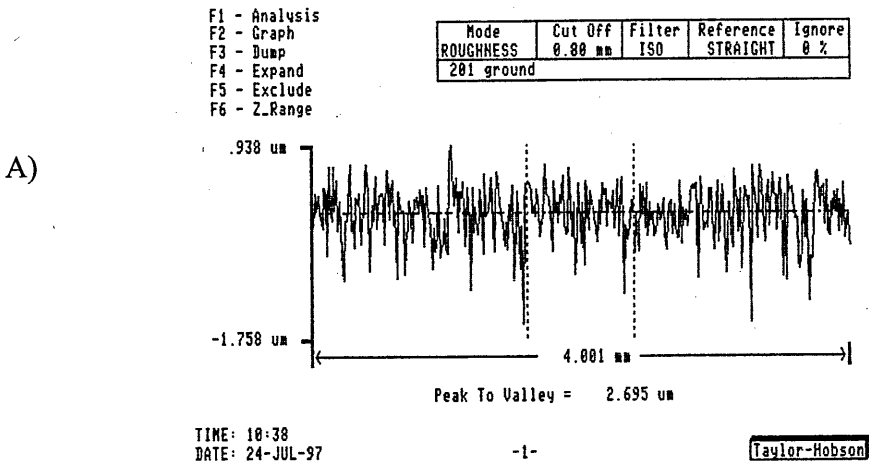
4.2.2 Ground ring quality

Table 4.2 below shows the ground input quality of rings used during trials.

Surface finish parameter	Ground quality
Ra μm	0.312
Rtm μm	2.3
Skew Rsk	-0.9
Delta q degrees	5.23

Table 4.2 Showing surface finish input quality from ground rings

Figure 4.3 & 4.4 below shows the surface roughness trace, typical roughness parameters, and the cross track profile after grinding, taken from a Talysurf.



F1 - Analysis

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
201 ground				

Rtm = 2.195 um	Lo = 4.881 mm	Ra = .314 um
Rpm = .761 um	Rp = .938 um	Rq = .404 um
Ry = 2.647 um	Rv = 1.758 um	Rsk = -.9
Rt1 = 1.887 um	Rt = 2.695 um	Rku = 4.4
Rt2 = 2.647 um		Delq = 5.37 Deg
Rt3 = 1.866 um	SLOPE = .07 Deg	Lamq = 26.982 um
Rt4 = 2.467 um		S = 14.887 um
Rt5 = 2.187 um		Sm = 23.942 um
		R3z = 1.728 um
		R3y = 1.899 um

B)

TIME: 10:38
DATE: 24-JUL-97

-2-

Taylor-Hobson

Figure 4.3: Roughness of ground ring, A) roughness trace, B) roughness parameters

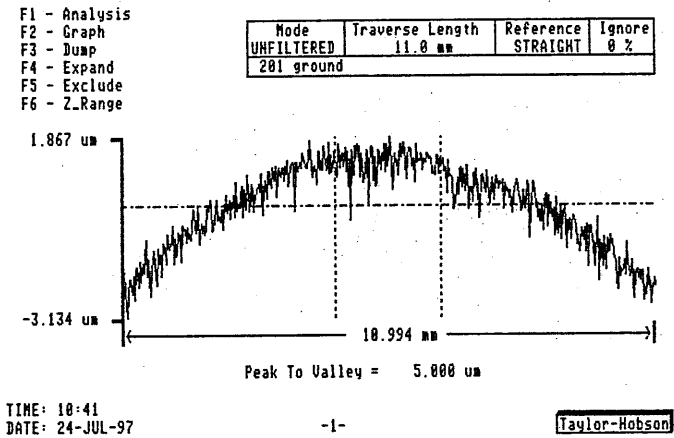


Figure 4.4: Cross track profile from ground ring

The bearing track has a logarithmic profile designed for better rolling contact mechanics.

Figure 4.5 shows a scanning electron microscope (SEM) picture of the surface from a ground ring. The rough ground surface shows evidence of over rolled material and leafing. There are even grinding chips and other debris stuck within the grinding grooves.

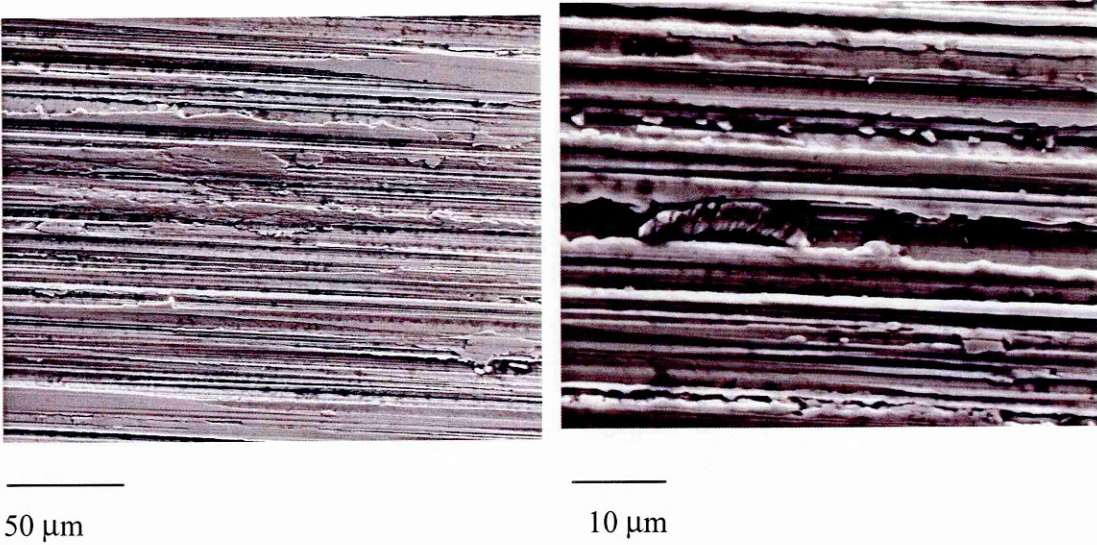


Figure 4.5: Showing SEM micrograph of ground surface

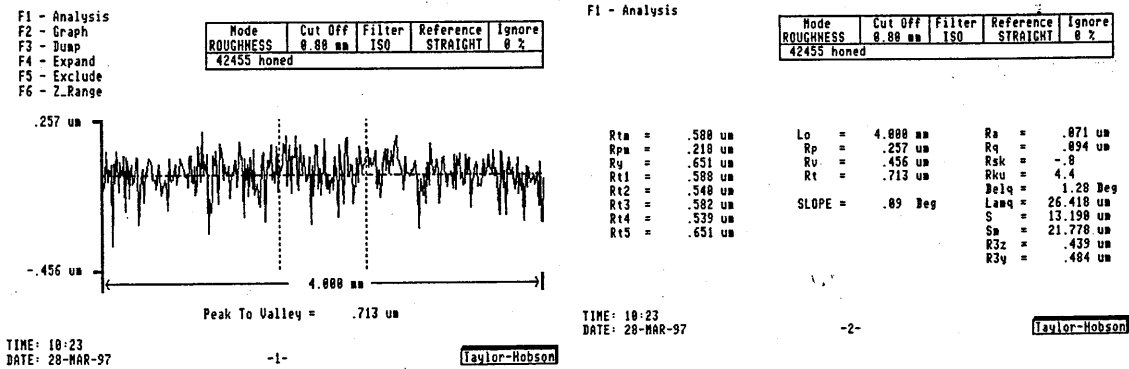
4.2.3 Honed input

Honed rings were used for some ECM trials but also for comparison with surfaces produced by ECM and electrofinishing. Table 4.3 below shows the surface finish of honed NU207 inner rings.

Table 4.3: Average surface finish parameters of honed ring

Surface finish parameter	Honed quality (1997)
Ra µm	0.06
Rtm µm	0.5
Skew Rsk	-1.1
Delta q degrees	0.95

Roughness measurement and cross track profile of a honed ring is shown in figures 4.6 and 4.7.



a) Roughness trace b) typical surface roughness values

Figure 4.6: Showing surface roughness of a honed ring

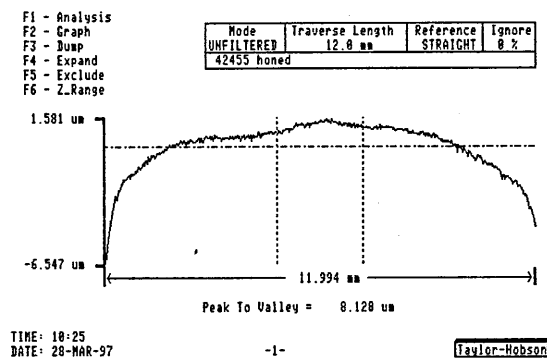


Figure 4.7: Showing the cross track profile from a honed ring

The surface morphology was also investigated using a scanning electron microscope (SEM); see figure 4.8. The honing lines in the circumferential direction are clearly evident as well as leafing and honing debris within the grooves which can fall off in use, resulting in noise and damage to the bearing. Figure 4.8 B) also shows the presence of a cut MnS inclusion.

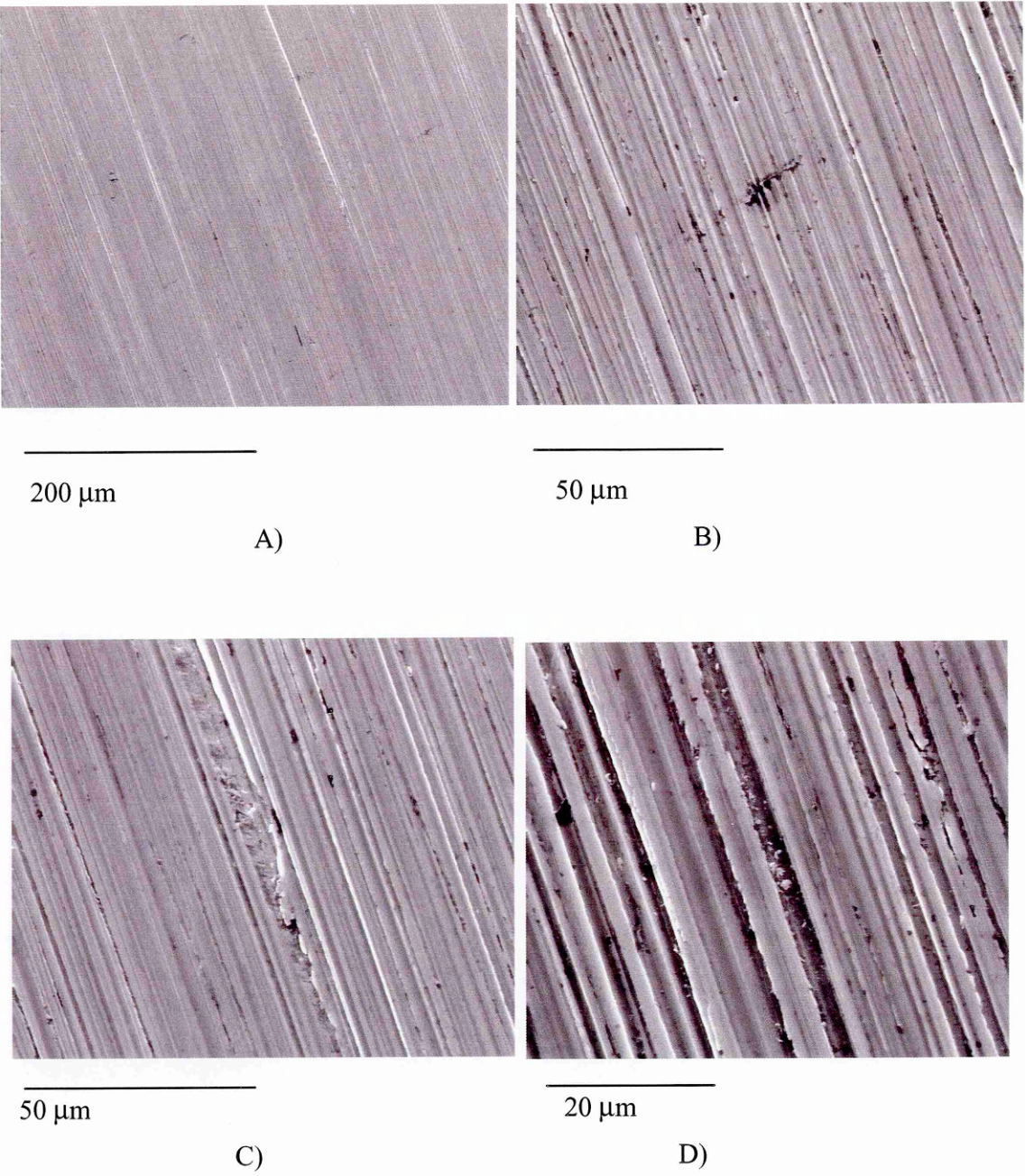


Figure 4.8: SEM micrographs showing the surface of a honed ring at different magnifications

Figure 4.9 shows a typical MWA multi-track waviness measurement for a honed ring. Note that the software filtered out over 2600 peaks during the calculation of the waviness.

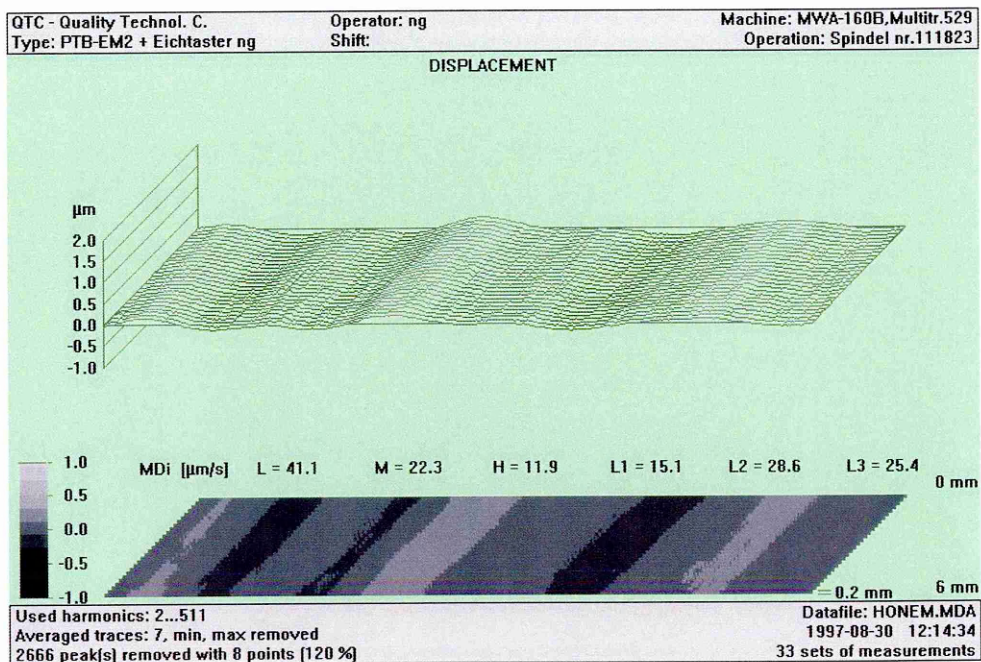


Figure 4.9: Waviness measurement on honed surface

The range of values observed for multi-track and single-track measurements are indicated in table 4.4 below.

Table 4.4 Showing MWA waviness from honed quality ring (1997) measurements taken in the single track and multi-track mode

	Single track	Multi-track
Roundness (μm)	0.2 - 0.9	0.2 - 0.9
L ($\mu\text{m/sec}$)	30 - 50	24 - 70
L1 ($\mu\text{m/sec}$)	10 - 40	30 - 75
L2 ($\mu\text{m/sec}$)	10- 25	15 - 20
L3 ($\mu\text{m/sec}$)	15 - 25	9 - 15
M ($\mu\text{m/sec}$)	80 - 140	20 - 30
H ($\mu\text{m/sec}$)	35-50	7 - 12

The requirements for the surface to be produced have not been implicitly stated. The main objective was to achieve fast surface finishing, to a roughness of $0.05\text{ }\mu\text{m Ra}$ or better and an R_t of $< 0.5\text{ }\mu\text{m}$. The cross track form must be maintained with the waviness below SKF limits depending on the quality level of the bearing being produced. Other general parameters are for the slope to be less than 1° and the skewness to be negative. The study was not to make a bearing surface but more to investigate the type of finishing possible.

4.3 Electrochemical machining of bearing rings

The earlier work on electrochemical machining of rings showed the biggest problem was the achievable waviness, which was either not improved or made worse particularly in the medium and high waviness bands. A honing operation was combined with ECM to improve the waviness, however this adds greater complexity and cost to any machining operation. If the waviness caused by the ECM could be reduced, a much simpler process could be developed. This section looks at the surface finishing characteristics of ECM and the waviness error drivers.

4.3.1 ECM only on ground surface

Electropolishing was envisaged to replace honing. Therefore investigations using ground input quality rings were undertaken using the ELMARI test rig. The material removal follows Faraday's law and the graph in figure 4.10 shows the diameter reduction with time using an electrode ($4 \times 14\text{ mm}$), a current of 100 amps (or current density $\sim 2\text{ A/mm}^2$), workspeed 1100 rpm, inter-electrode gap $\sim 100\text{ }\mu\text{m}$ using the 30 wt.% NaNO_3 electrolyte. The diameter removal accuracy was $\pm 1\text{ }\mu\text{m}$. In 8 seconds $22\text{ }\mu\text{m}$ was removed from the diameter of the NU207 inner ring. The material removal rate was $2.75\text{ }\mu\text{m / second}$ or $0.15\text{ }\mu\text{m per revolution}$ which can be considered the depth of cut. Using a higher current level can increase the removal rate.

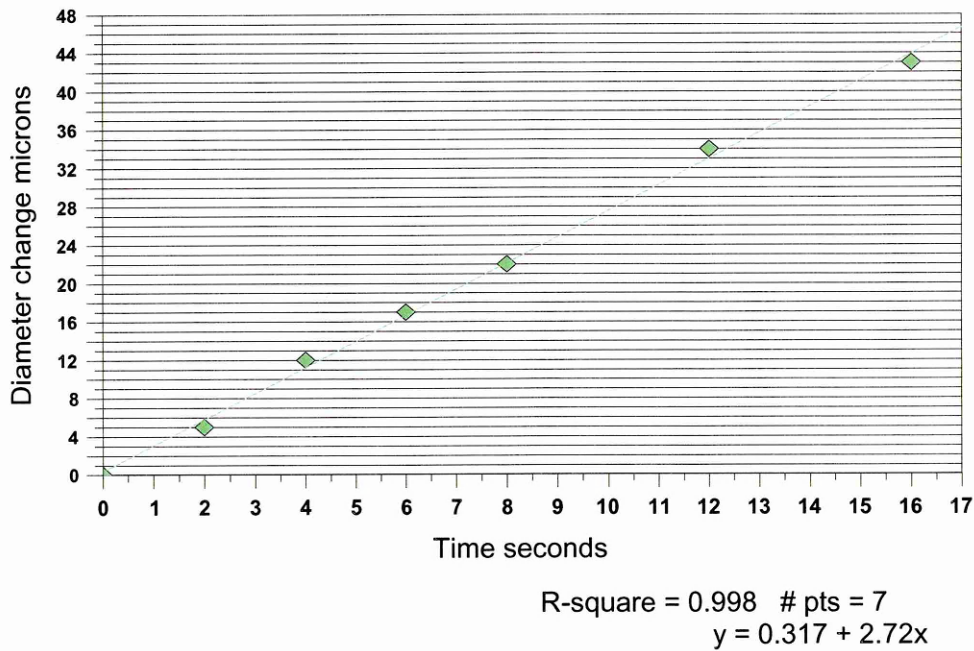


Figure 4.10: Material removal during ECM of a ground ring using 4 mm electrode, 1100rpm workspeed and 100 Amperes.

The mass removal during electropolishing is governed by Faraday's law:

$$\text{mass removed} = \frac{\rho A I t}{z F}$$

Essentially the mass removed depends on the total charge passed i.e. current (I) x time (t) for a set of ECM conditions. The atomic weight (A) of the dissolving element, and Faraday's constant (F=96500 C) are constants. The valency z for iron can be 2 or 3 or a mixture of the two and ρ is an efficiency factor depending of ECM conditions (flow, temperature, current density etc.). Under fixed conditions ECM can be used to control and accurately dimensionally size the workpiece.

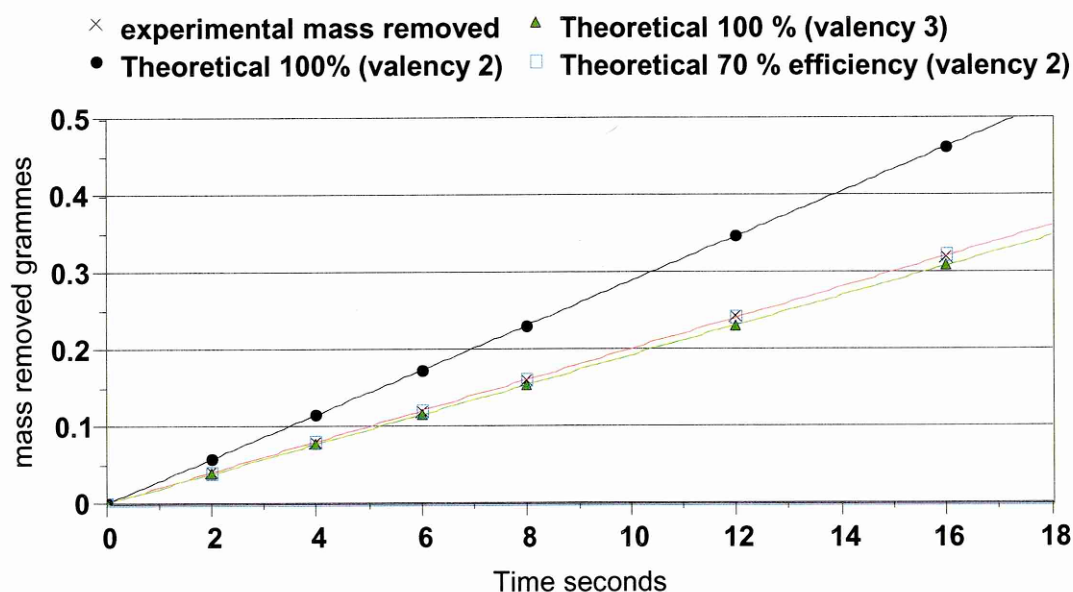


Figure 4.11: Graph showing the experimental and theoretical mass removed during ECM using the 4mm electrode and 100 amperes with a workspeed of 1100 rpm.

Figure 4.11 above shows the mass removed by ECM with time. Mass is a more accurate measure of material removal than diameter measurements. Also shown in the graph is the theoretical mass removed using Faraday's law assuming iron dissolves with a valency 2 or 3, and the process is working at 100 % efficiency. It can be seen that the experimental results lie in between the two theoretical lines. It was found that if it is assumed that the iron dissolved at valency 2 then the process is working at 70 % efficiency i.e. some of the current is used for other electrochemical reactions like oxygen evolution. For NaNO_3 electrolytes efficiencies have been reported in the literature ranging from 40 to 80 % depending on actual conditions used. In the graph above the 70 % efficiency and the experimental results lie exactly on top of each other. Alternatively iron could be dissolving in both valency 2 and 3, each reaction proceeding at a particular efficiency.

Besides controlling the diameter of rings, electropolishing must also provide the surface finish in as short a time as possible. Figure 4.12 shows the rate of surface finishing by electropolishing. The rate of surface finishing was found to be too slow. The ground surface $\text{Ra } 0.31 \mu\text{m}$ was improved to $\text{Ra } 0.13 \mu\text{m}$ after 16 seconds. The ECM appears to copy the surface only gradually removing the peaks.

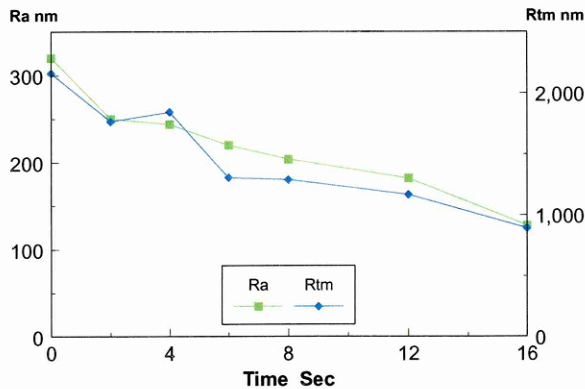


Figure 4.12: Improvement in Ra and Rtm with processing time during ECM

Skewness is found to remain approximately constant at ~ -0.7 , indicating that the electropolishing process is removing material from both surface peaks and valleys. See figure 4.13.

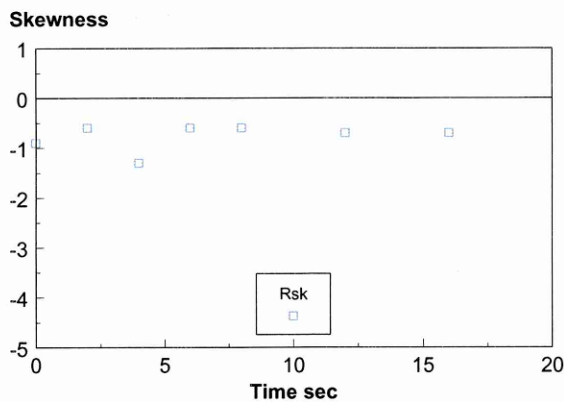


Figure 4.13: Graph showing change of skewness with ECM process time

The mean peak height shown in figure 4.14 is found to slowly fall from 760 nm to 344 nm in 16 seconds although not smoothly, perhaps indicating instability in the surface generation, which is likely to be from small variations in electrolyte flow in the inter-electrode gap.

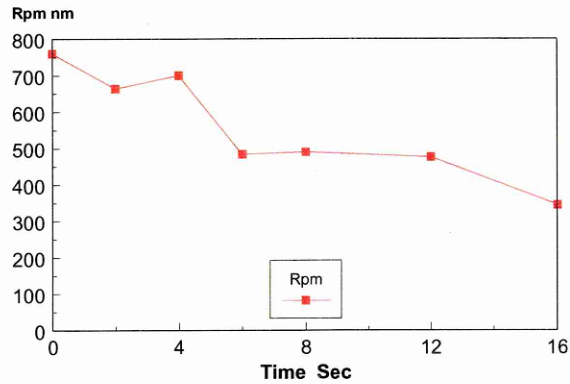


Figure 4.14: Rate of change of mean peak height with ECM time

The slope (Δq), figure 4.15 was also found to decrease smoothly from 5.2° to $\sim 0.82^\circ$ after 16 seconds.

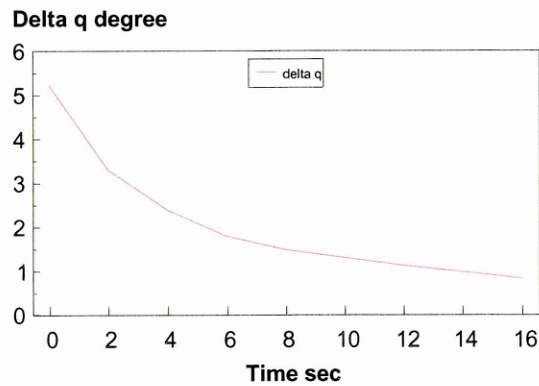


Figure 4.15: Change of slope with ECM time from ground input ring

From the results it is clear that ECM does improve the surface finish of a ground ring, but the rate of surface finishing is very slow. R_a , R_{tm} , and R_p all decrease gradually although the skewness remains fairly constant. The skewness is a measurement of asymmetry; a surface with many peaks will have a positive skewness while a surface with many valleys a negative skewness. This result suggests that material is being removed from the peaks and the valleys. This is also evident from the material removal. In 16 seconds $43\text{ }\mu\text{m}$ have been removed from the diameter of the ring, corresponding to $21.5\text{ }\mu\text{m}$ from the radius, while the R_{tm} mean peak to valley height has decreased by only $1.4\text{ }\mu\text{m}$. As will be seen later, honing attacks the peaks first which results in a sharp drop in skewness.

Previous work at ERC had shown that the final surface roughness from ECM finishing depends on the input roughness of the workpiece. The initial fast rate of surface finishing levels out after longer polishing times, which may relate to the decrease in slope with machining. ECM is very effective at removing sharp features, which has led to its use in deburring. As the surface peaks become more rounded the driving force or energy for the selectivity for material removal from the peaks will decrease.

The cross track profile following ECM is not affected dramatically, although slightly greater material removal from the edges generates increased crowning. Figure 4.16 shows the cross track form after electropolishing for 16 seconds. The increased material removal at the edges is attributed to the electrode size, which is 14 mm while the raceway width is only 12 mm resulting in an edge effect where the current is concentrated. This is further magnified by the chamfer on the ring, which increases the gap at the edge of the ring changing the electrolyte flow.

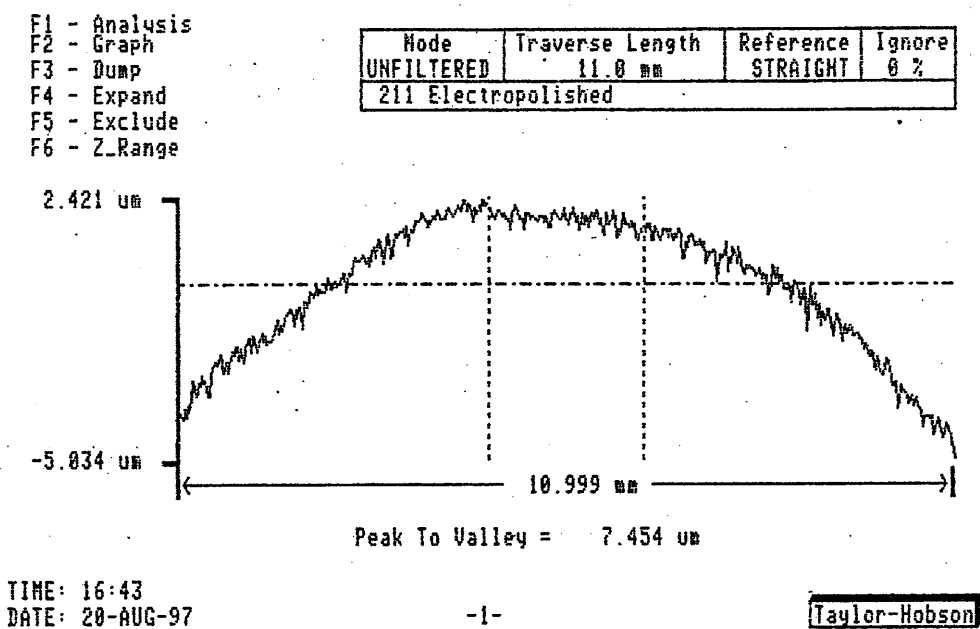


Figure 4.16: Cross track profile after electropolishing for 16 seconds

The waviness levels were also found to increase above that associated with the ground input quality. The medium and high waviness bands were both degraded. Figure 4.17 shows the effect of electropolishing time on the medium and high band waviness from ground ring input quality.

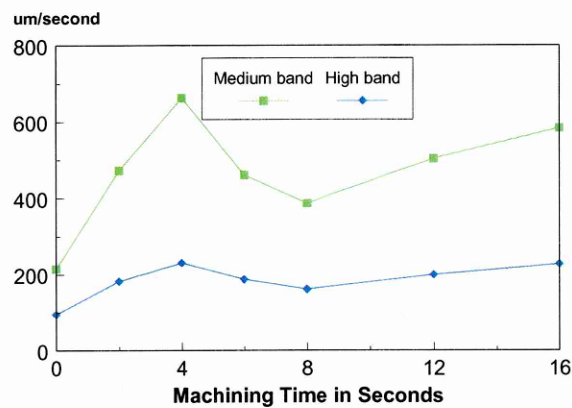


Figure 4.17: Graph showing the effect of electropolishing time on the medium and high band waviness; single track measurements (from ground input quality ring)

The figures 4.18 and 4.19 below show SEM micrographs after electropolishing for 8 seconds.

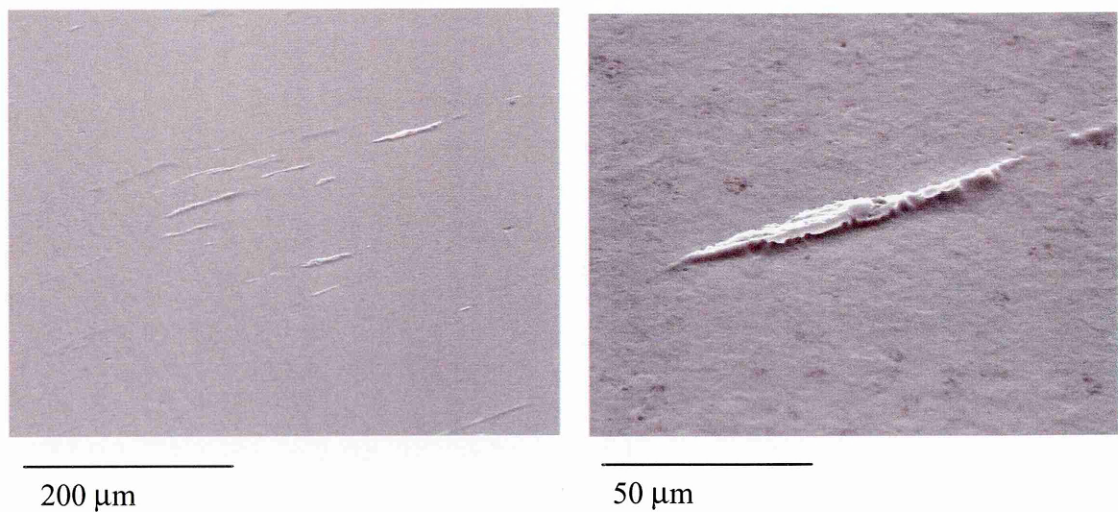
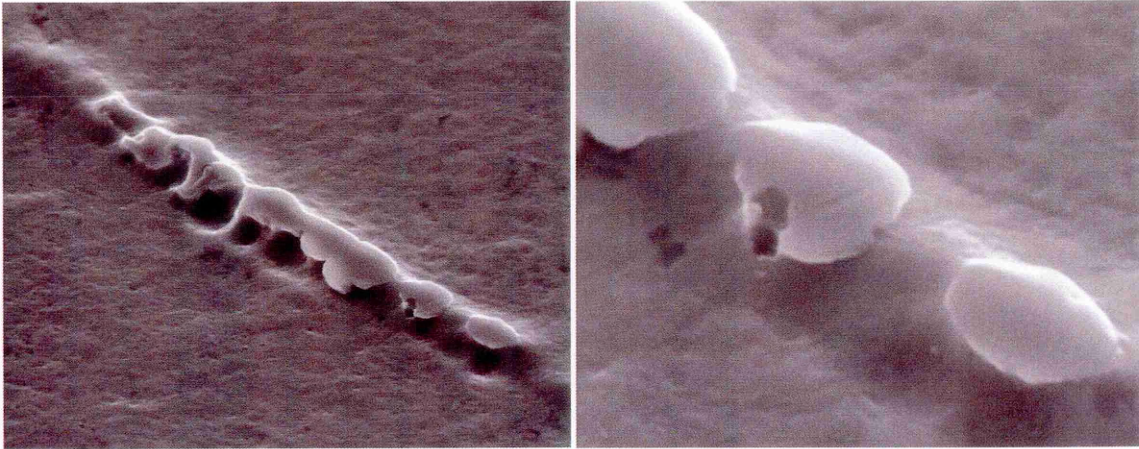


Figure 4.18: SEM micrograph of electropolished surface



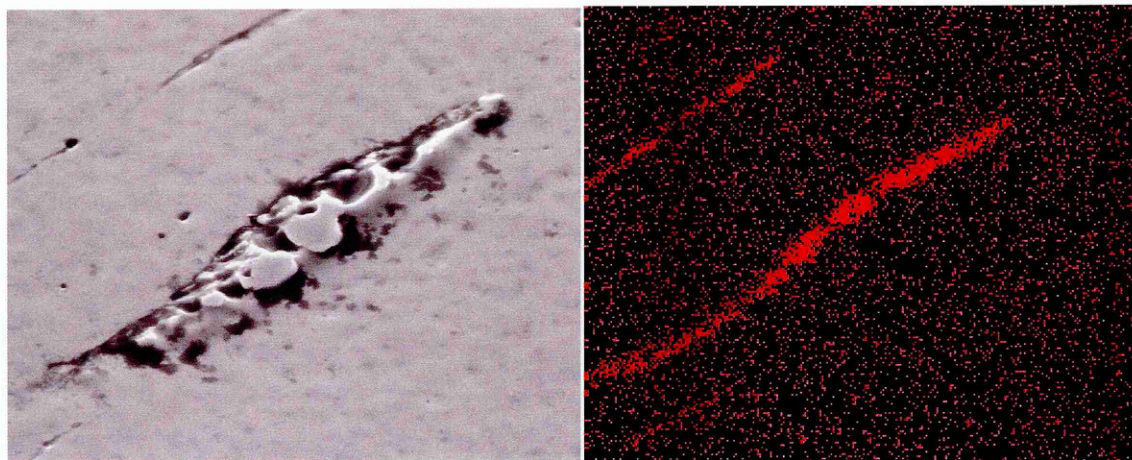
10 μm

5 μm

Figure 4.19: SEM micrographs at higher magnifications showing surface exposed features

It can be seen in figure 4.18 that the grinding lines have mostly been removed and the surface is without leafing. However the surface has large features up to 5 μm wide which can be over 100 μm long running in the cross track direction. It can be seen that the surface is essentially smooth and isotropic except for these features. At even higher magnifications, figure 4.19, it is found that on top of these surface hills, are isolated iron caps (platelets), which have not been dissolved. It appears that the ECM cannot dissolve these inclusions and that the current is directed around the inclusions causing undermining. Some metal has been separated from the bulk before it has been fully dissolved, without any electrical connection it cannot be dissolved and appears as iron caps.

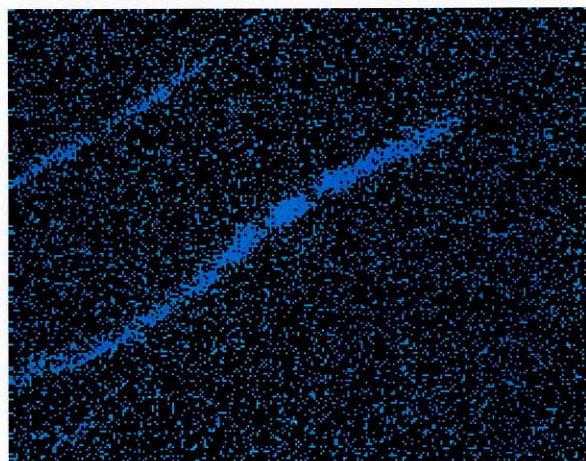
EDAX analysis shown in figure 4.20 identifies these inclusions to be MnS present in the steel from smelting. The MnS inclusions are aligned in the cross track direction as a result of extrusion into tube, the starting point for ring manufacture.



20 μm

A) SEM of inclusion

B) S distribution



C) Mn distribution

Figure 4.20: EDAX analysis of surface hill. A) SEM micrograph of area examined, B) S distribution, and C) Mn distribution

It was noted that a thinner 1mm electrode tended to result in more exposed MnS inclusions compared with the wider 4mm electrode which shows more valleys where the MnS inclusion has been completely undermined or has been removed by the electrolyte flow, figure 4.21.

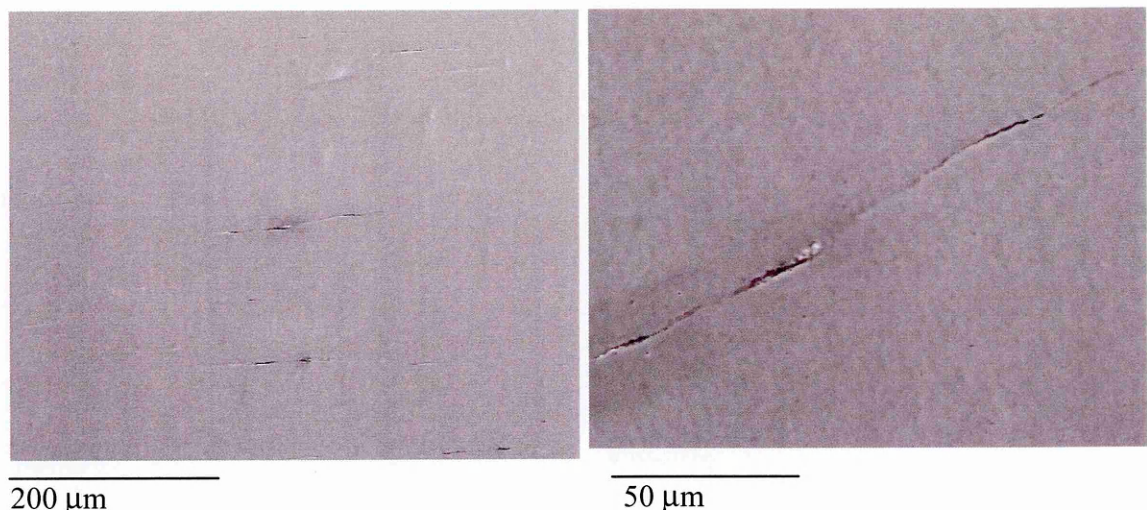


Figure 4.21: Showing surface produced with 4 mm electrode resulting in more valleys

An atomic force microscope (AFM), evaluated at Cranfield University, was also used to examine the surfaces produced by ECM; this can give details of the heights but also has higher resolution.

Figure 4.22 below shows a valley in an ECMed surface made using a 4 mm wide electrode. The depth of the valley is found to be 185 nm. Using the AFM microscope at high magnification on the surface away from the valleys, i.e. the isotropic areas, there could be seen small discs or platelets which are believed to be a result of etched spherical carbide particles.

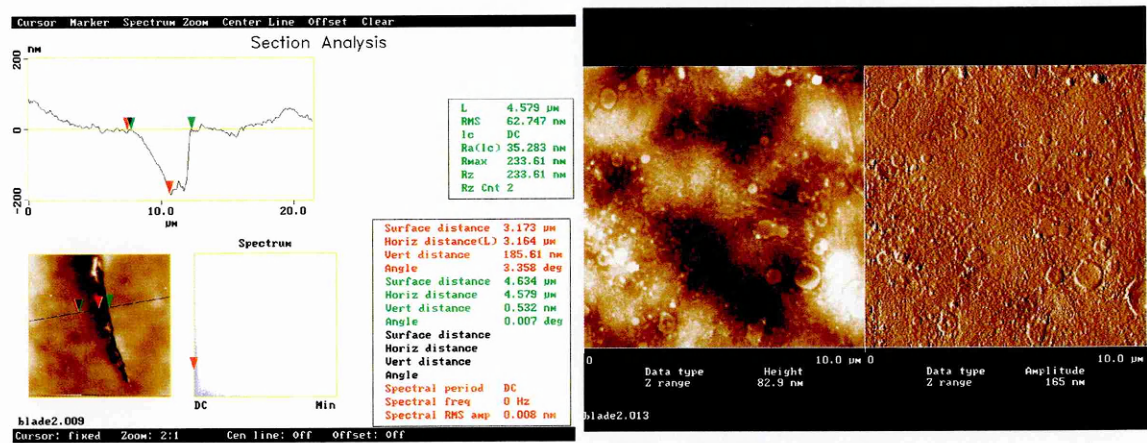


Figure 4.22: Atomic force microscope images of ECMed surface showing a valley and at higher magnification the isotropic surface region.

4.3.2 Honed input ring: Error drivers

The above results showed that ECM could improve the surface finish but made the waviness worse. Waviness is a critical parameter for bearing specifications, so if ECM is to work alone then the waviness must be improved. Electropolishing trials (pure ECM) were performed to establish the dominating characteristics that induce adverse waviness. To test the influence of ECM on waviness, tests were performed on honed rings since they have a better starting waviness.

4.3.2.1 Observations from the "Standardized" Electropolishing Test

First, some general experiments were performed to evaluate the surface finish and waviness generated by ECM on honed input quality rings, using the conditions shown in table 4.5 below.

Table 4.5: Standard test settings

Tests samples	CRB NU207 inner ring (honed quality)
Current level	100 Amps (current density ~ 1.8 Amps / mm ² for 4 mm wide electrode)
Voltage level	24-30 Volts (varying in this range under current control)
Electrode Width	4 mm
Electrolyte flow rate / pressure	5.2 litres @ 3.6 bar
Spindle speed	510 rpm
Working Gap	100 micron (+/- 10 microns)
Time	8 seconds (unless stated otherwise)

As expected surface roughness parameters were improved after the electropolishing process was applied to the conventionally honed surfaces. Results in Table 4.6 convincingly show the surface finish improvement.

Table 4.6: Summary of surface finishing parameters for honed and electropolished (honed input) rings

Surface Parameter	Honed Quality	Electropolished Surfaces
Roughness Ra microns	0.06	0.04
Roughness Rz (DIN) microns	0.5	0.3
Skew Rsk	-1.1	-0.6
Delta q degrees	0.95	0.47

Waviness of electropolished samples was measured using the MWA instrument in both a single track and multi-track mode, table 4.7. These measurements showed the following:

Assessment by single track MWA Measurement Mode

- * Delta R (roundness), L, L1, L2 and H were not significantly altered.
- * L3 and M were generally made slightly worse.

Assessment by multi-track MWA Measurement Mode

- * Delta R (roundness), L and L1 was generally improved.
- * L2 was generally not altered
- * L3 and M were made worse
- * H was unchanged

Table 4.7: Summary of waviness results from honed rings and electropolished rings (honed input quality)

	Honed		Electropolishing	
	Single track	Multi-track	Single track	Multi-track
Roundness (µm)	0.2 - 0.9	0.2 - 0.9	0.3 - 0.8	0.2 - 0.5
L (µm/sec)	30 - 50	24 - 70	30 - 60	24 - 40
L1 (µm/sec)	10 - 40	30 - 75	8 - 46	4 - 30
L2 (µm/sec)	10- 25	15 - 20	11 - 29	11 - 25
L3 (µm/sec)	15 - 25	9 - 15	20 - 28	13 - 25
M (µm/sec)	80 - 140	20 - 30	100 - 160	29 - 35
H (µm/sec)	35-50	7 - 12	35- 60	8 - 12

4.3.2.2 Error Drivers of ECM

It was considered that the following parameters could have a significant influence on the waviness levels introduced by the electropolishing process. Each of these factors were investigated to establish their affect on waviness.

- i) Workpiece Eccentricity
- ii) Electrical noise level associated with ECM test rig
- iii) Electrode Width

The results obtained by investigating the above three parameters showed the importance of material microstructure, as also demonstrated in the SEM micrographs shown before of ECMed surfaces.

- iv) Microstructure

I) Influence of Workpiece Eccentricity

The level of eccentricity was considered to be a possible influence on waviness since the working gap would vary with ring rotation, changing the electrolyte flow conditions and also causing variation in the current-voltage characteristics of the ECM process.

Tests were undertaken with samples precisely mounted onto the work spindle but with prescribed eccentricity levels of 0 μm, 10 μm, and 20 μm, set to a +/- 1 μm accuracy level. Samples were machined with the ECM parameters given in Table 4.5. The single-track waviness measurements are shown in Figure 4.23 below.

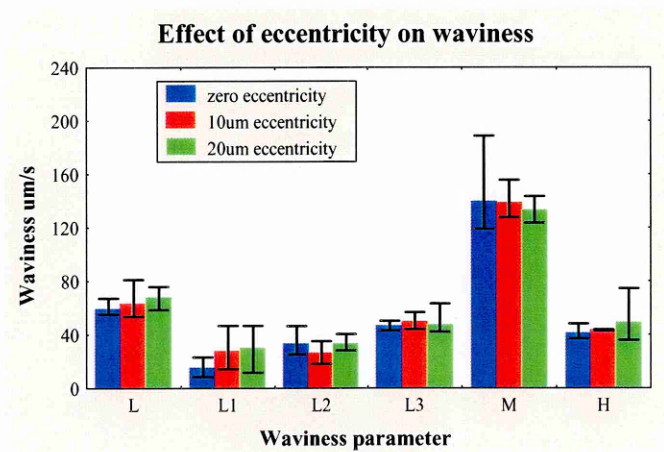


Figure 4.23: Graph showing influence of workpiece eccentricity on single-track waviness

This figure shows that the waviness, in all bands, is not significantly controlled by eccentricity errors. Such a result implies the "noise" associated with these tests, as portrayed by the error bars, is dominated by another feature / parameter.

II) Electrical noise level associated with ECM test rig

As ECM is an electrochemical process driven by an applied current it would be reasonable to assume that any fluctuations in this current would affect the machining process and have consequences for waviness. A series of investigations was therefore undertaken to establish:

- i) Sources of electrical noise associated with the test rig
- ii) Effect of a.c. ripple on ECM current
- iii) Effect of Motor Drive Signal

Sources of electrical noise from test rig

Electrical noise associated with the existing test rig was investigated. The method of passing the ECM current to the anodic workpiece, whilst mounted on the precision air-bearing spindle, is via a slip - brush ring arrangement. This positive electrical connection is made near the bottom of the spindle shaft by way of four spring loaded alloy brushes. This brush connection is located near to the a.c. synchronous spindle drive motor.

With the aid of a digital oscilloscope and a secondary brush-slip ring arrangement connected near the top of spindle shaft, the electrical noise associated with the test rig and the ECM process was investigated.

Noise associated with mains supply with the spindle amplifier switched off and no current applied was found to be 0.15 volts at 50 Hz mains frequency.

With the spindle drive amplifier switched on, a higher level of electrical noise is found. This electrical noise is at a high frequency and has a magnitude of 2-3V (~10% of operating voltage). The frequency of this noise was found to be 20 kHz, corresponding to the carrier signal used by the " Infranor" PWM drive amplifier. This drive amplifier controls the speed of the a.c. synchronous motor. The motor is directly mounted on the air bearing spindle shaft. Investigations of the influence of the spindle drive motor and the low frequency mains induced noise were subsequently carried out separately.

Effect of a.c. ripple on ECM current

The ECM current signal was found to have a 50 Hz a.c. ripple at 0.15 Volts (0.5% of operating voltage) induced from the electrical mains supply. Experiments were carried out to gain some knowledge of the sensitivity of waviness with respect to current stability. Tests were undertaken whereby varying levels of a.c. ripple were added to the ECM applied current. Current ripple was produced by a signal generator whose output was fed to the power supply as a control signal. The signal generator added a sine wave to the dc current of the ECM process to simulate the mains a.c. ripple, see Figure 4.24. The frequency and magnitude of this ripple was controllable in terms of magnitude, shape and frequency.

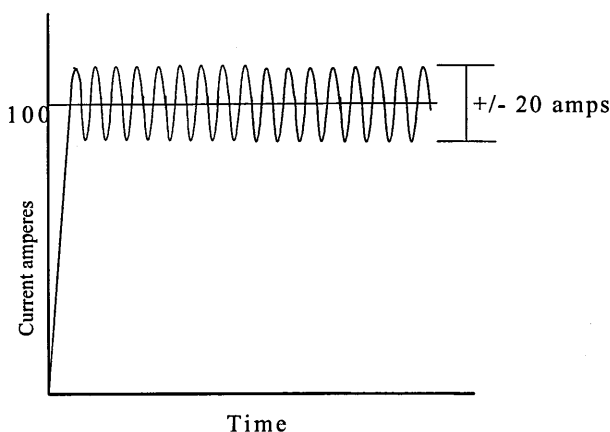


Figure 4.24: Schematic of a.c. ripple applied to ECM current

Test samples were produced using the parameters listed in Table 4.5 but with a sine wave ripple added to the 100 Amp current level. The frequency range of this current ripple was set in the range of 50-500 Hz, and the amplitude in the range of +/- 1 - 20% (1-20 Amps).

At a frequency of 50 Hz three amplitude levels were investigated, +/- 20 amps, +/- 5 amps, and +/- 1 amps. With the spindle speed of 510 rpm, a 50 Hz sine wave corresponds to ~6 waves per revolution. Undulations at this frequency are clearly evident on the MWA trace shown in Figure 4.25; in this case the current ripple amplitude was set at +/- 20 amps (+/- 20%). Using a ripple at the same frequency but with a +/- 5% amplitude also showed 6 wave undulations reproduced onto the workpiece surface. However the magnitude of the undulations is much smaller. When the current ripple amplitude is reduced to +/- 1 amp the six waves are not represented on the MWA trace.

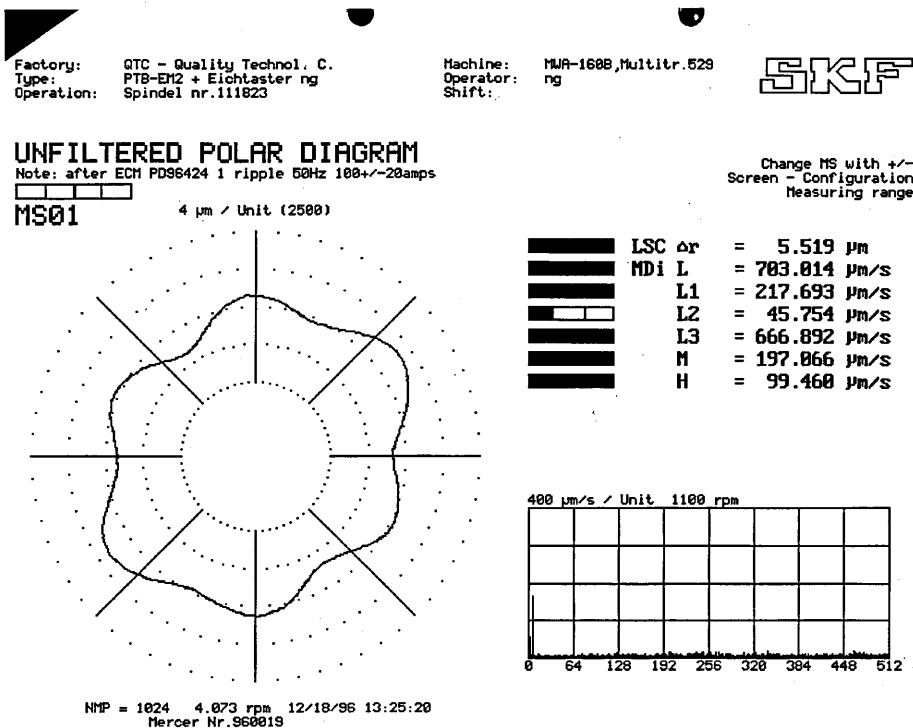


Figure 4.25: MWA trace from ECMed sample when a 100 +/- 20 amps 50 Hz sine wave is added, forming 6 lobes on circumference

This finding would indicate that the mains current ripple of 0.5% at 50 Hz is not a dominant error driver of waviness found on ECM samples.

A 100 Hz ripple produces 12 waves on the surface, when the current ripple is set to 100 +/- 20 amps, see figure 4.26. Similarly for 200 Hz and +/- 20 amps, 24 waves are present, but their peak-to-peak magnitude is much less at this frequency. With a 200 Hz and 5 amps ripple the 24 wave number is no longer a major frequency peak on the MWA trace. Tests were carried out at 500Hz and 5 kHz with a +/- 20% current ripple, and frequency peaks were not found corresponding to these frequencies.

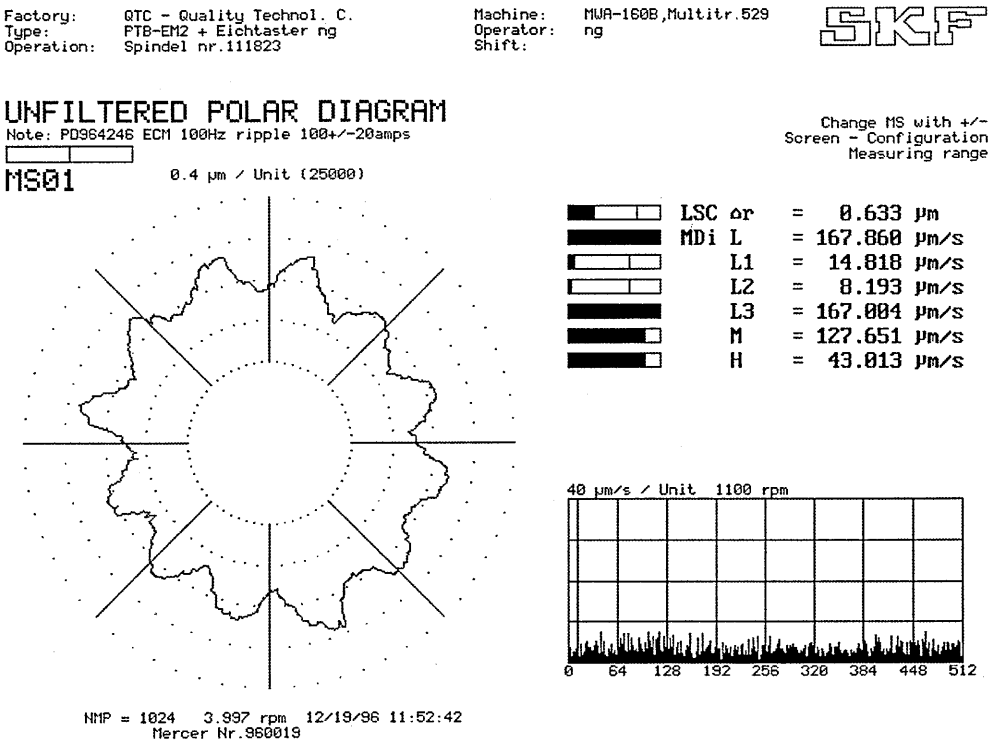


Figure 4.26: MWA trace from ECMed sample when a 100 +/- 20 amps 100 Hz sine wave is added, producing 12 lobes on circumference

Waviness values obtained for L, M and H bands were not degraded by current ripple over 500 Hz, even with magnitudes of +/- 20%. These results suggest that electrical noise level is not a dominant error driver and that ECM's sensitivity to current ripple is low in regard of its influence on waviness.

Effect of Motor Drive Signal

To confirm that the high frequency noise associated with the spindle drive amplifier was not influencing the quality of waviness found on ECMed rings, a de-coupled belt drive system was developed.

Results of tests carried out using the belt drive system in comparison with those obtained when using the direct drive motor with and without the drive belt attached are shown in Figure 4.27. Waviness values are shown as an average of MWA multi-track measurements. This figure indicates that waviness, in all bands, is not significantly influenced by the noise associated with the PWM drive amplifier.

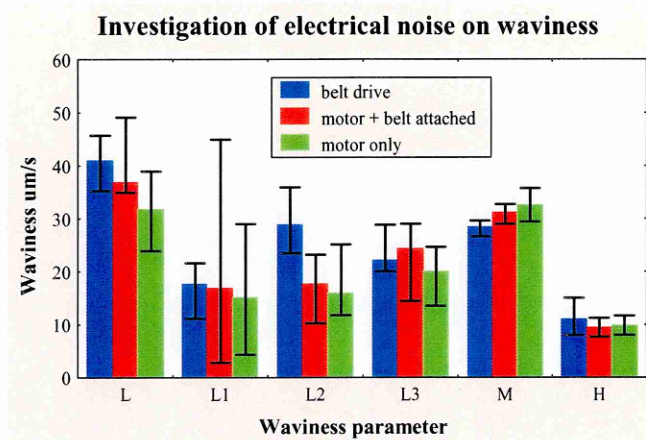


Figure 4.27: Investigation of Waviness from Spindle Drive Amplifier Using a Decoupled Belt Drive System (multi-track measurements)

The waviness values are found to be lower for multi-track readings than for single track because the data is filtered and averaged over 39 traces. MnS inclusions believed to contribute to waviness are random features and so when averaged they tend to cancel out. Again, the error bars overlap so there is no clear difference between measurements. This result indicates the signal driving the motor is not of major influence. It would appear that the belt drive system was however adversely affecting the low waviness band L2. This is likely to be a result of the low stiffness air-bearing spindle.

III) Electrode Width

Degradation of waviness quality after ECM machining when using the standardized test is most strong in the medium band range, 17-98 UDR (undulation per rev). On the NU207 inner ring test samples the medium band waviness represents wavelengths of 8 - 1.4 mm in the circumferential direction.

Initial work used electrodes of 4 mm thickness; these were chosen based on material removal rate targets. The influence of the electrode width was considered an important parameter influencing waviness quality. Tests were therefore carried out using electrodes of differing widths, 1, 2, and 4 mm.

Changing the electrode width requires a reduction in the applied current to avoid sparking and electrode damage. The current level was therefore adjusted to give the same current density for each electrode width $\sim 1.8 \text{ Amps/mm}^2$. The lower levels of applied current mean a longer machining time is required to remove the same amount of material.

The waviness levels found using the different electrodes are shown in Figure 4.28. Measurements were obtained using the MWA instrument in a multi-track mode. From the standardized electropolishing test results it was found that L3 and M waviness bands were degraded compared with standard honed quality. The results shown in Figure 4.28 indicate that the thinner width electrodes gave higher levels of waviness compared with the 4 mm wide electrode in the L3 and M bands. The effect on lower order waviness is not so clear because of the wide spread of the results, but the average values do appear to be better with the wider 4 mm electrode. Although the waviness is still much worse than the standard honed input ring.

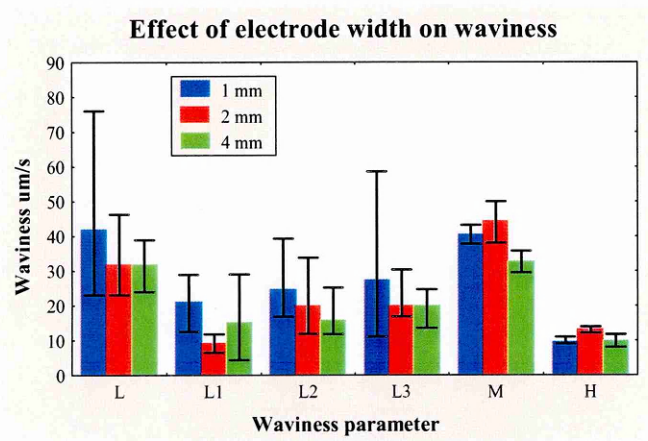


Figure 4.28: Influence of electrode width on waviness resulting from ECM

Upon examination of single track waviness measurements, taken from the 39 tracks which make up the multi-track measurements, a large number of sharp spikes up to $1 \mu\text{m}$ in height could be seen for the samples made with the thinner 1 and 2 mm wide electrodes, but also to a lesser degree with the 4 mm electrode, see Figure 4.29.

Factory: QTC - Quality Technol. C.
Type: PTB-EM2 + Eichaster ng
Operation: Spindel nr.111823

Machine: MWA-160B, Multitr. 529
Operator: ng
Shift:



MT - LINEAR DIAGRAM

Note: PD9642442 1mm electrode 24 sec
0.4 μm / Unit (25000)

Screen - Configuration
Measuring range

X: -13.40 Z: 7.01

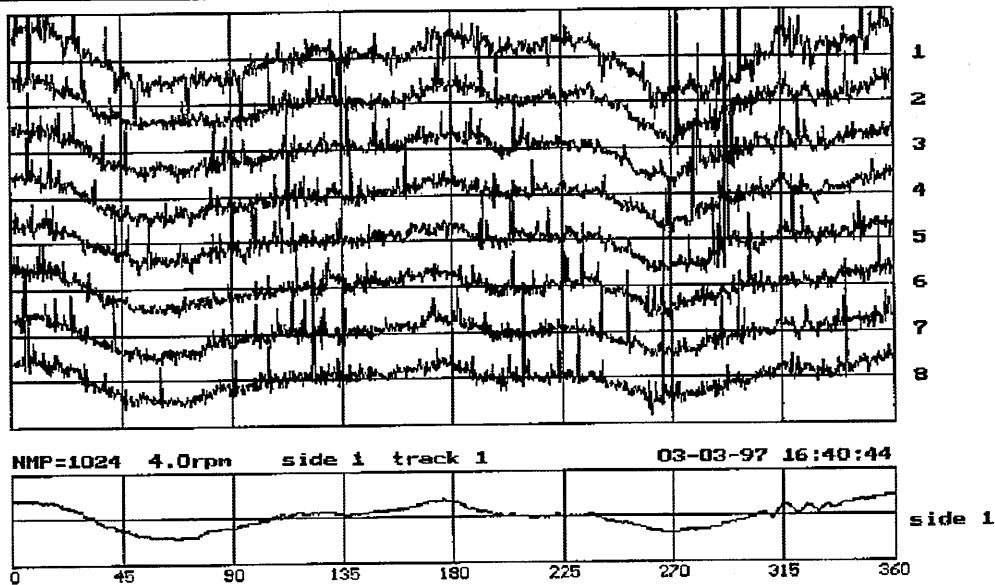


Figure 4.29: Individual tracks from the multi-track measurement of ECMed surface showing many peaks, current 35 amperes, 1 mm electrode, machining time 24 seconds.

Investigations on the surface of these ECM samples gave information on the importance of microstructure and material composition on measured waviness levels.

IV) Microstructure / Material Composition

ECM involves the anodic dissolution of the workpiece; different materials have different electrochemical properties and are therefore removed at different removal rates. 100Cr6 is a steel containing a number of elements Fe, C, alloying elements and impurities.

Examination of the ECM surfaces by electron microscopy reveals noticeable features of a particular shape as shown in earlier results. Feature size is 0.05-0.2 mm long by 3-5 μm wide and lie lengthways across the raceway track. These surface features are associated with MnS inclusions and present themselves as either surface peaks or valleys.

Electrode width and applied current appear to influence the form of these MnS related features. Smaller width electrodes are more strongly linked with MnS peaks. It is considered that the lower applied current (but similar current density) involves a less aggressive removal process, where the non-conductive MnS inclusions are not undermined as fast. At the same workpiece speed the time under the electrode is longer for the 4mm electrode and the depth of cut or material removed per revolution is greater.

Figure 4.30 below also indicates that the average medium band waviness is lower for a lower workpiece speed, although once again the spread in the measurements overlap. This may indicate a relationship with the time at which the workpiece is under the electrode.

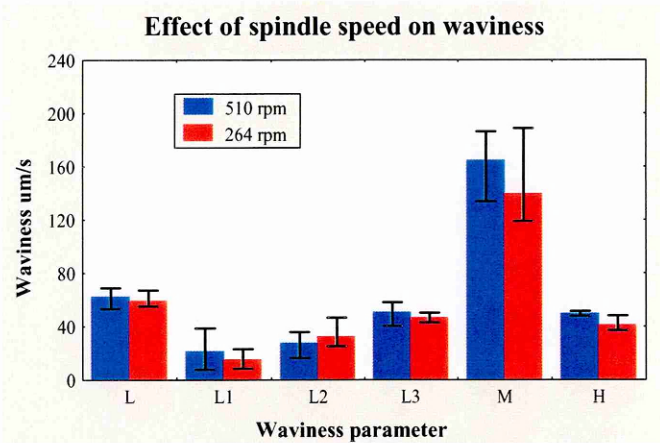


Figure 4.30: Effect of workspeed on waviness (single track measurements)

In general thinner electrodes produce more surface peaks. When measuring waviness in a single-track mode thinner electrodes gave correspondingly higher medium band waviness levels.

Whilst a clear understanding of the interactions of the electropolishing process and the MnS surface inclusions has not yet been established it is clear that changing the electrode width has influence on the morphology of electropolished surfaces. MnS inclusions will however

always be exposed by an ECM process and these will have an adverse effect on the measured value of waviness. This fact clearly has implications on the achievable waviness levels obtainable from a pure ECM process.

Summary of error drivers

1. The electropolishing process as applied to the finishing of bearing raceways exposes waviness influencing MnS inclusions within 100Cr6 steel. This fact means that a pure ECM process cannot be applied for finishing raceways when made from this important bearing material, at least when waviness is an important consideration.
2. The waviness level obtained from electropolishing is not very sensitive to fluctuations of applied current ($< 1\%$ @ frequency > 100 Hz.). Electrical noise around the present ECM test rig is not considered to be a limiting factor in respect of optimising waviness.
3. Medium band waviness is not highly sensitive to eccentricity levels in the range 10-20 microns peak - peak and therefore the sensitivity of waviness to changes of working gap at this level can be assumed to be low.
4. Electrode width, applied current and workspeed have an influence on the topography of the electropolished surfaces and directly influences waviness.
5. Electrolyte flow quality is considered important in respect of optimising electropolishing. This task is especially important when considering cross track profile requirements. It is difficult to change the flow conditions in a controlled way. The nozzle design had been changed to keep a uniform flow as much as possible by having the nozzle exit as close to the workpiece and having a longer flow channel to allow a laminar type flow to develop within the nozzle. A good indication of the flow conditions is the black line left on the workpiece when the current is switched off. This black line is an etched area resulting from the potential (V) drop when the current is switch off. If the flow is poor a wavy line is formed while for good flow conditions a fine straight black line is formed.

4.3.3 Summary on electropolishing.

1. Pure ECM "electropolishing" of bearing raceways is limited, and will always be so for 100Cr6 bearing material, in respect of waviness. The inhomogeneity of the 100Cr6 bearing steel resulted in the exposure of soft MnS inclusions which are non- conductive so are not removed by the ECM. These MnS inclusions resulted in higher measured levels of medium and high band waviness. Whether this would result in higher noise is not known since these inclusions are soft and likely to be removed during running in. They were removed easily by applying an abrasive superfinishing tape by hand onto the rotating workpiece, figure 4.31.

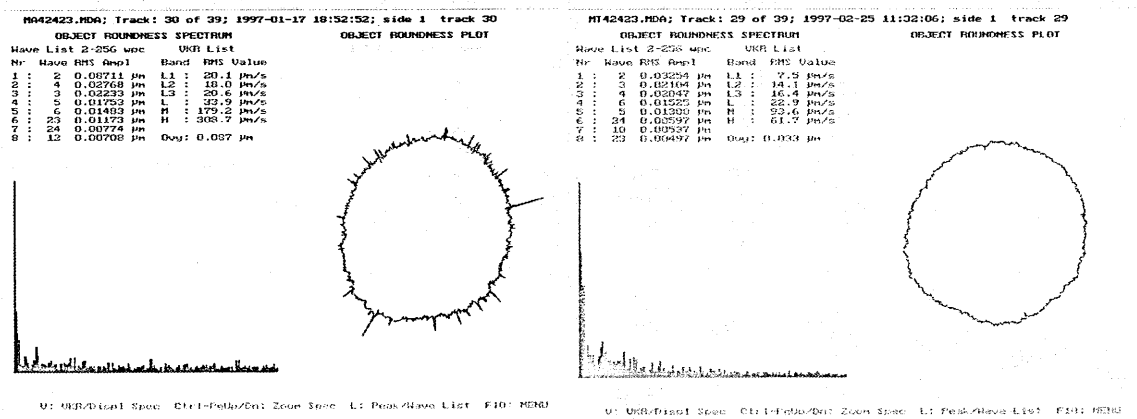


Figure 4.31: Showing an MWA trace before, and after applying by hand a 1µm diamond tape for a few seconds. The MnS peaks have been removed

- 2. The control of the electrolyte fluid dynamics has a strong influence on waviness and cross track form. Stabilizing this process parameter will permit some further optimisation.
- 3. Accurate high material removal can be achieved with ECM giving accuracy of +/- 1 µm.
- 4. Rate of surface finishing is too slow and the ultimate surface finish depends on input surface finish

4.4 Abrasive tape applied onto ECMed surface

4.4.1 Introduction

The very basic test to remove the MnS generated surface peaks by applying an abrasive by hand onto the rotating workpiece showed that a minimal abrasive process could remove the MnS peaks easily. Further work was then carried out in a more controlled manner to apply superfinishing tapes onto the ECMed surface to improve the measured waviness.

4.4.2 Experimental set-up

The abrasive tape trials were carried out using the ECM test rig on samples that had previously been ECMed. A tape finishing attachment was designed to statically apply the abrasive tape onto the ring surface see figure 4.32. A pneumatic cylinder regulated from the main air supply by a valve was used, and the pressure applied to the cylinder was calibrated to a corresponding force by measuring the displacement of the air-bearing spindle, which has a known stiffness.

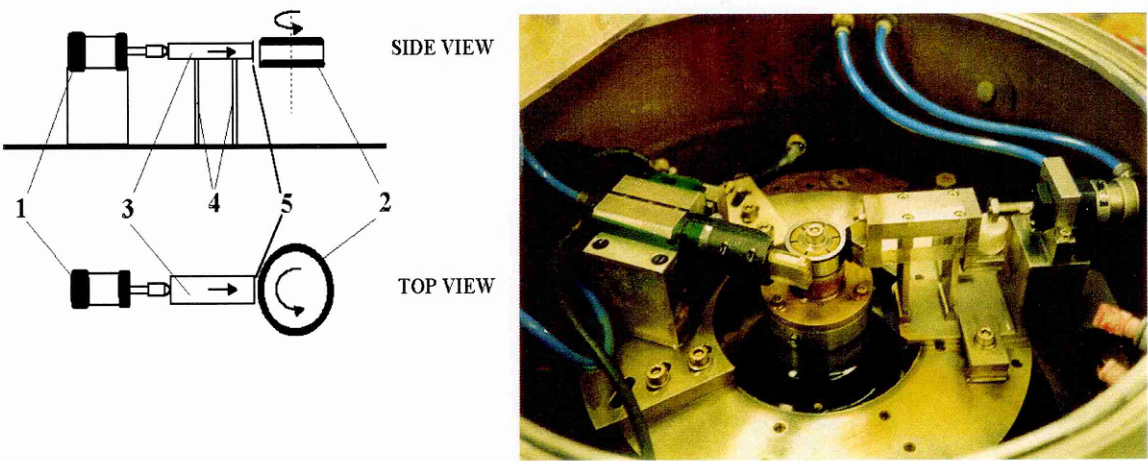


Figure 4.32 : Tape honing attachment, 1-pneumatic cylinder, 2-ring, 3-pushing block mounted on 4-cantilever beams and 5-tape

Parameters, which were investigated:

1) Pressure applied to pneumatic cylinder:

- i) 2 bar ii) 4 bar

2) Rotational speed of air spindle (cutting speed):

- i) 510 rpm ii) 1100 rpm

3) Abrasive grit type:

- i) Al_2O_3 alumina ii) CBN iii) diamond

4) Grit size

- i) Al_2O_3 9 & 3 microns
- ii) CBN 9 microns
- iii) Diamond 1 micron

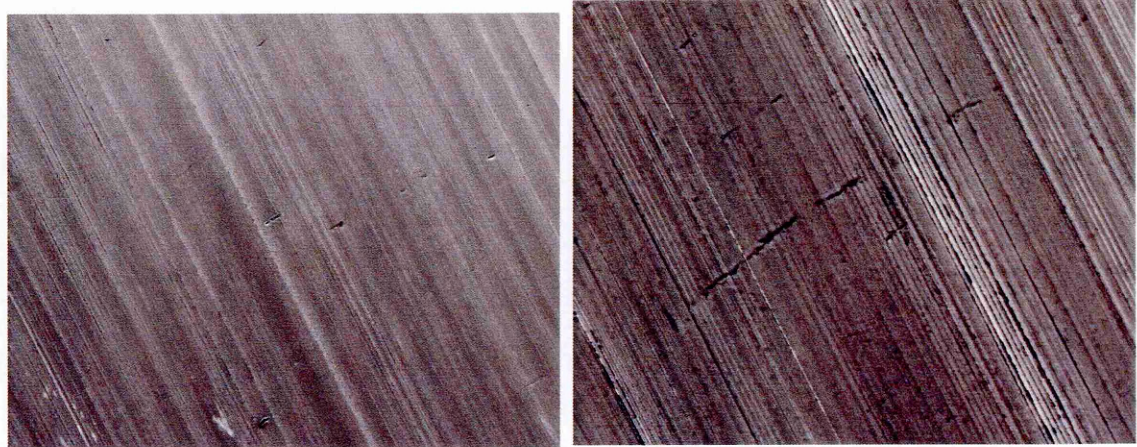
5) Cycle time 4 seconds

The tapes were supplied by the company 3M.

The actual force applied to the ring with 2 bar and 4 bar air pressure was measured as 70N (~0.6 MPa) and 150N (~1.25 MPa), the cutting speeds were 1.2 m/s and 2.6 m/s for 510 and 1100 rpm respectively. ECMed input rings (from honed input quality), which had previously been measured for roughness and waviness, were used to assess cutting performance on the low slope ECMed surfaces. Test numbers shown in graphs correspond to a set of processing parameters shown in table 4.8.

4.4.3 Results of applying superfinishing tape to an ECMed ring

A clear difference between the alumina and the CBN abrasive tapes was evident from the appearance of the actual rings. Rings cut using CBN had visible but fine honing lines from the 9 μm CBN grit tape, while it was not so evident that the alumina tape had cut. SEM micrographs are shown in figures (4.33 & 4.34). The CBN abrasive with its sharp and hard cutting edges was able to cut the low slope ECMed surface. The alumina was not as good at cutting the ECMed surface, and some lines can be seen but also pits and valleys are exposed. The 1 μm diamond abrasive was found not to cut well and was non-uniform in its cutting action.



200 μm

50 μm

Figure 4.33: Showing the effect of a 9 μm CBN tape on an ECMed surface at 1100 rpm & 4 bar



200 μm

50 μm

Figure 4.34: Surface of an ECMed ring after a 9μm alumina tape has been applied 510 rpm 4 bar

The use of an abrasive was envisaged to remove any surface irregularities associated with the MnS inclusions and hence reduce waviness. Figure 4.35 clearly shows that a minimal abrasive process easily removed the soft MnS peaks generated by the ECM operation on the raceway surface. Figure 4.35 shows two polar plots from a) ECMed ring showing the MnS peaks and b) after the abrasive tape has been applied to remove the peaks.

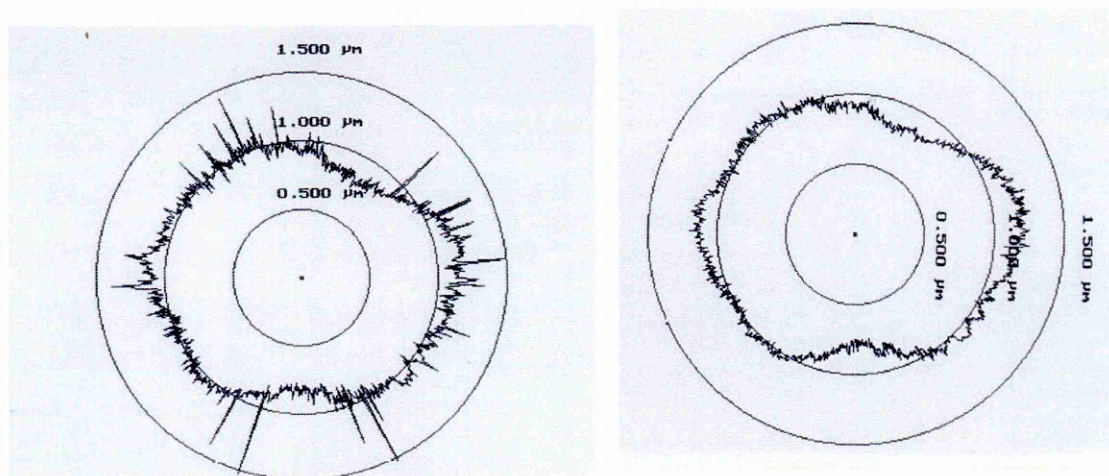


Figure 4.35: Polar plots showing the effectiveness of an abrasive to remove the MnS peaks

By applying an abrasive process onto an already ECMed surface, M and H band waviness is reduced, confirming that the MnS surface inhomogeneities cause the measured waviness in these bands. Figure 4.36 show that the medium M and the high H band waviness has been changed by using different operating parameters for the abrasive removal process. The figure shows how the input waviness quality affects the improvement in waviness, indicating that little material has been removed and that maybe a greater material removal is necessary.

An attractive side effect of using a minimal abrasive process is that other surface finishing parameters such as Ra, Rtm and slope are improved at the same time. See figures (4.37 & 4.38 & 4.39).

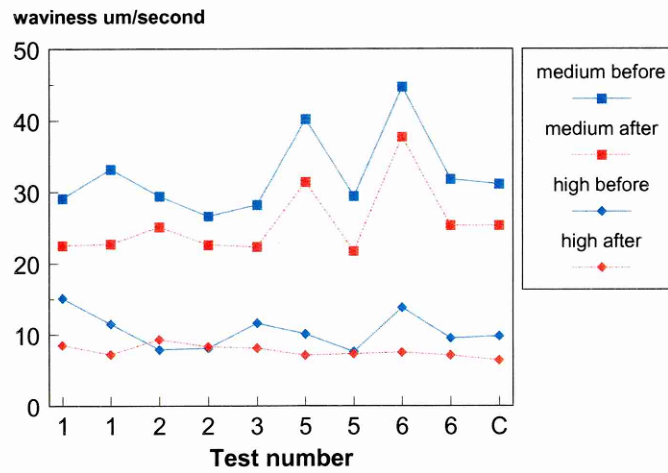


Figure 4.36: Change in medium and high band multi-track waviness measurements after an abrasive is applied to an ECMed ring

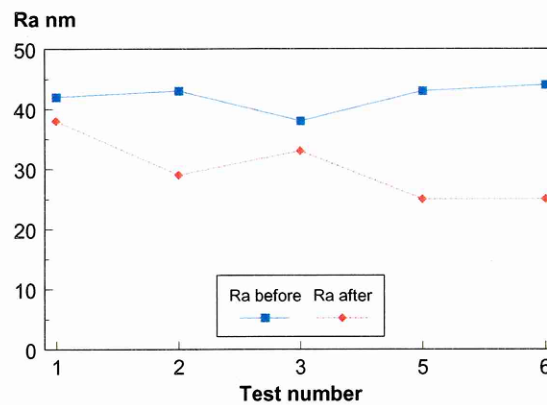


Figure 4.37: Change in R_a after applying abrasive tape to an ECMed surface

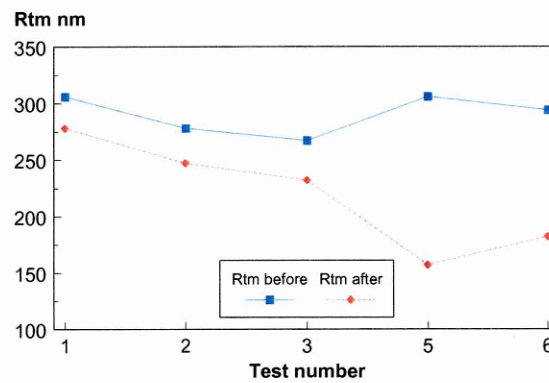


Figure 4.38: Change in mean peak to valley height following application of an abrasive tape to an ECMed surface

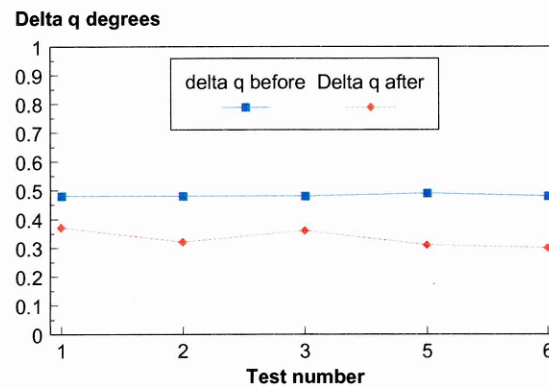


Figure 4.39: Change in slope of an ECMed surface after application of an abrasive tape

Table 4.8: Showing experimental conditions and results of applying a superfinishing tape to an ECMed surface

<i>Test</i>	<i>Description</i>	<i>Ra</i>	<i>Rtm</i>	<i>Rsk</i>	<i>Rku</i>	<i>Delta q</i>	<i>M Before</i>	<i>M After</i>	<i>H Before</i>	<i>H After</i>
1	9µm Al ₂ O ₃ 1100rpm 4bar	0.038	0.278	-1	5.8	0.37	29.1	22.5	15.1	8.5
	9µm Al ₂ O ₃ 1100rpm 4bar	0.033	0.211	-0.6	3.7	0.35	33.2	22.7	11.5	7.2
2	9µm Al ₂ O ₃ 510rpm 4bar	0.029	0.247	-1.2	8.8	0.32	29.4	25.1	7.9	9.3
	9µm Al ₂ O ₃ 510rpm 4bar	0.036	0.241	-0.7	4	0.36	26.6	22.6	8.1	8.3
3	3µm Al ₂ O ₃ 1100rpm 4bar	0.033	0.232	-0.6	4.2	0.36	28.2	22.3	11.6	8.1
	3µm Al ₂ O ₃ 1100rpm 4bar	0.037	0.289	-1.3	6.8	0.55	49.3	47.7		6.1
4	3µm Al ₂ O ₃ 510rpm 4bar	0.041	0.298	-0.6	4.4	0.33		45.6		6.2
	3µm Al ₂ O ₃ 510rpm 4bar	0.042	0.242	-0.1	2.8	0.26		38.6		5.9
5	9µm CBN 1100rpm 4bar	0.025	0.157	0.1	3.4	0.31	40.2	31.4	10.1	7.1
	9µm CBN 1100rpm 4bar	0.04	0.309	-0.4	4	0.71	29.4	21.7	7.6	7.3
6	9µm CBN 510rpm 4bar	0.025	0.182	-0.6	5.2	0.3	44.7	37.7	13.8	7.5
	9µm CBN 510rpm 4bar	0.022	0.143	-0.5	4.2	0.24	31.8	25.3	9.5	7.1
9	9µm Al ₂ O ₃ 1100rpm 2bar	0.044	0.318	-0.2	3.5	0.47	49.9	40.9	13.3	12.3
	9µm Al ₂ O ₃ 1100rpm 2bar	0.042	0.319	-0.5	5.4	0.46	43.1	41.4	8.9	5.9

12	3 μ m Al ₂ O ₃ 510rpm 2bar	0.037	0.254	-0.6	4.3	0.42	27.3	22.4	13.7	
	3 μ m Al ₂ O ₃ 510rpm 2bar	0.046	0.257	0.1	2.5	0.32		77.5		11.6
13	9 μ m CBN 1100rpm 2bar	0.032	0.244	-0.2	3.5	0.53	70.1	45.4	12.1	8.6
	9 μ m CBN 1100rpm 2bar	0.037	0.261	-0.1	3.1	0.54	40.9	30.6	13.1	8.6
14	9 μ m CBN 510rpm 2bar	0.053	0.384	-0.4	3.5	0.76	38.1	46.2	12.1	11,0
	9 μ m CBN 510rpm 2bar	0.056	0.562	-2.7	21.4	0.87	49.9	30.8	13.2	8.1
C	1 μ m diamond 1100rpm 4bar	0.047	0.363	-0.8	8.1	0.56	31.1	25.3	9.8	6.4
	1 μ m diamond 1100rpm 4bar	0.045	0.261	0	2.8	0.41		42.6		6.5
D	1 μ m diamond 510rpm 4bar	0.044	0.281	-0.3	2.9	0.34		87.7		8.9
	1 μ m diamond 510rpm 4bar	0.048	0.295	-0.4	4.3	0.36		56.7		7.2

4.4.4 Summary from abrasive tape applied to ECMed surface

- i) Medium band waviness of an ECMed ring is much improved by the use of an abrasive tape after ECM. The quality of such a ring is comparable with a standard honed ring. The high band is also generally improved or remains the same.
- ii) Other surface finishing parameters, such as surface roughness is better than honed quality. Average Ra for ECM followed by an abrasive is 0.035 μ m while a honed surface is $\sim$ 0.060 μ m. Similarly peak to valley height and delta q (slope) are lower.
- iii) The sharp cutting edges of CBN gave the best cutting action
- iv) The overall shape of ring was not affected by the abrasive, partly because of small contact area 10 x 12 mm and the use of small grit sizes, which removed minimal material.

4.5 Electrofinishing using coated abrasive tapes

The results discussed in section 4.3 & 4.4 demonstrate that material inhomogeneity of the bearing steel will have a major influence on achievable waviness, and that an abrasive process is able to remove these surface feature. Therefore a combined electro-mechanical process called electrofinishing has been investigated utilizing the fast controlled material removal of ECM with an abrasive process to improve waviness.

The previous work done at ERC proved such a "combined" process using honing stones could achieve a number of criteria needed for finishing bearing raceways. The current work has demonstrated that very high quality surfaces of $0.02\text{ }\mu\text{m Ra}$ can be achieved with a cycle time of 8 seconds or less from an input ground ring of $0.5\text{ }\mu\text{m Ra}$. However, the waviness, roundness and cross track profile quality provided by this "combined" process were found to be variable. Surface appearance was also subject to occasional but noticeable scratches.

The complexity of using a honing system inside an ECM facility raises questions regarding capital machine cost, operational difficulty / reliability and the consumable cost levels. Therefore investigations firstly employed simple superfinishing tapes supplied by 3M with the ECM process, since superfinishing tapes are easier to control than honing stones.

4.5.1 Effect of combining static abrasive tape and ECM

The graphs (4.40-4.45) clearly show that by applying ECM with statically applied superfinishing tape gives smoother more uniform cutting and allows the abrasive to work for longer times without becoming loaded (clogged with metal).

When the $9\text{ }\mu\text{m}$ CBN tape was applied to a ground ring without ECM although still with the NaNO_3 electrolyte flowing, the tape is able to remove $2 - 3\text{ }\mu\text{m}$ from diameter in the first 2 - 4 seconds and then the cutting action essentially stops, see figure 4.40. From the other surface finish parameters the tape appears to become loaded after ~ 6 seconds, corresponding to the bulk surface removable and not just surface peaks. This is also borne out in figure 4.43, which shows skewness. The onset of loading occurs when the bulk surface has started to be cut i.e. valley heights are reduced.

When ECM is applied at the same time the loading of the tape does not occur as readily. The increase in skew after 6 sec and the corresponding decrease in valley depths show that the tape with ECM was able to cut the bulk material, unlike when the tape was applied alone.

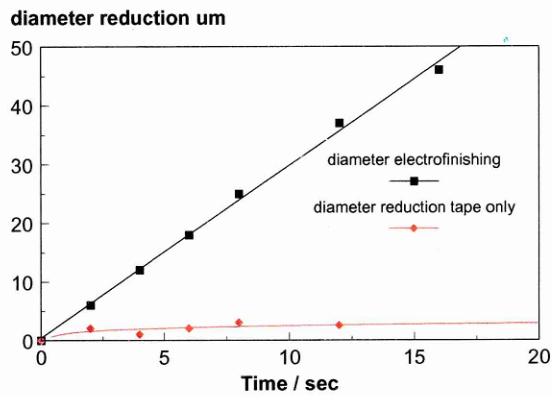


Figure 4.40: Graph comparing diameter reduction for tape honing with and without ECM, 9 μm CBN, 1100 rpm, 0.8 MPa

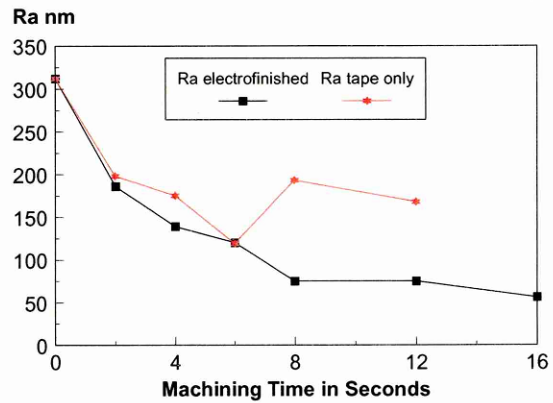


Figure 4.41: Rate of improvement in Ra for electrofinishing and tape finishing 9 μm CBN, 1100 rpm, 0.8 MPa

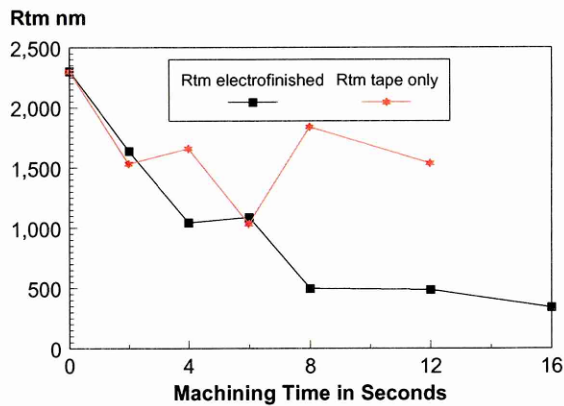


Figure 4.42: Showing rate of improvement in mean peak to valley height for electrofinishing using 9 μm CBN tape, 1100rpm and 0.8 MPa

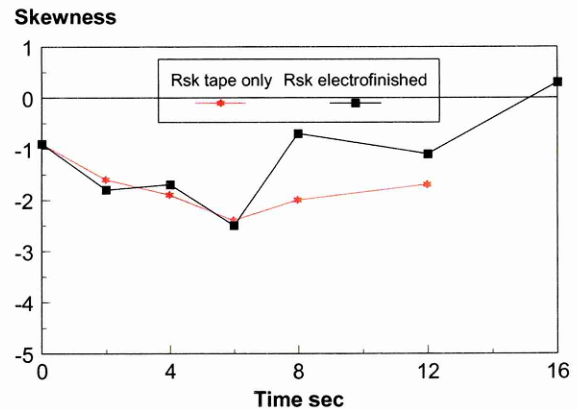


Figure 4.43: Graph showing change in skewness with machining time for electrofinishing with 9 μm CBN, 1100 rpm and 0.8 MPa

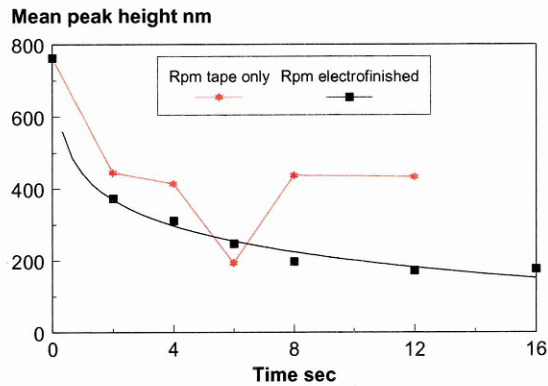


Figure 4.44: Graph showing the reduction in peak height with machining time for tape honing with and without ECM, 9 μm CBN, 1100 rpm, 0.8 MPa

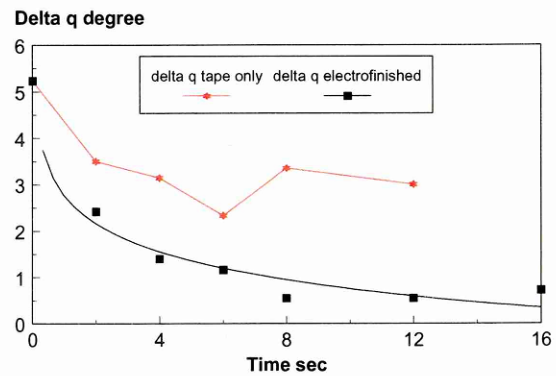


Figure 4.45 slope changes with machining time during electrofinishing and tape finishing 9 μm CBN, 1100 rpm, 0.8 MPa.

4.5.2 Effect of spindle speed on electrofinishing with 9 μm CBN abrasive tape

Initial results up to 6 seconds show that increasing the cutting speed has little influence on Ra and Rtm. While Rsk and Rpm are lower for the higher cutting speeds as would be expected if the honing process is responsible for the majority of the surface improvement. Delta q was found to be worst at higher speed again the surface is cut more times at higher speeds by the sharp CBN grits so a higher slope would be expected.

Between 6 - 8 seconds, electrofinishing at 2000 rpm becomes unstable/erratic; Rpm, Rtm and Ra increase slightly. The possibility exists for mechanical interactions / vibrations affecting the final finish or maybe the CBN grits are not as efficient due to tape loading.

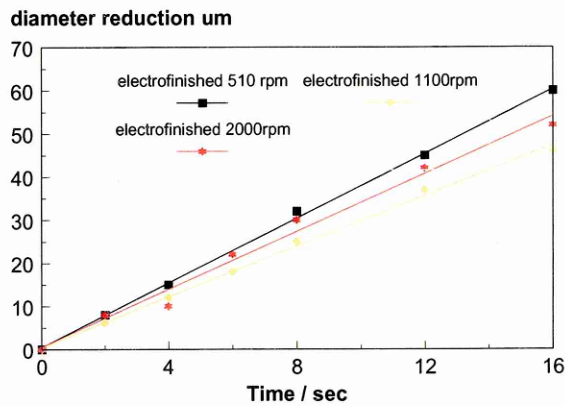


Figure 4.46: Effect of spindle speed on diameter reduction during electrofinishing with 9 μ m CBN, 0.8 MPa, and current 100 Amps.

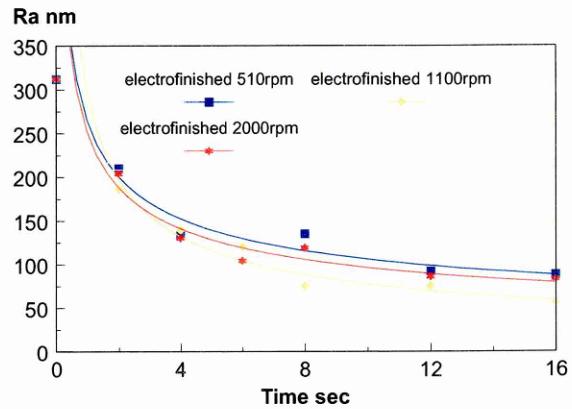


Figure 4.47: Effect of spindle speed during electrofinishing on improvement in Ra

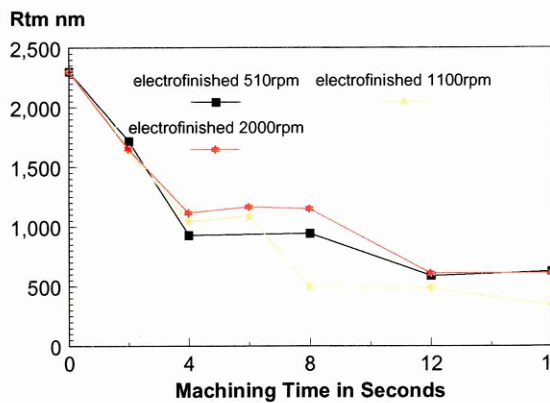


Figure 4.48: Change in Rtm with machining time for different spindle speeds

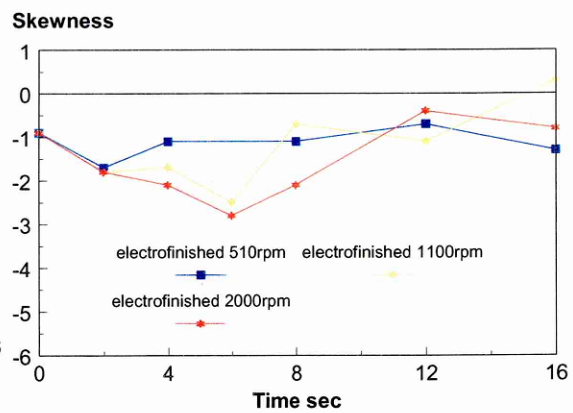


Figure 4.49: Showing change in Skewness with machining time during electrofinishing at different spindle speeds using 9 μ m CBN tape, 0.8 MPa and 100 Amps

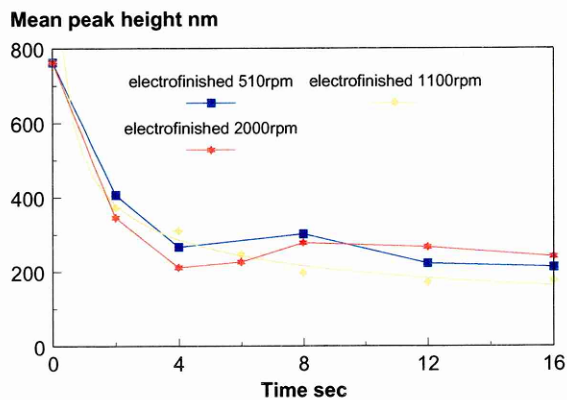


Figure 4.50: Showing how spindle speed effects rate mean peak height during electrofinishing using 9 μm CBN tape, 0.8 MPa and 100 Amps

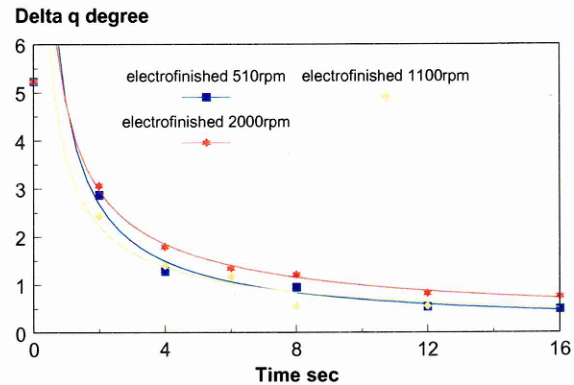


Figure 4.51: Showing how slope is affected by electrofinishing spindle speed

4.5.3 Effect of tape pressure on surface finishing by electrofinishing

The actual change in diameter reduction has remained approximately the same, figure 4.52, indicating that the majority of material removed is accomplished by the ECM mechanism.

Increasing the applied pressure during electrofinishing with tapes has the primary effect to increase the initial rate of surface enhancement, i.e. R_a , R_{tm} , R_{pm} , R_{sk} and Δq all improve at a faster rate, figures 4.53 - 4.57. It is interesting to note that after 8 seconds the measured roughness parameter for high and low applied pressures remains the same, indicating the ultimate surface finish for a particular grit size is not dependent on the applied pressure.

After ~ 8 seconds at the low and high pressures the valleys are beginning to be touched and reduced but only slowly to about $0.5 \mu\text{m}$. Maybe the surface of the tape is being reproduced or loading of the tape prevents further improvement by abrasion and the ECM is generating the surface finish.

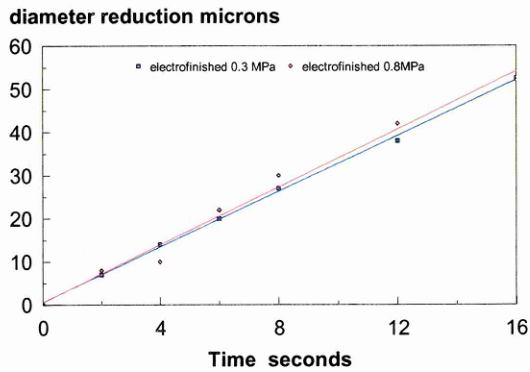


Figure 4.52: Showing the effect of electrofinishing pressure on diameter reduction using 9 μm CBN tape, 2000 rpm and 100 Amps

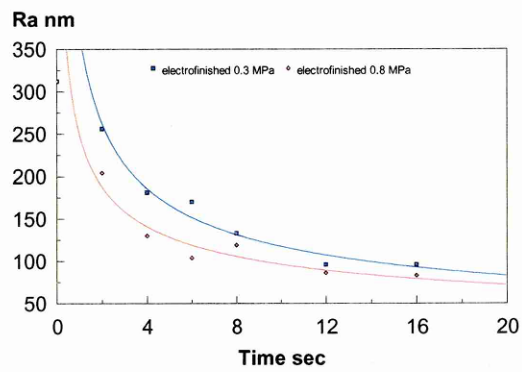


Figure 4.53: Showing the effect of electrofinishing pressure on improvement in Ra using 9 μm CBN tape, 2000 rpm and 100amps

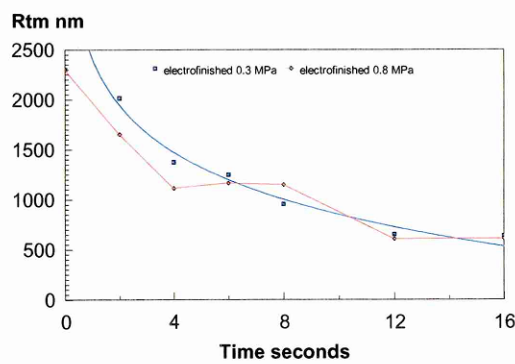


Figure 4.54: Showing the effect of electrofinishing pressure on reduction on mean peak - valley heights using 9 μm CBN tape, 2000 rpm and 100 Amps

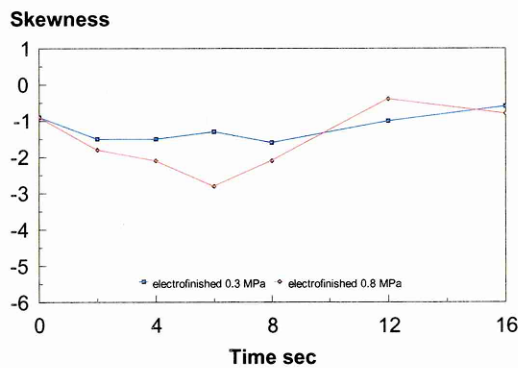


Figure 4.55: Showing the effect of electrofinishing pressure on skew using 9 μm CBN tape, 2000 rpm and 100 Amps

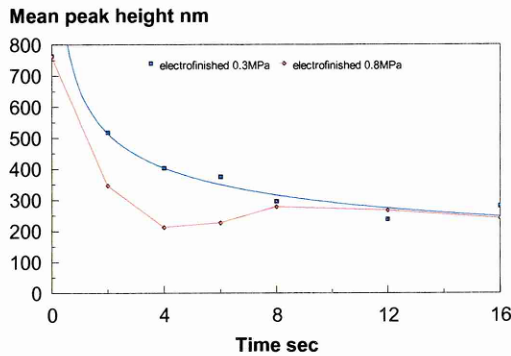


Figure 4.56: Showing the effect of pressure on mean peak height using 9 μm CBN tape, 2000 rpm and 100 Amps

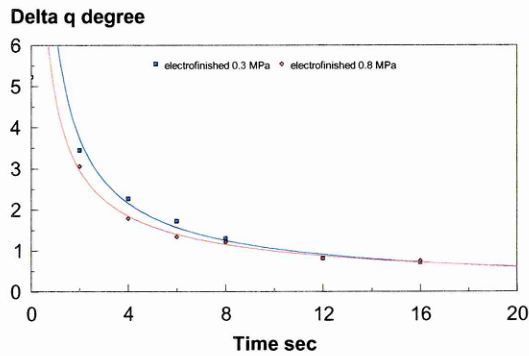


Figure 4.57: Showing the effect of pressure on rate of improvement of slope using 9 μm CBN tape, 2000 rpm and 100 Amps

Combining ECM with superfinishing tape appears to reduce the risk or the rate of tape loading by grinding debris/chips, allowing the tapes to work for longer. Higher speed and pressure give an improved rate of surface finishing, indicating that the abrasive material removal dominates the surface finishing mechanism. ECM is responsible for most of the diameter reduction. Changing the tape pressure did not have a major influence on the removal rate, although a speed effect was noticed. Rotation speed will influence the ECM process by changing the process efficiency. Lower speeds give higher material removal rates. ECM produces a thin oxide layer on the surface, which must be removed before material removal can proceed. This film is formed when the workpiece exits the electrode, therefore the more times the workpiece passes the electrode the more often an oxide film is formed which subsequently must be removed before material removal begins. This effect can also explain why material removal begins to improve again at higher speeds since the cutting action will help in removing these films.

Even during electrofinishing, loading of the tape occurs particularly at higher pressures and speed but the onset for loading is delayed. The visible appearance of the used tape clearly showed black loaded material. Improvements could be made by using continuous or step feed of the tape and tape oscillation is essential.

4.6 Electrofinishing using honing stones

The results presented in section 4.5 showed that by applying ECM together with the tape, maintained stable cutting action for longer, i.e. the tape was prevented from becoming loaded. However the rate of surface enhancement and final level of finish were not sufficient, so application of honing stones with ECM was investigated as honing stones show a degree of self dressing and therefore greater material removal capability.

4.6.1 Electrofinishing using soft SiC honing stone

Figure 4.58 shows the contribution to material removal when honing is combined with ECM. If honing and the ECM can be assumed to work independently then the contribution of honing to material removal is given by the mass removed by the combined process and subtracting the mass removed by the pure ECM process (assuming 70 % efficiency). The figure shows that material removed by the honing process increases and is able to cut for longer times when applied with electropolishing.

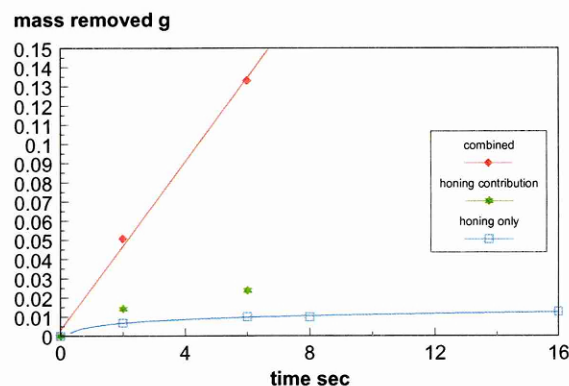


Figure 4.58: Showing the relative contribution of honing during the combined honing with ECM process and comparing with the mass removed from honing alone

It would therefore appear that the honing stone is somehow dressed by the ECM process preventing loading of the stone allowing the stone to work longer, similar to the situation with the superfinishing tapes.

The effect of combining ECM with honing is shown in figures (4.59-4.64) where the soft SiC stone (SC9 1200 04 60 VGL) supplied by Atlantic had been used with the ECM process. The material removal rate of the combined process is higher but still of the correct order of magnitude if the honing stone is able to cut for longer or if the ECM is operating at a higher efficiency as a result of the abrasion removing polarization layers as suggested by other researchers on ECM polishing.

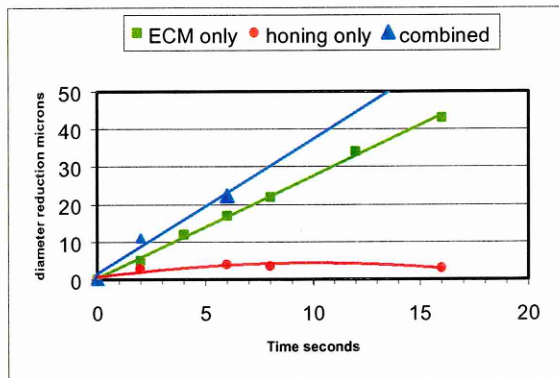


Figure 4.59: Comparison of diameter reduction for ECM only, honing only and combined ECM with honing

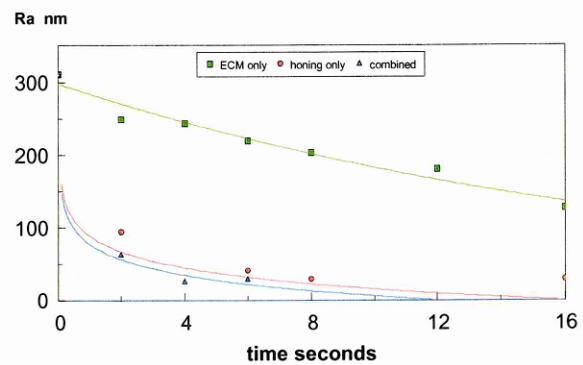


Figure 4.60: Comparing improvement in Ra for electropolishing, honing only and electrofinishing

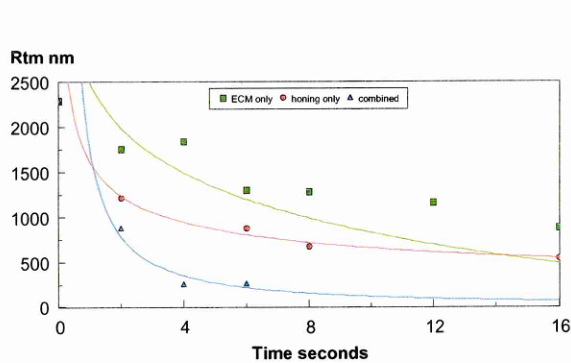


Figure 4.61: Comparing improvement in Rtm for ECM, honing only and electrofinishing

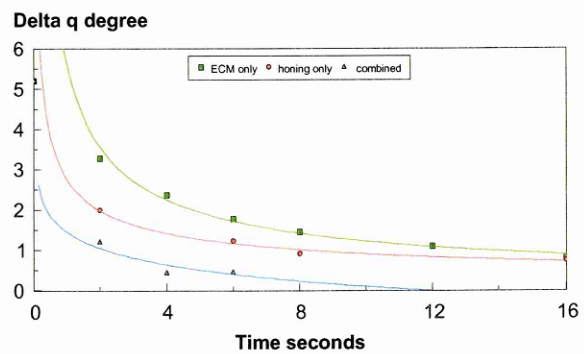


Figure 4.62: Comparing change in skewness for electropolishing, honing only and electrofinishing

Mean peak height nm

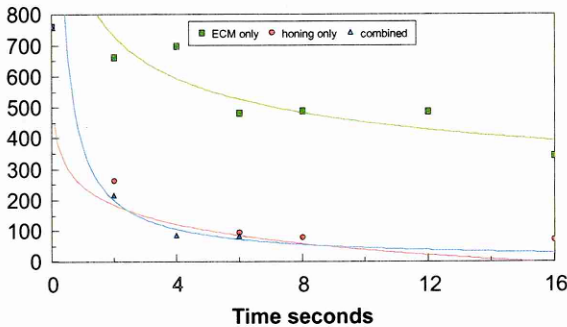


Figure 4.63: Change in mean peak height for electropolishing, honing only and electrofinishing

Delta q degree

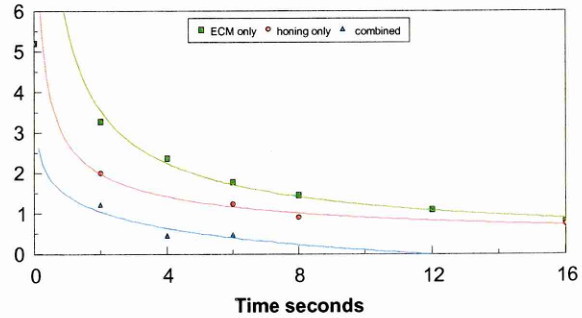


Figure 4.64: Comparing rate of change in slope for the process, honing only, ECM only and electrofinishing

Figure 4.60 shows the improvement in Ra for the combined electrofinishing process, ECM and honing only (using electrolyte as lubricant/coolant). Ra for the electrofinishing process is slightly better than that of honing alone, a surface of $0.02 \mu\text{m}$ Ra could be produced in 4 - 5 seconds. Rtm is strikingly reduced much faster than honing alone, and within 2 seconds of machining the honing stone is removing bulk material and after 4 seconds the grooves (valleys) from grinding have been removed. An Rtm of $\sim 0.25 \mu\text{m}$ could be produced. For ECM only the Ra and Rtm decrease slowly as discussed in section 4.3.1.

The Ra and mean peak height (Rpm) for electrofinishing and honing decrease at a similar rate indicating that the surface finishing is dominated by the abrasive honing. The big difference between electrofinishing and honing (in electrolyte) is shown in figures 4.61 & 4.62 which demonstrate how the mean peak - valley height (Rtm) and skewness (Rsk) change with processing time. Rtm decreases at a striking rate for the electrofinishing which is further depicted in the skewness graph which shows that the skewness becomes more negative during the first few seconds as surface peaks are removed and then starts to become more positive as the honing starts to remove bulk material i.e. the valley left from grinding. For honing alone in the electrolyte the skewness decreases initially as surface peaks are removed but stays negative since the honing stone stops cutting once it has reached the bulk surface and is unable to remove the deep valleys. This is further shown in the Rtm graph where for the electrofinishing the Rtm drops to a very low level but for honing alone the Rtm starts to fall but levels out after 6 - 8 seconds at a higher value.

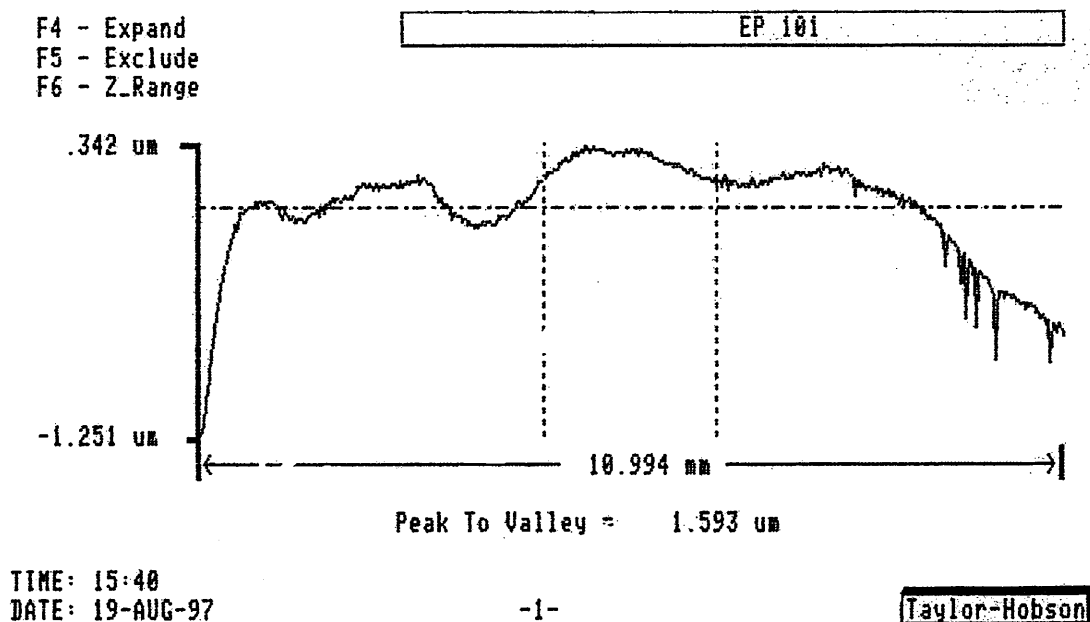
This would indicate that when honing is combined with ECM, the honing stone maintains its cutting ability for longer. The honing stone is somehow being dressed by the ECM

action. Without ECM the honing stone becomes clogged or the grits wear rapidly and the stone will no longer cut and remove material but instead rubs and burnishes the surface.

Another possible benefit of the electrofinishing technique is the very low slope surfaces it produces. The slope for the combined process is found to fall faster and to a lower final level.

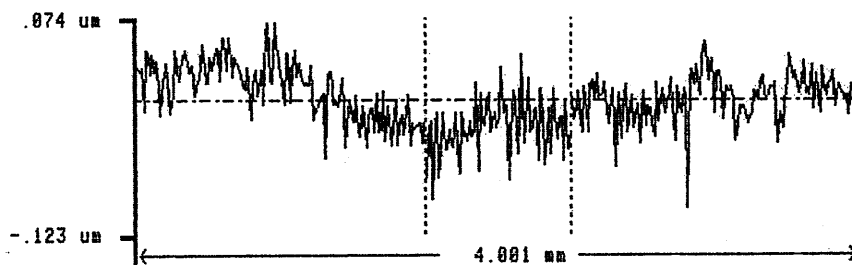
4.6.1.1 Comparison with previous electrofinishing work

A few samples from the previous electrofinishing work were available for comparison and verification of the excellent results reported. However no details on the exact processing conditions were known. Below, figure 4.65 shows the cross track profile and roughness traces from an electrofinished ring from the previous work, and in figure 4.66 is an example of the present electrofinishing process.



F1 - Analysis
 F2 - Graph
 F3 - Dump
 F4 - Expand
 F5 - Exclude
 F6 - Z_Range

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
EP 101				



Peak To Valley = .197 um

TIME: 15:38
 DATE: 19-AUG-97

-1-

Taylor-Hobson

F1 - Analysis

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
EP 101				

Rtm = .128 um	Lo = 4.001 mm	Ra = .022 um
Rpm = .054 um	Rp = .074 um	Rq = .027 um
Ry = .177 um	Rv = .123 um	Rsk = -.3
Rt1 = .091 um	Rt = .197 um	Rku = 3.3
Rt2 = .132 um		Delq = .25 Deg
Rt3 = .130 um	SLOPE = .03 Deg	Lamq = 39.281 um
Rt4 = .177 um		S = 15.171 um
Rt5 = .111 um		Sm = 36.188 um
		R3z = .096 um
		R3y = .114 um

TIME: 15:38
 DATE: 19-AUG-97

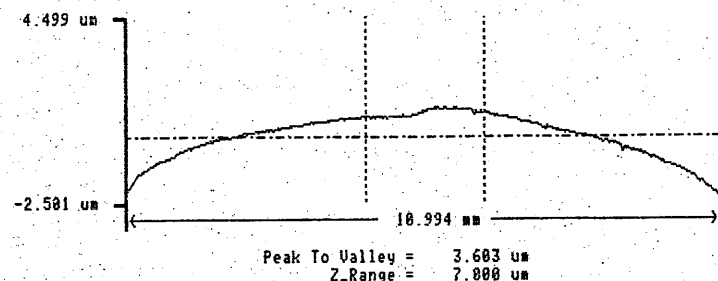
-2-

Taylor-Hobson

Figure 4.65: Earlier electrofinishing work showing cross track profile and roughness measurements

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z_Range *

Mode	Traverse Length	Reference	Ignore
UNFILTERED	11.0 mm	STRAIGHT	0 %
350 ECM + SiC honing 6 sec			



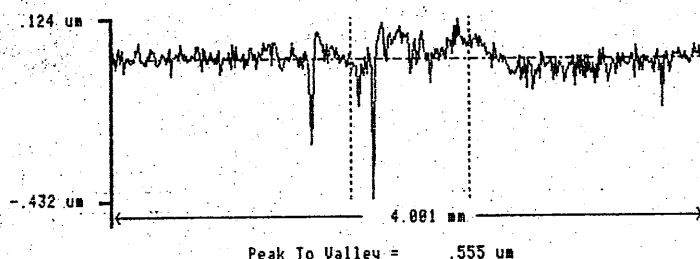
TIME: 17:43
DATE: 26-AUG-97

-1-

Taylor-Hobson

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z_Range

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
350 ECM + SiC honing 6 sec				



TIME: 17:45
DATE: 26-AUG-97

-1-

Taylor-Hobson

F1 - Analysis

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
350 ECM + SiC honing 6 sec				

Rtm = .318 um	Lo = 4.001 mm	Ra = .031 um
Rpm = .077 um	Rp = .124 um	Rq = .048 um
Ry = .555 um	Rv = .432 um	Rsk = -2.8
Rt1 = .166 um	Rt = .555 um	Rku = 22.9
Rt2 = .475 um		Delq = .48 Deg
Rt3 = .555 um	SLOPE = .06 Deg	Lamq = 36.233 um
Rt4 = .171 um		S = 13.734 um
Rt5 = .224 um		Sm = 26.522 um
		R3z = .139 um
		R3y = .191 um

TIME: 17:45
DATE: 26-AUG-97

-2-

Taylor-Hobson

Figure 4.66: Ring electrofinished for 6 seconds using SC1200 04 60 VGL, 90 amperes, 2000 rpm, 0.8 MPa honing pressure, 50 Hz oscillation and 0.5 mm oscillation amplitude

The figures above show how the earlier work had given very good surface finishes $0.022\text{ }\mu\text{m Ra}$ and a $R_{tm} < 0.128\text{ }\mu\text{m}$. However the cross track profile had been severely distorted. The present work using an improved honing attachment has not affected the cross track profile as much, although the surface finish was not quite as good, $0.03\text{ }\mu\text{m Ra}$ and a $R_{tm} 0.318\text{ }\mu\text{m}$. Similar surface finishes have been achieved with the present set-up by applying electrofinishing followed by a few seconds of honing only (no ECM), as will be shown later.

The other important criterion is the waviness for the bearing performance. Figures 4.67 & 4.68 show the waviness measurements obtained with electrofinishing under the previous and present testing.

Factory: ERC
Type: nu207
Operation:

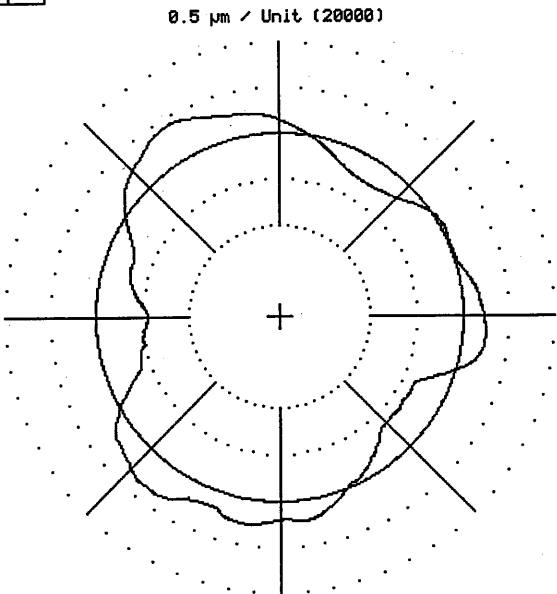
Machine: MWA 180B - NR. 6165
Operator: PJK
Shift:



UNFILTERED POLAR DIAGRAM

Note: EP 101
MS01

Change MS with +/-
Screen - Configuration
Measuring range



LSC

$\Delta r = 0.9906\text{ }\mu\text{m}$
 $X_m = -0.2155\text{ }\mu\text{m}$
 $Y_m = -1.2948\text{ }\mu\text{m}$

FFT

$H_3 = 0.3051\text{ }\mu\text{m}$
 $H_2 = 0.1741\text{ }\mu\text{m}$
 $H_5 = 0.0868\text{ }\mu\text{m}$

NMP = 1024 4.045 rpm 08/19/97 14:58:28
side 1 track 1

Figure 4.67: Showing a multi-track waviness plot from the previous work on electrofinishing

Factory: ERC
Type: nu207
Operation:

Machine: MWA 160B - NR. 6165
Operator: PJK
Shift:

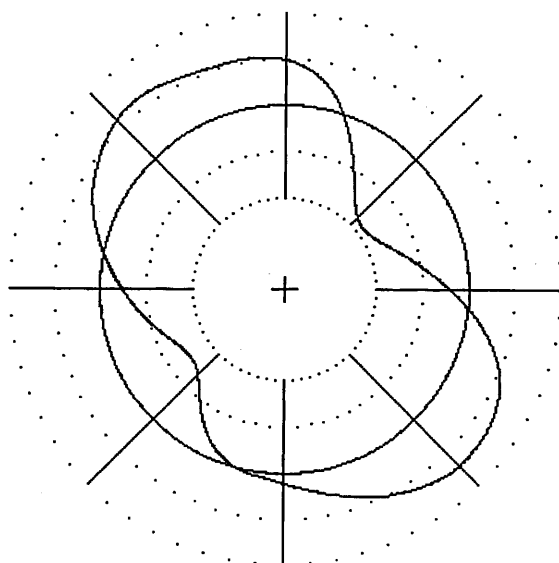
SKF

UNFILTERED POLAR DIAGRAM

Note: 350 SiC1200 + ECM 6sec

MS01

0.5 μm / Unit (20000)



NMP = 1024 3.986 rpm 09/01/97 09:37:40
side 1 track 1

Change MS with +/-
Screen - Configuration
Measuring range

LSC

Δr = 1.6391 μm
 X_m = 2.0719 μm
 Y_m = -4.3249 μm

FFT

H2 = 0.7104 μm
H3 = 0.1355 μm
H4 = 0.1253 μm

Figure 4.68: Multi-track waviness measurements from present work

Figure 4.67 & 4.68 clearly show that the low order waviness such as roundness are being severely affected by the electrofinishing process. The cause of this detrimental effect is believed to be the honing, which will be elaborated on later (see stone wear).

It is found that the medium and high band waviness are improved and are better than standard honed. Figure 4.69 below shows a more detailed analysis of the waviness presented in figure 4.68. Significantly the number of peaks removed by the filtering during waviness calculation shows far less peaks removed. This filtering is designed to remove peaks resulting from dirt or anomalous reading. This would indicate that the surface produced is much cleaner.

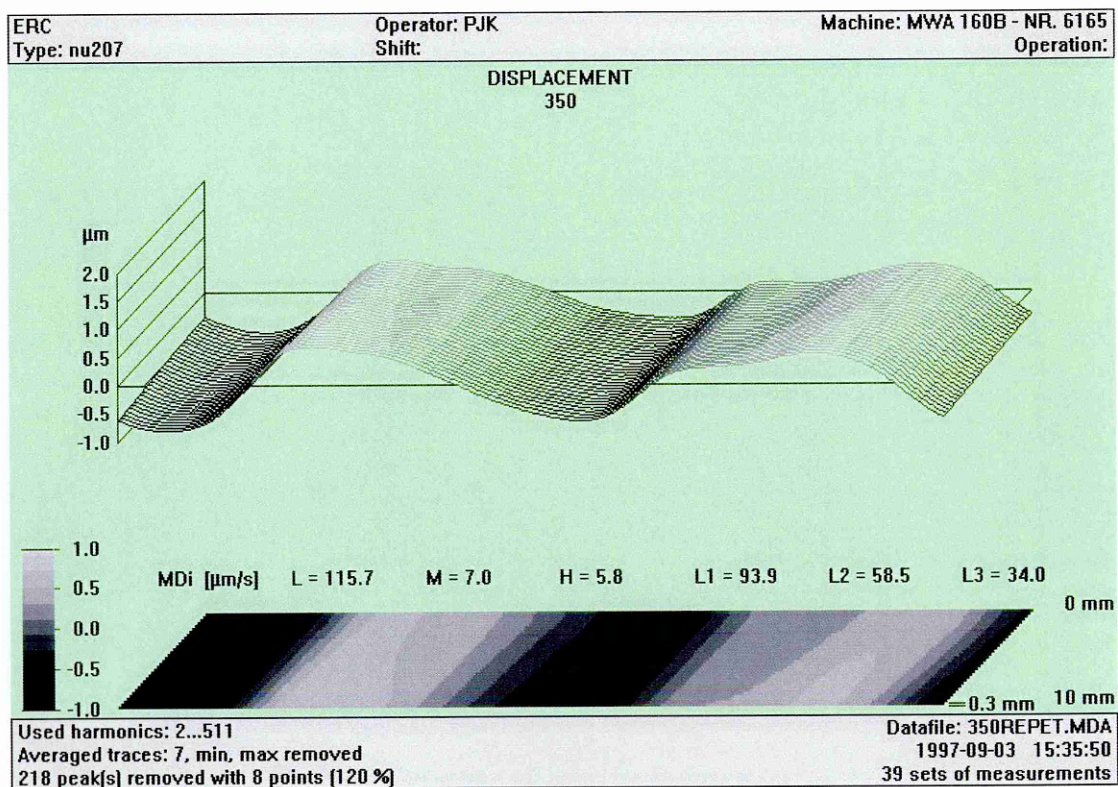


Figure 4.69: Showing the multi-track waviness measurement of an electrofinished surface using 1200 SiC for 6 seconds

Figure 4.70 shows an example of typical spikes, which are removed by the filtering which can be a result of dirt or damage on the bearing surface.

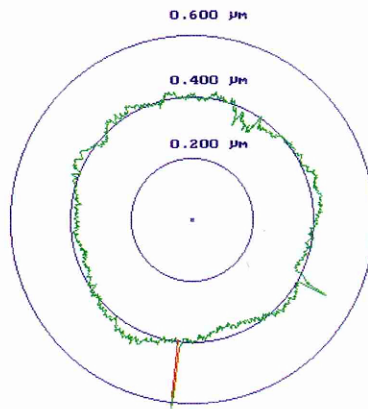
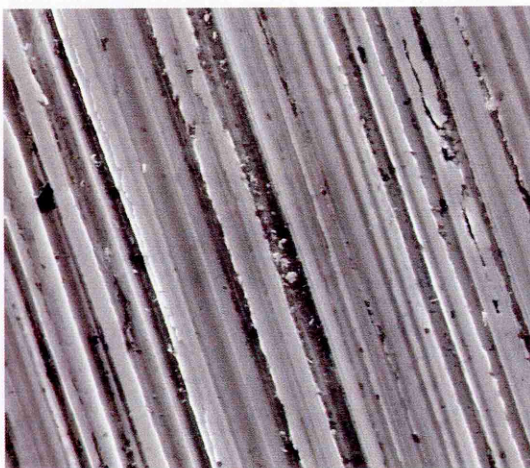


Figure 4.70: Showing spikes due to damage on the ring (from Noise and Vibration team at ERC)

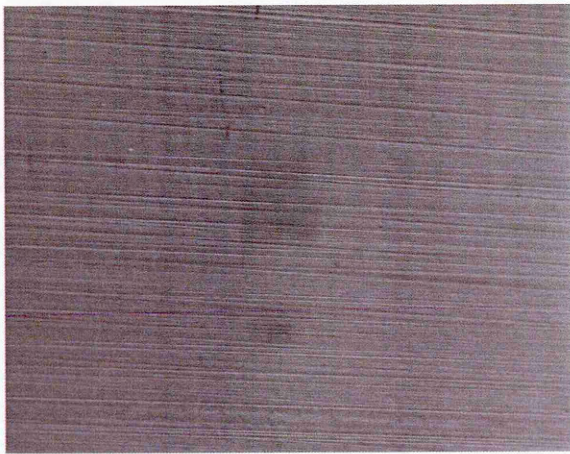
Further evidence for this cleaner surface is demonstrated by examination of this new low roughness surface by a scanning electron microscope (SEM). As a reminder, first is presented a standard honed surface, figure 4.71, which shows deep grooves and leafing as a result of the cutting process and cutting debris stuck into the grooves.



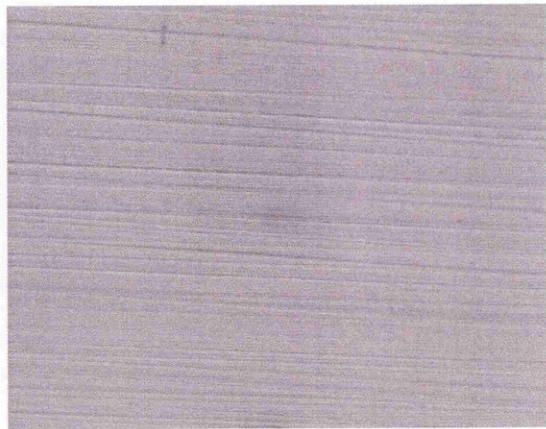
20 μm

Figure 4.71: SEM of honed surface

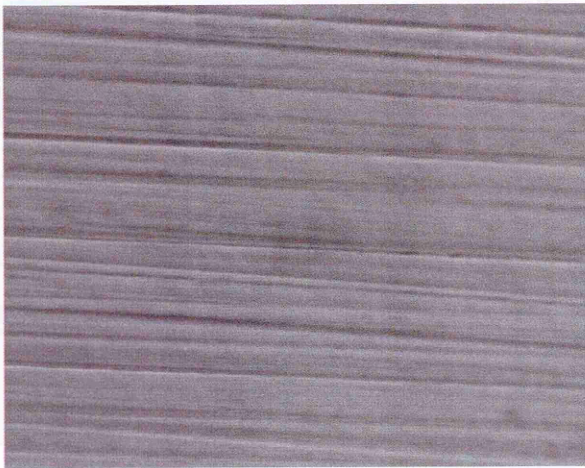
Below in figure 4.72 are SEM micrographs of a surface, which has been electrofinished using SiC for 5 seconds followed by 2 seconds of honing. This second honing step is to remove the thin black line left after the ECM current is switched off, but the honing also slightly improves the surface finishing by a burnishing action. The surface produced was found to be very much cleaner without honing debris and leafing compared to a normal honed ring.



50 μm



20 μm



10 μm

Figure 4.72: Showing SEM micrograph of electrofinished surface using 1200 SiC, 90 Amperes, 2000 rpm, 0.8 MPa, with 5 seconds electrofinishing + 2 seconds honing only.

Figure 4.73 shows the surface finish of a ring present in the SEM micrographs of figure 5.72. This surface had been produced by electrofinishing but with an additional 2 seconds of honing only. The surface is comparable with the results produced by the previous electrofinishing work, except the cross track profile is now much better.

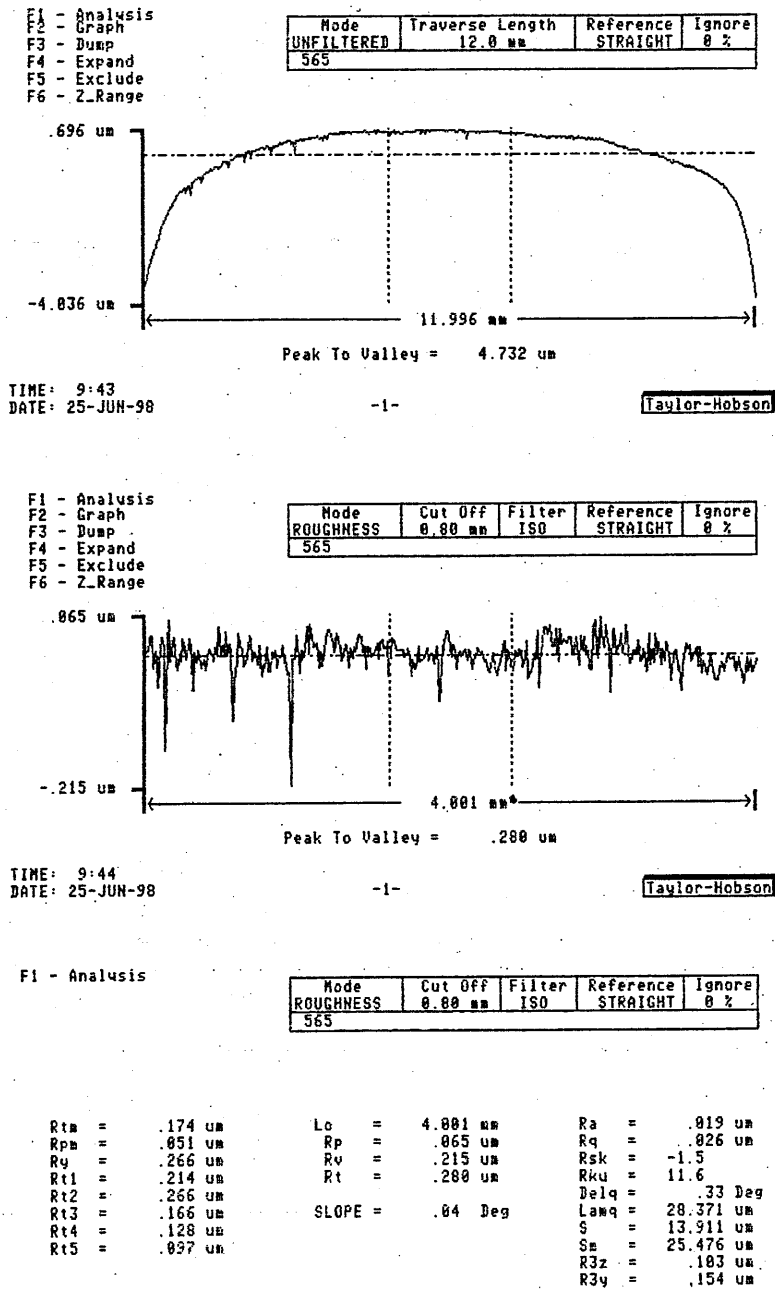


Figure 4.73: Showing cross track form and roughness of a surface produced by electrofinishing followed by 2 seconds of honing only

Table 4.9 below shows the additional surface finish improvement by allowing the honing stone to continue cutting for 2 seconds after the ECM current has been switched off.

Table 4.9: Surface improvements from a sequential electrofinished and superfinished step

Surface finish parameter	Electrofinishing 5 seconds	Electrofinishing 5 seconds + additional 2 seconds superfinishing
Ra μm	0.043	0.021
Rtm μm	0.320	0.191
Rt μm	0.560	0.344
Rpm μm	0.095	0.057
Rv μm	0.412	0.340
slope degrees	0.51	0.34
Rsk	-1.65	-2.2

4.6.1.2 Stone wear

The SC1200 04 60 VGL honing stone used in electrofinishing trials above was assessed for stone wear rate. Upon initial contact with the rough ground ring appreciable wear was found to occur. As the stone cuts the rough ground surface, both the cutting edges of the stone and the surface of the ring become smoother. Cutting or material removal then stops.

However, when a new ground ring is introduced its rough surface generates new cutting edges on the stone and cutting resumes. The stones therefore show a degree of self-dressing, the softer vitreous SiC stones would be expected to show greater self dressing ability.

The majority of stone wear occurs when the honing stone is first applied. The ratio of material removed to stone wear was found to be in the region of ~ 0.1 for the soft SiC stone. This was only a rough estimate using micron shims to measure the gap between the honing stone and workpiece before and after machining. However the stone wear was so large, greater than 300 μm per workpiece that it was clear the process was not economical purely from stone usage.

This ratio is low compared to the G- ratio of grinding processes (100 -1000) and suggests honing stone consumption for a combined process would be high. Typical superfinishing ratios G for honing are in the order of > 10 for conventional stones and up to 50 for superabrasive stones.

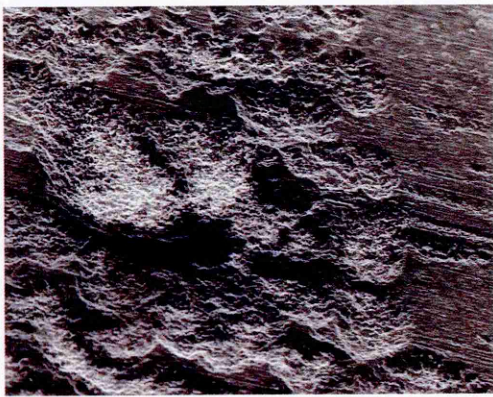
Such stones are used in production, possibly the extreme method of application of the honing stone in the combined process leads to this excessive stone wear. Honing is usually performed in neat honing oils and only occasionally in emulsions. The use of the water-based electrolyte without any lubricity would also contribute to this excessive stone wear.

4.6.2 Electrofinishing with other honing stones

In order to reduce the honing stone wear rate, which is unacceptable, different types of honing stones were tested, namely a harder grade SiC stone, sulphur impregnated SiC stone and a vitreous bonded CBN stone as follows:

- SC9 1200 05 50 VGL, a green SiC 3 μm grit size but with one grade higher hardness
- SC9 1200 04 60 VGL S, the same as the soft SiC stone but has been impregnated with S as a reinforcement for improved lubrication and wear resistance.
- Vitreous bonded #4000 CBN, (3 - 6 μm grit size) from Wendt Boart

The SiC-S treated stone (from Atlantic) has been tried and was indeed found to have much better wear resistance. However this has led to loading problems. It was also found that once the stone was loaded it was not self-dressed by the next incoming rough ring, and therefore machining remained non uniform with bands forming on the ring. The loading of the stone is most likely caused by incorrect machining parameters, the most critical of which is the pressure. Figure 4.74 shows spalling on the stone surface, which can happen if a stone becomes too loaded.



10 μm

Figure 4.74: SEM micrograph showing spalling on a heavily loaded SiC-S superfinishing stone.

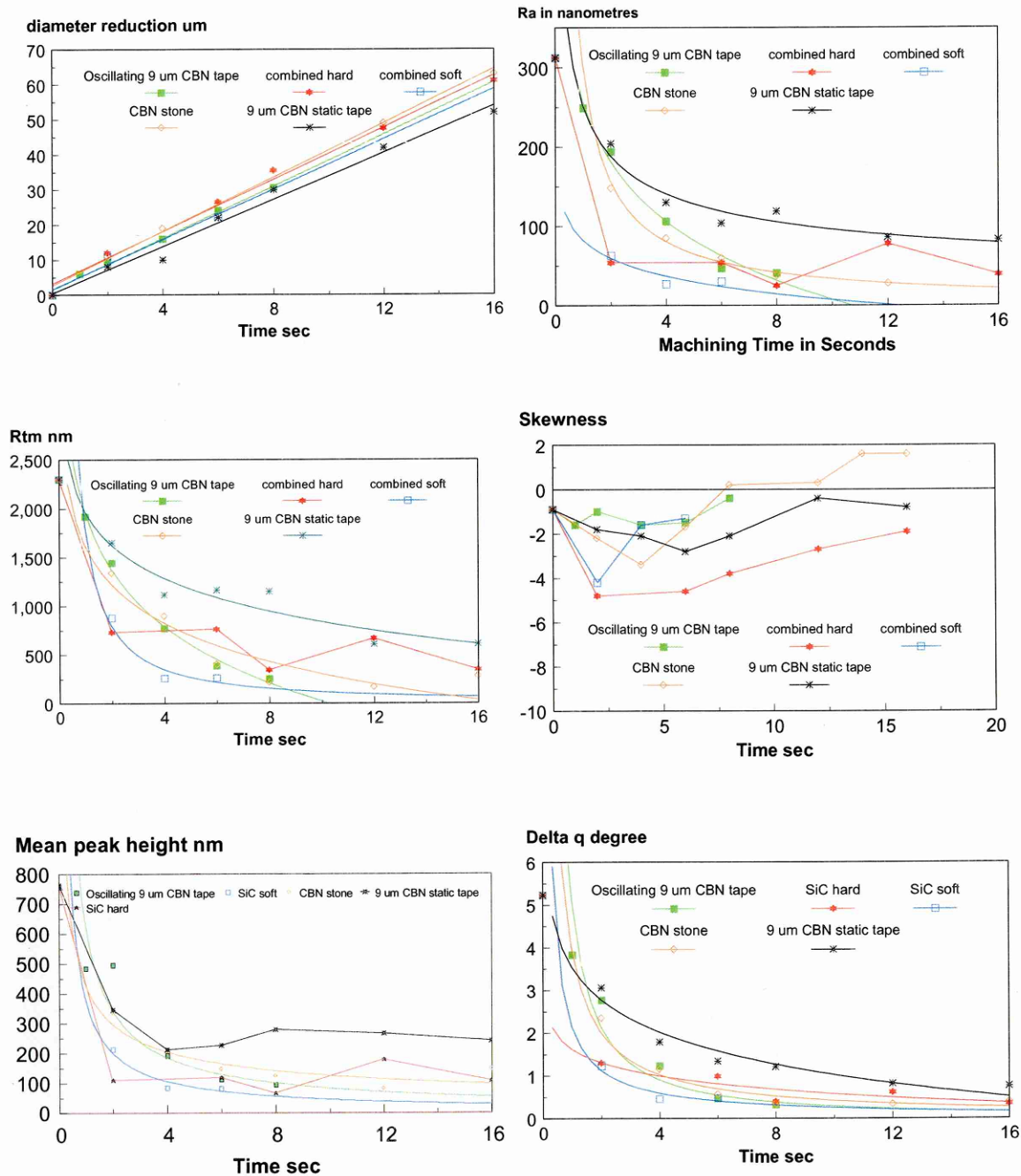


Figure 4.75 : Graphs comparing surface finishing and diameter reduction ability of electrofinishing using different abrasives

The graphs in figure 4.75 present for comparison, data on electrofinishing with the soft SiC stone, the harder grade SiC stone, and the CBN stone. Also included in the graphs are data on electrofinishing with static 9 μm CBN tape but also with oscillating 9 μm CBN tape.

Oscillation of the honing stone is very important for improved cutting and reduced stone loading, so it was important also to test oscillating superfinishing tapes for a fairer comparison. With the present machine it is difficult to apply an oscillating tape. This was accomplished by using the honing attachment and a preformed honing stone as the backing for the tape. The tape was stuck onto the honing stone. Conditions chosen used the same conditions as for the electrofinishing using honing stones, 50 Hz oscillation, 0.5 mm amplitude, 1.4 MPa and 2000 rpm workpiece speed

It can be seen that oscillation of the 9 μm CBN tape gives much improved uniformity in cutting and rate of surface finishing and the ultimate finish achievable is also better than when the tape is applied statically. After 8 seconds the finish is comparable with that of SiC electrofinishing. However a better method of applying the oscillating tape is needed with tape feed since the tape after use was completely black, indicating it was heavily loaded.

From the graphs it is clear that soft SiC gave the fastest improvement in surface finishing. However more data points are required. The hard SiC stone (SC9 1200 05 50 VGL) showed a similar behaviour to the soft SiC stone. However, application of the stone was more difficult.

The harder SiC stone was not able to conform to the cross track form so cutting was erratic. Measurements were taken on areas, which had appeared to be cut. The results show that the harder stone decreased the R_{tm} , Rpm and skew quicker in 2 seconds, while R_a and slope were reduced in a similar way to the soft SiC. However after 2 seconds the measurements became scattered and this coincided with a gradual increase in skewness i.e. the bulk material had started to be cut. The skewness increased slowly indicating that the honing was not working effectively at removing bulk material, and that the stone had become loaded.

A #4000 mesh vitreous bonded CBN stone was also found to be difficult to apply in order to achieve uniform cutting over the whole workpiece surface. A diamond dresser was used to achieve the correct stone profile, but even so cutting was not uniform over the workpiece and loading of the stone was a problem. Therefore roughness measurements were taken on cut areas.

4.6.2.1 Achievable waviness levels with Electrofinishing

Waviness has been highlighted as a concern when applying ECM, the application of honing with ECM certainly reduces waviness to at least similar levels to honing and also may provide the possibility to improve achievable waviness. See figures 4.76 & 4.77.

Application of static and oscillating 9 μm CBN tape with ECM gave higher waviness levels in the medium band compared to standard honing. This has been attributed to loading of the superfinishing tapes. Using a superfinishing attachment designed for tape superfinishing which would incorporate step or continuous feed should improve these results.

The CBN stone honing indicated that after 4 seconds medium band waviness levels are similar to honing and after 16 sec are much improved. However the actual shape of the rings have been distorted and lower band waviness levels are very poor. This is probably a result of the non-uniform cutting of the stone, resulting from loading of the stone and poor conformity between stone and workpiece.

The SiC stones showed that medium band waviness can be improved to a honed level and even better, although once again the shape is severely affected. The conditions chosen for electrofinishing were based on earlier work on electrofinishing using maximum oscillation frequency, maximum spindle speed and high cutting forces. The effect of changing these parameters was not investigated. Future work could then relax these conditions, which should improve ring roundness. Distortion of the ring during clamping should also be a consideration, as this would affect the lower waviness bands.

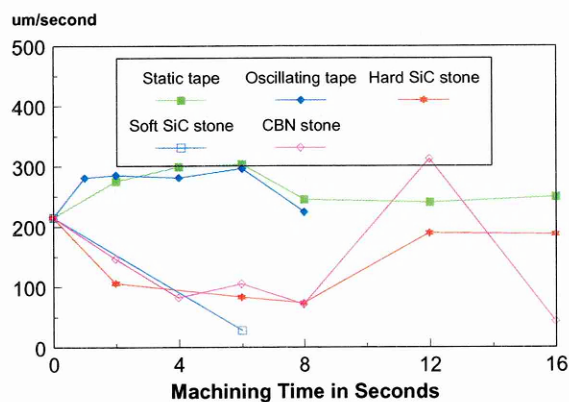


Figure 4.76: Single track medium waviness measurements comparing electrofinishing processes (N.B. honed quality 84 - 200 $\mu\text{m}/\text{sec}$)

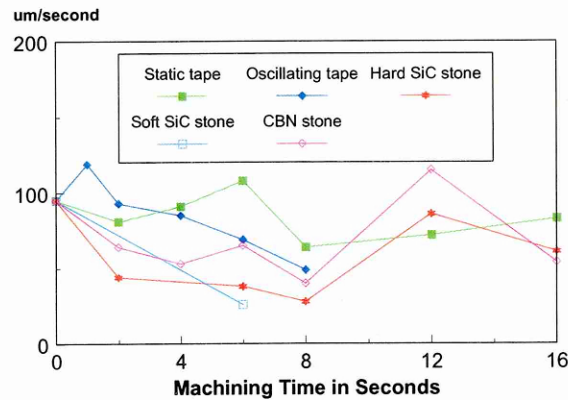


Figure 4.77: Single track high band waviness measurements comparing electrofinishing processes (N.B. honed quality 35 - 50 $\mu\text{m}/\text{sec}$)

4.6.4 Summary of the Electrofinishing Trials

The following conclusions can be made regarding the electrofinishing trials:

- Volumetric material removal rate of electrofinishing is dominated by the ECM process.
- Improvement of surface roughness achieved with the electrofinishing process is almost exclusively gained by the mechanical abrasive material removal process
- Honing stones are able to cut more effectively and for longer times when applied with ECM. This is likely to be a result of reduced loading of the honing stone, a type of stone dressing.
- Honing stone wear was found to be significant during electrofinishing. This level of wear is not considered applicable to high production applications. Attempts to improve stone wear by using harder grade stones result in loading and non-uniform surfaces being produced.
- The waviness quality is dominated by the mechanical abrasive process. Waviness quality in the medium band can be improved to standard honed quality or better. However the low order waviness is adversely affected, probably as a result of the high stone wear.
- Applying an oscillating superfinishing tape gave an improvement in rate of surface finishing and achievable surface finish compared to static tape. The surface roughness was sufficient for a bearing surface, although the waviness was poor due to tape loading. A stiffer oscillating tape attachment with step or continuous feed may show further improvements.

4.7 Electrolytic dressing of honing stone

This section is concerned with investigating an electrolytic dressing method to maintain stable cutting action of a honing stone and thereby improve the surface finish and waviness of bearing raceways. The work on electrofinishing showed that very good surface finishes, R_a 0.02 μm and R_{tm} 0.170 μm can be produced in a short time of less than 7 seconds. However there were concerns with regard to cost of an electrochemical system and the high rate of wear of the 1200 SiC honing stones, G ratio ~ 0.1 . The improvement in surface finishing was believed a result of a reduction in stone loading as a consequence of the ECM cleaning the raceway of metal debris and leafing and the self dressability of the soft vitreous bonded stone.

This section will look at a more direct method of electrolytic dressing of the honing stone, requiring simpler and less expensive equipment. The application of electrolytic dressing to the stone itself requires the stone to be conductive. This technique is closely related to another electrolytic dressing method called ELID (electrolytic In-process Dressing) where ceramics and metals are ground to very high surface finishes using fine grit metal bonded grinding wheels.

While trying to develop a more direct electrolytic dressing system a number of different bonded stones were assessed. The stones were provided by Wendt Boart.

- 1. Metal bonded CBN stone**
- 2. Copper filled resin bonded diamond stones**
- 3. Other conductive resin bonded stones**

Although this work was not particularly successful the results of testing are presented as it is believed further development could yield greater success. Work has been reported on ELID superfinishing using fine grit metal bonded wheels, which can control the aggressiveness of the cutting for material removal and surface finishing. The method presented here is more complicated since a grinding wheel has the entire circumference, which allows continuous in process dressing and cutting to be performed simultaneously, while a honing stone has one active area, which is in contact with the workpiece.

4.7.1 Metal bonded honing stones

An iron metal bonded #4000 mesh CBN honing stone supplied by Wendt Boart is shown below in figure 4.78. The CBN grits are clearly visible held within the metal bond. The CBN stone was first trued using an electroplated diamond rotary dresser to give the correct geometric form. Figure 4.79 shows the surface of the trued stone. It was not possible to identify any CBN grits on the surface as they were smeared over with metal or had been pulled out from the surface. A second operation to dress the stone is required to provide a cutting surface, which is more open with grit protrusion. For grinding wheels an alumina stick is often used to obtain grit protrusion. Figure 4.80 shows the surface of the honing stone after an alumina 600 grit stick was applied to the surface. Applying the alumina stick within the limited space of the test rig was difficult, and it can be seen that the alumina stick is eroding away the metal bond and some grit protrusion can be observed.

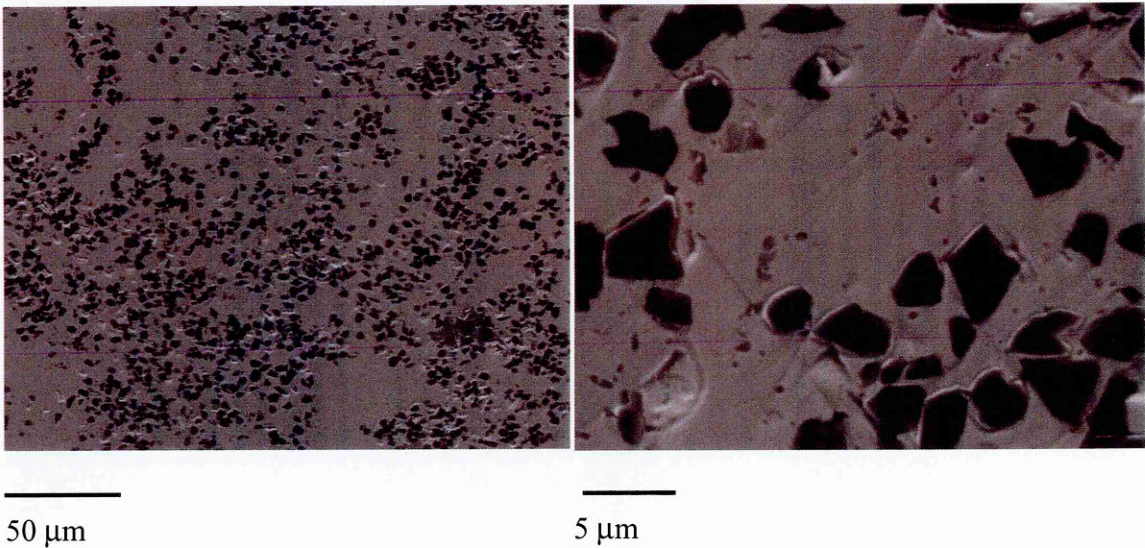
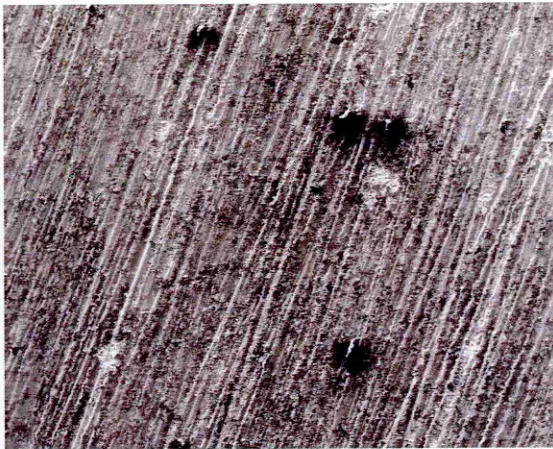
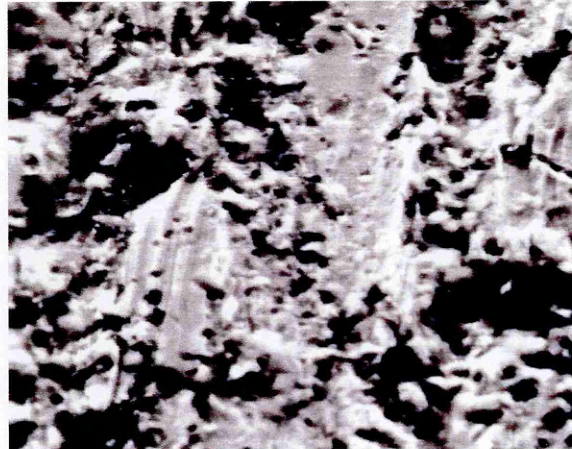


Figure 4.78: SEM micrograph showing metal bonded CBN honing stone, which has been metallographically prepared.



500 μm

Figure 4.79: Honing stone after truing with diamond dresser



20 μm

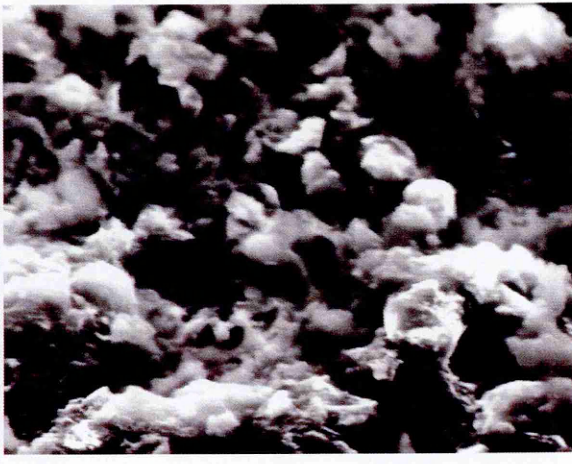
Figure 4.80: After dressing using alumina stick

These metal bonded stones are very hard and have a high wear resistance making them difficult to true. Figure 4.81 below shows the stone surface after electrochemical machining for > 20 seconds. With an electrolytic dressing system it may also be possible to true the stone in-situ, thereby maintain correct stone alignment. From figure 4.81 it is apparent that any inhomogeneities particularly non-conductive phases will not be removed, while the iron bond is removed this results in the appearance on the surfaces of hills. This is similar to the findings that MnS inclusions were exposed on the raceway surface during ECM.



500 μm

Figure 4.81: Truing by ECM



10 μm

Figure 4.82: Dressing using ECM

Figure 4.82 shows that ECM is also very effective in producing an open surface with grit protrusion. Here a diamond trued metal bonded stone was electrolytically dressed by a 10 Amp current for 1 second. CBN grit protrusion is very evident.

Even with the diamond rotary dresser, it has not been possible to correctly profile the metal bonded honing stone. In production vitreous bonded CBN has been used. These stones are trued with a rotary dresser, which puts an approximate profile onto the stone, which is then bedded in by honing say 20-30 rings until cutting occurs over the entire surface of the workpiece. However, the metal bond is very hard and the honing stone was not bedding in. This makes it difficult to determine achievable raceway surface finish quality, as machining does not occur over the whole surface.

4.7.1.1 Initial investigation of surfaces produced

Initial tests involved the present ECM test rig and the NaNO_3 electrolyte. The iron metal bonded stone was made the anode and the workpiece the cathode, so that material could be removed from the stone. A number of ways to apply the dressing current were tested. Since the stone was not correctly trued, information regarding surface finish capability and material removal rate can only be speculative.

Figures 4.83 show the raceway surface after honing only (no dressing in electrolyte) for a total of 15 seconds, at 4 bar, 2000 rpm workpiece speed, 50 Hz oscillation frequency. It is clear that grinding marks remain and the usual leafing.

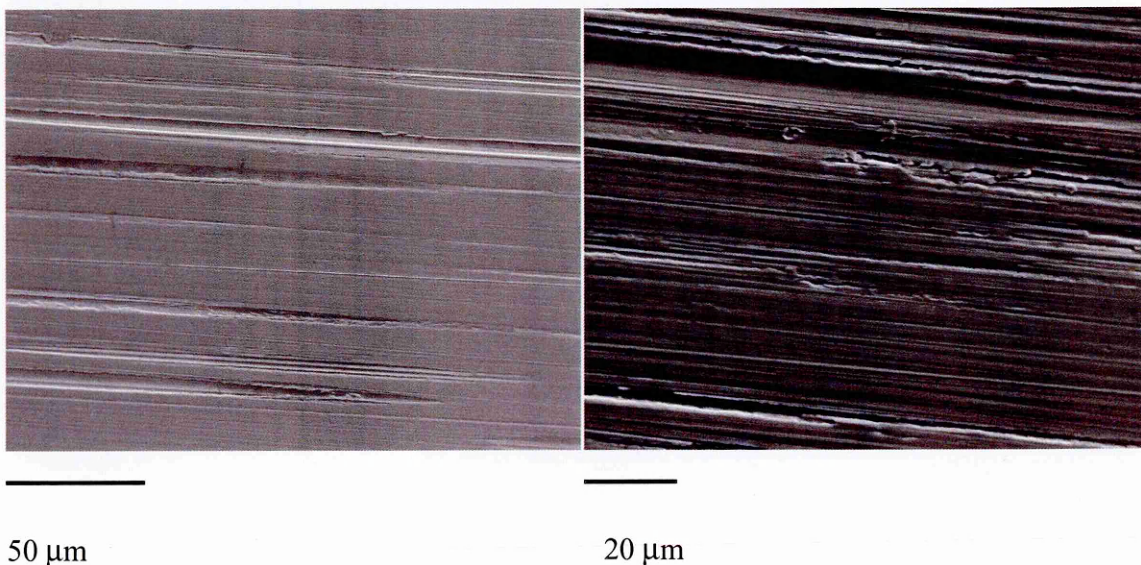


Figure 4.83: Surface of ring after honing without dressing

The first dressing method tried involved applying a 9 amps current continuously during the honing operation. Here only a very small voltage was drawn $< 1V$ indicating that the metal bond and ring were in contact. The material removal was also small as indicated by the presence of discontinuous grooves left over from grinding (figure 4.84). However the surface does appear to be smoother with less leafing.

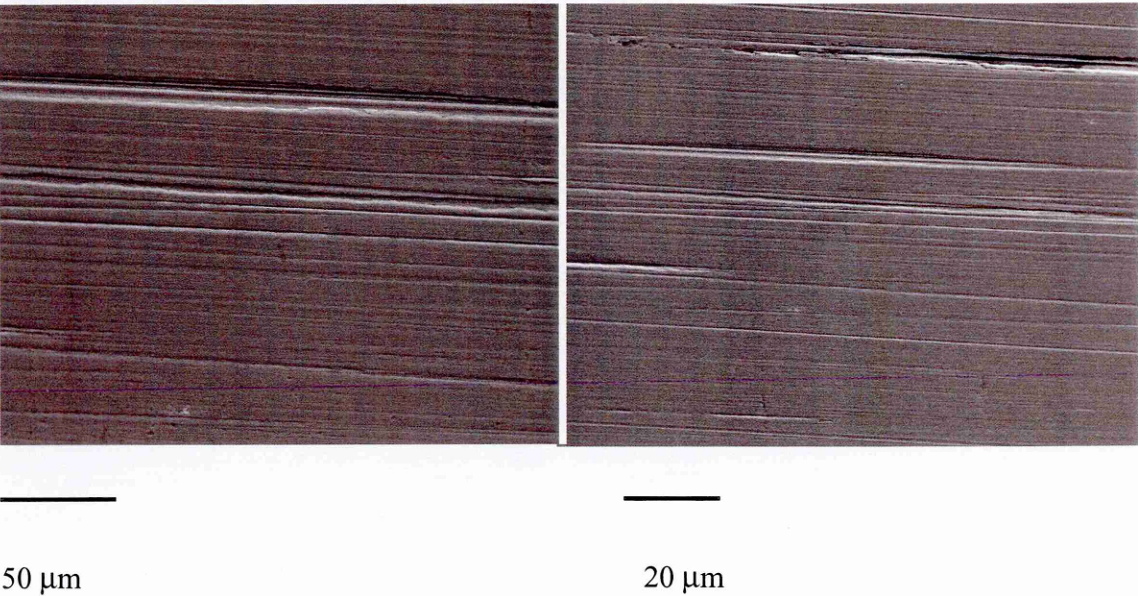
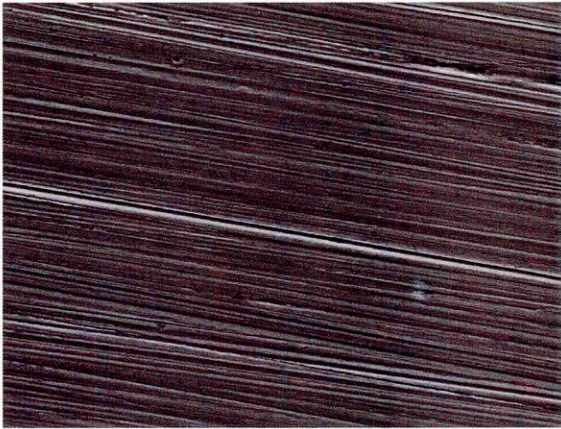
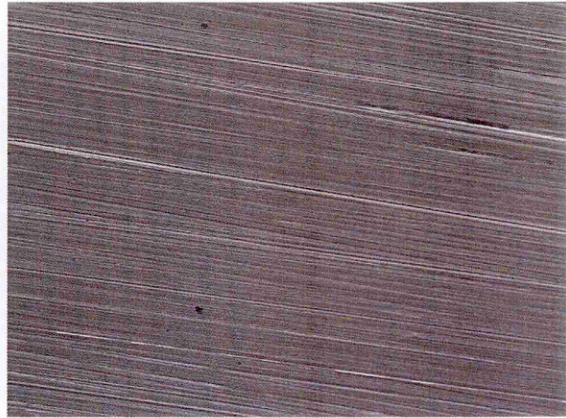


Figure 4.84: Honing with continuous electrolytic dressing

By actually separating the stone and ring and applying the electrolytic dressing in a form of electrochemical machining of the bond, free cutting grits protrude from the stone improving the material removal rate and producing a raceway surface that appears to be cut. Figure 4.85 shows more continuous grooves expected from a honing operation. During the dressing a pulsed dc current is applied. As the oxide layer builds up the voltage increases, although after the stone has been applied to the workpiece and is redressed the voltage level is back to its initial value indicating the oxide layer is removed during honing. This is why for a truly ELID process a continuous dressing system is needed. There is also evidence of microsparking (micro edm) occurring on the surface even when only a low current i.e. 10 amps is applied, figure 4.86. The spark damage is likely a result of poor inter-electrode gap conditions, i.e. electrolyte flow. Unlike electrofinishing, which employed a planar electrode, the honing stone has a curvature and a long gap width, which will affect the flow conditions.

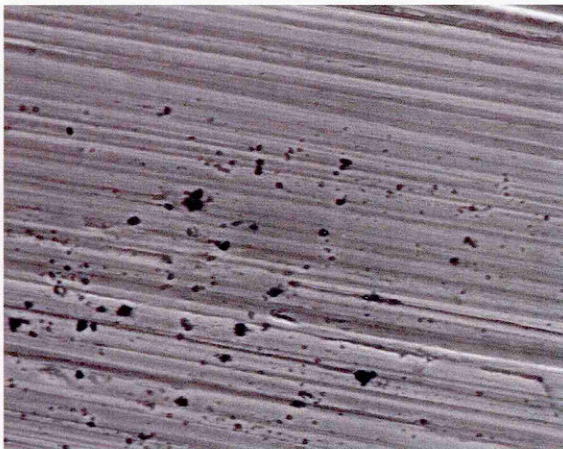


50 μm



20 μm

Figure 4.85: Honing with a discontinuous ECM dressing system



10 μm

Figure 4.86: Spark damage to surface of ring due to ECM dressing

At this point it is difficult to get an idea of surface finish, however the stones certainly cut more effectively when dressed electrolytically, allowing the protrusion of cutting points. The down side is that the surface finish may be adversely affected from a surface that appears cut, and not burnished as can happen with loaded stones.

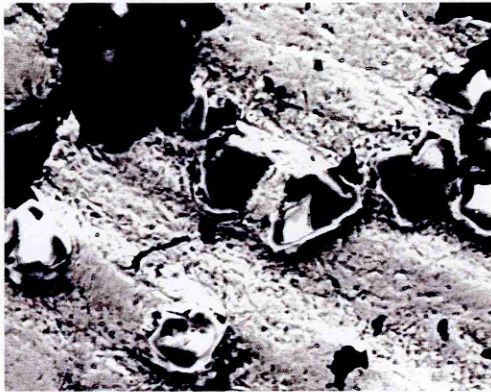
4.7.1.2 Summary using metal bonded stones

- 1) Metal bonded #4000 CBN honing stones are very difficult to true with the present set-up as a result of their high hardness and wear resistance.
- 2) An electrolytic dressing current is able to remove the bond and provide grit protrusion required for stable cutting action.
- 3) Honing with an electrolytic dressing system appears to increase the cutting ability of the fine grit stones.
- 4) The workpiece surface after honing with electrolytic dressing appears cut and not burnished.
- 5) Control of current is important to prevent sparking, which can cause damage to the bearing raceway.

4.7.2 Electrolytic dressing of conductive resin bonded diamond superfinishing stones

Electrolytic dressing trials using metal bonded stones were found to be complicated by the very high metal bond hardness. This meant that truing the stone over the large (10 x 14 mm) contact area could not be achieved. A rotary electroplated diamond dresser was provided for this purpose however it was still difficult to get the stones to "bed-in". It was therefore suggested to use a conductive resin bonded stone which is softer and easier to true, at least to investigate the possibility of electrolytic dressing.

Wendt Boart supplied two diamond stones of 2-4 micron and 4-8 micron grit sizes with a copper resin bond. Diamonds are not usually considered for machining ferrous materials because of high wear rates associated with carbon (diamond) diffusing into the ferrous workpiece surface. However at the pressure and workspeed used, diamond was believed to be suitable. Figure 4.87 is an SEM micrograph showing the metallographically prepared 4-8 μm diamond stone. Diamond grains are clearly visible as well as the copper resin bond.



5μm

Figure 4.87: Metallographically prepared surface from 4-8 micron diamond conductive resin bonded superfinishing stone

4.7.2.1 Electrolytic dressing behaviour of copper resin bonded superfinishing stones

Characterization of the surfaces produced has been made difficult because of spark damage. Using high frequency pulsing with low current levels has minimized the damage. The formation of an insulating layer or a barrier layer is again important as in ELID grinding.

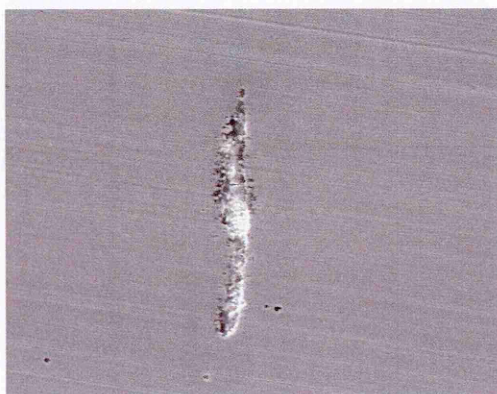
The copper bond was found to electrochemically dissolve when a current was applied, and sometimes the copper would plate-out on the workpiece. A barrier layer could still be formed by first allowing iron to load the stone and then electrolysing the stone, a black Fe oxide/hydroxide layer would form on the stone.

Monitoring the voltage also provides evidence of the existence of an insulating layer. The oxidation of the loaded iron resulted in the voltage increasing to maintain the current flow. When the stone was applied to the ring with the current still on, the voltage would drop quickly as the inter-electrode gap decreased. Depending on the current level, duty cycle and applied force, the voltage level would either find a stable level (fluctuate about level) or drop to ~ 0 Volts which would indicate that any layer of higher resistance has been removed and that the metal workpiece and conductive stone are in mechanical contact.

Obtaining good surfaces with little sparking was found to be easier as the surface became smoother. It is believed that the insulating layer is continually being abraded away by the workpiece while being repaired by the current, a balance must be maintained to achieve good surface finishes. Once the layer has been removed copper plate-out can occur and sparking.

A wide range of surface finishing data has been obtained, generally after much longer machining times (minutes) with many re-dressings, in order to maintain an insulating layer.

After 30 seconds superfinishing with 2-4 μm diamond a surface finish of R_a 15 nm, R_{tm} 346 nm, R_{pm} 45 nm and slope 0.51 degrees was measured. However these figures are distorted by the sparking which produces deep valleys, see figure 4.88. When sparking is kept to a minimum surfaces have been produced with R_a 15 nm, $R_{tm} \sim 100$ nm, R_{pm} 32 nm and slope 0.11 degrees. These surfaces are very consistent in quality, R_t (the maximum peak to valley in measurement profile) is also very low < 150 nm. The machining time for such a surface is much longer than any allowable cycle time but at least demonstrates the potential surface finishing of these diamond stones when sparking is kept to a minimum.



20 μm

Figure 4.88: Spark damage to ring surface originating from MnS inclusions

4.7.2.2 Summary using copper filled resin bonded stones

- 1) Sparking between stone and workpiece has resulted in non-optimum machining conditions.
- 2) Sparking has been associated with a break down of the oxidized layer on the stone. This can be caused in two ways
 - i) a chip can cause a short circuit by breaking through the barrier layer and touching underlying conductive metal bond
 - ii) damage to the insulating layer provides a path of least resistance for the current, so rapid electrochemical dissolution occurs producing heat and gases as by-products, which can lead to sparking in the very small gap.

- 3) Better design of the superfinishing stone is required. During electrochemical dressing the copper bond dissolved and did not form a precipitate or oxide layer on the stone surface, but instead tended to plate out on the workpiece. Without the insulating layer sparking arose. Only when the loaded iron was oxidized did better surface finishing occur since the iron forms an iron oxide/hydroxide layer.
- 4) Electrolyte flow is important to prevent sparking. The highly conforming contact area between the stone and workpiece makes it difficult for the electrolyte to penetrate through the gap. A smaller stone size has made it easier and maybe multi nozzles are required to ensure that the electrolyte is within the gap.
- 5) Generally the electrolytic dressing appears to improve the stability of cutting for the fine grit stones providing the improvement in surface topography.

In conclusion an electrolytic dressing system is certainly a possible method of producing high quality surfaces. From the literature it is clear that electrolytic dressing systems are being considered to achieve very high quality surfaces. These include techniques like ELID grinding and more recently ELID superfinishing using oscillating honing wheels. ELID grinding using conductive resin bonded wheels has also been reported¹⁵. However an electrolytic dressing system for superfinishing stones has not been addressed as yet in the literature.

4.7.3 Electrolytic dressing using other conductive honing stones

Three different stones were specially made by the superabrasive supplier Wendt Boart. The stones were all #4000 mesh (3-4 micron) diamond grits based on a resin bond. To provide the conductivity required for the electrolytic dressing process, metal fillers were added to the resin. Different types of metal fillers were investigated:

- 1) Aluminium
- 2) Iron
- 3) Mixed aluminium and iron (50/50)

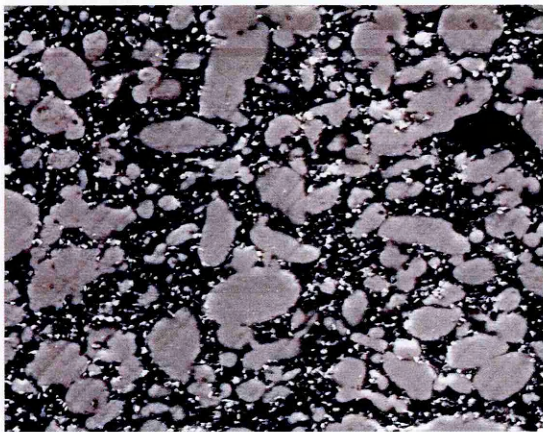
The metals have different electrochemical properties, iron is the standard metal chosen for ELID grinding work, while aluminium was considered because of its faster oxidation rate and expected harder, more wear resistant oxide.

The stones were first characterized by sectioning and metallographic investigation. Figures 4.89, 4.90 & 4.91 are scanning electron microscopy (SEM) micrographs showing the different stone structures.

Figure 4.89 shows the aluminium bonded resin stone; clearly visible are large platelets of Al metal separated by the resin. Within the resin are the diamond cutting grains. The electrolytic action will then oxidize or dissolve the metal component while the diamond grains are held firmly by the resin.

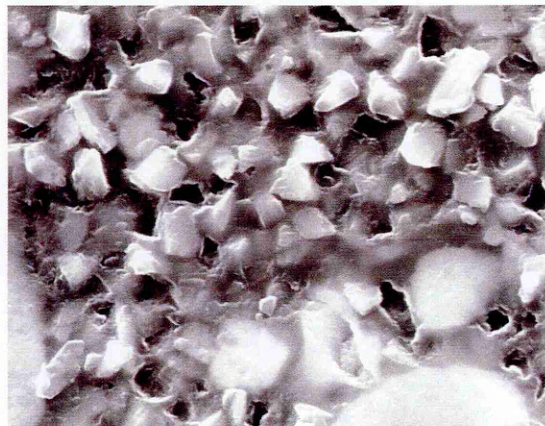
Figure 4.90 shows the iron resin bonded stone. The stone is non homogeneous; there is a thick outer compact skin but a less compact centre region, see figure 4.92. It appears that very fine size carbonyl iron powders were used (~2 microns) to make this stone. These particles are surrounded by the resin preventing diffusion and consolidation. This results in a soft stone, which is very reactive because of the very small size of the pure iron powder.

Figure 4.91 shows the mixed Fe/Al stone, which appears like a combination of the two metal filler types.



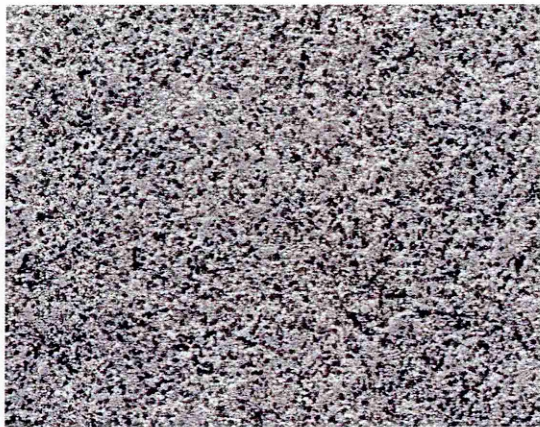
50 μm

Figure 4.89: SEM of Aluminium resin stone
blocky lumps of Al metal



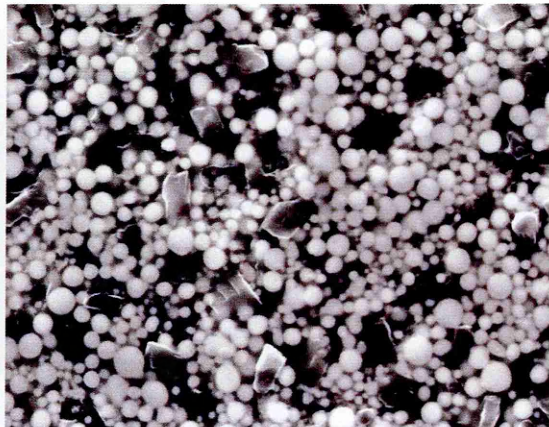
5 μm

Figure 4.89a: Al resin stone at
higher magnification diamonds held
within resin



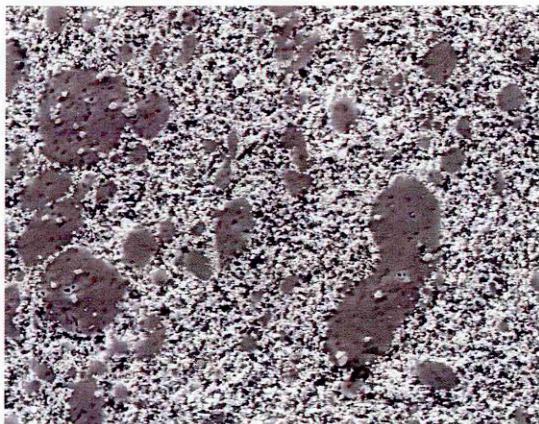
50 μm

Figure 4.90: SEM of iron resin bonded stone



5 μm

Figure 4.90a: Iron resin bonded stone (white Fe powder)



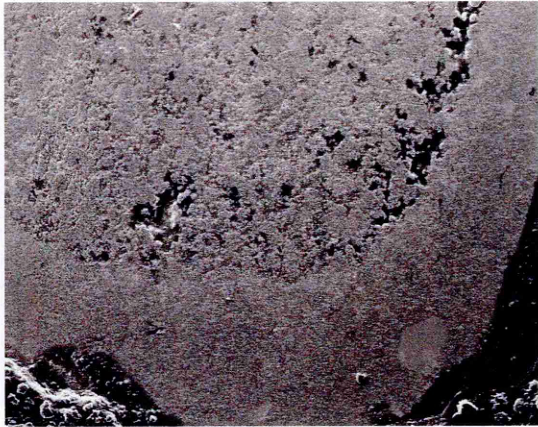
50 μm

Figure 4.91: SEM of Al/Fe resin bonded stone



5 μm

Figure 4.91a: Al/Fe resin bonded stone



500 μm

Figure 4.92: SEM image of Fe resin bonded diamond stone showing inhomogeneous structure

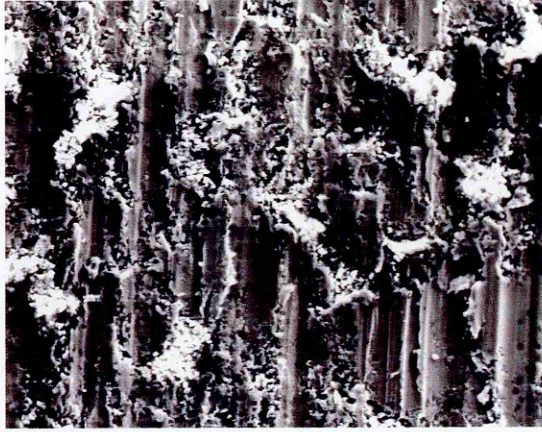
4.7.3.1 Truing

Most ELID work is performed on iron bonded grinding wheels although new work is now appearing using conductive resin bonded wheels for improved surface finishing. Metal bonded superfinishing stones were also first tried but the bond was too hard to true accurately on the ELMARI test rig. Resin bonded stones are much softer and easier to true. It was found that the iron resin bonded stone was the softest while the Al resin bonded was slightly harder. Figures 4.93 & 4.94 show the trued surface of the Fe and the Al resin bonded stones respectively one day after truing.



50 μm

Figure 4.93: Trued Fe bonded stone indicating high chemical reactivity



50 μm

Figure 4.94: Trued Al resin bonded stone showing the smearing of the soft Al and discontinuity associated with diamond grains

The Fe resin bonded stone shows very high reactivity with a high rate of oxide growth. This is because of the very small pure iron powders, which have a large surface area.

The Al resin bonded stone shows considerable less oxide formation. Al forms a thin oxide layer almost instantaneously, this compact layer preventing further oxidation. It was also seen that the soft Al metal smears over the surface. Also visible are discontinuities related to diamond agglomerates.

4.7.3.2 Pre-dressing

Before machining can begin, the stone must be pre-dressed to form an oxide layer that will self repair and self regulate itself. This oxide/insulating layer must provide electrical insulation between the stone and the workpiece (preventing sparking), prevent chip loading and must wear slowly to provide grit protrusion.

Considerable problems arose while trying to make the electrical connections to the stones. The Al stones cannot be soldered, so a mechanical clamping connection was used. However it was found that electrochemical reactions were occurring between the copper electrical cable and the Al stone, particularly in the presence of the electrolyte.

A second problem was trying to control where the current flows. The test rig is made totally from stainless steel to avoid corrosion problems but this means that everything is conductive. The stones were electrically insulated from the honing stone attachment. However as soon as the electrolyte washes the parts, conductive paths are formed between

the stone and test rig. The effect became greater as the insulating layer on the stone is formed. As the resistance between the stone and the workpiece increases, the tendency for stray currents to flow to other parts of the test rig increases.

Methods to overcome these problems, such as insulating sleeves covering the stone, silicone sealant, epoxy resin dip coating and even electrical insulating tape had limited success. A future solution would be to make the stone clamping part of the honing stone attachment from a plastic/insulator.

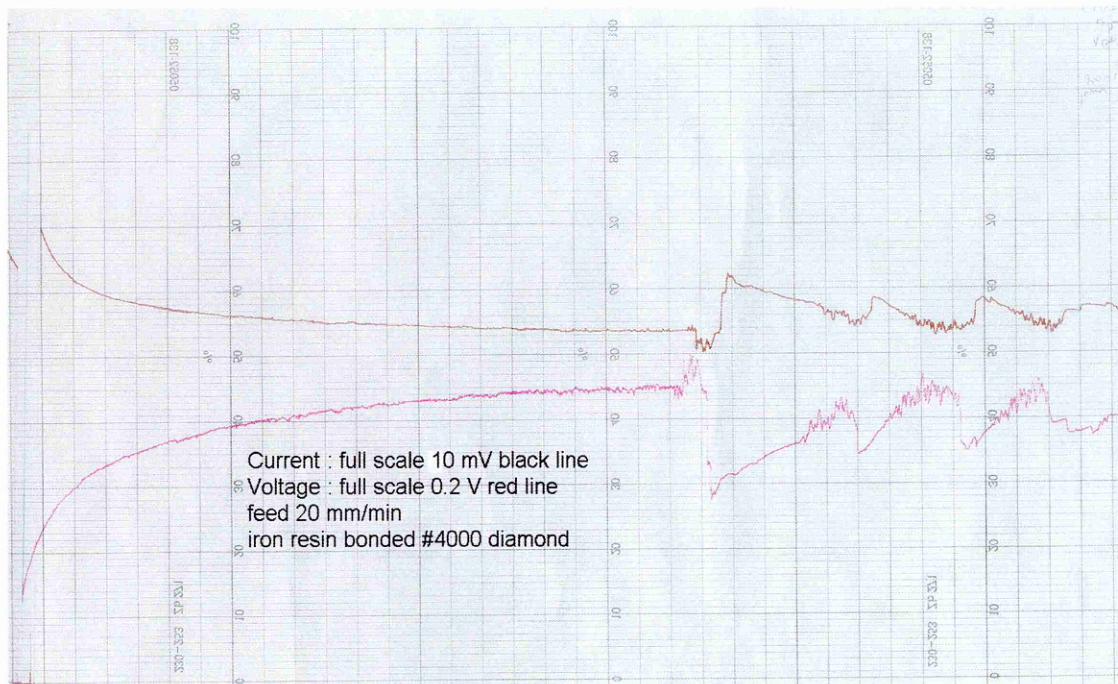
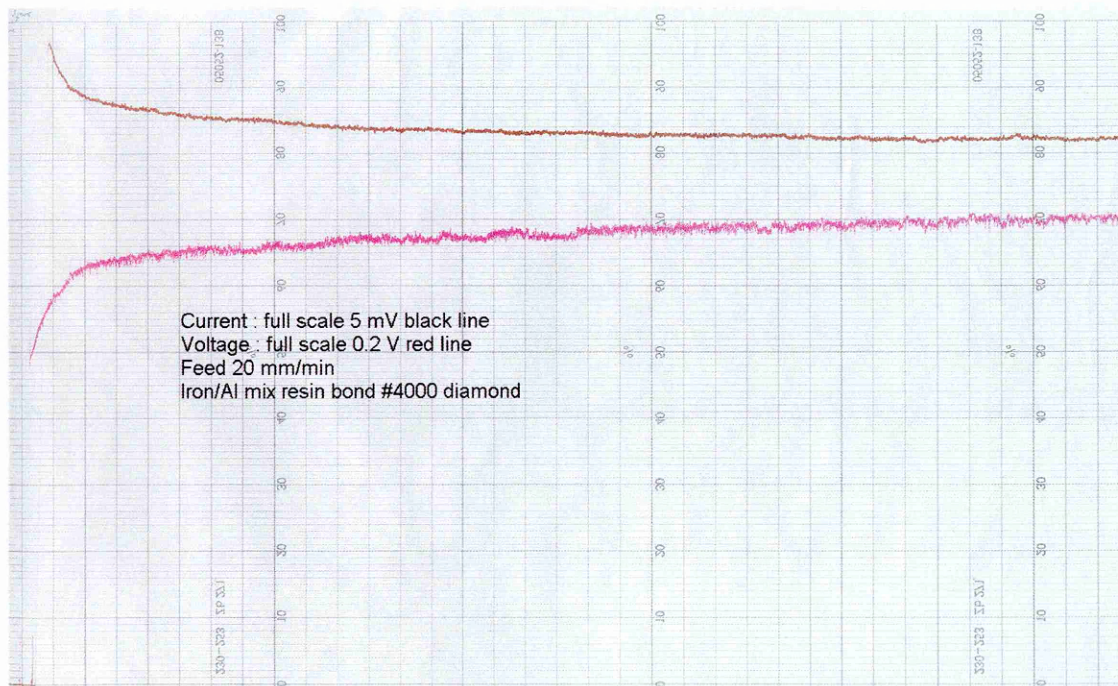
The stones were electrolytically dressed and their characteristic voltage/current curves recorded, figures 4.95, 4.96 & 4.97, along with SEM micrographs of the dressed surface, figures 4.98, 4.99 & 4.100.

To avoid sparking conditions which is indicated on the 10 Amp, 90V edm power supply used (from concept edm), initial work has been done using the on-off pulse set at 6 - 0 and the lowest possible current, 0.5 Amps.

For the iron resin bonded stone, the V-I characteristics are as expected, see figure 4.95. The voltage increases steadily as an oxide layer is formed and grows on the stone surface. The current level is found to decrease steadily until an approximate constant value is achieved. Instability is found to occur after prolonged dressing, and is believed to be caused by excessive oxide formation, which can be broken off by the electrolyte flow damaging the oxide layer. The SEM micrographs (figure 4.98) of the dressed Fe resin bonded surface shows a very rough surface with large oxide growths. Cracks are also visible resulting from rupture of the oxide layer. At higher magnification diamond grits are visible but also a network of holes, which appear to coincide with dissolved iron powder particles.

The Fe/Al mix resin bonded stone showed intermediate behaviour, figure 4.96, with the current and voltage in-between that of the Fe and Al resin bonded stones. Figure 4.99 shows SEM micrographs of the dressed surface shows again a mixed behaviour from that of the Al and Fe only resin bonded stones. Al, C, and O were detected but very little Fe.

The Al resin bonded stone showed a very rapid rise in voltage and an initial decrease in current, figure 4.97 as the Al forms a compact thin insulating oxide layer. The voltage then stays at the maximum 90 V. The current is seen to vary considerably, believed to be a result of stray currents. The SEM images show an open surface structure full of porosity resulting from the dissolution of the irregular, blocky Al metal filler. Al is still visible on the surface, generally inside holes. Qualitative composition analysis showed the presence of Al, O and diamond (C)



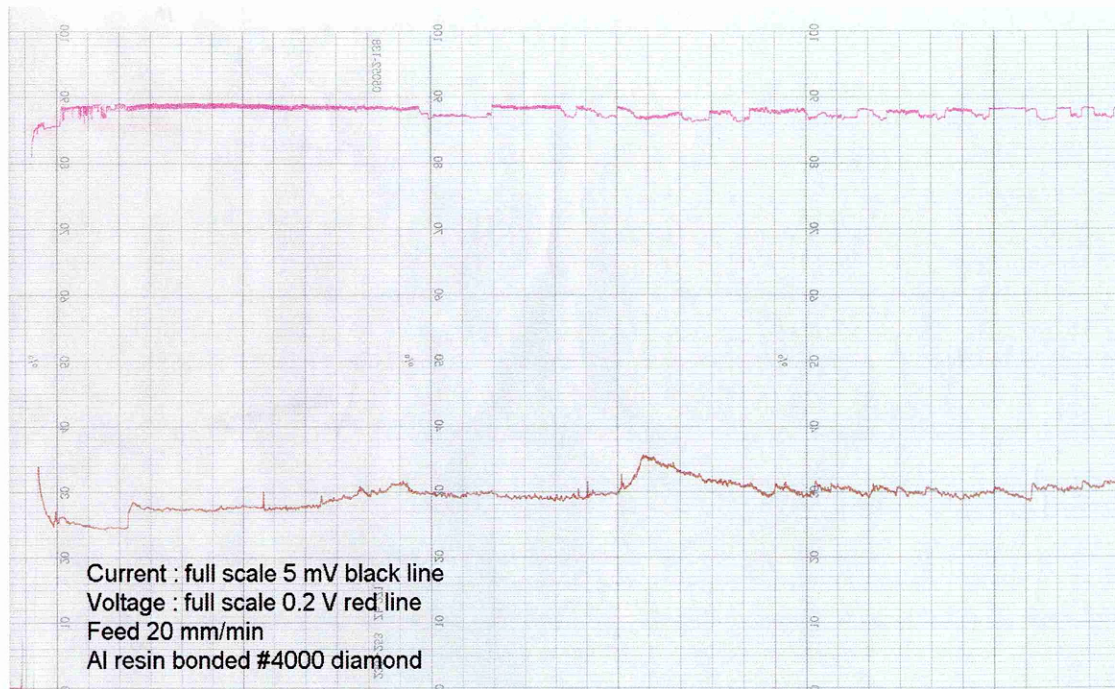
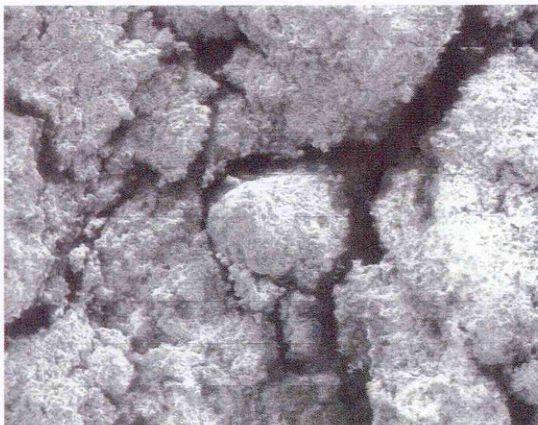
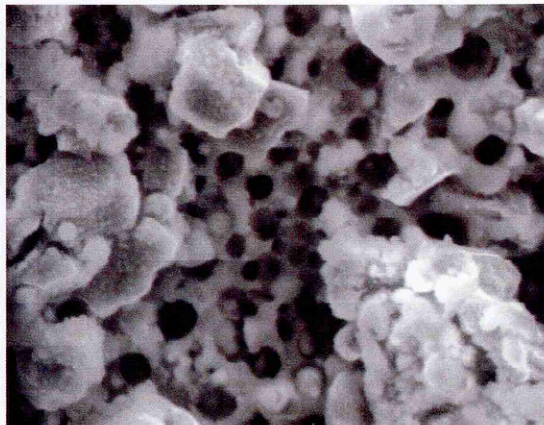


Figure 4.97: V - I characteristics during pre-dressing of the Al resin bonded #4000 diamond stone, Current ~ 0.5 A, voltage ~ 90V



50 μm

Figure 4.98: Electrolytically dressed Fe resin bonded stone



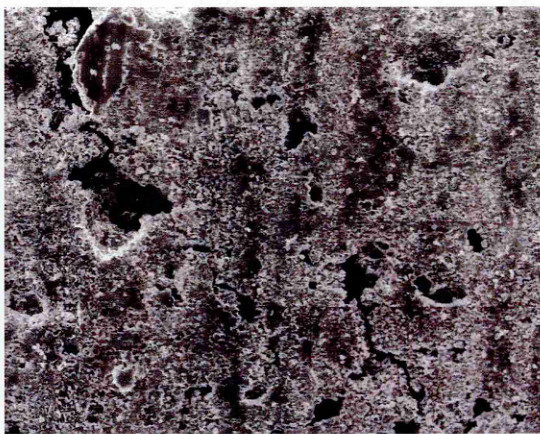
2 μm

Figure 4.98a: Dressed Fe resin bonded stone



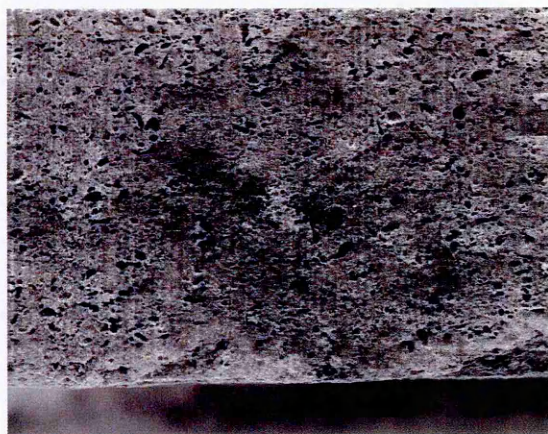
500 μm

Figure 4.99: Electrolytically dressed Al/Fe resin bonded stone



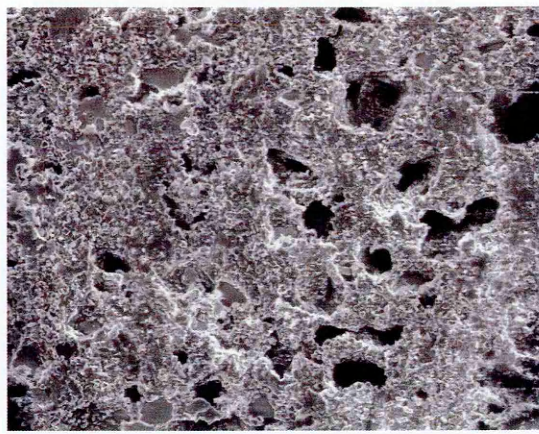
50 μm

Figure 4.99a: Dressed Al/Fe resin bonded stone



500μm

Figure 100: Dressed surface of Al resin bonded stone



50 μm

Figure 100a: Dressed Al resin bonded stone at higher magnification

4.7.3.3 Sparking & hydrogen embrittlement

There are two main concerns with applying the electrolytic dressing as described above:

Sparking

Work did not progress far enough to evaluate whether sparking during the honing operation could be prevented. It was found that the oxide layer could form an effective barrier, preventing the workpiece and stone coming into contact. This was indicated by the voltage maintaining a high level.

Hydrogen Embrittlement

The method presently being investigated makes the workpiece the cathode (- electrode) and the conductive superfinishing stone the anode (+ electrode). Applying a current results in dissolution and oxidation of the metal filler in the bond. This oxide layer is self-regulating in thickness and prevents cutting chips loading the stone surface, while maintaining fresh grit exposure for stable cutting conditions. The disadvantage is that hydrogen is produced at the workpiece surface, which could cause hydrogen embrittlement.

4.7.3.4 Summary of other metal filled resin bonded stones

- 1) It is possible to apply an electrolytic dressing to metal resin bonded superfinishing stones. Dressing characteristics (V/I behaviour) was similar to ELID grinding reports.
- 2) The Al filler oxidizes very fast but does not form a thick oxide layer.
- 3) While the Fe filler is very reactive because of its small particle size and purity. During electrolytic dressing it forms a thick oxide, which grows and flakes off, suggesting the current level was too high.
- 4) The diamond grits are held within the non-conductive resin, so it is possible to dissolve the metal filler away giving an open porous surface structure.
- 5) Hydrogen embrittlement is a concern for electrolytic dressing of superfinishing stones applied in the way described above. Although the exact extent is not known and alternative solutions are available.
- 6) The limited results on surface finish achieved indicate very high quality surface can be produced although the cycle times are expected to be too long for a production process for bearing raceways greater than 20 seconds.

4.8 Electrofinishing with water soluble synthetic lubricant

Applying a more direct form of electrolytic dressing to enhance honing was presented in the last section. This work was dropped because of problems and risks associated with sparking, hydrogen embrittlement but also cycle time. It was decided to concentrate on making electrofinishing work. The work on electrofinishing showed very fast surface finishing and good medium band waviness. The main problems were associated with the honing operation made difficult because of the use of the electrolyte as the lubricant/coolant. Most honing operations use neat honing oils with high lubricity. The use of the electrolyte gave high stone wear for the softer SiC stone, but loading problems if harder grade stones were used to improve the stone wear. This high stone wear is also believed responsible for the poor low band waviness. To allow the use of the harder stones the use of a water-based lubricant was considered to provide the lubricity. The lubricant company Cimcool Industrial Products B.V. were approached to give advice on a suitable lubricant for the application.

4.8.1 Water soluble synthetic lubricant

Although synthetic lubricants do not have the lubricity performance of oils (although becoming more competitive) they are generally easier to maintain i.e. fewer problems with bacteria, odours, mist, filtering and are more environmentally friendly.

The lubricant provided by Cimcool was based on an existing synthetic metalworking fluid used in machining of aluminium, which has excellent lubricity. Tests were performed using only the lubricant agent without the rust inhibitors and other additives (e.g. bactericide) found in the fully formulated metalworking fluid.

The lubricant additive is based on a polyoxypropylene-polyoxyethylene block copolymer. This lubricant is fully dissolved in the water until a certain temperature called the cloud point at which time the lubricant comes out of solution forming small oily droplets, which provide the lubricity. The cloud point can be changed by using different block copolymer (different number of carbon chains) so that the lubricant can be tailored to provide lubricity at the cutting temperature in the cutting zone.

Figure 4.101 below shows schematically the behaviour of the synthetic lubricant compared to soluble oil. At the cloud point the lubricant begins to form oily droplets and lubricity increases, at higher temperatures more oily droplets are formed and lubricity increases further. However above a certain temperature, the lubricity falls again as the oily droplets re-dissolve back into solution.

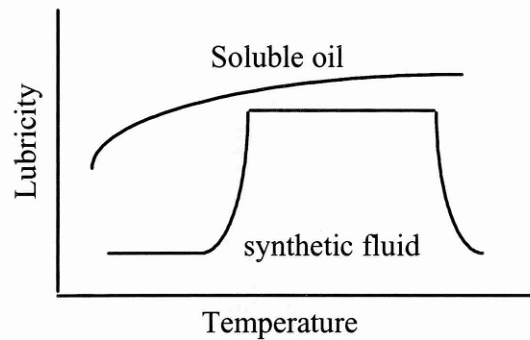


Figure 4.101: Schematic showing lubricating behaviour

Three lubricants which activate at different temperature (23 °C, 40 °C and 57°C) were initially assessed. The lubricant designed to activate at 57 °C was most effective. The true activation temperature of the lubricant was found to be lower because of the addition of the 30 wt. % NaNO_3 . See figure 4.102 below.

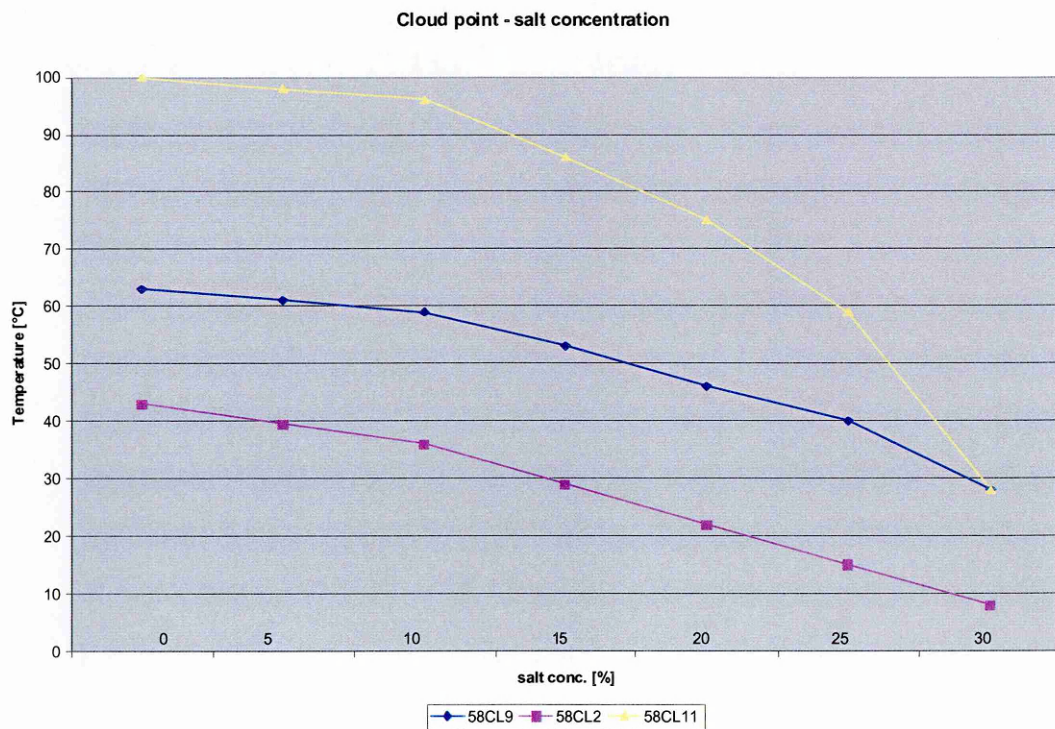


Figure 4.102: showing how cloud point changes with salt concentration (Courtesy of Cimcool)

4.8.2 Electrofinishing using SiC with lubricant added

Electrofinishing was performed using the softer grade 1200 SiC 04 60 VGL with 0.5 % lubricant added to the electrolyte. The stone wear rate did not improve but fluctuated ~120 - 300 $\mu\text{m}/\text{ring}$ and perhaps was slightly worst because of the better cutting resulting in more self-dressing and consequentially higher stone wear. This resulted in an improvement in the surface finish and removal of the ground layer, but also indicates that the stone grade was too soft.

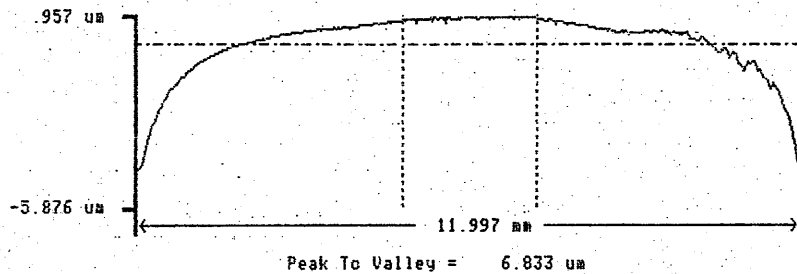
The harder SiC stone 1200 SiC 05 50 VGL performed more consistently with lower wear rate ~ 100 μm . However its performance fluctuated and did not always totally remove the ground layer. Some stone loading was still evident but much less than before.

Figure 4.103 below shows the cross track profile and roughness of an electrofinished ring using the hard SiC stone. There can be seen a number of deep 0.3 μm Rt scratches which is typical of a surface electrofinished with SiC. These scratches give a negative skew, a requirement for a bearing surface. There also appears to be slightly less cutting on the right side of the track which indicates either some loading or a problem with the honing stone attachment. The attachment is designed to give an oscillation but this is a linear oscillation while the track actually has a logarithmic profile.

The results indicate that the lubricant is needed to allow more stable cutting but also to allow harder honing stones to be used, which lowers the initial stone wear when the stone makes contact with the rough ground ring.

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z.Range

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542			



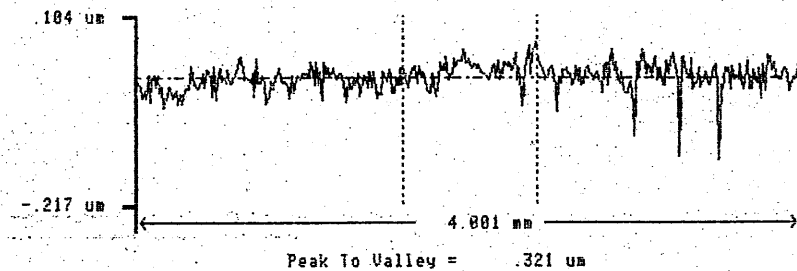
IME: 17: 4
ATE: 29-JUN-99

-1-

Taylor-Hobson

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude
F6 - Z.Range

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
542				



IME: 17: 5
ATE: 29-JUN-99

-1-

Taylor-Hobson

F1 - Analysis

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
542				

Rt = .169 um	Lo = 4.001 mm	Ra = .018 um
Rpm = .059 um	Rp = .104 um	Rq = .025 um
Ry = .321 um	Rv = .217 um	Rsk = -1.0
Rt1 = .086 um	Rt = .321 um	Rku = 14.6
Rt2 = .105 um		Delq = .28 Deg
Rt3 = .112 um	SLOPE = .04 Deg	Lamq = 31.622 um
Rt4 = .219 um		S = 12.979 um
Rt5 = .321 um		Sm = 25.252 um
		R3z = .098 um
		R3y = .102 um

Figure 4.103: Showing cross track profile and roughness after electrofinishing for 6 seconds using the hard SiC stone (10 x 14 mm) with the lubricant added, 4 bar, 2000rpm 90 amperes.

4.8.3 Electrofinishing using #4000 vitrified CBN and lubricant

With the lubricant added the #4000 (4 μm grit size) CBN stones (supplied by Wendt Boart) were much more consistent and showed much better cutting ability. This resulted in the total removal of the ground surface and an electrofinished surface, which appears more cut, compared to the surfaces electrofinished with SiC. The material removal rate was also faster.

4.8.3.1 10 x 14 #4000 CBN I grade

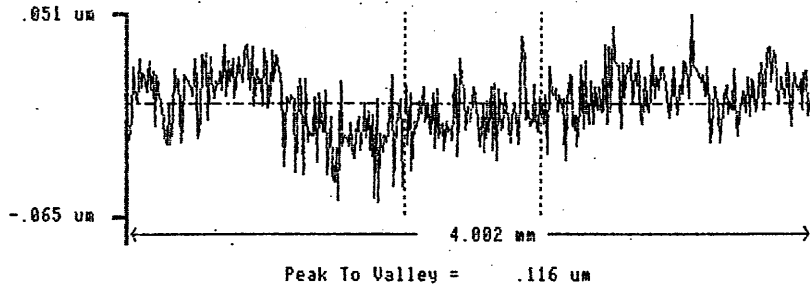
At high pressure 4 bar (1.5 MPa) the very aggressive cutting of CBN resulted in total removal of the ground surface very quickly but also resulted in cross track waviness. As the pressure was decreased this cross track waviness decreased along with honing stone wear from 10 μm to 1-2 μm per ring. However at the lower pressure it was found that the stone could not make the initial cut when applied to the next ground ring, probably because the stone was too smooth from the previous honing operation and the pressure was not high enough to generate the self-dressing. Some stone wear is therefore needed and critical for a successful and consistent honing operation. At lower pressures the stone does not cut at all.

Figure 4.104 shows the surface finish possible using the #400 CBN stone. The sample shown was electrofinished for 8 seconds using the #4000 CBN I grade stone, 2000 rpm, 100 Amps current and gap 100 μm and electrolyte 30 wt.% NaNO_3 . The stone wear was 2 μm . A wear rate of 10 μm /ring would allow a stone to last over 8 hours without intervention. This saves costs with regard to downtime associated with changing stones and ensuring the honing quality is achieved with the new stone.

Surfaces of $R_a < 0.02 \mu\text{m}$ are readily achieved with very low R_{tm} ($>150 \mu\text{m}$) and R_t values indicating a very uniform surface finish. As a consequence skewness is found to be slightly negative -0.1 but can fluctuate to positive or very negative by a single peak or valleys on the surface. The slope Δq was also found to be very low $\sim 0.2^\circ$. Figure 4.105 shows SEM pictures of the surface, which is very smooth with no leafing.

F1 - Analysis
 F2 - Graph
 F3 - Dump
 F4 - Expand
 F5 - Exclude
 F6 - Z_Range

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
A38				



TIME: 19:23
 DATE: 19-MAY-99

-1-

Taylor-Hobson

F1 - Analysis

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
A38				

Rtn = .089 um	Lo = 4.002 mm	Ra = .015 um
Rpm = .043 um	Rp = .051 um	Rq = .018 um
Ry = .108 um	Rv = .065 um	Rsk = -.3
Rt1 = .065 um	Rt = .116 um	Rku = 3.0
Rt2 = .108 um		Delq = .22 Deg
Rt3 = .101 um	SLOPE = .02 Deg	Lamq = 28.934 um
Rt4 = .084 um		S = 11.566 um
Rt5 = .084 um		Sm = 20.931 um
		R3z = .072 um
		R3y = .094 um

TIME: 19:23
 DATE: 19-MAY-99

-2-

Taylor-Hobson

F1 - Analysis

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
A38				

Rtn = .111 um	Lo = 4.001 mm	Ra = .016 um
Rpm = .051 um	Rp = .093 um	Rq = .021 um
Ry = .203 um	Rv = .109 um	Rsk = -.1
Rt1 = .078 um	Rt = .203 um	Rku = 4.3
Rt2 = .082 um		Delq = .24 Deg
Rt3 = .098 um	SLOPE = .03 Deg	Lamq = 30.834 um
Rt4 = .106 um		S = 11.864 um
Rt5 = .203 um		Sm = 23.449 um
		R3z = .090 um
		R3y = .140 um

Figure 4.104: Surface finish obtained by electrofinishing a ground surface for 8 seconds using a wide (14x10 mm) #4000 CBN stone

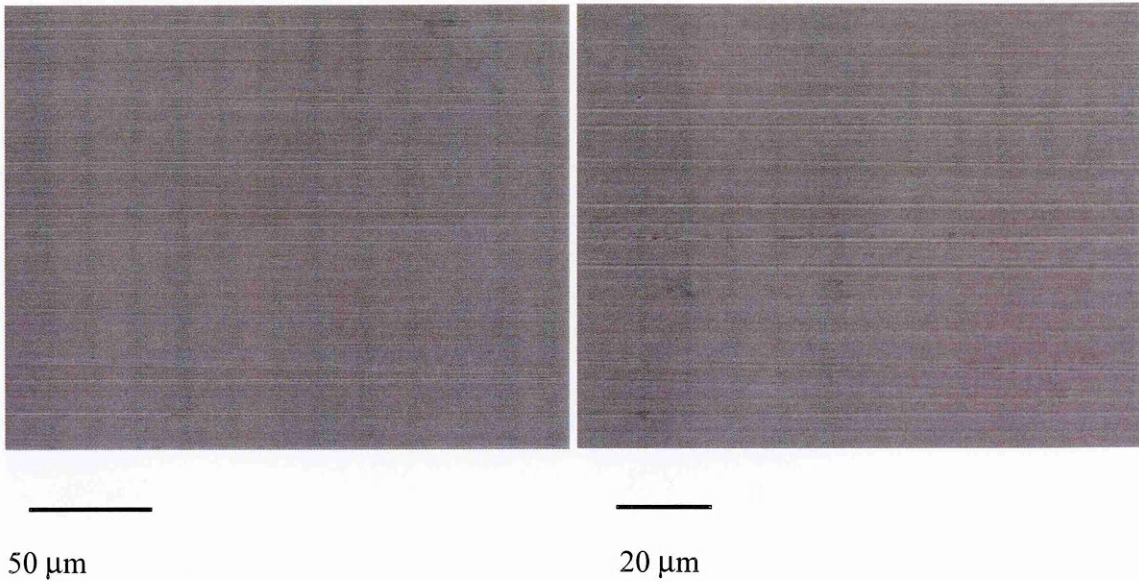


Figure 4.105: Showing SEM micrograph of surface produced by electrofinishing using #4000 CBN 14 x 10 mm I grade stone at 1.5 bar, 2000 rpm, 90 amperes for 8 seconds

When operating correctly the waviness was found to be very good, in the L, M and H band, see figure 4.110.

4.8.3.2 Changing stone width

When changing from conventional to superabrasive superfinishing stones it is generally advisable to reduce the stone width or use slotted honing stones to aid in removing the cutting chips and allow the lubricant into the cutting zone.

a) 8 x 14 #4000 CBN I grade

Again the honing stone was able to totally remove the ground surface in 5 seconds. The surfaces produced had $R_a < 0.02 \mu\text{m}$, however the same problem of no initial cut occurred at the lower pressures applied, likely because the stone surface was too smooth. Results are limited because the stone broke across its base. In general the stone surface appears clean, and occasionally black loaded lines are seen. Stone wear was found to be around $10 \mu\text{m}$.

b) 2 x 14 #4000 CBN J grade (harder grade)

Figures 4.106a & 4.107a show the rate of surface finishing during electrofinishing of a ground surface using #4000 CBN J grade stone 2 mm x 14 mm, 2000 rpm workspeed, 200 μm gap, and 90 amps ECM current and two different pressures 1 and 1.5 bar. The stone wear was between 12 and 18 μm. The surface is improved at a faster rate at higher pressures, which indicates that the surface improvement is dominated by the abrasive material removal and not the ECM material removal.

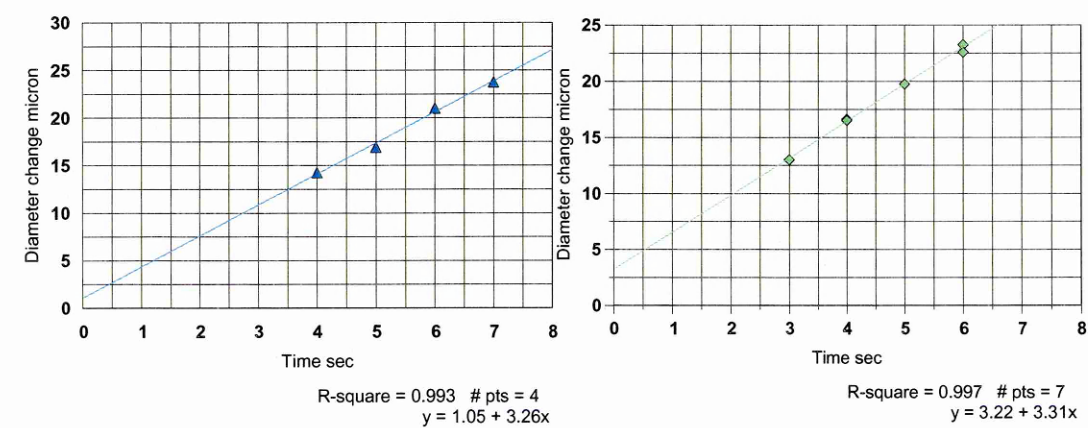


Figure 4.106: Rate of material removal during electrofinishing with (2x14mm) #4000 CBN stone at 1 bar

Figure 4.107: Rate of material removal during electrofinishing with (2x14) #4000 CBN stone at 1.5 bar

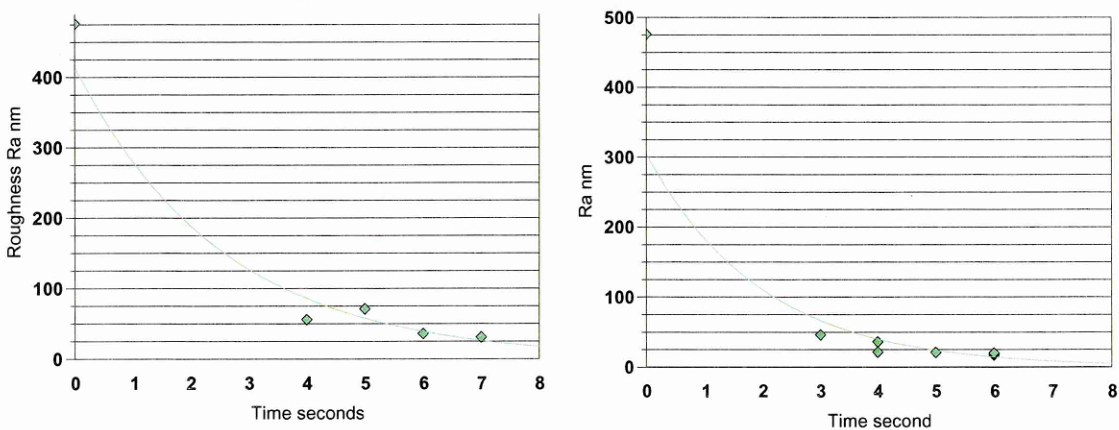


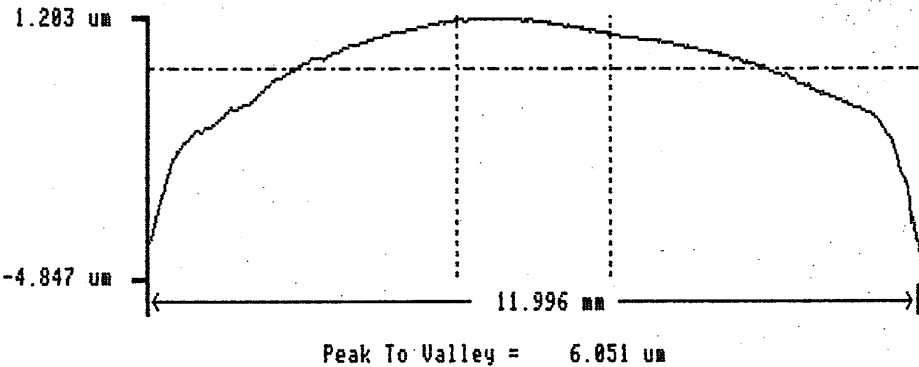
Figure 4.106a: Rate of surface finishing during electrofinishing using (2x14) #4000 CBN stone at 1 bar

Figure 4.107a: Rate of surface finishing during electrofinishing using (2x14 mm) #4000 CBN stone at 1.5 bar

Material removal rate is shown in figures 4.106 & 4.107 for the two pressures. The intercept on the y-axis is an indication of the abrasive material removal. The intercept is lower for the lower pressure. In both cases the material removal depends linearly with time and the slope of the line for the two pressures are similar indicating that the material removal is controlled by the ECM. The material removal accuracy was within +/- 0.5 μm .

- F1 - Analysis
- F2 - Graph
- F3 - Dump
- F4 - Expand
- F5 - Exclude
- F6 - Z.Range

Mode	Traverse Length	Reference	Ignore
UNFILTERED	12.0 mm	STRAIGHT	0 %
NI 6SEC ELECTROFINISHED			



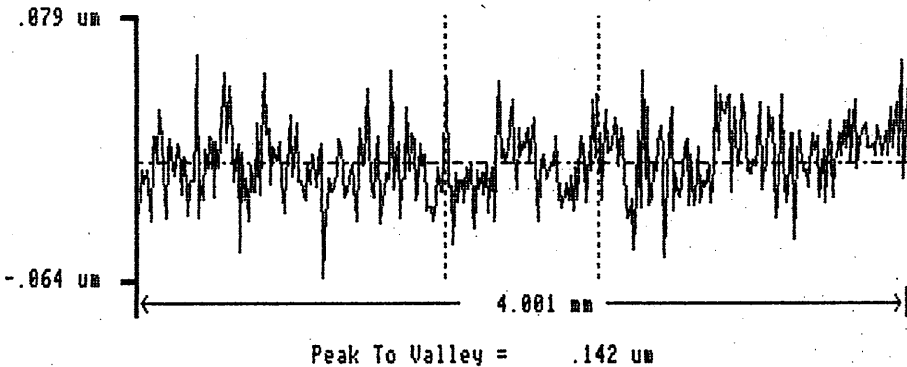
TIME: 15:46
DATE: 29-SEP-99

-1-

Taylor-Hobson

- F1 - Analysis
- F2 - Graph
- F3 - Dump
- F4 - Expand
- F5 - Exclude
- F6 - Z.Range

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
NI 6SEC ELECTROFINISHED				



TIME: 15:47
DATE: 29-SEP-99

-1-

Taylor-Hobson

F1 - Analysis

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.08 mm	ISO	STRAIGHT	0 %
NI 6SEC ELECTROFINISHED				

Rtm =	.116 um	Lo =	4.001 mm	Ra =	.016 um
Rpm =	.063 um	Rp =	.079 um	Rq =	.021 um
Ry =	.132 um	Rv =	.064 um	Rsk =	2
Rtl =	.107 um	Rt =	.142 um	Rku =	3.2
Rt2 =	.113 um			Delq =	.27 Deg
Rt3 =	.132 um	SLOPE =	.05 Deg	Lamq =	27.277 um
Rt4 =	.108 um			S =	11.356 um
Rt5 =	.121 um			Sm =	19.331 um
				R3z =	.089 um
				R3y =	.093 um

TIME: 15:47
DATE: 29-SEP-99

-2-

Taylor-Hobson

Figure 4.108: Showing the cross track profile and roughness measurement from an electrofinished ring using 2000rpm, 90 amperes, 1.5 bar, 2 x 14 mm J grade #4000 CBN for 6 seconds

Figure 4.108 shows the cross track form and roughness measurement for a ring electrofinished for 6 seconds using #4000 CBN. The cross track profile has been maintained and extremely good roughness achieved in a short cycle time. Ra is 16 nm, Rtm 116 nm and the slope is 0.27 °.

Figure 4.109 shows an MWA waviness plot for a ring, which was electrofinished for 6 seconds using the 2x14mm #4000 J grade CBN stone. The waviness (single track) ranged in the M band from 29 - 68 µm/s and in the H band from 44 - 98 µm/s. Although the M band waviness is better than standard honed, the H band is worse. Figure 4.110 is the waviness from a ring electrofinished with a wider 14x10 mm I grade #4000 CBN stone. In this case the waviness achieved is very good in the L, M and H band, M band 16 - 48 µm/s and H 16 - 48 µm/s, much better than standard honed.

(Standard honed M 80 -140 µm/s H 35- 50 µm/s)

The reason could be the wider stone or a lower stone wear

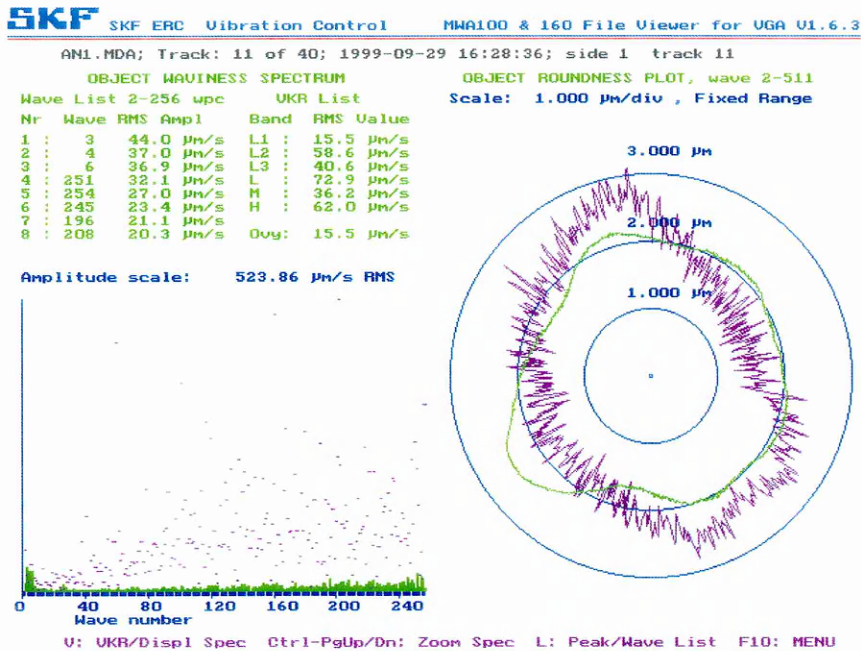


Figure 4.109: Shows MWA measurement from an electrofinished ring using 2x14mm (J grade) CBN stone for 6 seconds. (pink before, green after electrofinishing)

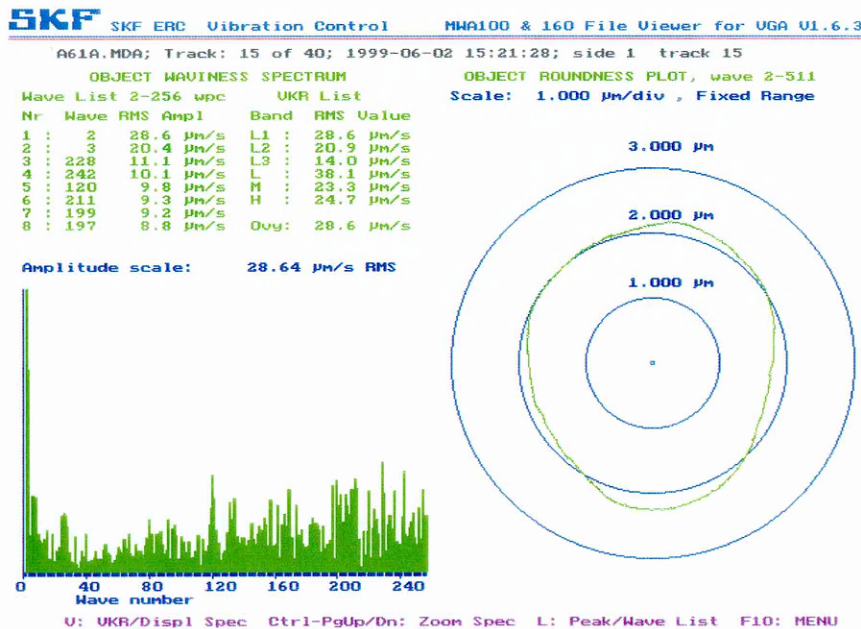


Figure 4.110: Electrofinished surface using 14x10mm CBN (I grade) stone for 8 seconds

4.8.4 Electrofinishing of turned surfaces

One possible mechanism for electrofinishing was the formation of an oxide on the surface of the ring, which is removed at the peaks by the abrasive; the freshly exposed metal peaks would then be selectively removed by the ECM action to give an increased rate of surface finish.

To investigate the influence of input surface finish on the electrofinishing process, a number of CRB rings were turned with a flat cross track profile in the tool room at ERC. The turned finish was 1.3 µm Ra and 4.6 µm Rtm.

4.8.4.1 Input quality

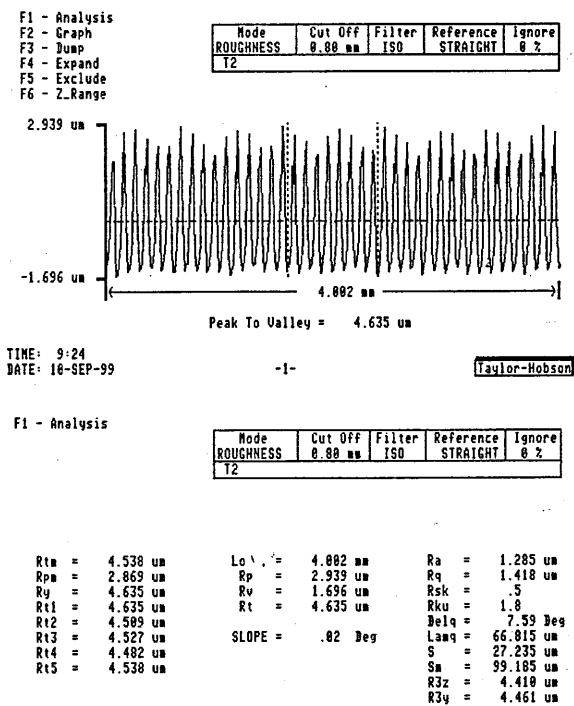


Figure 4.111: Showing the surface roughness from a turned surface

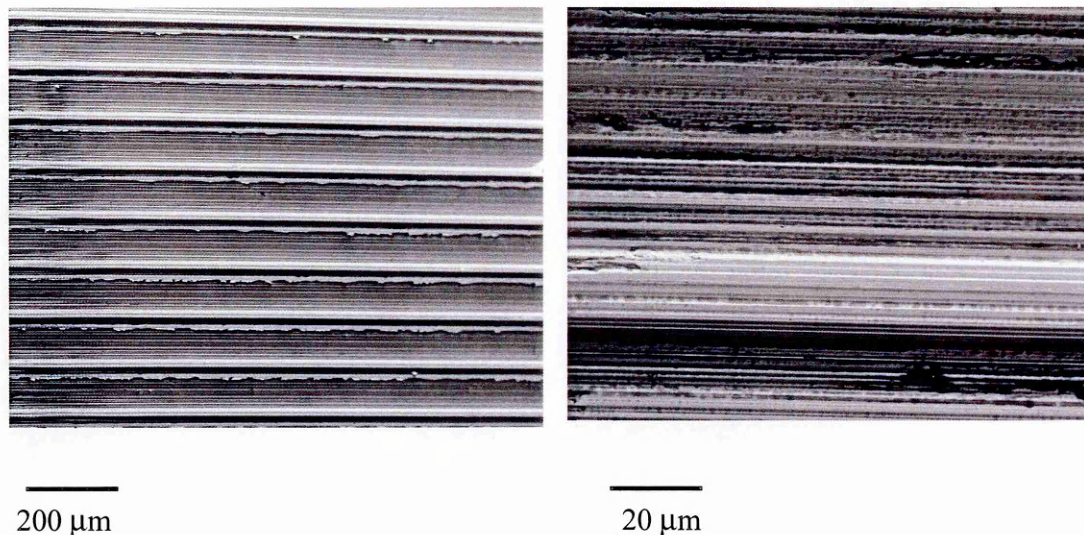


Figure 4.112: SEM micrographs of turned surface

The SEM micrographs above show the topography of the turned rings. The turning grooves are clearly visible. It also shows that there is roughness on two scales, a macro roughness from the turned peaks and a smaller roughness from the sliding of the cutting tool.

4.8.4.2 Diameter change and rate of surface finishing

The turned rings were electrofinished using 90 Amps, 2000 rpm, #4000 CBN J grade stone (B3J11S) dimension (2mm x 14mm), using NaNO_3 electrolyte with lubricant heated to 30 °C. The two stone pressures used 1.875 MPa and 3.3 MPa or forces of 45 N and 79.75 N respectively.

The figures below show how ECM only and electrofinishing at two pressures affects the diameter removal and the rate of surface finishing

For ECM only material removal rate is found to be highly controlled governed by Faraday's law varying linearly with time. The accuracy in material removal rate is $\pm 0.7 \mu\text{m}$, figure 4.113.

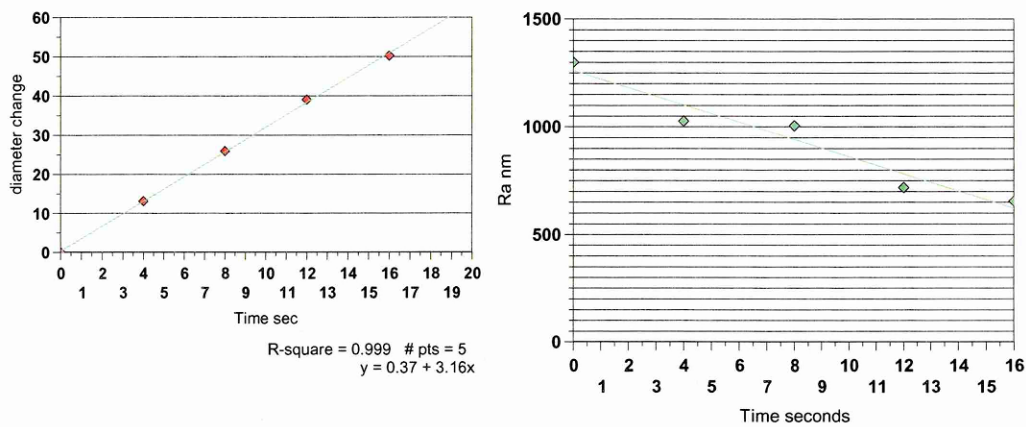


Figure 4.113: Diameter removal and rate of surface finishing by ECM only (90 amps, 2000 rpm, gap ~ 200 μm) on a turned surface

ECM improves the surface finish slowly, copying the turned surface and only gradually reducing the peak to valley heights. In 16 seconds the Ra is reduced from 1.2 μm to 0.65 μm Ra and the Rtm drops from 4.5 μm to 2.3 μm . The turned texture is still clearly visible on the surface see figure 4.114.

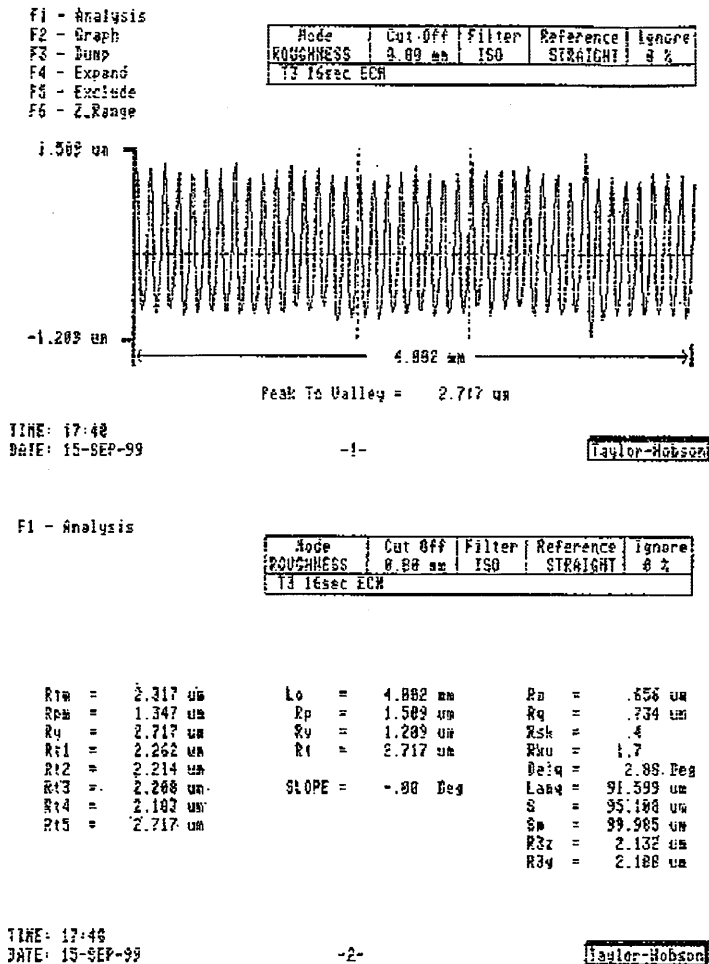


Figure 4.114: Roughness trace after turned surface is ECMed for 16 seconds. Showing turned surface is still evident

During electrofinishing the material removal is found to be highly controlled, figures 4.115 and 4.116. Electrofinishing at 1 bar gave a material removal accuracy of $\pm 0.5 \mu\text{m}$ with time. The material removed for the combined process is greater than for ECM only. When electrofinishing at 1.5 bar, the material removal is again within $\pm 0.5 \mu\text{m}$. The intercept with the y axis (diameter change) during electrofinishing is offset from zero by $8.3 \mu\text{m}$ and $9.1 \mu\text{m}$ respectively for 1 bar and 1.5 bar this can be considered the material removed by the honing operation. In reality this removal will occur in the first 2 -3 seconds.

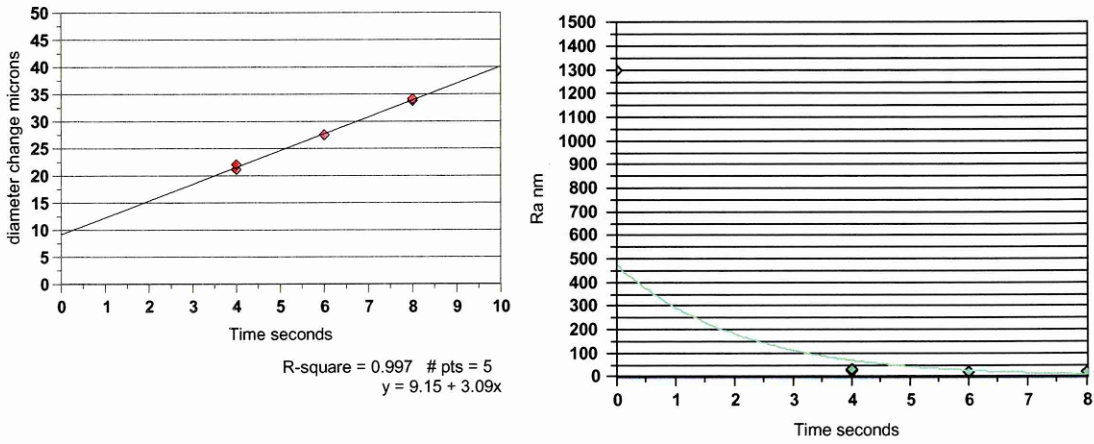


Figure 4.115: Diameter change and rate of change of Ra after electrofinishing a turned ring using (2 x 14 mm) J grade #4000 CBN at 1.5 bar, 2000 rpm and 90 amps .

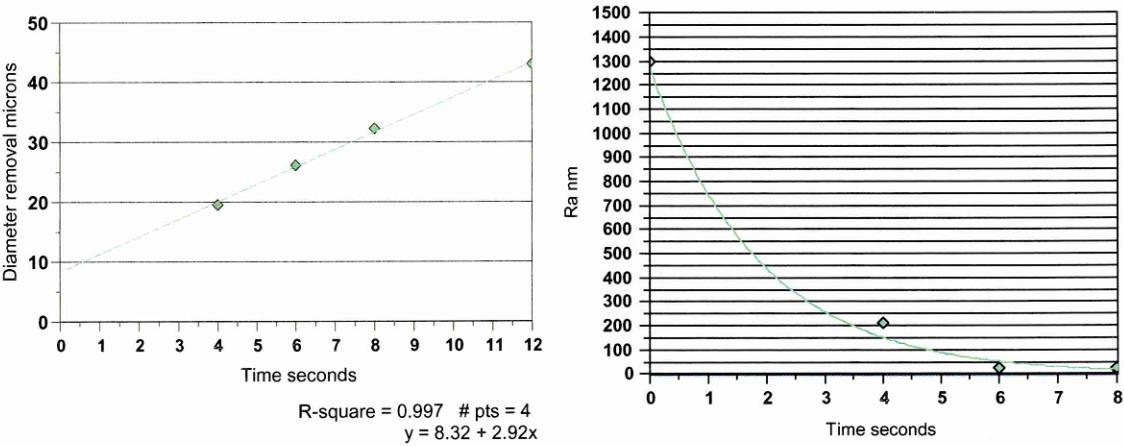
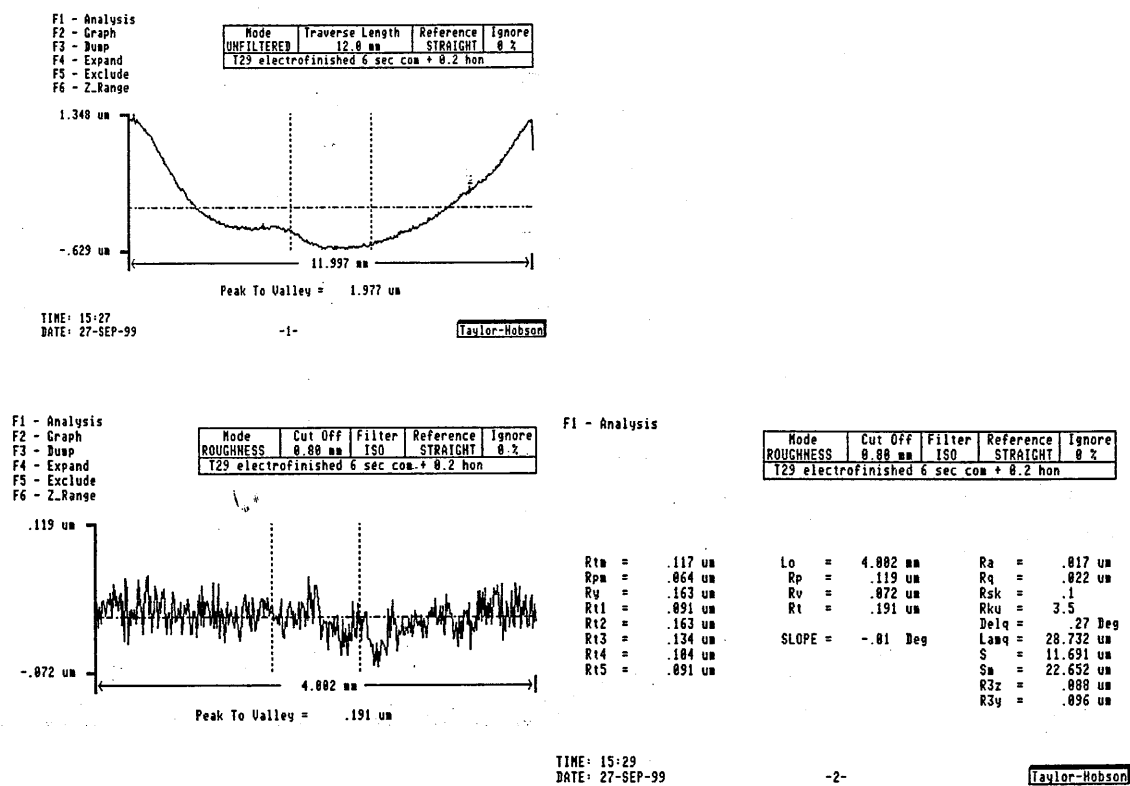


Figure 4.116: Diameter change and rate of change of Ra after electrofinishing a turned ring using (2 x 14 mm) J grade #4000 CBN at 1 bar, 2000 rpm and 90 amps

Electrofinishing can totally remove the turned surface and generate a new surface. At higher pressures the surface is improved at a faster rate, although the ultimate finish is similar at 0.018 μm Ra and an Rtm 0.135 μm . Figure 4.117 shows roughness measurement from a Talysurf of a sample, which was electrofinished for 6 seconds and then given 0.2 seconds of honing only. It is found that the initially flat turned cross track profile is altered in a fixed way to give a convex surface 2 μm deep. This is believed a result of the honing operation. The stone was probably too small or the oscillation amplitude needs to be increased, since it was found that the outer edges were not machined as effectively as the center. When electrofinishing is applied to ground surfaces with a logarithmic profile the initial profile was maintained.



4.8.4.3 Waviness

The roundness after the turning operation was very bad ranging from 1 µm to over 4 µm but was always improved by the electrofinishing process. The waviness levels was also improved, figure 4.118. The M band waviness was better than standard CRB honed from 3 years ago.

From the table 4.9 above it is clear that the electrofinishing process can give improved waviness levels. The fluctuation in the single track measurements are due to a few spikes on the surface. Use of higher pressure reduces the number of spikes appearing and applying the stone for 0.2 - 0.5 seconds longer removes these spikes. However applying the honing stone for too long can adversely affect the waviness particularly in the high band. The use of a wider honing stone may assist in reducing these spikes and better washing/flushing of the stone with lubricant would also help.

It is also noticed that the filtering used to calculate the waviness removes far more peaks from a standard honed surface (> 2000 peaks) than the electrofinished surface (< 600 peaks). Which indicates that an electrofinished surface is cleaner and more uniform.

Table 4.9: Summarizing waviness from electrofinishing of turned surfaces

Sample	Electrofinishing conditions	Δr before	Δr after	M band after multitask	M band single tracks	H band after multi-track
T22	1.5 bar CBN 8 sec	-	2.4	16.4	27-112	9.4
T23	1.5 bar CBN 8 sec	2.4	1.4	18	23-68	7.9
T2	1 bar CBN 8 sec.	1.5	0.97	14	22-464	6
T8	1 bar CBN 8 sec.	-	1.22	16.4	25-91	6.4
T29	1.5 bar CBN 6 sec com + 0.2 sec honing only	3.7	3.3	14	28 - 50 one spike on surface (224)	10
Standard honed	production 1996		0.2 - 0.9	20 - 30	80 - 140	7 - 12

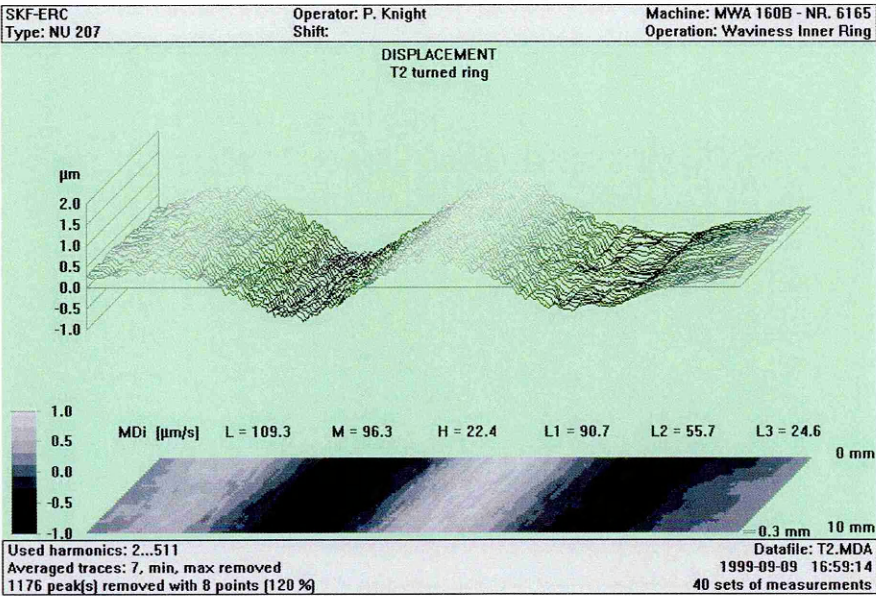
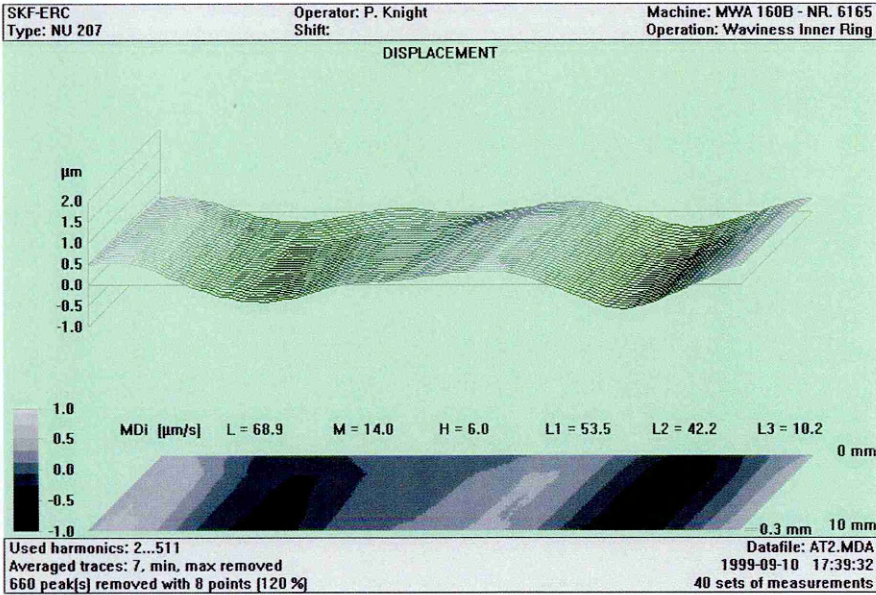


Figure 4.118: MWA measurement showing waviness before and after electrofinishing of turned surface

Figure 4.119 shows an SEM picture of the surface of a turned ring which was electrofinished for 6 seconds + 0.2 seconds with honing only. The surface is clearly cut and the turned surface has been removed.



20 μm

Figure 4.119: SEM from turned surface which has been electrofinished for 6 seconds + 0.2 honing only.

4.8.4.4 Summary on electrofinishing with lubricant

1. Electrofinishing (ECM + honing) has been shown to give fast surface finishing, improved surface finishes, accurate and controlled material removal with high material removal capability.
2. The use of synthetic lubricant gave immediate improvement in the honing, reducing stone loading and improving surface finish. It allowed the better application of the harder CBN stones and the harder grade SiC stone, which in turn gave improved stone wear of 2 - 20 μm / workpiece for CBN and $\sim 100\mu\text{m}$ /workpiece for SiC.
3. The surface roughness improvement is controlled by the honing operation. SiC cuts aggressively initially on the rough ground surface removing the peaks and valleys. Once the ground surface is removed and bulk material is reached, the cutting stops and rubbing/burnishing occurs. CBN shows better cutting but the cutting is again reduced when it reaches the bulk material, however the surface still appears cut after electrofinishing. The fact that the honing stone removes the ground surface, but then removes little material once it reaches the bulk material, means that a fixed amount of material is removed by the abrasive and allows for accurate diameter control by the ECM.
A ground surface 0.4 μm Ra was improved to 0.02 μm in 5 seconds by electrofinishing.
4. ECM removes material in a controlled way governed by Faraday's Law, depending on the current and time. This high, accurate material removal capability can be used for size control. When ECM is used alone an accuracy of $\pm 0.7 \mu\text{m}$ over a material removal range

of 50 μm can be achieved. Electrofinishing showed an accuracy of $\pm 1\ \mu\text{m}$ probably resulting from varying material removal by the honing and measuring inaccuracy.

4. Electrofinishing of turned surfaces shows great potential. A turned surface of 1.2 μm Ra, 4.5 μm Rtm was improved by electrofinishing in 6 seconds to 0.02 μm Ra, 0.2 μm Rtm with 25 μm material removal. Diameter removal was controlled to $\pm 0.5\ \mu\text{m}$.

5. Waviness measurements give the clearest indication that the honing is still not working correctly. The values range from extremely good to very bad. Poor waviness was attributed to a few peaks on the surface likely from some loading on the stone or trapped honing debris. Direct flushing of the stone is expected to give significant improvement in consistency, as during tests no direct flooding of the stone was used.

4.9 Electrochemical Machining of M2 rings

Also in view of a possible electrofinishing mechanism incorporating forming an oxide and removing this oxide, some trials were performed on M2 high-speed steel, which is highly alloyed and forms a thicker oxide layer.

4.9.1 ECM Behaviour

The rate of surface smoothing is important; the longer the machining current is applied the more material that will be removed and correspondingly more waste sludge produced. The effect of workpiece speed on the smoothing rate was investigated. Figure 4.120 below demonstrates the results.

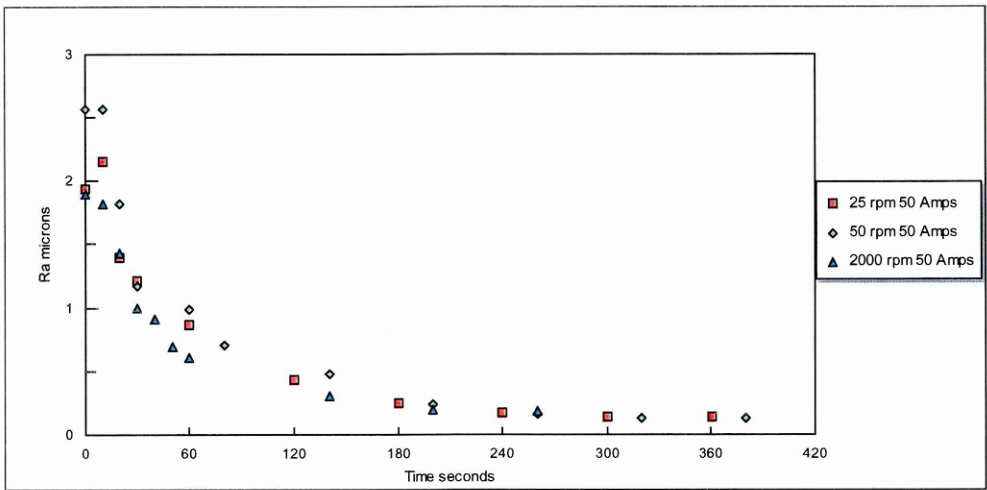
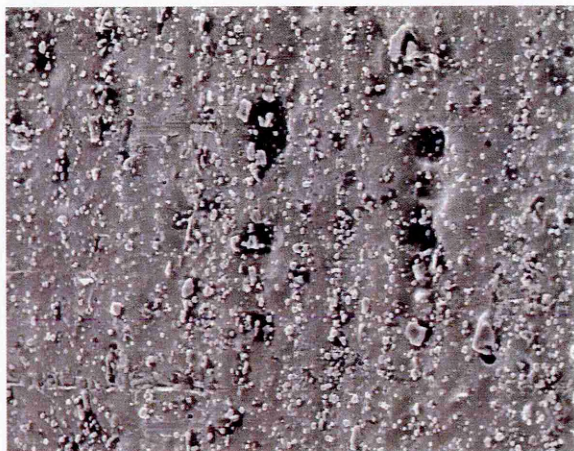


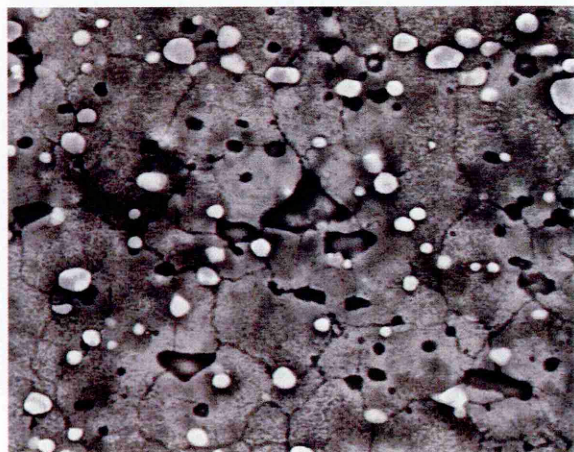
Figure 4.120: Showing the effect of workpiece speed on the rate of smoothing of ECM as indicated by the Ra value.

From figure 4.120 it appears that the higher workpiece speed gives a higher initial rate of surface enhancement. During machining at the higher speed, the surface of the ring became covered in a thick black layer, which could be easily washed off leaving a blackened surface. Machining at 50 rpm resulted in a shinier but still greyish surface, while 25 rpm gave a greyish surface with the appearance of banding. The ultimate level of finishing was however the same at around 0.13 microns Ra and was found to be dominated by the exposed surface carbides see figure 4.121 and 4.122.



100 μ m

Figure 4.121: Surface finish of M2 by ECM only



20 μ m

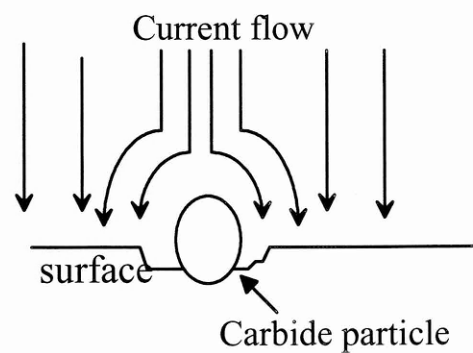


Figure 4.122: Showing carbide particles exposed on surface after ECM on M2

These carbide particles can be removed by applying an abrasive after the ECM operation. The surface then appears very shiny with a Ra of 0.07 microns.

The M2 rings had been heat-treated and were therefore covered in an oxide coating, which often had heat treatment flow patterns visible on the surface. It was found that ECM could still be applied to such a surface. The ECM dissolution occurred around these oxide layers. This was evident from measuring the mean peak to valley height R_{tm} . It was found that initially the R_{tm} actually increased as material was removed from around these oxides. The oxides were undermined and finally fell off. However it took up to 60 seconds to remove the heat treatment pattern see figure 4.123. Monitoring the voltage required to pass the constant current, also indicated the presence of a higher resistance layer at the beginning of machining. The voltage required goes up and then begins to drop as the coating is removed. The voltage level then will increase again as the inter-electrode gap increases as material is removed.

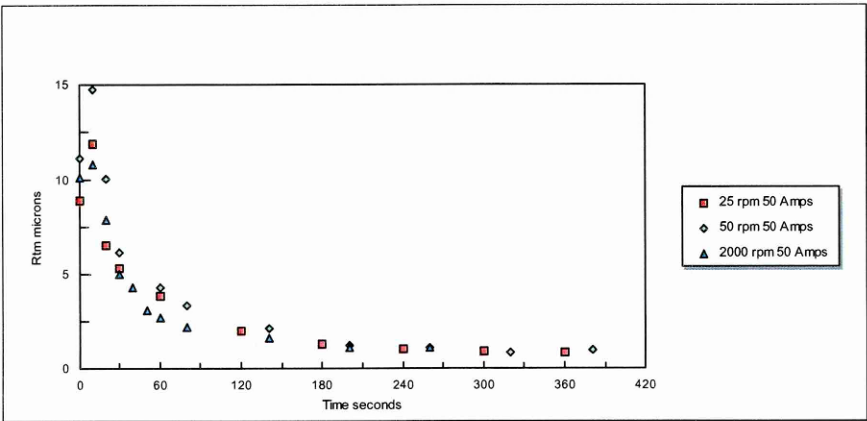


Figure 4.123: Graph showing how the mean peak to valley height (R_{tm}) changed with machining time. Note the initial increase in R_{tm}

4.9.2 Tape electrofinishing of M2 material

The 9 μm CBN superfinishing tape and ECM were applied together for 10 seconds machining intervals, at which point the surface was measured and the tape indexed to provide fresh cutting points. The results are shown in figure 4.124, which clearly shows how effective this combined process is at reducing surface roughness. The combined process is able to reduce the turned surface $R_a > 2$ microns to a $R_a < 0.13$ microns in 30 seconds which compares with over 200 seconds for ECM alone. The tape used on its own is also shown to be ineffective at improving surface finish, showing a linear decrease in roughness with time. Superfinishing tapes are designed to remove minimal material, so in this situation the tapes will become worn and loaded fairly quickly.

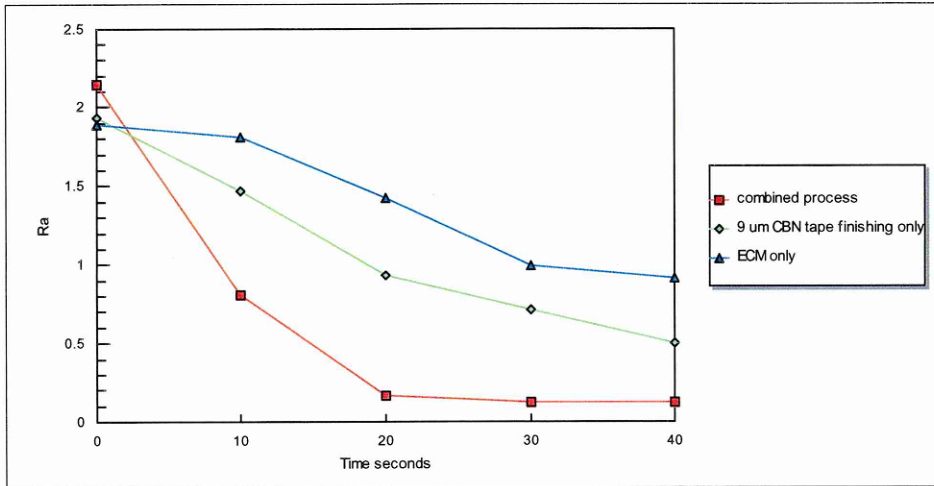
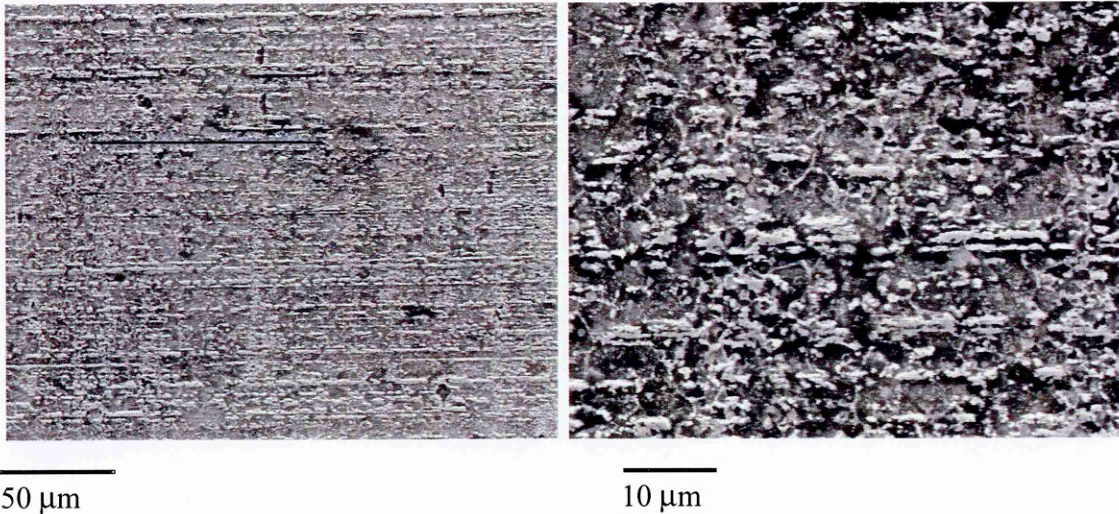


Figure 4.124: Graph showing the rate of surface improvement for the ECM only, tape only and the combined process

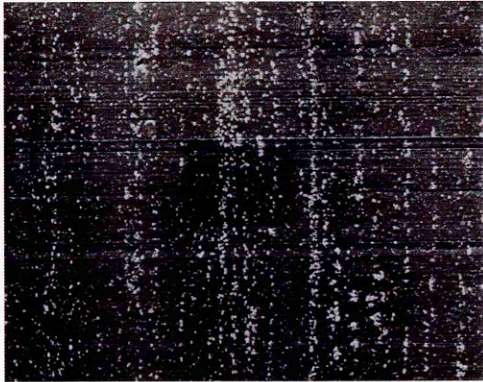
The combined action of ECM and tape show a synergistic effect i.e. they assist each other. The mechanism of this interaction is not clear. During the electrofinishing on NU207 rings these beneficial effects were assigned to improved dressing of the honing stone allowing it to cut for longer.

With the M2 steel, which has high Cr, V and W contents, an oxide layer is clearly present on the surface. SEM micrographs of the surface of a ring which had been machined using ECM and a 9 μm CBN superfinishing tape is shown in figures 4.125 & 4.126.



Figures 4.125 & 4.126: Showing surface of M2 ring after combined ECM and 9 μm superfinishing tape for 40 seconds using 2000 rpm, applied pressure 4.5 bar and using a current of 50 Amps.

The surface finish shown in figure 4.125 above is approximately $0.13\text{ }\mu\text{m Ra}$ and is again dominated by the presence of carbides and oxides on the surface. By applying the superfinishing on its own for an extra 10 - 20 seconds removes these particles producing a highly shiny and cut surface with a $Ra \sim 0.06 - 0.08\text{ }\mu\text{m}$, see figure 4.127.



50 μm

Figure 4.127: Surface of ring after combined ECM + tape (electrofinished) followed by tape only to completely remove the oxides and carbides present on surface

Figure 4.127 shows that carbides are still present on the surface, however now they appear to be cut instead of protruding from the surface. CBN abrasive tape was used for this operation whereas diamond abrasive is often recommended when machining carbides.

From the work above finishing times in the order of 40 - 50 seconds were possible. However while monitoring the current needed to maintain spindle speed it appeared that the abrasive was only effectively working during the first few seconds of operation. A series of tests was then performed where the machining interval was reduced from 10 seconds to 5 seconds.

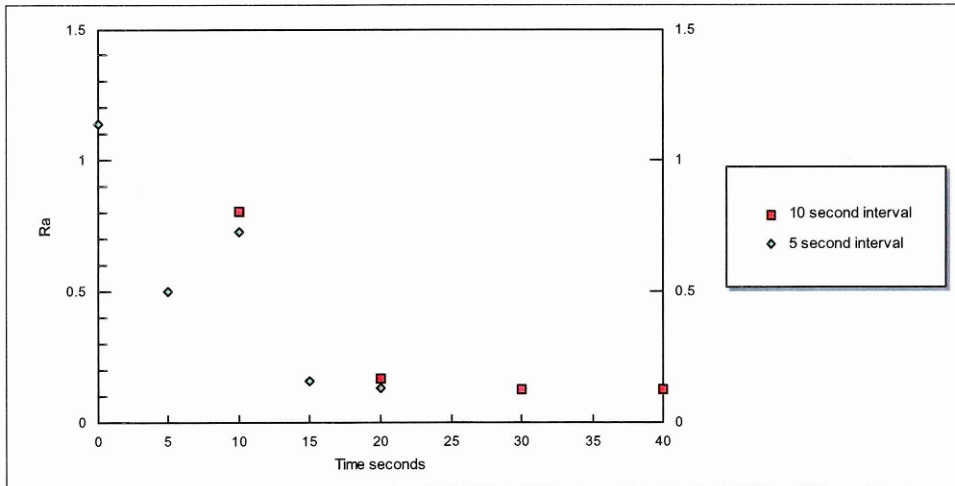


Figure 4.128: Showing the effect of reducing machining interval, effectively increasing the amount of superfinishing tape used i.e. providing more fresh cutting points

Figure 4.128 shows that 15 - 20 seconds are needed when machining with the 5 second interval to reached the same surface finished achieved after 30 sec with the 10 second interval. An error occurred for the 5 second interval at 10 seconds when the abrasive tape broke off and the actual roughness is found to increase, so the real improvement is not known. However it is clear that more efficient use of the abrasive gives a faster rate of surface improvement.

To make the abrasive work for longer, larger abrasive cutting grains can be used, or the use of oscillating tape or even a honing stone which continually regenerates fresh cutting edges. Also the use of harder diamond grits and a greater understanding of machining parameters when machining high-speed steels would assist.

During testing it was also found that by reducing the current from 80 Amps to 50 Amps did not affect the rate of surface finishing during electrofinishing.

4.9.3 Summary of ECM and electrofinishing on M2 material

- 1) ECM alone can produce a surface finish of $\sim 0.14 \mu\text{m Ra}$, the ultimate finish being very much dependent on the microstructure of the steel. Carbides, which are not conductive, are exposed onto the surface, the size and distributions (segregation) of these carbides limits the obtainable finish.
- 2) Because ECM improves the surface finish slowly, to obtain the required finish took 5 minutes, which removed 0.5 mm from the diameter of the ring.
- 3) Resulting from the heat treatment, the rings were oxidized; this oxidized layer was removed by the ECM action. The ECM dissolution occurs around the oxides, which in turn fall off. The heat treatment pattern was still evident after 60 seconds.
- 4) Applying an abrasive after ECM was effective at further reducing the surface roughness by removing the carbides exposed on the surface.
- 5) ECM combined at the same time with an abrasive was very effective at improving the surface finishing rate. A turned surface with $2 \mu\text{m Ra}$ was machined for 25 seconds to a Ra of $0.09 \mu\text{m}$, while surfaces of $0.06 \mu\text{m}$ have been produced.
- 6) Because of the faster finishing rate the actual material removed is much less, 0.06 mm from diameter.
- 7) Even faster finishing times should be possible because the abrasive action was only effective for the first few seconds, as shown when the machining interval was changed from 10 seconds to 5 seconds, the rate of surface enhancement in each interval was still similar. A better understanding of how to apply abrasives to M2 steel would assist in optimising the rate of surface finishing.
- 8) The combined ECM and abrasive appeared better at removing the segregated carbides, and by applying the abrasive separately at the end of the cycle tended to produce a uniform shiny cut surface.

5. Discussion

The results section describes the sequence of investigations undertaken to further develop and understand a superfinishing process for the surface finishing of bearing raceways. The process called electrofinishing combines electrochemical machining (ECM) with honing. This process was born from previous development work at SKF's Engineering and Research Centre (ERC), which firstly studied electrochemical machining for the finishing of raceways and subsequently combined ECM with honing. This early work found that ECM on its own (also called electropolishing) could improve a ground surface of 0.3 μm Ra to 0.1 μm Ra in 55 seconds. The machining cycle time was long and the amount of material removed from the raceway excessive. More importantly the waviness of the workpiece was very poor. To improve the waviness an abrasive process was included namely stone honing. This combined process called electrofinishing showed excellent promise in achieving very good surface finishing in a short time, but also gave the desired improvement in waviness. A surface of 0.02 μm Ra could be produced in 8 seconds and faster times were believed possible. Fatigue life tests on ECMed surfaces showed no detrimental effects of the lower compressive stresses associated with an ECM process.

With these very promising results a more detailed evaluation of the process was initiated with this PhD study to gain more process information and an understanding of the mechanisms involved to explain the fast rate of surface finishing.

Generally with abrasive finishing processes the requirements for high material removal and good surface finishing cannot be met in a single operation. For high material removal, honing stones with coarse grits are employed while for good surface finishing fine grit honing stones are used. Therefore to achieve very high surface finishes, through feed honing systems are often employed with a series of honing stones with decreasing grit size in order to achieve initially high material removal followed by fine surface finishing. Alternatively, a two stage honing operation is used with a rough honing and a fine honing stage. This can be performed in the same machine or on two machines but both have disadvantages in regard to increased cycle time and increased capital equipment cost respectively. A process with high material removal capability combined with very fine surface finishing could have many benefits.

In addition any new surface finishing process for bearing raceways must be competitive with existing surface finishing technologies with regard to cost and quality. Determination of cost should include the total process, since a new process capable of improving rough ground surfaces to very high quality surface finishes relaxes the requirements for grinding allowing increased productivity. The demands for improved bearing life and quieter running bearings has led to a general trend for improved surface finish, waviness and bearing geometry. Also mentioned in the literature survey, bearing manufacturers are also investigating new types of surface finishes (isotropic, minute recesses etc.) for improved functionality, particularly in starved lubrication conditions such as occurring in heavily loaded or low speed applications.

The results are presented in chronological order and detail the development route taken, from 1) ECM only 2) ECM followed by superfinishing tape, 3) electrofinishing with superfinishing tape, 4) electrofinishing with honing stones 5) direct electrolytic dressing of honing stone and 6) improved electrofinishing by adding a lubricant. The discussion is presented in a similar fashion to give a clearer picture of the directions taken.

5.1 ECM only

The main reason in the earlier work to combine ECM with honing was to reduce the waviness; this adds complexity and cost to any process. Also this new combined process would have to give significant benefits if it is to replace honing, the traditional finishing method for bearings, since an electrochemical process with its corrosive electrolyte must be added to the existing honing operation.

Section 4.3 therefore investigated whether ECM only could be improved to a point where it could be used for surface finishing of bearings and tried to determine the cause of the increased waviness in order to develop a far simpler process.

Ground rings were ECMed to investigate the rate of surface finishing. The electrode and electrode holder (incorporating the nozzle) were redesigned to give improved electrolyte flow. The main improvements were a longer flow channel to allow uniform/laminar flow to develop, the nozzle exit was closer to the inter-electrode gap to reduce turbulence of the electrolyte jet and finally the electrode was mounted and ground/polished flat onto the top face of the flow channel to prevent turbulence of the electrolyte flow by a step at the connection of the electrode to the nozzle.

The rate of surface finishing of a ground ring ($0.3 \mu\text{m Ra}$) was shown in figures 4.12 - 4.15. The roughness was improved to $0.13 \mu\text{m Ra}$ after 16 seconds, the other surface finishing parameters were also improved with machining time. The improvement in surface finish by ECM is summarized in table 5.1. The initial rate of surface finishing begins to decrease with longer machining times, which is more clearly demonstrated by the change in slope (Δq). The results show that ECM does improve the surface finish but slowly, copying the surface, removing material from the surface peaks and the valleys with only a slight preferential removal from the peaks, which results in a decrease in roughness. The skewness also shows that the ECM is removing material from the peaks and the valleys. The skewness for ECMed surfaces remains approximately constant, while for honing the skewness initially becomes more negative as the peaks are removed and then starts to increase as the valleys are removed. The driving force for this selectivity is likely linked to the surface slope. ECM is commonly used for deburring since the current is concentrated on the burrs or sharp edges. Further evidence for this lack of selectivity for peak removal is demonstrated by the rate of material removal. In 16 seconds $21.5 \mu\text{m}$ are removed from the radius of the ring while only $2.2 \mu\text{m}$ have been removed from the peaks.

Table 5.1: Showing the improvement in surface finishing by ECM on a ground ring

	Ground ring	Electropolished 16 seconds 100 amperes, 1100 rpm
Ra μm	0.3	0.128
Rtm μm	2.3	0.89
Rsk	-0.9	-0.7
Rpm μm	0.76	0.34
Δq slope degree	5.23	0.82

The final surface finish is dependent on the input quality as shown by ECM on honed surfaces (0.06 μm Ra) where a surface finish of 0.04 μm Ra could be achieved, see table 5.2. This may also relate to the wavelength of features on the surface as shown by McGeough⁵¹ that long wavelengths are levelled at a slower rate than short wavelengths. A honed surface has a finer scale (wavelength) than a ground surface.

Table 5.2: Showing the improvement in surface finishing by ECM on honed input ring

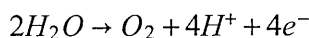
	Averaged honed surface finish	Electropolished Surfaces
Ra μm	0.07	0.04
Roughness Rtm μm	0.6	0.3
Skew Rsk	-0.7	-0.6
Rpm μm	0.23	0.12
Δq degrees	1.1	0.47

Also shown in the results is the reduction in workpiece diameter with machining time figure 4.10. The graph follows Faraday's law and is a straight line.

$$\text{mass removed} = \frac{\rho A I t}{z F}$$

The mass removed depends on the total charge passed i.e. current (I) x time (t) for a set of ECM conditions. The atomic weight (A) of the dissolving element and Faraday's constant (F=96500 C) are constants. The valency z for iron can be 2 or 3 or a mixture of the two and ρ is an efficiency factor depending of ECM conditions (flow, temperature, current density etc.).

Machining at 100 amperes (1.8 A/mm²) with a gap of 100 μ m and rotation speed of 1100 rpm, the diameter reduction was found to be 2.75 μ m per second. The material removal accuracy was within +/- 1 μ m. The process efficiency was found to be 70 % under these conditions assuming the iron is dissolving as Fe²⁺ this is in line with reported efficiency for NaNO₃ electrolyte. The loss of efficiency results from other electrochemical reactions occurring which do not remove material, such as oxygen generation.



ECM can be used to accurately remove material in a controlled way to high dimensional accuracies. It also shows that ECM has high material removal capability controlled by the time or the current used, which is not possible by honing.

The improved electrolyte flow gave an improved cross track profile, figure 4.16, although slightly greater material was removed from the edges of the raceway as a result of the electrode being 14 mm wide instead of the 12 mm track width.

Waviness measurements, figure 4.17, once again showed that ECM increased the medium and high band waviness above that of ground quality. Examination of the surfaces produced, using a scanning electron microscope, revealed a possible cause for this increased waviness. The surface after machining is essentially isotropic, apart from isolated surface features, which appeared as hills or valleys of 5 μ m wide and up to few 100 μ m long, figure 4.18. These features are in the cross track direction so would result in measured waviness, which is measured in the circumferential direction. Closer analysis of these features using EDAX to identify qualitatively the chemical composition showed them to be associated with MnS inclusions present in the steel from smelting. They are aligned in the cross track direction as a result of extrusion into tubes, the starting point for ring manufacture. At higher magnification some of these surface hills have small caps, which appear to be iron, which had not been electrochemically dissolved because their electrical connection to the bulk material had been cut off. There is also evidence of undermining by the current passing around the non-conductive MnS inclusions and possibly turbulence of the electrolyte flow around these obstacles resulting in pockets forming on the side of the inclusions. It was found that by reducing the electrode width to 2 mm, more valleys were formed but also the rotation speed had an influence on the waviness, which indicates the

time under the ECM current influences the surface topography. However it was not possible to completely eliminate these surface peaks since there is a depth distribution of MnS inclusions continually being exposed on the surface. It is not known how this measured increase in waviness would affect the bearing noise, since these soft inclusions would be knocked off easily during running. The iron caps could cause problems if knocked off since they could cause bearing damaged if over rolled in the contact.

To further evaluate the sources of waviness generation during ECM, tests were performed on honed rings, which had good starting waviness to investigate the detrimental effect of ECM on waviness. The electrical noise associated with the test rig was found to be due to the mains power of 0.15 volts at 50 Hz and the drive amplifier for the motor of 2-3 volts at 20kHz. To test if this electrical noise would result in waviness on the workpiece a series of tests was performed by superimposing a sine wave of different frequencies and magnitudes onto the ECM current. It was found that sine waves of large magnitude (± 20 amps) at low frequencies did result in waviness on the ring, but the effect diminished at higher frequencies. So the small magnitude mains noise and the higher frequency amplifier noise are not believed to be the cause for poor waviness. However the results do indicate that ECM could be used to generate deliberate low order waviness, figure 4.25, or with an in-process displacement sensor could be used to remove low order waviness by a feedback to the current supply. Eccentricity of the workpiece is also not believed to cause medium band waviness. Smaller electrode widths (1 and 2 mm) were found to degrade the medium band waviness more although large error bars often makes comparisons difficult. Similarly workpiece speed appears to influence waviness but again error bars overlap. From these results it would appear that the material microstructure has a dominating effect on the observed waviness. The electrode width and workspeed influence the surface topography after machining.

The electrolyte flow is also believed to influence waviness, although difficult to test in the present set-up. Previously work had reported that cross track form was affected by the electrolyte flow particularly when the electrolyte flow was perpendicular to the workpiece. The surface finishing rate has improved compared to the previous work where a ground surface of $0.3 \mu\text{m Ra}$ was improved to $0.1 \mu\text{m Ra}$ in 55 seconds while now with the improved parallel electrolyte flow a similar improvement in Ra can be achieved in only 16 seconds. A thin black line, which forms on the raceway upon switch off of the current, is a good indication of the flow conditions. Poor electrolyte flow results in a thicker wavy black line, while a thin black line indicates a more uniform flow. A smaller electrode gap gave a very thin faint black line. This line is a result of the voltage drop on switching off the current leading to etching and oxide formation due to low process efficiency. This black line affects the visual appearance of the bearing and is unacceptable particularly for bearings, which can be disassembled, such as cylindrical roller bearings.

The results from ECM only on ground surfaces show that although the surface finish was improved, the rate of surface finishing is still too slow for mass produced bearings and the final surface finish ($Ra \sim 0.12 \mu\text{m}$) is not acceptable for a bearing raceway. Also the waviness produced by ECM could not be improved sufficiently for bearing applications,

this increase in waviness is a result of exposed MnS inclusions, which cannot be removed by the ECM.

A simple test to verify the influence of these MnS inclusions on waviness was to apply an abrasive tape to rub the surface and remove these surface peaks. This was found to reduce the waviness, which indicates that these inclusions are the primary cause of the higher waviness introduced by the ECM. The thin black line is also removed.

5.2 ECM followed by superfinishing tape

The application of a minimal abrasive process onto the work surface after ECM to remove the MnS exposed hills would still be a simple process. A simple tape finishing attachment was used to statically apply a superfinishing tape.

The previous work had used honing stones but these are more difficult to control due to stone loading and self-dressing of the stone. Also the use of water as the lubricant/coolant is not common with honing stones, which usually uses neat honing oils for lubricity. Superfinishing tapes are simpler to apply than stones; they have a more controlled cutting topography and are more commonly used with water based cutting fluids. Superfinishing tapes are normally employed with a step or continuous feed system and tape oscillation. Since the abrasive was only to remove the MnS peaks, high material removal capability was not considered necessary; therefore a static superfinishing attachment without feed was considered adequate and simpler.

To remove the MnS inclusions in a controlled way a static tape superfinishing attachment was used to apply different tape superfinishing tapes in order to investigate the improvement in waviness. 9 μm and 3 μm alumina, 9 μm CBN and 1 μm diamond superfinishing tapes from 3M were tested on the ECMed surface (from honed input). The results showed that 9 μm CBN was able to cut the ECMed surface better than alumina. The SEM micrographs figure 4.33, clearly show the cut surface and even an MnS inclusion, which has been cut. The alumina tape finished surface appears more burnished and the MnS inclusions are clearly visible. The waviness after applying the tapes is also improved to levels similar as standard honed. The input waviness has an influence on the final waviness. Before and after polar plots figure 4.35, show that the shape of the ring has not changed which means very little material has been removed, only the MnS peaks. This indicates that maybe a greater amount of material removal is needed to improve the waviness further. An additional side effect of adding the minimal abrasive superfinishing tape is that the other surface finishing parameters such as R_a , R_{tm} and slope have all been further improved as shown in table 5.3.

Table 5.3: Showing the improvement in surface finishing by applying 9 μm CBN superfinishing tape to an ECMed surface

	ECMed surface + 4 seconds 9 μm CBN
Ra μm	0.025
Rtm μm	0.157
Rsk	0.1
Rpm μm	0.074
Δq slope degrees	0.31

5.3 Electrofinishing with superfinishing tape

The above showed that the waviness could be improved by removing the MnS peaks to levels similar to honing but also other surface finishing parameters could also be improved to a higher quality than honed, see tables 5.3 & 4.3. The above results were from a honed surface, which was ECMed for 8 seconds and then an abrasive was applied for 4 seconds. The next step was to apply the abrasive and ECM together at the same time on a ground surface. The reason for applying them at the same time was to reduce the cycle time but also to remove MnS hills as they form. The MnS hills are obstacles to electrolyte flow, which can cause turbulence or vortices, which will affect the roughness generated by ECM.

Tests were performed using the 9 μm CBN tape because it showed the best cutting action. Using the NaNO_3 electrolyte, tests were done applying the tape only and then electrofinishing with the superfinishing tape. Tests using the superfinishing tape only clearly indicate that the tape can initially improve the surface finish, removing surface peaks but after 4 - 6 seconds the process becomes unstable as the tape is worn and becomes loaded. The Ra and Rtm start to increase because of non-uniform cutting. The skewness gives a clear indication that the tape cannot remove the bulk material as the skewness initially becomes more negative as the peaks are removed but only gradually starts to increase after the cutting reaches the valleys.

When tape superfinishing is combined with ECM, the Ra and Rtm decrease more uniformly to a lower level, but also the skewness becomes more negative but then begins to rise as it cuts the bulk material, removing the valleys left from grinding.

During the first few seconds the tape only and electrofinishing improve surface finish in a similar way indicating that the surface finish improvement is a result of the abrasive action. The slope of the combined process is much lower than tape only which also indicates that the ECM is rounding off sharp asperities.

The ultimate level of surface finish was similar to a honed surface but not as good as the previous ECM followed by superfinishing. This indicates that the superfinishing tape even during electrofinishing still becomes loaded and stops cutting at some point and only burnishes. However the tape loading appears to be reduced and the process becomes more stable. The use of higher tape pressure increases the initial rate of surface finishing indicating the surface finishing mechanism is abrasive controlled. However using a higher pressure also shows such instability particularly in the Rpm at around 6 seconds of electrofinishing, which corresponds roughly to when the skewness increases i.e. bulk material is being removed.

The results indicate that the abrasive is performing the improvement in surface finishing while the ECM allows the tape to work longer before it becomes unstable due to loading. Loading of the tape still occurs with electrofinishing, as indicated by the blackening of the tape after use, but this loading appears to be delayed or the rate of loading decreased allowing the tape to machine for longer and more stably. However the optimum surface finish achievable is limited due to the loading of the tape, which then stops cutting and only rubs.

Tape electrofinishing at different work speeds also indicates a material removal effect on the ECM process. An influence of speed on material removal during ECM had been demonstrated by the previous work but not as large as shown in this work. It is believed to be related to the formation of oxide and its removal.

The ECM operation is in some way dressing the tape reducing the rate of loading. The abrasive is responsible for the improvement in surface finish so for fast cycle times an aggressive abrasive process is needed i.e. higher pressures and tape speeds, in such circumstances the tape must remove more material quickly so the tape becomes used up or loaded.

5.4 Electrofinishing Process using Honing Stones

From the above it is clear that the abrasive mechanism of electrofinishing is not a minimal material removal process but must perform the surface finishing to remove the ground surface. This is particularly the case if very fast cycle times are to be achieved. It would be possible to use superfinishing tapes in such instances however tape feed would be needed with oscillation to improve the material removal capability. Commercially available tape superfinishing attachments are large and would not fit into the test rig and also because of the corrosive electrolyte, a special tape superfinishing attachment made from stainless steel would be needed.

A honing stone superfinishing attachment had been used in the previous work. This attachment was made from stainless steel and provided stone oscillation and honing pressure. This attachment had been improved to increase its stiffness compared to the previous work. Honing stones have a greater material removal capability than tapes due to their self dressing ability. During honing the honing stone wears providing fresh cutting grits to maintain a higher material removal rate.

A number of honing stones were tested. The first tests were performed on a soft grade SiC stone (SC9 1200 04 60 VGL), which had been used in the previous work and had given very good results. The results showed that honing only and electrofinishing had similar rates of improvement of Ra and Rpm, which again indicates that the abrasive is performing most of the surface finishing. The main difference is found by examining the skewness and Rtm. It is clear that with electrofinishing the honing stone is able to remove the surface peaks but is also able to remove bulk material and the valleys left from grinding. With stone honing only in the electrolyte as a lubricant, the stone can cut the surface peaks but once it reaches the bulk material, stops cutting and only rubs the surface. The honing stone after electrofinishing appears clean, while with honing only the stone can have a few black lines indicating stone loading. The results again suggest that the abrasive process is improving the surface finish while the ECM is in some way reducing stone loading and allowing the stone to maintain cutting for longer and so removes the ground surface. The rate of surface finishing was very fast; within the first 4 - 5 seconds the ground surface had been totally removed giving a very good surface finish.

A ring, which was electrofinished for 6 seconds from a ground input, gave a $0.03\text{ }\mu\text{m}$ Ra. However the surface finishing was not quite as good as the previous work, although the cross track profile was now improved, likely as a result of the stiffer honing attachment, see figures 4.65 and 4.66.

It was found that by applying the honing stone for an additional 2 seconds after the electrofinishing gave similar results to the previous work. These 2 seconds of honing removes the thin black line from switching the current off but also burnishes the surface improving all surface finishing parameters, table 5.4.

It appears that some loading is actually required during honing to achieve higher surface finish. Conventional SiC stones are designed to cut at the beginning and gradually as the cutting grits become smoother and loaded, the surface finish begins to improve. The loaded stone is then redressed by the next rough workpiece. Also with abrasive tapes, coarse grit can be used initially to achieve the required removal rate, but as the tape becomes loaded the height of grit protrusion is reduced and the depth of cut is reduced and surface finishing occurs. The loading of the tapes and stones is uncontrolled so can give instability in cutting.

The waviness in the medium band, which was the main concern from the earlier ECM only work, was now much improved and even better than honed quality. However the low order waviness had deteriorated. More significantly the number of peaks removed by filtering during the calculation of waviness had been reduced indicating a cleaner, more uniform surface. It is also evident from comparison of scanning electron microscope micrographs of standard honed and electrofinished surfaces, figures 4.71 and 4.72, that the electrofinished surface as well as being smoother is also much cleaner with no leafing. This is likely a result of the ECM operation cleaning/deburring the surface of debris and leafing. This can also explain the reduced loading on the stone since this leafing could clog/load the honing stone on subsequent passage across the stone cutting face.

Table 5.4: Showing the surface finish achieved by electrofinishing

	Average of previous electrofinished samples	6 seconds electrofinished in present set-up	5 seconds electrofinished + 2 seconds honing only
Ra μm	0.026	0.031	0.019
Rtm μm	0.174	0.318	0.174
Rpm μm	0.055	0.077	0.051
Rsk	-0.8	-2.8	-1.5
Δq slope degree	0.24	0.48	0.33

It was noticed during testing that the stone appears to wear very rapidly. For a rough estimation of this wear, plastic micron shims were used to measured very roughly the stone wear before and after electrofinishing. The wear was found to be very large greater than 300 μm per cycle, this corresponds to a finishing ratio or G ratio of ~ 0.1 . This is a very low G ratio and would never be economical as a production technique. This high stone wear is a consequent of the very aggressive material removal, the soft honing stone and poor lubricity of the electrolyte. Such stones have been used in production without severe wear but they employ neat honing oils to give lubricity.

This high degree of stone wear is also thought to be the reason for the deterioration in the low order waviness as most of the stone wear occurs during the few seconds when the soft honing stone makes contact with the rough ground ring. The rapidly changing honing stone with changing cutting characteristics could result in a change in ring shape of a micron or less, figure 4.68.

To improve the stone wear, a harder SiC stone and a vitreous bonded CBN stone were tested. The harder stones were found to load more readily giving uneven cutting.

It is considered therefore that the rapid surface roughness improvement is primarily a consequence of the honing process. The ECM process only helps to prevent "loading" of the stone.

5.5 Electrolytic in-process dressing

The work on electrofinishing with honing stones indicates that very good surface finishes can be achieved in a single operation using fine grit honing stones. However these results used soft SiC stones, which wear too rapidly for an economical process. The use of harder stones resulted in unstable cutting due to stone loading. Although there are not many references to electrochemical honing, particularly as a production technique it is clear that

the main difficulties arise from the incompatibility of the liquids involved. Honing generally uses neat honing oils for lubricity, while ECM must use a conductive salt solution.

From the electrofinishing work it was believed that the electrochemical machining was reducing the rate of stone loading, allowing the superfinishing stone to cut for longer. The ECM action removes any leafing or any adherent/ rolled over metal thereby preventing it re-entering the cutting zone and loading the stone. It was then decided to investigate a more direct form of electrolytic dressing of the actual stone itself, similar to that used for ELID grinding wheels¹⁶⁵. To apply electrolytic dressing to the stone, the stone needs to be conductive.

Electrolytic In-process Dressing of grinding wheels (ELID) prevents loading of the wheel surface by forming an oxide layer on the metal bond wheel surface by an electrolytic action. The technique allows fine grit abrasive wheels to maintain stable fine finishing without the problems of loading and clogging often associated with higher material removal using fine grit abrasives.

ELID grinding was discussed in the literature survey, however applying such a system to a honing stone is not possible since a grinding wheel has the complete wheel circumference allowing electrolytic dressing and grinding to be performed simultaneously. However a honing stone has only one active cutting face, which is always in contact with the workpiece during the honing operation. Some work has been referenced using ELID superfinishing¹⁶⁴, which employs a fine grit metal bond wheel with oscillations. So although it produces very high quality surfaces and the electrolytic dressing current can control the wheels cut ability, it differs for stone honing in regard to contact geometry. A grinding wheel makes a line contact while a honing stone an area contact which has implications for achievable waviness.

A number of stones were provided by Wendt Boart. Initial work started on cast iron metal bond CBN stones which is often used in ELID grinding. This work made the workpiece the cathode and the metal bond honing stone the anode. ECM dressing was tested either continuously while the honing stone was in contact with the workpiece or discontinuously by separating the stone and workpiece before applying current. This work showed that ECM dressing did expose cutting grits particularly with the discontinuous form of dressing. However it was very difficult to true the metal bond stones and bed them in to cut uniformly over the entire ring surface. In a production machine with a greater stiffness from using a roller bearing spindle the truing may be easier.

It was then decided to test conductive resin bond diamond honing stones. These stones were made conductive by using copper filler in the resin. The resin bonded were much softer and easier to true, however the copper did not form a thick oxide layer during electrolysis instead the layer would rub off easily resulting in sparking and even copper plate-out onto the workpiece.

During the electrolytic dressing trials it became clear that the formation of a barrier layer was important for best operating conditions. Like ELID, maintaining and repairing this insulating layer is necessary for stable machining. The break down of this layer has drastic

results on surface finish and appearance of the raceway. Tests with the conductive resin bond diamond stones using the NaNO_3 electrolyte and a pulsed power supply showed two main problems, sparking and copper plate-out. Although the results are far from complete a number of conclusions can be drawn.

1) Sparking

Much of the roughness and waviness data generated had been adversely affected by micro sparking between the stone and the workpiece. This resulted in surfaces with large valleys. Possible causes for this sparking include:

- i) Short circuiting from cutting chips breaking through the insulating layer and making electrical contact with the conductive stone, figure 5.1.

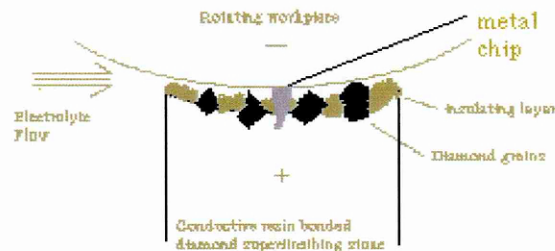


Figure 5.1: Showing possible sparking mechanism

- ii) Contact erosion of the insulating layer, which causes the breakdown of the layer. Any damage in the layer will provide the path of least resistance and a high current density will pass resulting in much heat and by products forming. If the flushing is poor then conditions will prevail for the initiation of electric discharge and workpiece damage.

Two techniques have been found in the literature, which actually utilizes this sparking.

a) A technique known as electrocontact discharge machining (ECDM)²⁰⁰ works in a similar way, by using the abrasive erosion of an insulating layer which occurs at the closest contact point, leading to discharge and material removal where the layer has been removed.

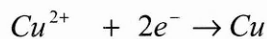
b) A hybrid process of electrodischarge machining and electrochemical machining²⁰¹ also works in a similar way. EDM is used in the manufacture of dies to achieve higher dimensional accuracies and ECM can be used for the surface finishing operation. However for ECM an electrically conductive medium must be used and for EDM an oil is often used. These two fluids are not compatible so two machines or two fluids (with cleaning and flushing of the system) must be used. Research has shown that it is possible to use a

conductive fluid for the ECM and by allowing gases, by-products and heat to build-up in the gap will result in electric discharge.

2) Plate-out of Copper

On a number of occasions copper from the superfinishing stone was found to plate the workpiece. This plating had occurred where the insulating layer on the stone had broken down. Again the broken part of the layer would concentrate metal dissolution at that point. The gap between the workpiece and stone is very small, a few microns. So even with low voltages ~ 10 Volts, the potential gradient V/cm or electric field is very large causing the Cu^{2+} ions to travel to the negative workpiece, and plate-out.

Previous work on pure electrochemical machining of NU 207 inner rings did not suffer from plate-out, because the Fe^{2+} ions reacted with the electrolyte forming a solid precipitate $\text{Fe}(\text{OH})_2$. However the copper did not form a solid precipitate so was able to plate-out.



Transfer of copper from the stone to the workpiece was also observed occasionally after sparking depending on the dressing conditions (pulse frequency, duty cycle and peak current).

From the above the basic requirements for the oxide layer can be considered

a) Maintenance of stable inter-electrode gap,

A gap between ring and stone is required so that the electrolyte can pass and the electrochemical reaction can occur. Therefore an insulating spacer is required to separate the stone and the ring. Possible ways to achieve this include i) abrasive grains protruding on stone surface preventing surfaces coming into contact ii) oxide/hydroxide layer forming a barrier layer preventing surface contact.

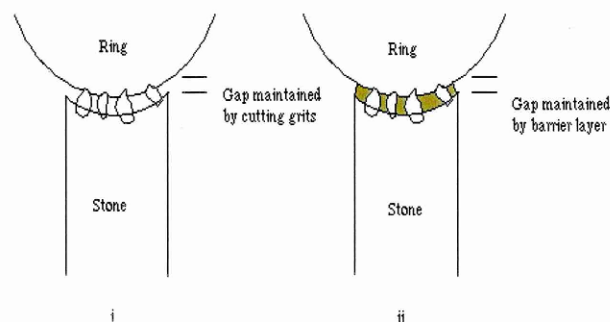


Figure 5.2: Possible methods to separate surfaces during in-process dressing

b) Spark prevention

i) Sparking can occur during chip formation and abrasive wear of the barrier layer. As the metal chips are formed they can break through the barrier layer and cause short circuits and sparking. Abrasion of the workpiece against the barrier layer can also cause wear and damage to the layer leading to sparking.

The bond material needs therefore to be selected so that repair of the damaged layer occurs rapidly and any oxide formed has a degree of wear resistance.

ii) Sparking from excessive heat in the gap.

The passage of a current across the gap results in heating and the formation of reaction by-products like O_2 and H_2 gases. This combination with very small gaps will lead to sparking.

The use of high frequency pulsing reduces the amount of heat and by-products formed and during the off period the gap conditions are restored. Good flushing of gap and good flow of electrolyte in the gap is also a requirement.

However the electrolyte must be able to enter the gap for the electrolysis or electrochemical reaction to occur. Therefore to maintain the electrochemical reaction this layer must be porous to allow electrolyte into the gap.

The layer could even help in the material removal or surface finishing, countering the sharp cutting of diamond or CBN grits producing an alternative surface finish. Such a technique is used with abrasive blends⁹³, where SiC and alumina are mixed together, thereby combining the surface finishing of SiC with the material removal properties of alumina.

The metal filler and its electrochemical properties together with hardness, wear resistance and structure of any chemically formed layer must be considered when considering a suitable conductive resin bond.

Possible metal fillers considered for the resin bonded honing stones included iron, since it is often used in ELID and aluminium, also tested was a mixture of 50% Al / 50% Fe.

Aluminium was considered because it is very reactive, forming oxides rapidly. Anodising of aluminium to increase the thickness of this oxide layer is a commercial electrochemical process. The oxide layer is made up of two layers, a) very thin oxide layer 1-2% of total layer thickness and b) porous oxide outer layer, figure 5.3.

The porous layer can provide space for electrolyte and chip flow while providing the insulating barrier needed to maintain the inter-electrode gap. The physical properties of the oxide layer formed can be change by using different Al alloys or by varying the process parameters such as current density and electrolyte e.g. phosphoric acid for higher porosity.

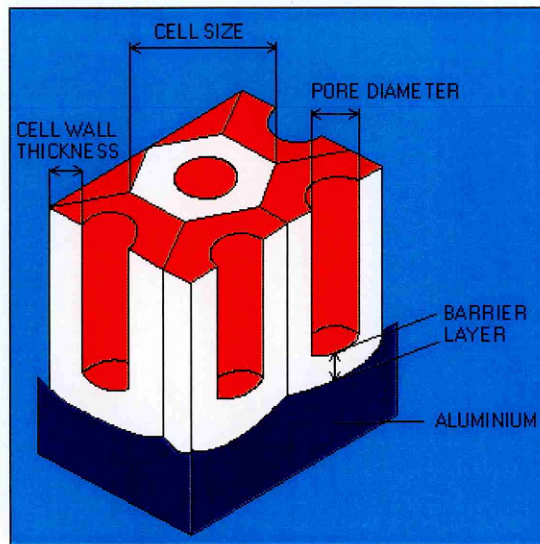


Figure 5.3: Schematic representation of oxide layer on aluminium

Although little actual testing was performed using this metal filled resin bonded honing stones, their dressing behaviour was studied. V-I characteristics show that the iron forms too thick an oxide layer, which is weak and falls off. This is evident from the increasing voltage as the layer forms but then begins to fluctuate as the layer breaks off, figure 4.95. The aluminium forms a thinner compact oxide since the voltage rises very quickly and the current drops very quickly, figure 4.97. The mixed Al/Fe stone showed intermediate behaviour, figure 4.96. SEM micrographs of the stone surfaces also show that the Fe formed a thick crumbly oxide while the aluminium stone were very porous figures 4.98 - 4.100.

Porous stones could have big advantages in superfinishing and there are reports where honing stone manufacturer¹⁰⁰ deliberately add porosity to CBN honing stones to allow the lubricant into the cutting zone, but also to provide pockets for chip flow out of the cutting zone reducing stone loading.

One possible problem with the above method is that the workpiece is made the cathode and therefore hydrogen is produced at the workpiece, which could cause hydrogen embrittlement. From examination of the literature on hydrogen embrittlement it became clear that a possible real problem existed. Electroplating²⁰² of coatings indicate an embrittling affect (fatigue life reduction), which was attributed to hydrogen generation accompanying the electroplating reaction. Here the workpiece is again the cathode. The plated workpieces are then baked at $\sim 200^{\circ}\text{C}$ for a few hours to drive out the hydrogen, (standard practice in the electroplating industry) which restores the fatigue life to approximately the original value. Other research papers²⁰³ actually used an electrolytic

method to deliberately charge a workpiece surface with hydrogen; here again the workpiece is the cathode. In this work chemicals were added to the solution to poison (prevent) the hydrogen atoms recombining at the surface but instead to force them to enter the workpiece surface. As the hydrogen concentration in the surface increases, a corresponding decrease in fatigue life was found.

For electrolytic dressing of metal resin filled stones the possible implications of hydrogen embrittlement are not fully known. However the current is applied for much shorter periods of time; seconds instead of minutes. The surface is continually flushed with liquid. It could be possible to use a secondary electrode placed near the stone instead of the workpiece as the cathode, but the electrolyte would need to have high throwing power.

At this point it was decided to drop the direct electrolytic dressing concept and return to the original electrofinishing idea. The reason for this change was that the limited evidence on direct electrolytic dressing suggests the process could give a very good surface finish but would have a longer cycle time (~20 seconds) but the risk of hydrogen embrittlement was the biggest concern.

5.6 Electrofinishing with lubricant

The electrofinishing work had shown that very fast cycle times could be achieved. There were only two problems 1) stone wear and 2) low band waviness. Both these problems are linked to difficulties with the honing operation resulting from using a water based salt solution instead of the usual neat honing oil with high lubricity.

To try to improve the honing operation, a water-soluble synthetic lubricant was added to the electrolyte. The lubricant is designed to be in solution up to a certain temperature called the cloud point where upon it comes out of solution forming oily droplets. A number of different cloud point lubricants were provided by Cimcool B.V but the one with the highest cloud appeared to give the best results, however the cloud point was affected by the salt concentration so the lubricant with cloud point of 57 °C at 0 salt concentration dropped to ~ 30 °C at 30 wt.% NaNO₃.

Electrofinishing with the soft SiC stone using the lubricant/electrolyte mix gave similar results to electrofinishing without. The stone wear also fluctuated from 100 µm to over 300 µm. This indicates that the stone is too soft. The use of the harder grade SiC stone now worked better, but did not always totally remove the ground surface and became clogged occasionally, although the stone wear was lower ~ 100 µm.

The lubricant had a dramatic effect on the performance of the vitreous bonded CBN stones. Previously without lubricant they became clogged very quickly and gave non-uniform surface finishing. With the lubricant added at 0.5 wt.%, the stones worked without too much difficulty once they were trued and bedded in. The 14 x 10 mm, I grade CBN stone showed very aggressive cutting. Within 4 seconds the stones had totally removed the ground surface, however it generated cross track waviness. To reduce this waviness, the

pressure was reduced, this lowered the cross track waviness, but also lowered the stone wear from $\sim 10\text{ }\mu\text{m}$ to $\sim 2\text{ }\mu\text{m}$.

A more exact method of measuring the stone wear was now employed using a LVDT and a rod, which could be located at the back of the honing stone during measurements.

At lower pressures the stone either didn't cut or would start cutting but wouldn't cut the next workpiece indicating that the stone was too smooth to generate the initial cut. It also indicates that some stone wear is needed for a stable repeatable process.

When the process did work, very good surface finishes could be achieved very quickly but also the waviness in the low and medium band were good and the stone wear small, being only $2\text{ }\mu\text{m}$ per workpiece. This means if the production rate was 800 ring/hours, a honing stone with 10 mm of CBN would last over 6 hours. This gives savings in production down time while a honing stone must be changed and the new ring quality ensured. A conventional stone, which could be 60 mm long, would only last maybe one hour.

The remaining problem was that the CBN was cutting too aggressively giving cross track waviness. Lowering the honing pressure decreased this waviness but then the stone stopped cutting. Attempts were then made to use different grade stones with different stone widths. With the lubricant/electrolyte mix applying these stones was easy, and they all cut very aggressively and removed the ground surface within 4 -5 seconds. A 2 x 14 mm J grade #4000 CBN stone was tested at two pressures; again the higher pressure gave the higher rate of surface roughness improvement. The material removal graphs, figures 4.106 and 4.107, shows that the slope of the least square fit line at the two pressures are similar indicating the majority of the material is governed by the ECM, while the y intercept on the diameter reduction axis is higher for the higher pressure indicating that slightly more material has been removed by the abrasive process at the higher pressure. Using the higher pressure and the thinner stones gave higher stone wear 10 -18 μm per workpiece, which although not affecting the cross track profile did affect the low order waviness or the shape of the workpiece (compared to the 10x 14 mm I grade #4000 CBN stone) either because of the thin stone size or the higher stone wear. In 6 seconds the 2 x 14 mm J grade stone could produce 0.016 μm Ra surface from a ground surface of $>0.3\text{ }\mu\text{m}$ Ra, the cross track was good and the waviness acceptable, however the wider stone did give better waviness. The other attribute of the process is the controlled material removal, which is dependent on the time and current. The results indicate that an accuracy of $\pm 1\text{ }\mu\text{m}$ is achievable.

A clear difference between electrofinishing with SiC and CBN stones was the visual appearance of the rings. With CBN the rings looked cut while with SiC, the rings looked shiny and more polished. The roughness traces also showed a clear difference. With SiC the surfaces showed a more negative skewness indicating deeper valleys while for CBN the R_t and the R_{tm} were similar but also the peak heights and valley heights were similar which gave a skewness of ~ 0 which fluctuated to positive or negative with a single peak or valley respectively. The higher stone wear of the SiC stone is likely forming a few deep valleys resulting in the more negative skew. One of the requirements for bearing surfaces is a negative skew. The other surface finishing parameters are easily met by electrofinishing with CBN or SiC. The other noticeable feature of electrofinishing is the very low slope

(Δq). This makes electrofinished surfaces different from other bearing surfaces. In the literature survey it was shown that low slope surfaces could improve bearing life. These new surfaces have not been tested yet for improved bearing functionality.

The results show that electrofinishing with CBN stones has been made to work more consistently by adding the lubricant. A more stable process was developed using the thinner honing stones but the stone wear (up to 18 μm) was too high for the more expensive superabrasive stone. The best results were obtained with the 10x14 mm I grade #4000 CBN stone which had a lower stone wear rate but also even better waviness, however the process was more unstable due to the stone not being able to make the initial cut when applied to the rough ring. This is believed to be a result of the stone cutting surface being too smooth or loaded, although the stone did not look loaded. Better application of honing by direct flooding of the stone to wash away cutting chips should also reduce the loading and improve the stability of the process.

5.7 Electrofinishing of turned surfaces

While investigating a possible mechanism for the rapid rate of surface finishing by electrofinishing a number of possible mechanisms were considered. To test these theories experiments were performed on turned rings but also on high-speed steel. The results are discussed below and afterwards an overview of the possible mechanisms considered.

5.7.1 Turned rings from 100Cr6

Results using electrofinishing on turned surface of 1.3 μm Ra indicate similar results to ground ring. Using 2x14 mm J grade #4000 CBN stone, the rate of surface roughness improvement was faster at higher stone pressure indicating the abrasive process is dominant in determining the rate of surface finishing. The stone wear was higher on the turned surfaces (up to 17 μm) as would be expected since the input roughness is higher. The material removal is again highly controlled with a y-axis intercept of around 9 μm for the higher pressure and 8.3 μm for the lower pressure. The R_{tm} for the turned surface is around 4.5 μm , which is equivalent to 9 μm on diameter. The y-axis intercept is then an indication of the material removed by the abrasion and the slope is the material removal rate by the ECM. When ECM is applied on its own the rate of surface finishing is slow, with the ECM copying the surface and only gradually improving Ra.

A surface of < 0.02 μm Ra could be produced in 6.2 seconds by electrofinishing, however the cross track profile had been changed. Rings previously used in trials were turned with a flat profile. This profile was changed into a convex surface of peak to valley 2 μm during electrofinishing. The reason is believed a result of the honing operation. Turning the rings had increased the track width while the honing stone was the same size.

The waviness of the electrofinished turned rings were improved. The roundness from turning was very bad but was always improved by electrofinishing. The medium band and

high band waviness were also good except for a few spikes on the surface affecting the single track waviness measurements most likely a result of loading or adherent material. It is believed that better flushing of the honing stone will further improve the results.

5.7.2 Turned rings for M2 high speed steel

While considering possible mechanism for electrofinishing, oxide formation was a likely candidate. M2 material is highly alloyed and when ECMed formed a thick black coating. A number of turned rings made from M2 material were electrofinished using 9 μm CBN statically applied superfinishing tape.

Tests were done initially using ECM only which showed the surface finish improved slowly to a limit of $\sim 0.13 \mu\text{m Ra}$ after 5 minutes, which gave a diameter removal of > 500 microns. The surface after machining was covered in a black coating, which could be washed off, but a grey coating still remained. The surface finish was limited because of the microstructure figure 4.120, which consisted of small carbide particles, which were not removed by the ECM as with MnS inclusions in 100Cr6. Applying a tape removes these carbide particles.

Tests applying electrofinishing with the 9 μm CBN tape and indexing every 10 seconds clearly indicate the presence of an oxide coating which has been broken up by the abrasion, figure 4.125. If the superfinishing tape is left on longer after the ECM current is switched off, the oxide layer is totally removed and the surface finish improved to $0.06 - 0.09 \mu\text{m Ra}$ and the surface appears cut. The more rapid rate of surface finishing (25 seconds) means less material is removed by the ECM, less than $60 \mu\text{m}$. It was found that by more effective use of the abrasive by indexing could reduce the finishing time further again indicating the abrasive as dominating the surface finishing process. The rate of surface finishing by electrofinishing was however significantly faster than the superfinishing tape on its own, which indicates a beneficial interaction, either by reduced tape loading as considered before, or related to the oxide formation as discussed below.

5.8 Possible electrofinishing mechanisms

Possible mechanisms for the fast surface finishing achieved by electrofinishing using fine grit honing stones and superfinishing tapes are considered below. As mentioned, usually a through feed or two stage honing is often used to achieve high material removal and fine surface finishing. However electrofinishing has been shown to give very good surface finishes $< 0.02 \mu\text{m Ra}$ in short cycle times 5 - 7 seconds from ground ($> 0.3 \mu\text{m Ra}$) but also turned ($1.2 \mu\text{m Ra}$) input quality rings using fine grit abrasives and ECM. Statically applied superfinishing tapes were found to work more stably, while honing stones showed more aggressive cutting and were able to completely remove the ground surface. The surface was also shown to be very smooth and clean without leafing and debris. The other noticeable feature was the very low Δq surface.

Possible mechanisms include:

1) Oxide formation on the workpiece resulting in reduced loading of the abrasive allowing it to work for longer or harder. Brittle oxide chips are less likely to load the abrasive than longer ductile ferrous chips. Chips formed are also contaminated so are less likely to hot weld or adhere to stone/tape. Evidence for reduced loading include:

a) Honing stones, which show high material removal, also show high stone wear rates, since the aggressive cutting action generates self-dressing. Electrofinishing using the soft SiC stone showed very high stone wear combined with high abrasive material removal. The ground surface was completely removed. When the SiC stone is used without the ECM the stone could remove the peaks but not the bulk material. Therefore when combined with ECM the honing stone can maintain its aggressive cutting action longer so continues to self-dress and wear.

b) Reduced tape loading was clearly demonstrated when electrofinishing with 9 μm CBN superfinishing tape. The electrofinishing process with superfinishing tape was more stable and could remove more material compared to just superfinishing tape alone.

2) ECM action forms an oxide layer on the surface of the workpiece, the abrasive removes this oxide only at the peaks, so that ECM is concentrated on the surface peaks the next time it passes under the electrode. This increased removal at the peaks is probably for a short time at which point the remaining oxide layer is removed by the ECM action and removal occurs over the entire surface. When the workpiece leaves the electrode zone a passivating layer is reformed for the abrasive to abrade again. A thick oxide layer was not present on 100Cr6 bearing steel, but was more clearly demonstrated on the high-speed steel.

a) Electrofinishing of turned M2 rings gave a surface finishing rate not possible by abrasive only. Superfinishing tapes usually are considered to improve the surface finish by $\sim 1/2$, therefore usually a sequence of superfinishing tapes are used to achieve high surface finishes. Also black oxide could be seen in the turned grooves during electrofinishing therefore the abrasive is not touching the bottom of the grooves. The black oxide would present a polarization layer for the ECM, making the ECM more selective on the peaks.

3) Electrochemical mechanical polishing ECMP similar to chemical mechanical polishing CMP, where the surface is oxidized to form a friable oxide, which is easier to remove/rub off than the ductile ferrous chips. Evidence for such a mechanism include:

a) thick black/grey layer (oxide ?) seen on M2 rings. Figure 4.125 clearly shows the abrasion of the layer.

b) for 100 Cr6 oxide formation not as clear although black surfaces can be formed by changing the ECM conditions. It is believed that a thin oxide layer is present on 100Cr6,

which may even increase the corrosion resistance since a number of electrofinished rings from the previous work show little sign of corrosion.

4) ECM action is very efficient at removing sharp edges or burrs. The burrs concentrate the electric field and current, increasing the material removal at the burr. Therefore the use of an abrasive, which continually generates a fresh sharp cut surface, will lead to increased removal from the peaks. Also the new cut surface will be more active i.e. less oxide formation, possibly giving higher electrochemical removal efficiency.

a) Figures 4.72 and 4.105 showed the very clean and smooth surface without leafing and debris after electrofinishing

b) Waviness data also showed less peaks removed by filtering during the calculation of waviness, figure 4.69, indicating the surface has less anonymous peaks.

5) A brittle oxide would give fine very hard particles, which would aid in the erosion of the bond, increasing stone wear and therefore maintaining cutting ability. Fine oxide particles could also aid in fine surface finishing of the workpiece.

6) Cleaning the raceway of cutting debris and leafing, which could load the stone or tape on subsequent passage into the cutting zone. The ECM would then reduce the rate of loading.

Of the possible mechanisms suggested the most likely is the cleaning of the workpiece by the ECM removing leafing and debris, which would reduce the loading on the superfinishing stone and tapes. The superfinishing stone or tape can then maintain its cutting action for longer. The results all show that the abrasive is dominant in surface finishing, and that the rate of surface finishing by honing only and electrofinishing with the SiC stone were similar except that with electrofinishing the honing stone could cut for longer.

For M2 other mechanisms are possible. The oxide layer formation is more pronounced with this high-speed steel. The high-speed steel has greater alloying additions Cr 3.8-4.5 %, Mo 4.7 - 5.2 %, V 1.7 - 2% and W 6 -6.7 % compared to bearing steel. The more brittle oxide material would produce less loading than the more ductile iron chips. An alternative mechanism could incorporate a chemical mechanical polishing (CMP) action where the surface is oxidized by the ECM and abraded by the abrasive tape, where upon it is re-oxidized. A further mechanism could result from the abrasion of the oxide layer at the peaks, which will then be attacked more aggressively by the ECM action giving rapid smoothing of the turned profile.

6. Conclusions

6.1 ECM (electropolishing)

1) The surface finish achieved by ECM depended on input surface finish. A ground surface of $0.3 \mu\text{m Ra}$ could be improved to $0.12 \mu\text{m Ra}$ in 16 seconds, while a honed surface of $0.06 \mu\text{m Ra}$ was improved to $0.04 \mu\text{m Ra}$ in 8 seconds.

2) ECM has high and accurate material removal capability depending on current and time according to Faraday's law. In 16 seconds 43 microns were removed from diameter (using 100 amperes and a workpiece speed 1100 rpm), with an accuracy of $\pm 1 \mu\text{m}$.

3) The waviness after ECM was very poor as a result of exposed MnS inclusions within the bearing steel, which are non-conductive and are therefore not removed by ECM.

4) The rate of surface finishing was too slow and the surface finish produced was not sufficient for a bearing surface. The material removed to achieve this surface finish was also too large, which when combined with the poor waviness indicates ECM cannot be used for bearing raceway finishing.

6.2 Electrofinishing (ECM combined with abrasive)

1) Combining ECM with superfinishing tapes clearly shows that the tape can cut more aggressively and maintain cutting for longer times.

2) Electrofinishing with soft SiC stones gave a rapid rate of surface finishing. A ground surface $0.3 \mu\text{m Ra}$ was improved to $0.04 \mu\text{m Ra}$ in 5 seconds and by applying the honing stone only to burnish the surface for an additional 2 seconds a surface finish of $0.02 \mu\text{m Ra}$ was produced, summarized in the table 6.1.

Table 6.1: Surface finished achieved by electrofinishing with SiC honing stone

Surface finish parameter	Electrofinishing 5 seconds	Electrofinishing 5 seconds + additional 2 seconds superfinishing
Ra μm	0.043	0.021
Rtm μm	0.320	0.191
Rt μm	0.560	0.344
Rpm μm	0.095	0.057
Rv μm	0.412	0.340
Δq degrees	0.51	0.34
Rsk	-1.65	-2.2

- 3) The aggressive cutting of the soft SiC stone led to excessive stone wear. The addition of a synthetic lubricant to the electrolyte did not improve the wear rate of the soft SiC stone. The stone was considered too soft. However the CBN stones worked more consistently after the synthetic lubricant was added.
- 4) The CBN stones showed very aggressive cutting removing the 0.3 μm Ra ground surface in less than 5 seconds producing a surface of < 0.02 μm Ra. A turned surface (1.2 μm Ra) was also electrofinished and resulted in a surface finish of <0.02 μm Ra.
- 5) Changing the honing pressure changed the rate of surface finishing, indicating that the abrasive was primarily responsible for the surface finish improvement, while the material removal rate was controlled by the ECM current. Material removal was highly controlled with an accuracy of $\pm 1\mu\text{m}$.
- 6) Surfaces produced using electrofinishing with SiC honing stones showed a more negative skewness compared to CBN electrofinished surfaces. Rings electrofinished with #4000 CBN honing stone appeared more cut, the skewness was nearly zero but fluctuated either positive or negative by a single peak or valley on the surface.

6.3 Electrofinishing mechanism

- 1) A number of possible finishing mechanisms have been suggested. The most likely for electrofinishing of 100Cr6 is related to the ECM operation cleaning the workpiece surface of cutting debris and leafing. This would reduce the rate of loading / clogging of the superfinishing stone or tape allowing it to cut more aggressively.
- 2) For M2 high-speed steel, which showed greater oxide formation ability due to its alloying additions, the mechanism could be related to the easier removal of the oxide compared to the hard metal.

7. Further work

The one main problem to overcome with electrofinishing is to obtain a stable and consistent honing operation in water. The honing operation is critical and presently is not consistent enough for a production process. The stones used during these trials were not designed to work in water but for honing oils. The synthetic lubricant gave a big improvement in the action of the honing stones. However even when the electrofinishing process was working consistently the stone wear rate was too high. Very few problems occurred with the ECM part of the process. Additional improvements should be investigated.

1. Different honing stones which are designed to work in water. There are stones commercially that have special bonds and wax treatment for improved lubricity.
2. Better application of the lubricant onto the honing stone for better flushing of the stone to wash away any honing debris and loose grits. Presently no direct flushing of stone was done although traditional honing always uses lubricant nozzles to flush honing stone.
3. Superfinishing tapes do not suffer the same loading/clogging problems associated with honing stones and are often used with water-based lubricants. This work indicated that rapid rate of surface finishing can be achieved particularly when the superfinishing tape is oscillated. A tape superfinishing attachment with oscillation and tape feed should be able to give good surface finishing but also improve the waviness, which was attributed to loading of the superfinishing tape.
4. ECMed only surfaces have not been extensively tested. The measured higher levels of waviness in the M and H band are a result of soft MnS inclusions, and it is not known how this would effect the bearing noise, particularly after running-in. Life tests have shown comparable life to standard honed rings, which was a concern since ECMed surfaces have lower compressive stresses. Better evaluation of ECMed surfaces is needed since not all bearing surface have such requirements for roughness and waviness.

Additional possible developments, which could be realized using the electrofinishing process include:

- 1) Diameter size control

ECM only and electrofinishing have demonstrated high accurate material removal capability. With a controlled process if the ring diameter is known before machining it is possible to control the ECM current or the time to control the material removed. With electrofinishing most of the surface finishing is accomplished within the first 4 seconds after which rubbing of the surface proceeds. Alternatively an in-process diameter measurement could be used to control the size.

2) Removing low order waviness

It has been shown that by controlling the current during ECM it is possible to produce waves on the bearing raceway. It is therefore also possible to remove low order waviness particularly roundness from the raceway. This would then give improved roundness and low order waviness, which is often not improved by honing but controlled by the grinding operation. The figure 7.1 below shows lobing produced on the ring raceway by controlling the ECM current. By measuring the waviness on the ring and using a feedback to the ECM current, low order waviness can be reduced.

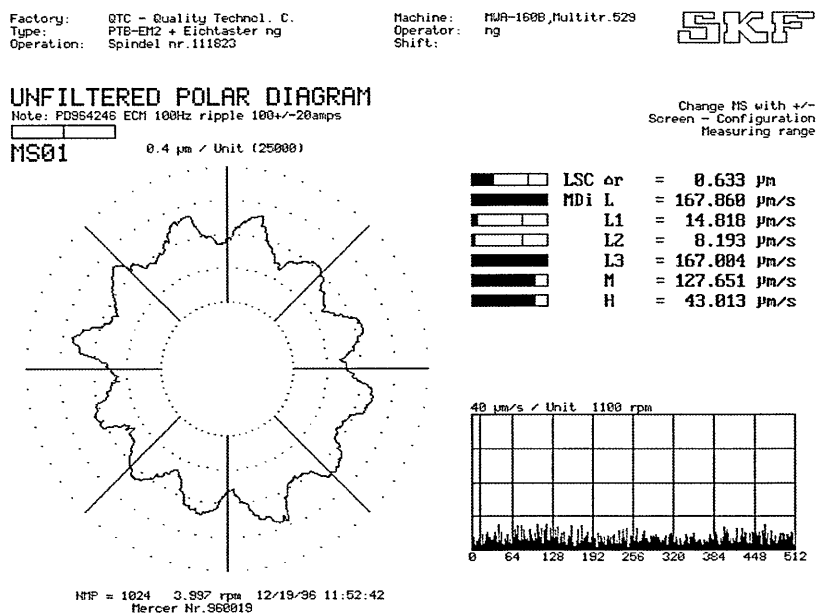


Figure 7.1: Showing 12 lobes formed on the raceway by controlling ECM current

- 3) ECM can be used for profiling which would give very consistent and accurate shape control on the raceways or flanges, although consistent ground input quality is needed.
- 4) Cleaning of surfaces and grooves.
- 5) Surface finishing of hard difficult to machine materials such as M2.

8. References

1. www.skf.com, website for SKF company
2. Puthanangady T.K and Malkin S., " Experimental investigation of the superfinishing process", Wear, 185, 1995, page 173 - 182
3. www.supfina.com, website of superfinishing company Supfina
4. www.thielenhaus.com, website of superfinishing company Thielenhaus
5. Whitehouse D J., Handbook of surface Metrology, IOP Publishing Ltd, 1994, page 724
6. Schwarz J, "Taking the mystery out of superfinishing", Machining Technology Newsletter, SME MTA, 3rd quarter, 7, 3, 1996
7. Varghese B. and Malkin S., " Rounding and lobe formation during superfinishing" SME report MR99-168. 1999
8. De Beers, "Honing", booklet of selected articles from Industrial Diamond Review
9. De Beers, "Honing" video
10. Gerhard H. and Barton K., "Characteristics of honing", SME report MR93-147, 1993
11. Delapena, "Precision Honing Mandrels and Accessories", Company literature
12. Fischer H., "The why, when and how of honing", SME report MR87-814, 1987
13. Engis, " Engis Single-Pass Superabrasive Bore finishing Systems" Company literature
14. Sunnen, " Sunnen: Precision Plated Diamond Honing Tools" Sunnen company literature
15. Hargreaves D.J. and Scot W., "The effect of honing on the frictional resistance of cylinder liners", SME Report MR98-215, 1998
16. Pawus P., "A study on the functional properties of honed cylinders surface during running-in", Wear, 176, 1994, page 247-254
17. Jeng Y-R, "Impact of plateaued surfaces on tribological performance", Tribology Transactions, 39, 2, 1996, page 354-361
18. Pawus P., "A study of the dependence of the functional properties of the cylinder liner surface layer on the operating conditions", Proc. Instn. Engrs., 210, page 17 - 27
19. Michail S.K., "The effect of Roughness on piston ring lubrication-Part II: the relationship between cylinder wall surface topography and oil Film thickness", Tribology Transactions, 38, 1, 1995, page 173-177
20. Michalski J. And Pawlus P., "Effects of metallurgical structure and cylinder surface topography on the wear of piston ring-cylinder assemblies under artificially increased dustiness conditions", Wear, 179, 1994, page 109-115

21. Gehring, "Laserhoning" Gehring company literature
22. Kostka, R, "The basics of coated abrasives", AES magazine, spring 1991, page 32-34
23. Kostka, R, "Microabrasives: a refinement in finishing", AES magazine, 30, 4, page 30 - 31
24. Wellborn W., "Synthetic Minerals-the foundation stone of modern abrasive tools", AES magazine, 31, 1, page 6-10
25. Anselment G., "SG coated abrasive products", AES magazine, summer 1989, page 14-15
26. Patent US5738695, "Abrasive article containing an inorganic phosphate", 3M, 1998
27. Stark C. and Will J.L., " Precision platen grinding with hollow body abrasive system", AES magazine, spring 1991, page 16 - 21
28. Patent US5454750, " Coated abrasive containing erodable agglomerates", 3M, 1995
29. MacPherson W. M., " Abrasive belt grinding" AES magazine, spring 1991, page 9 - 12
30. Marinescu I.D. and Dontu G., " Abrasive belt centerless grinding" Abrasive magazine, Feb/March 1999, page 9 - 13
31. Gagliardi J.J et al., " Some potentially useful parameters for interactive coated abrasive grinding" Trans. NAMRI/SME, XXI, 1993, page 159 - 165
32. Grelle C.J., " Rod, tube and piston polishing" AES magazine, Spring 1991, page 13 - 15
33. 3M, "Superabrasives and microfinishing systems" 3M sales literature
34. Hallum D., "Grinding innovations increase choices" American Machinist, Feb. 1996, page 31 - 34
35. Gagliardi J.J., " A finishing tool for the 21st century", SME report MR95-222, 1995
36. Gagliardi J.J., " Microreplication technology meets coated abrasive demands", Metal Finishing, Dec. 1995, page 15 - 19
37. Gagliardi J.J., " Relating bearing ratio to the performance of structured coated abrasives", SME report MR96-121, 1996
38. Visser R.G. and Dimberg A.P., " Coated abrasive superfinishing: creating functional surfaces on specialty steels and other materials", AES Magazine, Mar./Apr. 1988, page 16 - 31
39. Dimberg A.P. and Amundson S.E., " Roll superfinishing" SME report MR86-276, 1986
40. Gillespie L. K., Deburring and Edge Finishing Handbook, SME, 1999
41. Hashimoto F., "Modelling and optimization of vibratory finishing process", Annals of the CIRP, 45, 1, 1996, page 303 - 306
42. Tulinski E.H., "Centrifugal barrel finishing :more than precision deburring and surface finishing" Metal Finishing, July 1993, page 15 - 18

43. Gilliam R. and Aarons T., "The future of mass finishing", SME report FC98-128, 1998
44. Holland J.C., "Vibratory tubs and integrated vibratory finishing systems" SME report FC98-129, 1998
45. Risko D., "Using electrochemical machining as a competitive advantage", SME report MR90-405, 1990
46. Meleka A.H. and Glew D.A., "Electrochemical machining", International Metals Review, Sept. 1977, page 229 - 252
47. Atkey M., "Transforming blades the Rolls-Royce way", The Industrial Robot, Dec.1985, page 231 - 234
48. www.vmb-babenhausen.de, VMB ECM deburring systems company
49. Crow D.R., Principles and Applications of Electrochemistry, Blackie Academic & Professional, 4th edition, 1996
50. De Barr A.E and Oliver D.A, Electrochemical Machining, Macdonald & Co, 1968
51. McGeough J.A, Principles of Electrochemical Machining, Chapman and Hall, 1974
52. Datta M. et al, "Recent advances in the study of electrochemical micromachining", PED-Vol. 64, Manufacturing Science and Engineering, ASME, 1993, page 675 -691
53. Kops L. and Quach V.B., 'Investigation on the role of workpiece grain size in electrochemical machining process', Journal of Engineering for Industry, Transactions of the ASME, Feb. 1976, page 360 - 368
54. Kops L., " Effect of pattern of grain boundary network on metal removal rate in electrochemical machining", Annals of CIRP, 25, 1, 1976, page 125 - 130
55. Jeng M-C. et al, "The effects of carbon content and microstructure on the metal removal rate in electrochemical machining", Journal of Materials Processing Technology, 38, 1993, page 527 - 538
56. Konig W. and Lindenlauf P., "Surface generation in electrochemical machining", Annals of CIRP, 27, 1, 1978, page 97 - 100
57. Allgaier W. and Heusler K.E., "Steps and kinks on {211} iron surfaces and the kinetics of the iron electrode", J. of Applied Electrochemistry, Vol. 9, 1979, page 155 - 160
58. Hoar T.P., 'The production and breakdown of the passivity of metals', Corrosion Science, Vol. 7, 1967, page 341 - 355
59. Nagayama M. and Cohen M., " The anodic oxidation of iron in a neutral solution I. effect of ferrous ion and pH on the behavior of passive iron", J. Electrochem. Soc., Vol. 109, 9, 1963, page 781 - 790
60. Nagayama M. and Cohen M., " The anodic oxidation of iron in a neutral solution II. the nature and composition of the passive film", J.Electrochem. Soc., 110, 6, 1963, page 670 - 680

61. Bloom M.C. and Goldenberg L., " γ -Fe₂O₃ and the passivity of iron", Corrosion Science, Vol.5, 1965, page 623 - 630
62. Mao K.W., " ECM study in a closed-cell system", J.Electrochem. Soc., Vol. 118, 1971, page 1870- 1876
63. Janssen J., "STEM drilling applications for gas turbine blades", SME report MR91-521, 1991
64. Datta M. and Landolt D., ' On the role of mass transport in high rate dissolution of iron and nickel in ECM electrolytes-II Chlorate and Nitrates solutions', Electrochimica Acta, 25, 1979, page 1263 - 1271
65. Datta M. and Landolt D., " Surface brightening during high rate nickel dissolution in nitrates electrolytes", J. Electrochem. Soc., 122, 11, 1975, page 1466 - 1472
66. Datta M. and Landolt D., "Film breakdown on nickel under transpassive dissolution conditions in sodium nitrate solutions", J. Electrochem. Soc., 124, 4, 1977, page 483 - 289
67. Datta M. and Landolt D., ' On the role of mass transport in high rate dissolution of iron and nickel in ECM electrolytes-I Chloride solutions', Electrochimica Acta, 25, 1979, page 1255 - 1262
68. Wilson J.F., Practice and Theory of Electrochemical Machining, Wiley & Sons, 1971
69. Hardisty H. et al, " A finite element simulation of the electrochemical machining process", Annals of the CIRP, 42, 1, 1993, page 201 - 204
70. Narayanan O.H. et al, " Design of tools for electrochemical machining by the boundary element method", Proc. Instn. Mech. Engrs, vol 200, No. C3, 1986, page 195 - 205
71. Bauer R. and Caughel C.M., "Use of sol-gel technology for high performance abrasives", Abrasives Magazine, March/April 1999, page 20 -28
72. Malkin S., Grinding Technology - theory and applications of machining with abrasives, Society of Manufacturing Engineers, 1989
73. www.ge.com/superabrasives , GE superabrasives homepage
74. Yamamoto A. and Ueda T., "Action of sulfur in treated honing stick I - Contribution to finishing performance through reinforcing acting grits", Bull. Japan Soc. of Prec. Engg., 12, 1, March 1978, page 27 - 32
75. Yamamoto A. and Ueda T., "Action of sulfur in treated honing stick II - Reinforcement of acting grits and restraint of loading", Bull. Japan Soc. of Prec. Engg., 12, 4, Dec. 1978, page 201 - 206
76. Brumgard J.W., "Fundamentals of honing fluids", SME report MR93-145, 1993
77. Koelsch J.R., " Honing fluid performance", Manufacturing Engineering, Feb. 1994, page 51 - 55

78. Carius A.C., " Effects of grinding fluid type on CBN wheel performance, AES Magazine, summer 1990, page 22 - 27
79. Brumgard J.W., " Honing with water based fluids", SME report FC90-321, 1990
80. Kauth R.K., " Synthetics can replace oil in superabrasives applications", AES magazine, June-July 1988, page 20 - 21
81. Bennett B., " Cutting Fluids and superabrasive applications", AES magazine, page 12
82. Sluhan W., " Fluids used in grinding", AES magazine, Fall 1990, page 20 -21
83. Jain V.K. and Shukla D.S., " The role of fatty materials and water soluble inorganic solids in synthetic metal working fluids", Wear, 208, 1997, page 11 - 16
84. Kotvis P.V. and Tysoe W.T., "Surface chemistry of chlorinated hydrocarbon lubricant additives - Part I: Extreme-pressure tribology", Tribology Transactions 41, 1, 1998, page 117 - 123
85. Jain V.K. and Shukla D.S., " Study of the EP activity of water-soluble inorganic metallic salts for aqueous cutting fluids", Wear, 193, 1996, page 226 - 234
86. Passman F.J., "Microbial problems in metalworking fluids", AES magazine, June - July 1988, page 14 - 17
87. Dick R.M. and Foltz G.J., "Controlling costs for water-based cutting fluids", AES Magazine, June-July 1988, page 8 - 13
88. Sluhan W., "Water and grinding fluids", AES magazine, Spring 1991, page 22 - 23
89. Bienkowski K., "Coolants & Lubricants: Staying pure", Manufacturing Engineering, April 1993, page 55 - 61
90. Flores G., "Diamond and CBN honing technology", SME report MR98-209, 1998
91. Leaman R.M., " Honing with metal bond borazon ® CBN stones", SME report MR78-314, 1978
92. Matsumori N., "Ability of CBN stone in superfinishing and its application" SME report MR88-465, 1988
93. Hale I., "Principles of superfinishing: Conventional bonded abrasives and operating variables", SME report MR97-159, 1997
94. Atlantic honing stones, Sales brochure from Atlantic Schleifscheiben + Honsteine
97. Malkin S., Grinding Technology: theory and applications of machining with abrasives, SME, 1989
98. Farnum G.T., " Superabrasive honing: doing it right", Manufacturing Engineering, April 1987, page 44 - 47
99. Onchi Y., Matsumori N., Ikawa N. and Shimada S., " Cutting mechanism of superfinishing by fine CBN stone", Japan Society for Precision Engineering, 62,5, 1996, page 666 - 670

100. Onchi Y., Matsumori N. et al, " Porous fine CBN stones for high removal rate superfinishing", *Annals of the CIRP*, 44, 1, 1995, page 291 - 294
101. Matsumori N. and Onchi Y., "Advanced superfinishing with CBN and diamond stones", *SME report MR93-333*, 1993
102. Marinescu I.D. and Bordeianu E., "Optimization of the parameters in the superfinishing of the bearing ball track", *SME report MR94-166*, 1994
103. Marinescu I.D. et al., "High efficiency superfinishing of bearing rings with CBN", *SME report MR98-175*, 1998
104. Bordeianu E. and Marinescu I.D., "Superfinishing of bearing rings", *SME report MR95-206*, 1995
105. Puthanangady T.K., "Superfinishing of steels", *SME report MR94-169*, 1994
106. Chang S.H. et al, " Forces and specific energy in superfinishing of hardened steel", *Annals of the CIRP*, 46, 1, 1997, page 257 - 260
107. Varghese B and Malkin S., "Experimental investigation of methods to enhance stock removal for superfinishing", *Annals of the CIRP*, 47, 1, 1998, page 231 - 234
108. Chandhari R. and Malkin S., " Experimental investigation of reduced stroke superfinishing using ultrasonic vibrations", *SME report MR 95-207*, 1995
109. Gebel I.D., "Ultrasonic cleaning of superfinishing stones" *Russian Engineering Journal*, LII, 9, page 49 -51
110. "Superfinishing stones", Mizuho co. Ltd, sales catalogue
111. Rajurkar K.P. et al., " New developments in electro-chemical machining", *Annals of the CIRP*, 48, 2, 1999, page 1 - 13
112. Kozak J. and Rajurkar K.P., "Hybrid machining process evaluation and development", *Proc. 2nd Int. Conf. on Machining and Measurements of Sculptured Surfaces*, Sept. 2000, page 501 - 536
113. Chou Y.S. and Barash M.M., "Review on hard turning and CBN cutting tools", *SME report MR95-214*, 1995
114. Liu C.R. and Mittal S., "Single-step superfinish hard machining: feasibility and feasible cutting conditions", *Robotics & Computer-Integrated Manufacturing*, 12, 1, 1996, page 15-27
115. Yamaguchi H. and Gilmore J.R., " Deformability of the flexible grinding stone in a new abrasive machining process for three-dimensional geometry", *SME report MS98-186*, 1998
116. Klocke F. and Liermann J., "Roller burnishing of hard turned surfaces", *Int. J. Mach. Tools Manufact.*, 38, no. 5-6, 1998, page 419 - 423
117. Krymsky M.D., " Magnetic abrasive finishing", *Metal Finishing*, July 1993, page 21 - 25

118. Fox M. et al, "Magnetic abrasive finishing of rollers", *Annals of the CIRP*, 43, 1, 1994, page 181 - 184
119. Glauert A.M., *Practical methods in electron microscopy volume 1*, North-Holland Publishing Company, 1972
120. Kim D.E. and Suh N.P., "Chemical smoothing of rough metal surfaces", *Journal of Engineering for Industry*, 114, Nov. 1992, page 421 - 426
121. Zeidler D., et al, "Characterization of Cu chemical mechanical polishing by Electrochemical Investigation", *Microelectronic Engineering*, 33, 1997, page 259-265
122. Steigerwald J.M., et al, "Electrochemical Potential Measurements during the Chemical-Mechanical Polishing of Copper Thin Films", *J. Electrochem. Soc.*, 142, 7, 1995, page 2379-2385
123. Patent US4491500, "Method for Refinement of Metal Surfaces", REM Chemicals Inc., 1985
124. Patent US5503481, "Bearing Surfaces with Isotropic Finish" The Timken Company, 1996
125. Patent US5873770, "Vibratory Finishing Process", The Timken Company, 1999
126. Wang J.C. and Hsu S.M., "Chemically Assisted Machining of Ceramics", *Journal of Tribology*, 116, July 1994, page 423-429
127. Yasunaga N., "Recent advances in ultraprecision surface finishing technologies in Japan", *Proc. of the Int. Sym. Advances in Abrasives Technology*, July 1997, page 18 - 27
128. Landolt D., "Fundamental aspects of electropolishing", *Electrochimica Acta.*, 32, 1, 1987, page 1 - 11
129. *Plating and electropolishing*, page 303 - 309
130. *ASM Handbook, Metallography and Microstructures*, vol. 9, 1998
131. Chetty O.V.K., and Radhakrishnan V., "A study on the influence of grain size in electrochemical machining", *Int. J. Mach. Tool Des. Res.*, 21, 1, 1981, page 57 - 69
132. Chetty O.V.K., Murthy R.V.G.K. and Radhakrishnan V., "On some aspects of surface formation in ECM", *Journal of Engineering for Industry*, 103, August 1981, page 341 - 348
133. Osman H.M. and Abdel-Rahman M., "Integrity of surfaces produced by electrochemical machining" *Journal of Materials Processing Technology*, 37, 1993, page 667 - 677
134. Strode I. and Bassett M.B., "The effect of electrochemical machining on the surface integrity and mechanical properties of cast and wrought steels", *Wear*, 109, 1986, page 171 - 180
135. Bannard J.E. and O'Malley P., "The effect of ECM on the fatigue life of Co27Cr5Mo3Ni & stainless steel 316L", *ISEM* 7, 1983, page 443 - 452

136. Patent US 3730861, "Method of electrochemical machining", The Cincinnati Milling Machine Co., 1973
137. Patent US4456516, " Shaft rounding apparatus", Westinghouse Electric Corp., 1984
138. Hogan J.F, "Honing get electrolytic help", The Iron Age, April 15, 1965, page 106-107
139. Patent GB1119881 "A method and device for machining work pieces", Supfina Wieck & Hentzen, 1968
140. Budzynski A.F., "Research on optimization of the process of electrochemical honing EH", ISEM 7, 1983, page 355-371
141. Budzynski A.F., "Theoretical principles and technical factors of electrochemical honing", ISEM 6, 1980, page 352-356
142. Guoqiang Wei, "An investigation into the ability of correcting error in ECH process", Annals of the CIRP, 35, 1, 1986, page 103 - 106
143. Patent US4483755 "Method for the treatment of surfaces of a workpiece of carbon-containing cast iron", Linzenkirchner Kark et al., 1984
144. Patent EP0452501, "Method of super-mirror finishing with electrolytic grinding for internal surface of small-diameter tube", Agency Ind. Science Techn. (JP), 1991
145. Patent US4294673, "Method of mirror-finishing a cylindrical workpiece", Hitachi Shipbuilding Eng. Co., 1981
146. Patent US5911841, "Steel having excellent corrosion resistance", Ohmi T., 1999
147. Kimoto Y. et al, " Electrolytic mirror polishing assisted by mechanical abrasions of stainless steel", ISEM 6, page 362- 364
148. Kimoto Y. et al, " A study on high shape accuracy electrolytic-abrasive mirror finishing", JSPE, 54, 2, 88, page 353 - 358
149. Tam S.C. et al, "ECM-abrasive polishing of metals", Int. J. Prod. Res., 27, 10, 1989, page 1757 - 1768
150. Patent US4839005, "Electrolytic-abrasive polishing method of aluminium surface", Kobe Steel Ltd (JP), 1989
151. Takahata K. et al, "Fine surface finishing method for 3 - dimensional Microstructures", IEICE Trans. electron., E80-C, 2, Feb. 1997, page 291 - 296
152. Cole R.R., "Experimental Investigation of the Electrolytic Grinding Process", Journal of Engineering for Industry, May 1961, page 194-201
153. Storey O.W., "Electrolytic Grinding or Machining of Metals", J. Metals, 4, 1952, page 378-379
154. Trott L.L., "Electrolytic Grinding finishes microminiature parts", The Tool and Manufacturing Engineer, Jan.1964, page 81 - 82

155. Keeler G., "Electrolytic grinding- stubborn alloys less formidable", *Steel*, March 17, 1952, page 84-87
156. www.electrochemical.com, Compositron Corporation
157. Geddam A., "On Line Monitoring of Process Variables in Peripheral Electrochemical Grinding", SME paper MR95-132, 1995
158. Nankov M.M. et al., "Investigation of the process of external cylindrical electrochemical grinding with the face of a cup wheel made of synthetic superhard materials", *ISEM* 7, 1983, page 321-336
159. Patent US5045161, "Method and apparatus for electrolytically assisting the mechanical shaping of a workpiece", NAT Research Council (CA), 1991
160. Patent US5976347, "Micro cutting and system", Fuji Xerox Co Ltd (JP), 1999
161. Vidensky I.V. and Petrova I.V., "Electro-chemo-mechanical treatment: Facilitating steel grinding under electrochemical reduction of active cations", *J. Mater. Res.*, 8, 9, Sept. 1993, page 2224 - 2227
162. Ohmori H. And Nakagawa T., "Mirror surface grinding of silicon wafers with electrolytic in-process dressing", *Annals of the CIRP*, 39, 1, 1990, page 329 - 332
163. Ohmori H., "Electrolytic In-process dressing (ELID) grinding technique for ultraprecision mirror surface machining", *Int. J. Japan Soc. Prec. Eng.*, 26, 4, 1992, page 273 - 278
164. Ueda T. et al., "Effect of coolant of water-solution in superfinishing - application of electrolytic in-process dressing", *Japan Society for Precision Engineering*, 62, 2, 1996, page 252 - 257
165. Ohmori H. And Nakagawa T., "Utilization of nonlinear conditions in precision grinding with ELID (electrolytic in-process dressing) for fabrication of hard material components", *Annals of the CIRP*, 46, 1, 1997, page 261-264
166. Bandyopadhyay B.P et al., "Ductile regime mirror finish grinding of ceramics with electrolytic in-process dressing (ELID) grinding", *Materials and Manufacturing Processes*, 11, 5, 1996, page 789 - 801
167. Itoh Nobuhide et al., "Grinding characteristic of hard and brittle materials by ELID-lap grinding using fine grain wheels", *Materials and Manufacturing Processes*, 12, 6, 1997, page 1037-1048
168. Ohmori H., "Ultraprecision grinding of optical materials and components applying ELID (electrolytic in-process dressing)", *SPIE*, 2576, 1995, page 26-45
169. Qian J. Et al., "Cylindrical grinding of bearing steel with electrolytic in-process dressing", *Precision Engineering*, 24, 2000, page 153-159
170. Guitrau E.B., *The EDM handbook*, Hanser Gardner Publications, 1997

171. Masuzawa T. and Takawashi T., "Recent trends in EDM/ECM technologies in Japan", 12th International symposium for electromachining (ISEM12), 1998, page 1 - 15
172. Miyake H. et al., "Improvement of tool life through surface modification by electrical discharge machining", 12th International symposium for electromachining (ISEM12), 1998, page 261 - 270
173. Bogdan W. et al, "The influence of manufacturing processes on surface properties", Adv. Manuf. Eng., 1, July 1989, 187 - 202
174. Gawne D.T., "Tribology principles and applications in surface finishing", Trans. Inst. Metal Finish., 70 (3), 1992, page 152 - 158
175. Arnell R.D. et al, Tribology : Principles and Design Applications, Macmillan Education Ltd, 1991
176. Whitehouse D.J., Handbook of surface Metrology, IOP Publishing Ltd, 1994
177. Hamrock B.J., Fundamentals of Fluid Film Lubrication, NASA Reference Publication 1255, August 1991
178. Jacobson B., "At the boundary between lubrication and wear (part1)", Evolution, 2, 1998
179. SKF general catalogue, 1989
180. Ioannides E., and Harris T.A., "A new fatigue life model for rolling bearings", Journal of Tribology, 107, July 1985, page 367 - 378
181. Jacobson B., "Contamination and bearing life", Evolution, 3, 1994
182. Voskamp, A et al, "X-ray diffraction provides answers to bearing failure", Evolution, 4, 1997
183. Zhou R.S., "Surface topography and fatigue life of rolling contact bearings", Tribology Trans., 36, 3, 1993, page 329 - 340
184. Hoeprich M.R., "Rolling element bearing contact geometry analysis", Tribology Trans., 38, 4, 1995, page 879 - 882
185. Ai X., "Effect of three-dimensional random surface roughness on fatigue life of a lubricated contact", Journal of Tribology, 120, April 1998, page 159 - 164
186. Tripp J.H. and Ioannides E., "Effect of surface roughness on rolling bearing life", Proc. of Japan Int. Tribology Conf., Nagoya 1990, page 797 - 802
187. Patir N. and Cheng H.S., "Effect of surface roughness orientation on the central film thickness in E.H.D. contacts", Proc. 5th Leeds - Lyon Conf., Sept 1978, page 15 - 21
188. Horng J. H. et al, "The effect of surface irregularities on the tribological behavior of steel rollers under rolling-sliding contact", Journal of Tribology, 116, April 1994, page 209 - 218

189. Jeng Y-R., " Experimental study of the effects of surface roughness on friction", Tribology Trans., 33, 3, 1990, page 402 - 410
190. Akamatsu Y. et al, "Improvement in oil film formation under rolling contact by controlling surface roughness pattern", Proc. of the Japan Int. Tribology Conf., Nagoya 1990, page 761 - 766
191. Akamatsu Y. et al, "Improvement of roller bearing fatigue life by surface roughness modification", SAE report 910958
192. Akamatsu Y., "Improvement of rolling bearing fatigue life by reforming the surface roughness pattern", Japanese Journal of Tribology, 37, 7, 1992, page 819 - 826
193. Akamatsu Y., " Influence of surface roughness skewness on rolling contact fatigue life", Tribology Trans., 35, 4, 1992, page 745 -750
194. Akamatsu Y., " Influence of micro indents formed by electro-chemical jet machining on rolling bearing fatigue life", PED-Vol. 64, Manufacturing science and Engineering ASME, 1993, page 693 - 699
195. Patent US5397188, "Rolling Member", NTN Toyo Bearing Co. Ltd, 1995
196. Patent US5642947, "Balls for ball bearing", NTN Toyo Bearing Co. Ltd, 1997
197. Zhou R.S. and Hashimoto F., "A new rolling contact surface and "No run-in" performance bearings", Trans. of the ASME, 117, January 1995, page 166 - 170
198. Japanese Laid-Open Patent Application No. 8-232964, "Rolling member and method for manufacturing same", Koyo seiko Co., 1996
199. Patent US4916751, " Rolling bearing", Nippon Seiko KK, 1990
200. E.Pajak and Wieczorowski W., "Classification of discharges in electrocontact discharge machining (ECDM) by means of neural networks", 12th Int. Sym. for electromachining (ISEM), 1998, page 225 - 232
201. De Silva A. and McGeough J., " Hybrid electrodischarge-electrochemical process for roughning and finishing dies and moulds", 12th Int. Sym. for electromachining (ISEM), 1998, page 397 - 406
202. www.nucor-fastener.com/tds004.html, website on zinc electroplating of fasteners
203. Ciruna J.A and Szieleit H.J., " The effect of hydrogen on the rolling contact fatigue life of AISI 52100 and 44C steel balls", Wear, 24, 1973, page 107 - 118

9. Bibliography

1. De Barr A.E and Oliver D.A, Electrochemical Machining, Macdonald & Co, 1968
2. McGeough J.A, Principles of Electrochemical Machining, Chapman and Hall, 1974
3. Wilson J.F., Practice and Theory of Electrochemical Machining, John Wiley & Sons, 1971
4. Shaw M.C., Principles of Abrasive Processing, Clarendon Press, Oxford, 1996
5. Malkin S., Grinding Technologies : theory and applications of machining with abrasives, SME, Dearborn, 1989
6. Salmon S.C., Modern Grinding Process Technology, McGraw-Hill, 1992
7. Silliman J.D., Cutting and Grinding Fluids: Selection and Application, SME, Dearborn, 1992
8. Byers J.P, Metalworking Fluids, Marcel Dekker Inc., 1994
9. Whitehouse D.J., Handbook of Surface Metrology, IOP Publishing Ltd., 1994
- 10 Arnell R.D., Davies P.B et al, Tribology: Principles and Design Applications, MacMillan Education Ltd, 1991
11. Jacobson B.O., Rheology and Elastohydrodynamic Lubrication, Elsevier Science Publishers B.V., 1991