

CRANFIELD INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL ENGINEERING

Ph.D. Thesis

Academic Year 1978-79

M. NASIM MIAN M.Sc. (Leeds)

EFFECT OF OXIDES ON SURFACE TOPOGRAPHY
AND THERMAL CONTACT RESISTANCE

Supervisor:

Dr. P.W. O'Callaghan

November 1979

BEST COPY

AVAILABLE

Variable print quality

ACKNOWLEDGEMENTS

The author is highly indebted to Dr. P.W. O'Callaghan for his invaluable guidance throughout the period of this research.

Professor S.D. Probert is to be thanked for encouragement and his advice on script preparation.

Thanks are due to Mr. C.S. Chapman for his generous help with the experimental works, Mr. F. Clark of the Production Department, Dr. F. Al-Astrabadi and members of the test area for assistance in their respective disciplines.

Particular mention is to be made of Dr. J. Nicholls of the Materials Department for many useful discussions concerning oxidation and Mr. J. Hedge for his technical assistance with the measurements of oxide film thickness.

Correspondence of Professor R.W. Heimborg of Syracuse University, U.S.A., and Dr. K. Sanokawa of Japan Atomic Energy Research Institute is gratefully acknowledged.

Mrs. S. Thompson is to be expressed gratitude for typing and Dr. M. Painter of the Materials Department for tracing figures at a short notice.

The research work was performed under the grant by the Science Research Council.

The author would like to extend his thanks to Professor R.S. Fletcher for permission to carry out this research programme.

Finally the author must admire the patience of his ailing father and mother to await his return and the role of his younger sister Dr. Nadira Zareen towards help with treatment and finance.

ABSTRACT

The effect of oxides on the topographies of various random engineering surfaces and steady-state thermal contact resistances between oxide-free and oxidized metallic surfaces in contact in high vacua have been investigated. The results of many previous investigations indicated that such problems cannot be dealt with without a detailed study of the surface topographies, resulting in accurate surface characterisation. The distributions of the real micro-contact zones and heat transfer phenomena across interfaces could then be predicted.

Cylindrical specimens normally mild steel EN3B and commercially pure copper of nominal area $4.908 \times 10^{-4} \text{ m}^2$ were oxidized under controlled environmental conditions and subsequently pressed into contact at their flat faces. The oxide film thickness measurements were taken using a high resolution Stereoscan electron microscope. Surface topographies were quantified before and after oxidation to determine the effects of oxide films upon their topological characteristics.

Following a detailed analysis, two theories concerning the problem of predicting thermal contact resistances of oxidized joints having Gaussian distribution of surface heights have been developed. The developed theories establish the surface parameters measured to design a predictable thermal joint and apply for thin films of the order of naturally occurring oxides.

From a statistical analysis of the experimental measurements for freshly-assembled contacts, an empirical expression

$$(R = 66.0 P^{-0.945} \sigma^{-0.128} x^{0.0346})$$

has been established relating the loading pressure, mean roughness of the contacting surfaces and oxide film thickness to the thermal resistance of the contacts in high vacua.

Finally a method of producing joints with low thermal contact resistance (and vice versa) is suggested.

CONTENTS

Page

NOMENCLATURE

LIST OF FIGURES

CHAPTER ONE	INTRODUCTION	1
1.1	General description of the problem	1
1.2	Applications	1
1.3	Scope of investigation	2
1.3.1	Surface characterisation and topography	2
1.3.2	Area of actual contact	2
1.3.3	Thermal contact resistance	3
1.3.4	Electrical resistance	3
CHAPTER TWO	SURVEY OF EXISTING KNOWLEDGE	
2.1	General	4
2.1.1	Phenomena of oxidation	4
2.1.2	Kinetics of oxidation	4
2.1.3	Composition and nucleation of copper oxide	7
2.1.4	Epitaxial stresses	8
2.1.5	Recrystallization stresses	10
2.1.6	Compositional changes	10
2.1.7	Vacancy generation	10
2.1.8	Thermally induced stresses	10
2.2	Surface characterisation	11
2.2.1	Surface hardness	15
2.2.2	Surface roughness	17

2.2.3	Mean peak radius of curvature	17
2.2.4	Mean absolute surface slope	17
2.2.5	Surface waviness	18
2.2.6	Sampling interval	18
2.3	Surface deformation	18
2.3.1	Asperity interaction	22
2.4	Area of actual contact	22
2.5	Physical aspect of contact	23
2.6	Thermal contact resistance	24
2.6.1	Previous investigations	25
2.6.2	Analogy with electrical contact resistance	25

CHAPTER THREE TEST RIG DESCRIPTION AND EXPERIMENTAL DETAILS

3.1	Design criterion for the relocating attachment	27
3.2	The test rig assembly	27
3.2.1	The experimental chamber	27
3.2.2	Application of heat flux	33
3.2.3	Measurement of temperature	33
3.2.4	Loading mechanism	34
3.3	The Quantimet 720 Image Analyser	34
3.4	Profilometric measuring equipment	37
3.4.1	Surface analysis	37
3.5	Thermocouple calibration	37
3.6	Hardness measurements	39
3.7	Thermal conductivity measurements	39
3.8	Test rig observations	39
3.9	Measurement of interfacial thermal resistance	40

CHAPTER FOUR	EXPERIMENTAL TECHNIQUE FOR THE MEASUREMENT OF OXIDE FILM THICKNESS AND SURFACE TOPOGRAPHY	
4.1	Specimen preparation	42
4.2	Measurement of film thickness	42
4.2.1	Theoretical estimation of the growth of oxide films	58
4.2.2	Constant time and varied temperature estimation.	58
4.2.3	Constant temperature and varied time estimation	60
4.3	Surface topography measurements	62
4.4	Experimental results and discussion	62
4.4.1	Surface ordinate height distribution	69
4.4.2	Surface auto-correlation function	69
4.4.3	Mean surface slope versus data sampling interval	85
CHAPTER FIVE	THE AREA OF ACTUAL CONTACT	
5.1	Introduction	91
5.2	Methods of measuring the area of contact	91
5.3	Loading procedure	97
5.4	Analytical Predictions	97
5.4.1	Contact parameters for the oxide-free joint	107
5.4.2	Contact parameters for the oxidized joint	108
5.5	Experimental results and discussions	108
5.5.1	The area of actual contact	114
5.5.2	Size and mean number of micro-contacts	114
5.5.3	The area of contact of a turned surface	122
5.6	Conclusions	122
CHAPTER SIX	THEORETICAL DEVELOPMENT	
6.1	Introduction	123

6.1.1	Topographical features	123
6.1.2	Chemical composition	123
6.1.3	Physical structure	124
6.2	Contact between oxide-free surfaces	124
6.2.1	Assumptions	128
6.3.	Contact between oxidized surfaces	129
6.3.1	The contact mechanism	130
6.3.2	Brittle fracture of oxide films	130
6.3.3	Grease-filled contact	130
6.3.4	Soft thin oxide coatings	130
6.3.5	Insulated surface films	130
6.4	Theoretical details	134
6.4.1	The contact mechanism	134
6.4.2	Grease-filled contact	135
6.4.3	Soft thin oxide coatings	137
6.4.4	Insulated surface films	137
6.5	Thermal conductivity	137
6.6	Thermal contact resistance	138
6.6.1	Brittle fracture of oxide films	138
6.6.2	Grease-filled contact	143
6.6.3	Soft thin oxide coatings	144
6.7	The constriction resistance theory as applied to oxidized surfaces	144
6.7.1	Description of the contact model and theoretical analysis	144
6.7.2	Assumptions	150
6.8	Analytical solution	151
CHAPTER SEVEN	EXPERIMENTAL RESULTS, DISCUSSION AND COMPARISON	
7.1	Surface preparation and topography	154

7.2	Thermal contact resistance measurements	154
7.3	Results and discussions	155
7.3.1	Case A Brittle fracture of oxide films	155
7.3.2	Case B Grease-filled contact	155
7.3.3	Case C Soft thin oxide coatings	172
7.3.4	Case D Insulated surface films	172
7.3.5	Resistance between similar materials	172
7.3.6	Mean interfacial temperature	184
7.3.7	Period of heating	184
7.3.8	Reversal of heat flux	184
7.4	Comparison of theories	190
7.5	Conclusions	190
CHAPTER EIGHT	CONCLUSIONS	
8.1	Interfacial contact and compliance	194
8.2	Interfacial contact resistance	194
8.2.1	How to produce joint with low thermal contact resistance	195
8.2.2	Comparison of theories	195
APPENDIX I	ELECTRICAL RESISTANCE	A.1
APPENDIX II	COMPUTER PROGRAM FOR THE EVALUATION OF SURFACE PARAMETERS.	A.6
	Numerical results for the ordinate height distribution of specimen surfaces.	A.19
	Sample Calculations.	A.29
APPENDIX III	COMPUTER PROGRAM FOR THE PREDICTION OF THERMAL CONTACT RESISTANCE.	A.38
	Computer program for the multiple regression and correlation.	A.54

NOMENCLATURE

A_n	nominal area of pressed contact, m^2
A_{rm}	area of metal-to-metal contact, m^2
A_{rT}	total area of contact, m^2
$\bar{a}_m$	mean radius of metal-to-metal contact spots, m
$\bar{a}_o$	mean radius of contact spots between oxidized surfaces, m
$\bar{a}_{oo}$	mean radius of the contact spots for an oxide-to-oxide contact, m
$\bar{b}$	mean heat flow channel radius, m
D	oxidation rate constant
d	diameter of the flattened part of an asperity (as shown in fig. 6.5), m
D_1	proportionality constant for iron ($= 2.55 \times 10^{-7} m^2 hr^{-1}$)
D_m	diameter of the metallic contacts, m
D_o	diameter of the contacts due to the presence of the oxides, m
d_H	incremental movement of the anvil (as shown in fig. 6.5), m
E	elastic modulus, $N m^{-2}$
E^*	effective elastic modulus, $N m^{-2}$
E	$\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2},$
erf	error function

$F(\lambda)$	auto-correlation function defined by equations (2.5, 2.6)
$g(\gamma)$	constriction alleviation factor
J_0, J_1	Bessel functions of the first kind and of zero and first order
K	an arbitrary constant used in equations (4.5, 4.6)
K_1	an arbitrary constant used in equation (4.8).
k	thermal conductivity of the solid, $W m^{-1} K^{-1}$
k_s	harmonic mean thermal conductivity of the oxide-free contacting materials, $W m^{-1} K^{-1}$
k_{so}	harmonic mean thermal conductivity of the oxidized contacting materials, $W m^{-1} K^{-1}$
k_{TO}	total harmonic mean thermal conductivity including the conduction of the annular contacts of the oxidized contacting materials, $W m^{-1} K^{-1}$
L	Lorenz's constant, 2.4×10^{-8} , $W\Omega/degree^2$
l	length of the sampled profile, m
M	Vicker's micro-hardness of the softer of the two surfaces in contact, $N m^{-2}$
M_o	Vicker's micro-hardness of the oxide, $N m^{-2}$
M^*	effective contact hardness as described in equation (2.10), $N m^{-2}$
N_m	number of metal-to-metal contacts
N_o	number of contacts due to the presence of oxide
N_T	total number of the micro-contact spots

$\bar{n}_A$	number of the micro-contacts per unit area, m^{-2}
$\bar{n}_1$	number of the contact zones per unit length, m^{-1}
P	applied loading pressure, $N m^{-2}$
P_f	flow pressure, $N m^{-2}$
$p(\omega)$	power spectral density
Q	thermal current flowing across the contact, W
Q_1	activation energy, $(3.27 \times 10^6 J kg^{-1})$
R	thermal resistance of the unit area of the interface, $K m^2 W^{-1}$
R_1	gas constant, $(287 J kg^{-1} K^{-1})$
R_{mo}	thermal resistance per unit area of the metal-to-metal contact due to the presence of the oxide, $K m^2 W^{-1}$
R_{mod}	modified form to include the constriction resistance, $Km^2 W^{-1}$
R_{oo}	thermal resistance per unit nominal area due to the presence of the oxide-to-oxide contacts, $Km^2 W^{-1}$
R_T	total thermal resistance $= (R_{mo} + R_{oo}) A_n$, $Km^2 W^{-1}$
T	temperature, $^{\circ}K$
t	period of exposure of the specimen to an oxidizing atmosphere prior to being brought into contact with another specimen, hr.
U	mean plane separation, m
U_1	mean plane distance, m

v	thickness of the displaced material at the base of a surface valley as shown in fig. 6.5, m
W	applied load, N
X	total film thickness for a contact ($\equiv x_1 + x_2$), m
x	film thickness on one or other of the contacting surfaces, m
y	Linear dimension shown in fig. 5.6, m
$y(x)$	height of the surface profile, m
$y(x + \lambda)$	height of the surface profile at a co-ordinate $(x + \lambda)$, m
Z	mean separation between the peripheries of a contact and the next but one contact, m

GREEK SYMBOLS

α	exponent defining the decay of $F(\lambda)$
α_c	correlation distance
γ	geometric form factor for asperities = $(\frac{\bar{a}}{\bar{b}})$
$\delta(f - f_0)$	a delta function as defined in equation (2.8)
θ	base angle of a conical micro-asperity, radians
λ	Greenwood's plasticity index
λ_w	correlation wave length, m
ν	Poisson's ratio
ρ	radius of curvature, m
ρ_e	electrical resistivity, ohm-meter

ρ_s	mean peak radius of curvature, m
Δ_l	land length, μm
Δ_m	change in weight as defined in equation (2.1), N
Δ_T	difference between the steady state surface temperatures as determined by linear extrapolation of the axial temperature distributions to their respective contacting surfaces, $^{\circ}\text{C}$.
σ	R.M.S. roughness of a surface, μm
σ_s	effective surface roughness for a contact, μm
$\phi(t)$	probability function $= \frac{1}{\sqrt{2\pi}} \exp \left(-\frac{t^2}{2} \right)$
$\Phi(t)$	probability integral $= \int_0^t \phi(t) dt$
$ \bar{\psi} $	mean surface slope, radians
Ψ	normalised mean surface slope $= \bar{\psi} / \sigma, \mu\text{m}^{-1}$
Ψ_s	effective surface slope for a contact, μm^{-1}
ω	frequency
Ω	harmonic wave frequency

OPERATORS

$d()$ represents an increment in the quantity ()

SUBSCRIPTS

a, b	orthogonal directions a and b
e	electrical
f	under plastic conditions

m for the metal

l linear

mod modified

n nominal

o with oxide present

oo oxide-to-oxide contact

r real

T total

1, 2 relating to surface 1 or 2 respectively

LIST OF FIGURES

- Fig. 2.1 Iron-Oxygen phase diagram.
- Fig. 2.2 Composition of copper oxide as reported by several authors (21, 33, 34, 36).
- Fig. 2.3a Auto-correlation function of random surfaces.
- Fig. 2.3b Auto-correlation function of random surfaces with waviness.
- Fig. 2.4 Power Spectral Density, $P(w)$ for an exponential auto-correlation function.
- Fig. 2.5a Power Spectral Density plot for a sine wave.
- Fig. 2.5b Power Spectral Density plot for a wide-band random noise.
- Fig. 2.6a Power Spectral Density plot for a sine wave plus random noise.
- Fig. 2.6b Power Spectral Density plot for a narrow-band random noise.
- Fig. 2.7 Surface profiles indicating the carrier profile as periodic content and the superimposed random content as real surface roughness.
- Fig. 2.8a Variation of mean absolute surface slope with sampling interval.
- Fig. 2.8b Variation of mean peak radius of curvature with sampling interval.
- Fig. 2.9 Variation of mean surface slope with correlation for a roughened stainless steel surface (3).
- Fig. 2.10 Mean peak curvature at different correlation for a roughened stainless steel surface (3).

- Fig. 3.1 Detailed drawing of a specimen holding plate.
- Fig. 3.2 Detailed drawing of a relocating attachment.
- Fig. 3.3 Detailed drawing of the test specimen.
- Fig. 3.4 Schematic view of the test rig.
- Plate 3.1 The contact module.
- Plate 3.2 External view of the thermal rig in operation, showing vacuum chamber, loading arrangement and instrumentation layout.
- Plate 3.3 The Quantimet 720 Image Analyser.
- Plate 3.4 The Talysurf arrangement
- Plate 4.1 High temperature oxidation furnace.
- Plate 4.2 Electropolishing machine.
- Plate 4.3 Oxide-free and oxidized specimens.
 (i) polished surface (oxide-free)
 (ii) oxidized at 325°C for ten hours
 (iii) sand-blasted (oxide-free)
 (iv) sand-blasted oxidized at 300°C for five hours
- Plate 4.4 Stereoscan Electron Microscope (magnification x 20,000. Resolving power better than 25 nm).
- Plate 4.5 Reichert Metallographic Microscope. Magnification x 2000. Resolution limit better than 0.34 μm .

- Plate 4.6 Sequence of operations for film thickness measurements.
- (i) oxidized specimen
 - (ii) specimen after cutting
 - (iii) test sample as mounted on bakelite holder.
- Plate 4.7 Spark erosion machine showing cutting operation of the oxidized specimen for microscopical film thickness measurements.
- Plate 4.8 Top view of the test sample mount on bakelite holder.
- Plate 4.9 Cross-section of the oxide film on an EN3B mild steel specimen oxidized at 325°C for 168 hours. Measurements taken with a Stereoscan Electron Microscope. x 20,000. Film thickness, 1.30 μm .
- Plate 4.10 Growth of oxide film on an EN3B mild steel specimen oxidized at 250°C for 336 hours. The photograph taken by Stereoscan Electron Microscope shows the mode of deposition of the oxide.
- Fig. 4.1 Activation energy plot.
- Plate 4.11 Nominally flat and smooth EN3B mild steel specimens surface oxidized at 325°C for ten hours.
- Plate 4.12 Nominally flat and smooth surface oxidized at 250°C for 336 hours.
- Plate 4.13 Nominally flat and smooth (commercially pure) copper surface oxidized by immersing in water for 48 hours and then leaving overnight in open atmosphere.
- Plate 4.14 Turned surface oxidized at 325°C for ten hours.
- Plate 4.15 Ground mild steel specimen oxidized at 70°C and 80% humidity for 72 hours

- Fig. 4.2 Talysurf trace of a nominally flat and smooth surface M1; (a) before oxidation, (b) after oxidation.
- Fig. 4.3 Talysurf trace of a nominally flat and smooth surface M2; (a) before oxidation, (b) after oxidation.
- Fig. 4.4 Talysurf trace of a nominally flat and rough surface M3; (a) before oxidation, (b) after oxidation.
- Fig. 4.5 Talysurf trace of a ground surface (across the lay) M4; (a) before oxidation, (b) after oxidation
- Fig. 4.6 Talysurf trace of a fine-turned surface M5; (a) before oxidation, (b) after oxidation.
- Fig. 4.7 Cumulative ordinate distribution for a polished surface M1. (Thin film).
- Fig. 4.8 Cumulative ordinate distribution for a polished surface M2, (Thick film).
- Fig. 4.9 Cumulative ordinate distribution for a sand-blasted surface M3.
- Fig. 4.10 Cumulative ordinate distribution for a ground surface M4.
- Fig. 4.11 Cumulative ordinate distribution for a fine-turned surface M5.
- Fig. 4.12 Variation of the auto-correlation function with sampling interval for the polished surface M1 before and after oxidation.
- Fig. 4.13 Variation of the auto-correlation function with the sampling interval for the polished surface M2 before and after oxidation. (Thick film)

- Fig. 4.14 Variation of the auto-correlation function with the sampling interval for the sand-blasted surface M3 before and after oxidation.
- Fig. 4.15 Variation of the auto-correlation function with the sampling interval for the ground surface M4 before and after oxidation.
- Fig. 4.16 Variation of the auto-correlation function with the sampling interval for the fine-turned surface M5.
- Fig. 4.17 Variation of the mean absolute surface slope with sampling interval for the polished surface M1.
- Fig. 4.18 Variation of the mean absolute surface slope with sampling interval for the polished surface M2. (Thick film)
- Fig. 4.19 Variation of the mean absolute surface slope with sampling interval for sand-blasted surface M3.
- Fig. 4.20 Variation of the mean absolute surface slope with sampling interval for the ground surface M4 (across the lay).
- Fig. 4.21 Variation of the mean absolute surface slope with sampling interval for the fine-turned surface M5.
- Fig. 5.1 Cumulative percent of ordinates for sand-blasted stainless steel surface (upper specimen M6, see Table 4.1). Numerical results for the surface heights are given in Appendix II, Table A.
- Fig. 5.2 Cumulative percent of ordinates for commercially pure copper surface (lower specimen M7, see Table 4.1). Numerical results are given in Appendix II, Table B.
- Fig. 5.3 Cumulative percent of ordinates for the sand-blasted stainless steel surface (upper specimen M22, see Table 4.1). Numerical results for the surface heights are given in Appendix II, Table C.

- Fig. 5.4 Cumulative percent of ordinates for sandblasted stainless steel surface (upper specimen M23, see Table 4.1). Numerical results for the surface heights are given in Appendix II, Table D.
- Fig. 5.5 Cumulative percent of ordinates for commercially pure aluminium surface M38 (see Table 4.1). Numerical results for the surface heights are given in Appendix II, Table E.
- Fig. 5.6 Sectional view of the formation of circular micro-contacts when a soft, smooth surface is pressed against a hard, oxidized, rough surface for one asperity.
- Fig. 5.7 Size distribution of a stainless steel/copper contact. (load = 17.79 kN).
- Fig. 5.8 Size distribution of a stainless steel/copper contact. (load = 26.68 kN).
- Fig. 5.9 Size distribution of a stainless steel/copper contact. (load = 35.58 kN).
- Fig. 5.10 Size distribution of a stainless steel/copper contact. (load = 44.48 kN).
- Fig. 5.11 Variation of the real area (copper flat) with applied loading.
- Fig. 5.12 Variation of the total area; (copper flat) with applied loading.
- Fig. 5.13 Variation of the real area with applied loading. (Increase in effective surface roughness).
- Fig. 5.14 Variation of the total area with applied loading.
- Fig. 5.15 Variation of the real area (aluminium flat with applied loading).
- Fig. 5.16 Variation of the number of metal-to-metal contacts with applied loading. (Corresponds to Fig. 5.11).

Fig. 5.17 Variation of the total number of micro-contacts with applied loading. (Corresponds to Fig. 5.12).

Plate 5.1 Contact features produced on the smooth copper surface by pressing sand-blasted stainless steel upon it under an applied load, 17.79 kN. As observed on the Quantimet in the detection mode.

Plate 5.2 Contact features produced on the smooth copper surface by pressing sand-blasted stainless steel upon it under an applied load of 26.68 kN. As observed on the Quantimet in the detection mode.

Plate 5.3 Contact features produced on the smooth copper surface by pressing sand-blasted stainless steel upon it under an applied load of 35.58 kN. As observed on the Quantimet in the detection mode.

Plate 5.4 Contact features produced on the smooth copper surface by pressing sand-blasted stainless steel upon it under an applied load of 44.48 kN. As observed on the Quantimet in the detection mode.

Plate 5.5 The Denison Compression machine used for pressing the specimen assemblies. Pressing capacity, 50 Tons.

Plate 5.6 View of the stainless steel sand-blasted surface (upper specimen) after it pressed a smooth copper surface (lower specimen) under an applied load, 44.48 kN. As observed on the Quantimet in the no-detection mode.

Plate 5.7 Contact features produced on an oxidized turned copper surface by pressing sand-blasted stainless steel upon it under an applied load of 40 kN. As observed on the Quantimet in the no-detection mode.

Plate 5.8 Contact features produced on the oxidized turned copper surface by pressing sand-blasted stainless steel upon it under an applied load of 42.45 kN. As observed on the Quantimet in the no-detection mode.

- Plate 5.9 Contact features produced on the oxidized turned copper surface by pressing sand-blasted stainless steel upon it under an applied load of 44.48 kN. As observed on the Quantimet in the no-detection mode.
- Fig. 6.1 Ideal representation of the formation of circular micro-contact spots due to a hard, oxidized rough surface being pressed against a softer oxidized, flat surface.
- Fig. 6.2 Specimen assembly showing the distribution of heat flux and the region of constriction;
(a) radius of the micro-contact and (b) radius of the heat flow channel feeding a micro-contact.
- Fig. 6.3a Brittle fracture of oxide films.
- Fig. 6.3b Grease-filled contact.
- Fig. 6.3c Insulated surface films.
- Fig. 6.4 Schematic view of the contact between two nominally flat, oxidized surfaces, the magnification perpendicular to the mean interfacial plane for the purpose of this drawing being many times that in the direction of the plane.
- Fig. 6.5 Deformation of an asperity on a relatively soft surface by being pressed against a much harder, flat surface.
- Fig. 6.6 Diagrammatic representation of an oxide-to-oxide contact.
- Fig. 6.7 Diagrammatic representation of a metal-to-metal contact for oxidized contacting surfaces.
- Fig. 6.8 Ordinate height distribution of a commercially pure copper surface.
- Fig. 6.9 Estimation of the percentage contact.

- Fig. 7.1 Cumulative height distribution for an optically flat surface before and after oxidation.
- Fig. 7.2 Variation of the metal-to-metal areas of contact with loading.
- Fig. 7.3 Variation of the total areas of contact with loading.
- Fig. 7.4 Variation of the number of metal-to-metal contact with loading. (Increase in surface roughness of softer surface).
- Fig. 7.5 Figure corresponds to Figure 7.3. (Increase in surface roughness of the softer surface).
- Fig. 7.6 Prediction of the total number of micro-contacts from Yips' theory (6) and its modified form.
- Fig. 7.7 Variation of the total number of micro-contacts from Yip's theory (6) and its modified form.
- Fig. 7.8 Comparison of the predictions for the oxide-free as well as oxidized contact from the developed theory, an alternative theory (6) and its modified form with the experimental results.
- Fig. 7.9 Effect of the increase of the film thickness and comparison of theories.
- Fig. 7.10 Prediction of the resistance of the oxide-free contact from the observed number of micro-contacts.
- Fig. 7.11 Prediction of the resistance of the oxidized contact from the observed number of micro-contacts.
- Fig. 7.12 Variation of the thermal contact resistance of the oxide-free surface with roughness.
- Fig. 7.13 Variation of the thermal contact resistance of the oxidized surface with roughness.

- Fig. 7.14 Effect of the increase of the oxide film thickness.
- Fig. 7.15 Application of the developed theory to the oxide-free as well as oxidized contact and comparison with the Yip's theory (6) and its modified form.
- Fig. 7.16 Variation of the contact resistance with film thickness and comparison of theories.
- Fig. 7.17 Comparison of theories.
- Fig. 7.18 Comparison of theories.
- Fig. 7.19 Effect of oxide on the thermal resistance of the mild steel-to-mild steel contact.
- Fig. 7.20 Prediction and comparison of the thermal resistance of the oxidized mild steel-to-mild steel contact.
- Fig. 7.21 Effect of oxide on the thermal resistance of the copper-to-copper contact.
- Fig. 7.22 Prediction and comparison of the thermal resistance of the oxidized copper-to-copper contact.
- Fig. 7.23 Thermal resistance characteristics for pressed contact between EN3B steel specimens in high vacuum.
- Fig. 7.24 The effect of the variation of film thickness on thermal contact resistance.
- Fig. 7.25 Hysteresis due to load reversal.
- Fig. 7.26 Thermal resistance ratio as a function of the ratio of the film thickness to surface roughness
- Fig. 7.27 Dimensionless variation of thermal contact resistance with the pressure.

- Fig. 7.28 Scatter of experimental data.
- Fig. 7.29 Comparison of present empirical data with prediction from Yip's theory (6).
- Fig. 7.30 Thermal resistance characteristics for a ground mild steel-to-mild steel contact.
- Fig. 7.31 Thermal resistance characteristics for a fine turned mild steel-to-mild steel contact.
- Fig. 7.32 Comparison of predictions for the oxidized contact.
- Fig. 7.33 Comparison of the predictions for the oxidized contact (effect of film thickness).

CHAPTER ONE

INTRODUCTION

1.1 GENERAL DESCRIPTION OF THE PROBLEM

The interface formed by two surfaces in contact produces an additional resistance to the flow of heat from one contacting member to the other. When this interface is corroded or even mildly covered with oxide as a result of exposure to its atmosphere, the contact resistance increases. Further, the degree of oxidation depends mainly upon the composition of the underlying metal and its surface finish, the period of exposure, and the severity of the environment.

When two metals are brought into contact, the presence of oxides in addition to the surface roughness or other irregularities of the mating surfaces tends to reduce the metal-to-metal contact. This is further affected by the poor thermal conductivity of the oxides and consequently produces a higher degree of thermal isolation between the contacting surfaces leading occasionally to excessive temperatures of some critical components.

One of the earliest investigations in this area was initiated by Jacobs & Starr (1) in an attempt to collect experimental data for the design of cryogenic thermal joints. Since that time, some work has been undertaken in connection with the thermal contact. A large variation in the experimental data of various researchers (2, 3, 4) exists, therefore further research is necessary.

The contact configuration and the thermal behaviour depend upon the size, shape and location of the true contact area as well as upon the distribution of the flux crossing the interface.

An accurate prediction for a particular assembly would need to consider the contact in relation to all other thermo-physical and mechanical aspects and there exists no completely comprehensive theory (5, 6) to predict contact resistance between engineering surfaces.

1.2 APPLICATIONS

An exceptionally high rate of corrosion in the form of black magnetite occurs at pressed contacts and this has been found in mild steel magnox reactors (7). Hypersonic air flows induce high rates of localised heating in aircraft structures and so an estimation of the thermal stresses produced requires a knowledge of the temperature distributions at the joints. Other applications where contacts occur between oxidized surfaces are in heat pipes, high-power communication satellites and unsatisfactorily welded joints (8).

Engineers have been concerned with the effects of contact resistance on the design of root-fixing of gas turbine blades (9).

Recently, the space programme has given rise to extensive studies of contact phenomena (10).

The presence of oxide films has a detrimental effect on, for example the performance of electrical relays (11, 12), and the rate of heat transfer across bolted joints (10, 13). Oxide effects must therefore, be considered at the design stage, especially in the situations where only narrow design margins can be tolerated such as in communication technology (8).

In any practical situation an electrical or thermal current has to pass from one metal to another through a contact. The conduction of electricity in continuous conductors whether metallic or gaseous has long been studied but the analogy of this phenomenon with the flow of the thermal current still remains a research topic. The particular physical form and the operating conditions of the electrical contact depend on the function it has to perform. The design may vary from the large iron clad circuit breakers (14), transformer laminations (15) to the electrostatic contact.

Typical examples (16) to which the electrical phenomenon applies are radio thermionic valve pins in their sockets, earth screens in their holders, wave-change switches of radio receivers and locating clips and slides for integrated circuit boards. The potential difference across the contact is often as low as micro-volt and the current involved only a few micro-amperes.

1.3 SCOPE OF INVESTIGATION

This investigation involves a study of the surface oxidation, surface characterisation and topography measurements and the mechanism of heat transfer across the interfaces. It considers in detail the following aspects associated with the contact resistance phenomena.

1.3.1 Surface Characterization and Topography

Various engineering surfaces have been characterised and a study of the surface topography and the oxidation phenomenon has been carried out.

1.3.2 The Area of Actual Contact

The effect of oxides on surface topography and the areas of actual contact have been investigated. The dependence of the shapes, sizes and distributions of micro-contacts upon interfacial loads have been examined using the Quantimet Image Analyser.

1.3.3 Thermal Contact Resistance

The thermal contact resistance of both the unoxidized and the oxidized joints were measured in high vacua. The effect of oxides on thermal contact resistance under varied loading pressures, surface roughnesses and film thicknesses have been determined.

An attempt has been made to predict the thermal contact resistance directly from an intermediate experimental stage, i.e. from the area of actual contact. An empirical expression endorsed by the experimental results of the thermal contact resistance has been developed and related to the surface oxide film build-up. This required an accurate measurement of the oxide film thickness which was measured using a high resolution Stereoscan Electron Microscope.

The experimental data obtained have been compared with the existing theories (5, 6). The existing theory has been modified and a theory developed to predict the thermal contact resistance of the oxidized joints.

1.3.4 Electrical Resistance

The investigation has been extended to obtain experimental values for the electrical resistance of the contact.

CHAPTER TWO

SURVEY OF THE EXISTING KNOWLEDGE

2.1 GENERAL

The survey of the existing knowledge has been divided into four sections, i.e. phenomena of oxidation, surface characterization and topography, area of actual contact, thermal contact resistance and its analogy with the electrical contact resistance. The first section attempts to present a general survey of the phenomena of low temperature oxidation and since the aim of this experimental investigation is to study the effect of oxides on surface topography and hence on thermal contact resistance, therefore, emphasis is placed on the latter. There is very little literature available related to this topic.

2.1.1 Phenomena of Oxidation

Many metals when in contact with their surrounding atmosphere exhibit some form of corrosion. Oxidation, a common type of corrosion in metals, results in a thin film of oxide being formed on the outer surface of a metal exposed to an environment such as the atmosphere, fresh or sea water. For example, mild steel or iron can grow, in 100 hours, a film thickness of $20 \text{ \AA}$ (17) in air or oxygen; the oxidation film thickness of aluminium alloys varies from 30 to $3000 \text{ \AA}$ when such metals are exposed to air of various humidities. When condensation occurs, the rate of oxidation is much greater. This thin film of oxide often causes electrical problems in mechanical joints and interfaces between spacecraft structures and electrical components (12, 18). The same phenomenon, although to a lesser extent, exists in a variety of thermal designs, (e.g. heat pipes).

2.1.2 Kinetics of Oxidation

Oxidation is rarely, if ever, carried out under equilibrium conditions. Nevertheless, thermodynamic data can be of some value in understanding the reactions occurring during oxidation, and, more particularly, during corrosion. Thermodynamic data will predict whether a given oxide may or may not be formed under specific temperature and pressure conditions. Although, for example, FeO is thermodynamically unstable below 570°C (19), yet it has been found to form at temperatures well below 570°C (20, 21), and may be retained at room temperature in oxide layers formed at high temperatures. The iron-oxygen phase diagram is shown in Fig. 2.1 (19). Thermodynamic data is unable to predict whether an oxide will be formed in any given time and, in the practical situation, the kinetics of the oxidation process are of greater interest. The rate of oxidation, under given conditions, may be dependent on the rate of reaction at one of the phase boundaries, but is usually controlled by the rate of movement of reactants through the oxide film. Under such conditions the increase in weight of an oxidizing specimen may be said to

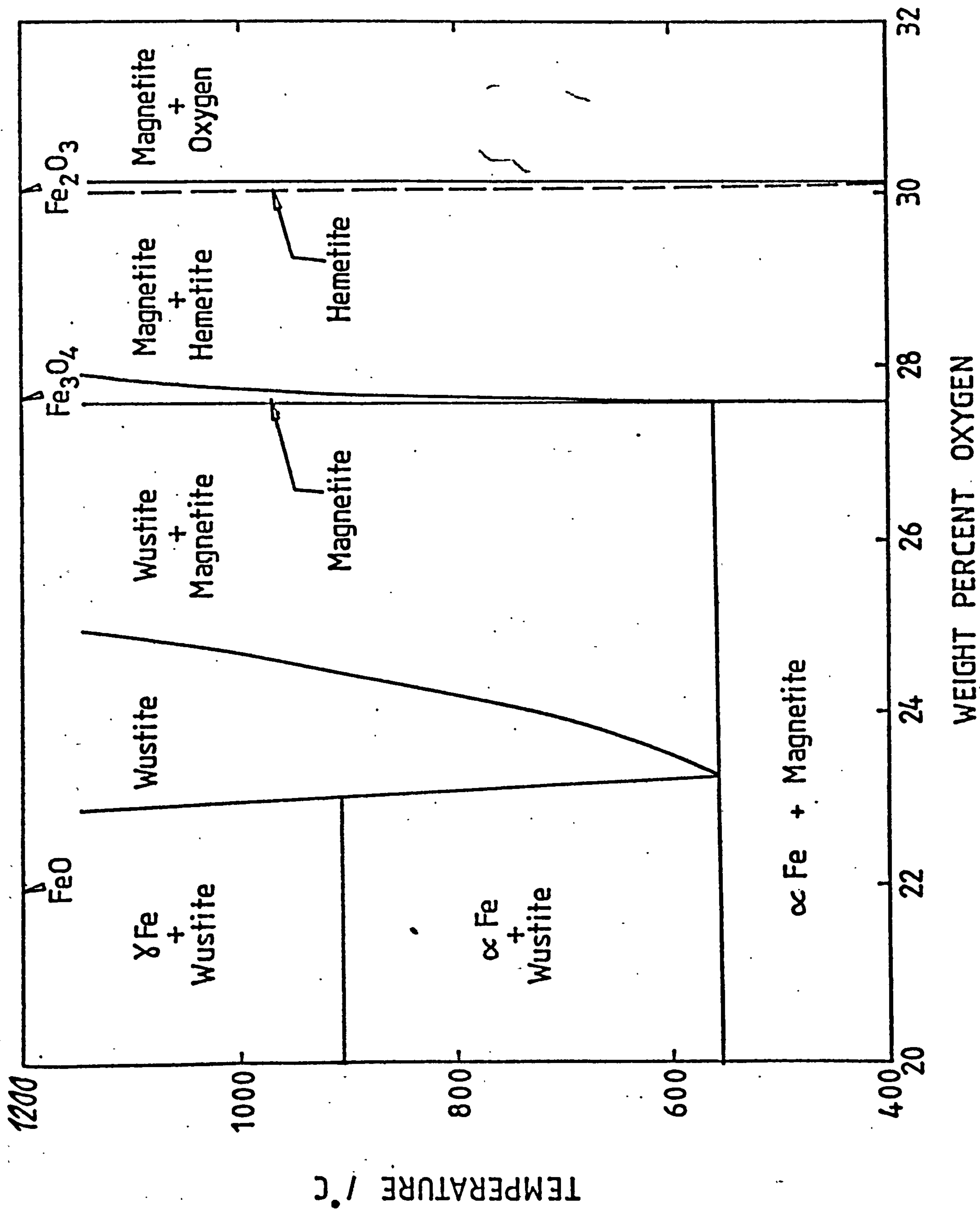


Fig. 2.1 Iron-Oxygen phase diagram.

MISSING

PRINT

vary with time according to one, or a combination of several, well defined relationships. After the initial, thin film stage, iron and mild steels oxidize in a manner approximating to a parabolic relationship at temperatures above 200°-300°C, and the change in weight, Δm , varies with time t as :-

$$(\Delta m)^2 = k t \quad \dots (2.1)$$

where k is the rate constant, which varies with temperature in a manner governed by an Arrhenius type of equation :-

$$D = D_1 e^{-Q_1/R_1 T} \quad \dots (2.2)$$

D = oxidation rate constant, $m^2 \text{ hr}^{-1}$

D_1 = proportionality constant, $m^2 \text{ hr}^{-1}$ (2.3)

Q_1 = activation energy, $J \text{ kg}^{-1}$

R_1 = gas constant, $J \text{ kg}^{-1} \text{ K}^{-1}$

For pure iron, oxidized in air in the temperature range 497°C-903°C, the following expression has been determined (22) empirically :-

$$D = 0.37 e^{-33000/R_1 T} \quad \dots (2.4)$$

The mechanism by which the metal and/or oxygen are transported through the scale has been the subject of much conjecture. The usually accepted model, resulting from the work of Wagner (23, 24, 25) assumes that the scale is either a semiconductor or an ionic conductor. Diffusion across the scale requires a concentration gradient which means that the composition of the oxide must vary from the stoichiometric composition. In the case of FeO, the lattice is metal deficient and termed a p-type semiconductor, in which the cations (positively charged ions which move towards cathode) are the only mobile species. Fe₃O₄ is also metal deficient but has a smaller range of composition than FeO, although in Fe₃O₄ the anion is said to diffuse as well as the cation (19). Fe₂O₃ is an n-type semiconductor deficient in oxygen and the anion is the only mobile species (19). On iron all three oxides are formed at temperatures above 570°C (26), when heated in air at normal pressures.

Holmes (27) presents self diffusion coefficients, which are the coefficients for the relevant anion and cation species diffusing in any given oxide, as a function of $1/T$. This data should enable the rate of oxide growth to be calculated for given conditions, but for this approach to be applied to a practical oxidation process several factors have to be considered. For example, it is necessary to know the type and composition of the oxide produced, and which oxide layer is rate controlling in multi-layer oxides. Also the self diffusion coefficients must be determined under conditions appropriate to the state existing during oxidation, i.e. at the same oxygen partial pressure for cationic diffusion, and oxides in equilibrium with the metal for anionic diffusion.

For example, examination of this data suggests that the rate of oxidation of Fe to Fe₂O₃ (by anion or cation diffusion) might be expected to be slower than the rate of oxidation of Cr to Cr₂O₃ (by anion or cation

diffusion), but this is known to be untrue. The explanation for this is said to be due to the possibility of Fe_2O_3 showing much larger departures from stoichiometry (27). Davies et al (19) report that the relative proportions of the three oxides vary with temperature, whilst Paidassi (26), reports virtually constant proportions of 95% FeO , 4% Fe_3O_4 and 1% Fe_2O_3 , over the temperature range 700°C - 1250°C . Paidassi however notes that these constant results are only applicable to scales that remain strongly adherent to the metal, since the presence of a discontinuity at the interface modifies the constitution of the scale.

Thus, there are inherent difficulties in approaching the subject of oxidation by studying kinetics alone. Bernard (28) has listed some of the reasons why the growth rate of an oxide growing under normal conditions cannot be specified with any great accuracy, and hence is likely to be non-reproducible. These are :-

- (a) the process of transfer across an interface which has a rate approximately independent of time, is coexisting with the diffusion process which has a rate decreasing with time, and this combination can lead to discontinuities in growth rate.
- (b) changes in oxide/metal adherence which may produce changes in the rate of transfer of reactants across the interface and therefore affect rate of oxidation.
- (c) variations in the chemical composition of the oxide film which modify the diffusion conditions.
- (d) recrystallisation of the oxide.

Lawless (29) discussed other factors which can provide problems in kinetic studies. He suggested that purity of both the metal and the atmosphere are extremely important since, for example, very small concentrations of a contaminant, such as H_2S , in the oxidising atmosphere can have a profound effect on the rate of oxidation.

If, however, all the conditions that may be standardised are controlled there is still a basic variability in kinetic results obtained under apparently identical conditions. This may be largely due to the seemingly random nature of oxide cracking and changes in adherence, which greatly influence the rate of oxide growth. The study of oxidation therefore requires information concerning the mechanical properties of oxides, their adherence to the metal, and the effects of stresses and contaminants on these factors.

2.1.3 Composition and Nucleation of Copper Oxide

Oxide films formed on copper in air or oxygen at temperatures above about 200°C consist of two layers, an outer layer of cupric oxide, (CuO), and an inner layer of cuprous oxide, (Cu_2O).

The formation of copper oxide is similar to many gas/metal reactions, that is it proceeds according to the mechanism of nucleation

and growth. Gronlund (30) distinguished with the optical microscope three successive stages for the nucleation and growth of copper oxide at 500°C and at a pressure less than 1 mm. Hg :

- 1) An incubation period during which no nuclei were observed.
- 2) A period of growth of Cu_2O nuclei that started abruptly and ended when the nuclei fused together.
- 3) A period of uniform growth and the appearance of CuO .

The theory which governs the growth of such a composition oxide film has been developed by Jost (31), Wagner (32), and Valensi (33). The relative thicknesses of the two layers and a function of the ratio of the rate constants governing the two partial reactions. Since the activation energies for these reactions are usually different, the thickness ratio will vary with temperature, but it should be independent of time and film thickness provided that the rate law holds for both partial reactions.

The empirical situation is illustrated by Fig. 2.2 where the $\text{CuO} : \text{Cu}_2\text{O}$ ratios reported by several authors have been collected. Included is Valensi's theoretical curve which he confirmed with experimental data for the temperature range 800-900°C. CuO decomposes at 1030°C, below this temperature the CuO content of the scales increases with increasing temperature and reaches a maximum value at intermediate temperatures, a trend observed by all authors.

Below 400°C, published information is conflicting. Valensi's theoretical curve demanded 100% CuO in the film formed at the low temperatures whereas electron diffraction and coulometric work (34, 35) show conclusively that below approximately 250°C Cu_2O is the only oxide formed and even when CuO does eventually appear it does not become predominant. Valensi claimed that the reason for this difference was that dissolved gases were present in the metal used. However, a more recent investigation (36), where the copper had been melted and heat treated in vacua, confirmed the electron diffraction and coulometric work.

2.1.4 Epitaxial Stresses

Since the lattice of the metal and the oxide are normally appreciably different and the oxide nucleates and grows on the metal surface, stresses will be produced due to the epitaxy (37).

Any epitaxial stress produced will be a maximum at the interface and reducing to zero at the free surface. It is probably more correct to consider the cation sublattice in the oxide, rather than the bulk lattice constants, but the stresses produced in the sublattice are extremely difficult to predict. Also, these epitaxial stresses will only be effective over a short distance and will only be of real importance for thin film growth at low temperatures or pressures.

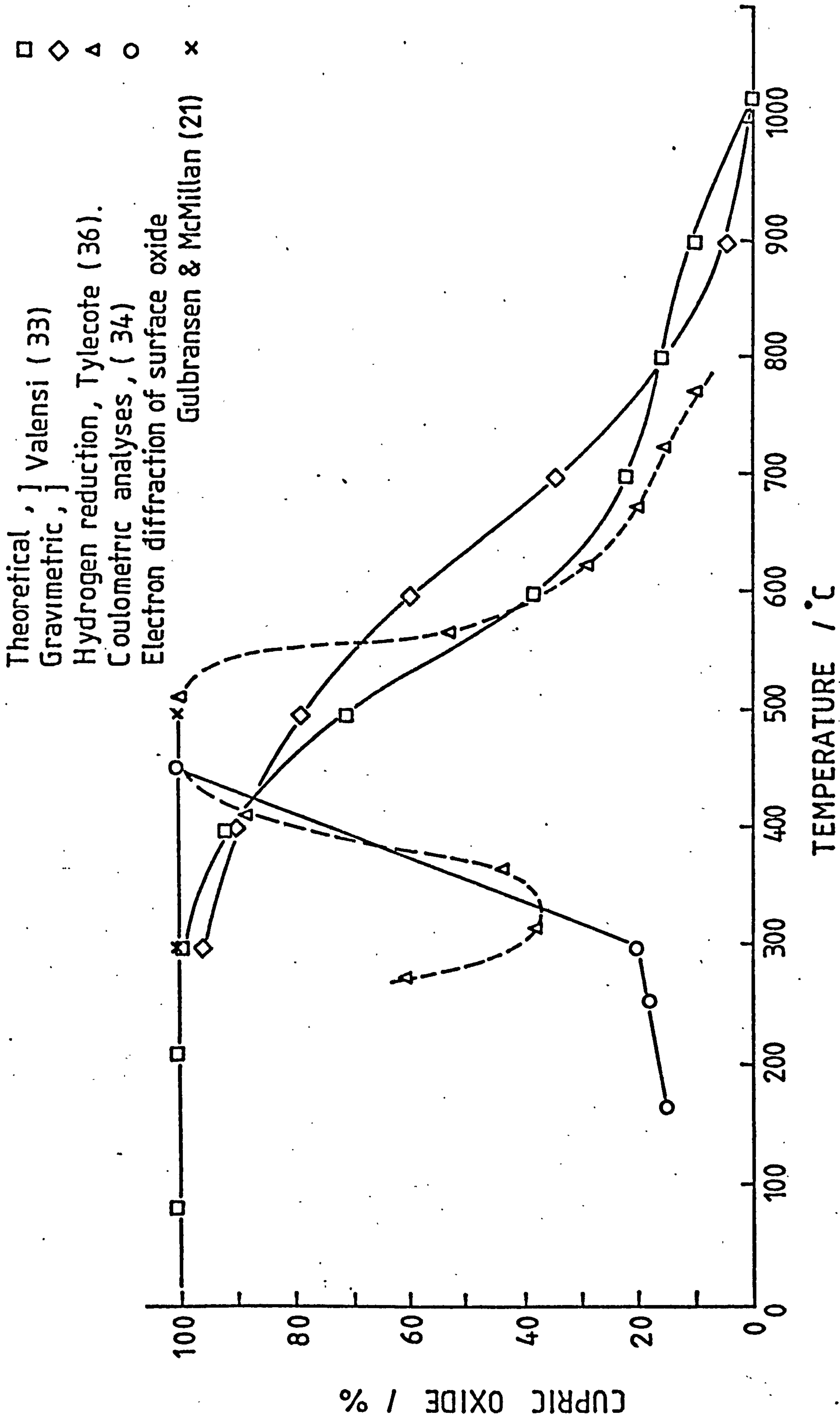


FIG. 2,2
Composition of copper oxide as reported by
several authors (21, 33, 34, 36).

2.1.5 Recrystallisation Stresses

It has been suggested (38) that any recrystallisation occurring in the oxide could lead to the production of stresses in that area, but it seems equally likely that such recrystallisation could act as a stress relief mechanism (39).

2.1.6 Compositional Changes

If there are compositional changes in either the metal or the oxide in the region of the interface during oxidation, then stresses may be produced. This could well be important in the oxidation of Fe where the three oxides are usually present and are able to exist over a wide stoichiometry range. For example, Howes and Richardson (40) suggest that the tensile stresses produced during the early stages of oxidation of Fe-Cr alloys are due to changes in the amount of iron present in the scale during growth.

Phase changes in the substrate may also impose stresses on the growing oxide film, due to the accompanying volume changes.

2.1.7 Vacancy Generation

Metals, such as iron, that oxidise by outward diffusion of cations produce vacancies at the metal/oxide interface. Some of these vacancies will undoubtedly precipitate at interface sinks, and will have a profound effect on adherence.

Differences in oxide thickness may exist between adjacent grains as a result of different orientations, since it is well known that the rate of oxidation varies on different crystallographic planes, (41, 42).

2.18. Thermally Induced Stresses

In the practical situation the stresses produced by temperature fluctuations are likely to be of more significance than the growth induced stresses because they may be much greater, and because engineering components do not normally operate isothermally. Some stresses will be produced because of the thermal gradient existing across the section during heating or cooling, but differences in expansion coefficients of oxide and metal will be of greater importance.

There is much conjecture concerning the mechanisms operating when oxides plastically deform, and it seems likely that more than one mechanism may act at any time. The relative contribution of each mechanism depending principally on temperature and on the particular oxide system.

2.2 SURFACE CHARACTERISATION

Many surfaces generated by machining processes contain both random and periodic variations of surface heights. Separation of these components is possible by analysing the two-dimensional surface profile autocorrelation functions defined by

$$F(\lambda) = \lim_{x \rightarrow \infty} \frac{1}{x} \int_{-x/2}^{+x/2} y(x)y(x + \lambda) dx \quad \dots (2.5)$$

where $y(x)$ is the profile height ordinate at a horizontal station x and $y(x + \lambda)$ the height of an adjacent position $x + \lambda$.

Examples of two basic autocorrelation functions are shown in Fig. 2.3. The random profile autocorrelation function Fig. 2.3a falls to and remains at zero. At this stage the surface ordinates considered in the construction of the curve are statistically independent. This function may be expressed as

$$F(\lambda) = e^{-x/\alpha_c} \quad \dots (2.6)$$

where α_c is the correlation distance (43). The autocorrelation function of the second profile Fig. 2.3b exhibits a periodic variation similar to that of the parent profile. The initial decay is characteristic of the surface random component and the mean distance between points where the function becomes zero is an indication of the half wave-length of the surface waviness. Although the periodic function in many surface profiles may not be as easily defined as in this example, the basic approach is similar. Many engineering surfaces can be categorised in terms of their autocorrelation functions but at present such a description is at best only approximate (43). Nevertheless, the ability to separate the random and periodic components of a profile is an important property of the autocorrelation function.

Another function known as the power spectral density is the Fourier Transform of the autocorrelation function. It defines the relative amplitude density of the discrete wavelengths which are contained in the profile variations, i.e. it shows the dominant frequencies in the profile (44). Large wavelength periodic components appear as a spike in the power spectral density curve. Generally, for a random signal a wide spectral density distribution gives an autocorrelation function with the high rate of decay and vice-versa (44). The power spectral density, $P(\omega)$, and the autocorrelation function are related by (45, 46).

$$F(\lambda) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} P(\omega) \exp(i\omega\lambda) d\omega \quad \dots (2.7)$$

For the exponential correlation function (45, 46) the power spectral density is white noise limited only in the upper frequencies by 6 dB per octave (Fig. 2.4). The discrete power spectrum for a sine wave, as illustrated in Fig. 2.5a, is defined by :

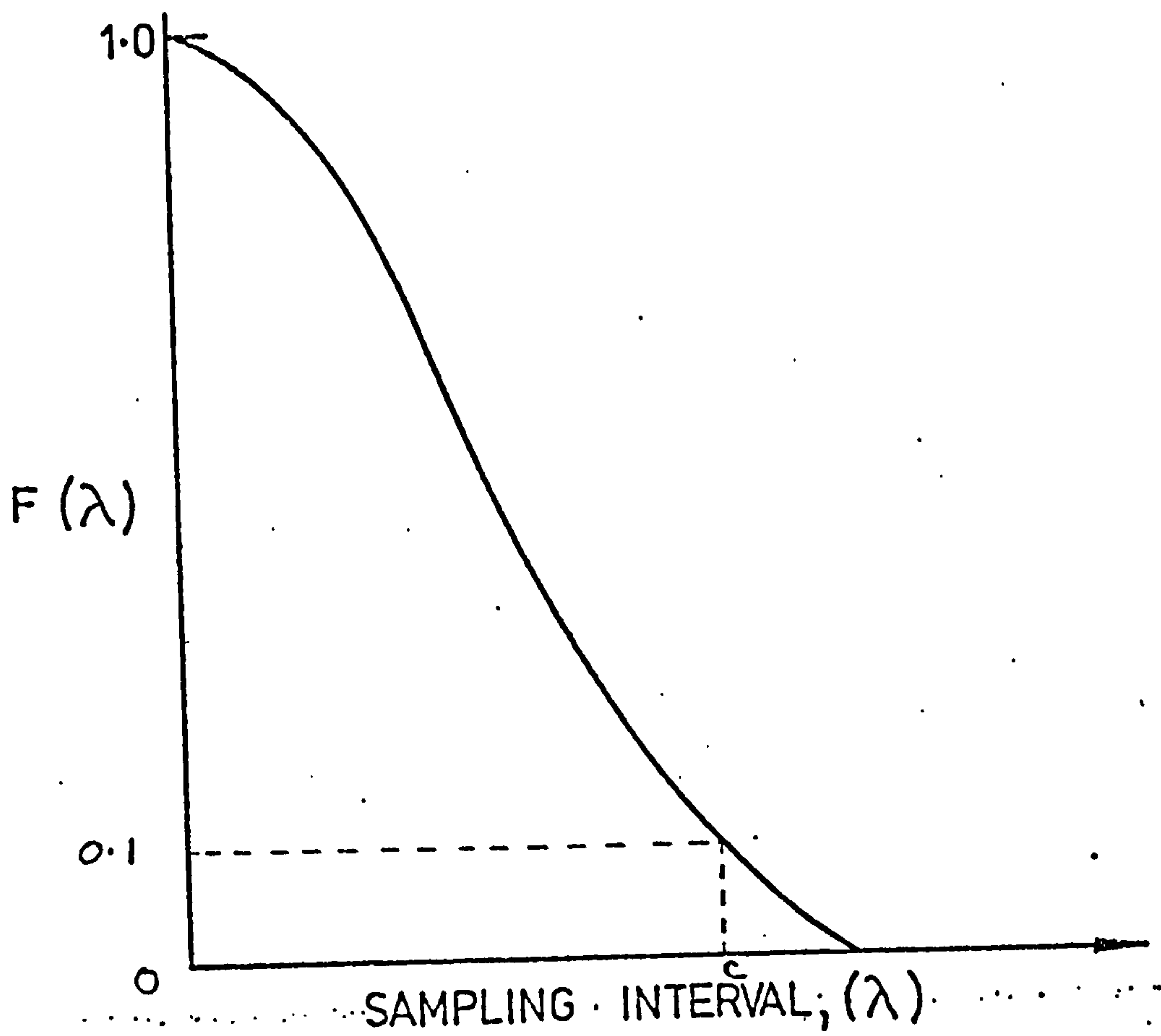


Fig. 2.3a Auto-correlation function of random surfaces.

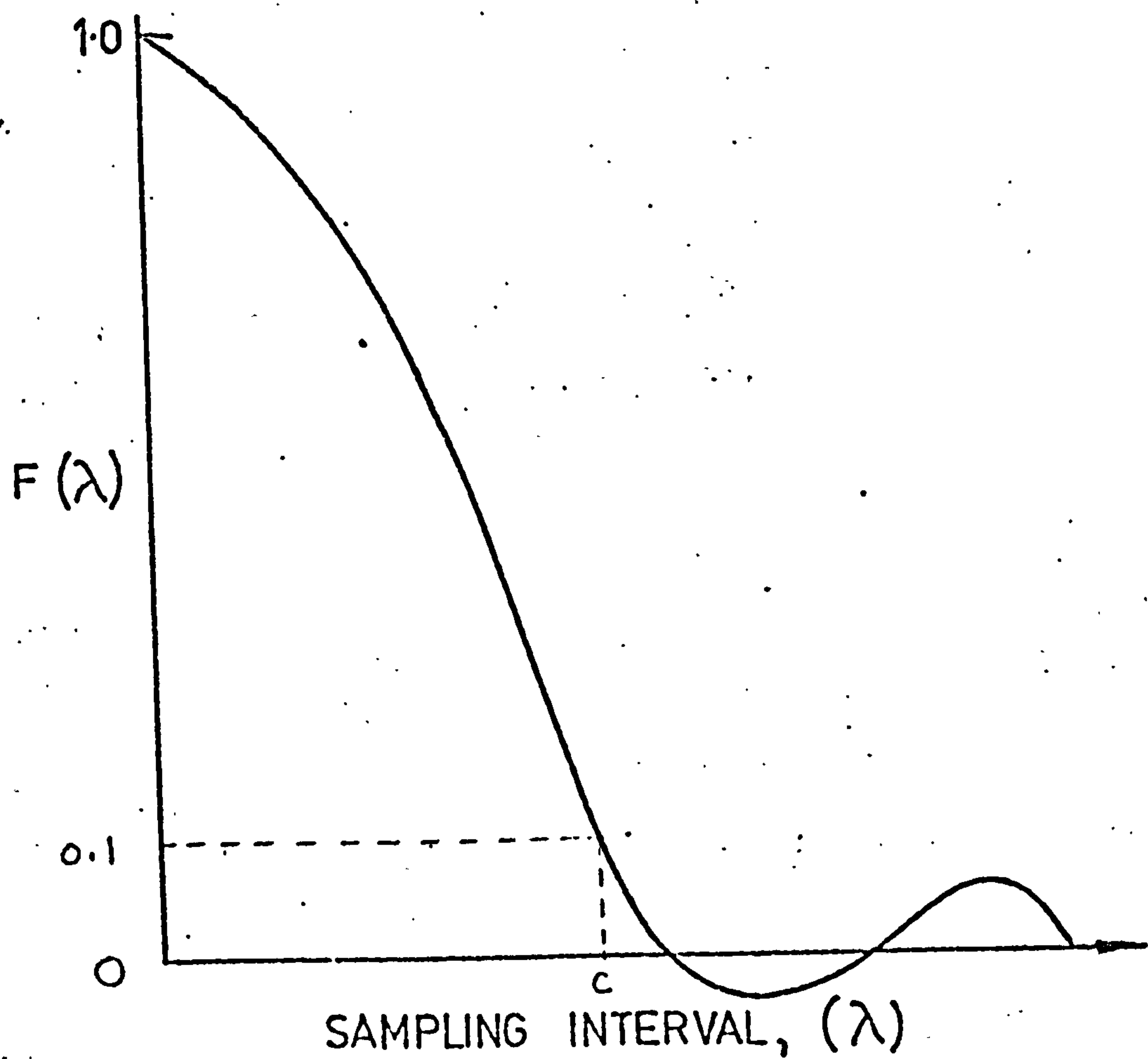


Fig. 2.3b Auto-correlation function of random surfaces with waviness.

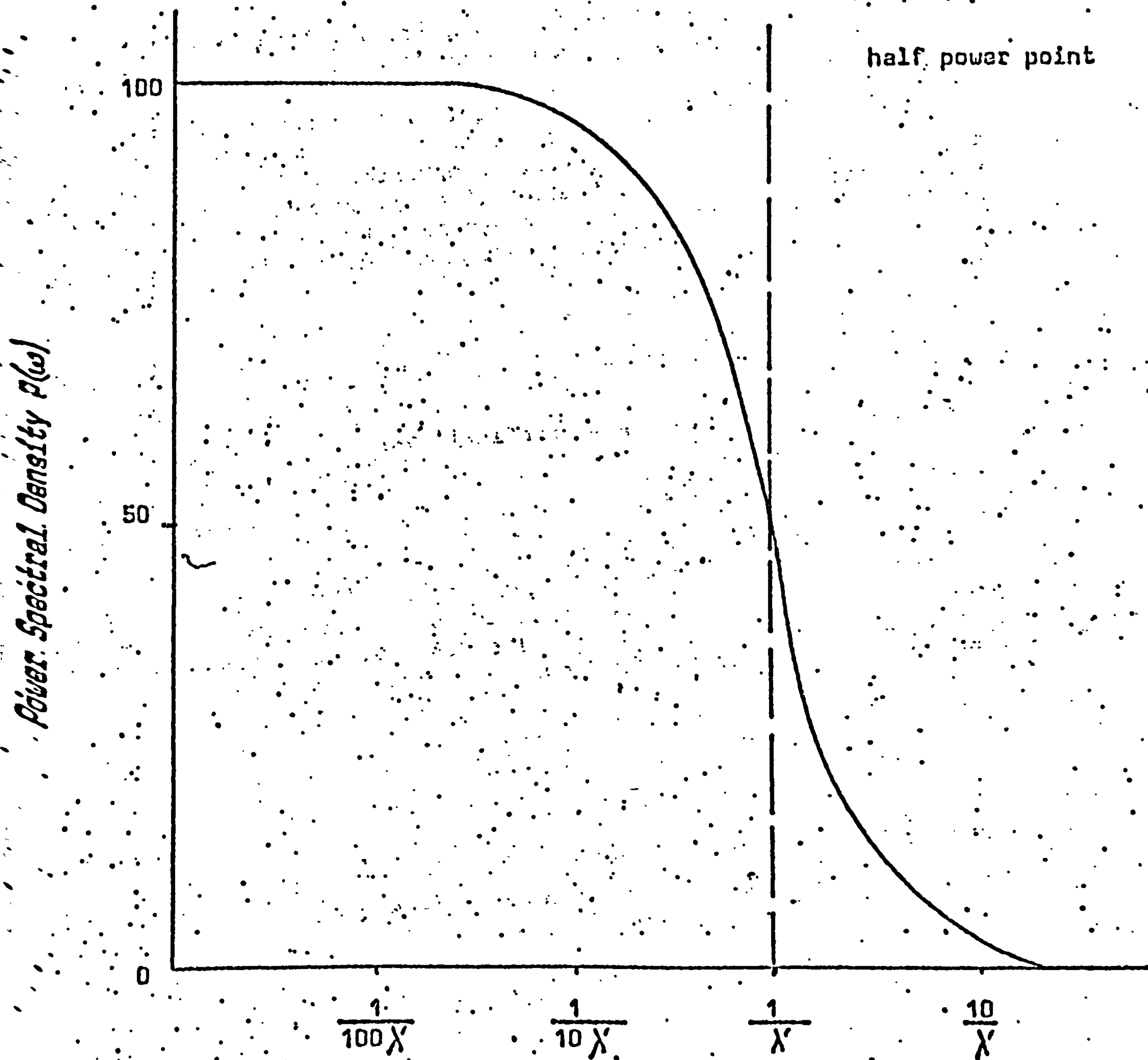


Fig. 2.4

Power Spectral Density, $P(\omega)$ for an exponential auto-correlation function.

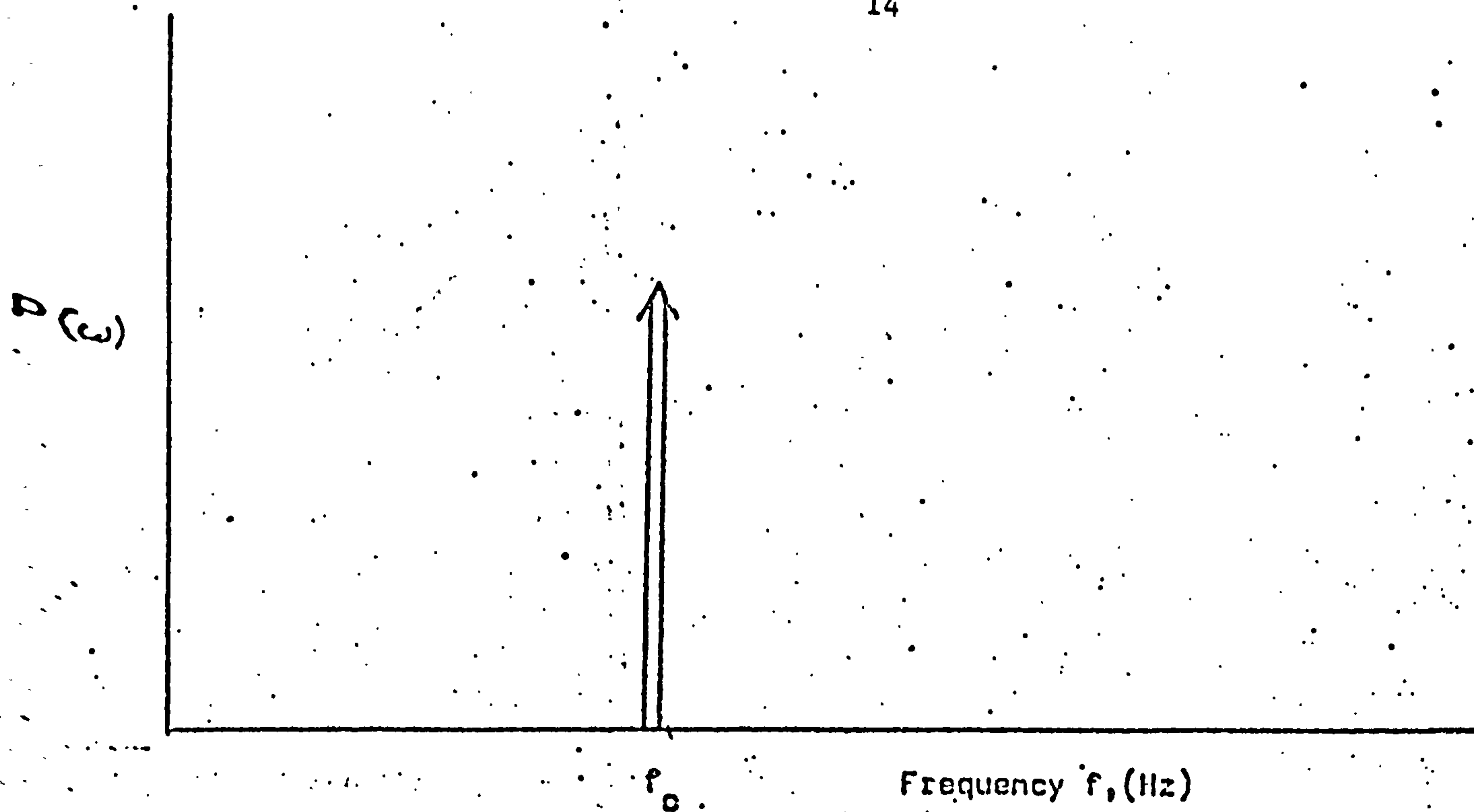


Fig. 2.5a Power Spectral Density plot for a sine wave.

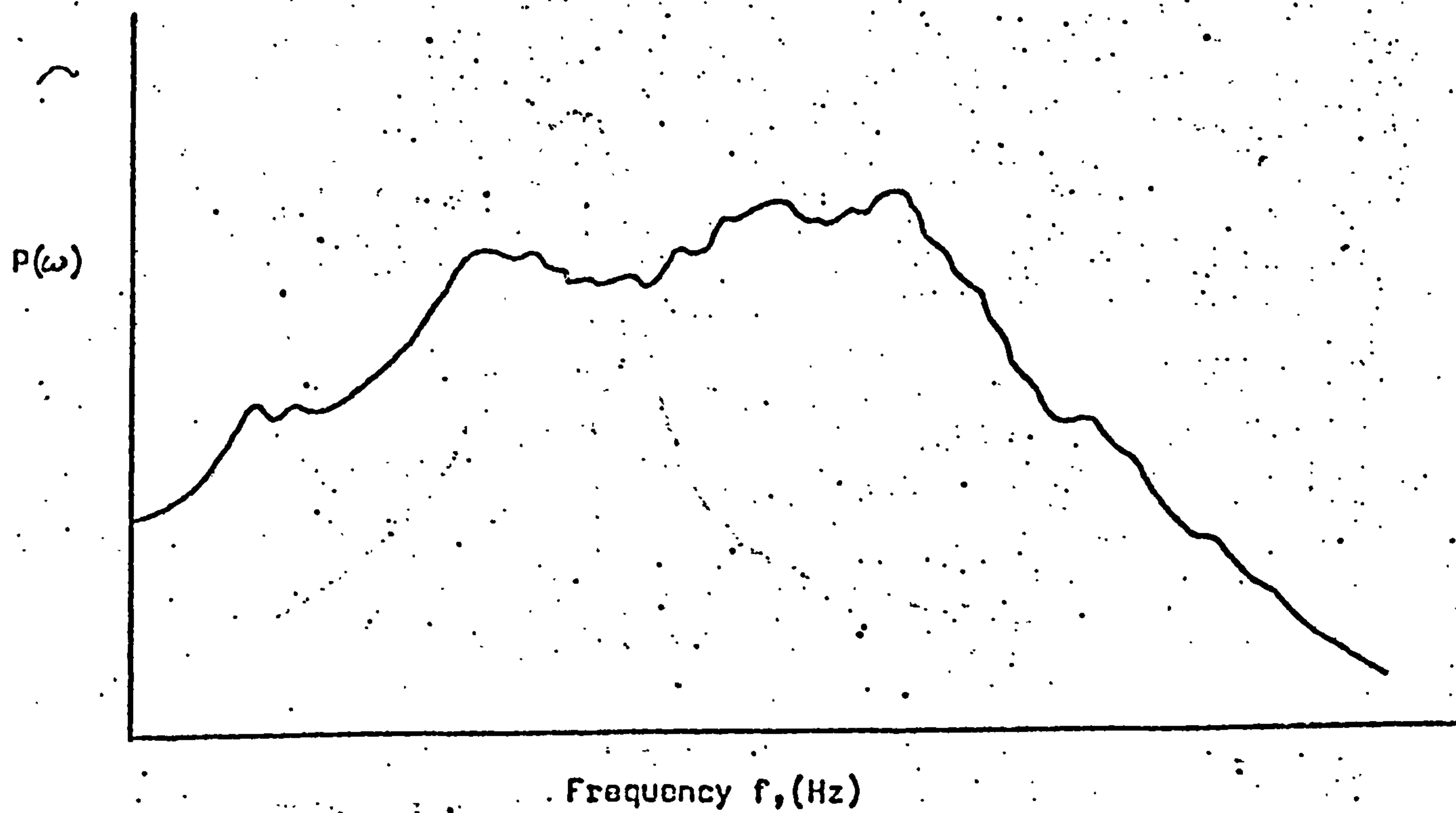


Fig. 2.5b Power Spectral Density plot for a wide-band random noise.

$$P(\omega) = \sigma^2 \delta(f - f_0) \quad \dots \quad (2.8)$$

where $\delta(f - f_0)$ denotes a delta function at $f = f_0$. In words, the power spectral density function of a sine wave is infinitely large at the frequency of the sine wave and zero at all other frequencies. However, the integral of power spectrum over any frequency range that includes the sinusoidal frequency has a finite value equal to the mean square value (σ^2) of the sine wave.

The relatively smooth and broad power spectral density illustrated in Fig. 2.5b gives rise to the descriptive term 'wide-band' for this type of random data. For the hypothetical case of white noise, this power spectral density is uniform over all frequencies by definition. The power spectral density of the sine wave plus random data is simply the sum of the power spectral density for the sine wave and random data separately, as illustrated in Fig. 2.6a. On the other hand, the power spectral density of the narrow-band noise in Fig. 2.6b is sharply peaked as for a sine wave (hence the term 'narrow-band'), but still smoothly continuous as for random data.

In surface specification, the autocorrelation function is generally preferred to the power spectral density because periodic variation in the profile appear as a similar periodic variation in the curve of autocorrelation function versus ordinate separation.

2.2.1 Surface Hardness

It is assumed that the contacting regions deform in an ideal plastic manner (47 - 51), the true contact between a rough surface and a softer flat surface (45) can be regarded as due to a number of small indentations (51, 52). Hence the true contact pressure equals the micro-indentation hardness (47-51, 52).

$$\frac{A_{rm}}{A_n} = P/M \quad \dots \quad (2.9)$$

The use of the Meyer hardness of the softer material has been recommended for this particular case (53). However for the contact between a rough surface and a harder flat surface, where the asperities themselves tend to deform rather than penetrate, it has been suggested (54) that the Mallock hardness of the softer material (which equals approximately one half the indentation hardness) should be used in eqn. 2.9. A better relationship (47, 55-60) takes the form

$$\frac{A_{rm}}{A_n} = (P/M^*) \quad \dots \quad (2.10)$$

where the effective contact hardness, M^* varies with load due to work hardening and asperity interaction. The uncertainty of the relationship between effective contact hardness and loading is a factor towards inaccurate prediction of the area of actual contact.

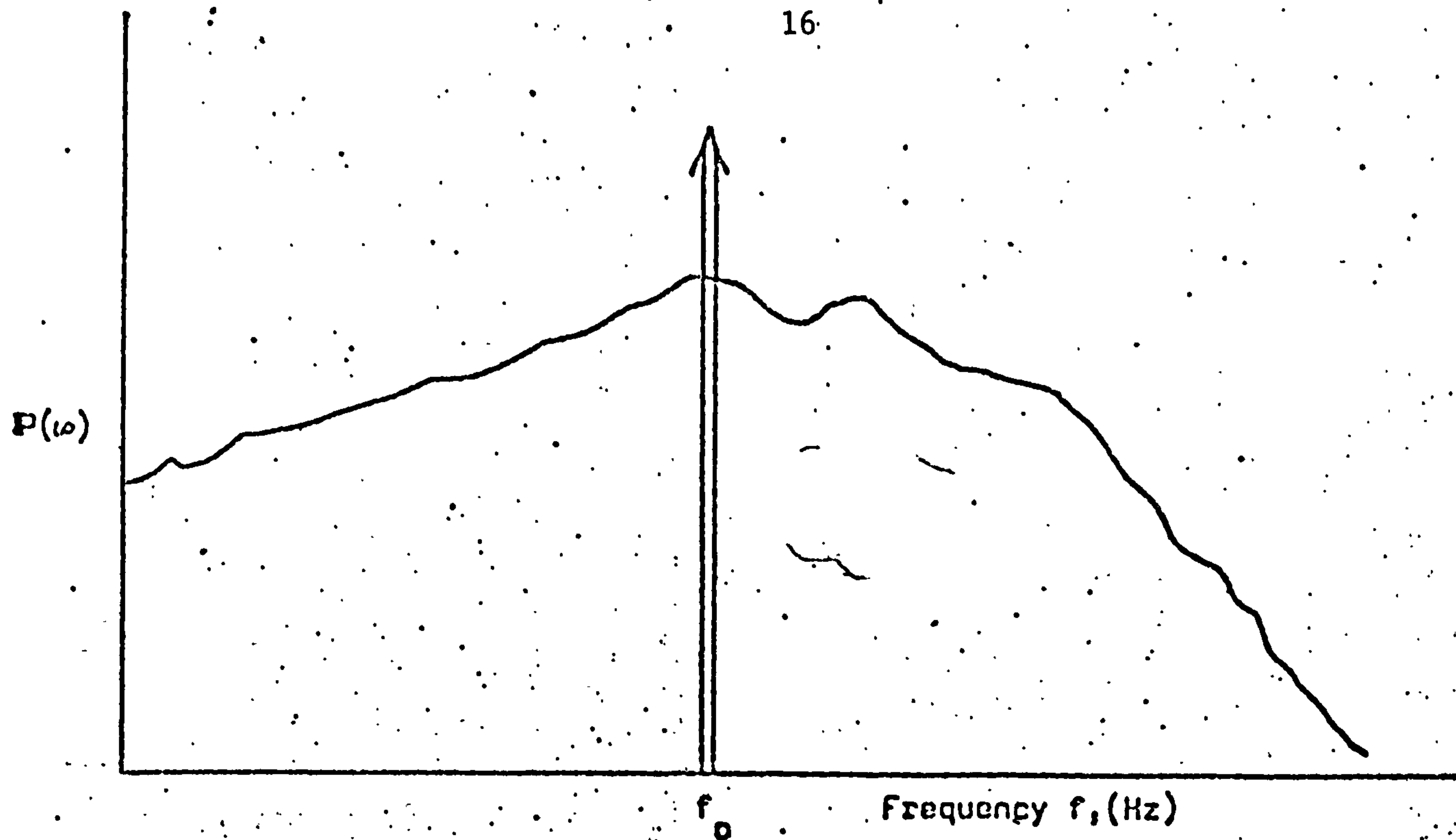


Fig. 2.6a Power Spectral Density plot for a sine wave plus random noise.

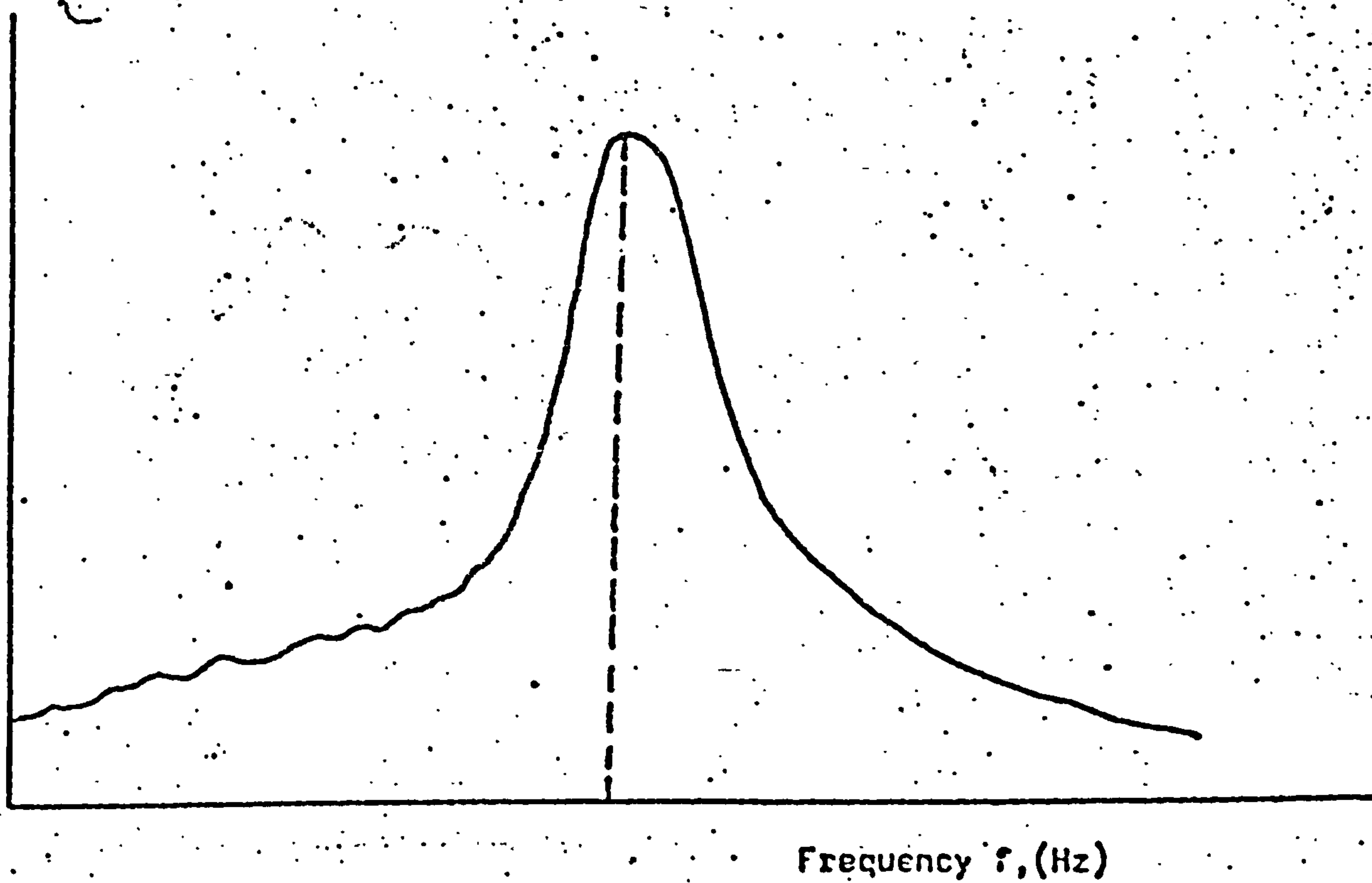


Fig. 2.6b Power Spectral Density plot for a narrow-band random noise.

2.2.2 Surface Roughness

This is a measure of the spread of the surface heights above a mean plane. The r.m.s. roughness, σ , is the standard deviation of this distribution and, for a normal distribution of heights, may be determined using gaussian distribution paper (47, 52, 61-67). When the distribution is skewed it has been suggested (47) that the value of σ should be taken from the upper portion of the profile where the contact would occur. Also the r.m.s. value of roughness should be used when specifying the contact between two dissimilar surfaces, i.e.

$$\sigma_s = (\sigma_1^2 + \sigma_2^2)^{\frac{1}{2}} \quad \dots \quad (2.11)$$

2.2.3 Mean Peak Radius of Curvature

This parameter may be usefully employed in conjunction with the elastic modulus, E^* , of the contact and the contact hardness, M , to predict whether the deformation under load is elastic or plastic. The plasticity index, λ , is defined (48-50) as

$$\lambda = \frac{E^*}{M} \left(\frac{\sigma_s}{\rho_s} \right)^{\frac{1}{2}} \quad \dots \quad (2.12)$$

when the effective values of the elastic modulus E^* and mean peak radius of curvature, ρ_s , of the contacting surfaces are given respectively by

$$\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \quad \dots \quad (2.13)$$

and

$$\frac{1}{\rho_s} = \frac{1}{\rho_1} + \frac{1}{\rho_2} \quad \dots \quad (2.14)$$

Greenwood (48-50) proposed that, when $\lambda < 0.7$, deformation under all loads would be elastic, whereas for values of $\lambda > 1.0$, all deformations would be plastic.

2.2.4 Mean Absolute Surface Slope

If the contact can be considered to be a number of increasing cones of base angle, θ , the mean size and number of contact regions formed under a given load can be estimated from a knowledge of the mean profile slope, ψ_s , and the roughness, σ_s . The usual technique is to sample surface heights

at regular intervals using a profilometer linked to a data-logging system (2, 47, 52). The recorded information may be analysed numerically to obtain, σ , ρ , and $|\Psi|$. The r.m.s. value of the mean absolute slopes of two dissimilar surfaces is taken as the effective value for the contact, i.e.

$$\Psi_s = \left[\frac{|\bar{\Psi}_1|^2 + \dots + |\bar{\Psi}_2|^2}{\sigma_1^2 + \sigma_2^2} \right]^{1/2} \dots \quad (2.15)$$

2.2.5 Surface Waviness

For a number of engineering surfaces the carrier profile upon which the roughness is superimposed (Fig. 2.7) contains regular periodic waveforms. The sampling interval which should be selected to produce data relating to waviness should be large enough to take into account the microscopic deviations. Waviness may be quantified by the correlation wavelength and mean amplitude.

2.2.6 Sampling Interval

Whitehouse and Archard (69) showed that both $|\Psi|$ and ρ vary systematically with sampling interval (see Fig. 2.8).

The values of the surface parameters measured using digitised profilometric traverses depend upon the interval between sampled ordinates. Figures 2.9 and 2.10 show how the measured values (3) of mean slope and peak radius of curvature vary with sampling interval for a nominally non-wavy surface. It remains unexplained from the literature which values of the sampling interval or correlation should be chosen in order that valid estimates of the surface parameters, Ψ and ρ are produced for the prediction of the distribution of sizes of micro-contact bridges. Data analysed at a sampling interval corresponding to a correlation of about 0.1 provide information regarding the mean structure of the surfaces. This sampling interval relates to the mean distance between asperities. In order to obtain data relating to a mean idealised asperity a shorter sampling interval corresponding to a correlation exceeding 0.1 is needed.

2.3 SURFACE DEFORMATION

As early as 1881, the deformation of two smooth hemispheres in contact was investigated theoretically by Hertz (70). However, when the local stress exceeds the elastic limit of the materials as in the case of contact between the micro-irregularities of surfaces, Hertzian elastic theory can no longer apply. In view of this, Bowden and Tabor (71) suggested that for contact between rough surfaces, the local contact pressure reaches so high a value that a local plastic flow of the contact

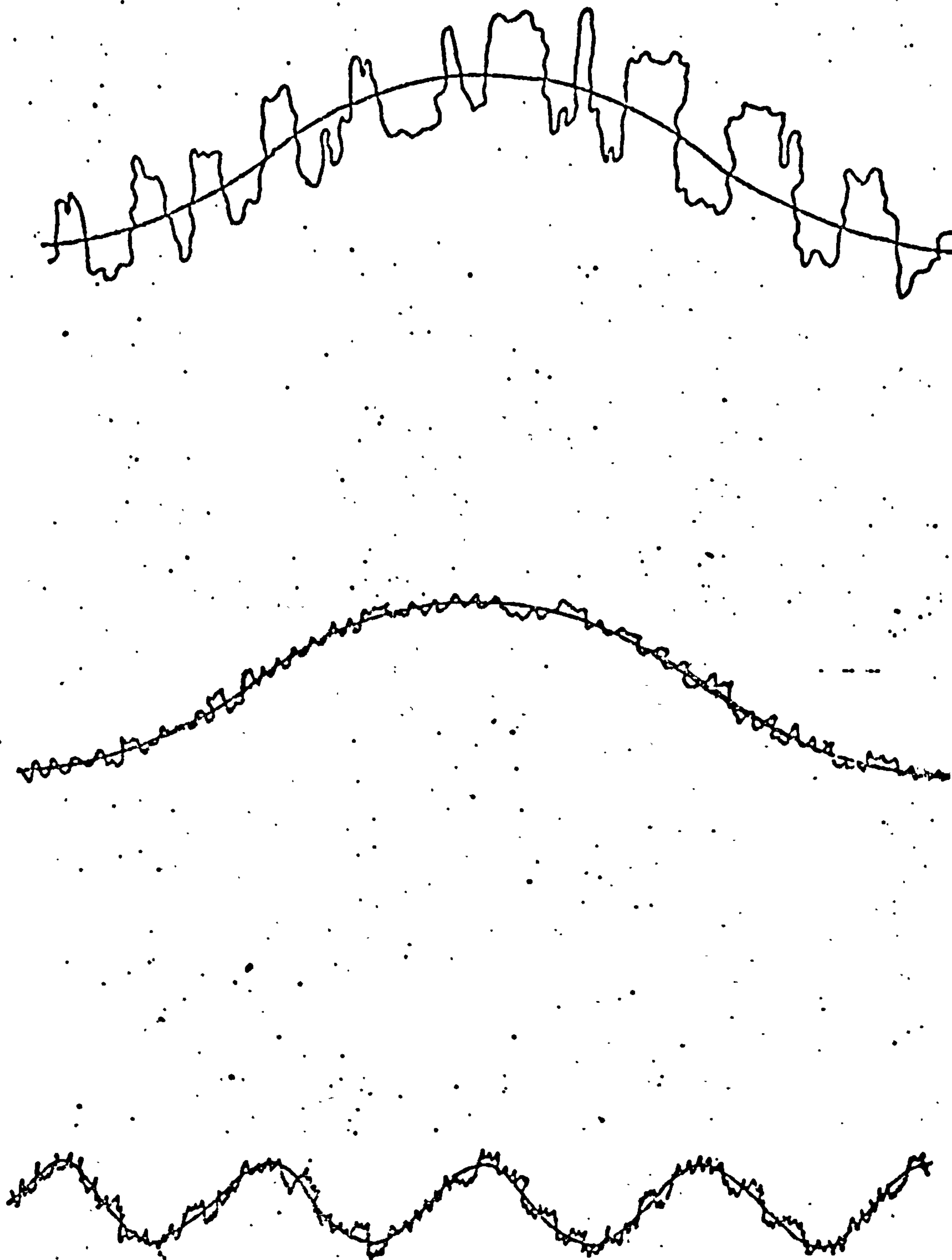


Fig. 2.7

Surface profiles indicating the carrier profile as periodic content and the superimposed random content as real surface roughness.

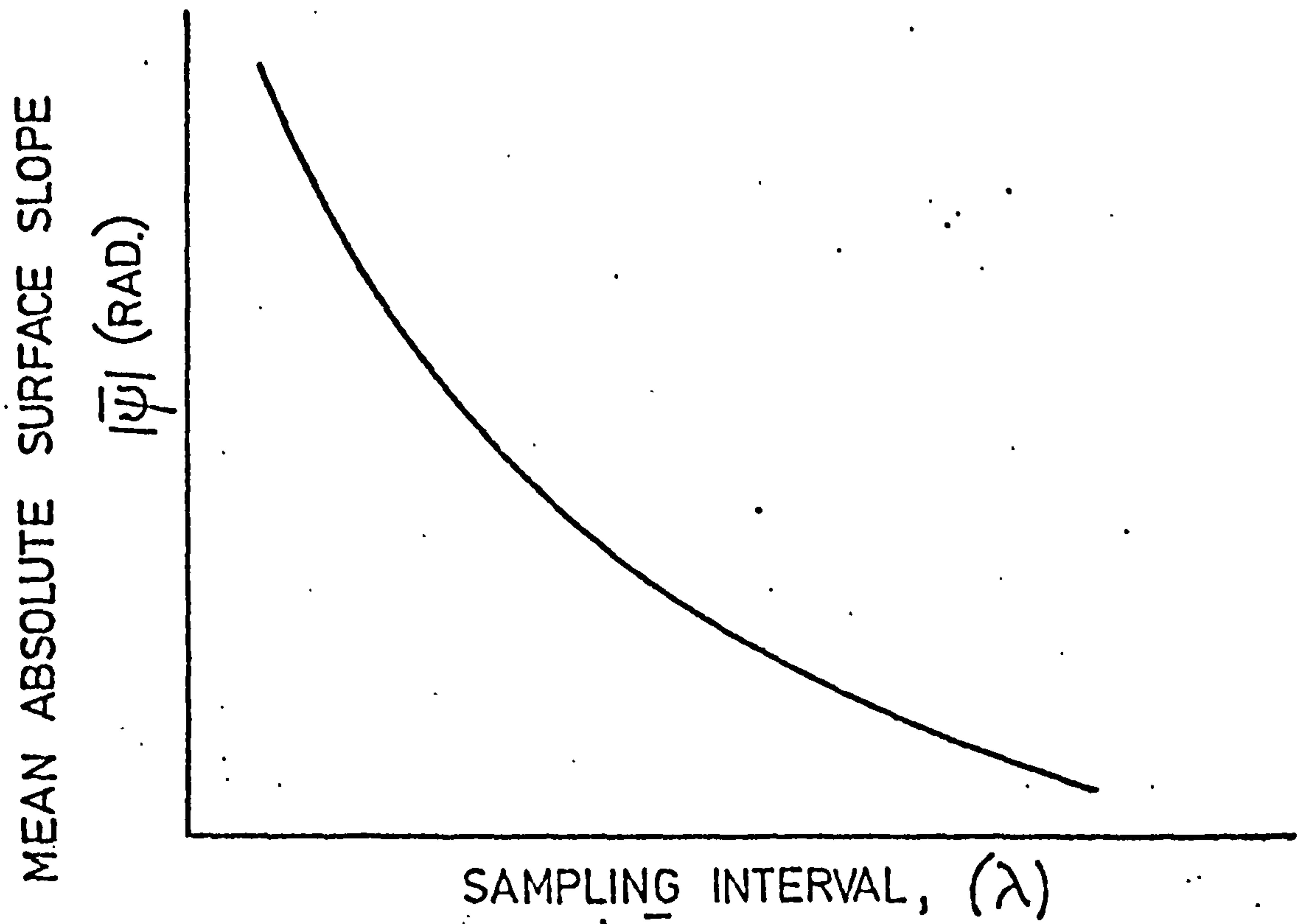


Fig. 2.8a Variation of mean absolute surface slope with sampling interval.

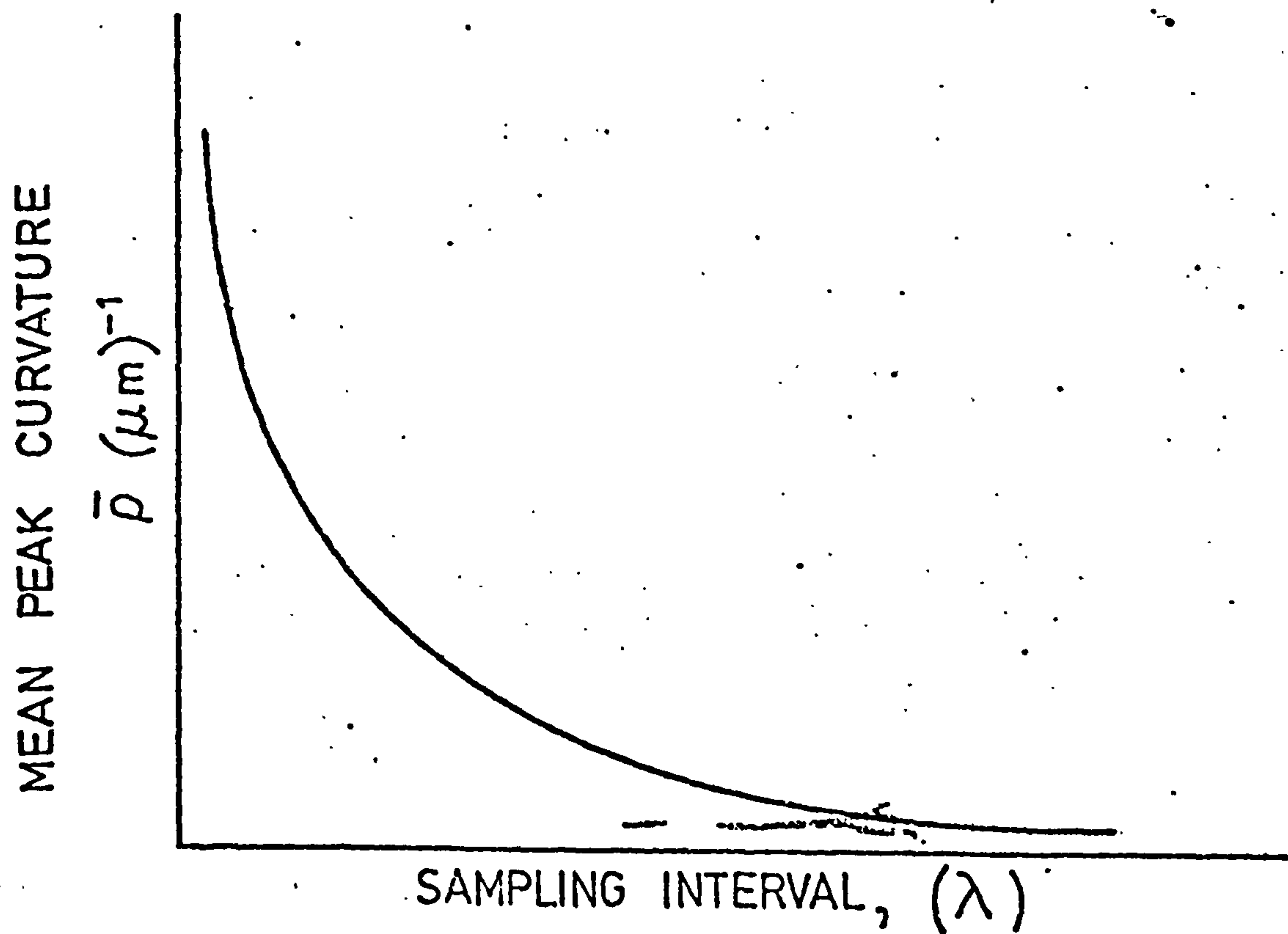


Fig. 2.8b Variation of mean peak radius of curvature with sampling interval.

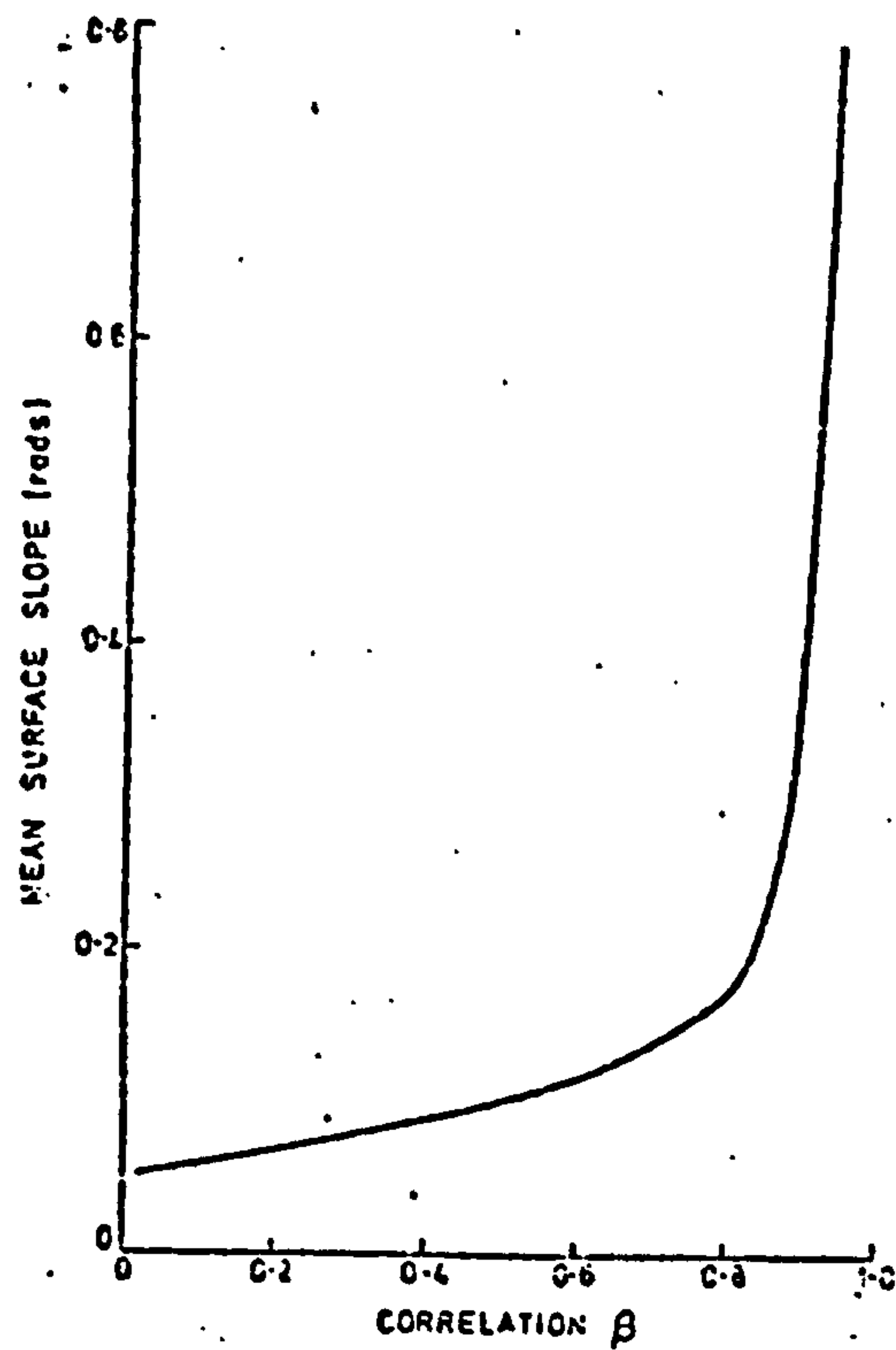


Fig. 2.9 Variation of mean surface slope with correlation for a roughened stainless steel surface(3).

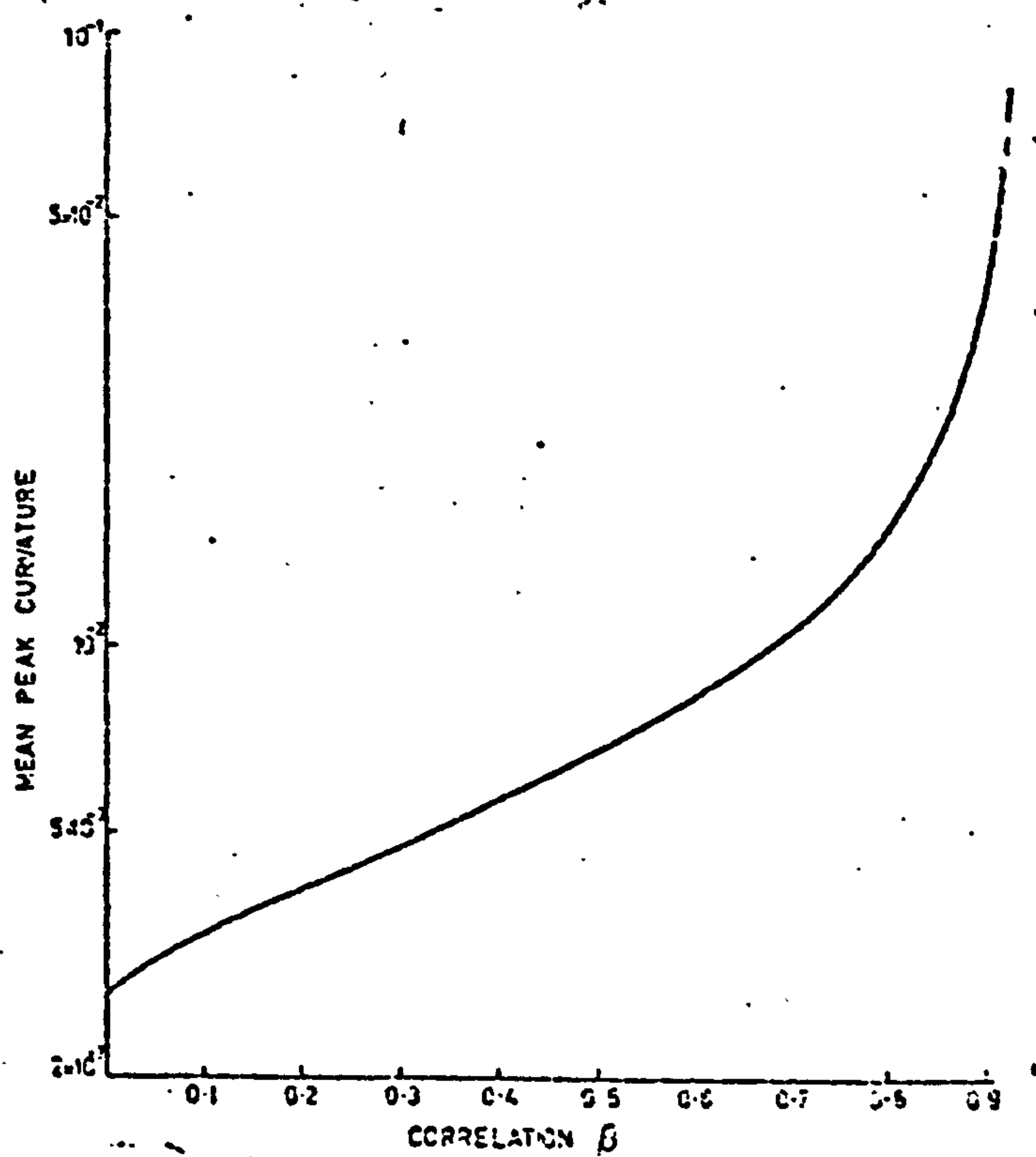


Fig. 2.10 Mean peak curvature at different correlation for a roughened stainless steel surface(3).

frequently occurs. The study of friction (72), has shown that in most cases the normal applied load on a surface is proportional to the real area of contact. The proportionality varies according to the relative amount of plastic deformation. For fully plastic deformation it can be expressed mathematically (73), as defined by equation (2.9). This equation has further been utilized by Holm (12), Fenech and Rohsenow (74), Mikic et al (75), and D'yachenko (76) to successfully predict the total area of contact.

The question as to when a transition takes place from elastic to plastic flow and to what degree a surface has deformed plastically still remains open. However, as a guide, an answer could be obtained by calculating Greenwood and Williamson's "plasticity-index" (48), which relates the topographic and material characteristics of a surface. This has previously been defined in equation (2.12). They suggested that whenever the plasticity-index exceeds unity the asperities will deform plastically regardless of the magnitude of the load applied.

2.3.1 Asperity Interaction

According to the classical view the behaviour of surfaces in plastic contact should not change significantly as the load is increased the true contact area should remain proportional to the load. However, the unexpectedly high resistance to crushing shown by surface asperities under high loads (78) is incompatible with this simple relation. Nevertheless, the classical approach, which neglects the interaction of asperities, has been moderately successful in explaining friction, adhesion and certain electrical contact phenomena (72). Williamson (78) showed that the non-linear increase in the degree of contact with load is a property of any surface with closely spaced asperities, whereas the classical approach considers the non-linearity of the relation to be an anomaly which can be accounted for only by invoking a special mechanism such as work hardening. His experimental study for the persistence of asperities at very high loads led him to the hypothesis that a proper treatment of plastic contact must allow for the interaction of asperities, i.e. the phenomenon would result from the collective behaviour of the whole asperity population.

Moore (79) demonstrated the persistence of the surface asperities and found it impossible to make the asperities disappear, however hard he pressed. Many workers (80) have advanced possible reasons for this - but none of them provides an adequate explanation of the phenomenon.

2.4 AREA OF ACTUAL CONTACT

The contact of surfaces was first researched closely in the fields of electrical engineering and tribology. The two main approaches towards this specification have been termed the asperity model (51) and the profilometric approach (50). The area of actual contact and number of contact spots per unit area may be obtained by integrating geometric parameters, obtained from traverses across two profiles placed side by side (81, 82). Using an analogue computer, the 'datum plane spacing'

may be varied, effectively 'moving' the surfaces closer together or further apart. In this way, a variation of the area ratio is obtained which is assumed to be a known function of the contact pressure. Greenwood and Williamson described an alternative method (48) in which a numerical record of the surface profile was obtained by connecting a digital voltmeter across the pen recorder of the profilometer. The readings were punched on paper tape which could be fed into a digital computer. Thus any desired parameter could be evaluated.

Bowden and Tabor (72) proposed for fully plastic deformations that the real area of contact A_{rm} equals $\frac{W}{M}$, where M is the indentation hardness. Hill (83) showed by a theoretical analysis using slip-line theory that compressing an infinite wedge was identical with the indentation process, and gave the same value for M .

The characterisation of a contact, from the point of view of the contact resistances and interfacial wear, specifies A_{rm} , $\bar{n}_A$ and $\bar{a}_m$ (50). The topic is reviewed by Bowden and Tabor (71, 72) and extensively by others (52, 58, 85, 86). The mean number of contact spots per unit area $\bar{n}_A$ is assumed to be a function of the mean number of contact zones per unit length, $\bar{n}_L$, of the surface-trace. It was originally supposed that $\bar{n}_A$ could be evaluated from the product of two values of $\bar{n}_L$ taken from traces in orthogonal directions (76, 80, 86, 87). Greenwood (50) maintained that, for a random surface, $\bar{n}_A = \bar{n}_L$, whilst Tsukizoe and Hisakado (45, 46) showed that $\bar{n}_A > \bar{n}_L$. Thomas (54) derived a relationship of the form

$$\bar{n}_A = \bar{n}_L / 2\bar{a}_m \quad \dots \quad (2.16)$$

The most rigorous statistical analysis of surface parameters originally proposed by Tsukizoe and Hisakado have been investigated and modified to take into account the effect of oxides. The results are plotted and discussed in Chapter 7.

One of the requirements to predict the thermal contact resistance of oxidized joints is an accurate measurement of the actual contact area which in this case emerges from oxide-oxide, oxide-metal and metal-to-metal contacts. The area of actual contact was measured using a Quantimet Image Analyser.

For the oxidized joints (having thin films) an overall increase in the total real area of contact has always been observed experimentally.

2.5 PHYSICAL ASPECT OF CONTACT

The physical aspect of contact between solid-solid or solid-contaminant-solid is fundamental to the phenomenon of friction, lubrication and wear. Mechanical contact is a complex of points through which pressure is distributed and any investigation of the contact between solids, as it affects the flow of heat or electricity between them, must

start from a consideration of the mechanical deformation of the contact on a microscopic scale. In spite of the vast number of theoretical (4, 49, 93) and experimental reports available (52) the mechanism of heat transference across contacts is still not completely understood.

The thermal contact resistance R , is defined as

$$R = \Delta T A_n / Q \quad \dots \quad (2.17)$$

where Q is the heat flow rate normal to the contacting surfaces and ΔT is the temperature drop across the interface. Heat may be transferred across this interface by means of radiation, convection, and conduction through the interstitial fluid as well as contact spots.

The behaviour of the area of actual contact and hence of the solid conductive component of the thermal resistance of a joint formed between two solid surfaces which are pressed together requires :

- (a) an adequate specification of the contacting surfaces;
- (b) an analytical prediction, endorsed by experimental observations, for the number and distribution of the sizes of the micro-contact bridges and macro-contact regions formed when the two fully-defined surfaces are pressed together; and
- (c) a prediction of the overall constriction resistance (to conducted heat) arising from the distribution of micro-contacting bridges established.

Although considerable advances have been achieved with respect to these requirements (43-55), the need still exists for a detailed description of surfaces and contact parameters which can be evaluated to provide the necessary information for the prediction of contact resistance.

2.6 THERMAL CONTACT RESISTANCE

It has been observed throughout the investigation that oxide films enhance the thermal resistance of contacts. This aspect was examined in detail with particular attention being given to the effects of surface and environmental temperatures and surface preparation on the rate of oxide film build-up.

Measurements of thermal contact resistance were obtained for contacts containing oxide films on a variety of surface finishes. This provided a useful relationship between thermal contact resistances and oxide film thicknesses.

Modifications to the current theories concerning the prediction of the thermal resistance of oxide-free contacts has been made to allow for the presence of oxide films at the interfaces.

2.6.1 Previous Investigations

Relatively little is known concerning the effects of oxide build-up on thermal contact resistance. Yip (5, 6) whilst studying the effects of oxide films on thermal contact resistance developed a theoretical model based on constriction resistance considerations for nominally flat and oxidized surfaces, but without oxide film thickness measurements, could not produce quantitative results. However, measured oxide film thicknesses and other data corresponding to the pressed contacts, when substituted in the proposed theory (5) verified the prediction.

Clausing (11), recognized the common occurrence of heavily-oxidised surfaces, but stated that, for freshly-machined surfaces, oxide film resistance was only of secondary importance. He concluded that, microscopic constriction resistance was not significant for many engineering surfaces; for magnesium samples where the macroscopic resistance was small due to the adoption of particularly flat specimens, oxide film resistance played a dominant role.

Skipper and Wootton (101) achieved a sixfold increase in the Uranium-to-Can thermal contact resistance due to oxidation of a magnesium alloy can. Their study involved oxide films up to 5.2×10^{-5} m thick.

Fenech and Rohsenow (74) stated that oxide films which are always present on metallic surfaces do not appreciably affect the thermal resistance of a contact, but had considerable significance on the electrical resistance. Fried (56) and Barzelay et al (102) both observed decreases in thermal contact resistance with increasing surface roughness. Wadhwa (103) showed analytically that adsorbed gases and surface oxides acted as low-pass filters because of weak adsorption bonds and this caused phonons within the body of the contacting metals, with frequencies greater than the cut-off frequency of the adsorbate, to be reflected and consequently reduced the effective thermal conductance of the interface.

Recently a few researchers (88, 142) examined steady state thermal constriction resistance of the doubly-connected planar areas bounded by coaxial circles, squares and equilateral triangles under uniform Neumann flux conditions (143). They developed an analytical solution for the circular annular contact area and hence a surface element method to obtain numerical values and correlations of the dimensionless constriction resistance for the square and triangle. The subject has been advanced but the applicability of these correlations has been demonstrated to be limited.

2.6.2 Analogy with Electrical Contact Resistance

Since the history of electric contact study is relatively longer, its many fundamental concepts have been better established. The analogy between electric and heat conduction and the existing electric contact theories have been accelerating the progress of the thermal contact study, particularly in the area of constriction resistance. However, most surface films existing at the interface will serve as a good electric insulator having an electrical resistivity many orders greater than that

of the contact members. On the contrary, if the thermal conductivities of the surface films and the contact members should be assumed to be comparable, then consequently the effect of surface films on the thermal contact resistance is less pronounced. In actual practice the surface films are the oxides of the base metal and the measurements of the thermal conductivity have shown that the oxides have lower thermal conductivities than that of their underlying materials.

However, in the absence of surface films at the interface steady-state current and heat conduction can be analogous under identical boundary conditions. Therefore, it should be possible to relate the electrical resistance with the thermal resistance through the Wiedemann Franz law (16).

Early developments in electrical constriction resistance were by Kottler(105) and Holm (12) who postulated that electric conduction takes place through circular contact spots. Later, mutual action of the neighbouring contacts was brought into consideration by Greenwood (50). Such findings seem to explain the discrepancy of macroscopic resistance hypothesised by Holm (12) earlier. These solutions, however, neglect the fact that the interface of the surface in contact does not usually have an infinite extent and are therefore applicable in general. Roess (106) further modified Holm's solution to include this specimen boundary effect by assuming that the heat distribution within the radius of contact is proportional to a where a , is the radius of contact. Following this modification Chao (75) successfully applied Roess's solution to demonstrate dominant effect of the macrocontact upon the overall thermal contact resistance. Later on, Mikic and Rohsenow (104) showed that, in case the dimension of the roughness is comparable to that of the waviness deviation, it is inadequate to neglect the micro-constriction resistance resulting from discrete microcontacts. Applying the boundary effect on Holm's solution, Mikic et al were able to demonstrate the effects of both surface roughness and mono-waviness.

Because of the limited application of the above methods, a more general one was proposed by Yip and Venart (107) to account for the simultaneous effects of the distribution of micro and macrocontacts as well as their mutual interaction, but the applicability of the method is limited to known contact configurations.

After an extensive survey of the literature concerning surface topography, deformation and contact resistances it has appeared to the author that none of the existing theories for contact resistance could provide a compact and complete solution to the problem and hence further work on the development and modification of theories.

CHAPTER THREE

TEST RIG DESCRIPTION AND EXPERIMENTAL DETAILS

3.1 DESIGN CRITERION FOR THE RELOCATING ATTACHMENT

During the course of this work, various aspects of the thermal resistance of pressed contacts were investigated. In each case surface topography measurements of the specimen assemblies were taken before and after oxidation; a preliminary requirement for the study of oxidized surfaces was to devise a system to achieve the same stylus track of the surface as before oxidation. This system was required to be detachable so as to take without disturbing the oxide-free specimens elsewhere for oxidation, after their initial surface topography measurements had been taken. The proposed experimental measurements confirmed modification to the equipment associated with the profilometer.

A modification of the relocating device (108), fig. 3.1 and fig. 3.2 was carried out which consists of a holding plate to accommodate the specimen fig 3.3, fits into relocating attachment and the whole assembly rests on the Talysurf-4 table making a three point contact. Necessary allowances for the lateral expansion of the specimens when heated are shown in the detailed drawings provided. An increase in the RMS roughness of the oxidized surface was observed as given in Table 4.1.

The experimental programme was carefully controlled to provide :

- (i) accurate data to aid the understanding of the heat transfer mechanism, involving ;
- (ii) data to check existing and new analytical methods;
- (iii) data for empirical predictions.

3.2 THE TEST RIG ASSEMBLY

This was a modified version of the rig developed and used by Jones (109) and consists of the following :

3.2.1 The Experimental Chamber

The specimen assembly and heater/cooler systems were mounted on a stainless steel base plate (on top of the existing lower cooler via a stainless steel adapter) which was in turn supported by a rigid steel framework (fig. 3.4 and plate 3.1). A stainless steel vacuum chamber, with a highly polished internal surface, was placed over the test assembly and sealed by an 'O' ring against the upper surface of the base plate (plate 3.1). The services and the loading shaft were introduced into the experimental chamber through the base plate.

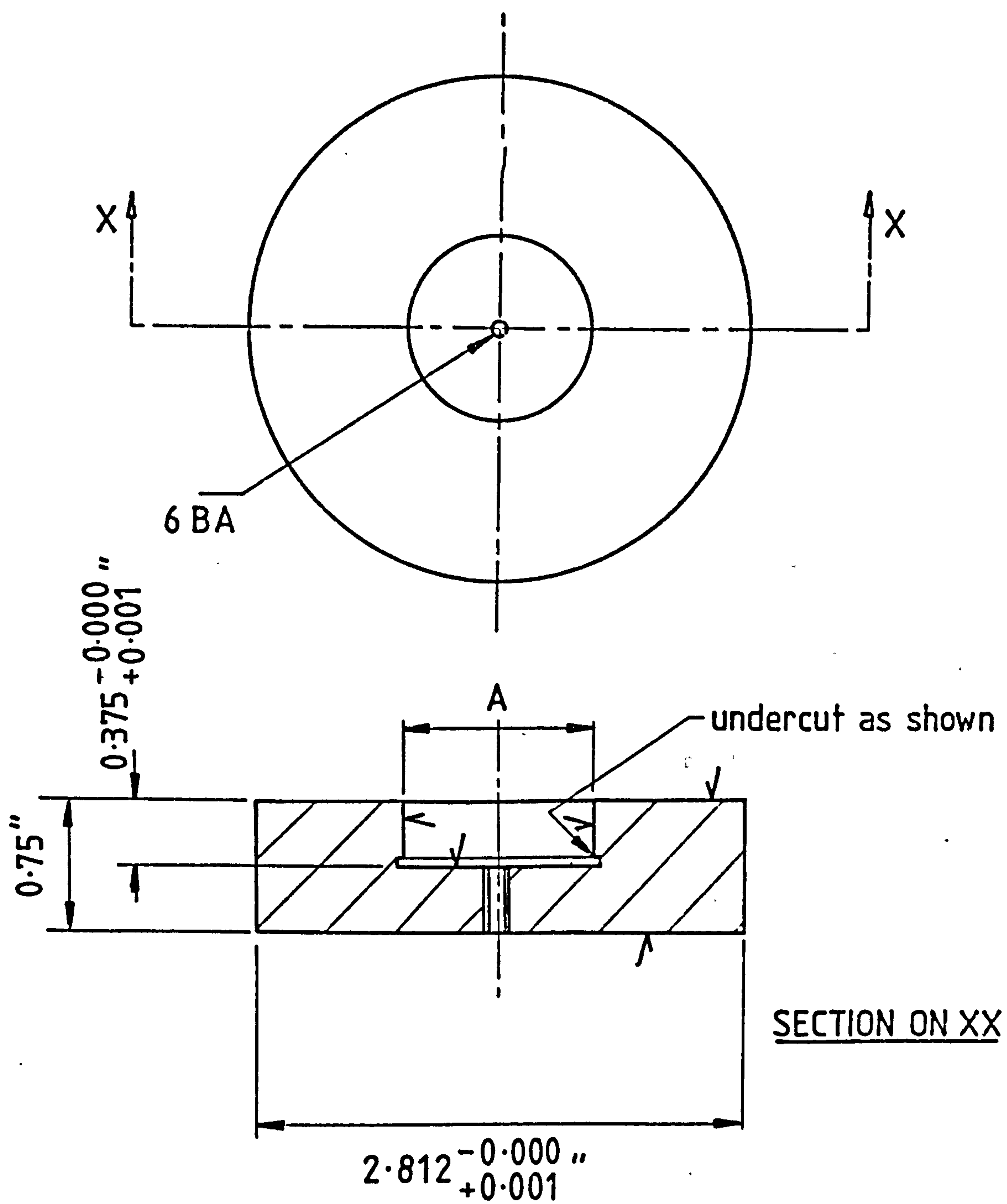


FIG. 3,1	DIMENSION A	0.504 ^{+0.0008} / _{-0.0000} "
		0.992 ^{+0.001} / _{-0.000} "
		0.984 ^{+0.001} / _{-0.000} "

FIG. 3,1

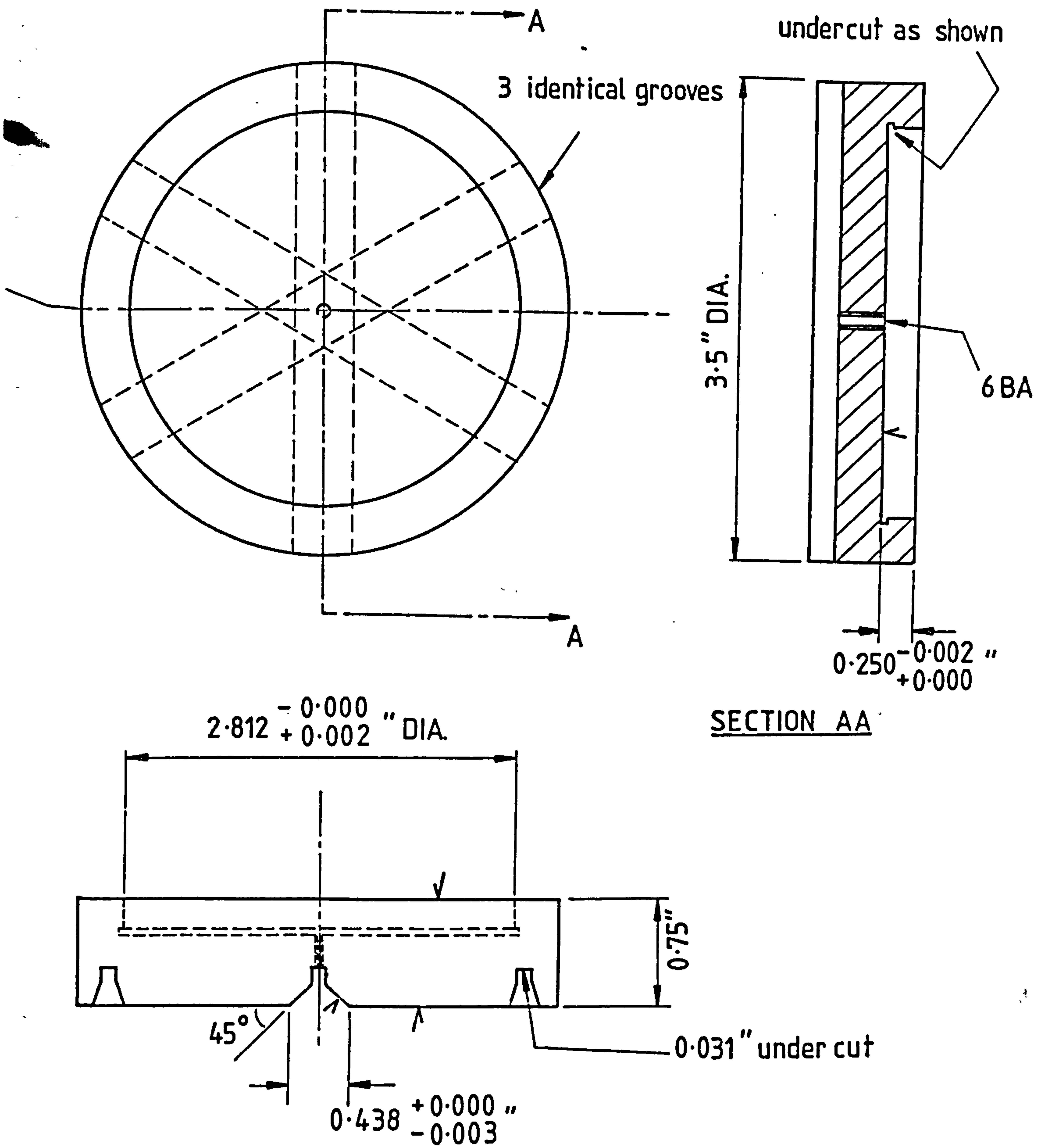
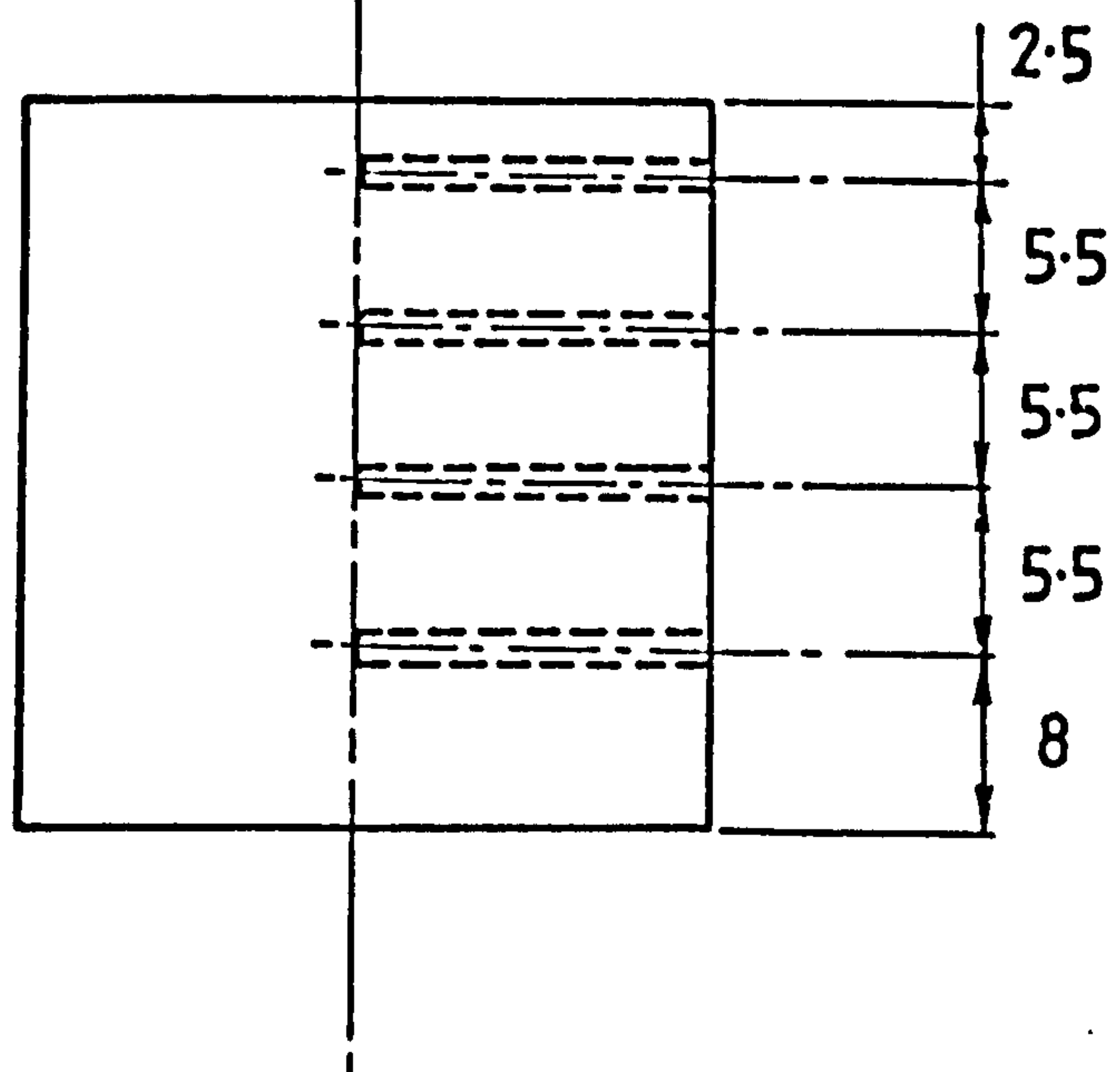
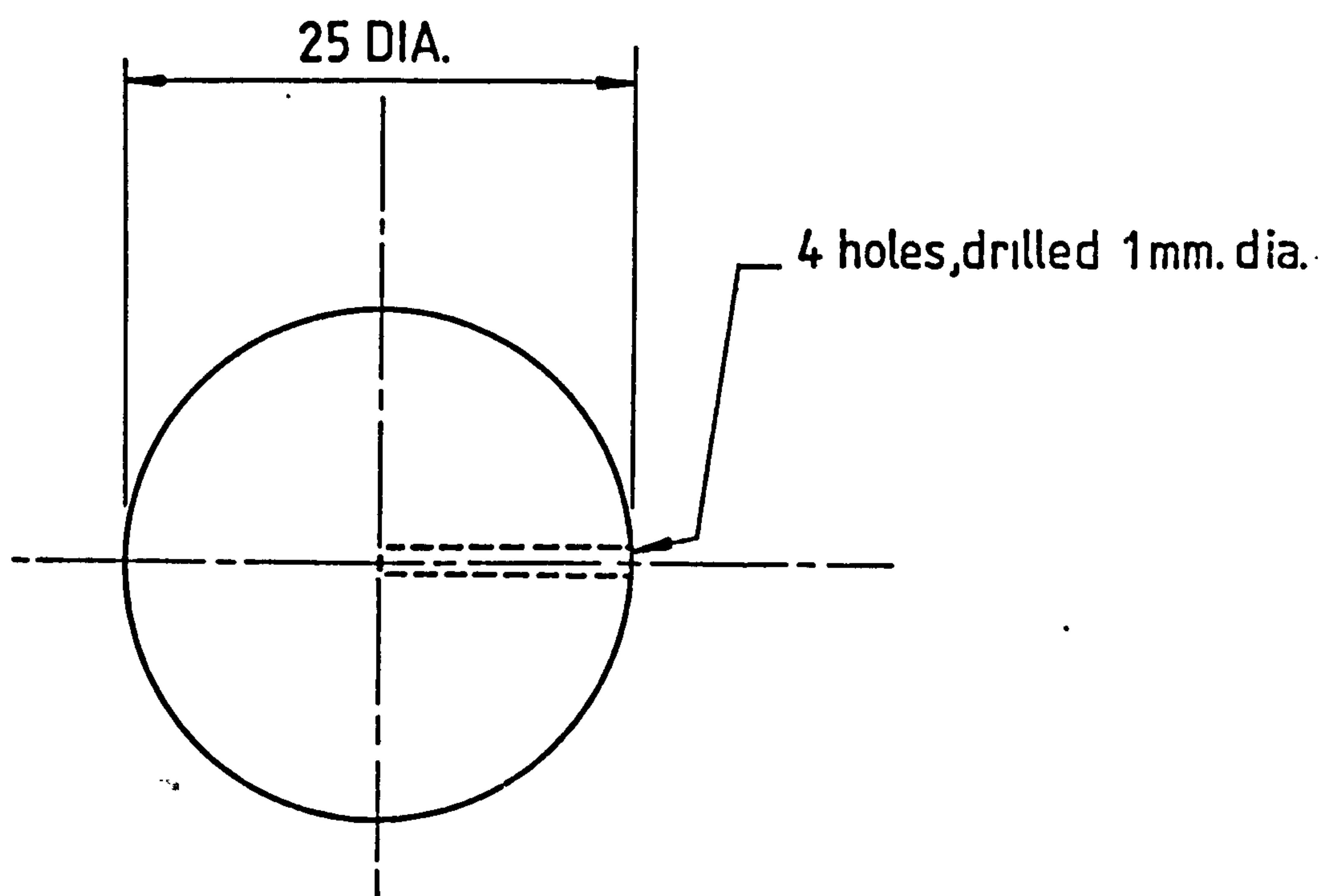


FIG. 3,2

30



all dimensions in mm.

FIG. 3,3

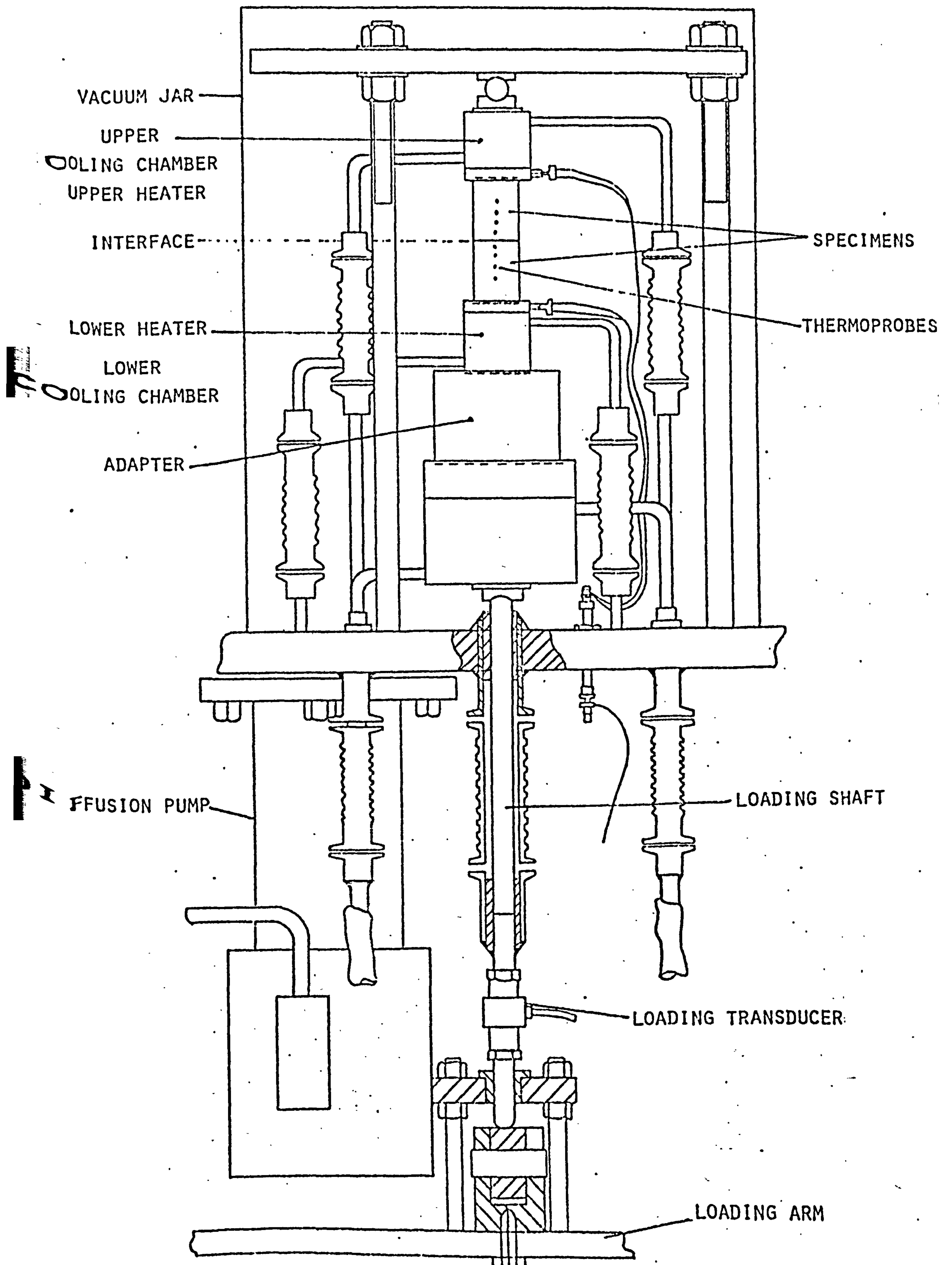


Fig. 3.4 Schematic view of the test rig.

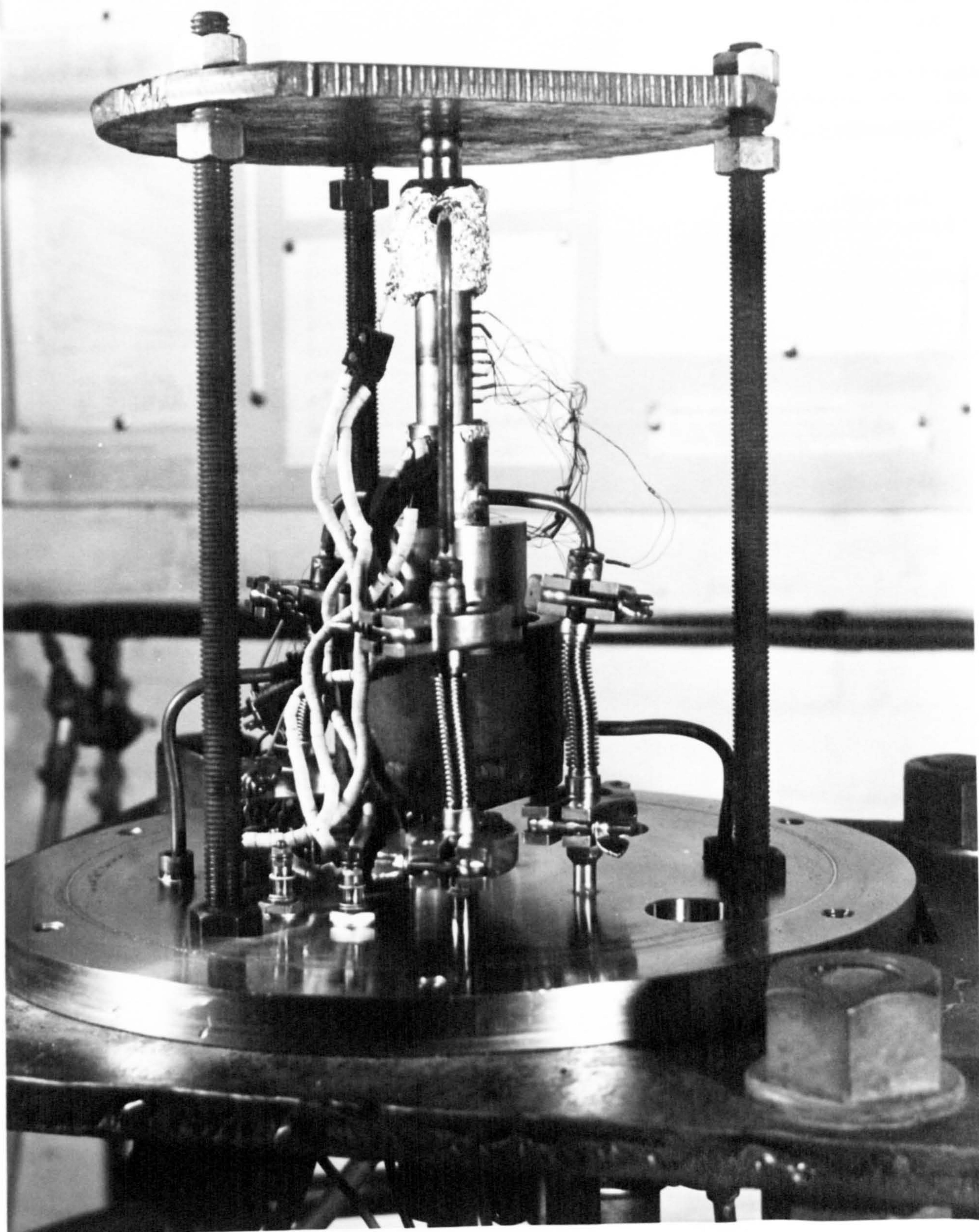


Plate 3.1

The contact module.

The loading shaft (fig. 3.4) passed upwards through a P.T.F.E. bearing in the centre of the base plate. Its hemispherical end was located in a hardened steel conical seating pressed into the bottom of the lower heater/cooler assembly. The thrust was transmitted to the top plate via a similar arrangement, using a ball bearing, thus ensuring kinematic loading. Applied force was transmitted to the shaft by means of a lever and hanging weights. Rigidly incorporated in the loading shaft was a Kistler, quartz crystal, load transducer. An overload cut-out was provided to avoid damage to the bellows. A diffusion pump, fitted with a baffle to avoid back-streaming, was bolted to the underside of the base plate. This extracted the air through a 80 mm diameter hole set to one side of the loading shaft.

The test module consisted of a set of similar heater/cooler systems, one each side of the specimen pair. These were manufactured from commercially pure copper, to reduce total resistance, and consisted of a baffled cooling chamber, recessed one end to accommodate a double spiral of ceramic, insulated stainless steel sheathed, nichrome resistance element. The heating element was covered by a stainless steel plate which was also recessed to accommodate the specimen. Heater supply leads passed through three glass to metal seals in the base plate. Copper cooling water pipes for the top cooler were brazed into the base plate, and two Edwards 'Tombac' bellows connected in the line to give maximum flexibility. Pipes from the lower cooler passed, with considerable clearance, through flanges brazed into the base plate. Vacuum integrity was preserved by the Edwards 'Tombac' bellows clamped between this flange and a similar one brazed to the lower part of the pipe.

The specimens were fine-turned to 25 mm diameter and cut 30 mm long. In each of the two specimens for each test, four 1.0 mm diameter holes were drilled along the axis to accommodate the thermocouples as shown in fig. 3.3. The first hole was 2.5 mm from the face under investigation and the rest were 5.5 mm apart. The external surfaces of the heaters, coolers and specimens were polished to reduce their emissivities.

3.2.2 Application of Heat Flux

The heaters were supplied from a 0-75 V 6A Phillips Pe 1520 power supply. Similar heater/cooler assemblies were placed at each end of the specimen assembly, and were capable of working at steady constant temperatures.

3.2.3 Measurement of Temperature

Temperature measurements were obtained from thermojunctions in the specimens. To minimise heat conduction along the leads very fine (0.12 mm dia.) copper-constantan thermoelement wires were used. As long as practicable the leads were used between the thermoprobes and the lead-through mounted on the base plate of the vacuum chamber and were carefully positioned to avoid them touching anything inside the chamber.

The thermoprobes were produced under the microscope using a 'Spemley' thermojunction spot welder so that their lengths were of the order of their diameters. The thermoprobes so formed were strengthened using 1.0 mm O/D hypodermic stainless steel sheath, and insulated with epoxy resin adhesive. The thermoelements were passed through the base plate via the leadthrough. This consisted of a disc housing 40 lead-through pins, each pin containing a hole 0.76 mm in diameter. The thermoelement wires outside the chambers were connected to an isothermal plug and socket unit and were then passed into an oil-immersed switchbox (plate 3.2). All the constantan arms in the switchbox were connected via a common lead to the constantan side of the reference junction, which was immersed in melting ice. The temperature of each thermojunction was measured in turn by a digital voltmeter, which had an accuracy of one micro-volt.

3.2.4 Loading Mechanism

The load monitoring circuit consisted of a Kistler type 902A-SN-52178 quartz load washer connected to a Kistler charge amplifier. The output from charge amplifier was fed directly into a Tektronix 5103 N oscilloscope which displayed the input as a continuous line on a calibrated grid screen.

A certain amount of drift of the load line on the oscilloscope was experienced which may have introduced marginal errors into the experimental procedure. However, gripping the two test specimens initially together at virtually zero loading could be a source of minor error.

The load cell was calibrated by the manufacturers and had an error of less than 1%. The overall error was in fact a little higher than this also due to the differential pressure across the bellows, under high vacuum and a small amount of stiffness in the bearings and cooling pipes. Results for the applied load were corroborated by calculations using the mechanical advantage of the loading system. It was ensured that the charge amplifier had been grounded and the oscilloscope reset to the zero datum before contact occurred. The load transmission system was capable of complete recovery upon removal of load.

3.3 THE QUANTIMET 720 IMAGE ANALYSER

The deformation of the optically flat soft surface in contact with a flat rough hard surface was analysed using a Quantimet 720 Image Analyser (plate 3.3). The technique involved the formation of the image of the surface deformation under a microscope. The image was then passed onto a 720 line vidicon scanner whose output was automatically passed through a detector. The detector selected features for measurements in terms of their common grey level relative to a white level setting. The Quantimet was operated in several modes of detection.

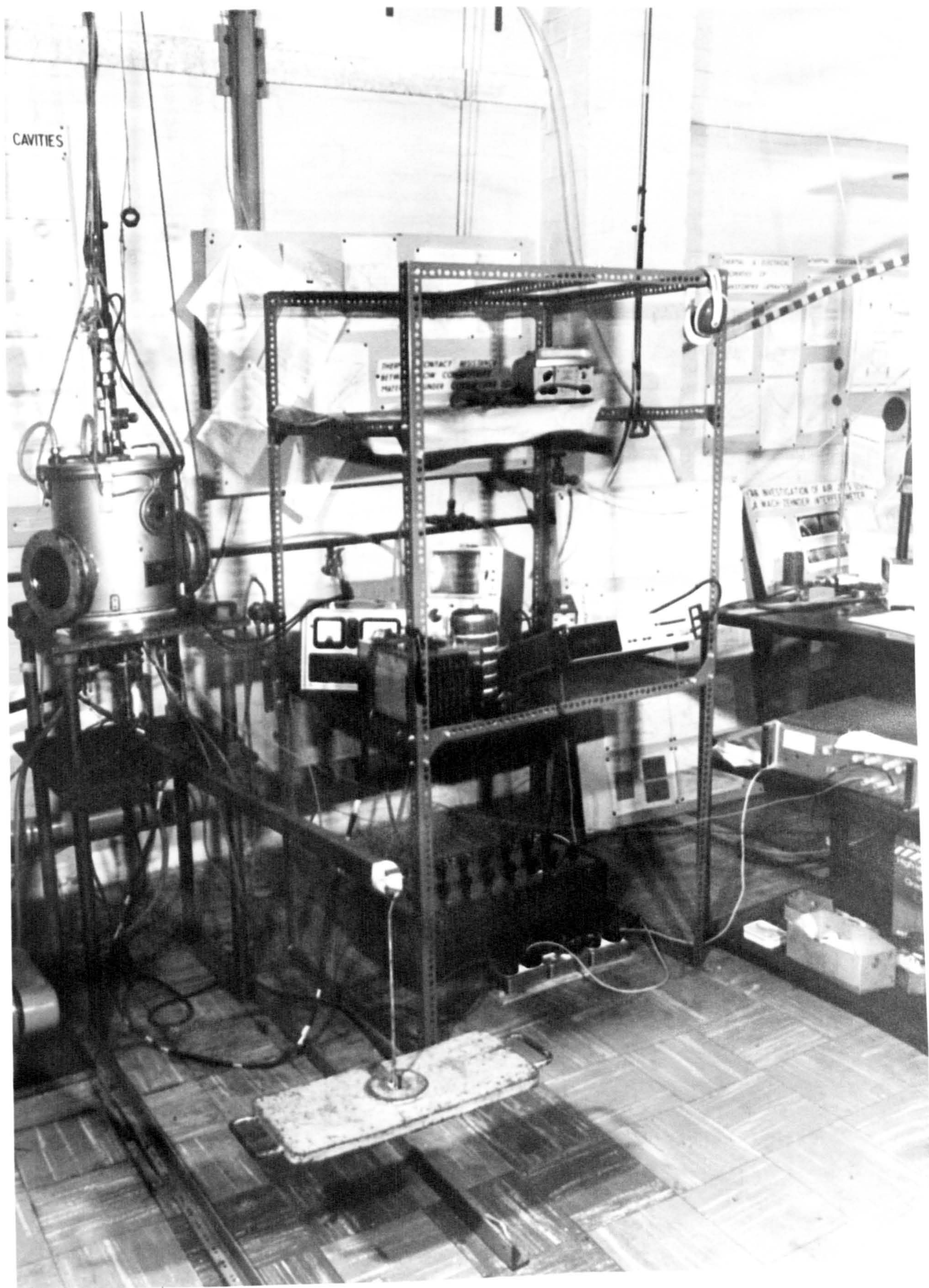


Plate 3.2 External view of the thermal rig in operation, showing vacuum chamber, loading arrangement and instrumentation layout.

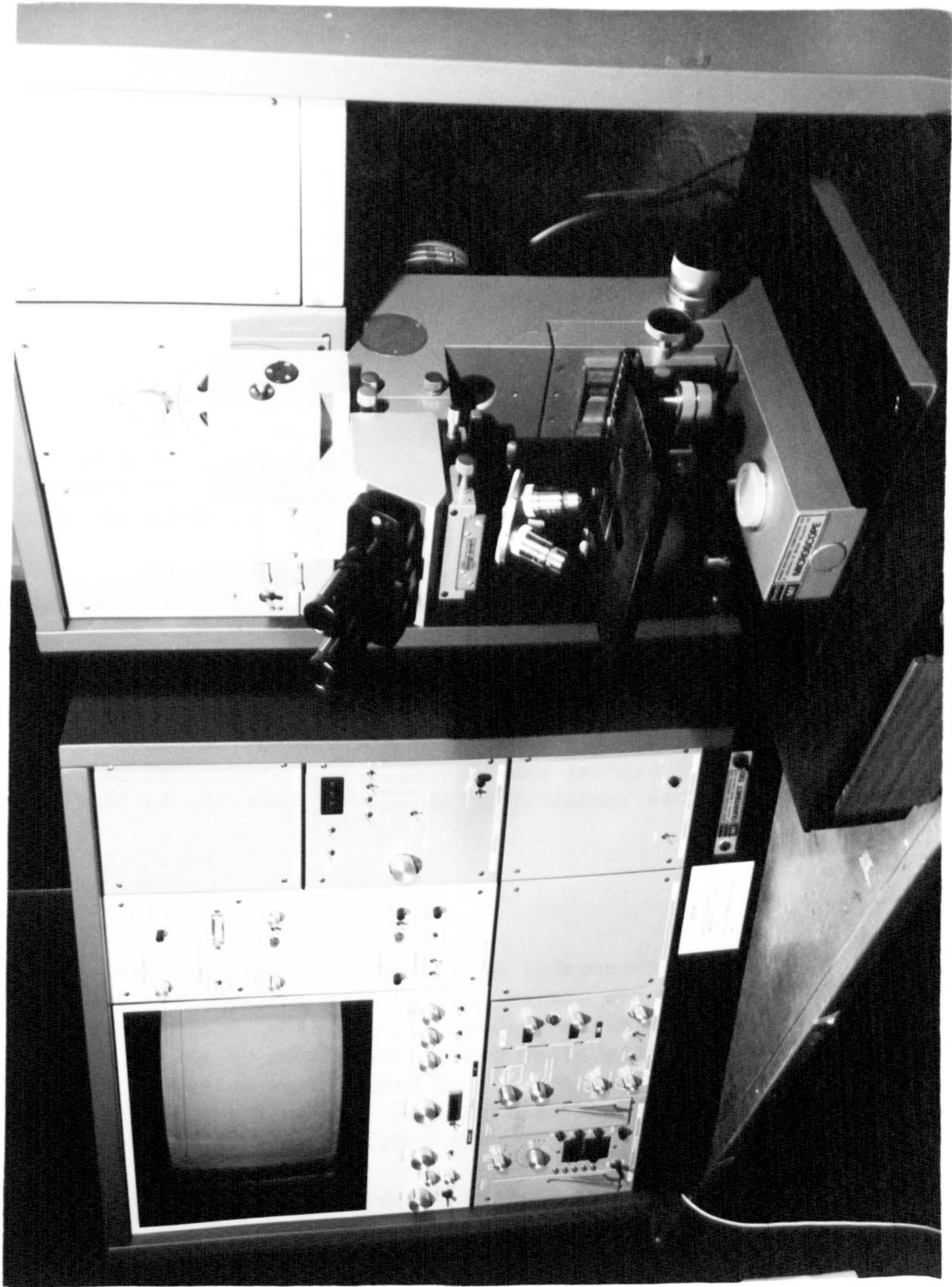


Plate 3.3 The Quantimet 720 Image Analyser.

3.4 PROFILOMETRIC MEASURING EQUIPMENT

A Talysurf 4 profilometer was used to obtain profile traces before and after oxidation for the selected specimen surfaces. Each specimen was held stationary and the stylus of the instrument was traversed across the surface at a constant speed. The stylus behaved essentially as a transducer converting the variation in height to a variable voltage. The output fed two recording media. The first was a simple pen-recorder, which fed a Data Logger attachment. Plate 3.4 shows the Talysurf and the Data Logger. It was found for a digitising rate of 18 characters per second, 3200 ordinates per test run could be expected, having a sample separation of 2.822 μm . Specification of surface analysis equipment is given in reference (108). To ensure that false readings were not punched on the paper tape, the Data Logger had to be switched on/off after/before the Talysurf trace began/finished.

3.4.1 Surface Analysis

Analysis of the ordinate height information was obtained by using a standard topography program STP 6 (110). Program details appear in Appendix II. Input to the program was via an off-line paper tape together with the parameter cards.

The ordinates were read from the paper tape and converted to micrometers using the vertical magnification factor. The spacing of these ordinates was prescribed by the sampling interval. With this information, the program computed a mean line and then referred all the ordinates to this mean line. The program then proceeded to compute the various statistical parameters based on Greenwood and Williamson (48) model (i.e. three-point analysis of a profile presented in digital form with small sampling interval), and Whitehouse and Archard (69) model (i.e. digital analysis of the same profile using different sampling interval).

3.5 THERMOCOUPLE CALIBRATION

Thermocouples were calibrated independently in a heat sink containing alternatively melting ice, boiling water, and oil at room temperature. Any thermocouple which gave a reading different from the standard calibration tables by more than 5 micro volts was replaced. As a final check the thermocouples were fitted to the specimens positioned between the heater/coolers inside the chamber; with both electrical and water supplies to the heater/coolers switched off.

To ensure good thermal contact between the thermoprobe and the specimen, the holes in the specimen were packed with high temperature silicon vacuum grease before insertion of the thermoprobes. The drawback with this method was that pockets of air trapped in the grease expanded on evacuating the chamber, pushing the thermoprobes out of position. Whenever thermoprobes were disturbed it was necessary to pump down the chamber with the rotary pump for about fifteen minutes, switch off the pump, vent the system, remove the chamber and reposition the thermoprobes. The

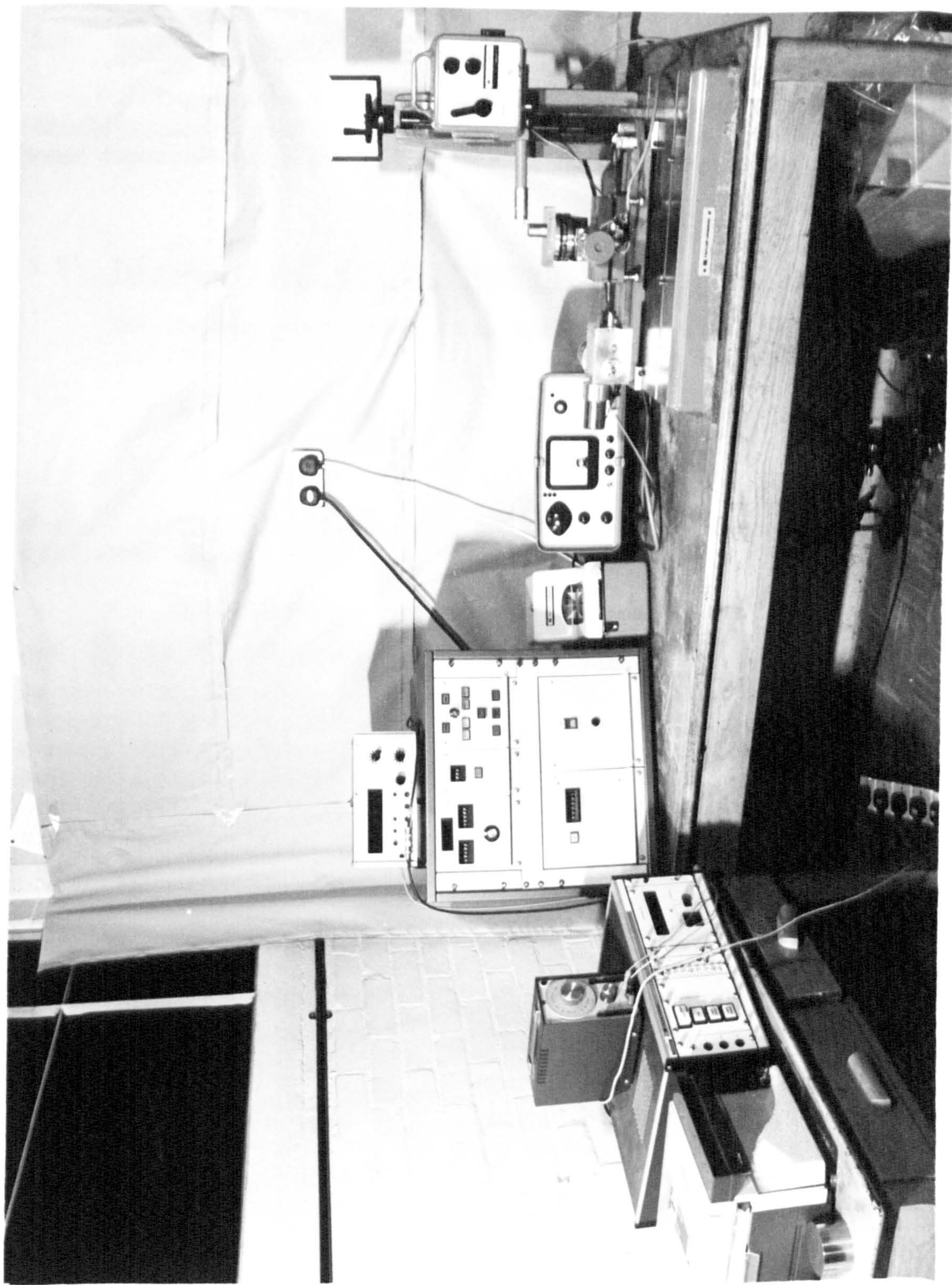


Plate 3.4

The Talysurf arrangement.

thermoprobes would then remain in position during subsequent evacuations of the system, this could be checked by observation through the windows in the vacuum chamber.

3.6 HARDNESS MEASUREMENTS

The specimen Vicker's indentation hardness was measured by a Reichert metallographic microscope. The ocular readings thus obtained were converted into the S.I. units using the recommended charts.

3.7 THERMAL CONDUCTIVITY MEASUREMENTS

The thermal conductivity was obtained from the Fourier's law,

$$k = - \frac{Q}{A \cdot \frac{dt}{dx}} \quad \dots \quad (3.1)$$

where Q is the heat flow rate = 0.8362 W for an oxide-free mild steel-to-mild steel contact.

A = the cross-sectional area of the specimen of 0.025 m dia.
and $\frac{dt}{dx}$ is the temperature gradient = $36.40 \text{ K}^\circ \text{ m}^{-1}$, which was determined by measuring the slope of a fitted straight line through the temperatures recorded at various distances from the interface. Therefore, the average thermal conductivity calculated from equation (3.1) for an oxide-free mild steel-to-mild steel contact was $46.85 \text{ Wm}^{-1} \text{ K}^{-1}$; a little lower than the tabulated value, $47 \text{ Wm}^{-1} \text{ K}^{-1}$. Similarly an average value for that of oxidized mild steel contact was $43.08 \text{ Wm}^{-1} \text{ K}^{-1}$.

3.8 TEST RIG OBSERVATIONS

During every test the vacuum pressure, input wattage, applied loading and thermocouple reading were recorded. The coolant flow was maintained at a constant rate ($10^{-5} \pm 2 \times 10^{-6} \text{ m}^3/\text{s}$) for all tests.

Readings were taken when a vacuum of better than 10^{-4} torr was attained. At the start of testing, the thermocouple readings were taken with the heater/cooler assemblies non-operational. This served as a final check on the thermocouples, and ensured that no temperature gradient was apparent in the system. When the first loading, or heat flux measurement, was applied to the system, twenty-four hours was allowed to elapse before readings were taken. Subsequent relaxation times, following increments in input variables, were found to be less than four hours. The system was allowed to cool down before any heat flux reversal to avoid the danger of damage due to high thermal stresses.

The source effectiveness may be defined as the ratio of axial heat flux to heater power dissipation. The corresponding values of the percentage efficiency are given in brackets next to the values of axial heat in Table 3.1. There was a tendency for the efficiency to drop off slightly with increased heater dissipation for both directions of heat flow. This is understandable, since a larger proportion of heater power was lost by radiation, to the inner walls of the chamber, at the higher temperatures associated with higher levels of heat generation. However, no systematic variation between the efficiencies of the upper and the lower heater were observed.

3.9 MEASUREMENT OF INTERFACIAL THERMAL RESISTANCE

The thermal resistance of the unit area of contact which is defined by :

$$R = \frac{\Delta T}{Q/A_n} \quad \dots \quad (3.2)$$

where ΔT represents the steady state difference between the surface temperatures on either side of the interface as obtained by linear extrapolation of the temperature distribution in both solids and Q is the steady state thermal current flowing across the contact of nominal area A_n ; was calculated using a computer program (47), as given in Appendix III.

Throughout this work a reading was regarded as significant only if the heat flux in the lower temperature specimen was less than 5% smaller than that in the higher temperature specimen.

The source or sink efficiency which may be defined as the ratio of axial heat flux of the hotter specimen to the axial heat flux of the colder specimen was 95%.

Table 3.1SYSTEM SOURCE EFFECTIVENESS

Power Input (W)	Lower Heater Power Dissipation (W)	Upper Heater Power Dissipation (W)
3.5	1.78 (50.9%)	1.85 (52.9%)
10.5	5.20 (49.5%)	5.10 (48.6%)
17.5	7.6 (43.4%)	7.85 (44.9%)

CHAPTER FOUR

EXPERIMENTAL TECHNIQUE FOR THE MEASUREMENT OF OXIDE FILM THICKNESS AND SURFACE TOPOGRAPHY

4.1 SPECIMEN PREPARATION

Cylindrical specimens of 25 mm dia. and 30 mm long were made from (EN 3B steel) mild steel and commercially pure copper. Randomly rough surfaces were obtained by gritblasting. Each specimen was lapped and polished to flatness within a third of a wavelength of sodium light ($0.19 \mu\text{m}$). The surfaces were then roughened by grit blasting the specimen end faces. Different roughnesses (see Table 4.1) were achieved using different sizes of blastytes. The test specimens were then marked and having measured their surface characteristics a set of these specimens (two for the purpose of measuring real area of contact, and thermal contact resistance and the third for film thickness measurements) were placed in a high temperature furnace (Plate 4.1) for oxidation at a pre-determined temperature and for set exposure times. The entire surface area of each specimen was oxidized, but the requirement was to oxidize specimen plane ends only. This need was met by electro-polishing (Plate 4.2) the EN 3B mild steel specimens in a bath of acetic acid glacial 60.05 (8 parts) and perchloric acid 60-62% relative density = 1.54 (1 part) for 10 to 15 seconds at an input of 200 mA and 80V.

Various specimens with ground surface finish were also used. At a time four mild steel and four copper specimens were fitted into holding jigs and after measuring their surface characteristics a pair of each of the copper and mild steel were placed in an environmental chamber for oxidation at a pre-determined temperature, humidity and time.

4.2 MEASUREMENT OF FILM THICKNESS

In general, the oxide film thickness was measured as a function of time and oxidation temperature, but for the purpose of actual measurements of oxide film the oxidized specimens were characterised into two categories, i.e. either flat, very smooth or flat and rough (Plate 4.3). Those having very smooth surfaces had comparatively uniform oxide layers whose thickness could be measured by the higher resolving power of the Stereoscan Electron Microscope (Plate 4.4) which had a resolution limit of $2.5 \times 10^{-8} \text{ m}$. Thicker films were measured with the Reichert Metallographic microscope (Plate 4.5) which had a resolution limit of $3.3 \times 10^{-7} \text{ m}$.

A sample of $2.5 \times 15 \text{ mm}$ was cut from one of the oxidized specimens (Plate 4.6) using a spark erosion machine, (Plate 4.7) for the purpose of viewing it on the Stereoscan (owing to the large dimensions of the specimens it was not possible to view them directly with the Stereoscan). The sample was mounted in such a manner (Plate 4.8) that the oxide grown could be seen in the form of a layer along the metal surface. The thickness of this layer was measured (Plate 4.9 and 4.10). For the purpose of relative

Table 4.1DETAILS OF SPECIMENSDiameter of Specimens = 25.0 ± 0.1 mmLength of Specimens = 30.0 ± 0.1 mm

Identi- fication Code	Material	Type of Surface Finish	RMS Roughness Before Oxidation (μm)	Thickness of Oxide $\times 10^{-4}$ (μm)	RMS Roughness After Oxidation (μm)
M1	Mild Steel (EN 3B)	Nominally flat and smooth	0.080	3500	0.088
M2	Mild Steel (EN 3B)	Nominally flat and smooth	0.0816	6000	0.845
M3	Mild Steel (EN 3B)	Nominally flat and rough	2.129	1180	1.943
M4	Mild Steel (EN 3B)	Ground	0.45 (across the lay)	Oxidized at 70°C and 80% humidity for 72 hours	2.289 (across the lay)
M5	Commer- cially Pure Copper	Nominally flat and smooth	1.20	2000	1.625

Table 4.1 Continued

Identification Code	Material	Applied Load (kN)	Surface Description	Surface Roughness prior to Oxidation and Loading (RMS), (μm)	Film Thickness (μm)	Hardness prior to Oxidation (GN m ⁻²)
M6	Stainless steel	17.79	Nominally flat & rough	2.558	-	3.95
M7	Commercially pure copper		Nominally flat & smooth	0.0828	-	0.99
M8	Stainless steel	17.79	Nominally flat & rough	2.558	-	3.95
M9	Commercially pure copper		Nominally flat, smooth and oxidized	0.0828	0.12	0.99
M10	Stainless steel	26.68	Nominally flat & rough	2.558	-	3.95
M11	Commercially pure copper		Nominally flat & smooth	0.0828	-	0.99
M12	Stainless steel	26.68	Nominally flat & rough	2.558	-	3.95
M13	Commercially pure copper		Nominally flat, smooth and oxidized	0.0828	0.12	0.99
M14	Stainless steel	35.58	Nominally flat & rough	2.558	-	3.95
M15	Commercially pure copper		Nominally flat & smooth	0.0828	-	0.99
M16	Stainless steel	35.58	Nominally flat & rough	2.558	-	3.95
M17	Commercially pure copper		Nominally flat, smooth and oxidized	0.0828	0.12	0.99

Table 4.1 Continued

Identification Code	Material	Applied Load (kN)	Surface Description	Surface Roughness prior to Oxidation and Loading (RMS), (μm)	Film Thickness (μm)	Hardness prior to Oxidation (GN m ⁻²)
M18	Stainless steel	44.48	Nominally flat & rough	2.558	-	3.95
M19	Commercially pure copper		Nominally flat & smooth	0.0828	-	0.99
M20	Stainless steel	44.48	Nominally flat & rough	2.558	-	3.95
M21	Commercially pure copper		Nominally flat, smooth and oxidized	0.0828	0.12	0.99
M22	Stainless steel	17.79	Nominally flat & rough	2.829	-	3.95
M23	Commercially pure copper		Nominally flat & rough	0.0828	-	0.99
M24	Stainless steel	17.79	Nominally flat & rough	2.829	-	3.95
M25	Commercially pure copper		Nominally flat, rough and oxidized	0.0828	0.12	0.99
M26	Stainless steel	26.68	Nominally flat & rough	2.829	-	3.95
M27	Commercially pure copper		Nominally flat & smooth	0.0828	-	0.99
M28	Stainless steel	26.68	Nominally flat & rough	2.829	-	3.95
M29	Commercially pure copper		Nominally flat, smooth and oxidized	0.0828	0.12	0.99

Table 4.1 Continued

Identification Code	Material	Applied Load (kN)	Surface Description	Surface Roughness prior to Oxidation and Loading (RMS), (μm)	Film Thickness (μm)	Hardness prior to Oxidation (GN m ⁻²)
M30	Stainless steel	35.58	Nominally flat & rough	2.829	-	3.95
M31	Commercially pure copper		Nominally flat & smooth	0.0828	-	0.99
M32	Stainless steel	35.58	Nominally flat & rough	2.829	-	3.95
M33	Commercially pure copper		Nominally flat, smooth and oxidized	0.0828	0.12	0.99
M34	Stainless steel	44.48	Nominally flat & rough	2.829	-	3.95
M35	Commercially pure copper		Nominally flat & smooth	0.0828	-	0.99
M36	Stainless steel	44.48	Nominally flat & rough	2.829	-	3.95
M37	Commercially pure copper		Nominally flat, smooth and oxidized	0.0828	0.12	0.99
M38	Stainless steel	17.79	Nominally flat & rough	3.460	-	3.95
M39	Commercially pure aluminium		Nominally flat & smooth	0.088	-	1.14
M40	Stainless steel	26.68	Nominally flat & rough	3.460	-	3.95
M41	Commercially pure aluminium		Nominally flat & smooth	0.088	-	1.14

Table 4.1 Continued

Identification Code	Material	Applied Load (kN)	Surface Description	Surface Roughness prior to Oxidation and Loading (RMS), (μm)	Film Thickness (μm)	Hardness prior to Oxidation (GN m ⁻²)
M42	Stainless steel	35.58	Nominally flat & rough	3.460	-	3.95
M43	Commercially pure aluminium		Nominally flat & smooth	0.088	-	1.14
M44	Stainless steel	44.48	Nominally flat & rough	3.460	-	3.95
M45	Commercially pure aluminium		Nominally flat & smooth	0.088	-	1.14

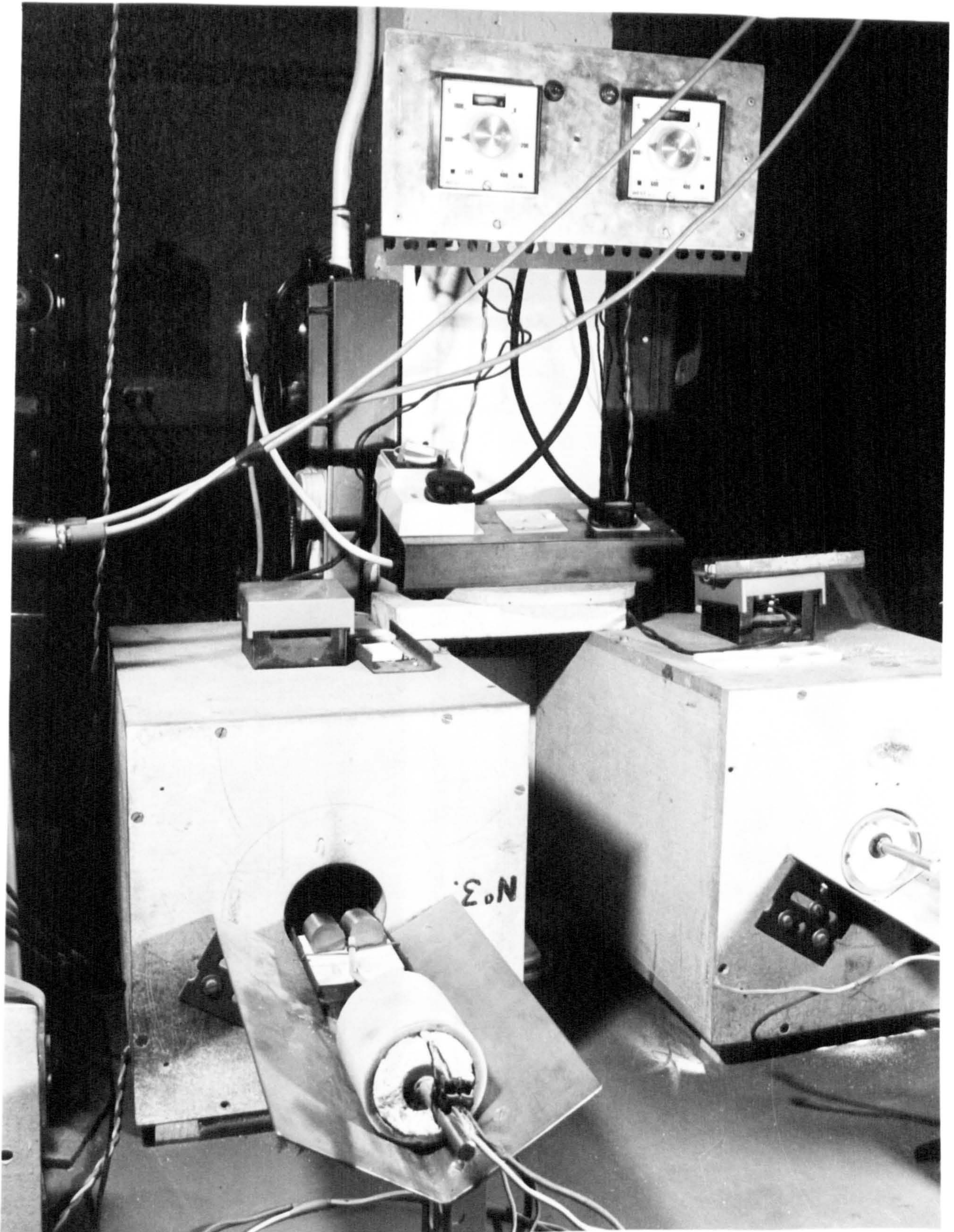
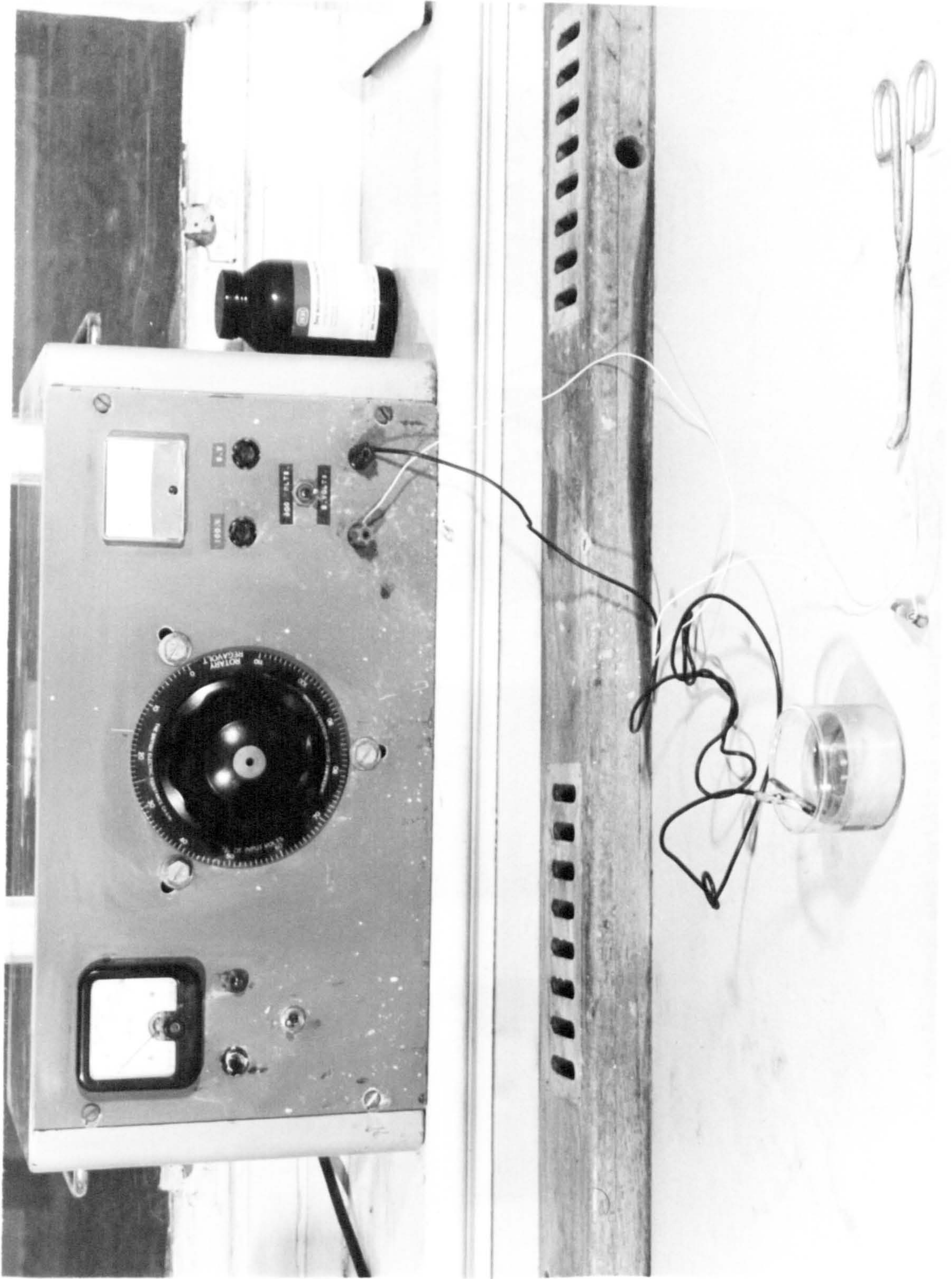


Plate 4.1 High temperature oxidation furnace.



Electropolishing machine.

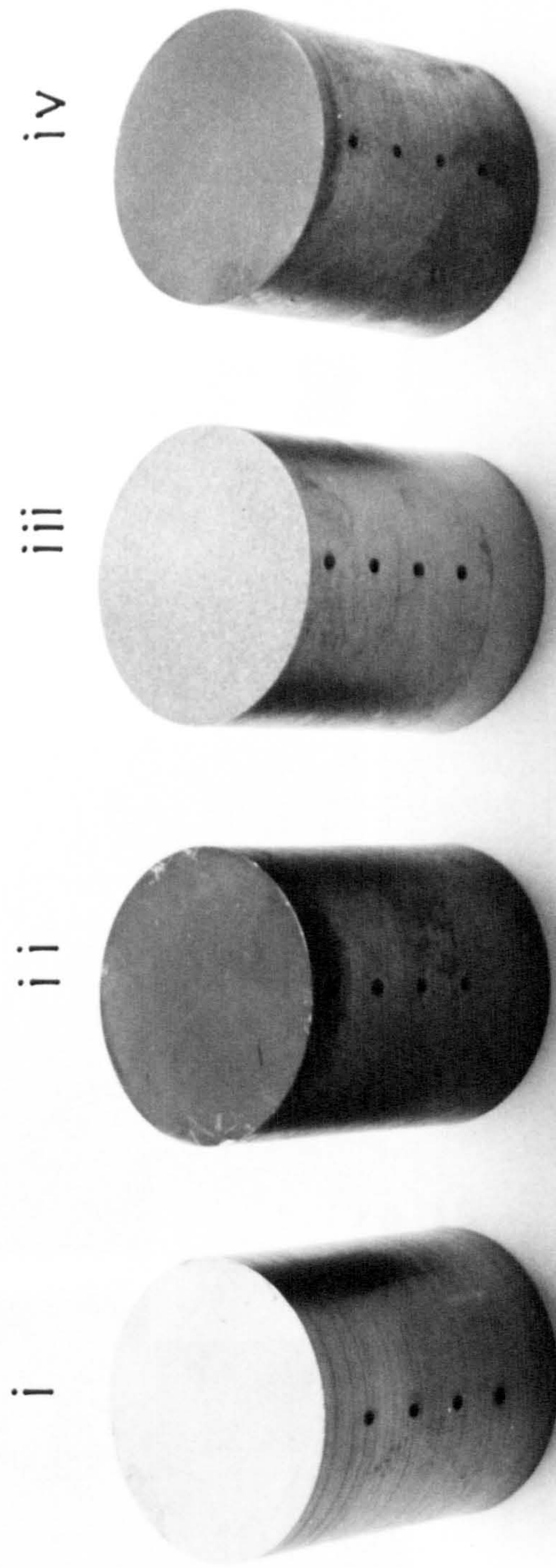


Plate 4.3 Oxide-free and oxidized specimens. (i) polished surface (oxide-free)
(ii) oxidized at 325°C for ten hours. (iii) sand-blasted (oxide-free)
(iv) sand-blasted oxidized at 300°C for five hours.

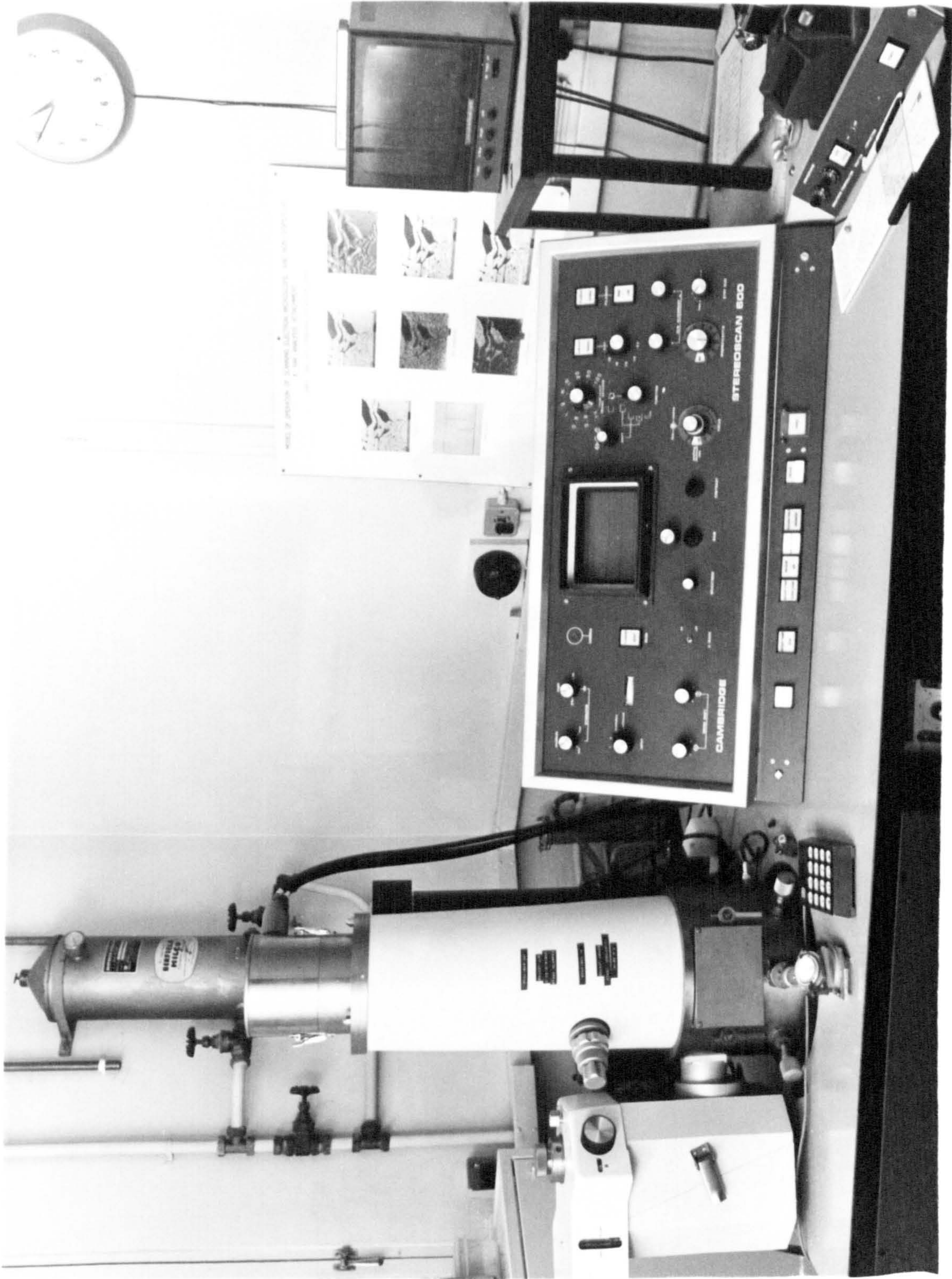


Plate 4.4 Stereoscan Electron Microscope (magnification X 20,000. Resolving power better than 25 nm).

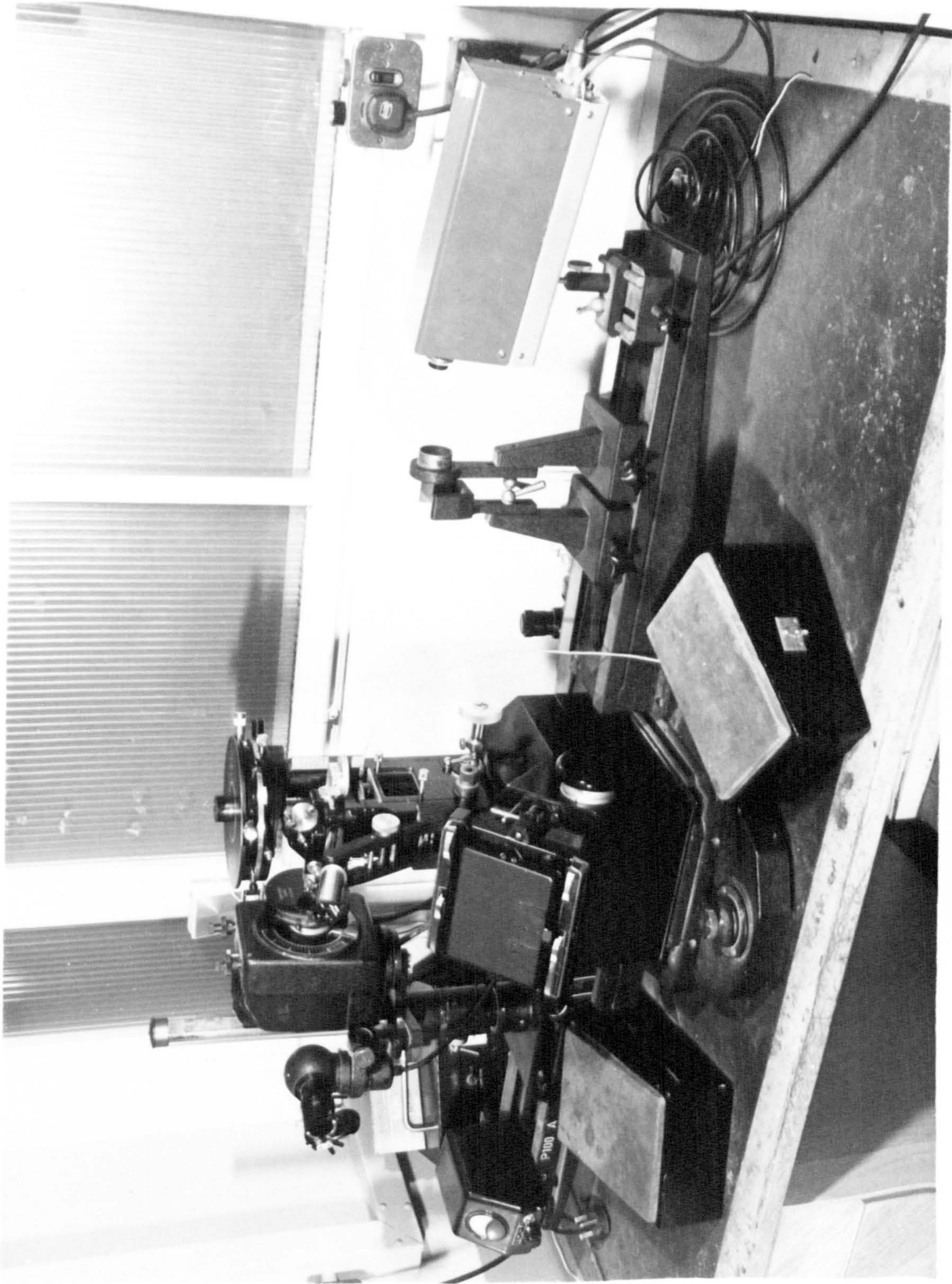


Plate 4.5 Reichert Metallographic Microscope. Magnification X 2000. Resolution limit better than $0.34 \mu\text{m}$.

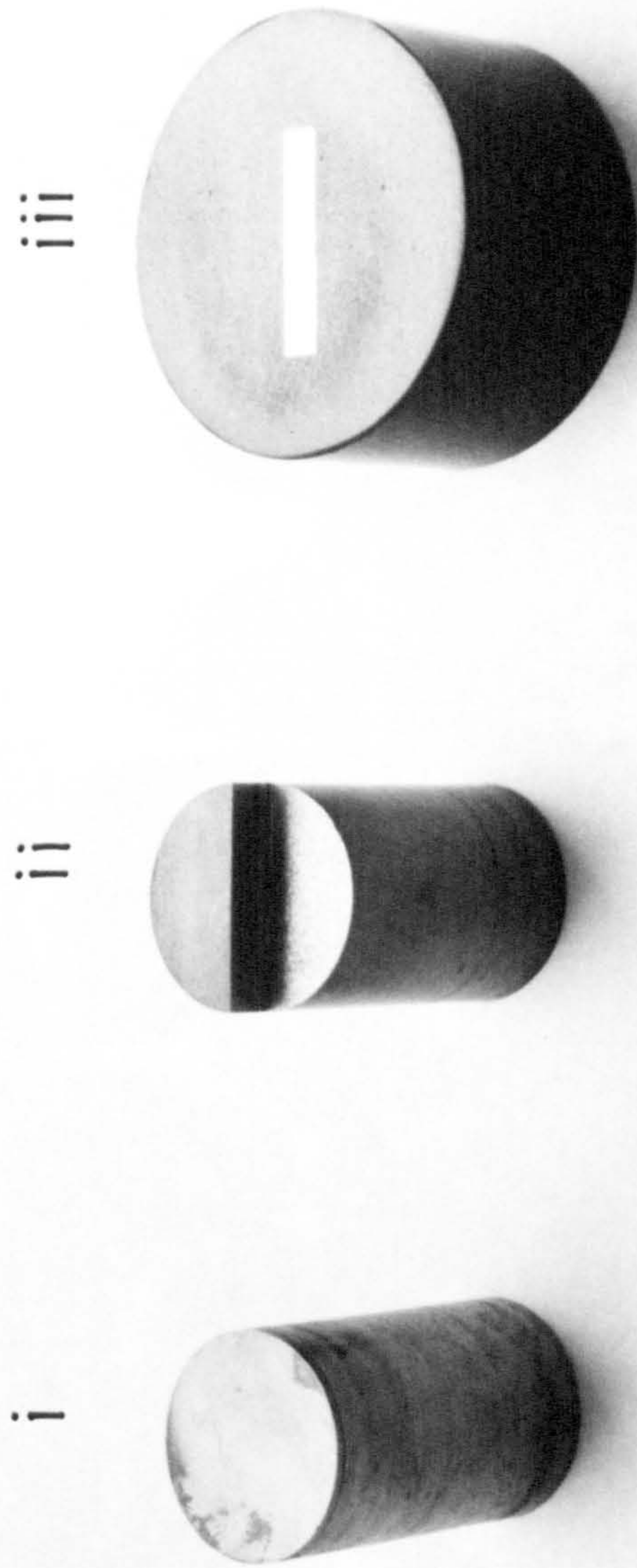


Plate 4.6 Sequence of operations for film thickness measurements. (i) oxidized specimen (ii) specimen after cutting (iii) test sample as mounted on bakelite holder.



Plate 4.7 Spark erosion machine showing cutting operation of the oxidized specimen for microscopical film thickness measurements.

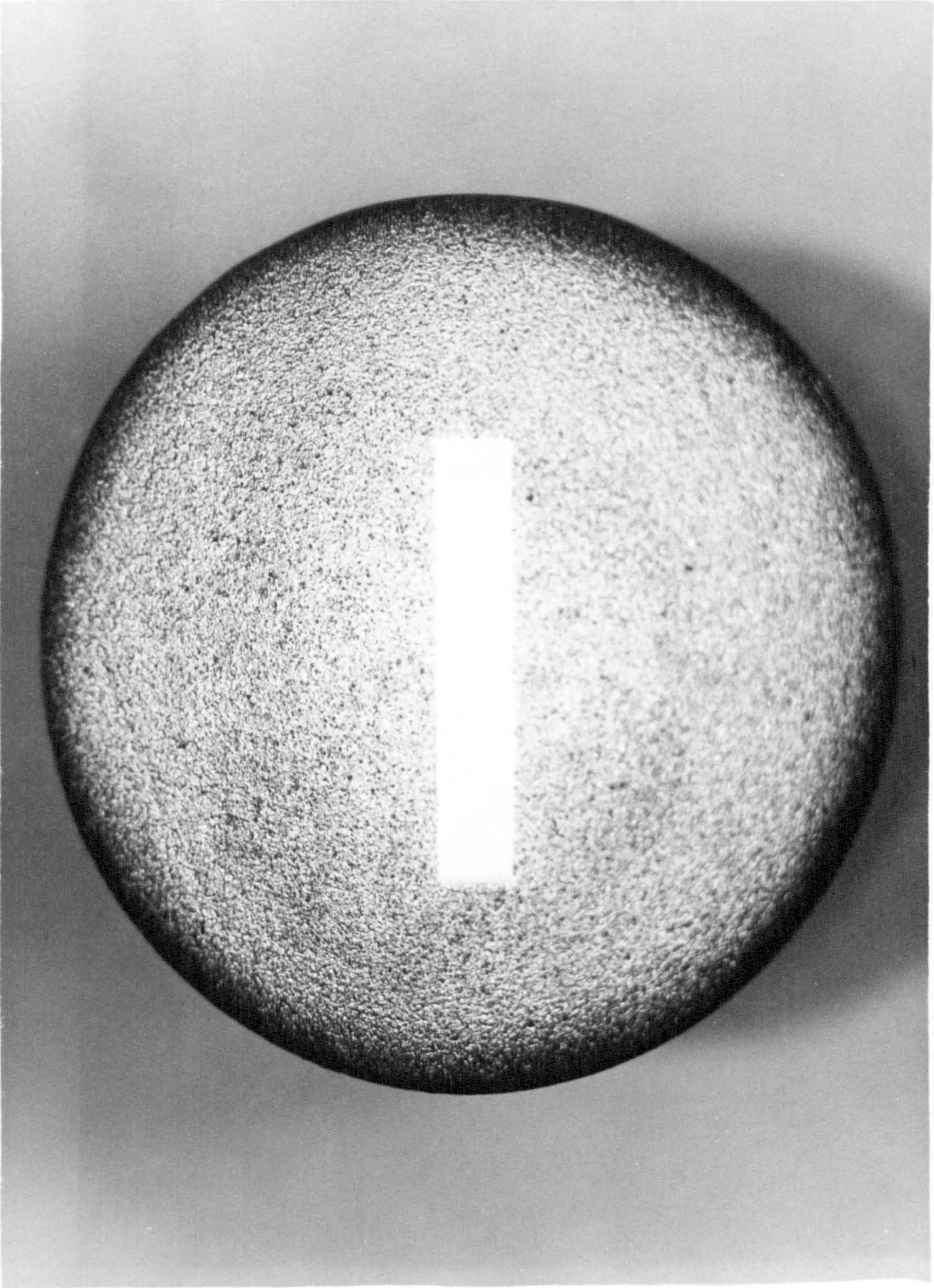


Plate 4.8 Top view of the test sample mount on bakelite holder.

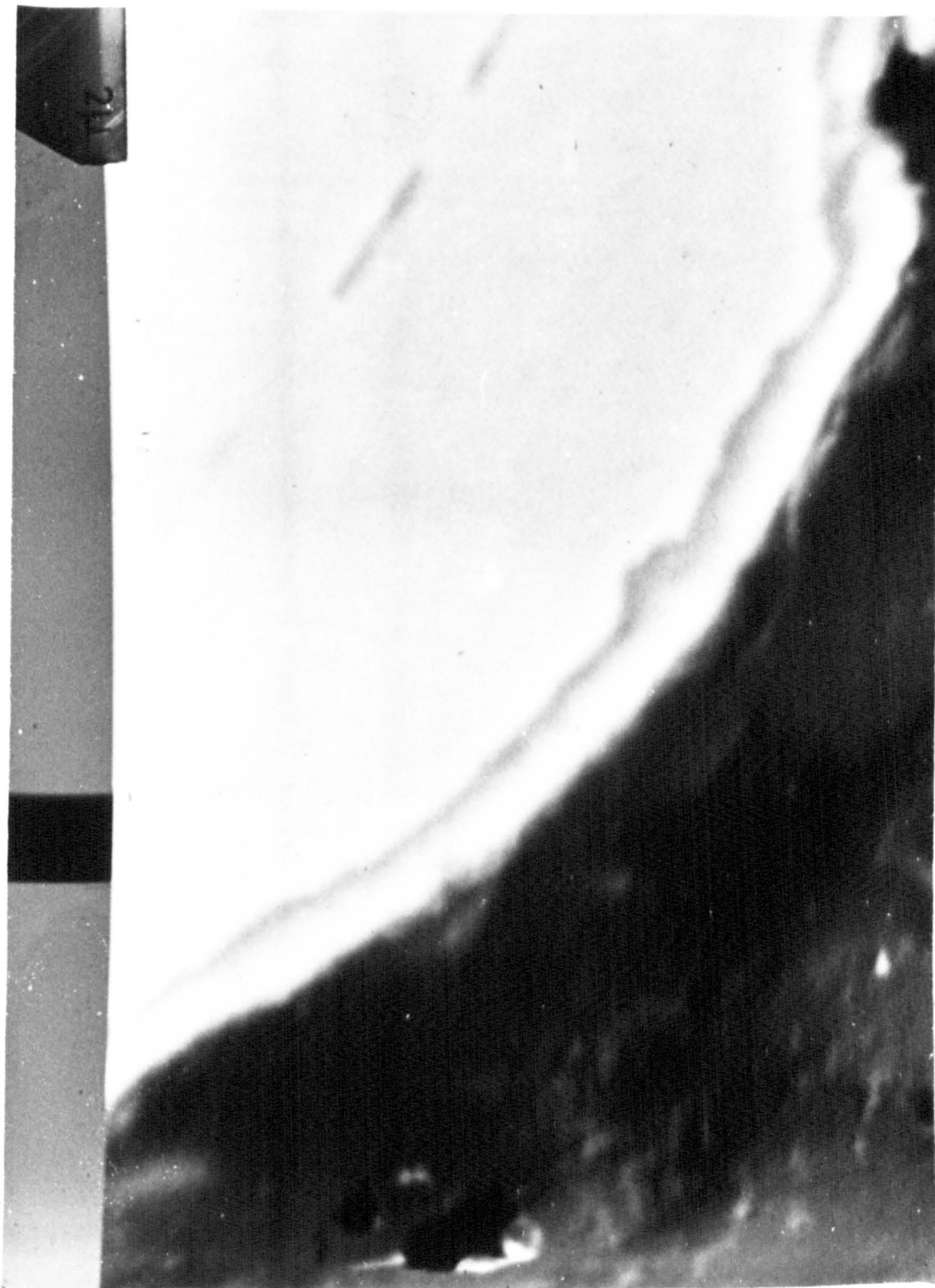


Plate 4.9 Cross-section of the oxide film on an EN3B mild steel specimen oxidized at 325^o C for 168 hours. Measurements taken with a Stereoscan Electron Microscope. X 20,000. Film thickness, 1.30 μm .

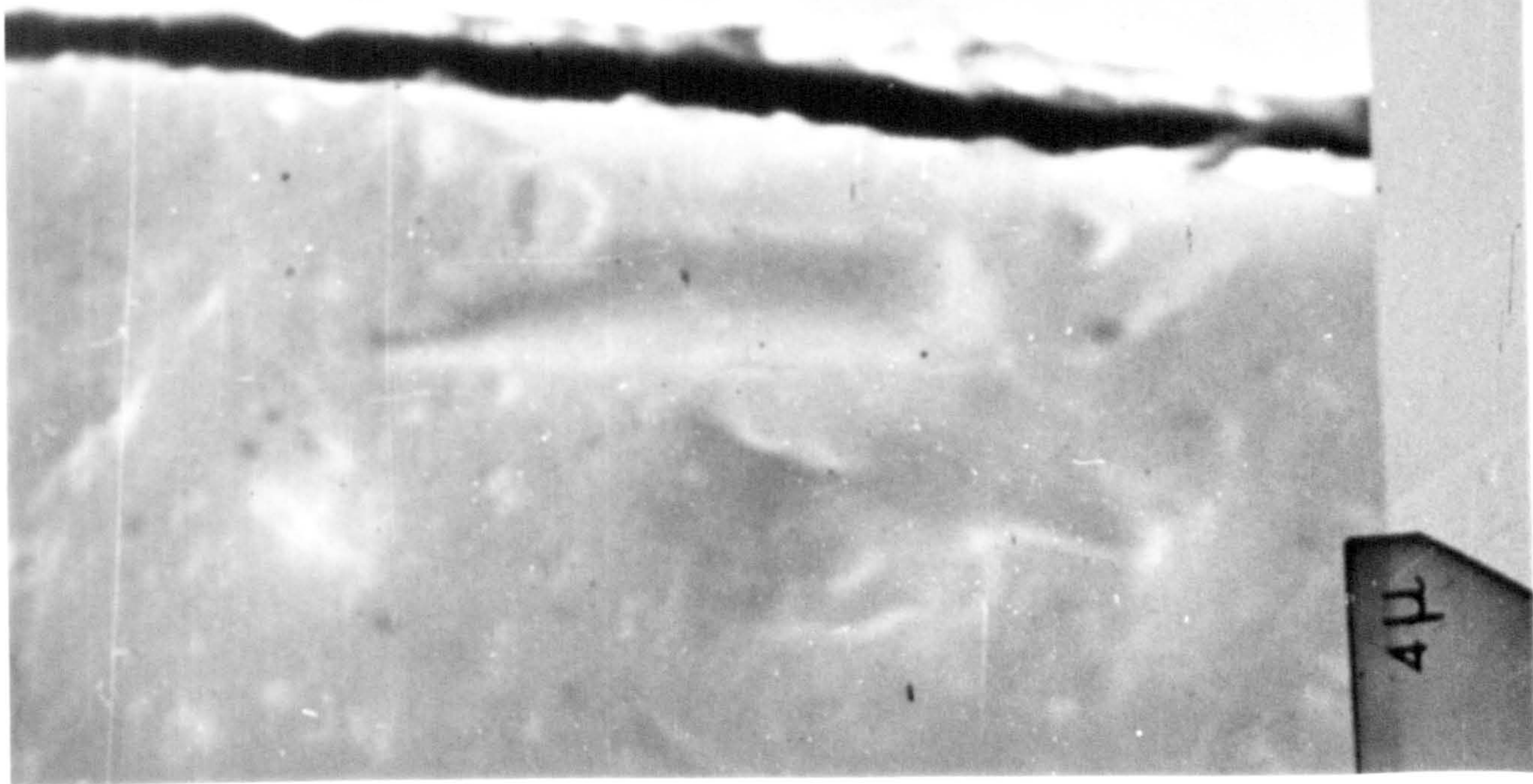


Plate 4.10 Growth of oxide film on an EN3B mild steel specimen oxidized at 250°C for 336 hours. The photograph taken by Stereoscan Electron Microscope shows the mode of deposition of the oxide.

comparison between the substrate and the oxide layer, the surface of the sample was mechanically polished in sequences with emery papers of decreasing coarseness, (240-600 grit). To prevent overheating of the test sample, this operation was carried out using water as a coolant.

Specimens were held in such a way that each successive polishing operation was made at right angles to the operation until the scratches produced by previous papers had been removed. It was thoroughly washed with water each time before changing over to finer emery paper so as to avoid the retention of coarse grit. Finally it was polished from a roughness of about 6 μm down to $\frac{1}{2}$ μm on a selvyt cloth impregnated with diamond paste and lubricated with paraffin. The oxide film thickness on the roughened surfaces, because of their unevenness, could not be measured by electron optics but had to be estimated. This was accomplished by mathematically treating Arrhenius equation using the information obtained from the interference colour charts of Davies, Evans and Agard (111) as given in Table 4.2. Their values were assumed to be most relevant to this work.

4.2.1 Theoretical Estimation of the Growth of the Oxide Films

4.2.2 Constant Time and Varied Temperature Estimation

$$D = D_1 \cdot e^{-Q_1/R_1 T} \quad \dots \quad (4.1)$$

is the general form of the Arrhenius equation (112) where

D = the oxidation rate constant, $\text{m}^2 \text{hr}^{-1}$

D_1 = proportionality constant

R_1 = gas constant, $\text{J kg}^{-1} \text{K}^{-1}$

Q_1 = activation energy, J kg^{-1}

T = the absolute temperature, $^\circ\text{K}$

$$x = \sqrt{D t} \quad \dots \quad (4.2)$$

expresses the parabolic oxidation rate relationship (112) in terms of film thickness,

where

t = time, in hours

x = the film thickness in m.

Rearranging and by substituting the value of D from equation (4.1), equation (4.2) can be written as

Table 4.2THICKNESS OF OXIDE FILMS ON IRON (111)

TREATMENT		Colour of Oxide Layers	Oxide Thickness (10^{-10} m)		
Exposure Period (hours)	Temperature °C		Fe ₂ O ₃	Fe ₃ O ₄	Total
0.25	225	pale straw	77	nil	77
2	225	golden brown	103	nil	103
4	225	reddish brown	132	nil	132
8	225	red	152	nil	152
3	250	deep red	159	nil	159
6	250	purple	159	nil	159
9	250	violet	210	36	246
12	250	blue	224	68	292
2	300	greenish blue	224	170	414
5	300	greenish silver	303	241	544
8	300	greenish straw	350	288	638
11	300	straw	380	385	765
8	325	greyish brown	521	463	984
10	325	greyish pink	606	574	1180

$$x^2 = D_1 \cdot e^{-Q_1/R_1T} \cdot t \quad \dots \quad (4.3)$$

Now for the purpose of using information provided in the interference colour charts so as to obtain a further estimation of film thickness, values of film thickness at varied temperatures for the same time were substituted into (4.1) after giving a theoretical treatment, i.e. holding t as constant, so equation (4.3) can be written as :

$$x^2 = K \cdot e^{-Q_1/R_1T} \quad \dots \quad (4.4)$$

where $K = D \cdot t = \text{a constant}$

Taking logs

$$2 \log x = \log K - \frac{Q_1}{R_1T} \quad \dots \quad (4.5)$$

Since $\frac{Q_1}{R_1}$ also = a constant

therefore, in theory $\log x$ is a linear function of $(-\frac{1}{T})$

From the slope of a plot of $\frac{1}{T}$ as a function of $\log x$ (see Fig. 4.1) the value of activation energy was calculated.

The calculated value of the activation energy namely 3.27×10^6 J/Kg gave

$$D_1 = 2.55 \times 10^{-7} \text{ m}^2 \text{ hr}^{-1}$$

Equation (4.4) gives an estimate of the temperature which will be required to grow a film of oxide in a known time.

4.2.3 Constant Temperature and Varied Time Estimation

The parabolic relationship equation (4.2) can be written as

$$x^2 = Dt \quad \dots \quad (4.6)$$

or

$$x \propto \sqrt{t} \quad \dots \quad (4.7)$$

or

$$x = K_1 \sqrt{t} \quad \dots \quad (4.8)$$

where K_1 is an arbitrary constant.

Text cut off in original

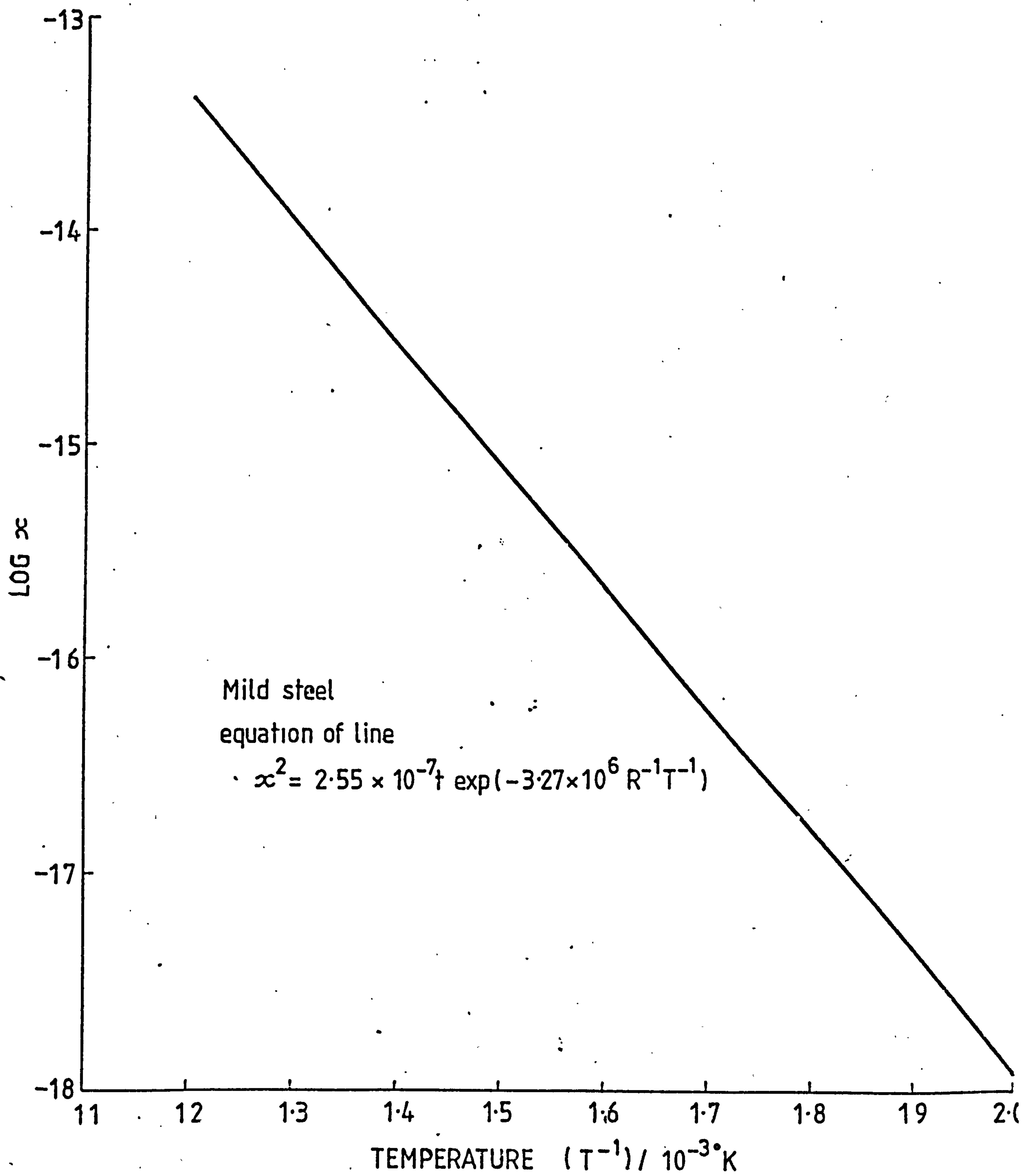


FIG. 4.1

Substituting various values of film thickness and time from interference charts for the same temperature an average value of the constant K_1 was calculated.

In certain cases the lower temperature longer period approach gave better results with this estimation.

Characteristics and the mode of deposition of oxide on various selected surfaces (i.e. polished, turned and ground) have been shown (see Table 4.3 and Plates 4.11 to 4.15), as could be viewed, the oxides grew in an uneven manner.

4.3 SURFACE TOPOGRAPHY MEASUREMENTS

Surface roughnesses, ordinate height distribution, autocorrelation functions and profile mean absolute slopes of the test specimens were measured with a Talysurf - 4 stylus instrument before and after oxidation. The signals emitted by the profilometer were fed into a Solartron data logger comprising of a buffer amplifier, analogue-to-digital converter and a high speed tape punch. The data tape was processed using a surface analysis program (110).

4.4 EXPERIMENTAL RESULTS AND DISCUSSION

Various types of surface finish were examined. These were produced by polishing, sandblasting, grinding and turning (see Table 4.1 for specimen surfaces M1 - M5). The surface parameters: RMS roughness, mean absolute surface slope, auto-correlation function and ordinate height distribution relating to each of the test specimens were evaluated using a surface analysis computer program (110) before and after oxidation.

The presence of thin oxide films (produced at temperature below 500°C) had an increasing effect on the RMS roughness of smooth surfaces, M1, M2, however, the effect was much more noticeable for the initially rougher surfaces (i.e. sand blasted) where the oxides had a smoothing effect. Gulbransean & Wysong (113) found little variation in the thicknesses of oxide films found on polished or abraded (4/0 emery paper) tungsten and molybdenum surfaces. The effects of initial surface finish dominate the topography of the oxidized surface for comparatively thin oxide films. Surface roughness is thus important in the formation of thin films rather than on scales. Benard (114) found that electrolytically polished iron surfaces scaled (after two hours exposure to an air atmosphere at 850°C) to somewhat smaller extent than surfaces abraded with various grades of emery paper. The differences detected were however relatively small.

The oxide build-up on ground mild steel and copper (the oxides were produced in an environmental chamber at relatively low temperature and high humidity) led to a marked increase in the RMS roughness, (see Table 4.1). This may be attributed to the uneven and flaky characteristics of the oxide produced due to the presence of the water vapour (Plate 4.15).

Table 4.3

Material, Surface Topography and Treatment
of the Selected Specimens

(Related photographs show the mode of
deposition of oxide on various surfaces)

Photograph Identifi- cation	Material	Surface Description	Treatment	
			Temperature of Oxidation °C	Time of Oxidation hours
Plate 4.11	EB 3B mild steel	Nominally flat and smooth	325	10
Plate 4.12	EN 3B mild steel	Nominally flat and smooth	250	336
Plate 4.13	Commerically pure copper	Nominally flat and smooth	Oxidized by immersing in water and then leaving in open atmos- phere.	Immersed in water for 48 hours and left overnight in open atmosphere
Plate 4.14	EN 3B mild steel	Turned	325	10
Plate 4.15	EN 3B mild steel	Ground	Oxidized in the environ- mental chamber at 70°C and 80% humidity	72



Plate 4.11 Nominally flat and smooth EN3B mild steel specimens surface oxidized at 325°C for ten hours.



Plate 4.12 Nominally flat and smooth surface oxidized
at 250°C for 336 hours.



Plate 4.13 Nominally flat and smooth (commercially pure) copper surface oxidized by immersing in water for 48 hours and then leaving overnight in open atmosphere.

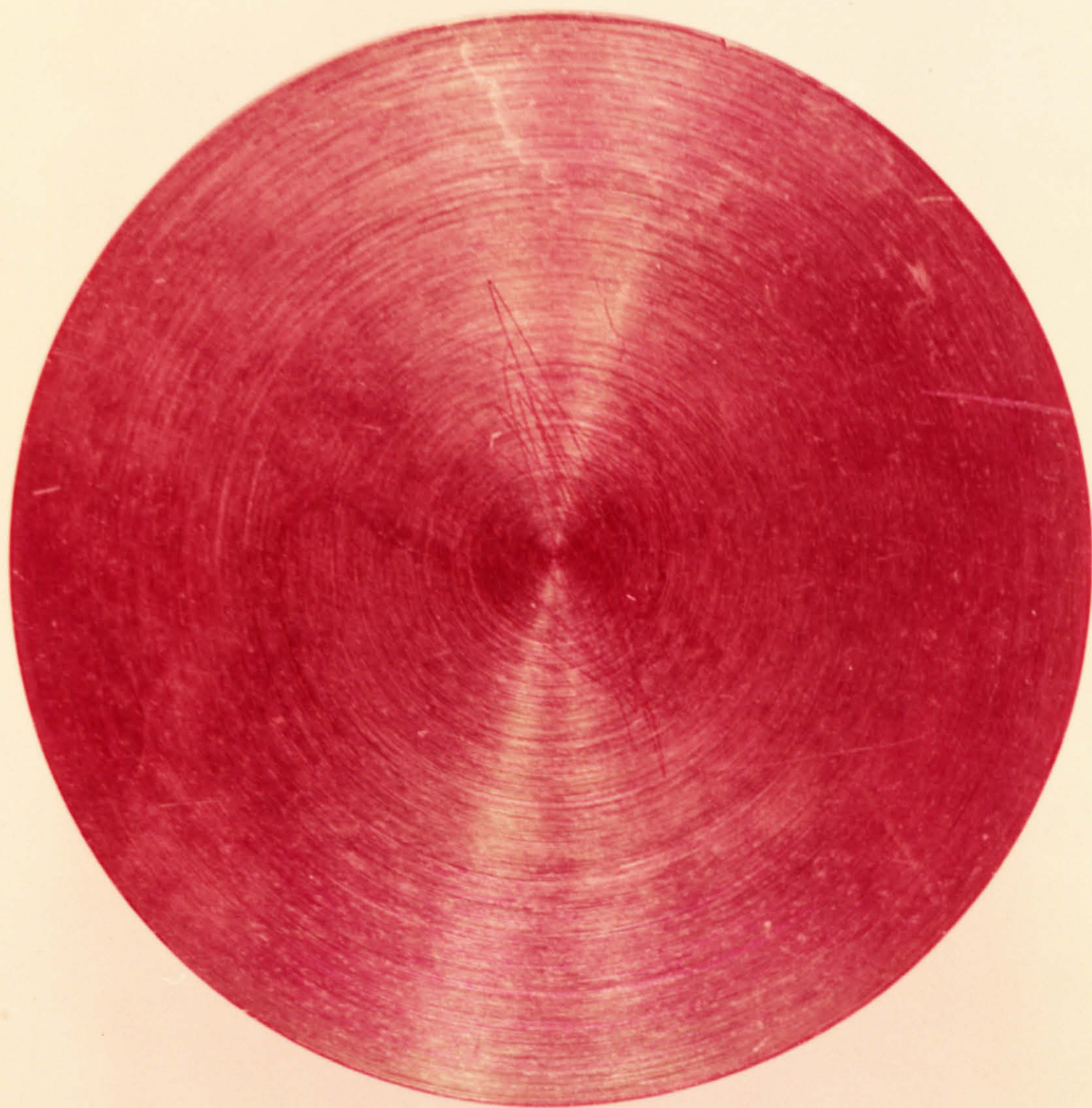


Plate 4.14 Turned surface oxidized at 325°C for ten hours.

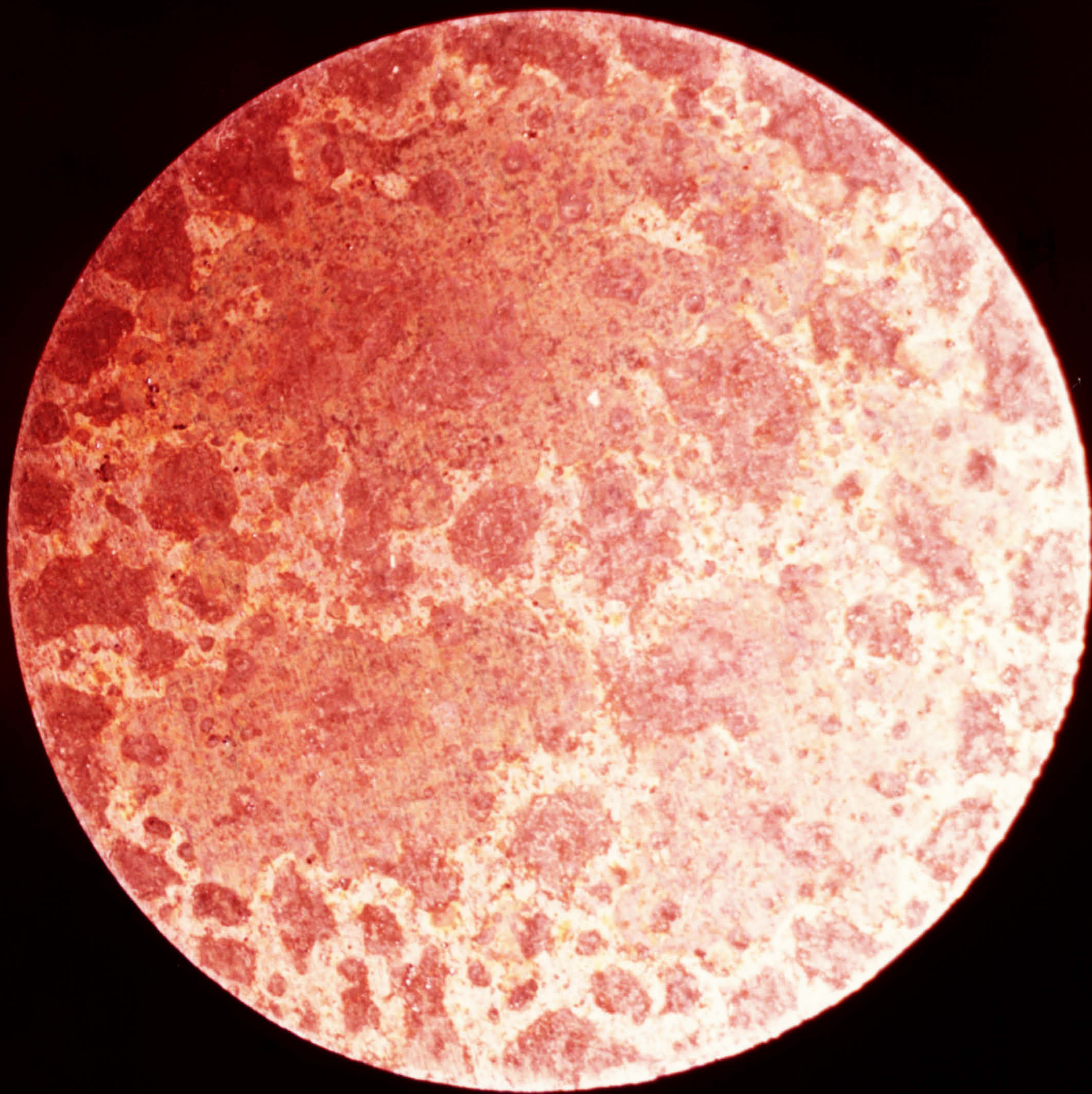


Plate 4.15 Ground mild steel specimen oxidized at 70°C and 80% humidity for 72 hours.

The presence of water vapour may alter, not only the oxidation rate, but also the composition of the scale. For example, the ferrous (iron) content of scales formed on steel has been found to vary considerably (113). An effect of water vapour on the oxidation of iron was also recorded by Winterbottom (115), for the low temperature range. Acceleration as well as retardation of oxidation rates by moisture was observed, and the change of 'driving potential of the transport process' owing to absorbed water vapour was suggested as the main cause of the effect.

4.4.1 Surface Ordinate Height Distribution

The ordinate height distribution for each of the surface profiles (see Figs. 4.2 to 4.8) investigated is shown in cumulative form in Figs. 4.7 - 4.11. It can be seen that the distributions for the surfaces prepared by polishing and grit-blasting were initially random and remained so after oxidation. This allows contact configuration theories which assume Gaussian distribution of surface height to be used for predicting the thermal contact resistances of oxidized surfaces.

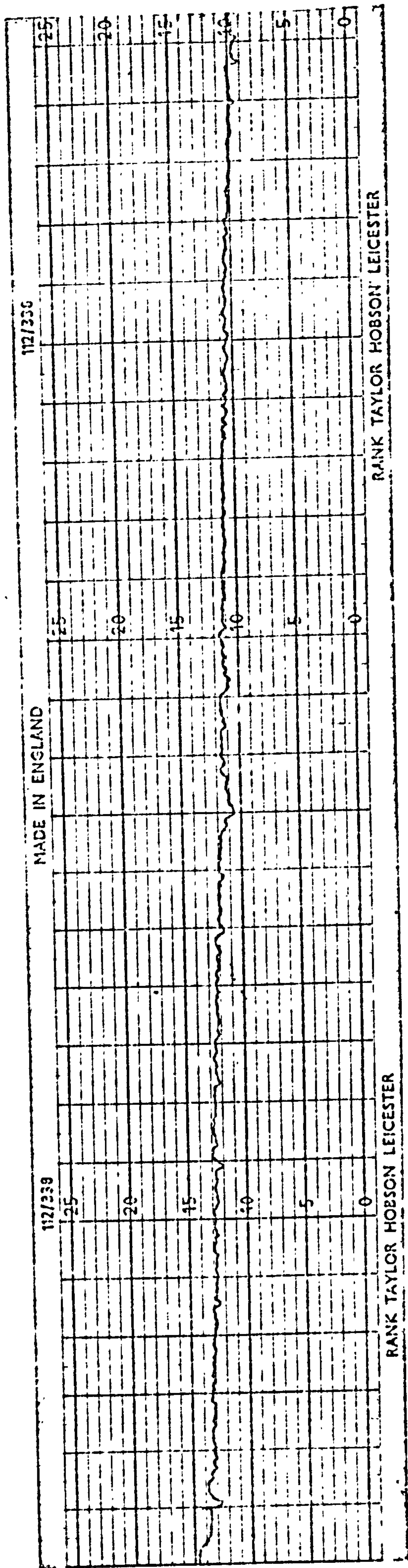
The ordinate height distribution for the oxide-free ground surfaces were originally Gaussian but became skewed after oxidation (Fig. 4.10). This was inevitable because, as reported earlier, oxide build-up in the presence of water vapour caused marked increases in the RMS roughnesses. Thus the uneven redistribution of surface heights seems to result from a preference for oxidation at the asperity tips.

4.4.2 Surface Auto-Correlation Function

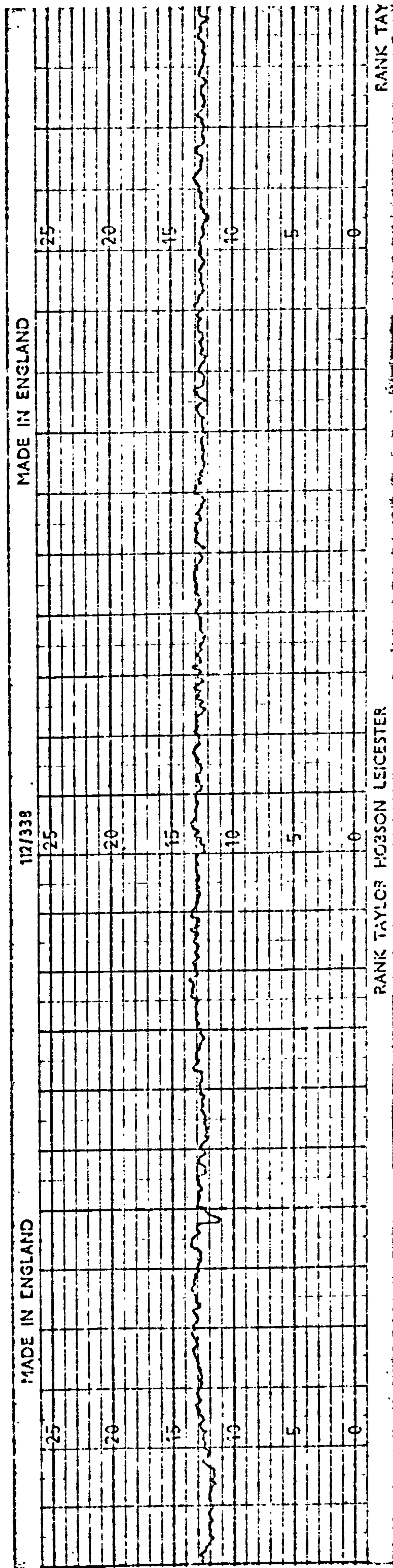
The variations of auto-correlation with data sampling intervals for each of the surfaces considered before and after oxidation are shown in Figs. 4.12-4.16. It can be seen that the shape of the curves for surfaces produced by polishing and grit-blasting exhibit a decay from unity and remain positive, which is a characteristic of purely random surfaces. Such curves may be approximated by an expression of the form described by equation (2.6). The surface roughness of the optically flat and smooth and machined surfaces increased after oxidation (figs. 4.12, 4.13, 4.15 & 4.16). A smoothing effect was observed on the sand-blasted surfaces (Fig. 4.14). In general the presence of thin films increased the surface roughness. The change in surface characteristics resulting from oxidation; which is rarely carried out under equilibrium conditions (112) can be attributed to the mode of growth of oxides.

A carrier profile having a harmonic wave frequency Ω with a superimposed random function may be used to describe the auto-correlation function for the ground surface (see Fig. 4.15).

$$\text{i.e. } F(\lambda) = e^{-\alpha \lambda_{\omega}} \cos \Omega \lambda_{\omega} \dots (4.9)$$



(a) $\sigma = 0.080 \mu\text{m}$ (RMS)

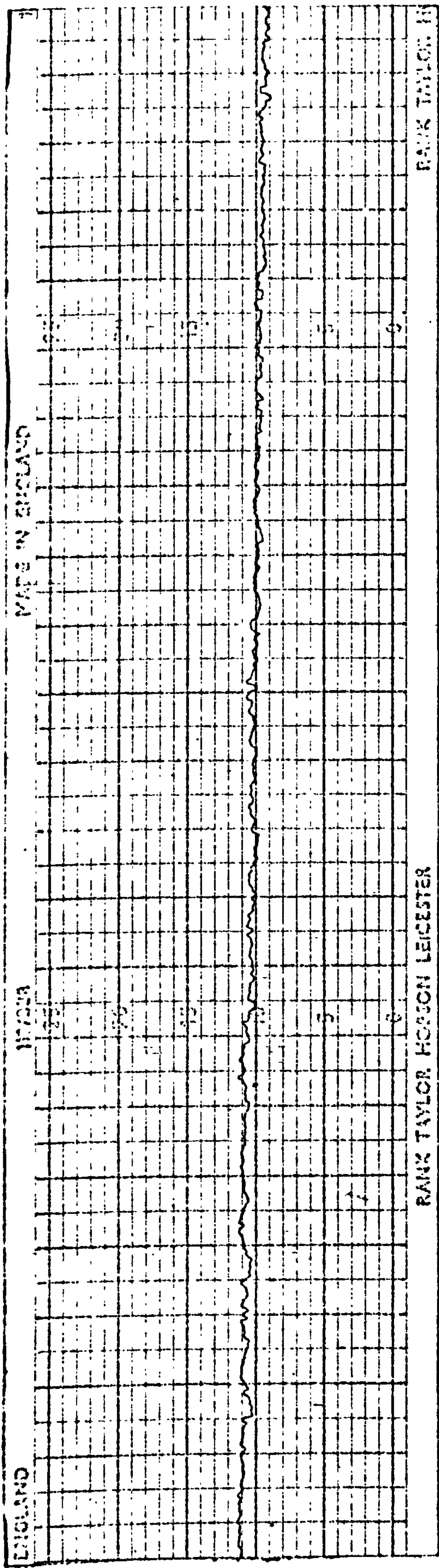


(b) $\sigma = 0.088 \mu\text{m}$ (RMS)

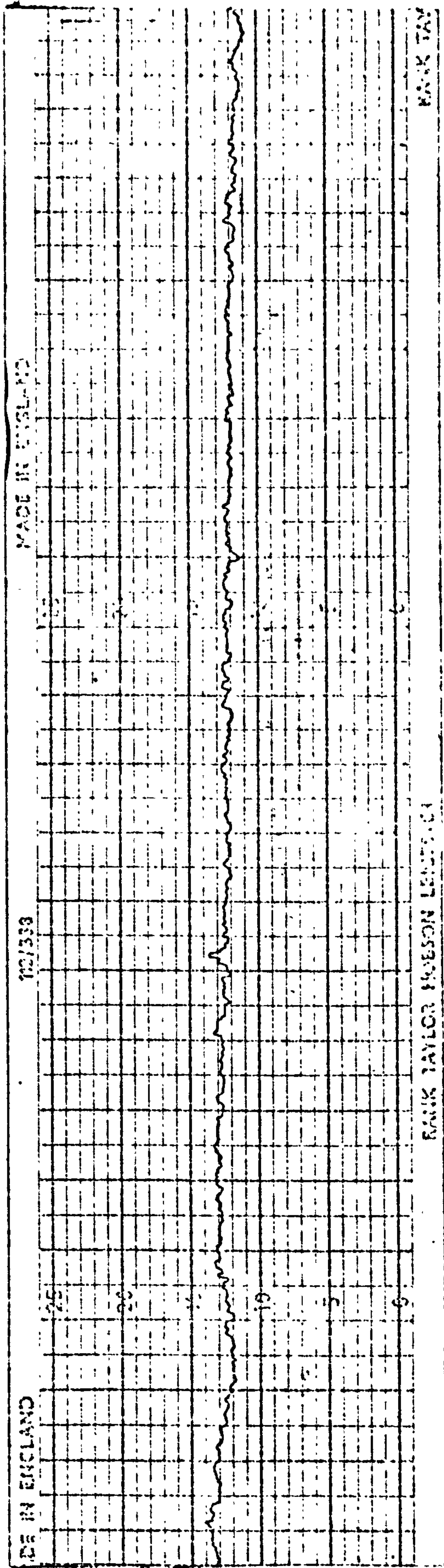
Fig 4.2 Talysurf trace of a nominally flat and smooth surface M1
(a) before oxidation; (b) after oxidation

1 μm

100 μm



(a) $\sigma = 0.0816 \mu\text{m (RMS)}$

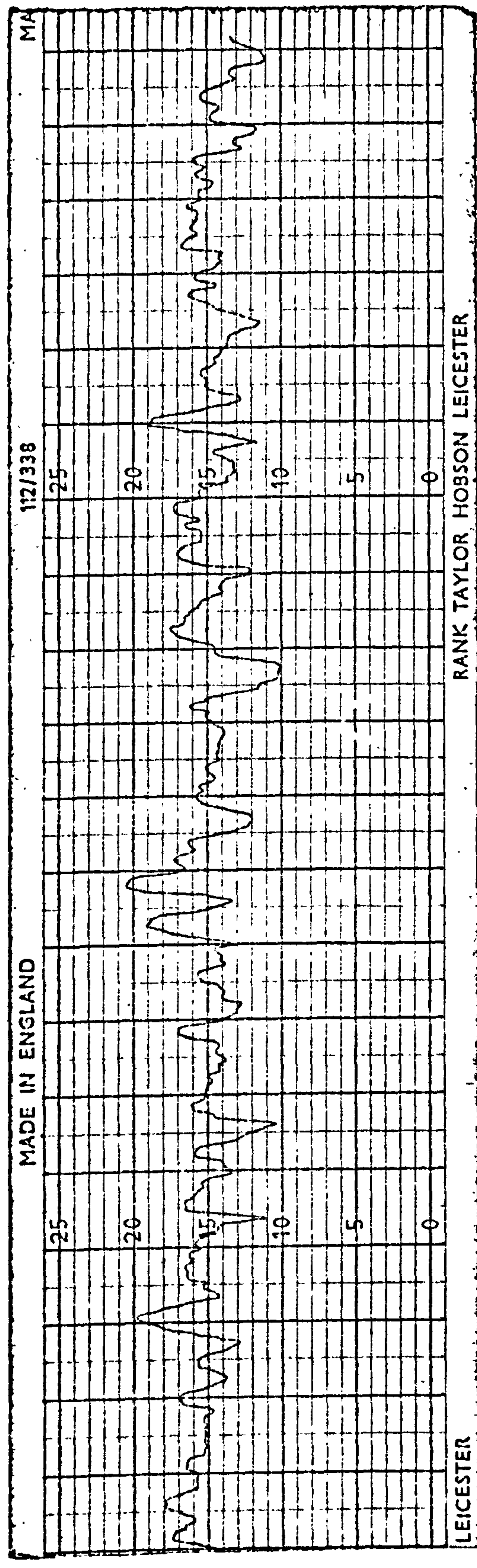


(b) $\sigma = 0.845 \mu\text{m (RMS)}$

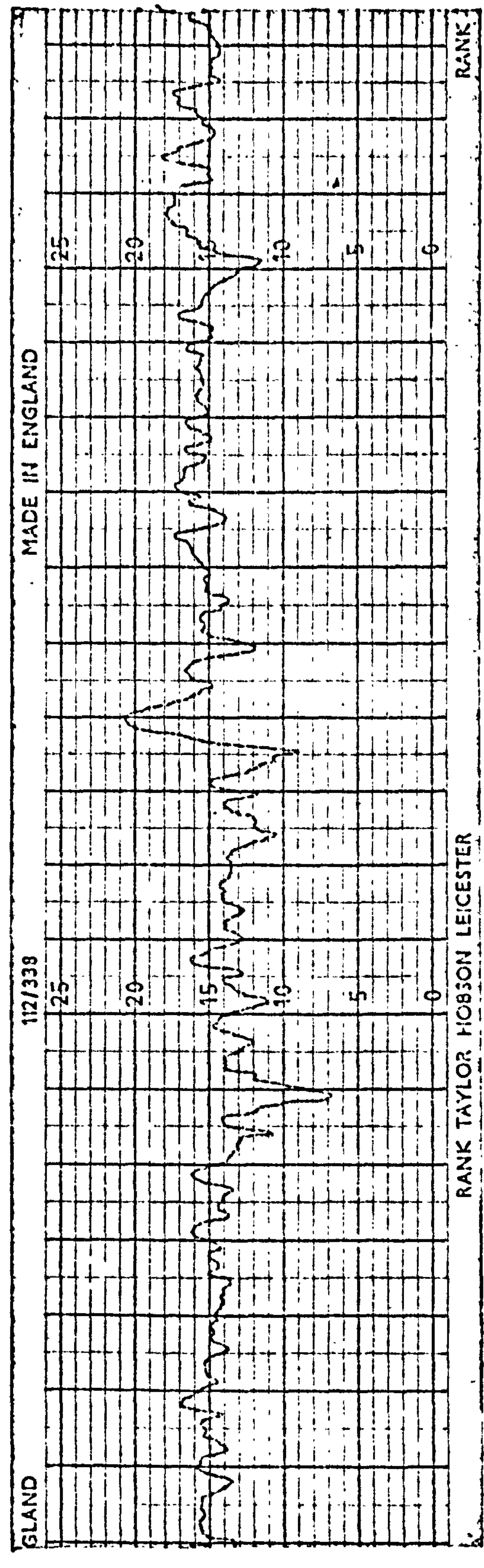
Fig. 4.3 Talysurf trace of a nominally flat and smooth surface M2
(a) before oxidation; (b) after oxidation

1 μm

100 μm

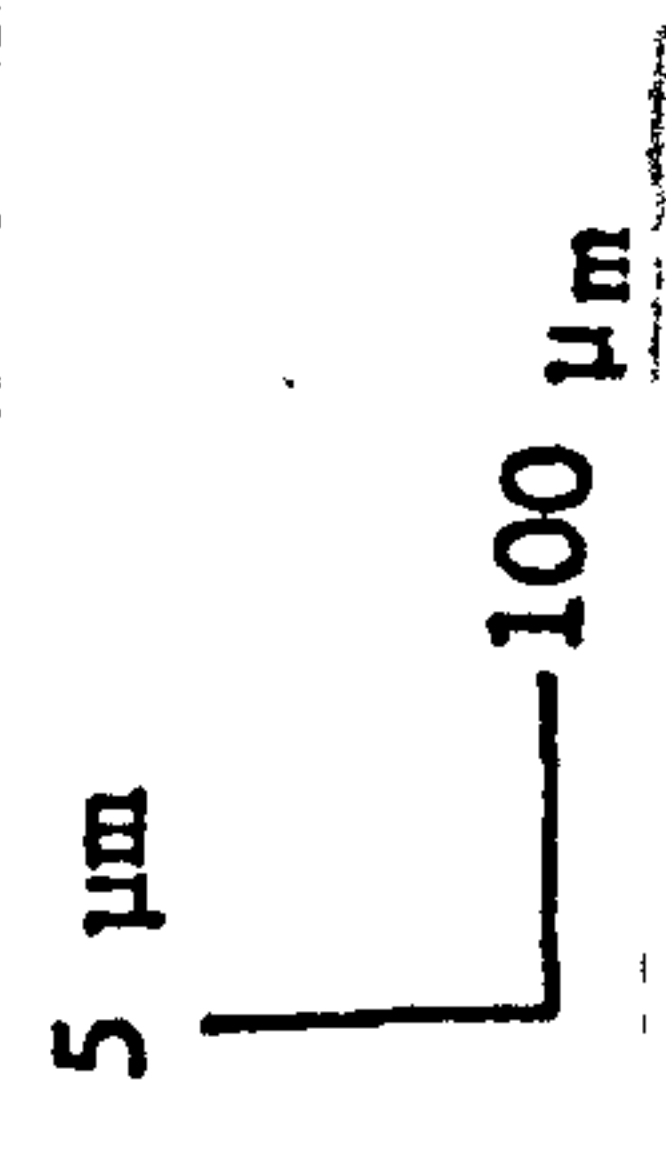


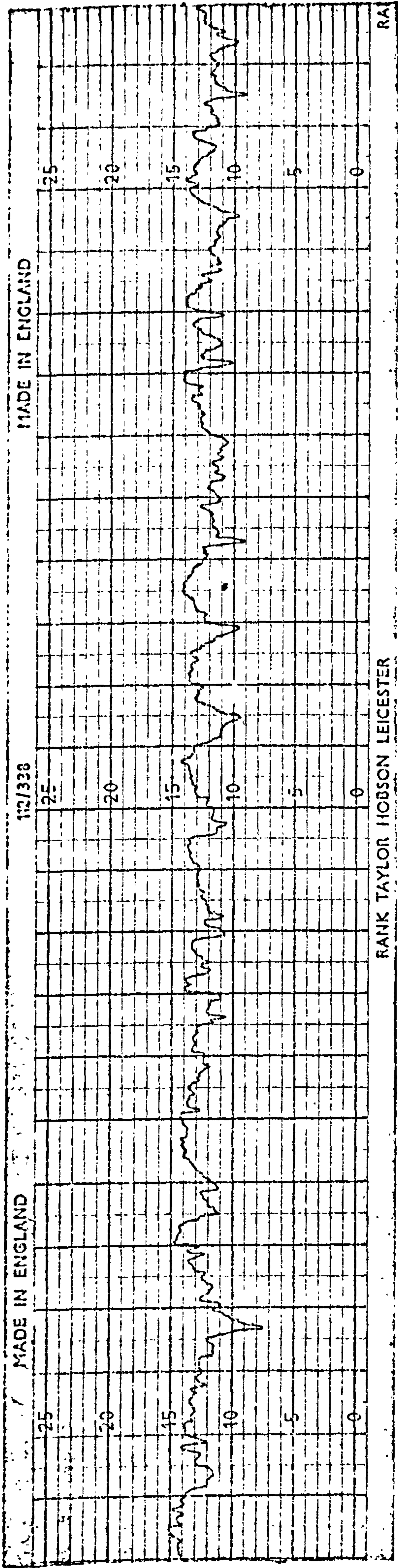
(a) $\sigma = 2.129 \mu\text{m (RMS)}$



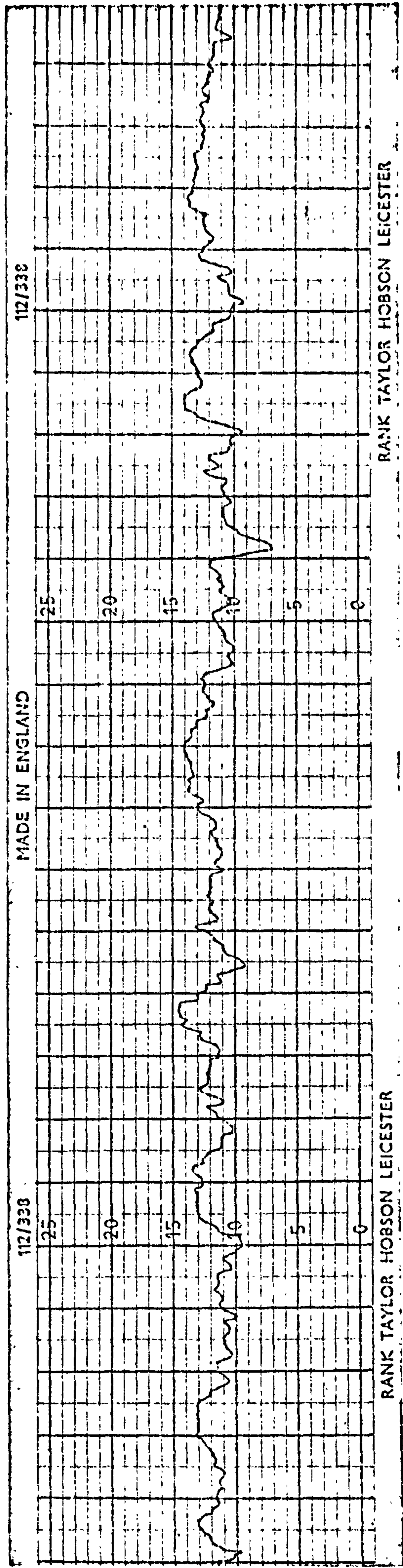
(b) $\sigma = 1.943 \mu\text{m (RMS)}$

Fig. 4.4 Talysurf trace of a nominally flat and rough surface M.3
(a) before oxidation. (b) after oxidation





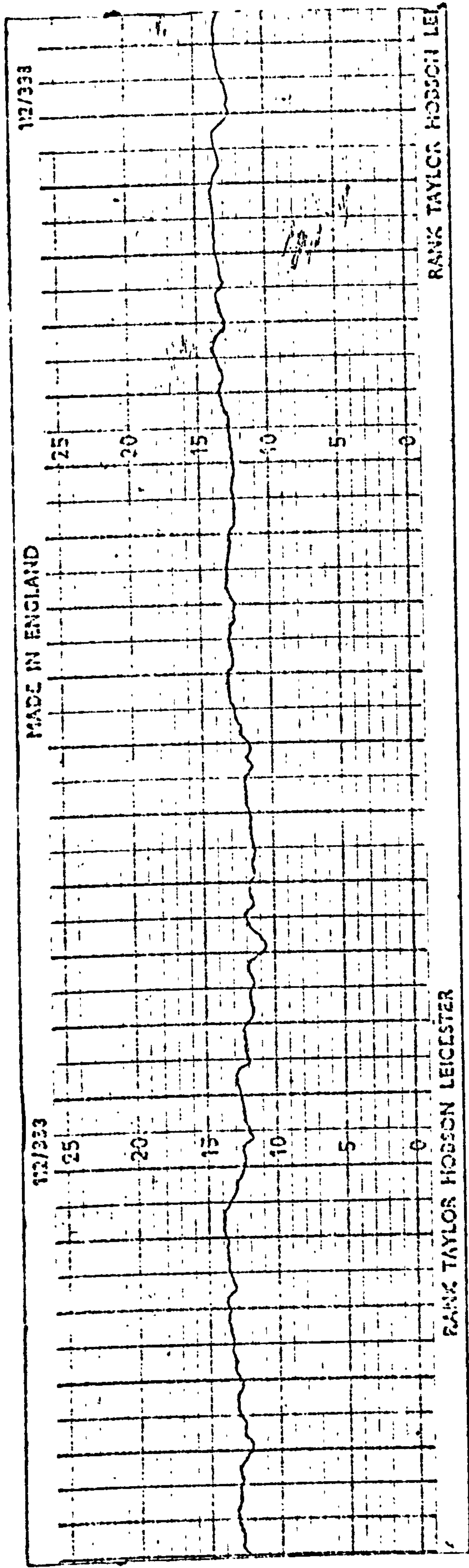
(a) $\sigma = 0.45 \mu\text{m (RMS)}$



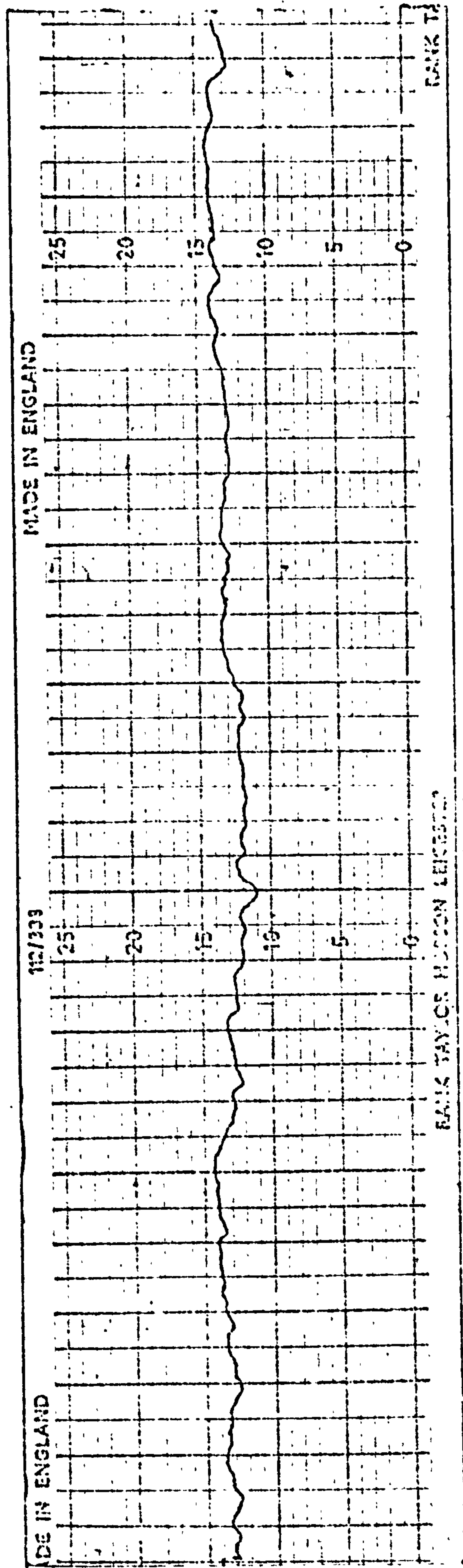
(b) $\sigma = 2.289 \mu\text{m (RMS)}$

Fig. 4.5 Talysurf trace of a ground surface (across the lay) M4
(a) before oxidation; (b) after oxidation

2 μm
100 μm



(a) $\sigma = 1.20 \mu\text{m}$ (RMS)



(b) $\sigma = 1.625 \mu\text{m}$ (RMS)

Fig. 4.6 Talysurf trace of a fine turned surface M5
(a) before oxidation; (b) after oxidation

1 μm
100 μm

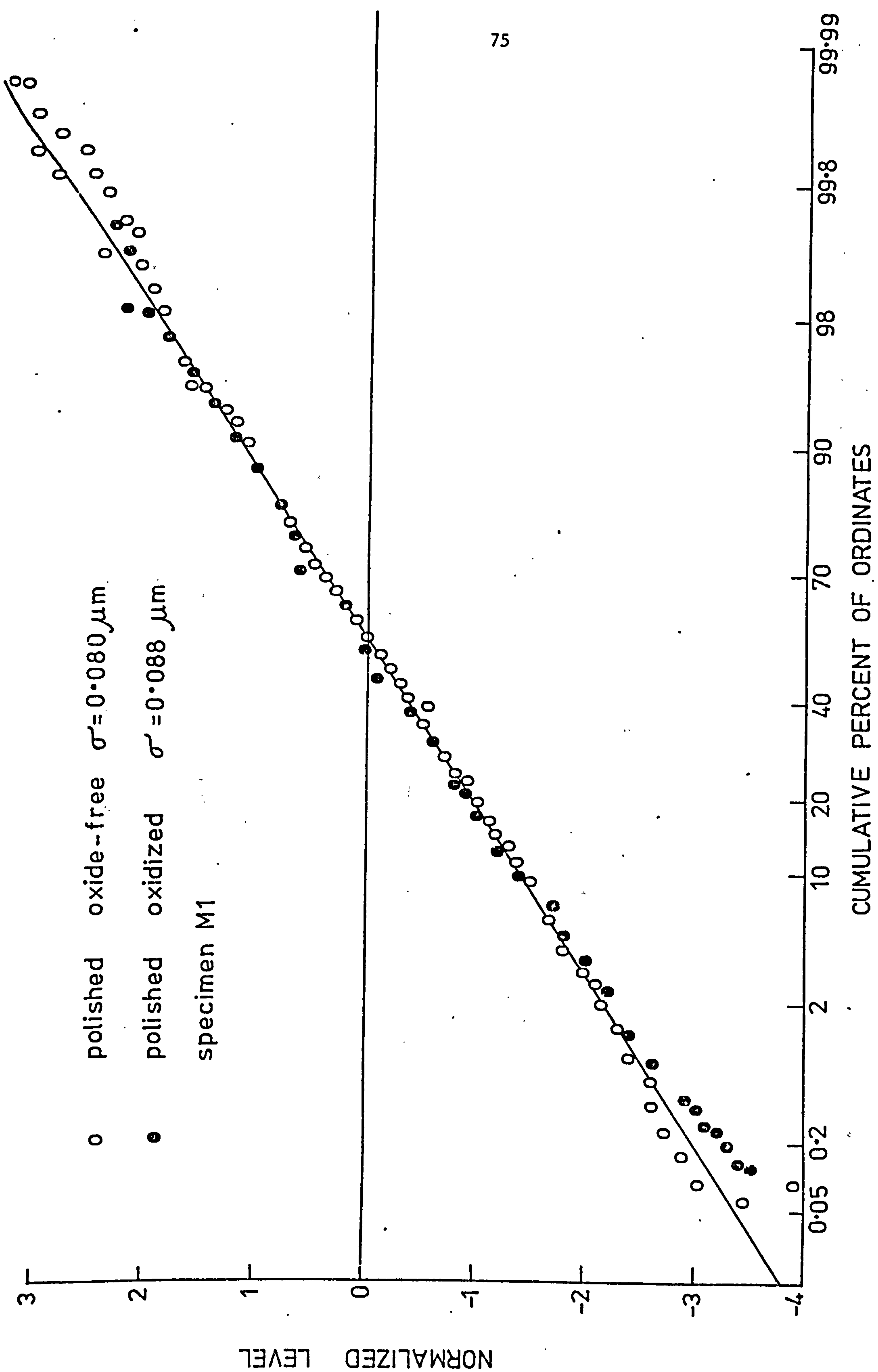


FIG. 4.7

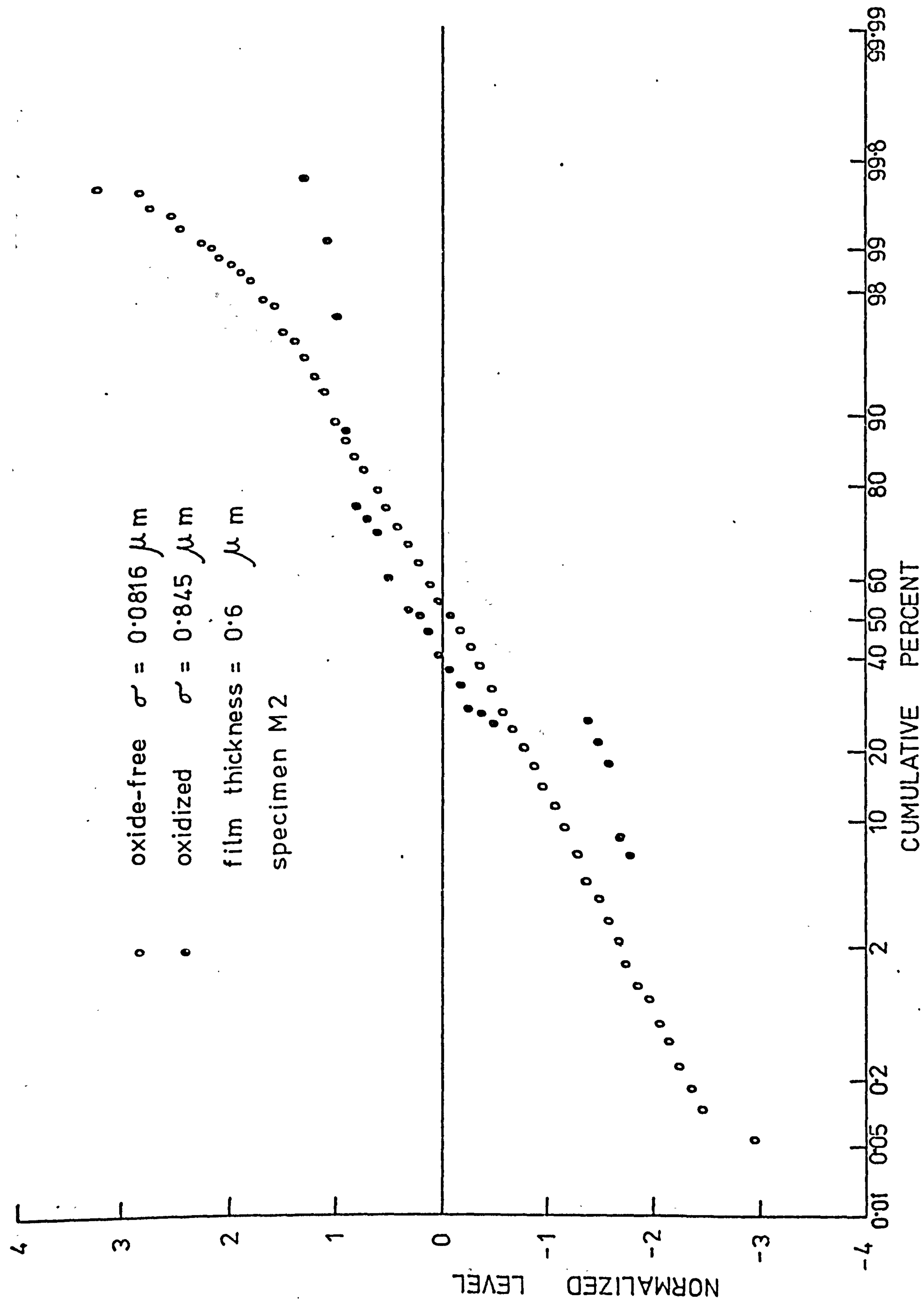


FIG. 4.8

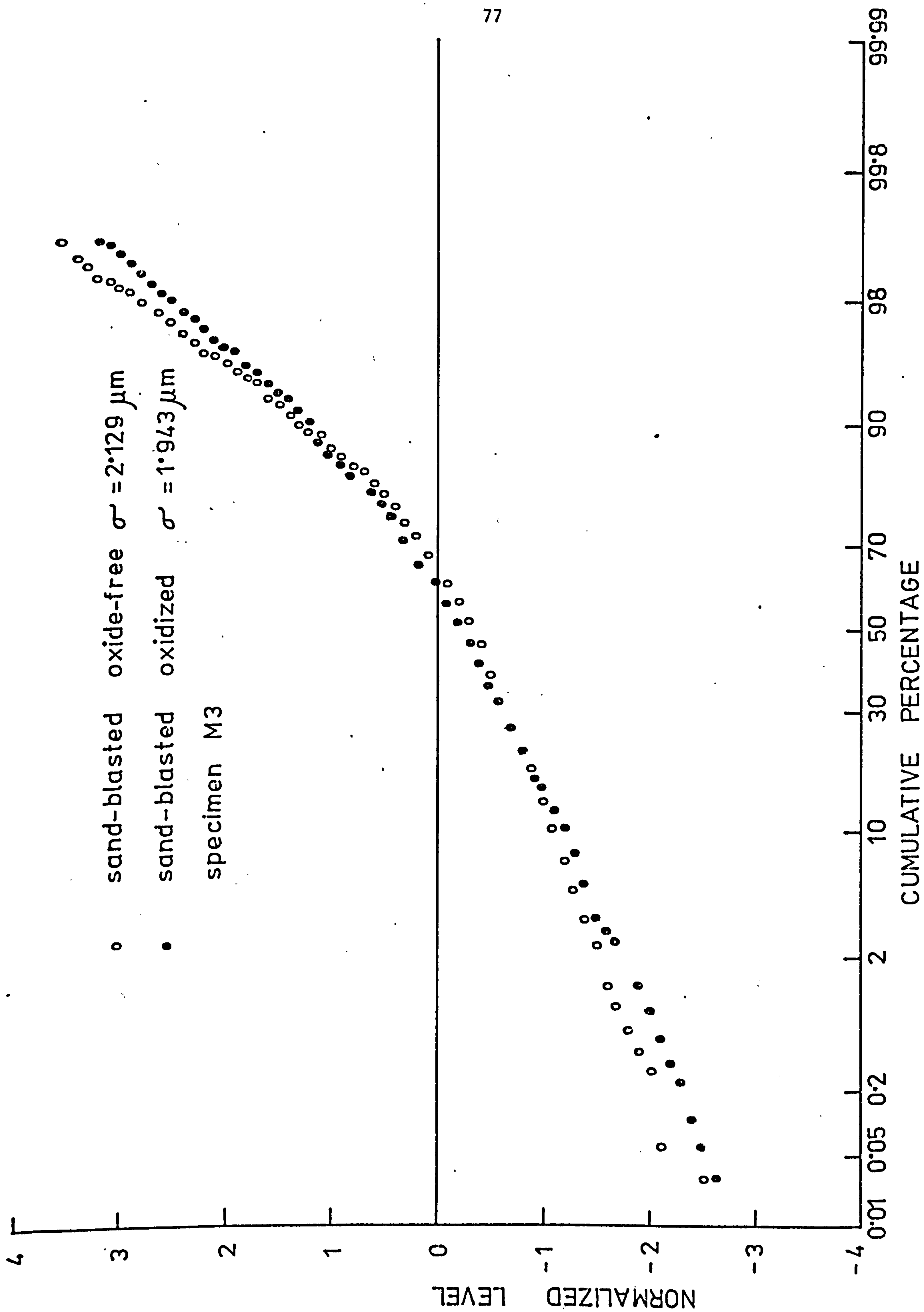


FIG. 4.9

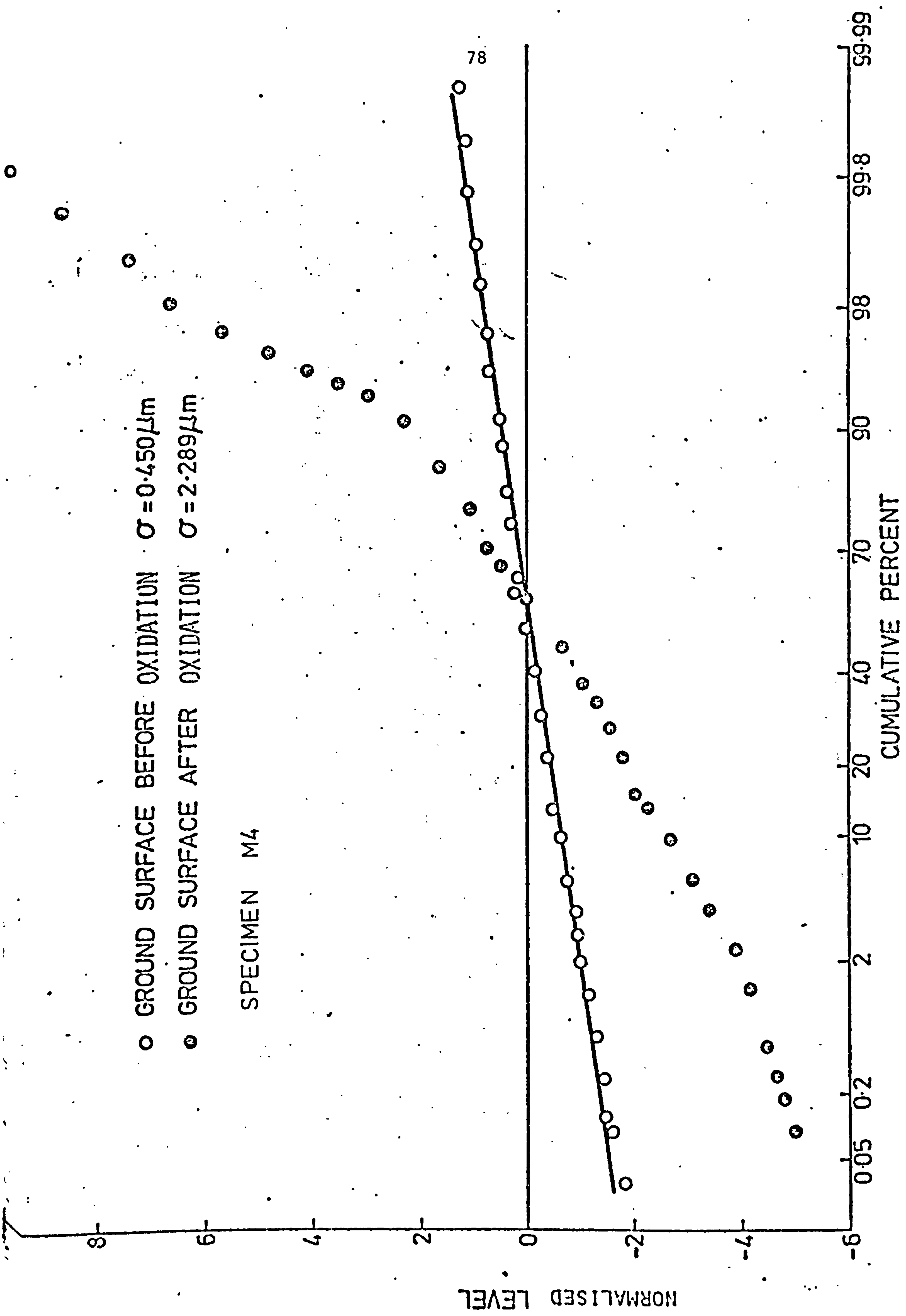


FIG. 4.10

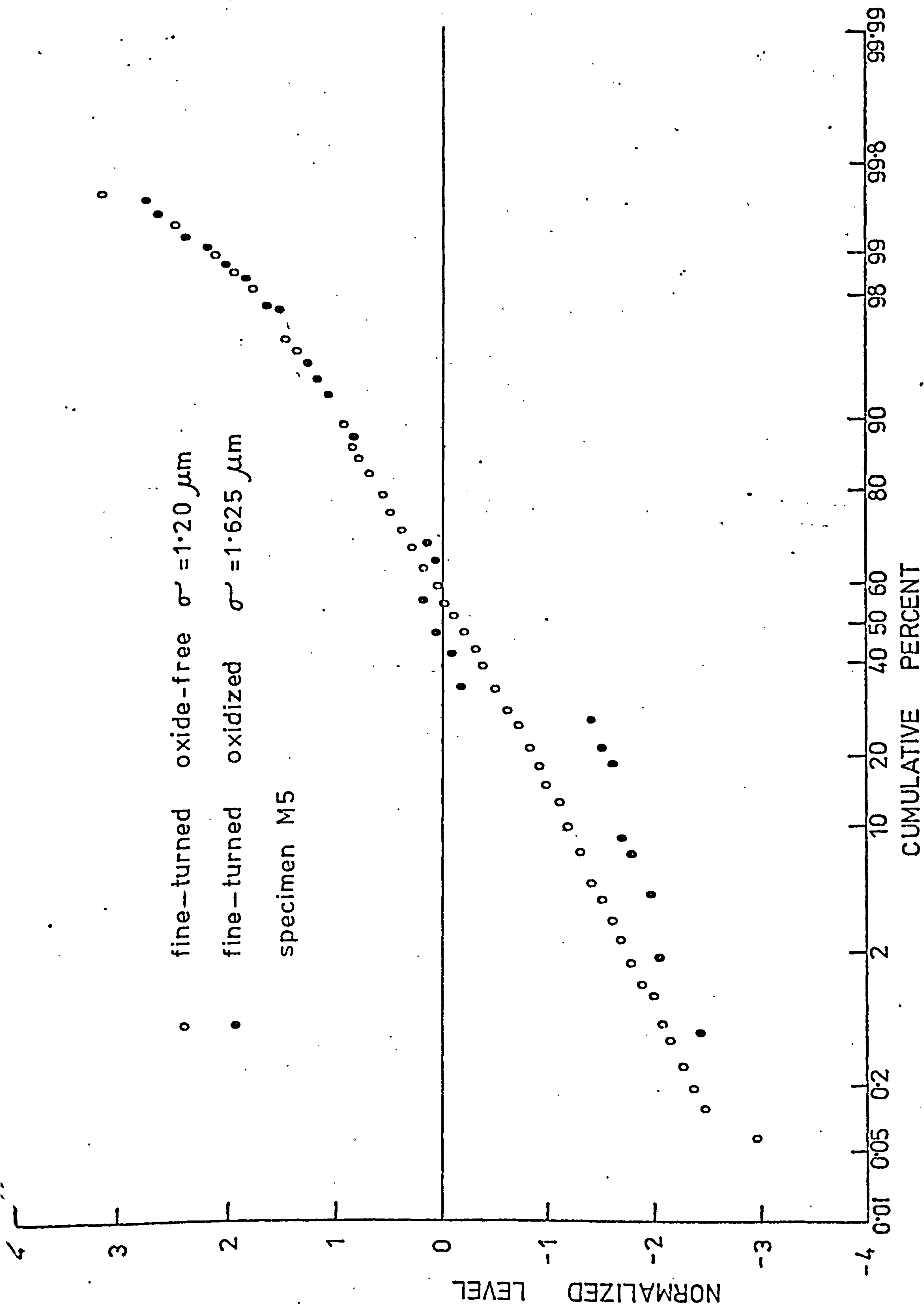


FIG. 4.11

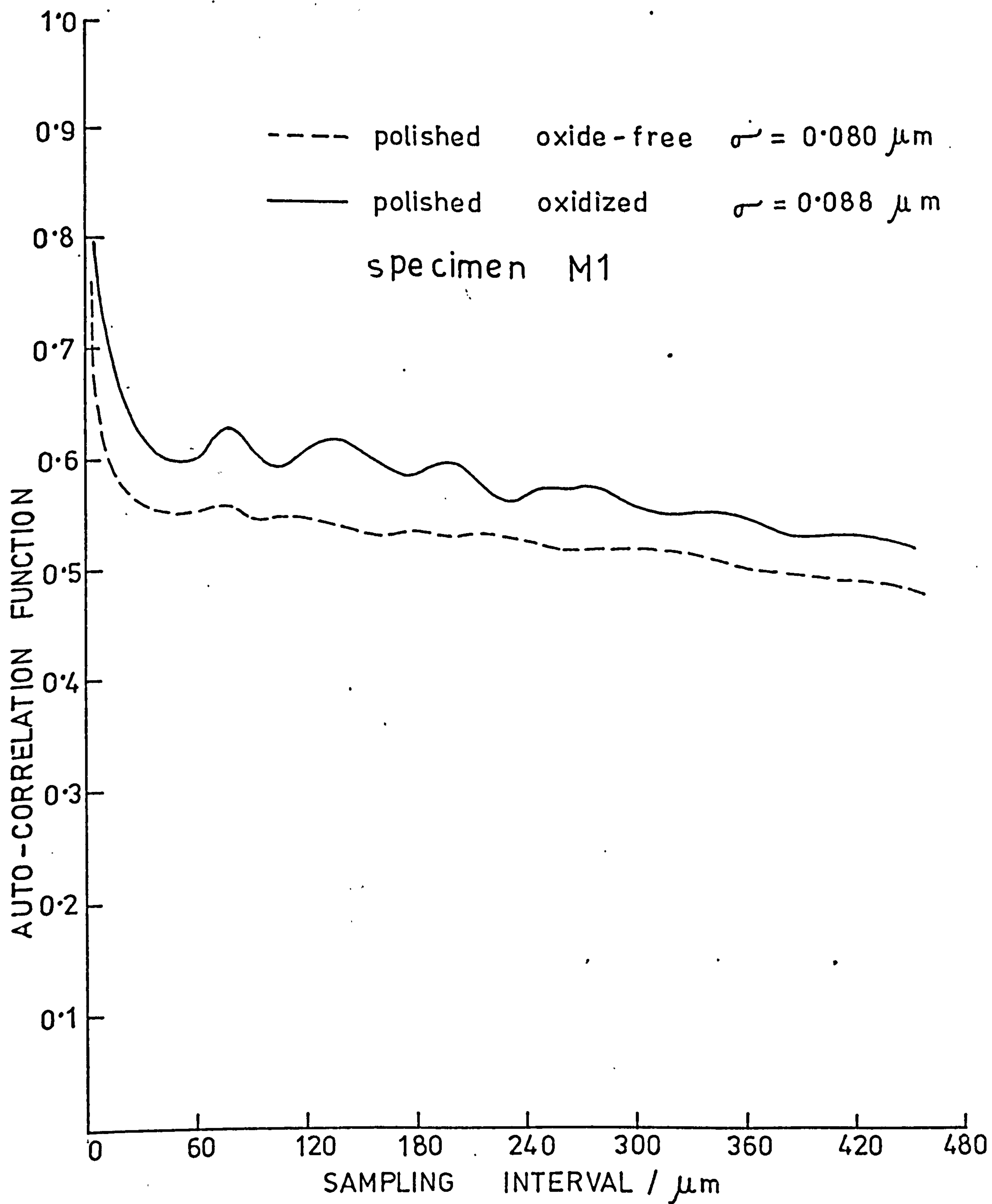


FIG. 4.12

TEXT BOUND INTO THE SPINE

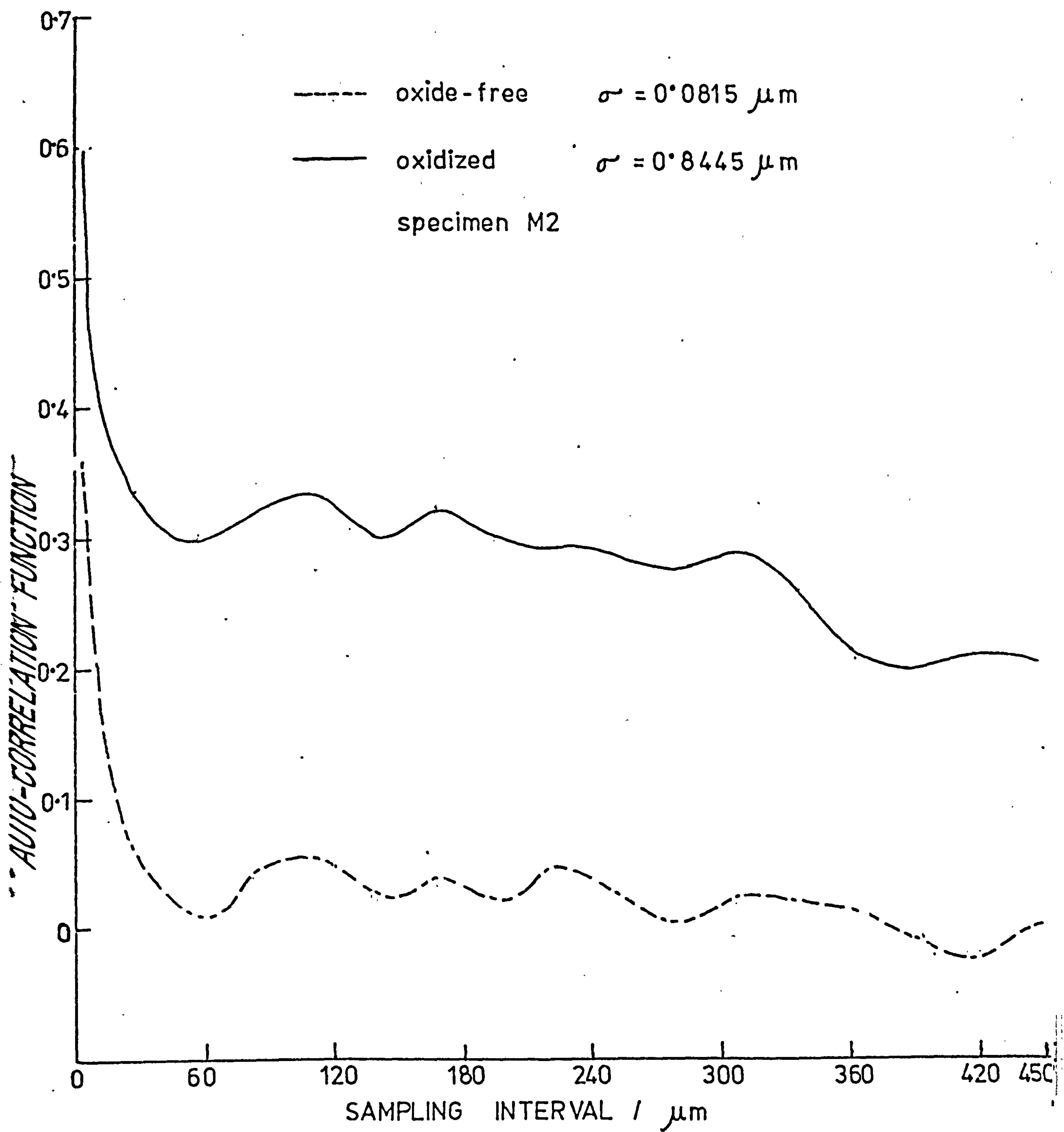


FIG. 4.13

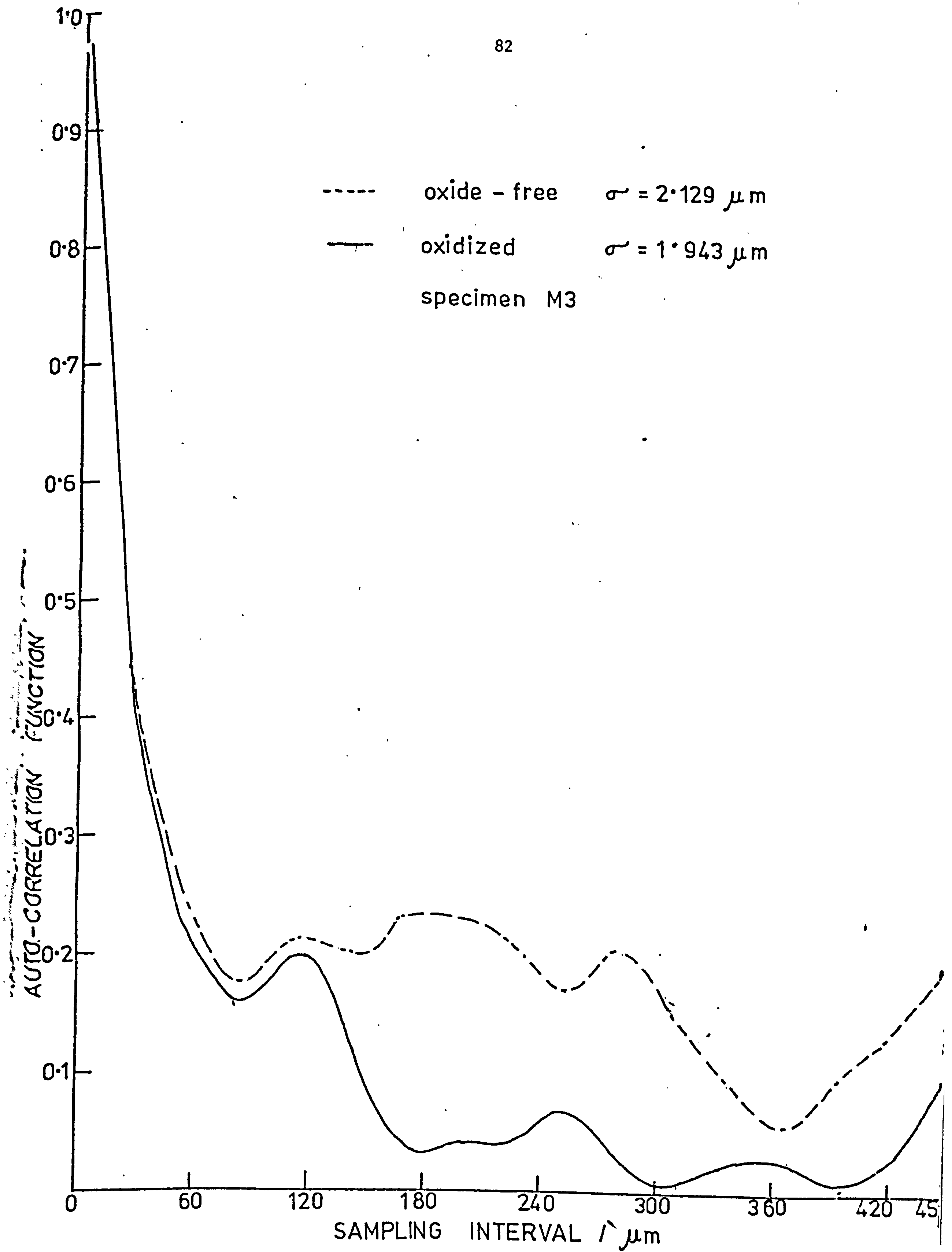


FIG. 4.14

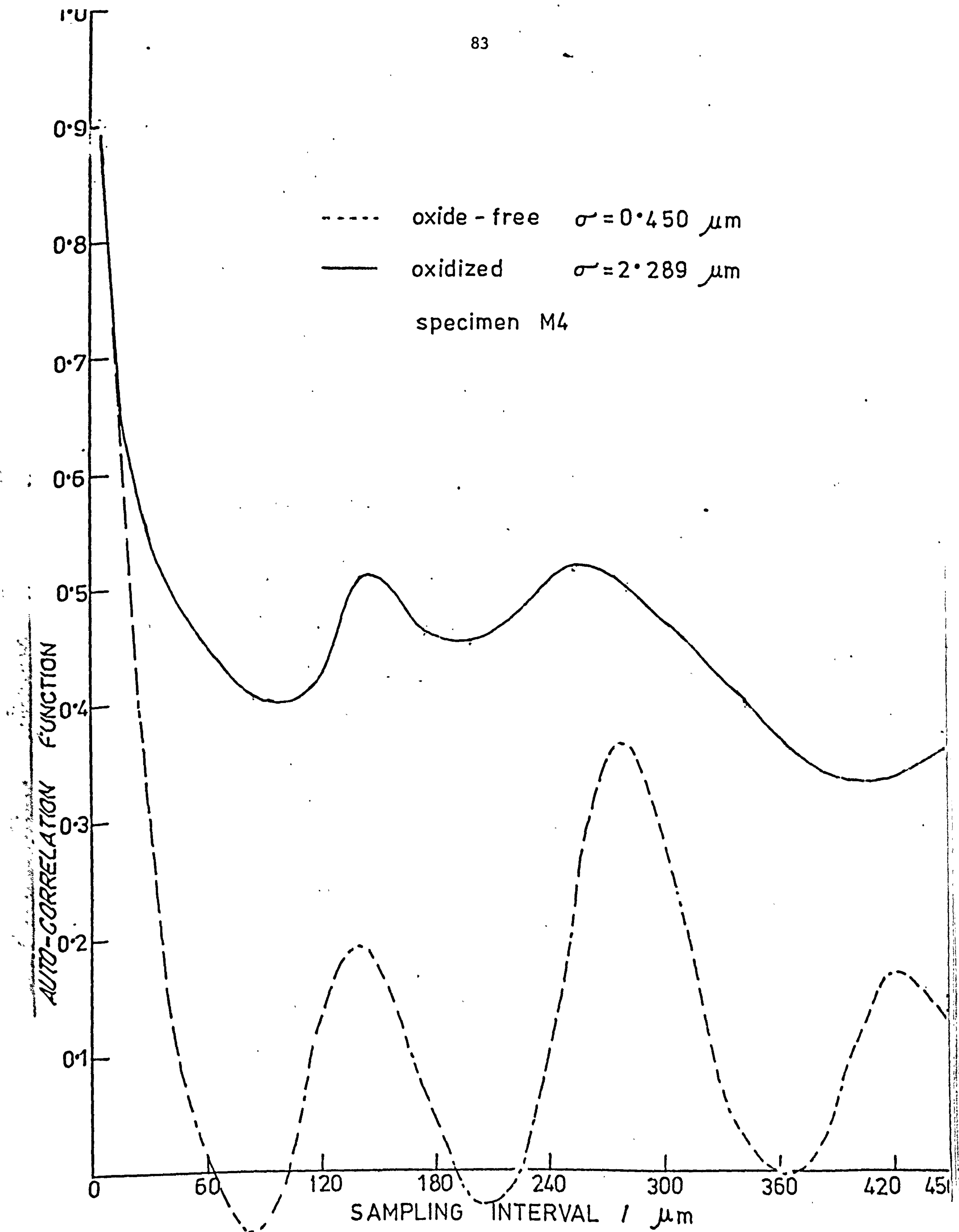


FIG. 4.15

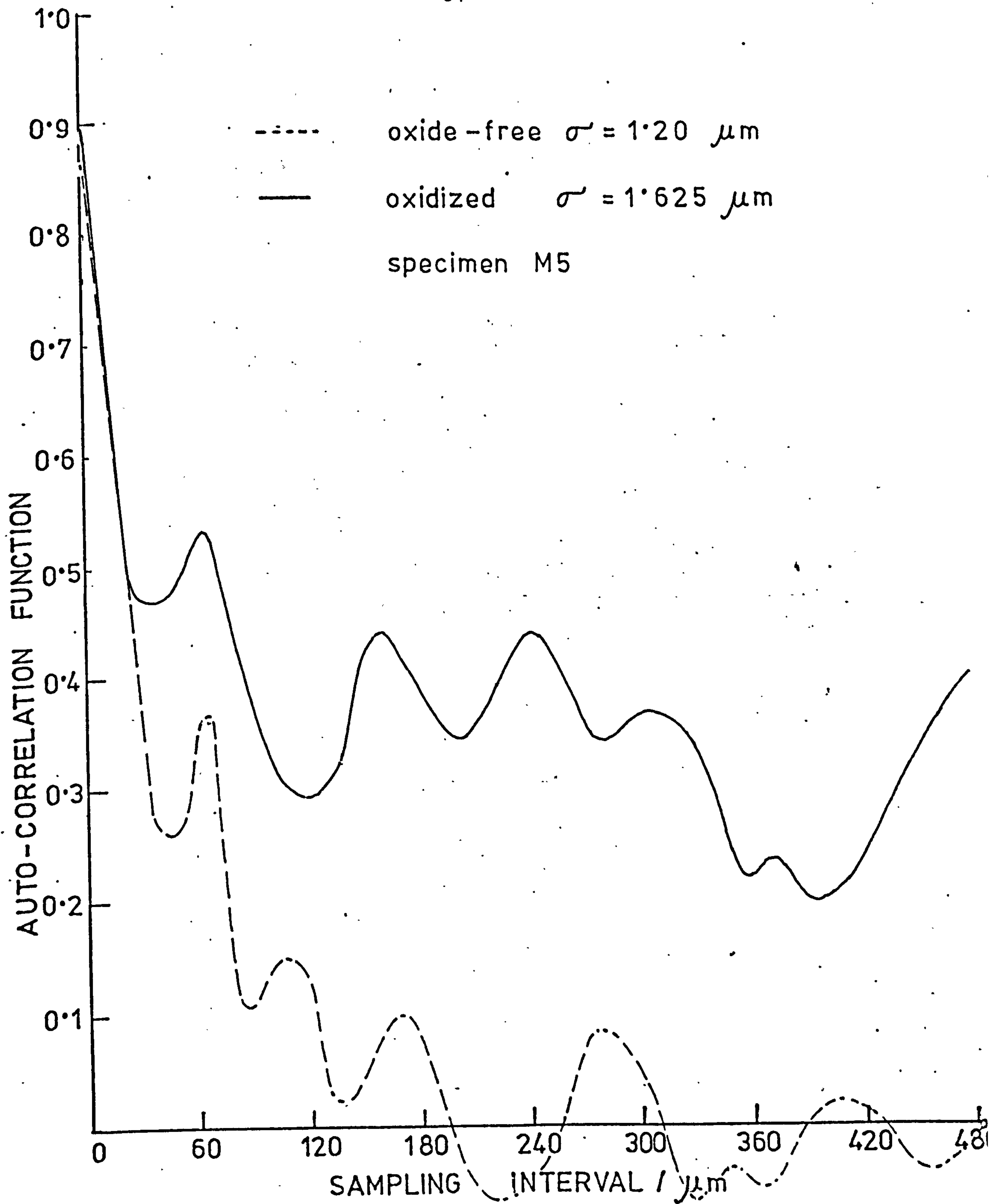


FIG. 4.16

For the present case, the correlation wavelength λ_ω was $50 \times 2.822 \mu\text{m}$ (i.e) 0.0141 mm). The shape of the function depends on the ratio

$\frac{\alpha}{\Omega}$. If $\frac{\alpha}{\Omega} \rightarrow 0$, the function $F(\lambda)$ approaches the cosine, i.e. $F(\lambda) = \cos \Omega \lambda_\omega$.

Alternatively, if the ratio increases, the correlation function tends to the shape described by equation (4.9). The effect of oxide build-up (at 70°C and 80% humidity for 72 hours) had a smoothing effect of the auto-correlation function (i.e. having a higher correlation than that for oxide-free ground surface).

Peklenik (43) suggested a range of auto-correlation functions of engineering surfaces, i.e. linear to sinusoidal to exponential functions. The real surfaces cannot always be described by equations (2.6 and 4.9) but by a combination of the elementary correlation functions expressed by

$$F(\lambda) = \sum_{k=0}^m A_k \exp(-\alpha_k \lambda) + \sum_{m=0}^p A_m \exp(-\alpha_m \lambda) \cos \Omega_m \lambda \\ + \sum_{r=0}^w A_r \exp(-\alpha_r \lambda) \sin \Omega_r \lambda \quad \dots \quad (4.10)$$

where A_k , A_m , A_r and C are constants;

α_k , α_m and α_r are exponents

and Ω_k , Ω_m and Ω_r are carrier frequencies

The auto-correlation function of the fine-turned surface (Fig. 4.16) can be approximated by equation (4.10). The correlation and the r.m.s. roughness parameter of the oxidized fine-turned surface increased.

4.4.3 Mean Surface Slope Versus Data Sampling Interval

The variation of the mean surface slope with data sampling interval for polished, grit-blasted, ground and fine turned surfaces before and after oxidation are shown in Figs. 4.17-4.21. It can be seen that the presence of oxide had little or no effect on the value of surface slope for the polished, sand-blasted and fine-turned surfaces (Fig. 4.17-4.19 & 4.21). It increased for the oxidized ground surface (Fig. 4.20) especially at low sampling interval.

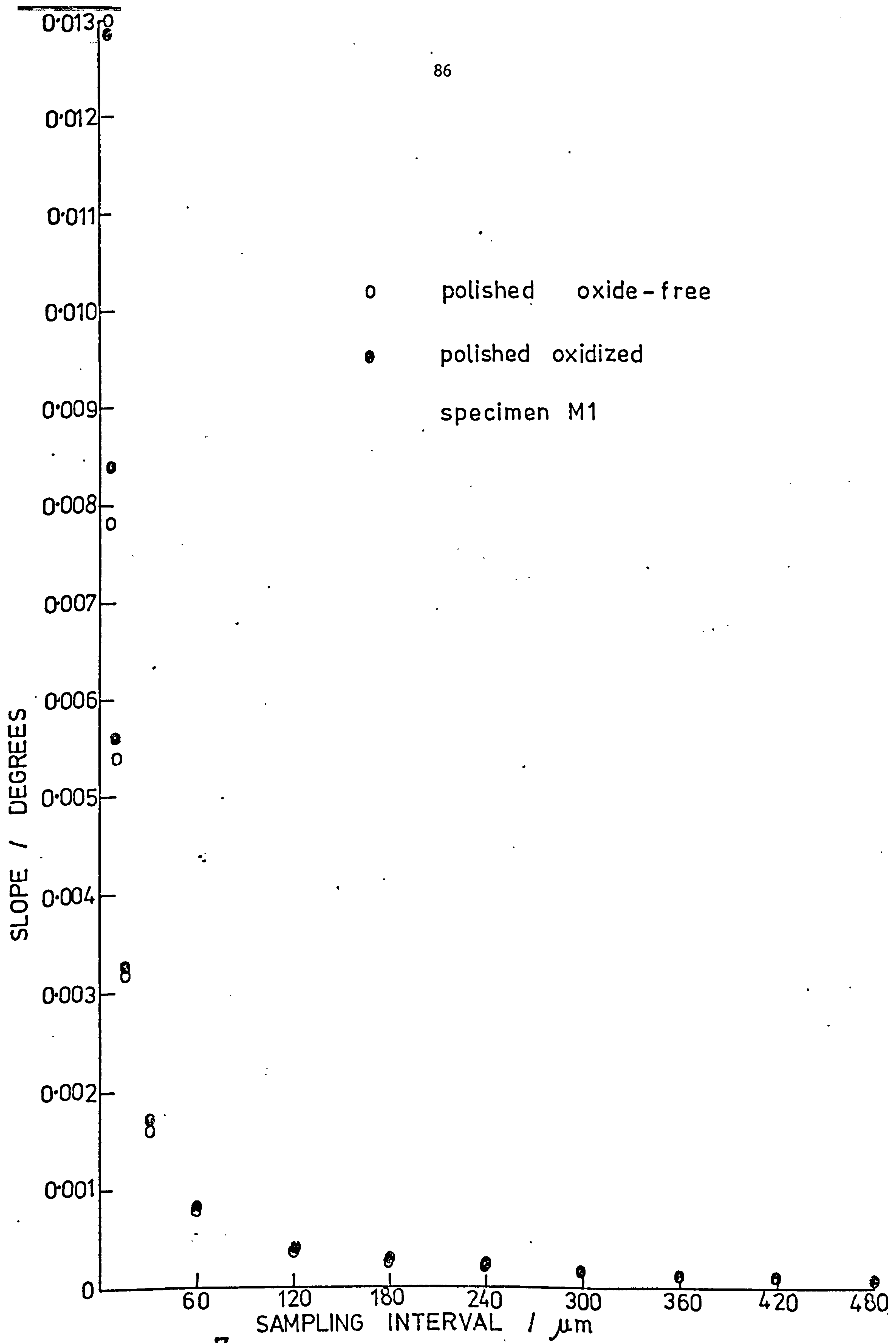


FIG. 4.17

SLOPE / DEGREES

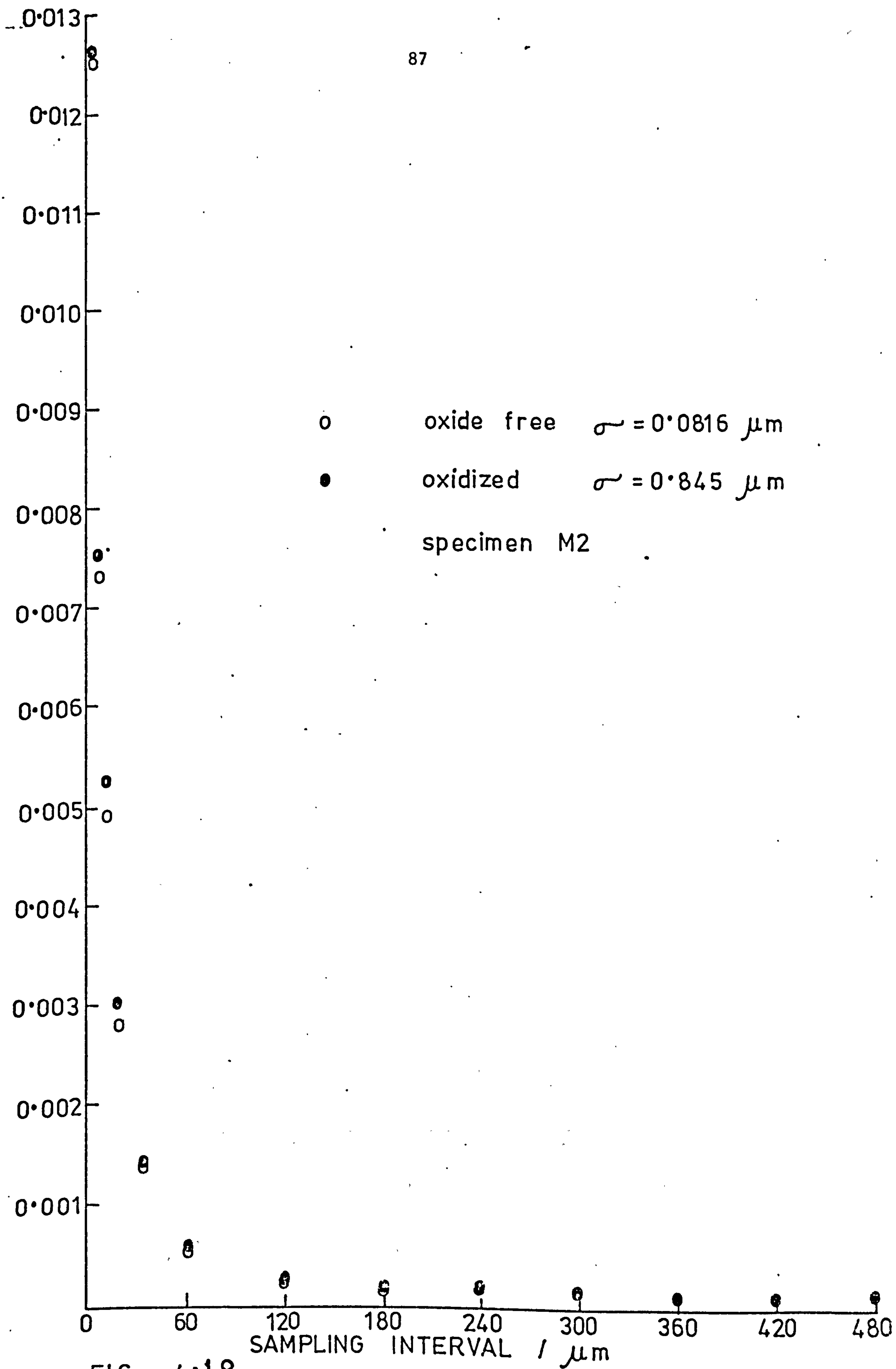


FIG. 4.18

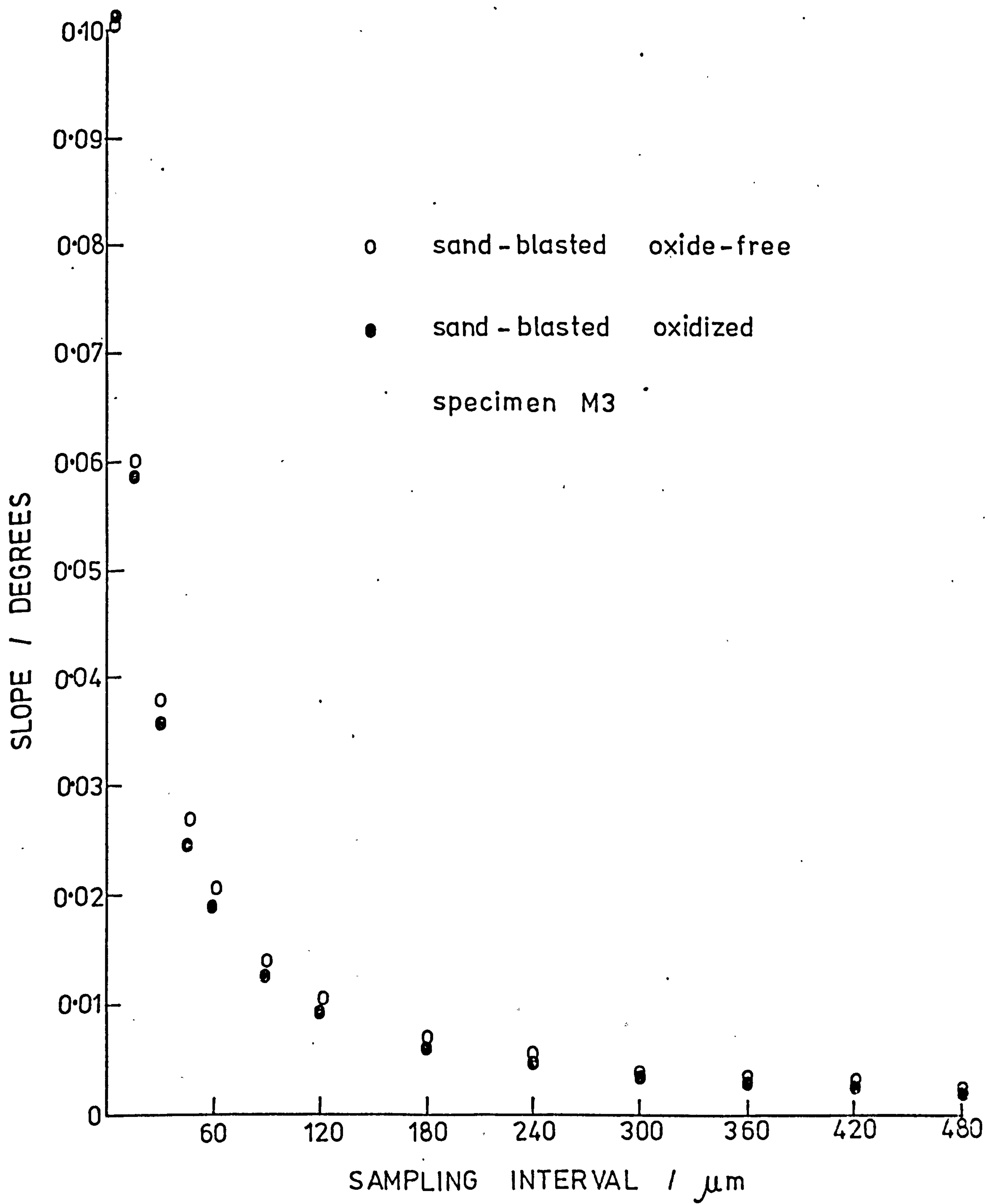


FIG. 4.19

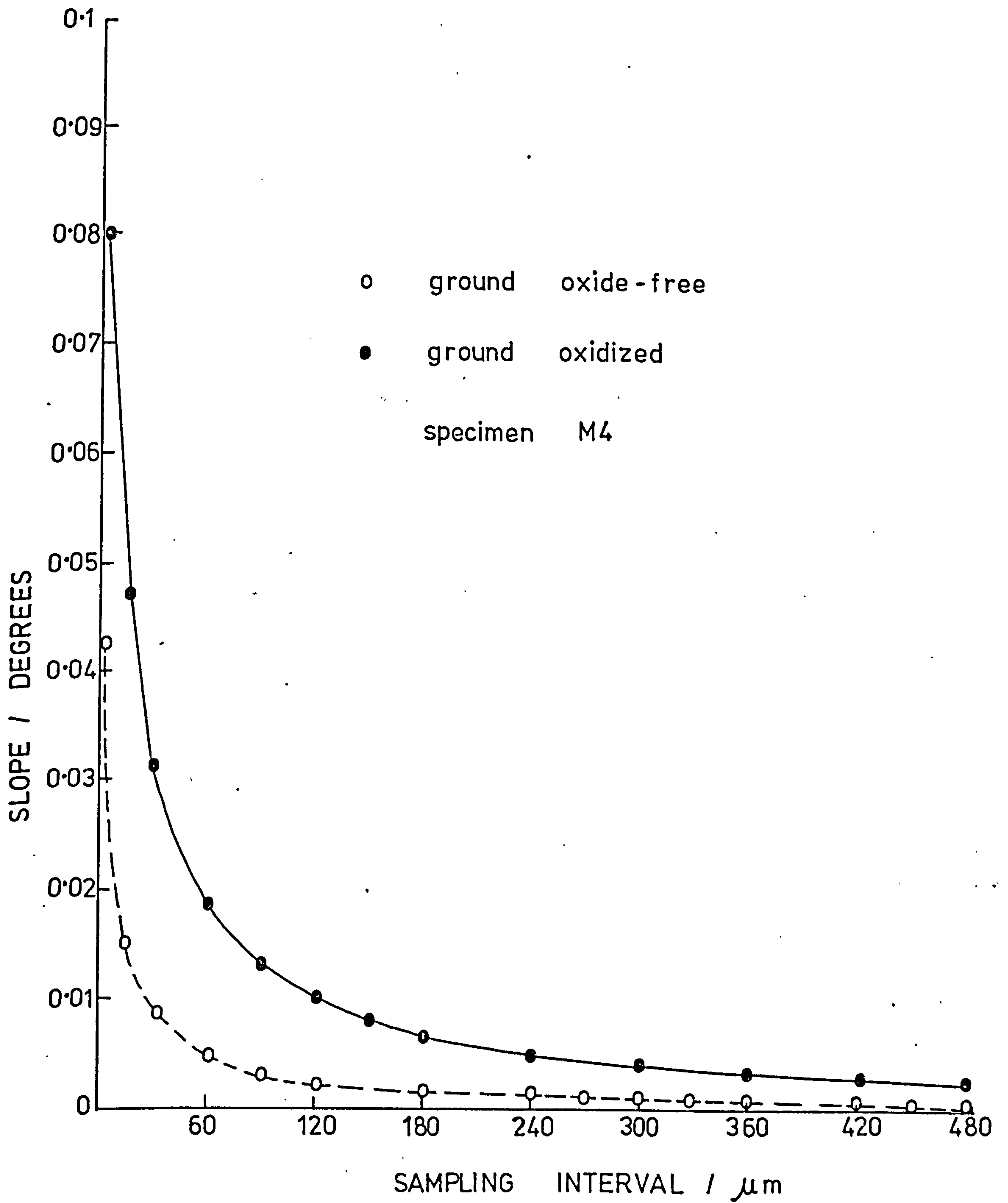


FIG. 4.20

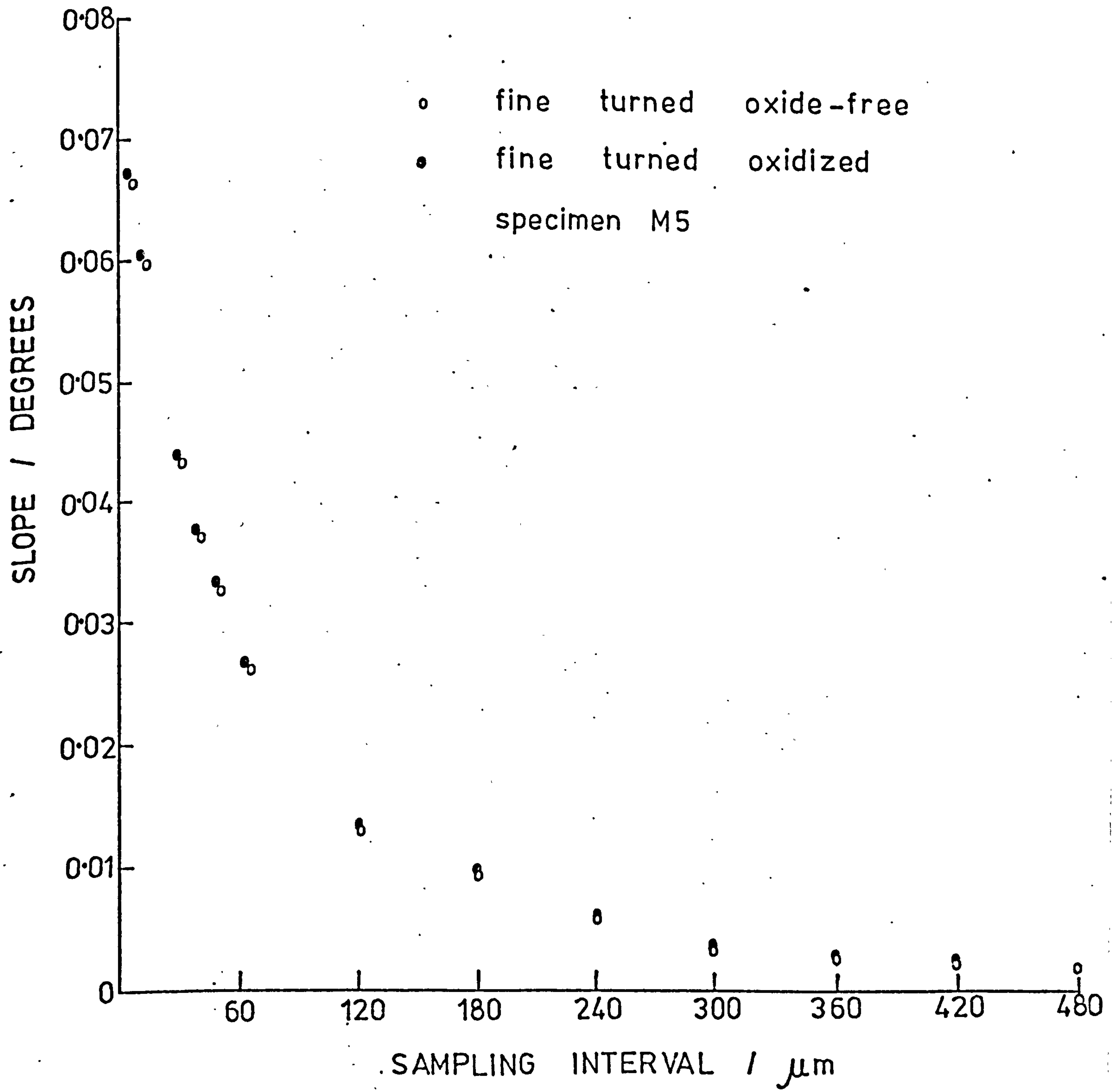


FIG. 4 • 21

CHAPTER FIVE

THE AREA OF ACTUAL CONTACT

5.1 INTRODUCTION

When two bodies are placed together actual contact only occurs over a small proportion of the nominal contact area. The area of actual contact or more precisely the number of micro-contacts usually govern the interfacial thermal and electrical resistances.

A surface may be characterised by its RMS roughness, mean flatness, mean absolute slope and the mean peak radius of curvature (52). If the distribution of the surface heights be expressed statistically as has been shown in (Figs. 5.1-5.5) (numerical results for the distribution of surface heights are given in Appendix II (Tables A - E)), then formulae can be developed to predict the area of actual contact, A_c and hence the variation of the thermal contact resistance with applied loading (50, 116, 117, 118).

It has been found that if a sufficiently large area is considered, the distribution of surface heights is essentially Gaussian for most surface finishes (48, 82, 119).

5.2 METHODS OF MEASURING THE AREA OF CONTACT

Contacts amongst the transparent materials may be observed directly using prisms or parallel faced optical flats (120). Dyson and Hirst (92) impressed nominally flat metal surfaces against metallized glass surfaces and examined the impressions produced under phase contrast microscopy. This method indicates all elastic and plastic deformations.

Thomas (53) developed the technique to examine the contact between opaque materials. A roughened surface was loaded against a softer optically flat metal surface and the resulting plastic impressions examined under the microscope using a Normaski interference phase contrast microscopy (94).

A method known as microcartography involves the surface being visualized by the construction of a contour map. A set of parallel profilometric traces are taken at equal spacings. The array of surface profiles taken side by side gives a magnified representation of the surface. The procedure is tedious (121).

In the present investigation the micro-contacts were counted and sized using a Quantimet 720 Image Analysing Computer (Plate 3.3). The technique involved the formation of an Image of the test surface using reflection microscopy and is described below.

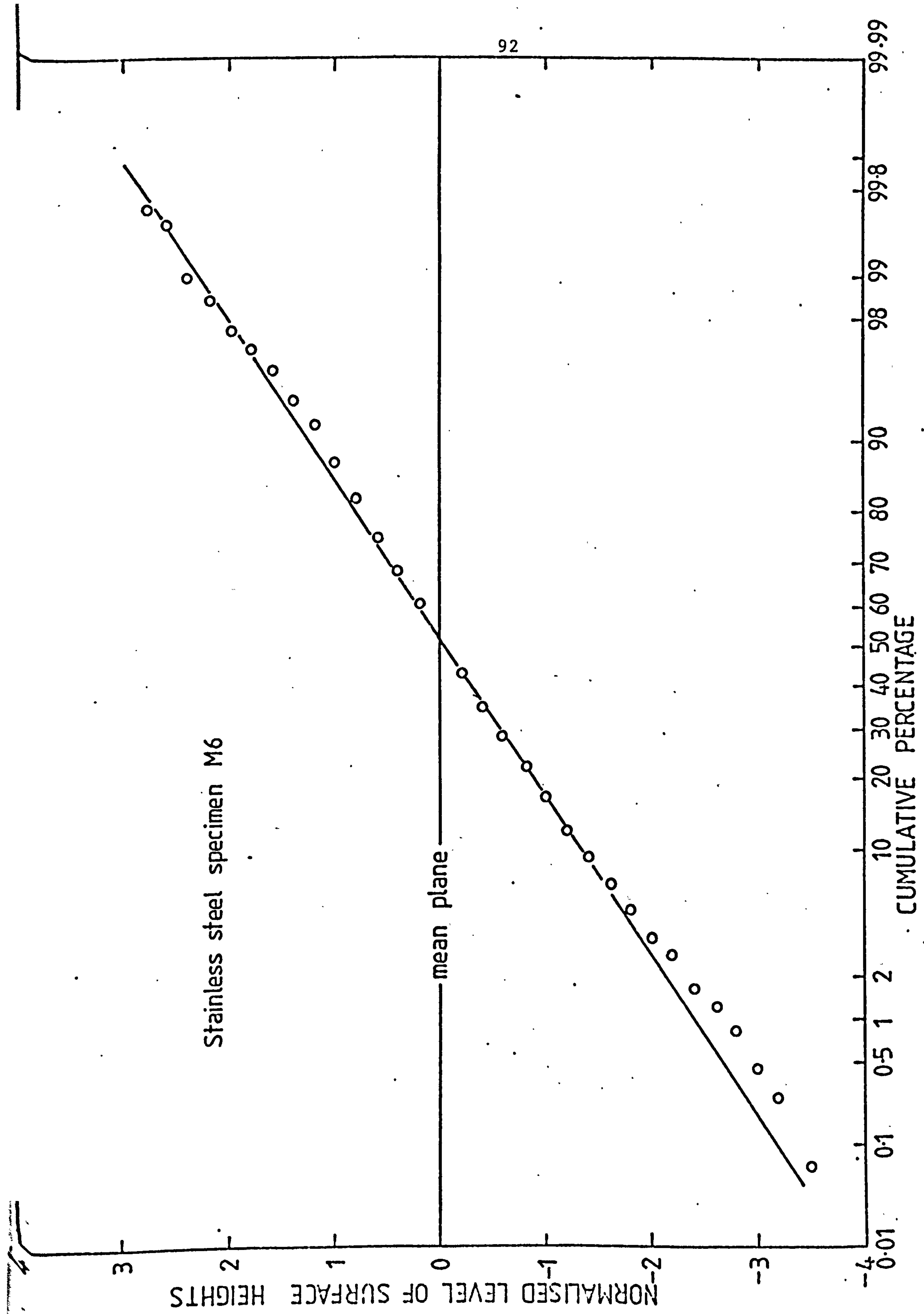


FIG. 5.1

NORMALISED LEVEL OF SURFACE HEIGHTS

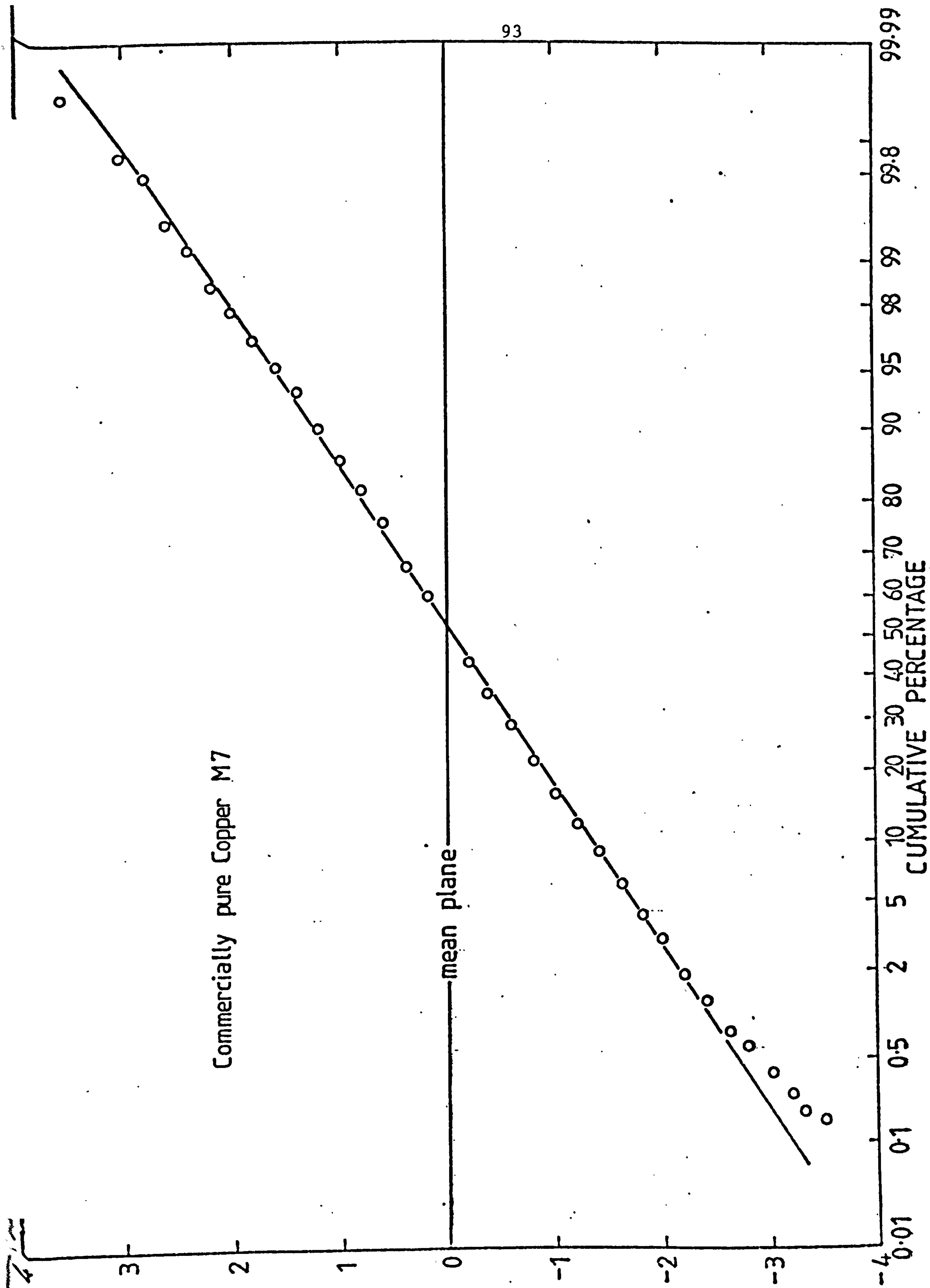
Commercially pure Copper M7

mean plane

93

CUMULATIVE PERCENTAGE

FIG. 5,2



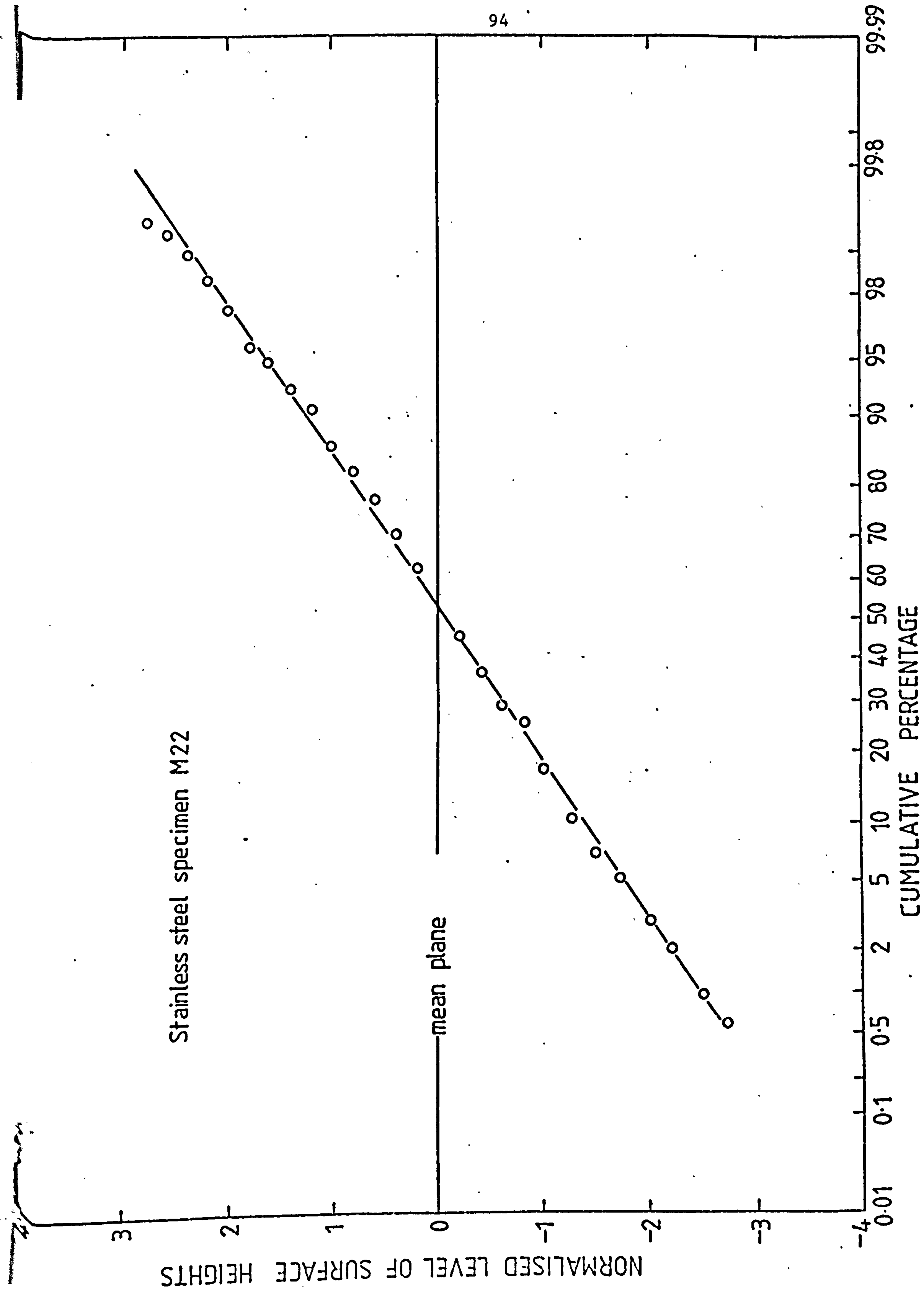


FIG. 5.3

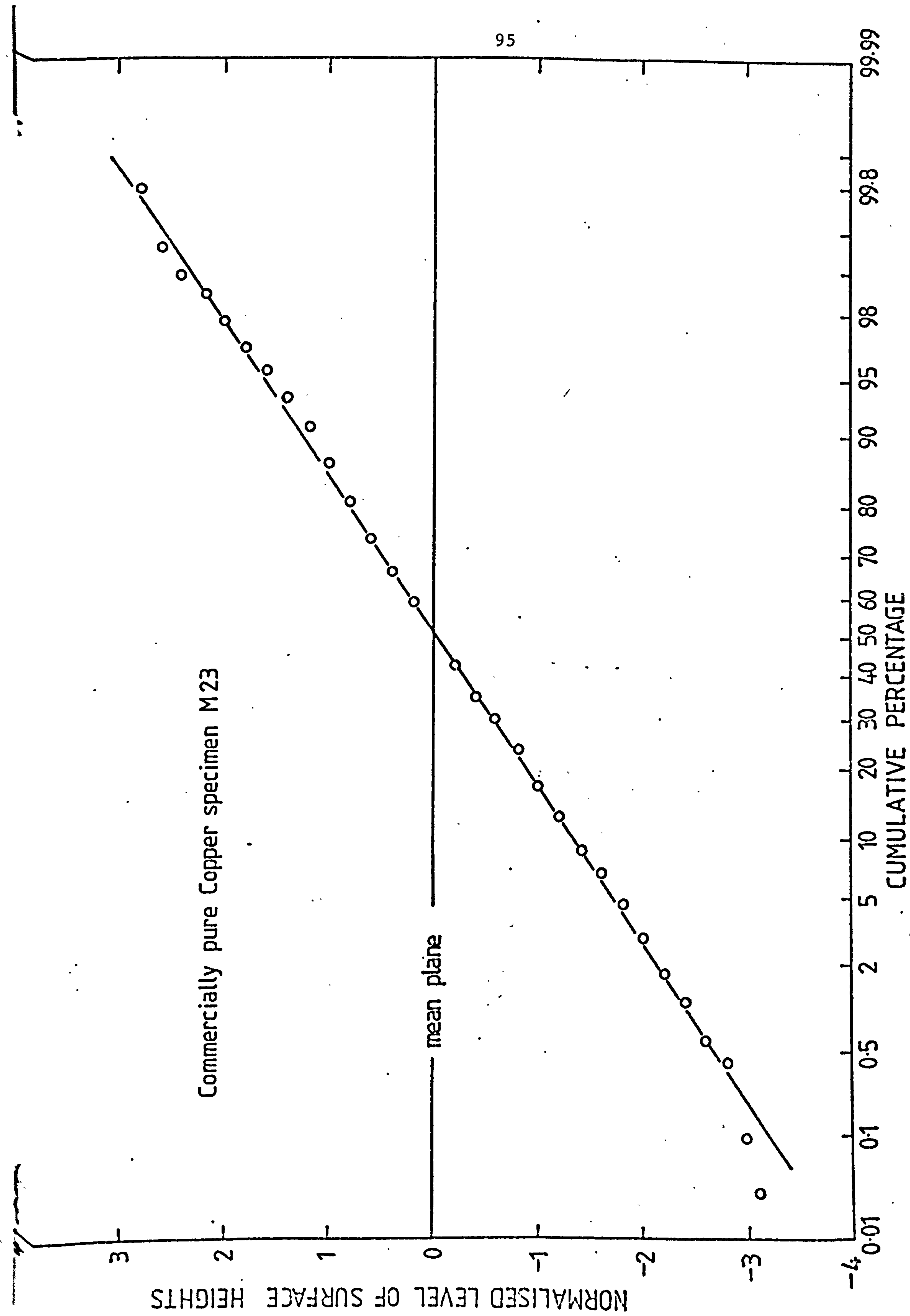


FIG. 5.4

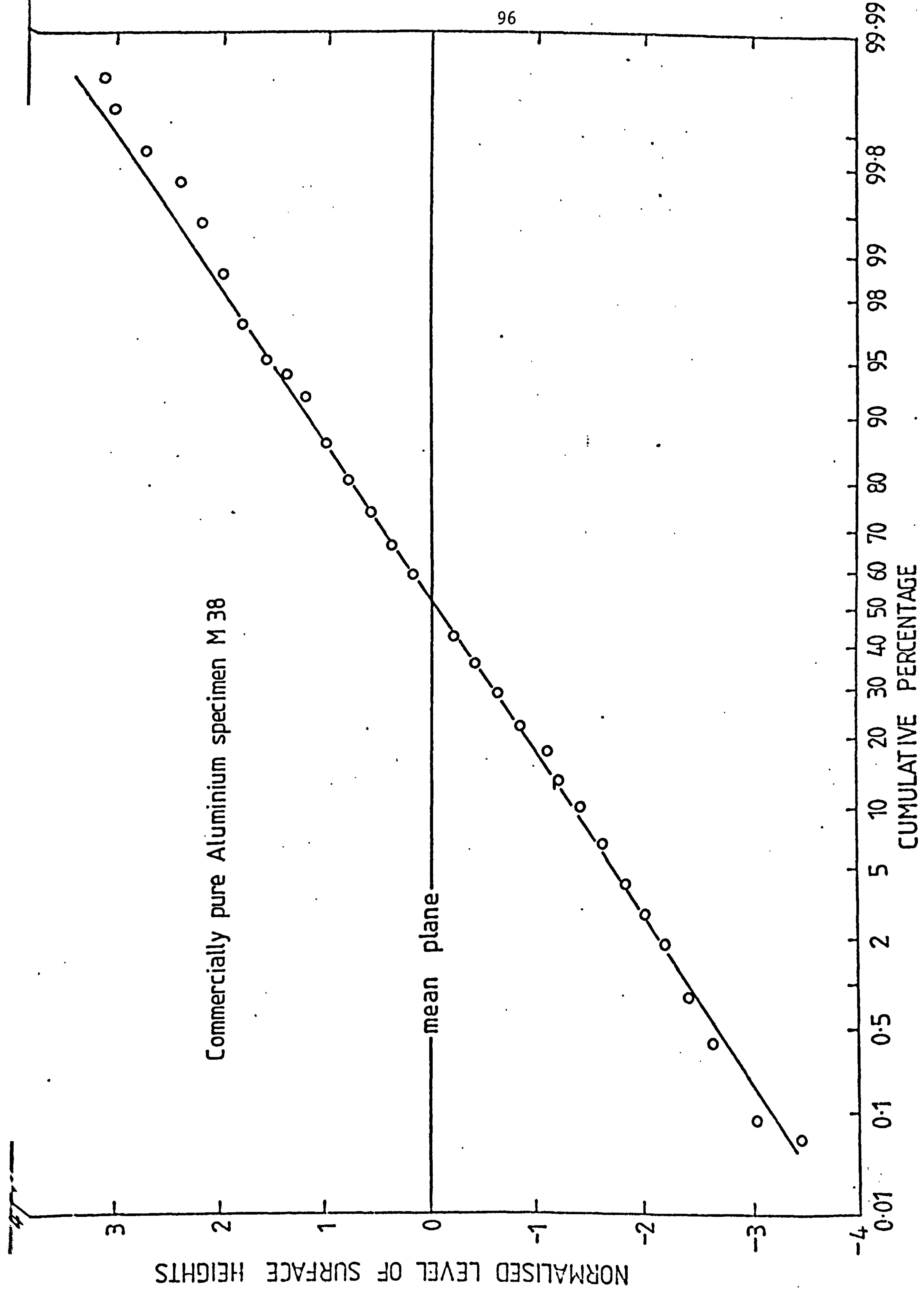


FIG. 5,5

The Quantimet 720 uses a precision vidicon scanner specially developed for high resolution image analysis. The scanner is digitally controlled with a scan rate of 10.6 frames per second and a scan standard of 720 lines. The digital control divides the image into a matrix of precisely and reproducibly positioned picture points. This allows all processing after digitisation of the grey level of each picture point to be digital. Each scan line is divided into 890 separately resolvable picture points, thereby dividing the image into 500,000 discrete picture points. Threshold setting, in terms of setting the correct grey level at which features are detected, is the most likely source of error in the analysis of the image. Shading arises from non-uniform illumination and from variations in electrical response across the face of a scanner tube. To reduce this effect to an acceptable level the manufacturers have incorporated an automatic shading, across the field of view, which automatically corrects for both optical and electronic shading.

The live frame size is 625 picture point vertical dimension and 800 picture point horizontal dimension, giving a frame size of 500,000 picture point area. The detected image was calibrated by replacing the specimen with a graticule. For the magnification used in the test series, the equivalent length of one side of a picture point was $3.85 \mu\text{m}$ giving a picture point area of $14.82 \mu\text{m}^2$. The equivalent frame size was 7.4 mm^2 . The measurements showing the real area of contact in picture points are shown in Plates 5.1-5.4 for the detection mode of the Quantimet and Plates 5.6-5.9 when operating in the no-detection mode.

5.3 LOADING PROCEDURE

A Denison Compression machine (Plate 5.5) was used to press the roughened stainless steel specimens onto the softer optical flats. Much care was exercised to ensure that the mean planes of the contacting specimen surfaces were parallel. The machine had a loading capacity of 50 tons. Each stainless steel specimen was loaded against a fresh optical flat (specimens M6 - M45). Greenwood's (49) plasticity index, λ , described in Chapter 2 by equations (2.11 - 2.14) was calculated. This was greater than unity, it implied that the contact under all loads was plastic.

5.4 ANALYTICAL PREDICTIONS

When two surfaces are pressed together, intimate contact occurs only at a few isolated regions called contact bridges or 'a' spots (12). The number N and the size a_i of these micro-contacts produced are functions of the surface parameters and the contact pressure. The mean number of the contact spots per unit area, N_A , and their mean radius, $\bar{a}$ may be predicted analytically or measured experimentally. The random surface is assumed to intersect with a rigid plane (45) which progressively approaches the surface. The real area per unit nominal area of the contact, A_{rm}/A_n under the applied pressure, p as given by (11, 104) is,

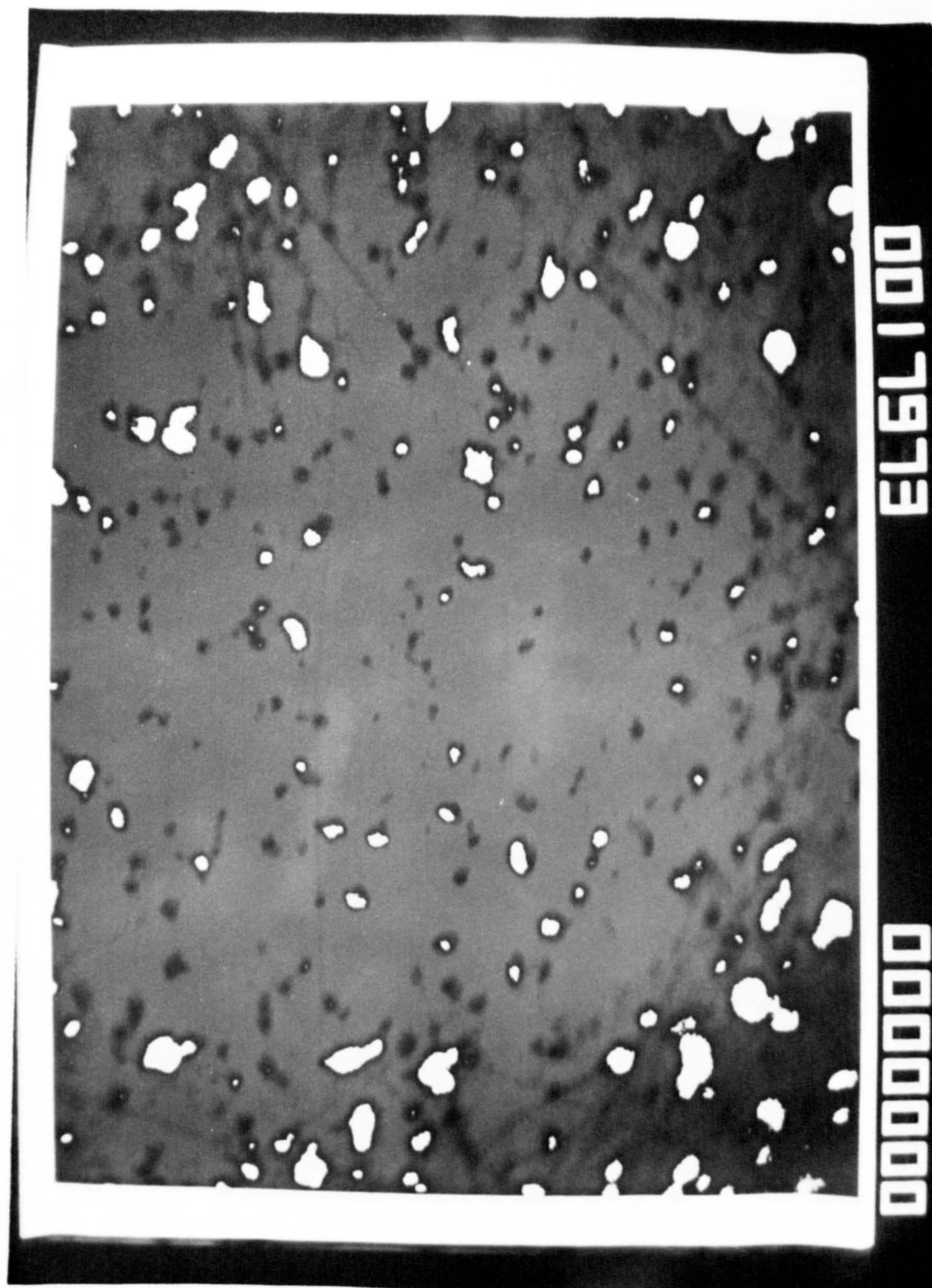


Plate 5.1 Contact features produced on the smooth copper surface by pressing sand-blasted stainless steel upon it under an applied load, 17.79kN. As observed on the Quantimet in the detection mode.

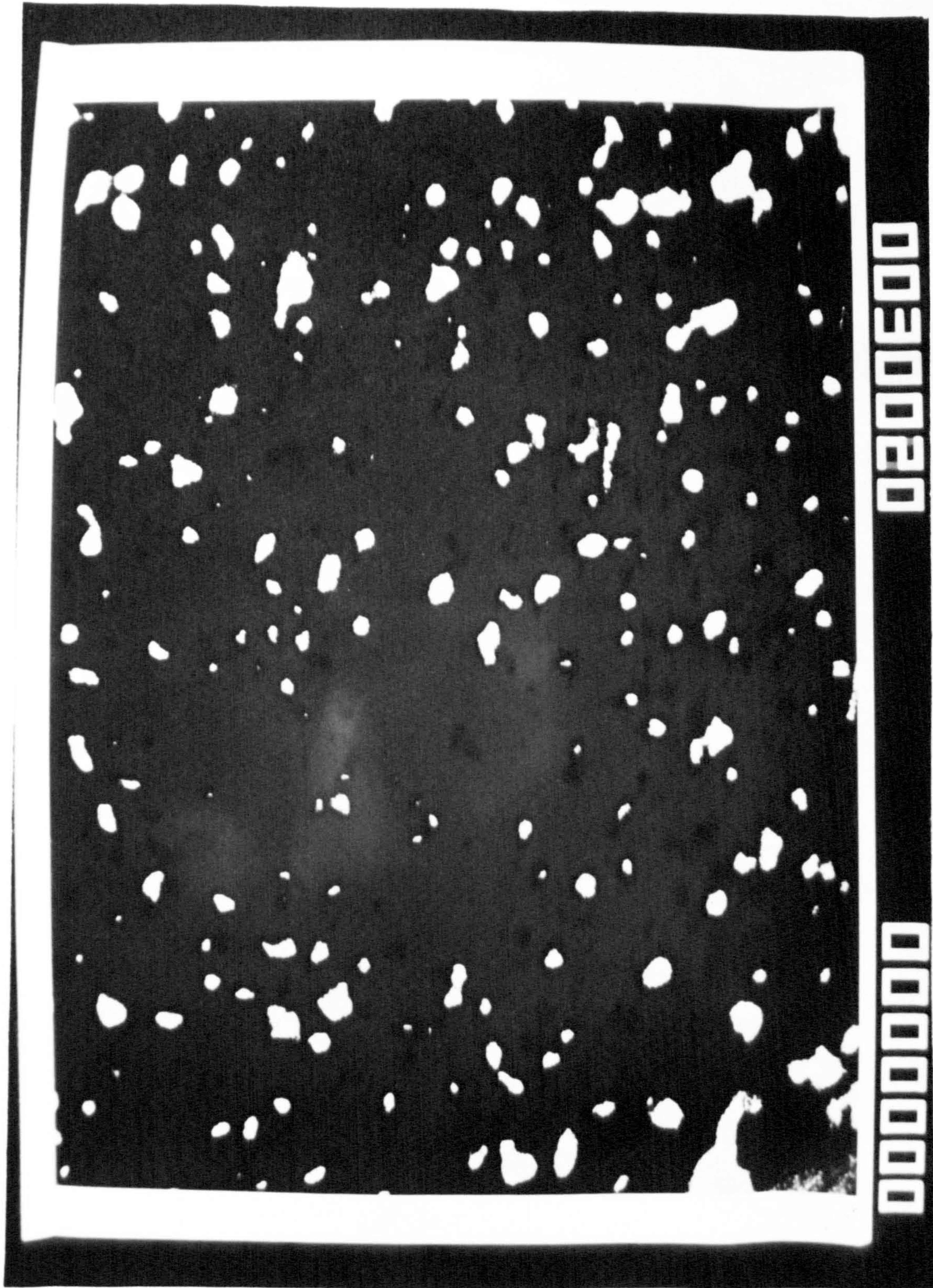


Plate 5.2 Contact features produced on the smooth copper surface by pressing sand-blasted stainless steel upon it under an applied load of 26.68 kN. As observed on the Quantimet in the detection mode.

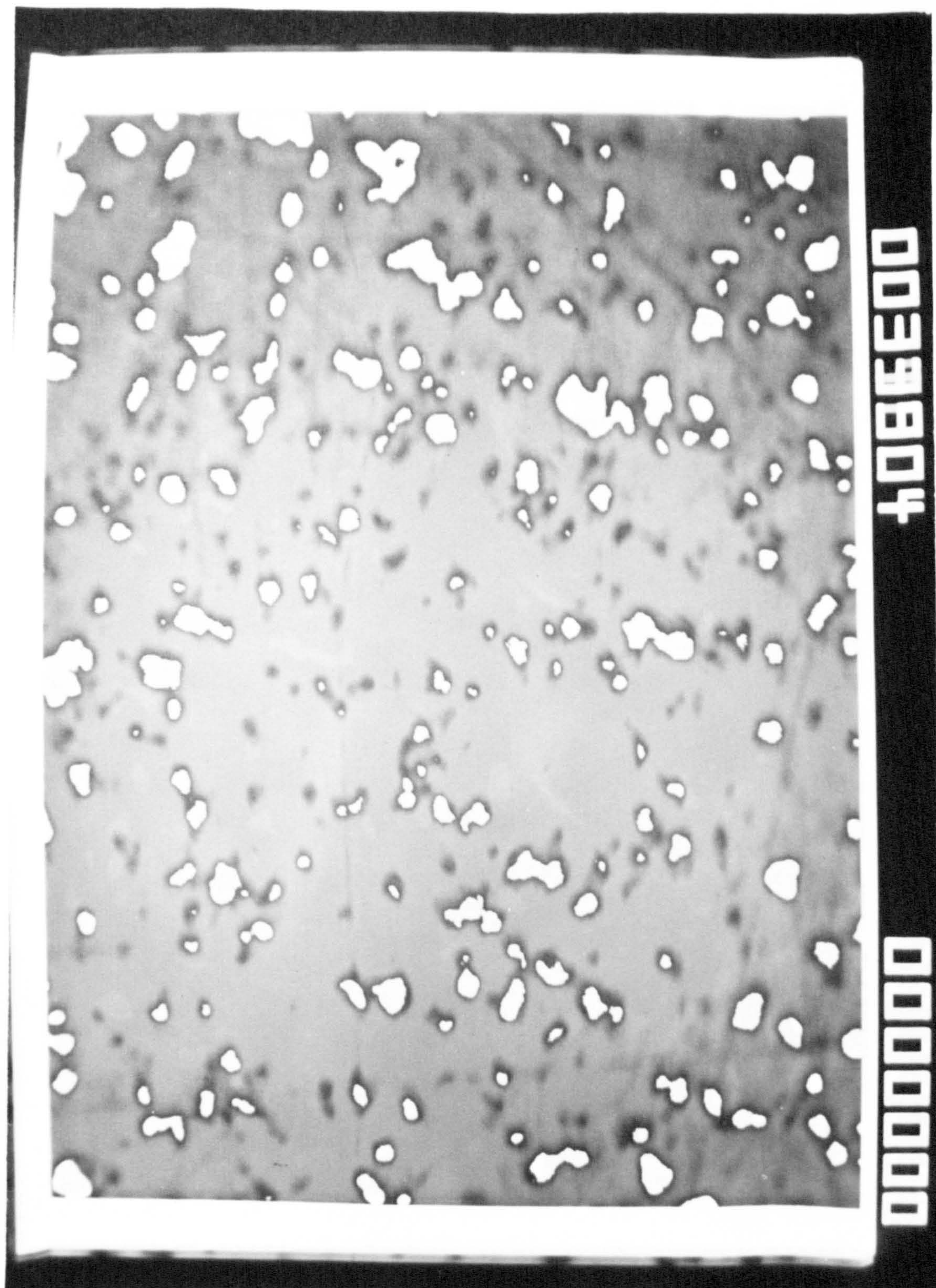


Plate 5.3 Contact features produced on the smooth copper surface by pressing sand-blasted stainless steel upon it under an applied load of 35.58 kN. As observed on the Quantimet in the detection mode.

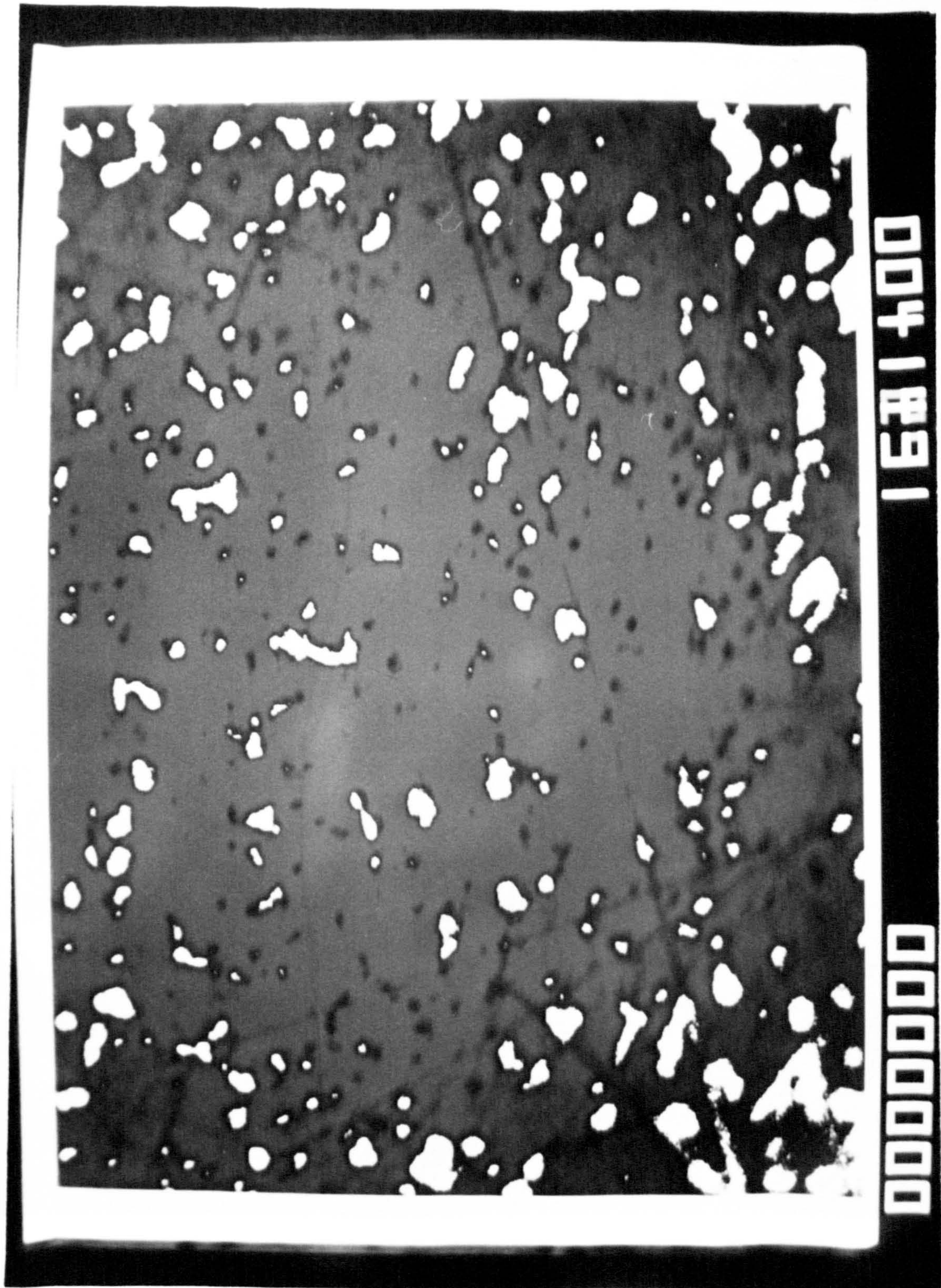


Plate 5.4 Contact features produced on the smooth copper surface by pressing sand-blasted stainless steel upon it under an applied load of 44.48kN. As observed on the Quantimet in the detection mode.



Plate 5.5 The Denison Compression machine used for pressing the specimen assemblies. Pressing capacity, 50 Tons.

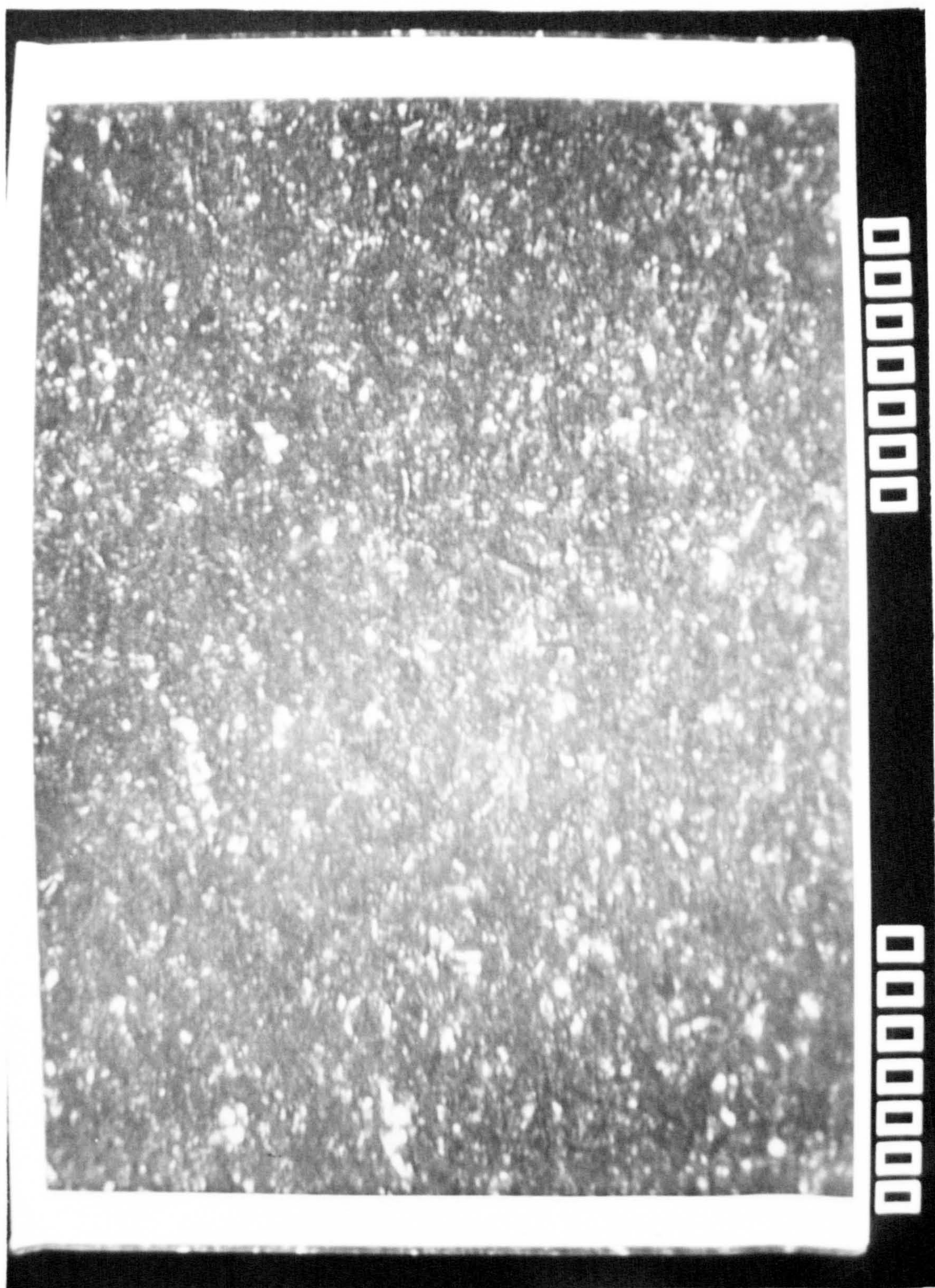


Plate 5.6 View of the stainless steel sand-blasted surface (upper specimen) after it pressed a smooth copper surface (lower specimen) under an applied load, 44.48 kN. As observed on the Quantimet in the no detection mode.

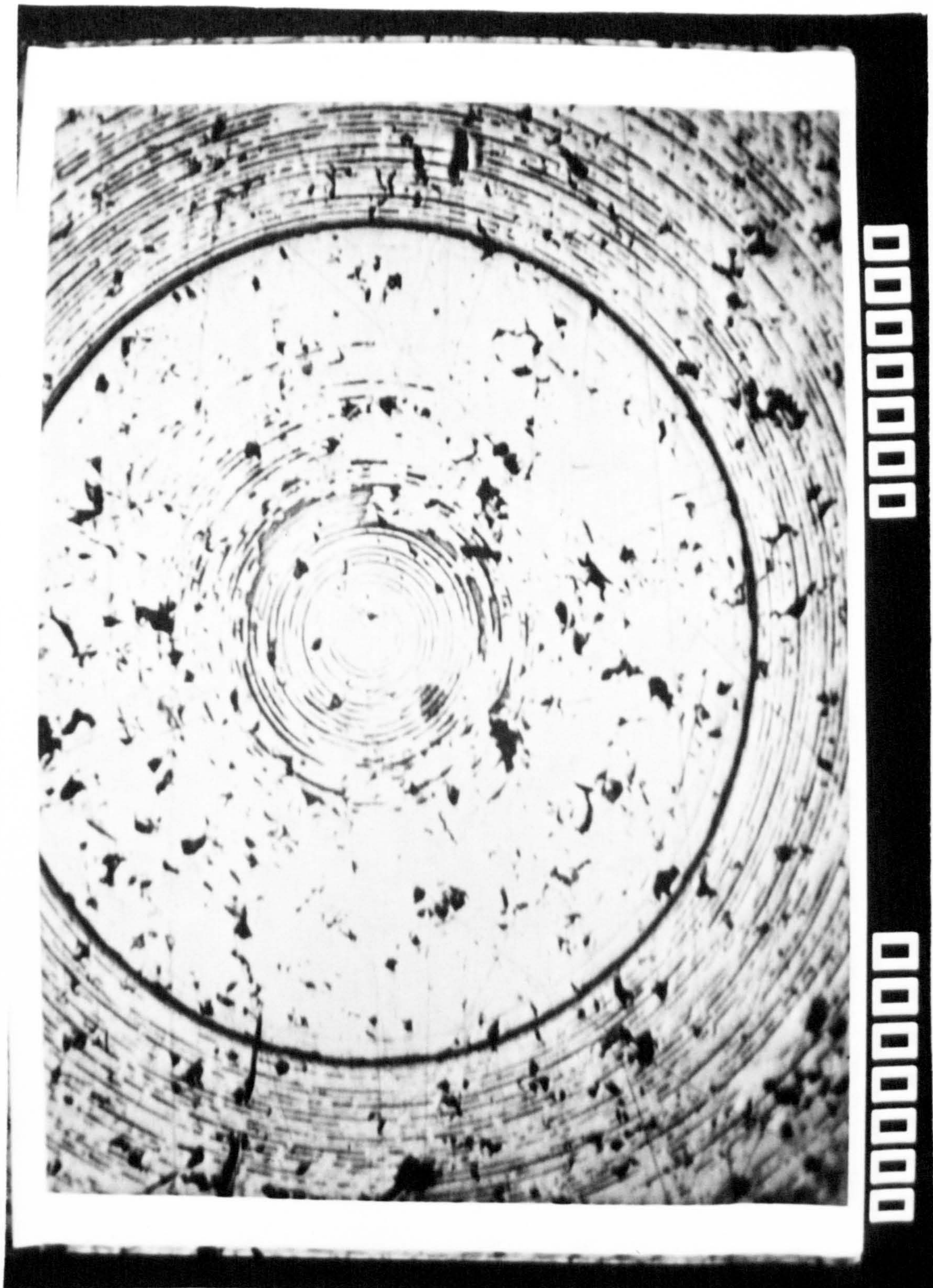


Plate 5.7 Contact features produced on an oxidized turned copper surface by pressing sand-blasted stainless steel upon it under an applied load of 40 kN. As observed on the Quantimet in the no-detection mode.

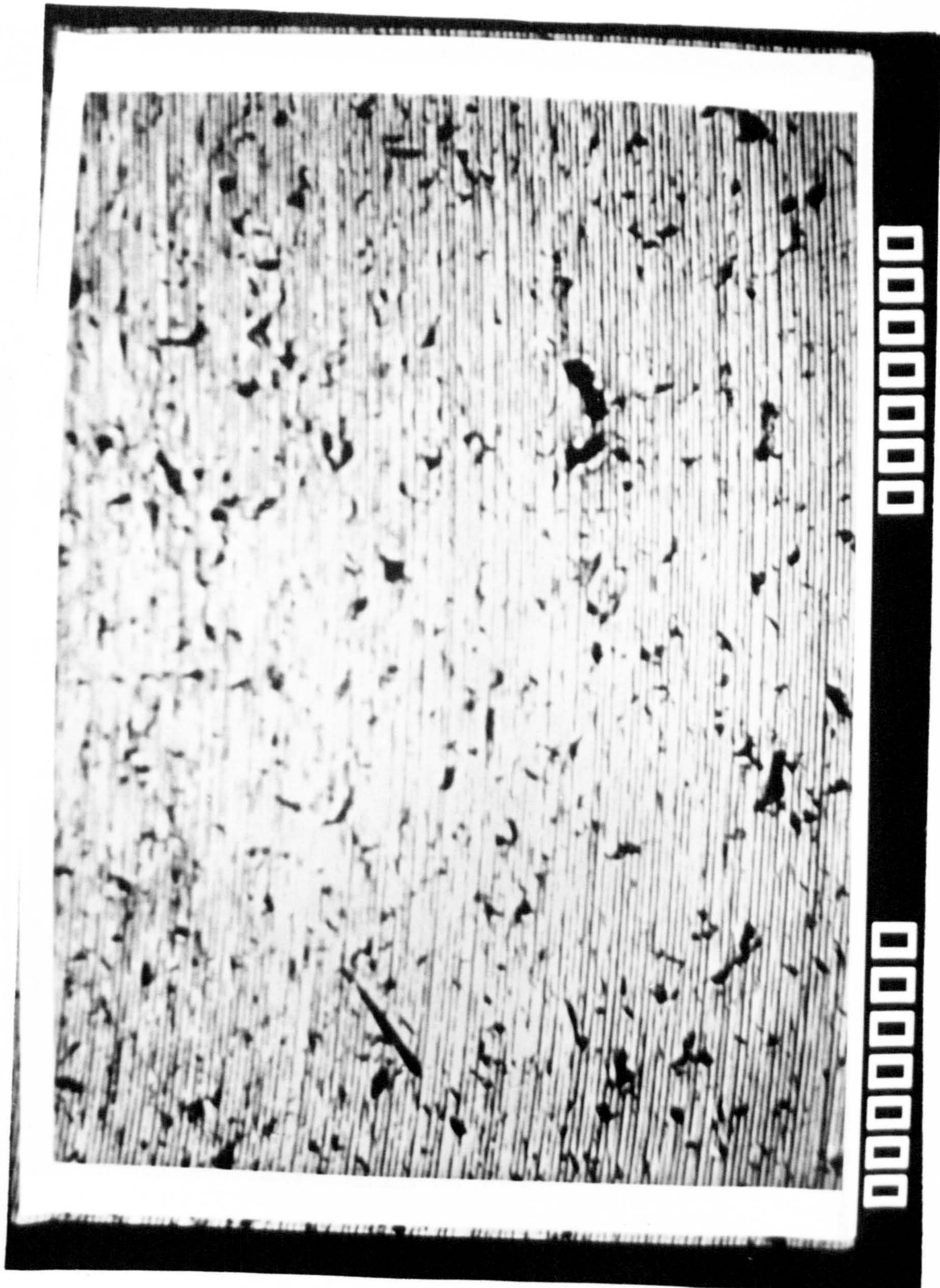


Plate 5.8 Contact features produced on the oxidized turned copper surface by pressing sand-blasted stainless steel upon it under an applied load of 42.45 kN. As observed on the Quantimet in the no-detection mode.

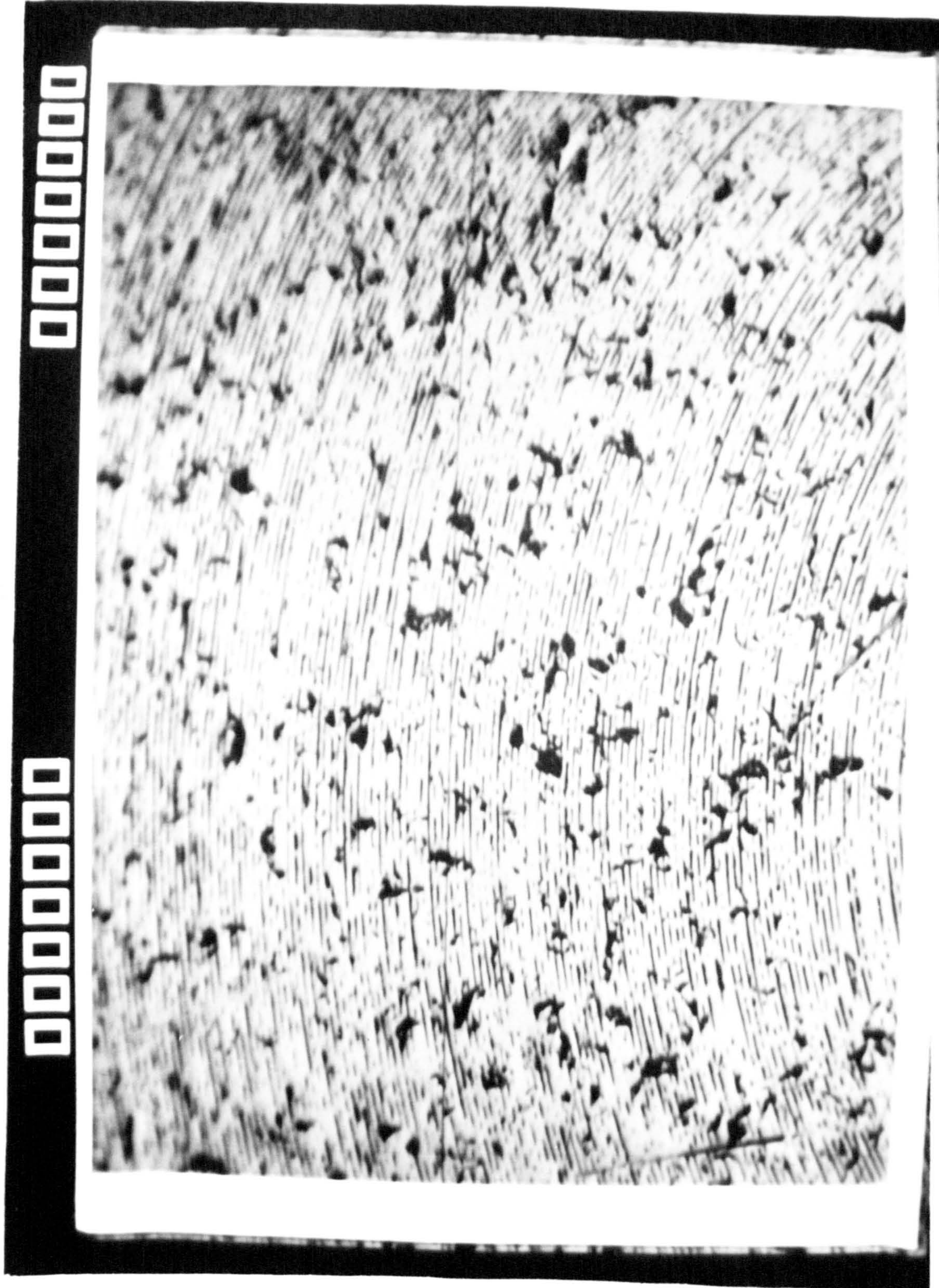


Plate 5.9 Contact features produced on the oxidized turned copper surface by pressing sand-blasted stainless steel upon it under an applied load of 44.48 kN. As observed on the Quantimet in the no-detection mode.

$$\frac{A_{rm}}{A_n} = \frac{P}{P_f} \quad \dots \quad (5.1)$$

where P_f is the flow pressure which is commonly assumed to correspond to the hardness of the softer contacting material, i.e.

$$\frac{A_{rm}}{A_n} = \frac{P}{M} \quad \dots \quad (5.2)$$

5.4.1 Contact Parameters for Oxide-Free Joint

The dimensionless expressions for the number and the mean size of the oxide-free contacts by Thomas and Probert (52) from the theory of Tsukizoe and Hisakado (45, 46) are

$$\frac{P}{M} = \frac{1}{2} - \phi(t_m) \quad \dots \quad (5.3)$$

$$\bar{a}_m \psi = \frac{2}{\pi t_m} \quad \dots \quad (5.4)$$

$$\bar{N}_m = \frac{\pi t_m \phi(t_m) \psi^2}{8} \quad \dots \quad (5.5)$$

If therefore, the micro-contact configuration is considered to be equivalent to N bridges, then the area of actual contact supported by the micro-contact bridges of size a_i is given by

$$A_r = \sum_{i=1}^{\infty} N \pi (a_i)^2 \quad \dots \quad (5.6)$$

or

$$A_r = N \pi (\bar{a}_m)^2 \quad \dots \quad (5.7)$$

where $\bar{a}_m$ is the mean radius of the micro-contact bridges.

5.4.2 Contact Parameters for Oxidized Joints

From Fig. 5.6 it can be seen that the mean contact spot radius for the oxidized contact is

$$\bar{a}_o = \bar{a}_m + \frac{x}{\tan \theta} \quad \dots \quad (5.8)$$

where $\bar{a}_o$ is the average radius of the micro-contact due to the presence of oxide and θ is the base angle of the conical asperities.

Similarly the total number of micro-contacts per unit nominal area is

$$\bar{N}_T = \frac{\pi t_o \phi(t_o) \psi^2}{8} \quad \dots \quad (5.9)$$

where t_o and $\phi(t_o)$ is the dimensionless mean plane separation and the probability function due to the presence of oxide.

Therefore, the total area of contact which is the sum of oxide-to-oxide, oxide-to-metal and metal-to-metal contacts is

$$A_{rT} = \pi \bar{a}_o^2 \bar{N}_T \quad \dots \quad (5.10)$$

5.5 EXPERIMENTAL RESULTS AND DISCUSSIONS

Tests were conducted to determine the effect of oxides and the loading pressure on contact features. The contacts formed were between flat, rough stainless steel EN58B and optically flat commercially pure copper (oxide-free and oxidized), and stainless steel EN58B and commercially pure aluminium. Relatively high pressures (17.79 - 44.48 kN) were used, this was so as to ensure that the micro-contacts were clearly indented upon the soft flat surface.

Normalized level of surface heights versus the cumulative percent of all the specimen surfaces used was plotted on Gaussian probability paper (Figs. 5.1-5.5). Since the data lie approximately on a straight line, therefore, to a first approximation, all the surfaces were Gaussian.

Figures 5.7-5.10 (size distribution; the contacting specimen details in Table 4.1) represent number of contact spots per unit area as a function of contact spot radius. The number of micro-contacts increased with the applied loading for both the oxide-free as well as oxidized contacts.

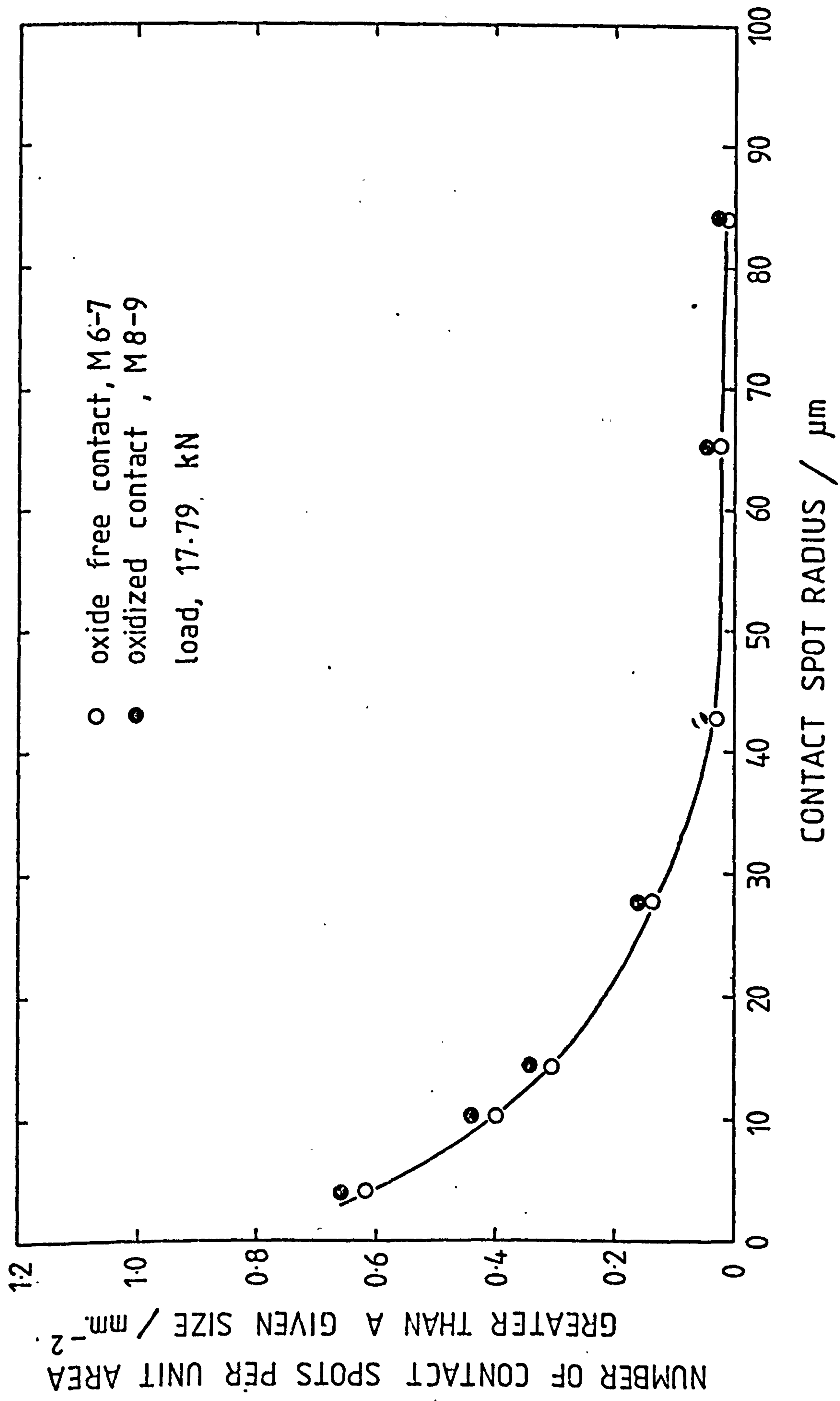


FIG 5,7

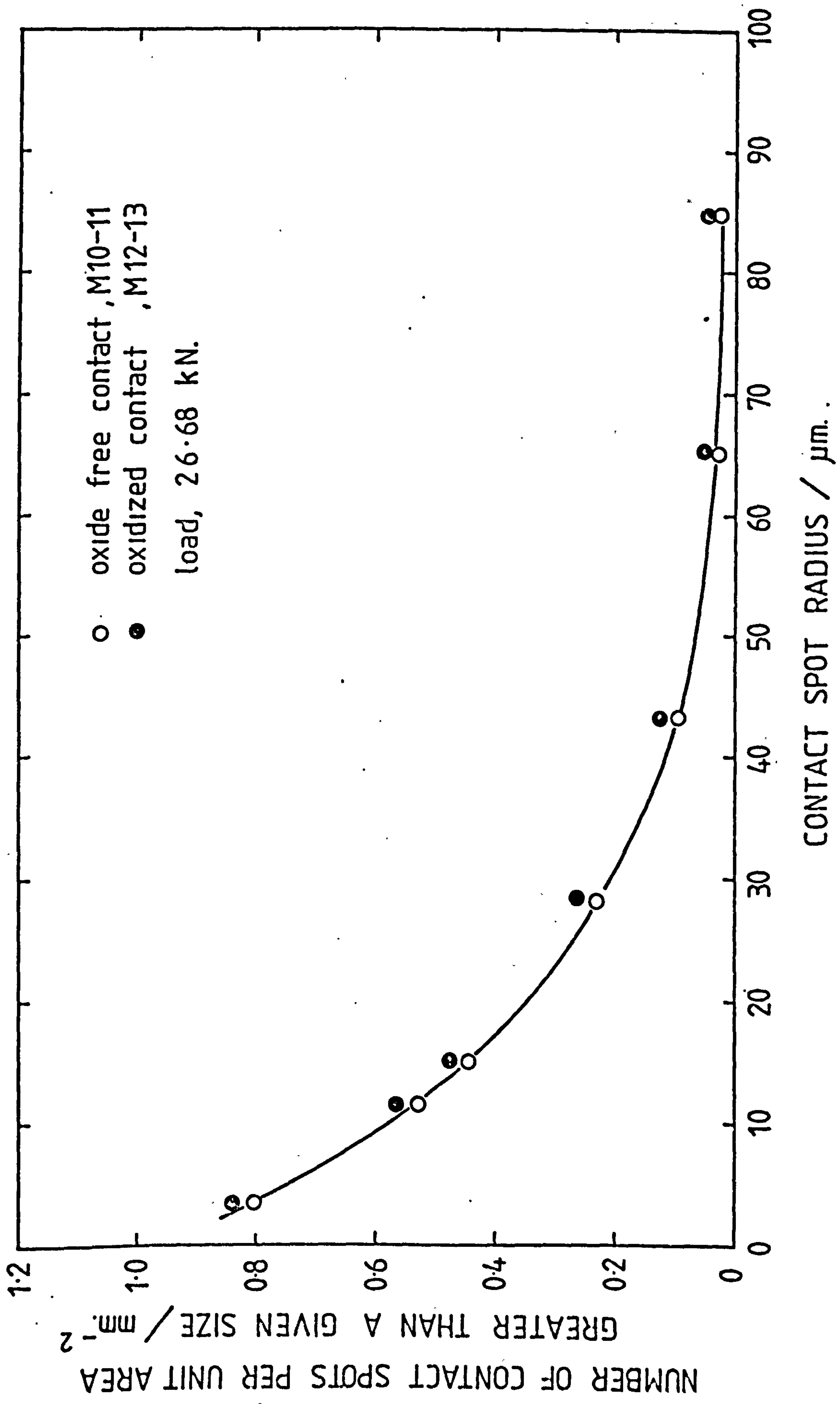


FIG. 5,8

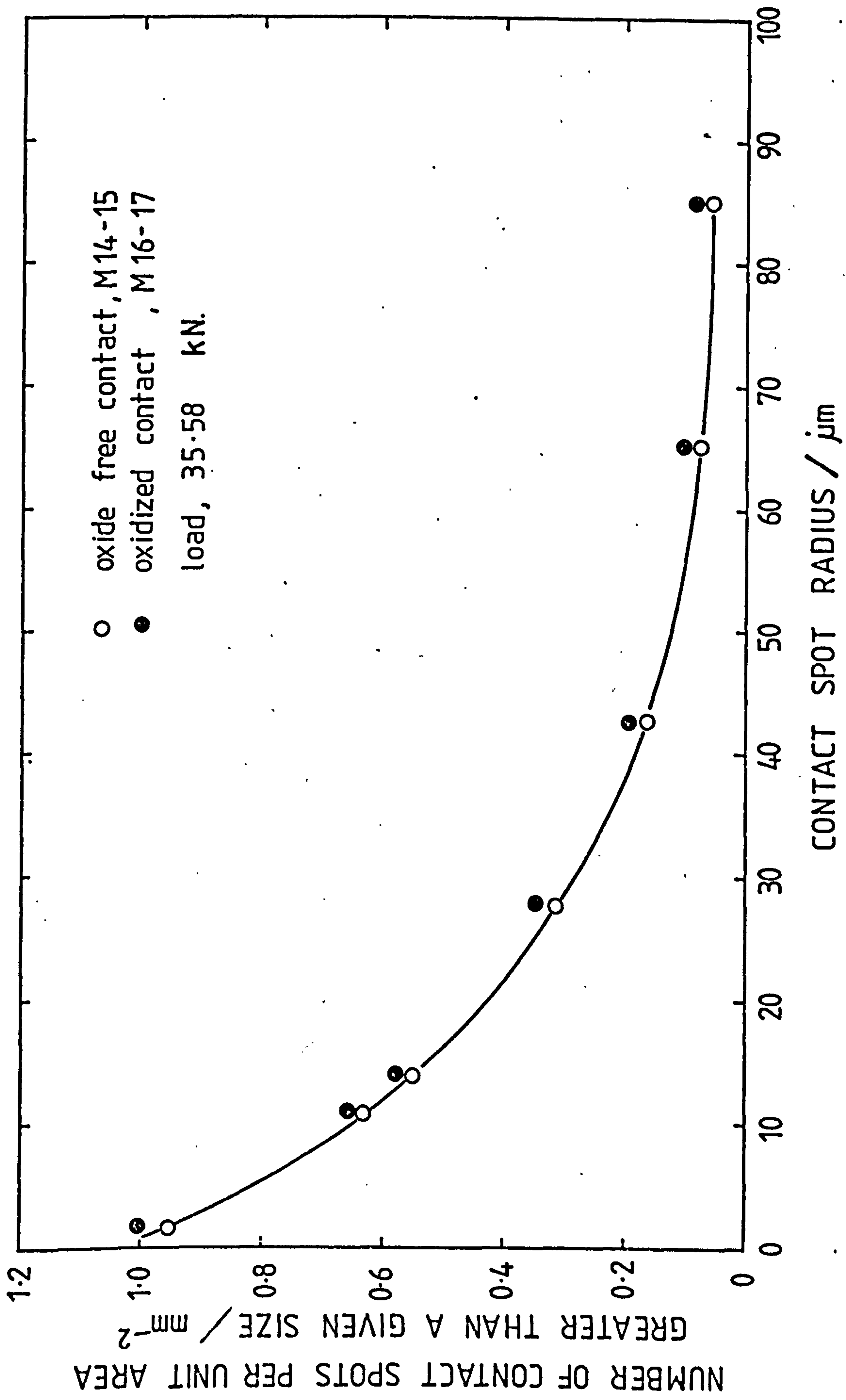


FIG. 5,9

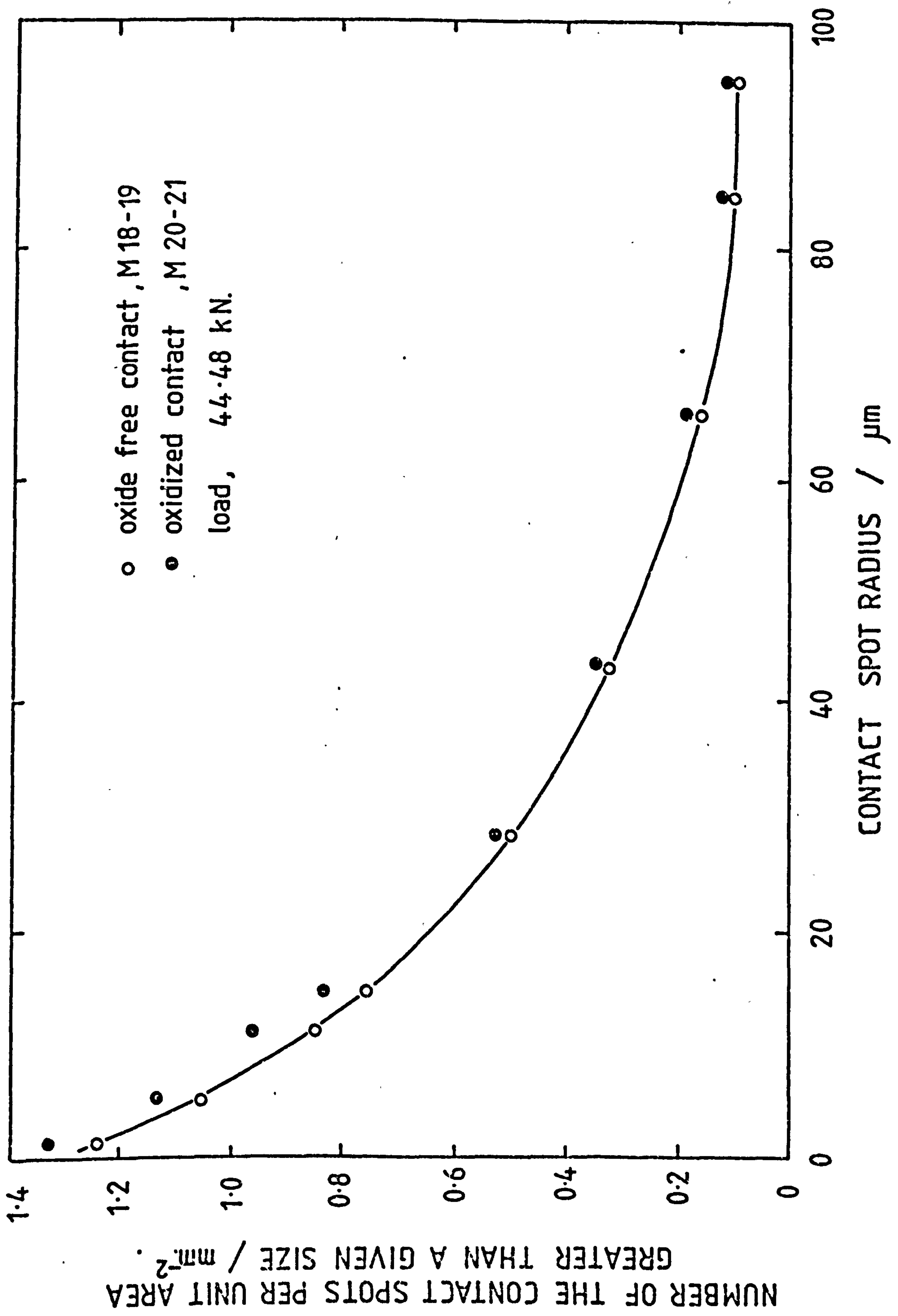


FIG. 5,10

5.5.1 The Area of Actual Contact

Figs. 5.11-5.15 present the area of actual contact. The straight lines predicting the area of actual contact were fitted by equations (5.7 and 5.10) for the oxide free and the oxidized contact respectively by selecting the values of the mean absolute surface slope, $|\bar{\Psi}|$, to match the experimental data points. Sample calculations showing the values of the slope used to calculate the area of actual contact (Fig. 5.11) are given in Appendix II. The total area of the contact defined as the sum of the real area of metal-to-metal contact and the additional area of oxide-to-metal contact showed an increase, compared with that of the oxide free contact as expected and also increased with the loading pressure. It could be concluded that the presence of the oxides improves compliance between the contacting surfaces.

In the theoretical analysis it was assumed that the area of actual contact per unit nominal area is equal to the non-dimensional loading pressure, but the dependency of the real area of contact on surface roughness at high pressure indicated that the relationship was of the form

$$\frac{A_r}{A_n} = C (P/M)^\eta \quad \dots \quad (5.11)$$

The value of the constant C and η , depend upon the loading selected. Higher loading pressures cause interference (122) between the neighbouring asperities.

5.5.2 Size and Mean Number of Micro-Contacts

The experimentally observed number of micro-contacts (Figs. 5.16 and 5.17) were less than the predicted number of micro-contacts. The predicted straight lines were fitted by using equations 5.5 and 5.9 for the oxide-free and the oxidized contact respectively.

The experimental values of the mean radius of the micro-contacts for both the oxide-free as well as oxidized contact were calculated from the measured real area of contact assuming circular micro-contacts, i.e.

$$A_r = \pi \bar{a}^2 N \quad \dots \quad (5.12)$$

where N is the number of micro-contacts as directly observed using the Quantimet 720 Image Analyser. The experimental values for the oxide-free micro-contacts ranged between 4 - 8 μm while that for oxidized contact between 10 - 15 μm . The measured values were lower than the theoretical predictions. D'Yachenko (76) measured the radius of micro-contacts using a photometric technique and observed $\bar{a}$ to be 22.5 μm .

It has been assumed (89) that the radius of the mean contact spot is constant at low loads. Some investigators (51, 91) have considered an increase in both $\bar{N}_A$ and $\bar{a}$ with applied loading. Bowden and Tabor (72) obtained values of $\bar{a}$ between 50 and 210 μm by working back from thermal

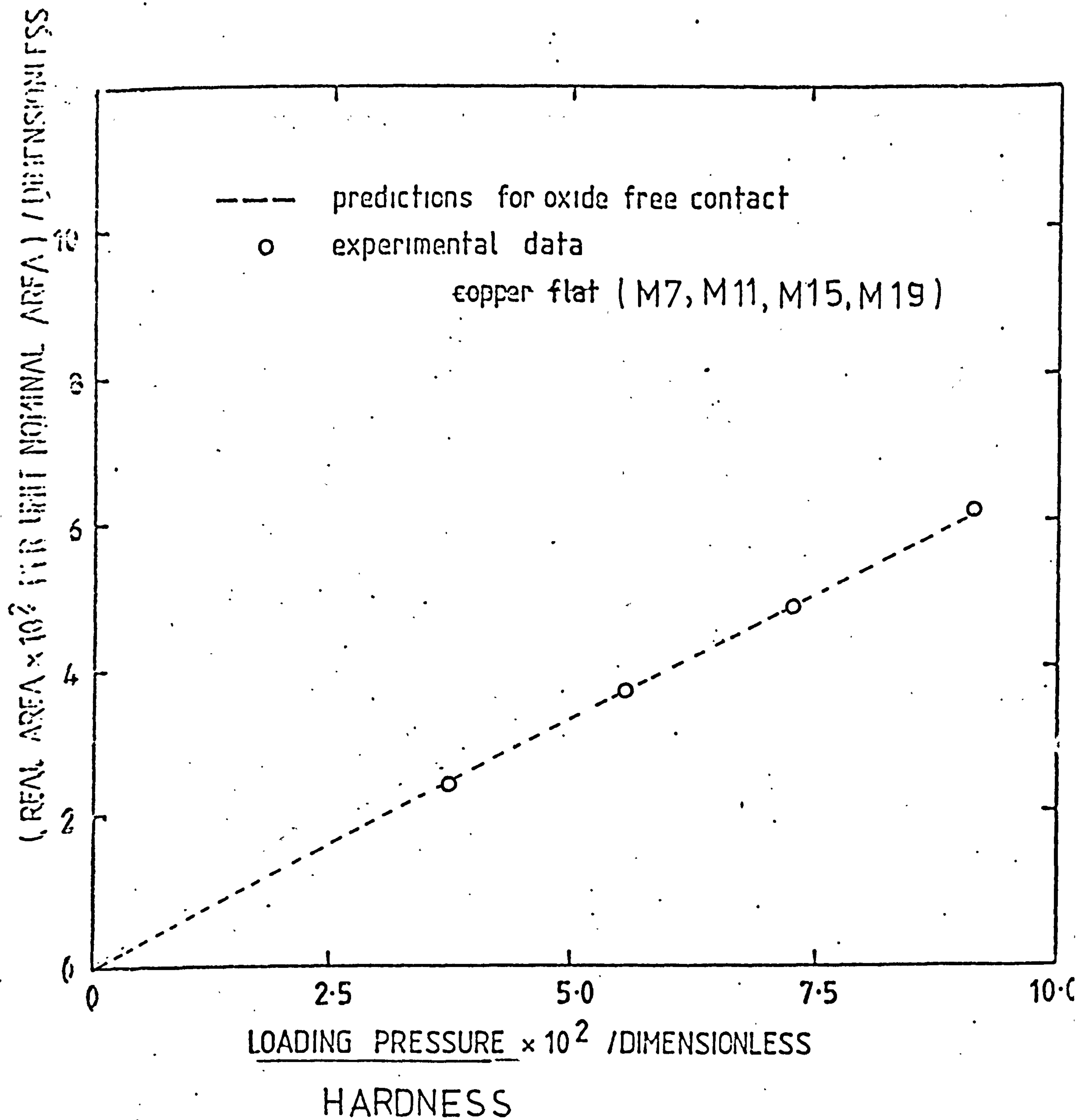


FIG. 5,11

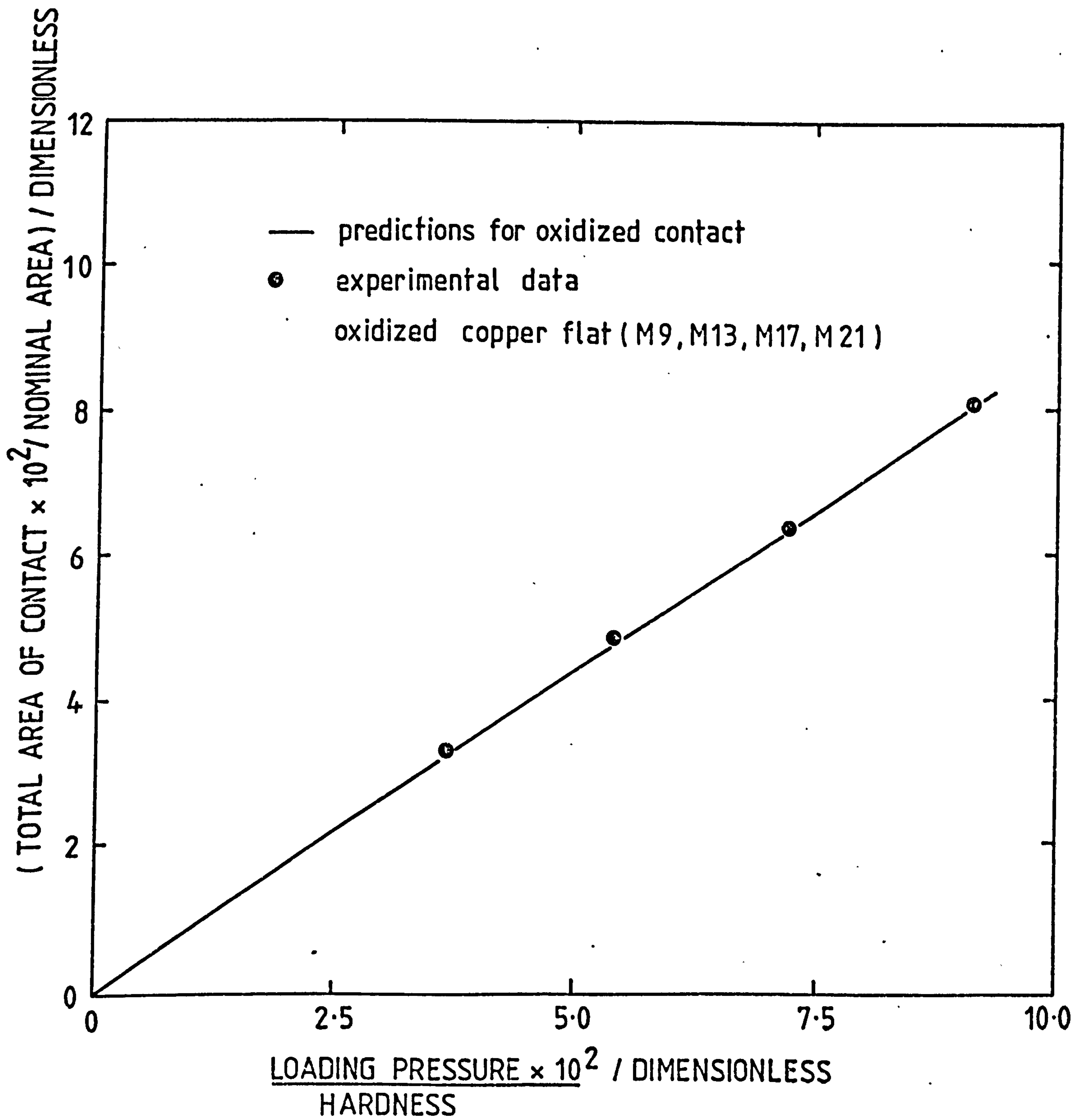


FIG. 5,12

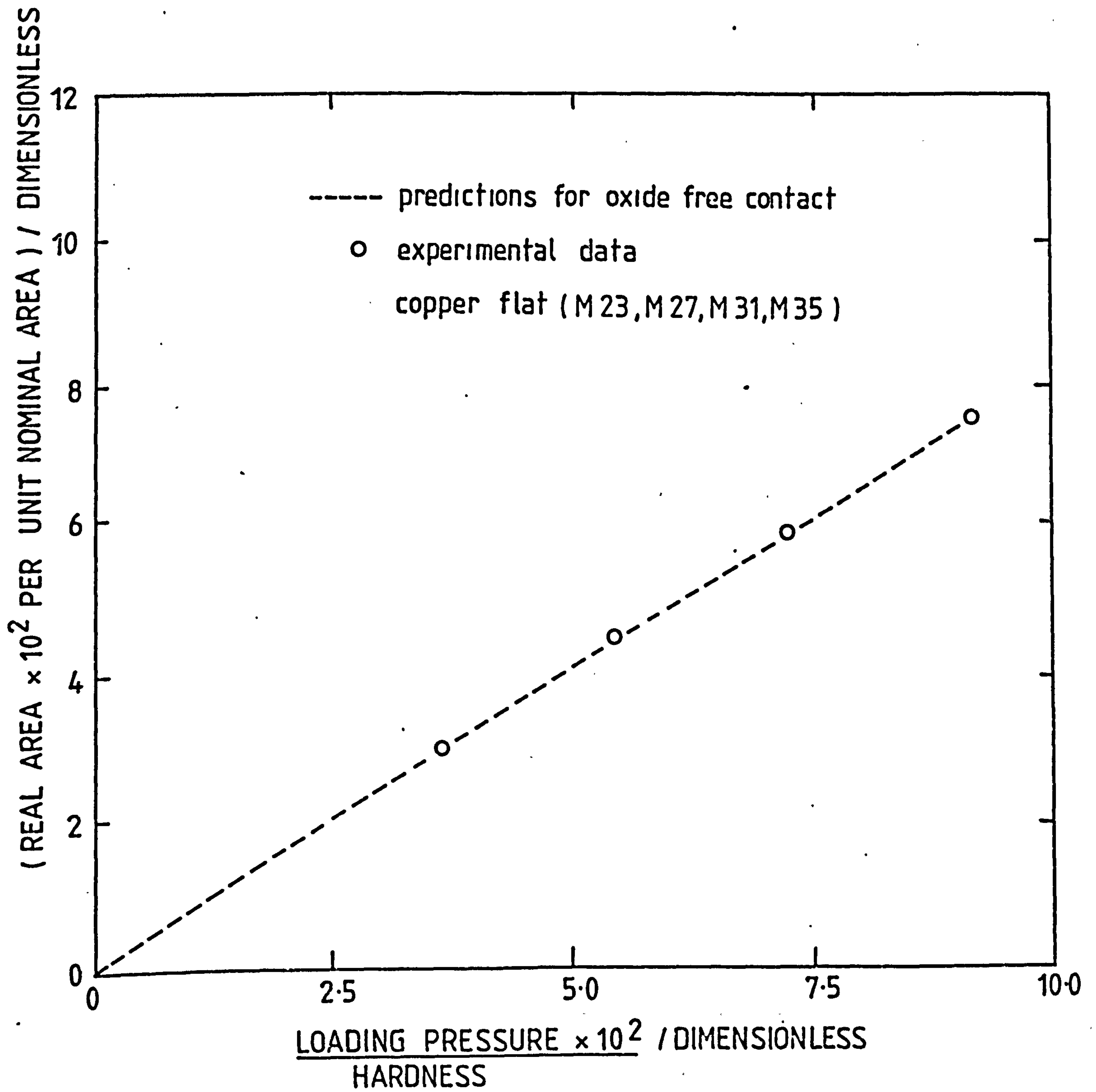


FIG. 5,13

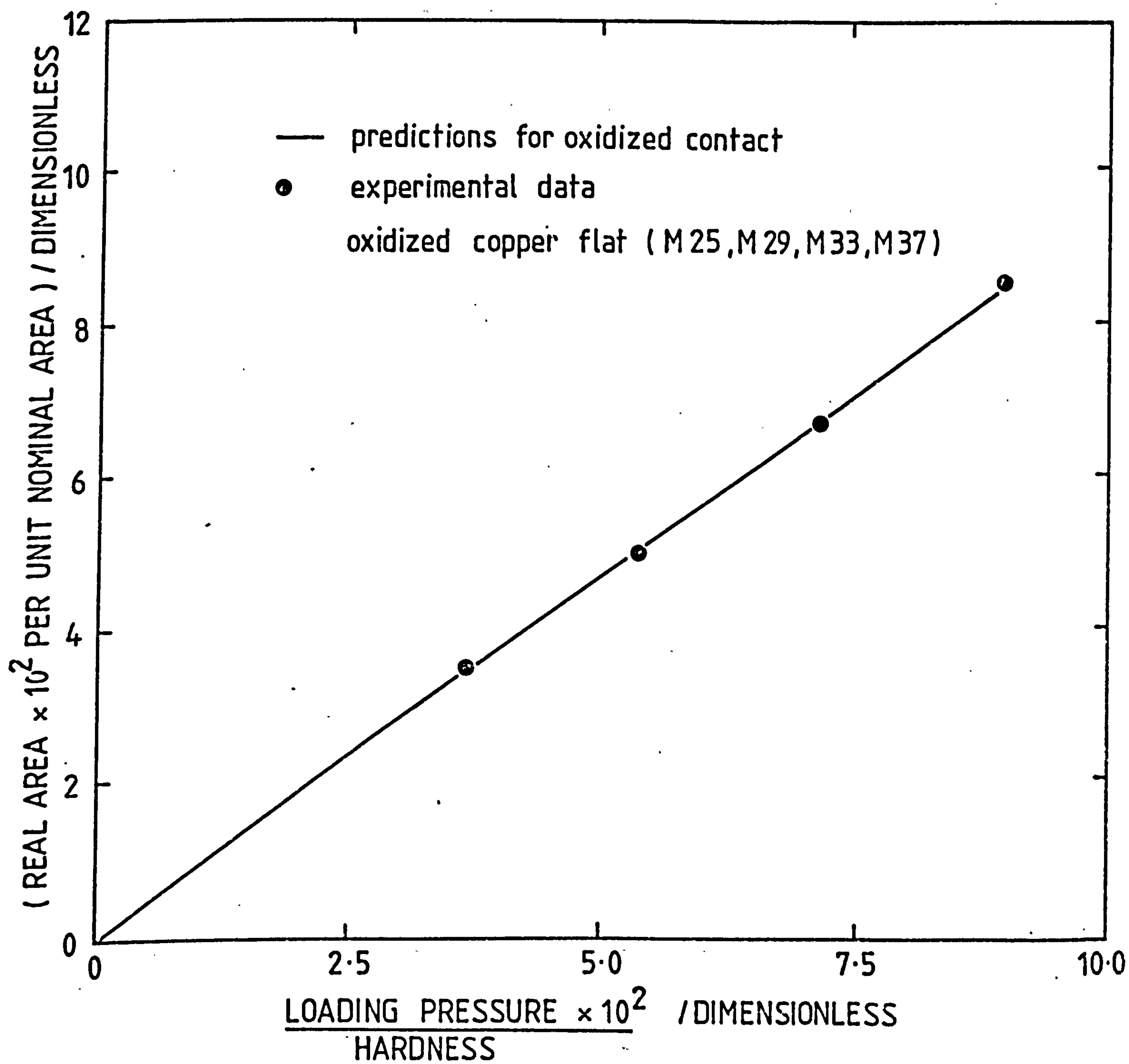


FIG. 5,14

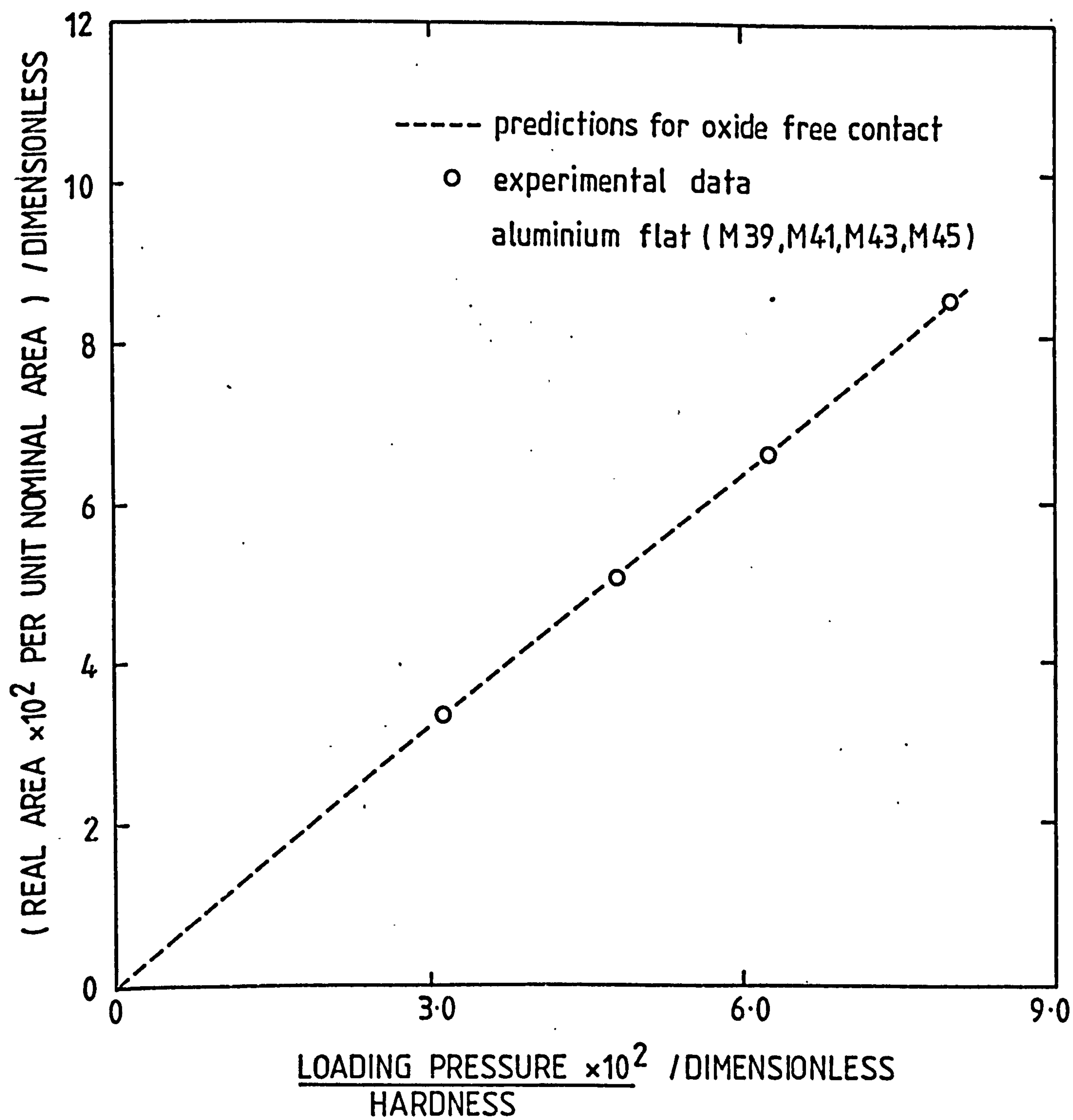


FIG. 5,15

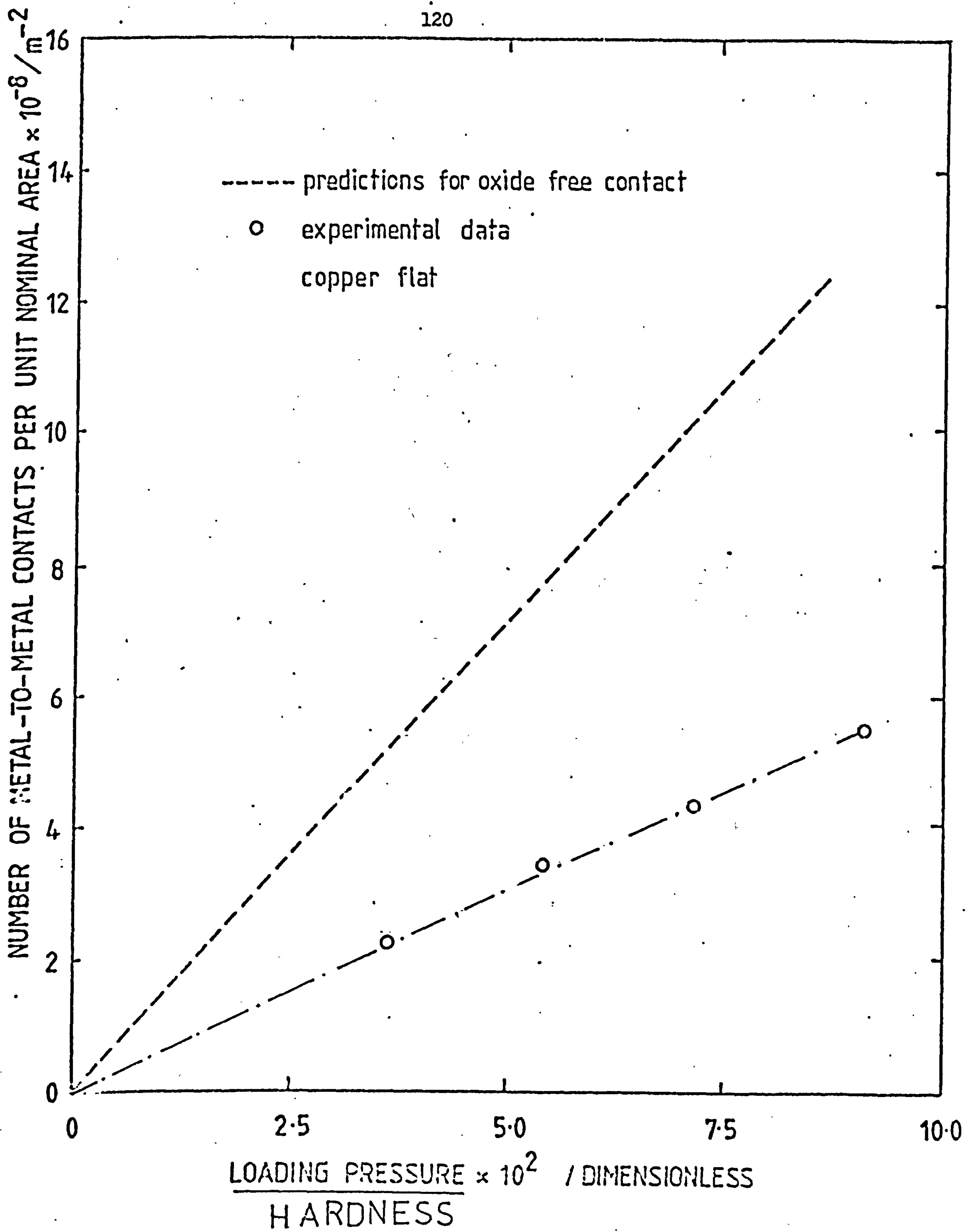


FIG. 5,16

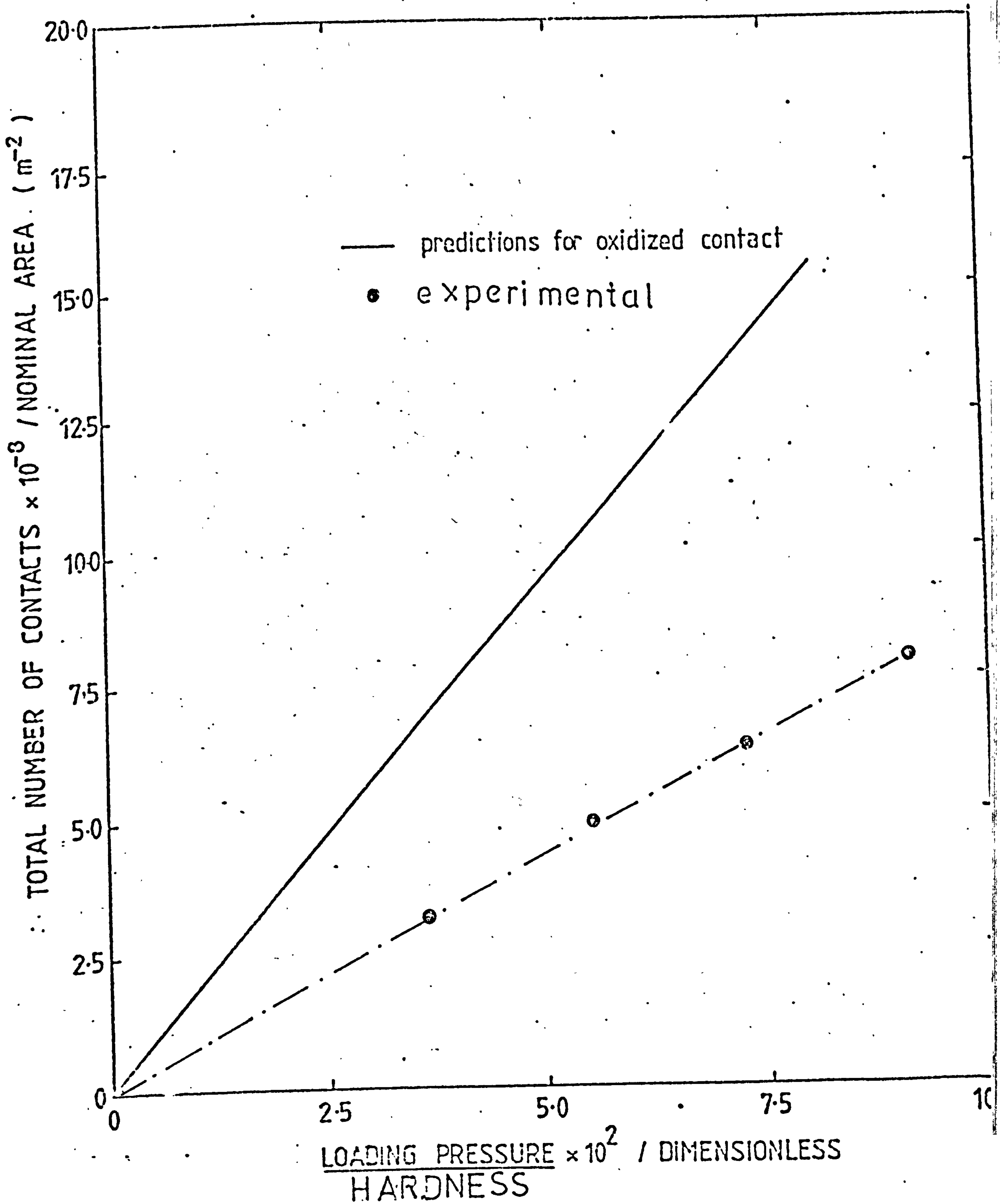


FIG 5,17

conductance measurements. Greenwood (49) calculated a value of $\bar{a}$ of 216 μm . These values are large compared with the present observations and probably indicate the radius of the macro-contact rather than that of the individual micro-contact.

Other reasons of discrepancy between the experimental and theoretical predictions for the number of contact spots is the limitation of the experimental technique to detect the micro-contacts less than 1 micron. Also the theoretical predictions assume the micro-contacts to be circular, while well over 70% micro-contacts were observed to be non-circular.

5.5.3 The Area of Actual Contact of a Turned Surface

Finally the contact features were produced on an oxidized turned copper by pressing sandblasted stainless steel upon it under a loading range of 40 to 44.48 kN (see plates 5.7-5.9; photographs were taken in the no-detection mode of the Quantimet). When the surface roughness of the impressed surface was of the order of the surface roughness of the pressurizing specimen, then the contact also occurred at the ridges. As could be viewed the micro-contacts were non-circular, had no regular shape and a number of them probably less than one micrometer diameter along with other surface irregularities, therefore, no meaningful results could be obtained.

5.6 CONCLUSIONS

The presence of oxides leads to an improved compliance between the contacting surfaces.

The presence of oxides leads to an overall increase in the area of contact. This is mainly due to the increase in the average radius of micro-contact.

Observations of the number of micro-contacts exhibited discrepancies with the predictions. This was due to the limitation of the experimental technique to detect the smallest micro-contacts which became lost in the very fine surface irregularities not removable by polishing.

The theory assumes the shape of the micro-contacts to be circular while well over 70% of the observed micro-contacts were non-circular. The theoretical predictions were, therefore, in excess of experimental observations.

The machined surfaces had a number of micro-contacts of irregular shape.

Future work on the Quantimet may be examinations of the shape of the micro-contacts for various machined surfaces and measurement of their contact features. This will require accurate counts of the smallest micro-contacts and a device to filter the background noise.

CHAPTER SIX

THEORETICAL DEVELOPMENT

6.1 INTRODUCTION

The compliance as well as the number of micro-contacts, their distribution and the real contact area affect the resistance to heat transfer or electrical flow between two surfaces which are pressed together (2, 3, 123, 124). As the surface material of each body suffers both elastic and plastic strains, the behaviour of the contact depends upon :

- (i) the magnitude, direction and time-dependence of the applied force:
- (ii) the topographies, stiffnesses and hardnesses of the contacting surfaces; and
- (iii) the presence of contaminant layers (e.g. oxides or greases) and/or interfacial fluids.

When two bodies are pressed together, true contact occurs over only a small fraction of the nominal interfacial area. If the elastic limit of either contacting material is not exceeded, Hertz' equations (70) can be used to describe the stresses in the contact region. Even though, the applied force is normally sufficient to cause plastic deformation of the asperity peaks, the microscopic features of the surface texture are not usually completely suppressed even under very high loads. Deformations of the asperity peaks of freshly-assembled surfaces pressed together are predominantly plastic (71, 126). However, to a first approximation, the real area of contact versus loading characteristics usually exhibits little hysteresis provided the maximum load applied previously is not subsequently exceeded.

A surface can be characterised according to its topography, chemical composition and physical structure :-

6.1.1 Topographical Features

The profile of a metal surface provides a description of such features as roughness distribution and lay which affect the contact behaviour.

6.1.2 Chemical Composition

A metal surface in engineering practice is usually covered by a film: this may be of grease or other deposit, in addition to the

oxides of the metal substrate. Such superficial layers are mixtures of several chemical species (metal atoms, oxygen ions and one or more metal ions). The rate of the oxide growth on the metal substrate is dependent upon surface topography, structure, temperature and fluid environment (4, 112).

6.1.3 Physical Structure

Even for perfectly smooth surfaces, free from films, the deformation and contact resistance behaviour may be influenced by adsorbed gas atoms, lattice imperfections and crystallinity variations. Some mechanical polishing processes also cause structural changes in the bulk material near the surface (128).

6.2 CONTACT BETWEEN OXIDE-FREE SURFACES

Tsukizoe and Hisakado (45, 46) considered the analysis for the contact between (i) a rough isotropic surface with a Gaussian distribution of surface heights and having no flatness deviations and (ii) a smooth flat surface. This description ideally fits the contact model (Fig. 6.1) developed to study the contact parameters and the thermal resistance arising as a consequence of the passage of the current across the interface (Fig. 6.2).

Thomas and Probert (93) extended the analysis to show that for a metal-to-metal contact the number of contacts, $\bar{N}_m$, per unit area and the number $\bar{N}_L$, per unit length, the average contact spot radius, $\bar{a}_m$, and the real area $\bar{A}_{rm}$ per unit nominal area are given by the following dimensionless relationships.

$$\frac{\bar{N}_m}{\psi^2} = \frac{\pi}{8} t_m \phi(t_m) \quad \dots \quad (6.1)$$

If the contacting specimens are either of dissimilar materials or possess differing surface topographies, then the effective surface roughness for a contact can be assumed to be

$$\sigma_s = (\sigma_1^2 + \sigma_2^2)^{\frac{1}{2}} \quad \dots \quad (6.2)$$

and the effective surface slope

$$\psi_s = \left[\frac{|\bar{\psi}_1|^2 + \dots + |\bar{\psi}_2|^2}{\sigma_1^2 + \sigma_2^2} \right]^{\frac{1}{2}} \quad \dots \quad (6.3)$$

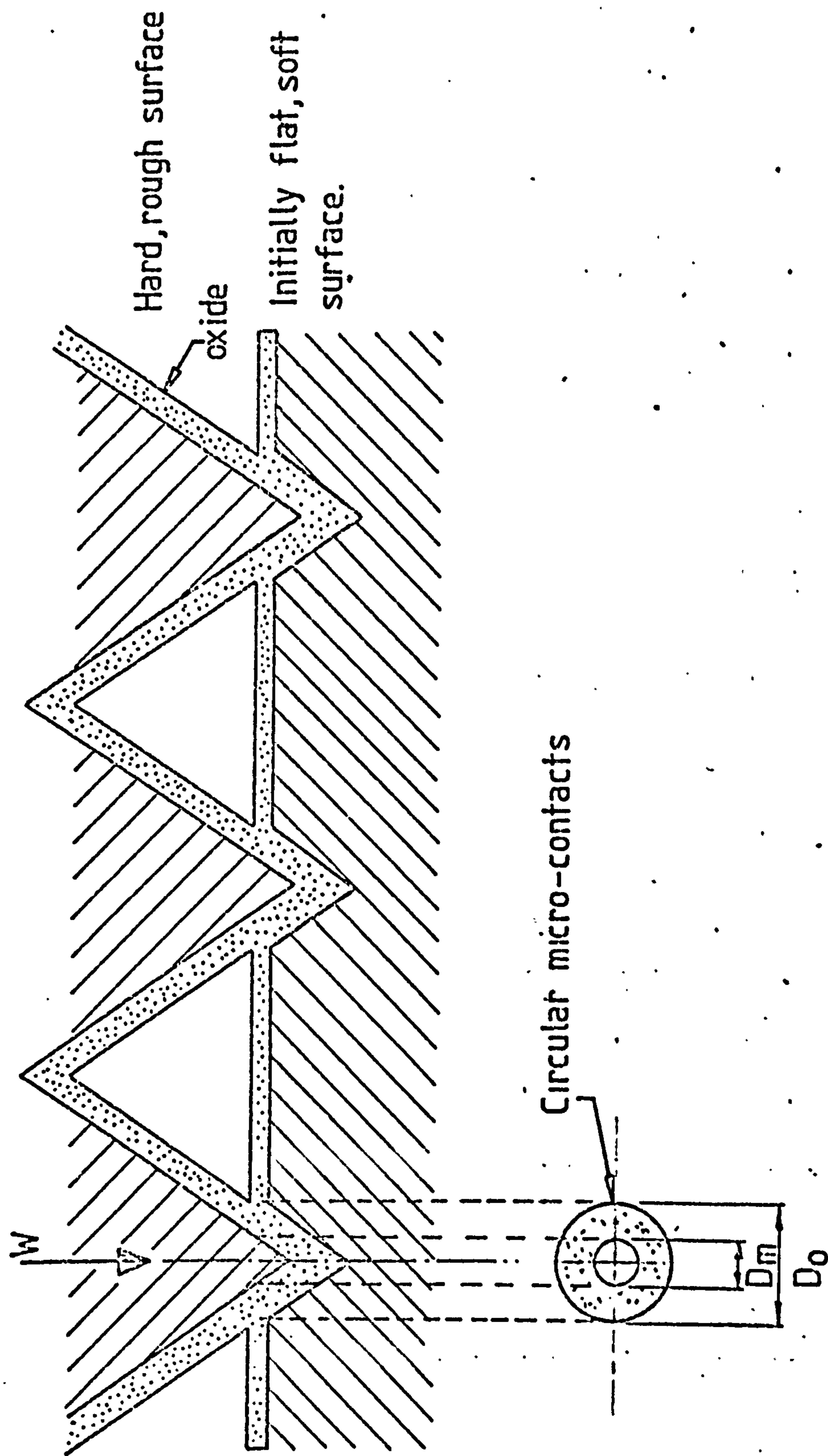


FIG. 6,1

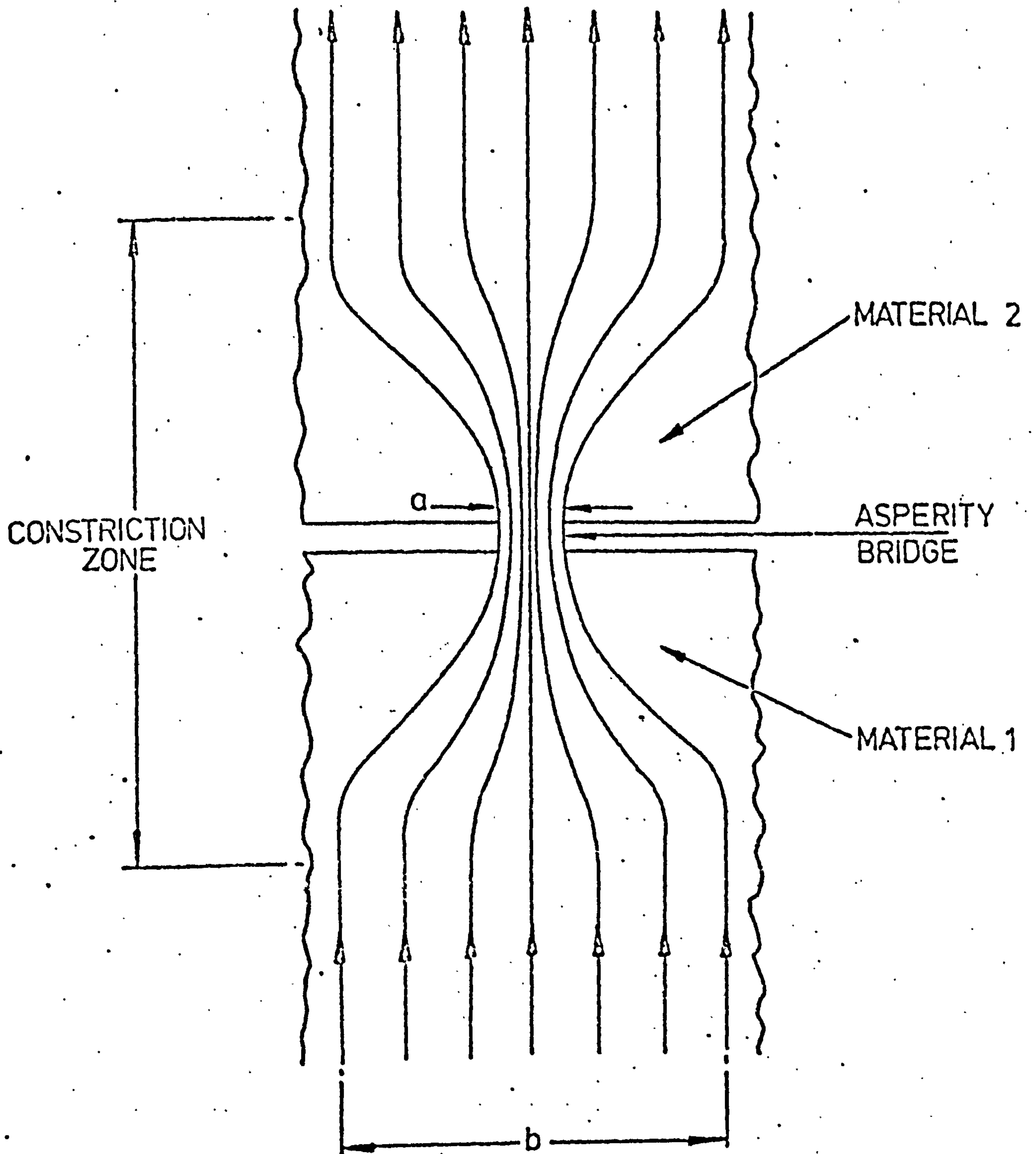


FIG. 6,2

where $|\bar{\psi}_1|$ and $|\bar{\psi}_2|$ are the mean slopes of surfaces 1 and 2 respectively and $\Psi = |\bar{\psi}|/\sigma$ is the normalized mean surface slope (45, 46, 122).

$$\frac{\bar{N}_L}{\Psi} = \frac{\phi(t_m)}{2} \quad \dots \quad (6.4)$$

$$\bar{a}_m \Psi = \frac{2}{\pi t_m} \quad \dots \quad (6.5)$$

$$A_{rm} = \pi \bar{a}_m^2 N_m \quad \dots \quad (6.6)$$

The dimensionless separation t_m is related to the ratio of the nominal pressure P to the surface hardness M of the softer surface by the expression

$$\frac{P}{M} = \frac{1}{2} - \phi(t_m) \quad \dots \quad (6.7)$$

where $\phi(t_m)$ represents the probability integral $\int_0^t \phi(t_m) \cdot dt$ and $\phi(t_m)$ is the probability function, $\frac{1}{\sqrt{2\pi}} \exp(-t_m^2/2)$ and are tabulated functions.(134). The average land length $\bar{l}$ is defined as the bearing length fraction, $\frac{\Delta L}{L}$ which according to plastic deformation assumptions is equal to P/M divided by the number of contacts per unit length and hence

$$\bar{l} = \frac{\sigma}{|\bar{\psi}|} \frac{1 - 2 \phi(t_m)}{\phi(t_m)} \quad \dots \quad (6.8)$$

An alternative relationship between the number of contacts per unit area, $\bar{N}_m$ and per unit length $\bar{N}_L$ may be derived from (6.1), 6.4), and (6.5) as follows :

$$\bar{a}_m \bar{N}_m = \frac{\Psi \phi(t_m)}{4} = \frac{\bar{N}_L}{2} \quad \dots \quad (6.9)$$

$$\text{i.e.} \quad \frac{\bar{N}_L}{\bar{N}_m} = 2 \bar{a}_m \quad \dots \quad (6.10)$$

The harmonic mean thermal conductivity, k_s , for the surfaces having different conductivities is defined (49, 50), by,

$$\frac{2}{k_s} = \frac{1}{k_1} + \frac{1}{k_2} \quad \dots \quad (6.11)$$

The thermal resistance of the unit area, R (for oxide-free surfaces) of an array of independent circular micro-contacts of mean radius $\bar{a}_m$ is given according to (47) by the expression :

$$R = \frac{1}{2 \bar{a}_m \bar{N}_m k_s} \quad \dots \quad (6.12)$$

Because of the multiplicity of true contacts, the constrictions of the heat flows to each of these asperity bridges are not independent. Consequently a constriction alleviation factor $g(\gamma)$ has been introduced (135, 136) to account for the experimentally observed behaviour.

If $\gamma = \frac{\bar{a}}{\bar{b}}$ where the mean heat flow channel radius b equals

$\left(\frac{A_n}{\pi N_T}\right)^{\frac{1}{2}}$, then the constriction alleviation factor

$$g(\gamma) = 1 - 1.409\gamma + 0.296\gamma^3 + \dots \quad \dots \quad (6.13)$$

Therefore, the modified constriction resistance,

$$R_{\text{mod}} = R \cdot g(\gamma) \quad \dots \quad (6.14)$$

The theory it is alleged is true whether the softer surface is the rougher or smoother of the contacting surfaces provided the hardness, M of the softer surface is used in the calculations.

6.2.1 Assumptions

- i) The rough surface is random and isotropic and the distribution of surface heights is Gaussian, therefore any surface profile of sufficient length will contain identical information.
- ii) The ratio of the real to the apparent contact area is equivalent to the bearing fraction of the surface profile (at a particular level considered).
- iii) The displaced material by truncation of the asperity tips as a result of the contact of the flat surface is assumed to be negligible.

- iv) The contact surfaces deform in an ideal plastic manner. This implies that the flow pressure is almost independent of the load provided there is no working hardening.
- v) The analysis applies only if no interference occurs between the neighbouring asperities.
- vi) The surface asperities are assumed to be right circular cones of identical included angle, the magnitude of which depends upon the surface roughness. The contact regions are then circular.
- vii) The base angle of the asperities is small, i.e.

$$\theta = \sin \theta \approx \tan \theta \quad \dots \quad (6.15)$$

6.3 CONTACTS BETWEEN OXIDIZED SURFACES

When two, nominally flat, oxidized surfaces are brought into contact under a uniform loading, a proportion of the apparent contact area touches at discrete zones as shown in Fig. 6.4. The mean planes of the two oxidized surfaces are separated from the interface by distances u_1 and u_2 respectively. Similarly the metal substrates are $u_1 + x_1$ and $u_2 + x_2$ respectively from the interfacial planes.

A relationship between the normalized mean plane separation t_m , the real area A_r of the contact, and the applied loading P is

$$\Phi(t_m) = \int_0^t \phi(t_m) dt = \frac{1}{2} - \frac{P}{M} \quad \dots \quad (6.16)$$

where M is the surface micro-hardness of the softer of the two contacting material (2), and the normal probability function

$$\phi(t_m) = \frac{1}{\sqrt{2\pi}} \exp \left(-\frac{t_m^2}{2} \right) \quad \dots \quad (6.17)$$

Now from Fig. 6.4 it can be seen that

$$t_o = t_m - (x_1^* + x_2^*) \quad \dots \quad (6.18)$$

where t_o represents the non-dimensional mean plane separation for the oxidized contacting surfaces.

If both x_1 and x_2 remain constant over the nominal contact area then the presence of the oxides would not affect the profiles of the surfaces. This assumption is reasonable for clean, initially rough surfaces (133).

For each value of t_o (obtained from equation 6.18), $\phi(t_o)$ can be obtained from statistical tables (134).

6.3.1 The Contact Mechanism

In general an oxidized contact gives rise to the mechanisms outlined below.

6.3.2 Brittle Fracture of Oxide Films (Case A) $M_o > M_m$

Fig. 6.3a, in this situation; at light loads the hardness of the oxide M_o will be more significant compared with the hardness of the metal, M_m . An increase in the loading pressure breaks the oxide film leaving the debris of the oxide. An oxide-to-oxide, oxide-to-metal and metal-to-metal contact occurs.

6.3.3 'Grease' Filled Contact (Case B) $M_o < M_m$

In this case (Fig. 6.3b) the oxides are considered as softer than the softer metal. The voids fill in upon contact and an oxide-to-metal and a metal-to-metal contact occurs.

6.3.4 Soft Thin Oxide Coatings (Case C) $x < u_1$ $M_o < M_m$

Fig. 6.3c, the oxides are considered as softer than the metal. The contact comprises of a sandwiched border of oxide between the contacting surfaces, oxide-to-metal and metal-to-metal contact occurs.

6.3.5 Insulated Surface Films (Case D) $\frac{x}{u_1} > 1$

Fig. 6.3d, this tends to reduce number of direct metal-to-metal contacts. An oxide-to-oxide contact occurs at low loads. The thermal contact resistance in this case will be a ratio of the oxide film thickness to its thermal conductivity.

Other forms in terms of the applications of the contact mechanism are hard thin surface coatings, soft thin insulated films and hard thin insulated films.

MECHANISM

Case A , Brittle fracture of oxide films $M_o > M_m$ and $\alpha < \sigma$

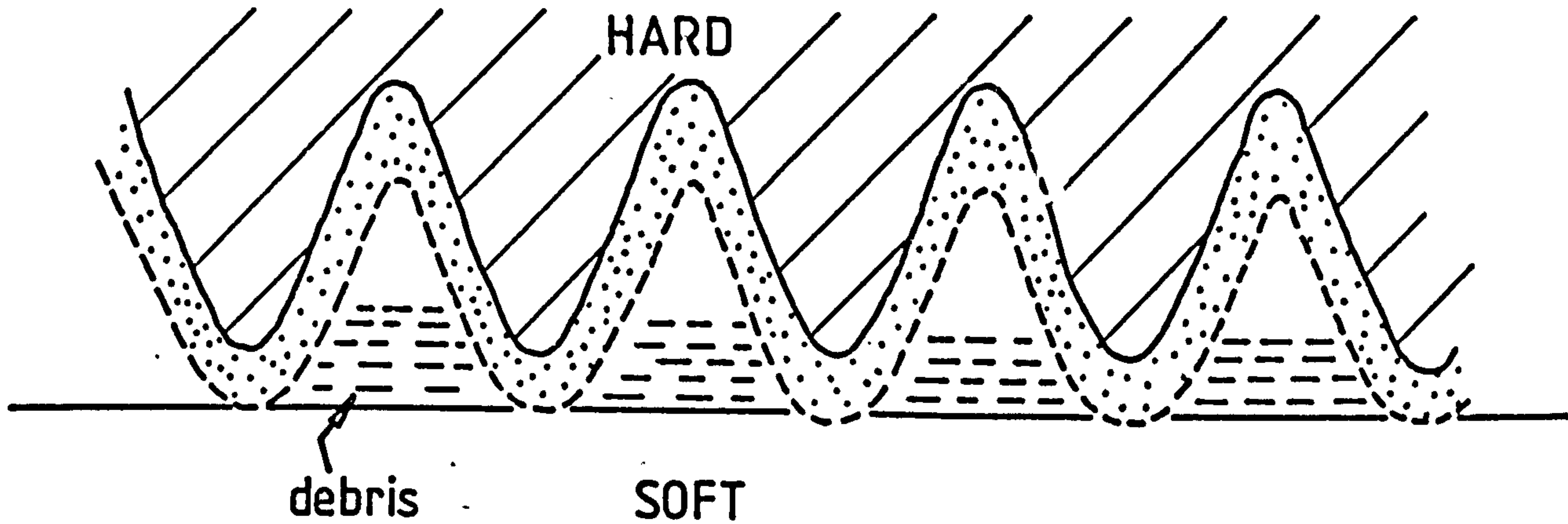


FIG. 6,3 a

Case B , 'Grease' filled contact $M_o < M_m$ and $\alpha < \sigma$ (oxide softer than the softer metal.)

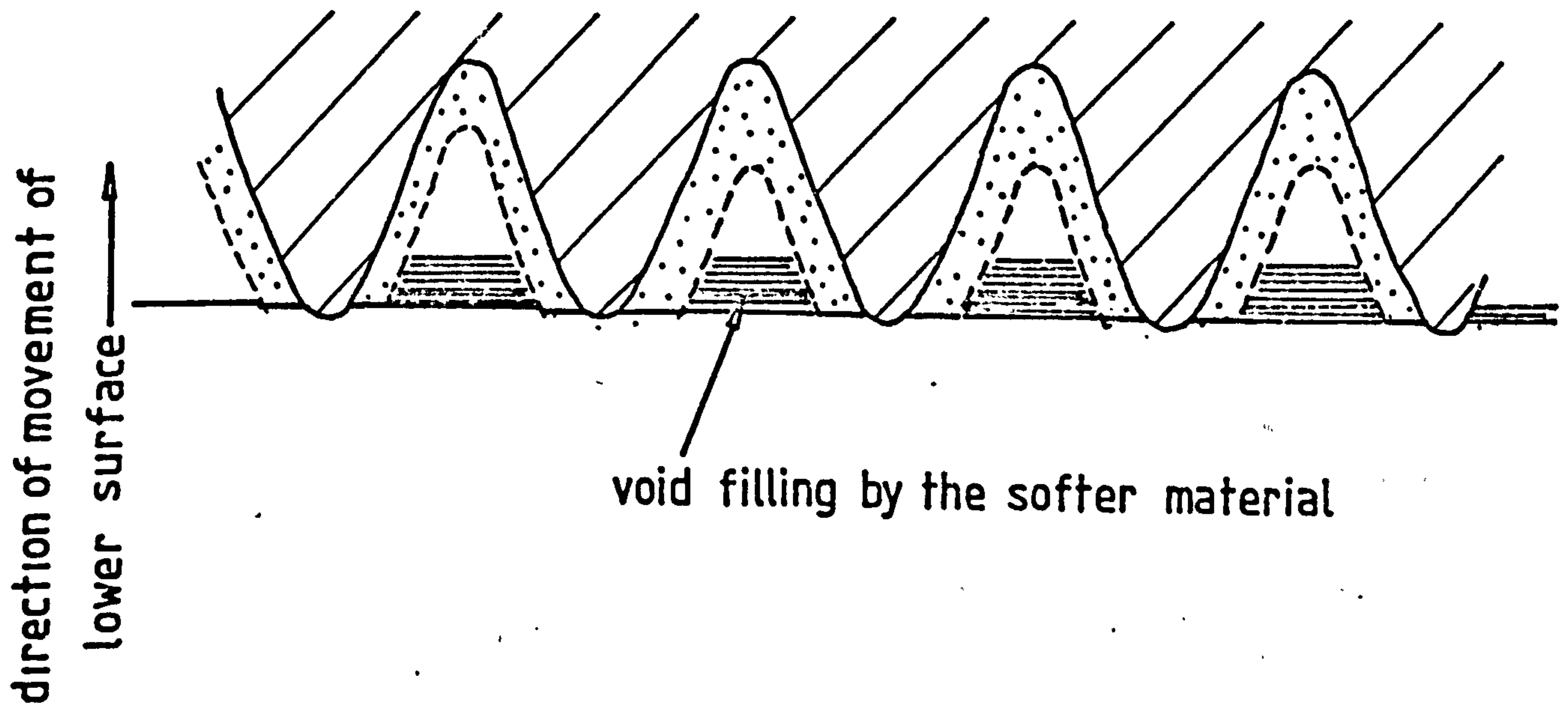


FIG 6,3 b

Case c , Thin surface coatings $\alpha/u_t < 1$

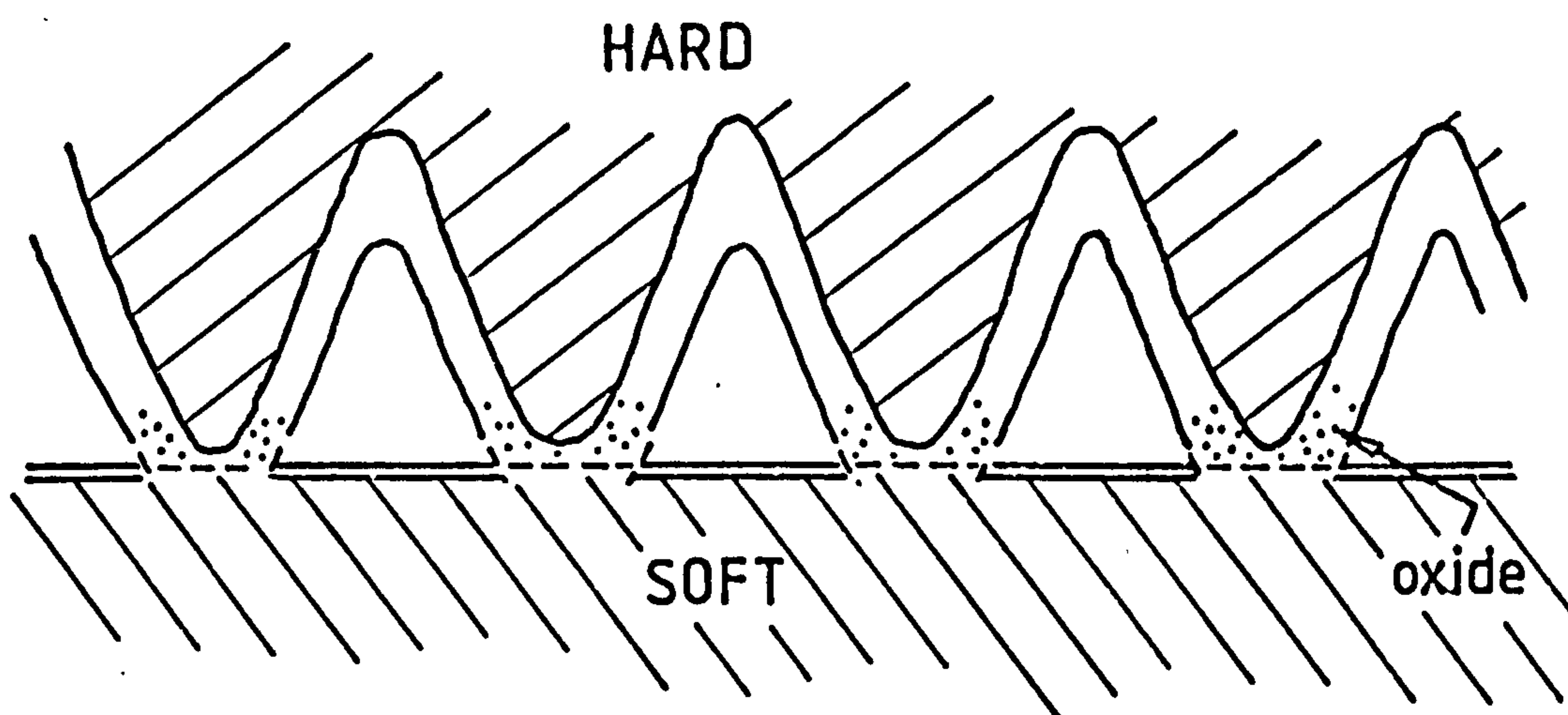


FIG 6, 3c

Case d , Insulated surface films $\alpha/u_t > 1$

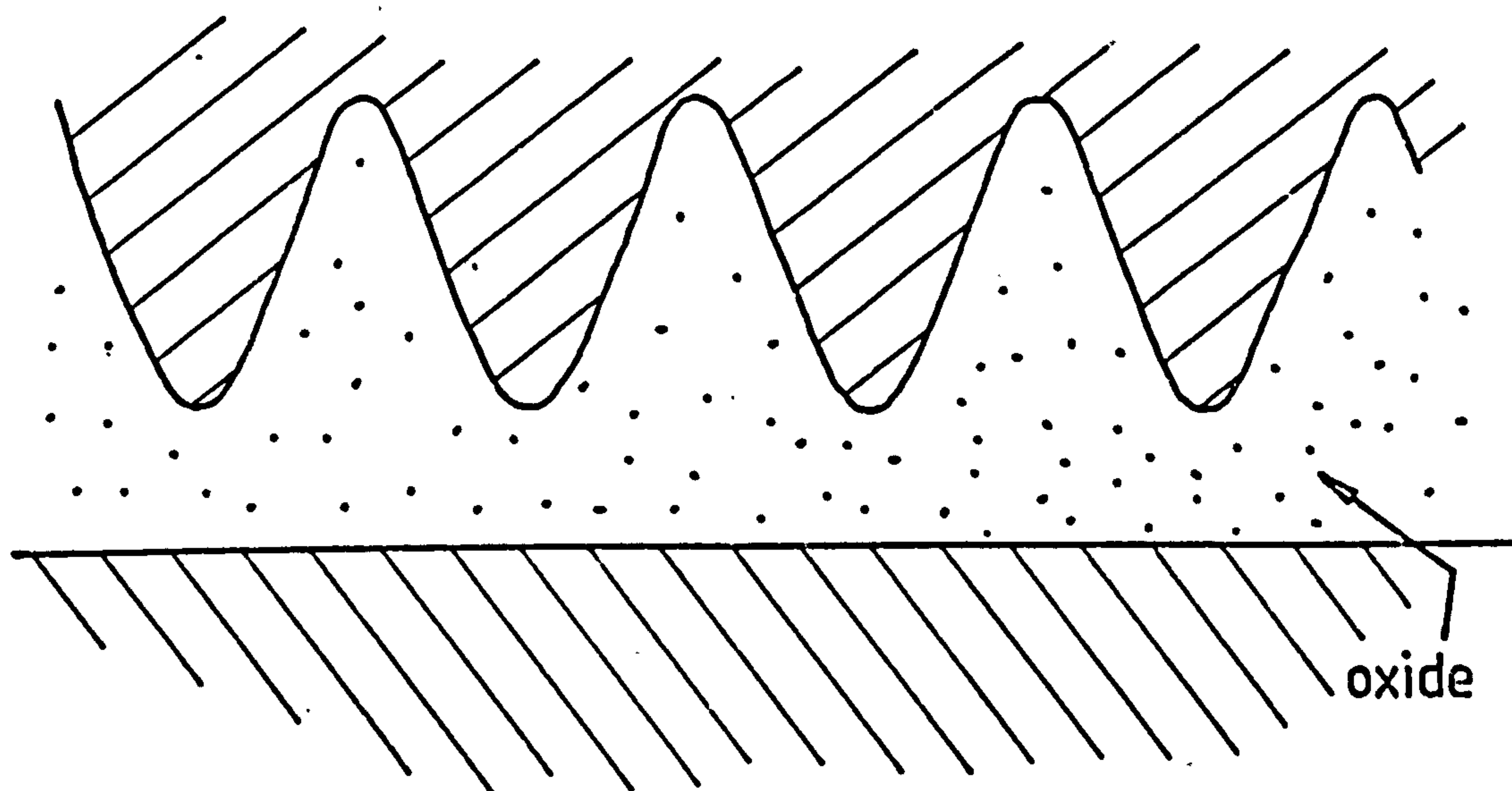


FIG 6, 3 d

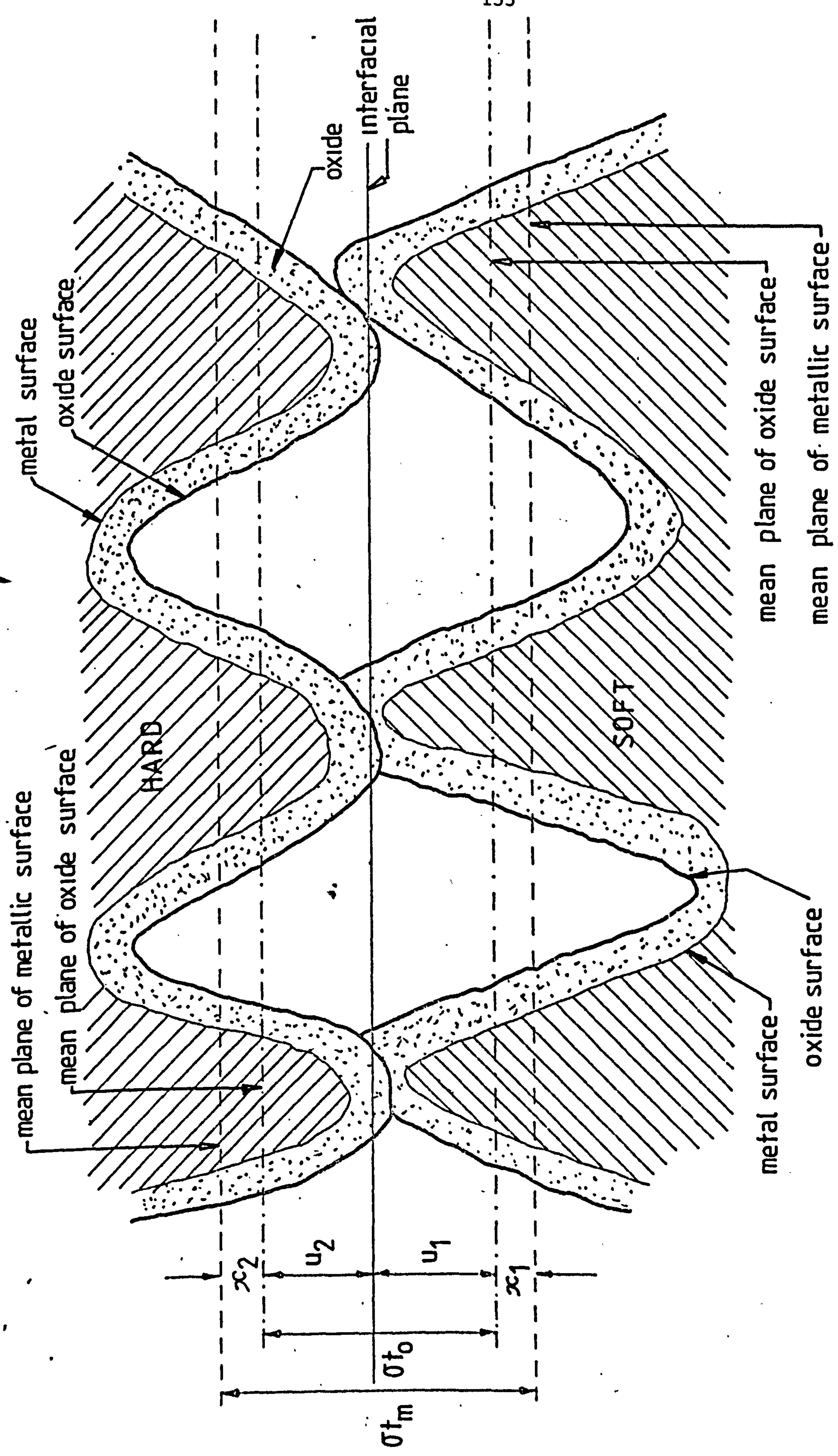


FIG. 6.4

6.4 THEORETICAL DETAILS

6.4.1 The Contact Mechanism (Case A) $M_o > M_m$

The hardness of the oxide, M_o will be more significant compared with the hardness of the metal, M_m at light loads (Fig. 6.3a). An increase in the pressure breaks the oxide film leaving debris of oxide and hence the oxide-to-oxide, oxide-to-metal and metal-to-metal contact occurs. Now for this case the mean contact spot radius of the metal-to-metal contact as from equation 6.5 is

$$\bar{a}_m = \frac{2}{\pi \psi t_m} \quad \dots \quad (6.19)$$

From Fig. 5.6, it can be seen that the mean contact spot radius for the oxidized contact,

$$\bar{a}_o = \bar{a}_m + \frac{x}{\tan \theta} \quad \dots \quad (6.20)$$

For joints having thin films the total area of contact which is the sum of the real area of metal-to-metal contact and the additional area due to the presence of the oxide is

$$A_{rT} = \pi \bar{a}_o^2 N_T = \pi \bar{a}_m^2 N_m + \pi \bar{a}_{oo}^2 N_o \quad \dots \quad (6.21)$$

mean contact spot radius of the oxide-to-oxide contact,

$$\bar{a}_{oo}^2 = (\bar{a}_o^2 N_T - \bar{a}_m^2 N_m) / N_o \quad \dots \quad (6.22)$$

From equation (6.1) the mean number of metal-to-metal microcontacts is

$$N_m = \frac{\pi \psi^2 t_m \phi(t_m) A_n}{8} \quad \dots \quad (6.23)$$

where A_n is the nominal area of the contacting specimen assembly. Similarly for oxidized surfaces, the total number N_T of micro-contacts including oxide-to-oxide, oxide-to-metal and metal-to-metal true contacts, (for the sake of simplicity the number of oxide-to-metal contacts is considered as the number of metal-to-metal contacts) is given by :

$$N_T = \frac{\pi \psi^2 t_o \phi(t_o) A_n}{8} \quad \dots \quad (6.24)$$

However,

$$N_T = N_m + N_o \quad \dots \quad (6.25)$$

true contact being assumed to occur where the surface profile crosses the interface (6) - see Fig. 6.4. As a first approximation the asperities were considered to (i) be right circular cones of identical included angle, (ii) deform in an ideal plastic manner producing circular contact spots (Fig. 6.5 and Fig. 6.1) and (iii) be uniformly distributed over the apparent contact area.

6.4.2 'Grease' Filled Contact (Case B) $M_o < M_m$

In this case (Fig. 6.3b), the oxides are considered as softer than the softer metal. The voids fill in upon contact and an oxide-to-metal and a metal-to-metal contact occurs.

Now for this case the mean contact spot radius of the metal-to-metal contact is

$$\bar{a}_m = \frac{2}{\pi \psi t_m} \quad \dots \quad (6.26)$$

From Fig. 5.6 it can be seen that the mean contact spot radius for the oxidized contact

$$\bar{a}_o = \bar{a}_m + \frac{x}{\tan \theta} \quad \dots \quad (6.27)$$

the total area of contact is,

$$A_{rT} = \pi \bar{a}_o^2 N_T \quad \dots \quad (6.28)$$

the mean number of metal-to-metal micro-contacts is

$$N_m = \frac{\pi \psi^2 t_m \phi(t_m) A_n}{8} \quad \dots \quad (6.29)$$

Where A_n is the nominal area of the contacting specimen assembly. Similarly the total number of micro-contacts (i.e. oxide-to-metal and metal-to-metal) is given by

$$N_T = \frac{\pi \psi^2 t_o \phi(t_o) A_n}{8} \quad \dots \quad (6.30)$$

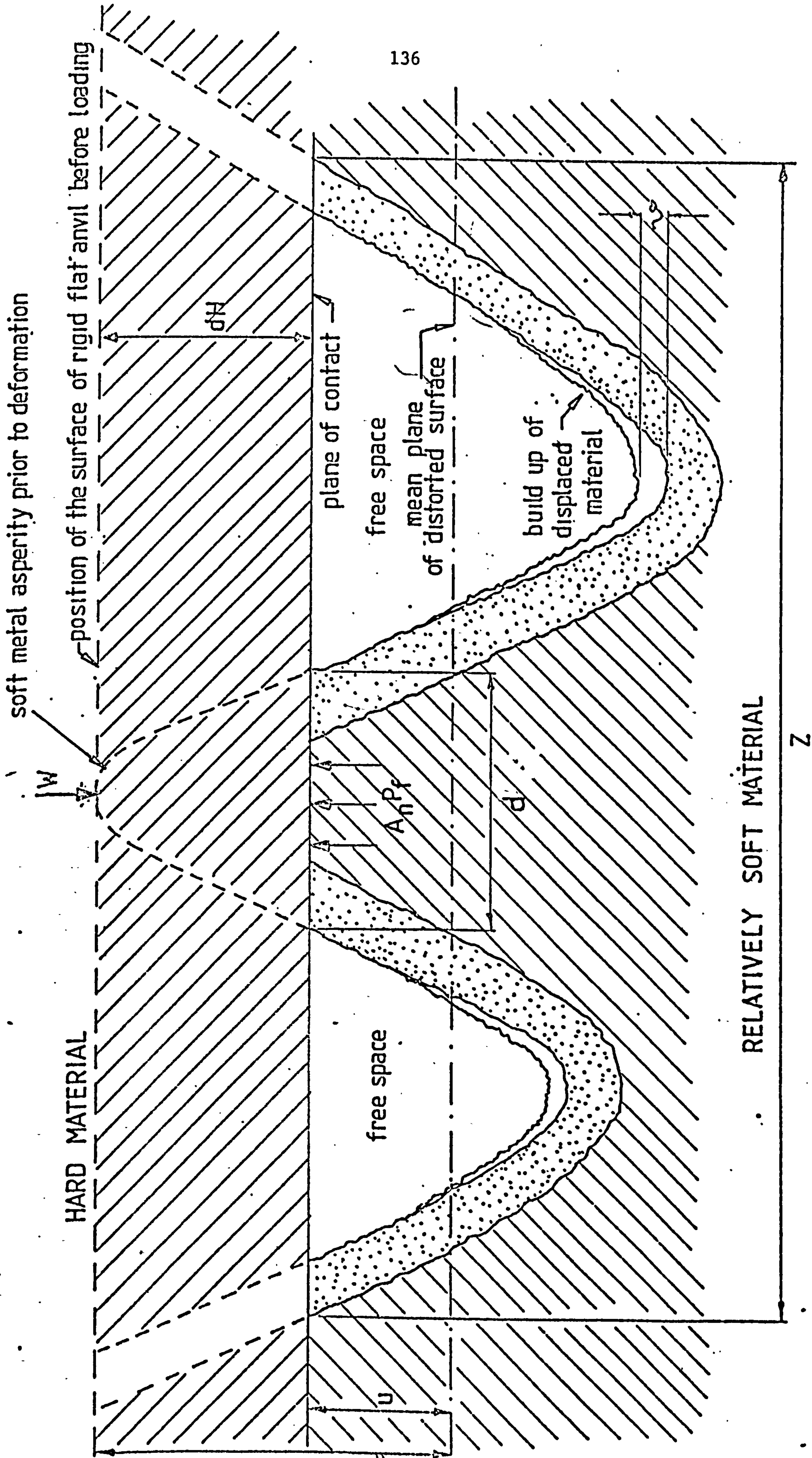


FIG. 6,5

where

$$N_T = N_m + N_o \quad \dots \quad (6.31)$$

6.4.3 Soft Thin Oxide Coatings (Case C) $x < \delta$

Fig. 6.3c, oxides are considered as softer than the metal. The contact comprises of a sandwiched border of oxide between the contacting surfaces. Oxide-to-metal and metal-to-metal contact occurs.

Now for this case the mean contact spot radius for metal-to-metal contact is

$$\bar{a}_m = \frac{2}{\pi \psi t_m} \quad \dots \quad (6.32)$$

From Fig. 5.6 it can be seen that the mean contact spot radius for the contact due to the presence of oxide is

$$\bar{a}_o = \bar{a}_m + \frac{x}{\tan \theta} \quad \dots \quad (6.33)$$

the total area of contact is given by,

$$A_{rT} = \pi \bar{a}_o^2 N_T \quad \dots \quad (6.34)$$

the mean number of the total micro-contacts is

$$N_T = \frac{\pi \psi^2 t_o \phi(t_o) A_n}{8} \quad \dots \quad (6.35)$$

6.4.4 Insulated Surface Films (Case D) $\frac{x}{u_1} < 1$

Fig. 6.3d, this tends to reduce a direct metal-to-metal contact. An oxide-to-oxide contact occurs at low load. Elevated loads would fracture the oxide film.

6.5 THERMAL CONDUCTIVITY

The harmonic mean thermal conductivity k_s (49, 50), of the metal-to-metal contact for dissimilar materials is

$$k_s = \frac{2 k_1 k_2}{k_1 + k_2} \quad \dots \quad (6.36)$$

Where k_1 and k_2 represent respectively the conductivities of the contacting materials of surfaces 1 and 2. The radiative contribution to the heat leak across the contact is negligible because of the small temperature difference across the interface and its relatively low mean temperature.

Assuming parallel path of the heat flux the harmonic mean thermal conductivity k_{so} for the oxide-to-oxide contact (see Fig. 6.6) is

$$\frac{4}{k_{so}} = \frac{1}{k_{m1}} + \frac{1}{k_{o1}} + \frac{1}{k_{m2}} + \frac{1}{k_{o2}} \quad \dots \quad (6.37)$$

and that for the metal-to-metal contact for the oxidized contacting surfaces (see Fig. 6.7) is

$$\frac{2}{k_s} = \frac{1}{k_{m1}} + \frac{1}{k_{m2}} \quad \dots \quad (6.38)$$

$$\frac{2}{k_{so}} = \frac{1}{k_{o1}} + \frac{1}{k_{o2}} \quad \dots \quad (6.39)$$

therefore, the total harmonic mean thermal conductivity k_{TO} is

$$k_{TO} = \% k_s + \% k_{so} \quad \dots \quad (6.40)$$

where the percentage of the contact can be obtained from Fig. 6.9 which is obtained from Fig. 6.8.

6.6 THERMAL CONTACT RESISTANCE

6.6.1 Brittle Fracture of Oxide Films (Case A)

The constriction resistance per unit area for N_m micro-contacts of mean radius $\bar{a}_o$ is given according to Ref. (47) as

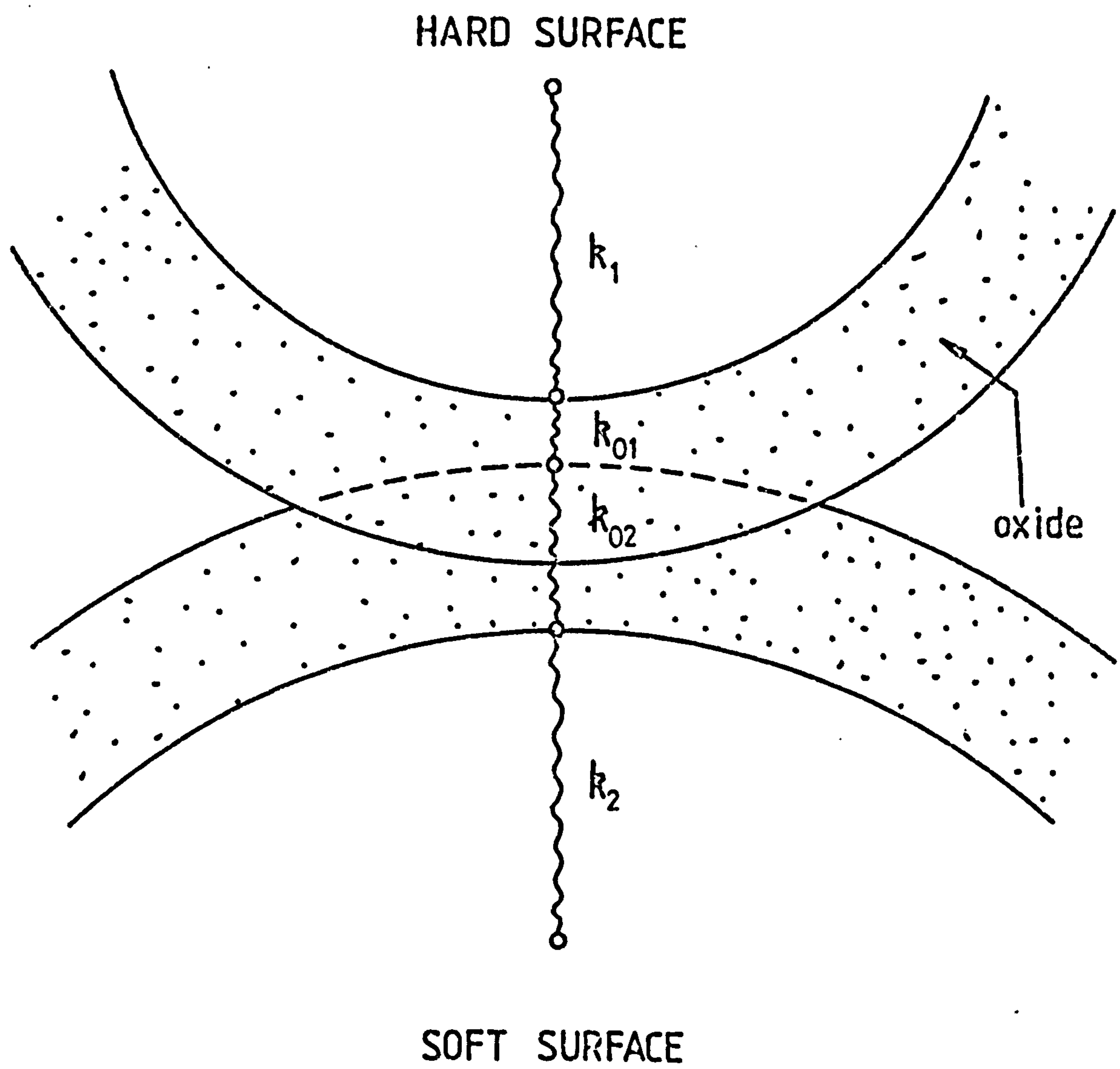


FIG. 6,6

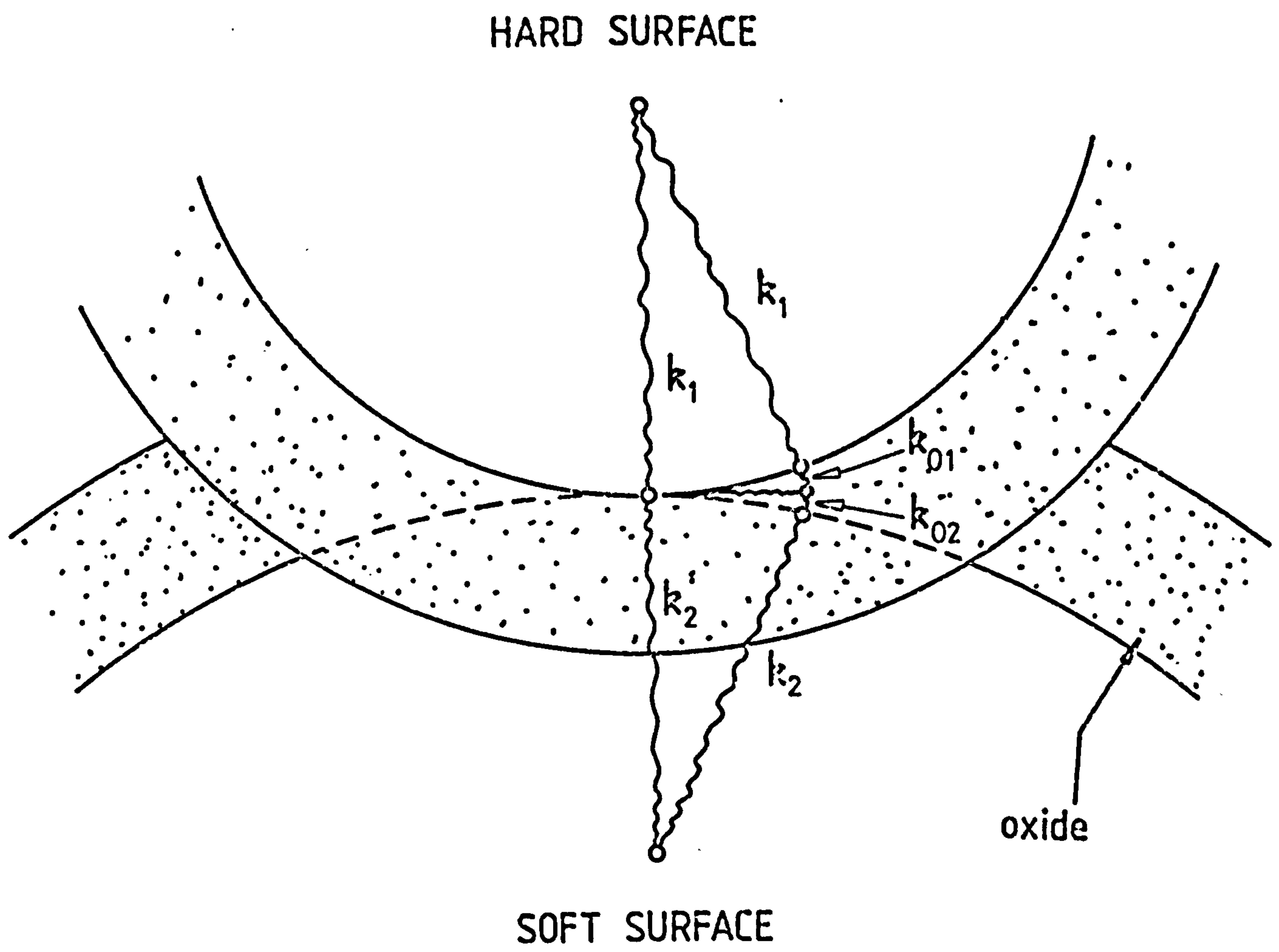


FIG. 6,7

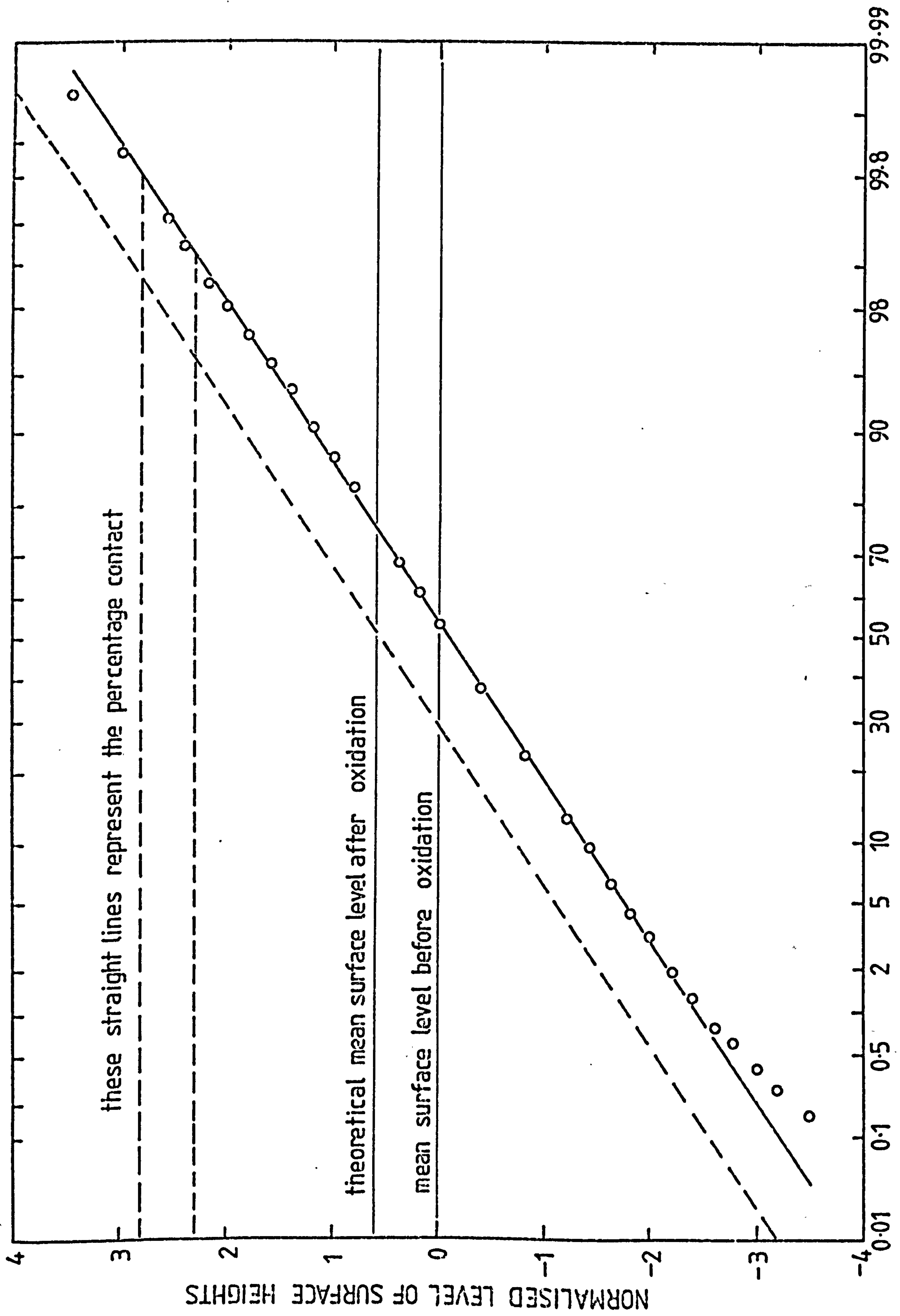


FIG. 6.8 CUMULATIVE PERCENTAGE OF ORDINATES

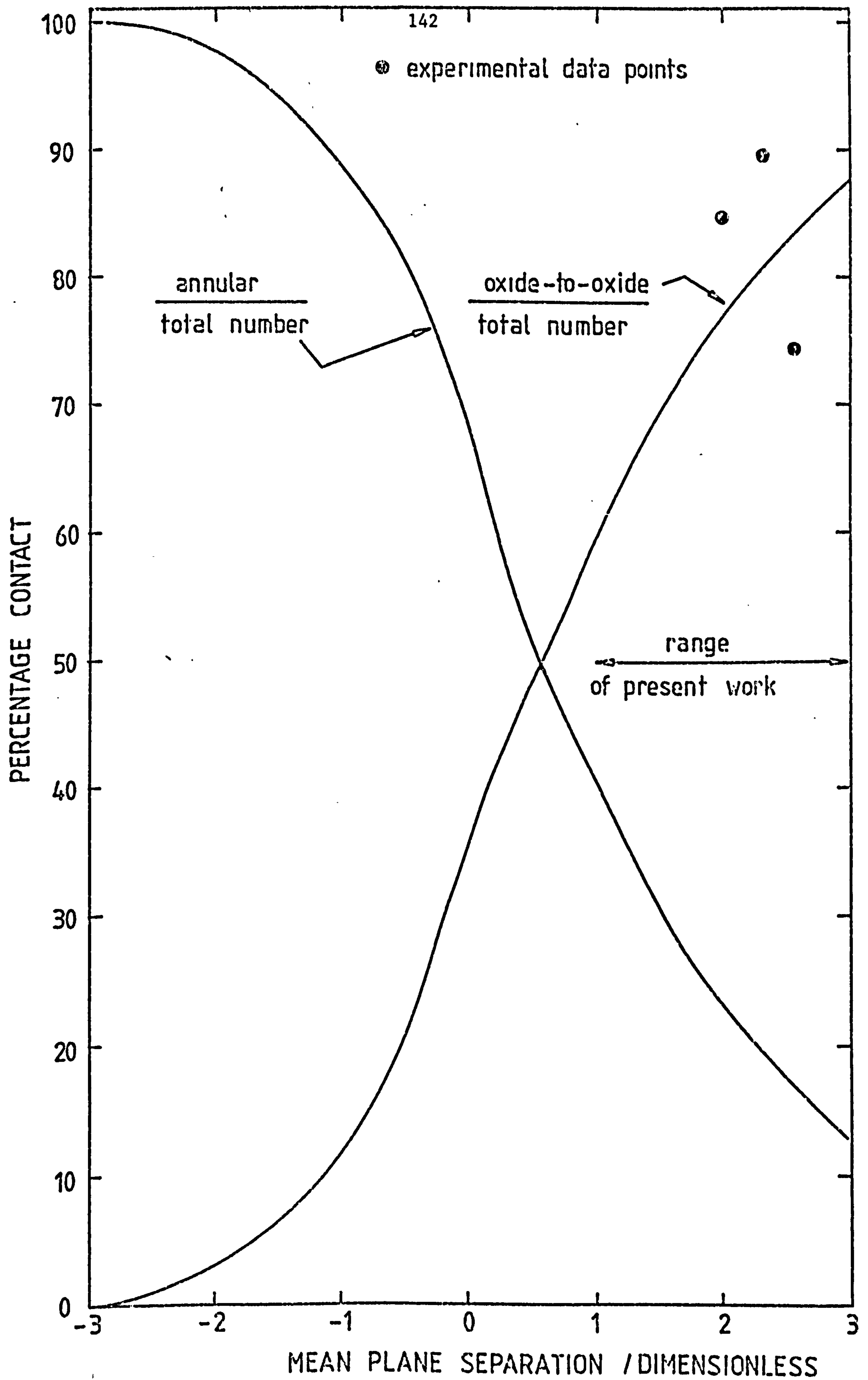


FIG. 6,9

$$R_{mo} = \frac{1}{2 \bar{a}_o N_m k_{TO}} \quad \dots (6.41)$$

The constriction resistance per unit area for N_o micro-contacts of mean radius $\bar{a}_{oo}$, becomes

$$R_{oo} = \frac{1}{2 \bar{a}_{oo} N_o k_{so}} \quad \dots (6.42)$$

and therefore, the total resistance is

$$R_T = (R_{mo} + R_{oo}) A_n \quad \dots (6.43)$$

and as shown in equation 6.14 the modified constriction resistance,

$$R_{mod} = R_T \cdot g(\gamma) \quad \dots (6.44)$$

6.6.2 Grease-Filled Contact (Case B)

The constriction resistance per unit area for N_m micro-contacts of mean radius $\bar{a}_o$ is given

$$R_{mo} = \frac{1}{2 \bar{a}_o N_m k_{TO}} \quad \dots (6.45)$$

similarly the constriction resistance per unit area for N_o micro-contacts of mean radius $\bar{a}_o$ becomes

$$R_o = \frac{1}{2 \bar{a}_o N_o k_{so}} \quad \dots (6.46)$$

now the total conductance for this case is

$$\frac{1}{R_T} = \left(\frac{1}{R_{mo}} + \frac{1}{R_o} \right) / A_n \quad \dots (6.47)$$

and the total resistance is

$$R_T = \frac{A_n}{\left(\frac{1}{R_{mo}} + \frac{1}{R_o}\right)} \quad \dots \quad (6.48)$$

and therefore,

$$R_{mod} = R_T \cdot g(\gamma) \quad \dots \quad (6.49)$$

6.6.3 Soft Thin Oxide Coatings (Case C)

The constriction resistance per unit area for N_T micro-contacts of mean radius $\bar{a}_o$ becomes

$$R_T = \frac{1}{2 \bar{a}_o N_T k_{so}} \quad \dots \quad (6.50)$$

and

$$R_{mod} = R_T \cdot g(\gamma) \quad \dots \quad (6.51)$$

6.7 THE CONSTRICTION RESISTANCE THEORY AS APPLIED TO OXIDIZED SURFACES

This is based on the work originated by Yip (6), who could not obtain quantitative confirmation of the model proposed because of the lack of information on the actual oxide film thickness of the tested specimens. Since the film thickness on actual specimens has been measured, therefore, an examination of the theory was carried out, for comparative purposes.

6.7.1 Description of the Contact Model and Theoretical Analysis

When two nominally flat and rough oxidized surfaces with an apparent contact area of A_n come into contact under a uniform stress, p , as shown in Fig. 6.4, it is assumed (133) that the oxides form uniformly on the two surfaces with thickness of x_1 and x_2 respectively. Such assumptions are commonly used in oxidation studies, in the determination of the rate of the oxide growth, and can be justified if the composition of the surrounding atmosphere is homogeneous.

It is assumed further that contact occurs where the surface profiles of the metal and the oxide cross the interface. For random surfaces, the probability of contact-area ratio, which is the ratio between the real contact and apparent contact areas, can be expressed in the form of :-

$$\gamma_{m1} = \int_{t_1 + x_1}^{\infty} \int_{t_1 + x_1}^{\infty} \phi(t_a) \phi(t_b) dt_a dt_b \quad \dots \quad (6.52)$$

$$\gamma_{m2} = \int_{t_2 + x_2}^{\infty} \int_{t_2 + x_2}^{\infty} \phi(t_a) \phi(t_b) dt_a dt_b \quad \dots \quad (6.53)$$

for metal contact, and

$$\gamma_{T1} = \int_{t_1}^{\infty} \int_{t_1}^{\infty} \phi(t_a) \phi(t_b) dt_a dt_b \quad \dots \quad (6.54)$$

$$\gamma_{T2} = \int_{t_2}^{\infty} \int_{t_2}^{\infty} \phi(t_a) \phi(t_b) dt_a dt_b \quad \dots \quad (6.55)$$

for oxide and metal contacts. Here $\phi(t_a)$ and $\phi(t_b)$ are independent and uncorrelated probability functions in two orthogonal directions and are given by

$$\phi(t) = \frac{1}{\sqrt{2\pi}} \exp(-t^2/2) \quad \dots \quad (6.56)$$

for normal surfaces (2). Substitution of equation (6.56) in equations (6.52 - 6.55) results in :

$$\gamma_{m1} = \frac{1}{4} (1 - \operatorname{erf}(t_1 + x_1^*)/\sqrt{2})^2 \quad \dots \quad (6.57)$$

$$\gamma_{m2} = \frac{1}{4} (1 - \operatorname{erf}(t_2 + x_2^*)/\sqrt{2})^2 \quad \dots \quad (6.58)$$

$$\gamma_{T1} = \frac{1}{4} (1 - \operatorname{erf} (t_1/\sqrt{2}))^2 \quad \dots \quad (6.59)$$

$$\gamma_{T2} = \frac{1}{4} (1 - \operatorname{erf} (t_2/\sqrt{2}))^2 \quad \dots \quad (6.60)$$

The contact area ratios may be related to the interfacial loading pressure P and the micro hardness M_m of the materials by

$$\frac{P}{M} = \gamma_{m1} + \gamma_{m2} + (\gamma_{T1} + \gamma_{m1}) + (\gamma_{T2} - \gamma_{m2}) \frac{M_o}{M_m} \quad (6.61)$$

for fully plastic deformation.

Since the lower and upper surfaces are in direct contact, the total contact area of the upper and lower surface is equal; hence $\gamma_{T1} = \gamma_{T2}$. In view of equations (6.59 - 6.60), it follows that $t_1 = t_2 = t$, and equations (6.57 - 6.60) could further be reduced to

$$\gamma_{m1} = \frac{1}{4} (1 - \operatorname{erf} (t + x_1^*)/\sqrt{2})^2 \quad \dots \quad (6.62)$$

$$\gamma_{m2} = \frac{1}{4} (1 - \operatorname{erf} (t + x_2^*)/\sqrt{2})^2 \quad \dots \quad (6.63)$$

$$\gamma_{T1} = \gamma_{T2} = \frac{1}{4} (1 - \operatorname{erf} (t/\sqrt{2}))^2 \quad \dots \quad (6.64)$$

P , M_o , M_m , x_1 , and x_2 are independent variables; hence the four unknowns, γ_{m1} , γ_{m2} , γ_{T1} , (γ_{T2}), and t can be obtained from equation (6.61) and equations (6.62 - 6.64).

Because of the presence of oxide films, some of the oxide contact is made in annular regions, which are assumed to be symmetric about the metallic contact spots. The mean radii of the contact spots can be given by

$$\bar{a}_{m1} = (A_n \gamma_{m1} / N_{m1} \pi)^{\frac{1}{2}} \quad \dots \quad (6.65)$$

$$\bar{a}_{m2} = (A_n \gamma_{m2} / N_{m2} \pi)^{\frac{1}{2}} \quad \dots \quad (6.66)$$

for metal contact and

$$\bar{a}_{01} = (A_n \gamma_{T1} / N_{T1} \pi)^{\frac{1}{2}} \quad \dots \quad (6.67)$$

$$\bar{a}_{02} = (A_n \gamma_{T2} / N_{T2} \pi)^{\frac{1}{2}} \quad \dots \quad (6.68)$$

for oxide contacts. N_{m1} , N_{m2} , and N_{T1} , N_{T2} are respectively the number of metal and oxide contacts which could be visualised here as the number of crossings of the surface undulations over the common interface, and are given by :

$$\frac{N_{m1}}{A_n} = \psi^2 / 8\pi \exp - (t + x_1^*)^2 \quad \dots \quad (6.69)$$

$$\frac{N_{m2}}{A_n} = \psi^2 / 8\pi \exp - (t + x_2^*)^2 \quad \dots \quad (6.70)$$

$$\frac{N_{T1}}{A_n} = \psi^2 / 8\pi \exp (-t^2) \quad \dots \quad (6.71)$$

$$\frac{N_{T2}}{A_n} = \psi^2 / 8\pi \exp (-t^2) \quad \dots \quad (6.72)$$

where

$$\psi = \frac{|\bar{\Psi}|}{\sigma}$$

where σ is the RMS roughness and $|\bar{\Psi}|$ is the absolute mean slope of surface irregularities which can be determined from the surface profile measurements. The number of circular oxide contacts is, therefore,

$$N_{01} = N_{T1} - N_{m1} \quad \dots \quad (6.73)$$

$$N_{02} = N_{T2} - N_{m2} \quad \dots \quad (6.74)$$

The constriction resistance within the apparent contact area, A_n for the upper half of the resistance can be expressed as the sum of the resistances of all the contacts in parallel (107). Based on the constriction theory, the reciprocal of the constriction resistance of the upper half is given by

$$\begin{aligned} 1/R_{m01} = & (\pi/4\phi_1) (k_{m1}\bar{a}_{m1}N_{m1} + k_{m1}\bar{a}_{m2}N_{m2} + k_{01}\bar{a}_{01}N_{01} + k_{01}\bar{a}_{02}N_{02}) \\ & + (\pi/4\phi_2) (k_{01}\bar{a}_{01}N_{m1} + k_{01}\bar{a}_{02}N_{m2}) \dots (6.75) \end{aligned}$$

where ϕ_1 and ϕ_2 are the constriction factors for circular and annular contacts, respectively. The uniform heat flux assumption used in the steady state heat-conduction equation leads to an upper bound solution for ϕ_1 and ϕ_2 :

$$\phi = \frac{1}{y\alpha^2(2-\alpha)^2} \int_{n=1}^{\infty} \frac{J_1(y\beta_n) - 1 - \alpha J_1(y\beta_n(1-\alpha))^2}{\beta_n^3 J_0^2(\beta_n)} \dots (6.76)$$

with

$$J_1(\beta_n) = 0 \dots (6.77)$$

where y is the square root of the total contact area ratio, given as

$$y = \sqrt{\gamma_{t1} + \gamma_{t2}} \dots (6.78)$$

and α is the annular contact width ratio, approximated by

$$\alpha = \frac{(\bar{a}_{01} - \bar{a}_{m1}) + (\bar{a}_{02} - \bar{a}_{m2})}{\bar{a}_{01} + \bar{a}_{02}} \dots (6.79)$$

Similarly, the reciprocal of the constriction resistance for the lower half of the interface can be described by

$$\begin{aligned}
1/R_{m02} = & (\pi/4\phi_1) (k_{m2} \bar{a}_{m1} N_{m1} + k_{m2} \bar{a}_{m2} N_{m2} \\
& + k_{02} \bar{a}_{01} N_{0L} + k_{02} \bar{a}_{02} N_{02}) \\
& + (\pi/4\phi_2) (k_{02} \bar{a}_{02} N_{m1} + k_{02} \bar{a}_{02} N_{m2}) \dots (6.80)
\end{aligned}$$

The total constriction resistance is, therefore,

$$R_{Tot} = R_{m01} + R_{m02} \dots (6.81)$$

for the upper and lower halves of the interface.

A close examination of equations (6.62 - 6.81) shows that once the parameters, σ , $|\bar{\psi}|$, x^* , P/M_m , M_o/M_m , k_m and k_o , are identified for the upper and lower surfaces, the constriction resistance can be calculated.

A computer program has been developed (see Appendix III) and the approach taken has been to assign an initial value of t and then to solve for γ_m , γ_T , P/M_m and R_{Tot} to establish the relationship between R_{Tot} and P/M .

The theory is based on the concept of level crossing theory according to which the micro-contacts would appear on any contacting surface which crosses the level and hence provides little for comparison with the present theory. Therefore, the theory had to be modified so as to enable the prediction of the contact parameters of the softer of the contacting surfaces. This was achieved by replacing the mean surface slope Ψ where $\Psi = \frac{|\bar{\psi}|}{\delta}$ by the effective surface slope in equation (6.70), i.e.

$$N_{m2}/A_n = \psi_s^2/8\pi \exp - (t + x_2^*)^2 \dots (6.82)$$

Similarly replacing Ψ with ψ_s in equation (6.72)

i.e.

$$N_{T2}/A_n = \psi_s^2/8\pi \exp - t^2 \dots (6.83)$$

Also since the top and the bottom surfaces are in direct contact therefore, $\bar{a}_{m1} = \bar{a}_{m2}$ and $\bar{a}_{o1} = \bar{a}_{o2}$ and also the number of contacts of the upper surface is equal to the number of micro-contacts of the lower surface.

Where $\bar{a}_{m2}$ and $\bar{a}_{o2}$ is given by equations (6.66) and (6.68) respectively; y and α from equation (6.78) and equation (6.79) respectively is

$$y = \sqrt{2 rt_2} \quad \dots \quad (6.84)$$

$$\alpha = \frac{\bar{a}_{o1} - \bar{a}_{m1}}{\bar{a}_{o1}} \quad \dots \quad (6.85)$$

and therefore equation (6.75) for the reciprocal of the thermal resistance for the upper half of the interface can be written as

$$\begin{aligned} \frac{1}{R_{m01}} &= (\pi/4\phi_1) (2 k_{m1} \bar{a}_{m2} N_{m2} + 2 k_{o1} \bar{a}_{o2} N_{o2}) \\ &+ (\pi/4\phi_2) (2 k_{o1} \bar{a}_{o2} N_{m2}) \quad \dots \quad (6.86) \end{aligned}$$

and similarly equation (5.80) for the reciprocal of the thermal resistance for the lower half of the interface can be written as

$$\begin{aligned} \frac{1}{R_{m02}} &= \pi/4\phi_1 (2 k_{m2} \bar{a}_{m2} N_{m2} + 2 k_{o2} \bar{a}_{o2} N_{o2}) \\ &+ \frac{\pi}{4\phi_2} (2 k_{o2} \bar{a}_{o2} N_{m2}) \quad \dots \quad (6.87) \end{aligned}$$

this modification predicted comparatively higher resistances.

6.7.2 Assumptions

- i) Oxides form uniformly on the surfaces studied and so the presence of oxide does not alter the original profile of the surface.

- ii) Heat conduction mode at the point of contact is considered and the role of radiation and fluid convection/conduction is regarded as suppressed by low thermal differential across the interface (i.e. less than 50°C) and by the low surrounding pressures.
- iii) The heat flux is uniform.
- iv) The deformation is fully plastic.
- v) The number of the oxide and metal contacts are visualized as crossings and the contact is assumed to occur where the surface profile of the metal and the oxide cross the interface.
- vi) The contact spots are circular and uniformly distributed within the apparent contact area.
- vii) Micro-contact resistance has been considered only, the macro-contact resistance is negligibly small for flat surfaces in contact under a uniform loading pressure.
- viii) The loading pressure, P , the hardness of the metal, M_m , the hardness and film thickness of the oxide M_o and x , respectively, have been treated as independent variables.
- ix) It is assumed that the total area of the upper contacting surface is equal to the total area of the lower surface. This assumption is limited in the sense that it suppresses the allowance for different oxide levels on each contacting surface.

6.8 ANALYTICAL SOLUTION

From Fig. 5.6 which represents a hard rough surface in contact with a soft smooth flat surface

$$y = \frac{x}{\tan \theta} \quad \dots \quad (6.88)$$

and

$$\bar{a}_o = \bar{a}_m + y \quad \dots \quad (6.89)$$

The dimensionless real area of metal-to-metal contact due to the presence of the oxide can be predicted from probability integral, i.e.

$$A_{rmo}/A_n = \frac{1}{2} - \frac{1}{\sqrt{2\pi}} \int_0^{\beta} e^{-t^2/2} \cdot dt \quad \dots \quad (6.90)$$

similarly the dimensionless total area of contact

$$A_o/A_n = \frac{1}{2} - \frac{1}{\sqrt{2\pi}} \int_0^\beta \exp \left(-t - \frac{x_1}{\sigma_1} - \frac{x_2}{\sigma_2} \right)^2 / 2 \cdot d \left(t - \frac{x_1}{\sigma_1} - \frac{x_2}{\sigma_2} \right) \cdot \dots \dots \dots (6.91)$$

A solution for the above equations can be obtained by using tabulated values of error functions (134) or alternatively:

$$\text{erf} (\alpha) = \frac{2}{\sqrt{\pi}} \int_0^\alpha e^{-t^2/2} \cdot dt \cdot \dots \dots (6.92)$$

and its approximate solution

$$\text{erf} (\alpha) = \frac{2}{\sqrt{\pi}} \left(\alpha - \frac{\alpha^3}{3} + \frac{\alpha^5}{5.2} - \frac{\alpha^7}{7.3} + \dots \right) \dots \dots (6.93)$$

Now assuming circular micro-contacts the dimensionless real area of metal-to-metal contact as obtained from equation (6.90) can be written as

$$\frac{A_{rmo}}{A_n} = \frac{\pi \bar{a}_m^2 N_{mo}}{A_n} \dots \dots (6.94)$$

or

$$A_{rmo} = \pi \bar{a}_{mo}^2 N_{mo} \dots \dots (6.95)$$

and its corresponding thermal resistance.

$$R_{mo} = \frac{1}{2 \bar{a}_{mo} N_{mo} k_{To}} \dots \dots (6.96)$$

Similarly the dimensionless total area of contact as obtained from equation (6.91) can be written as

$$A_{rT} = \pi \bar{a}_o^2 N_T \quad \dots \quad (6.97)$$

or

$$N_T = A_{rT} / \pi \bar{a}_o^2 \quad \dots \quad (6.98)$$

also

$$N_T = N_{mo} + N_{oo} \quad \dots \quad (6.99)$$

∴ Number of oxide-to-oxide contact

$$N_{oo} = N_T - N_{mo} \quad \dots \quad (6.100)$$

Similarly the radius of the oxide-to-oxide contact

$$\pi \bar{a}_o^2 N_T = \pi \bar{a}_{mo}^2 N_{mo} + \pi (N_T - N_{mo}) \pi \bar{a}_{oo}^2 N_T \quad \dots \quad (6.101)$$

and

$$R_{oo} = \frac{1}{2 \bar{a}_{oo} k_s N_{oo}} \quad \dots \quad (6.102)$$

and the total resistance

$$R_{TOT} = (R_{mo} + R_{oo}) A_n \quad \dots \quad (6.103)$$

CHAPTER SEVEN

EXPERIMENTAL RESULTS AND DISCUSSION

7.1 SURFACE PREPARATION AND TOPOGRAPHY MEASUREMENTS

Each contact shown schematically in Fig. 6.2 comprised a mild steel EN3B upper specimen pressed against a commercially pure copper lower specimen.

The upper and lower specimens were ground, lapped and polished. The specimen end surfaces were sand-blasted and the specimens oxidized in a controlled environment. They were aligned in the thermal-contact rig, with their end faces horizontal. Their flatness deviations were measured by means of a Rank Taylor Hobson Talysurf 3 with a 152 mm specimen movement traversing table. The departures from a straight line movement did not exceed 2.5 μm even when operating under a maximum table load of 66N.

The pulses emitted by a Talysurf 4 profilometer were fed into a Solartron data logging system, which recorded 3200 ordinates, on the paper tape for each surface trace. The study was carried out with pre-selected input 'vertical' magnification for the surface ranging from 2,000 to 20,000 and a 'horizontal' magnification of 100. The data tape was subsequently processed using a surface analysis program (110) to evaluate the surface parameters, i.e. r.m.s. roughness and the mean surface slope etc.

The real area of contact of the actual specimens used for measuring thermal contact resistance was measured using a Quantimet 720 Image Analyser for the final test rig loading pressure, i.e. at $2 \times 10^7 \text{ N m}^{-2}$. During the vacuum tests it was not possible to measure the real area of contact formed between the specimens for intermediate stages, i.e. after each load increment. As an alternative the specimen assembly (comprising of the upper and the lower specimens) which had the same surface characteristics was separately pressed in the test rig under the same loading as applied during the vacuum tests and its area of actual contact measured.

7.2 THERMAL CONTACT RESISTANCE MEASUREMENTS

The degreased, oxidized specimens were placed in a vacuum test rig (109) and the contact resistance was measured using well-tried procedures (129, 130).

7.3 RESULTS AND DISCUSSION

A series of tests (hard rough surface in contact with a soft smooth surface) were conducted in vacuum better than 10^{-4} torrs. The contact resistances of both the oxide-free and the oxidized surfaces were measured. A preliminary requirement was to select a material which rapidly oxidizes, has its frequent use in engineering applications and could represent an ideal contact model. The contact model comprised of a mild steel EN3B upper specimen in contact with copper lower specimen.

Surface topography measurements in each case were taken before and after oxidation (see Fig. 7.1). The height distribution measurements of surface asperities revealed that the growth of the oxide was irregular and uneven. This made impracticable the measurement of the oxide film thickness by means of the Talysurf 4. Therefore, the predicted level on the surface profile was calculated by adding the oxide film thickness (normalized) measured using a Stereoscan Electron Microscope to the absolute value of the dimensionless mean plane separation.

7.3.1 CASE A (Brittle Fracture of Oxide Films)

For all the tests conducted the observed real area of contact (see Fig. 7.2 and Fig. 7.3) and its corresponding number of micro-contacts (see Fig. 7.4 and Fig. 7.5) were lower than those predicted as expected because of the inability of the experimental technique to detect micro-contacts of less than one micron. The theoretical predictions could therefore, be expected to be in excess of number of contacts detectable.

The predicted total area of the contact (defined as the sum of the real area of oxide-to-oxide contact and the additional area of the oxide-to-metal contact) increased due to the presence of the oxide but because the measured thermal conductivity of the oxide was less than that of the metal, therefore, it resulted in an increase of the overall thermal contact resistance.

Figs. (7.8 - 7.14) in which the thermal contact resistance is plotted as a function of the loading pressure for both the oxide-free and the oxidized contacts indicates that the thermal contact resistances increased as an effect of oxidation. The theoretical thermal resistance for the oxide-free and the oxidized contacts were predicted from equation (6.14) and equation (6.44) respectively using the values of the mean surface slope established by computer search procedures; to match the experimentally measured values of thermal contact resistance. Sample calculations showing the values of the slope used to calculate the thermal contact resistance (Fig. 7.8) are given in Appendix II. The theoretical resistance showed an increase when predicted from the observed number of micro-contacts (Figs. 7.10-7.13).

7.3.2 CASE B (Grease-filled Contact)

Figs. (7.15 & 7.16) present the resistance of the oxide-free as well as the oxidized contact. The predicted resistance of the oxidized contact would decrease compared with the oxide-free contact.

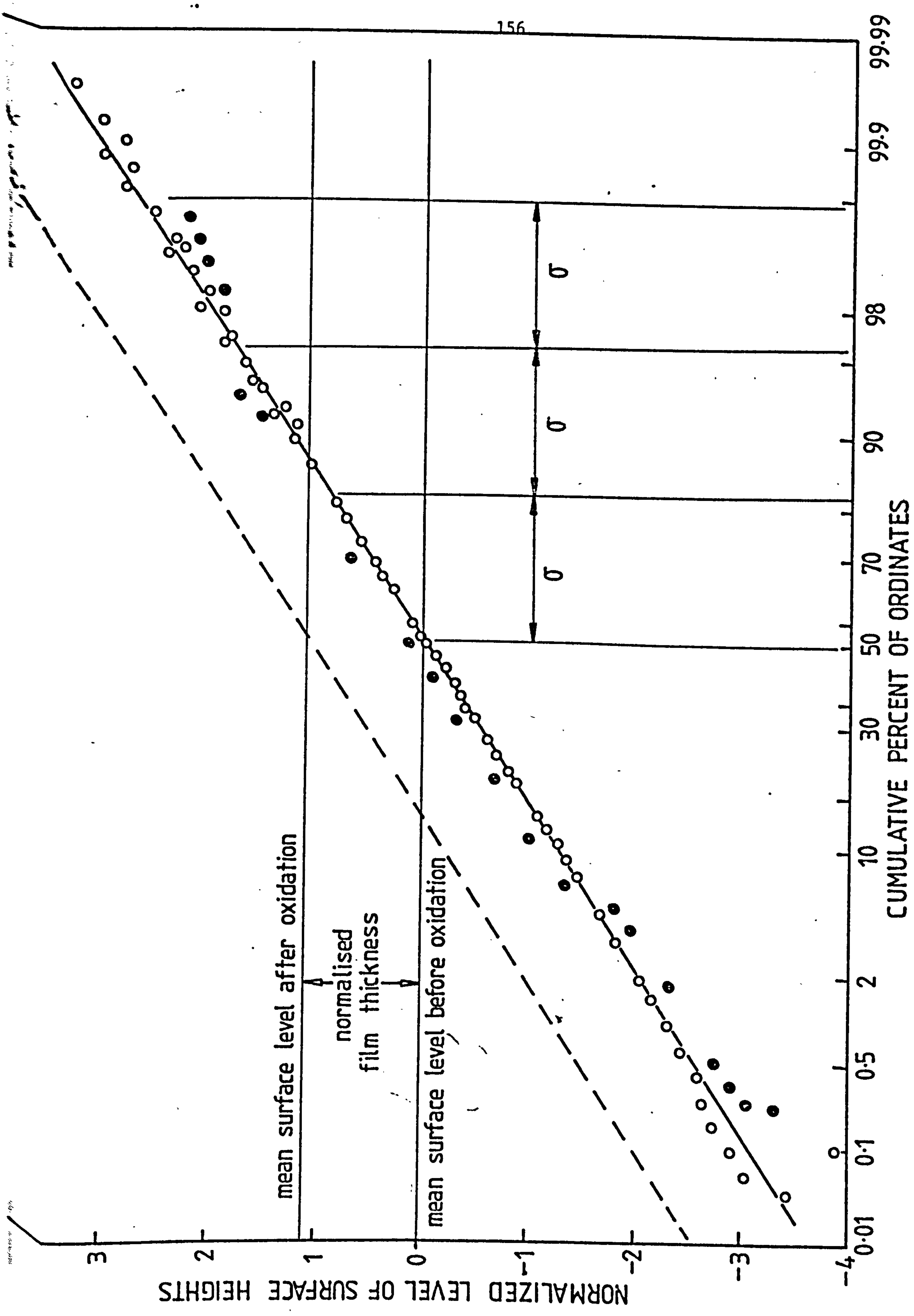


FIG. 7.1

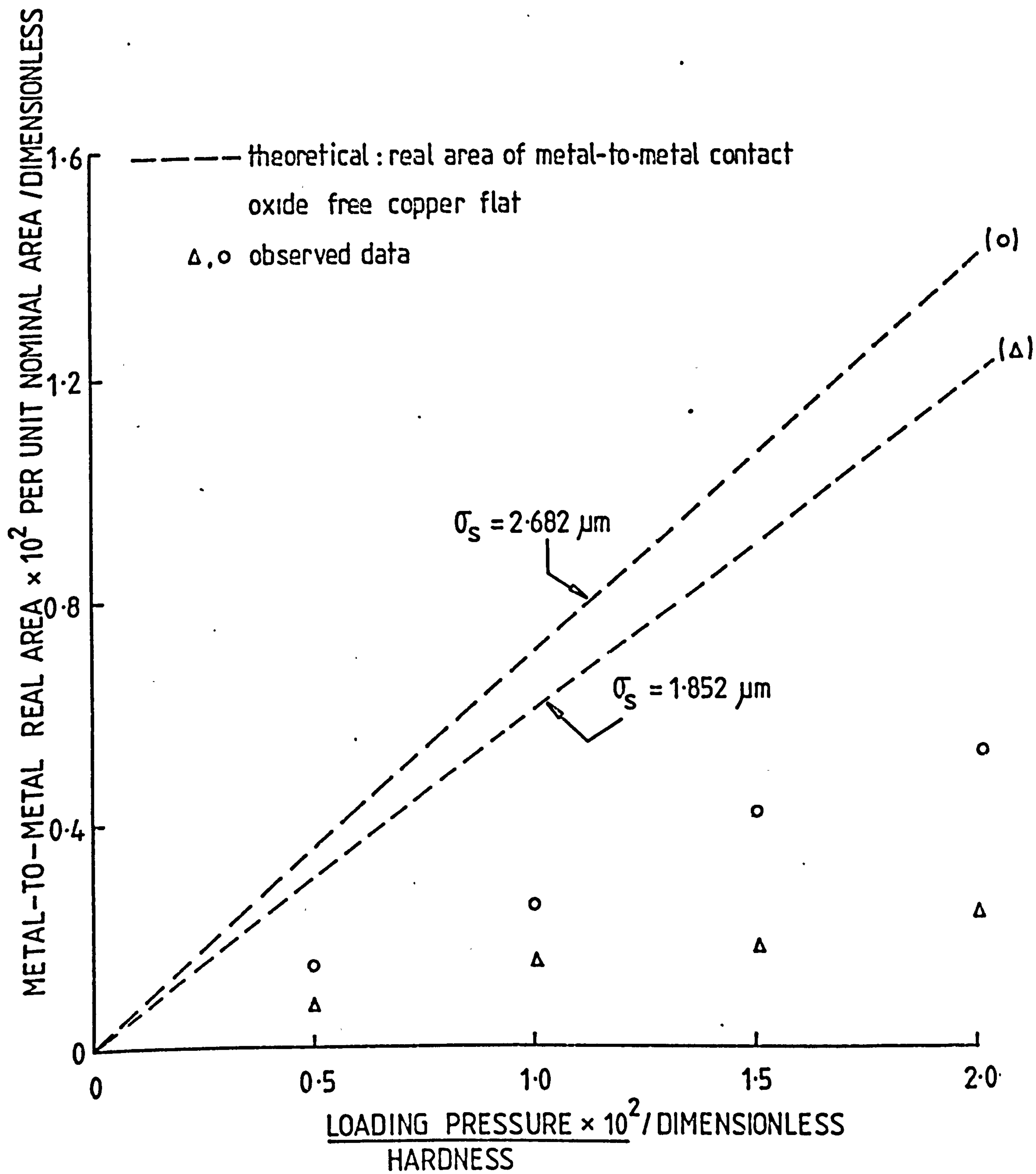


FIG. 7,2

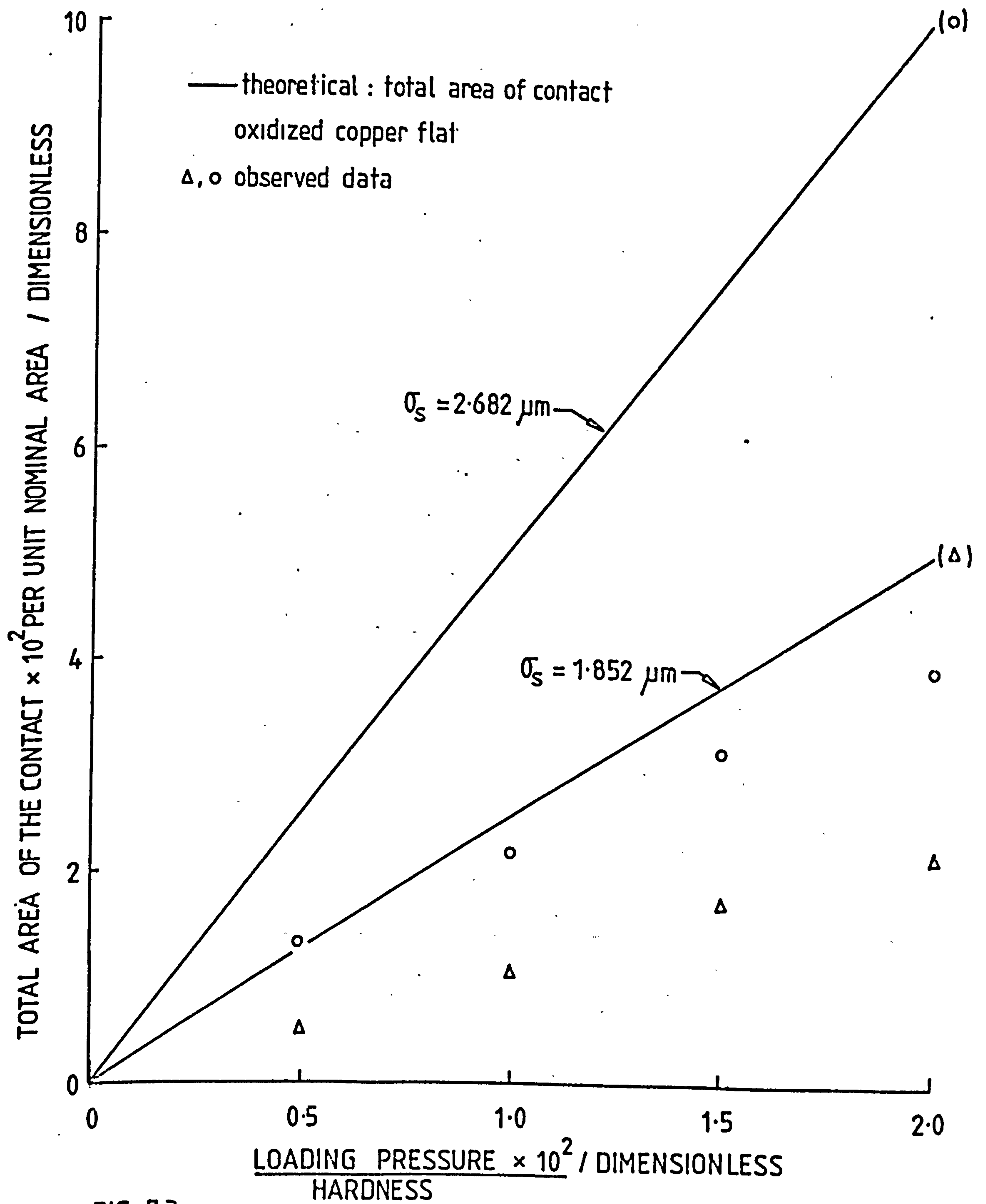


FIG. 7.3

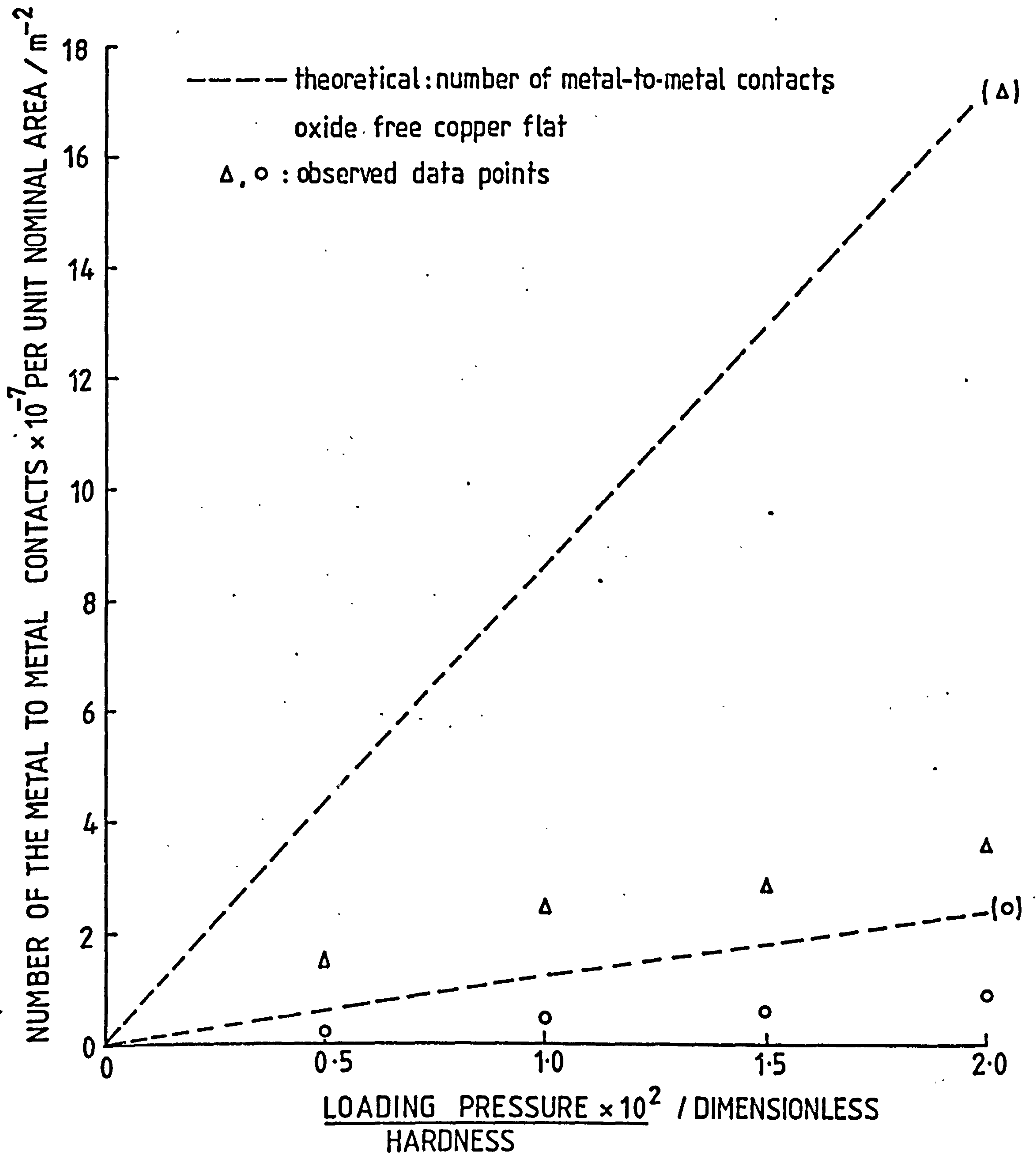


FIG. 7,4

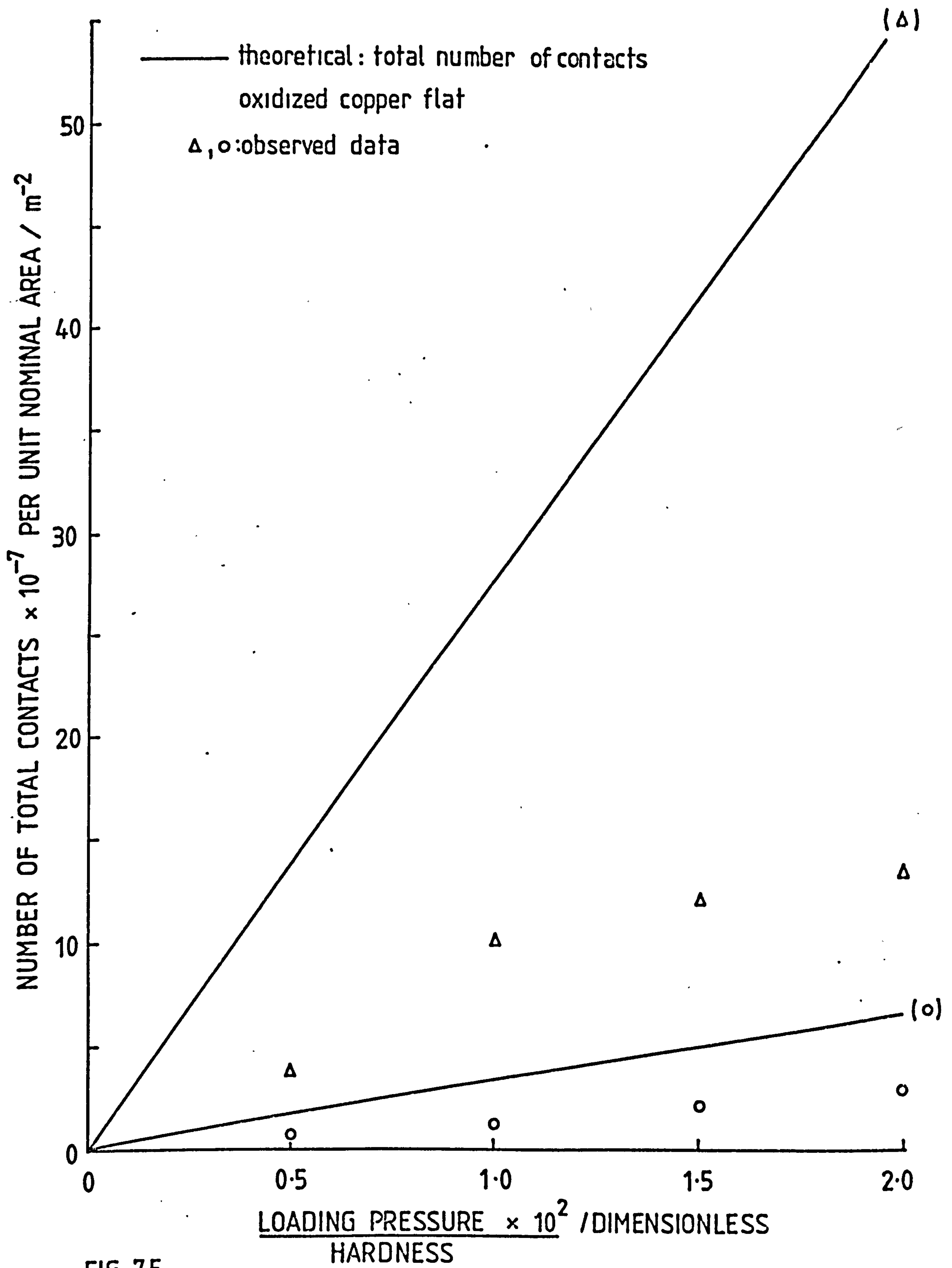


FIG. 7,5

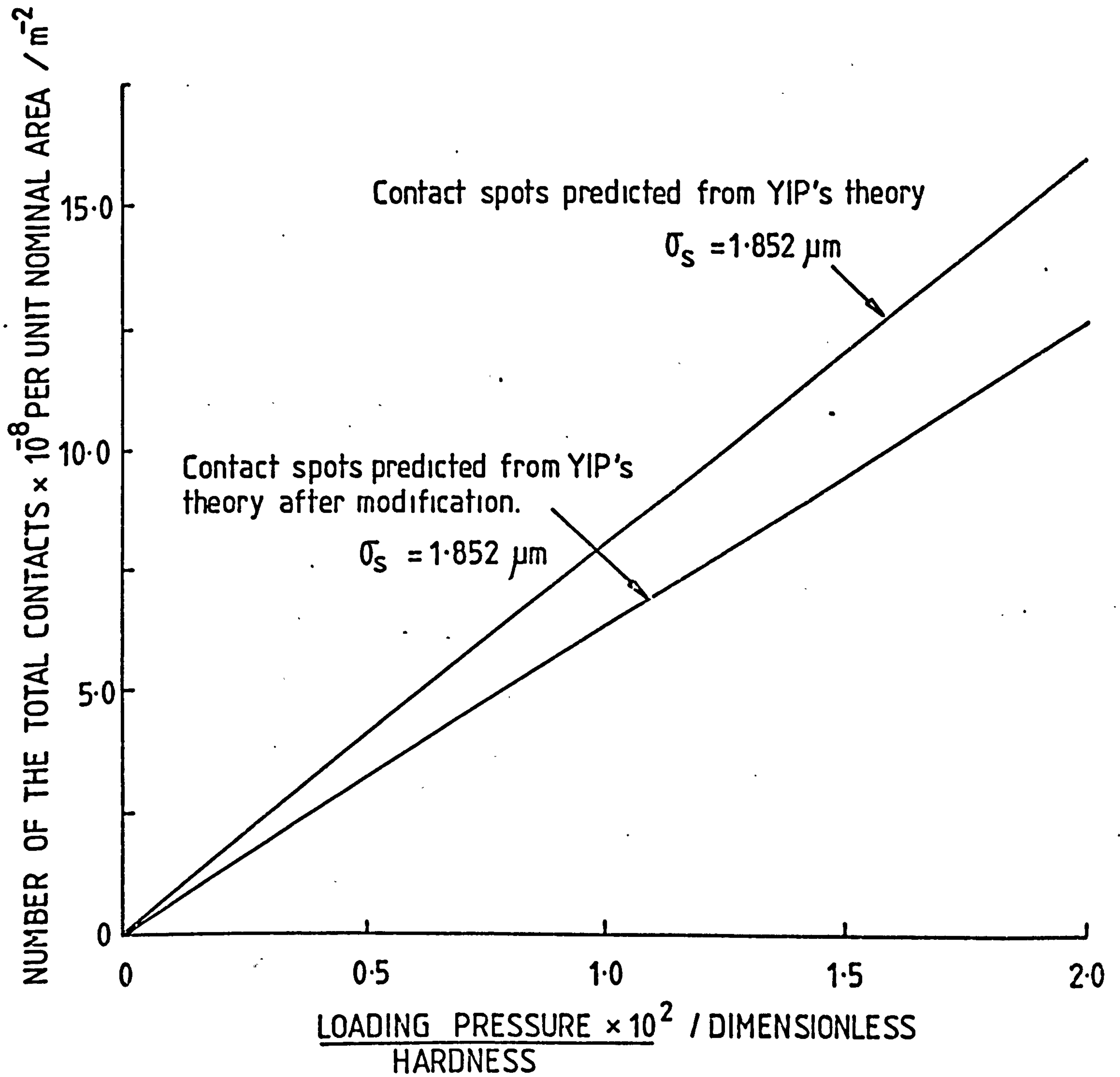


FIG. 7,6

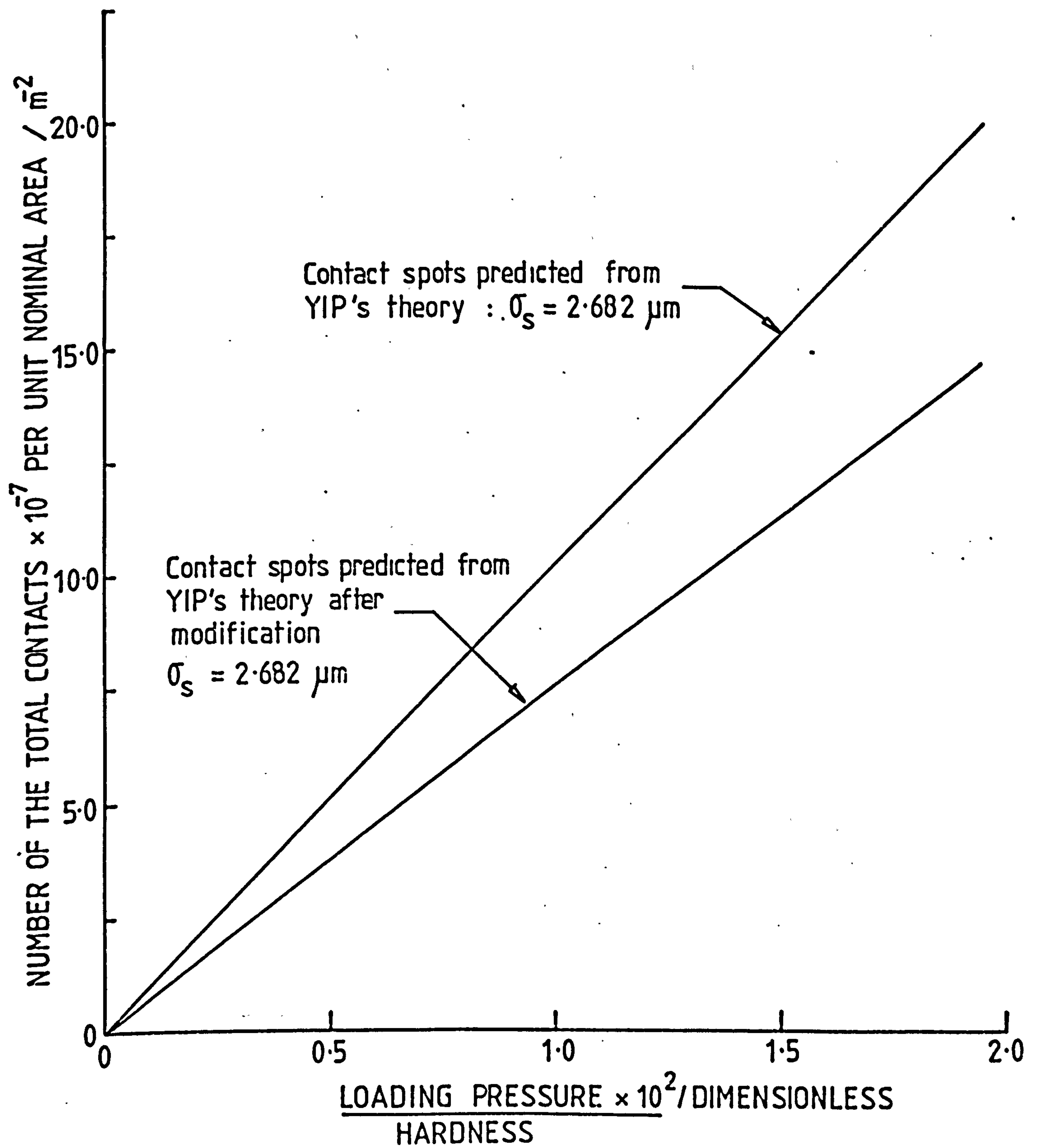


FIG. 7,7

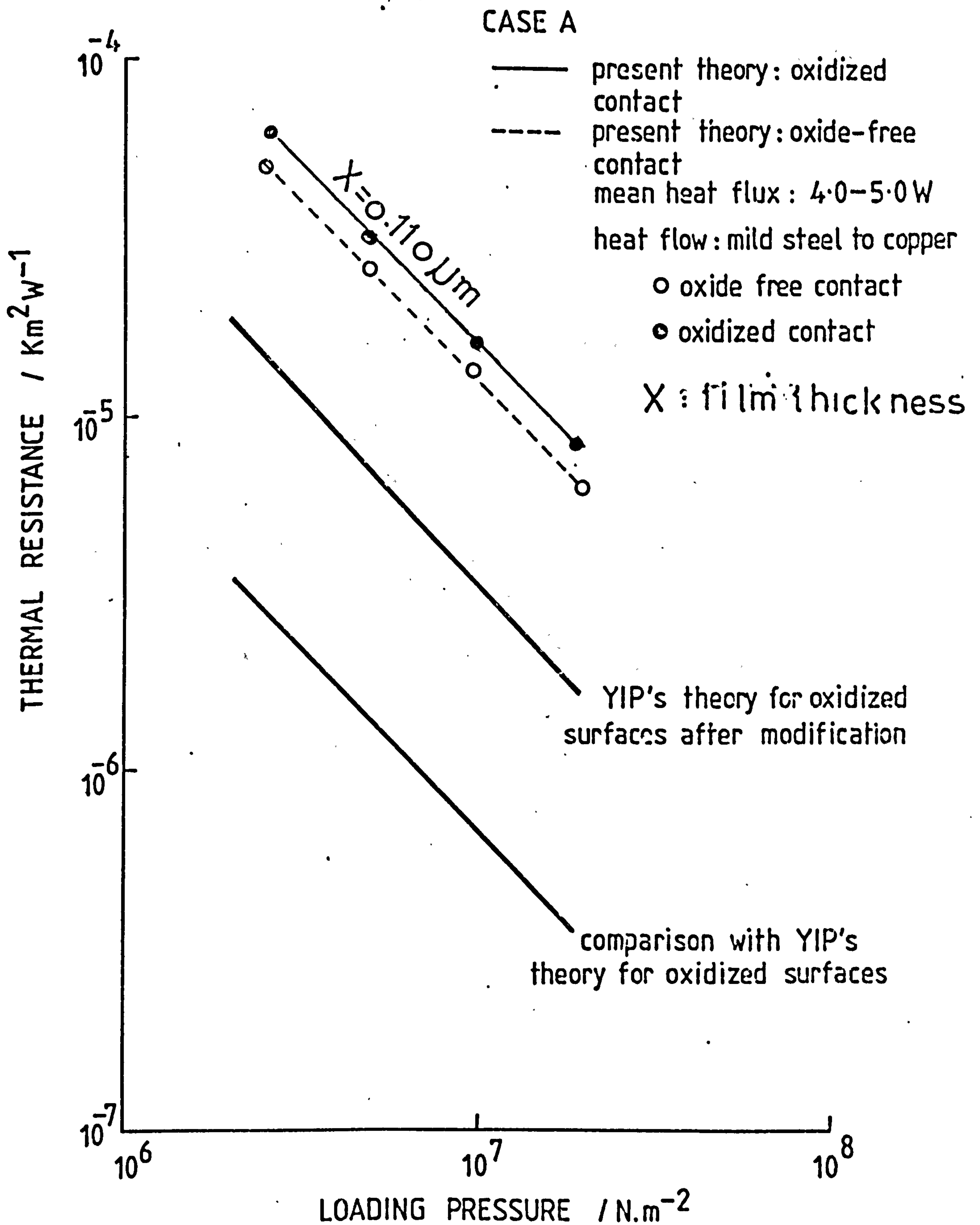


FIG. 7.8

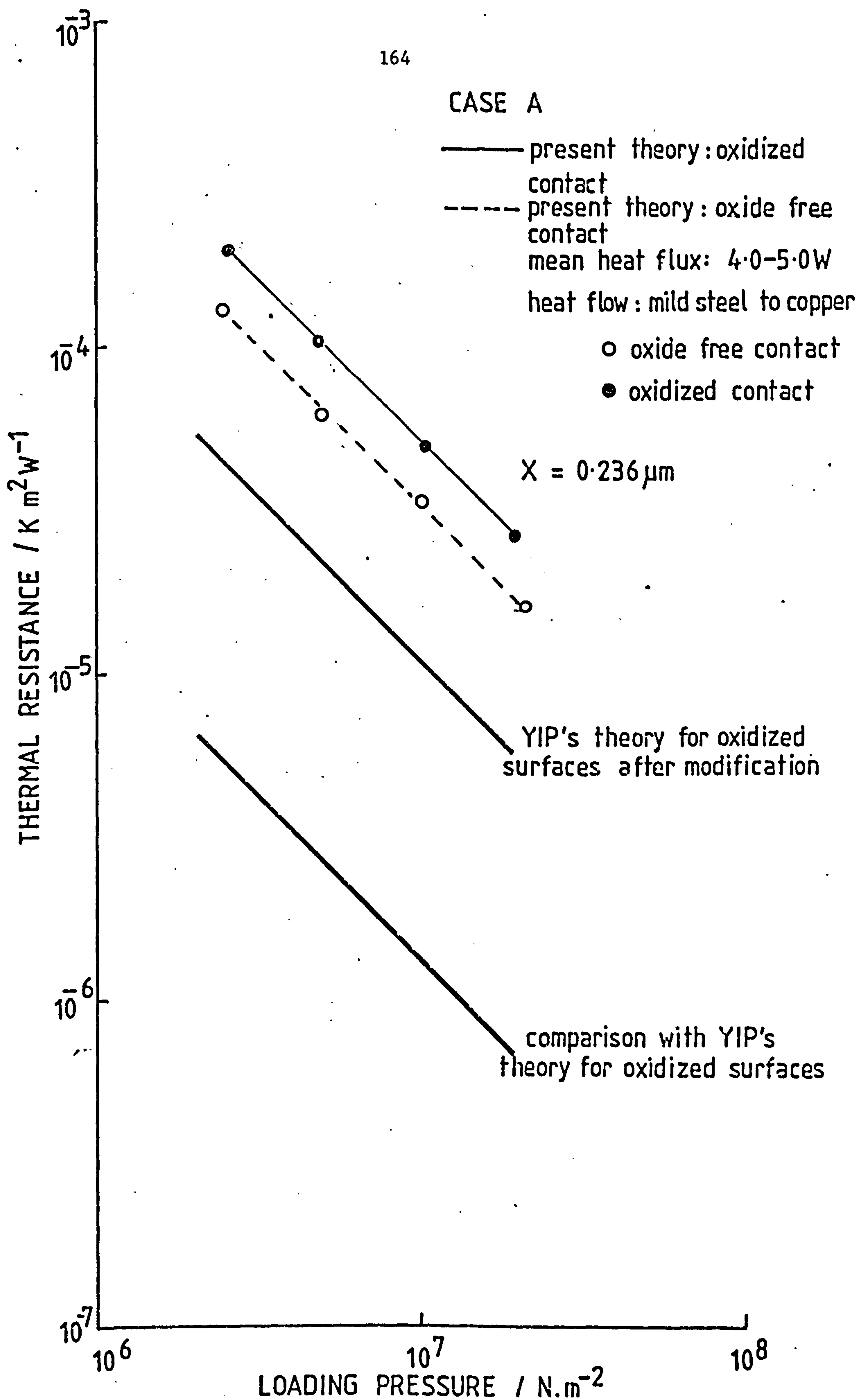


FIG. 7.9

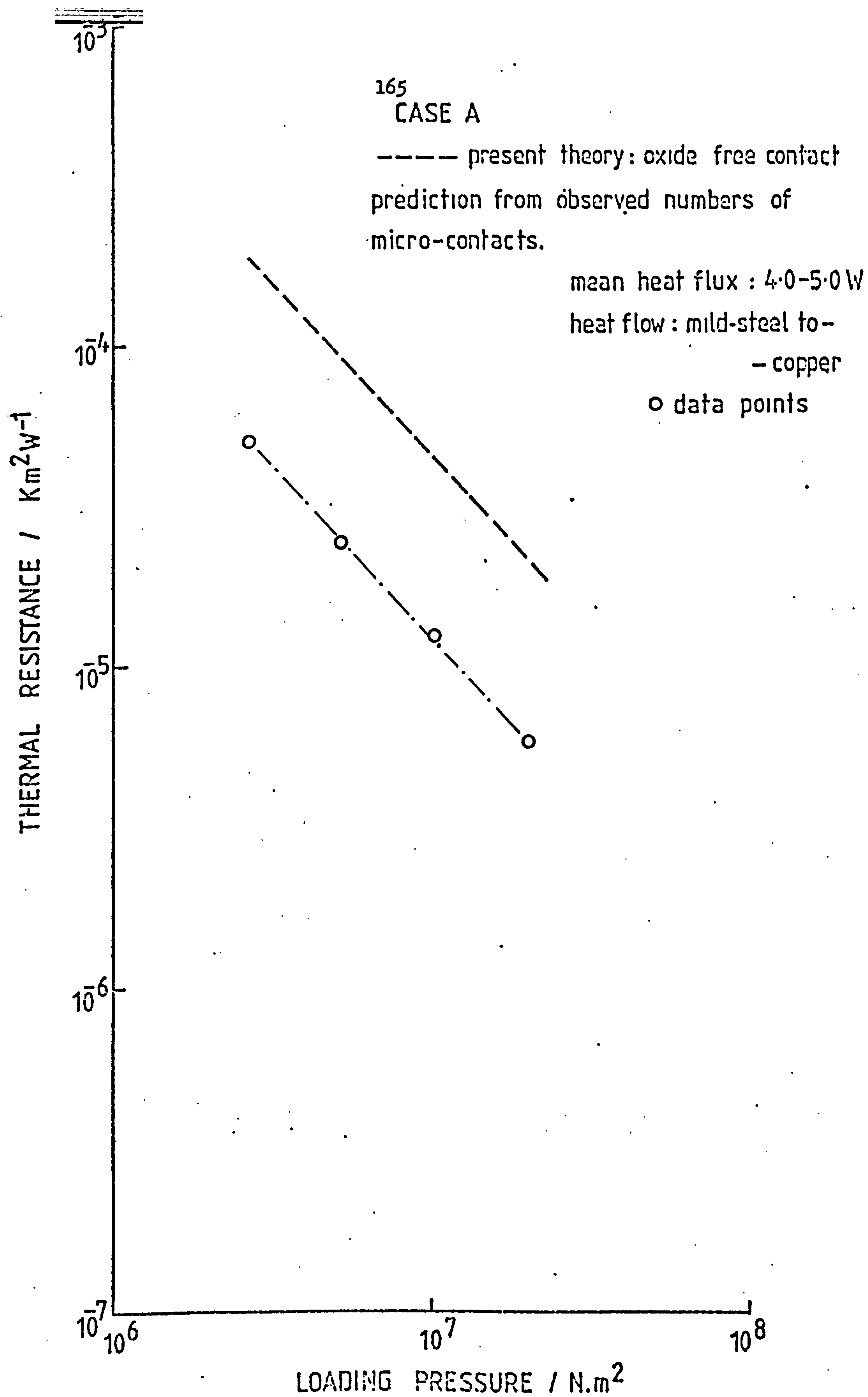


FIG. 7,10

CASE A

— present theory: oxidized contact
 predictions from observed number of
 micro-contacts.

mean heat flux: 4.0-5.0 W

heat flow: mild steel to -

-copper

○ data points

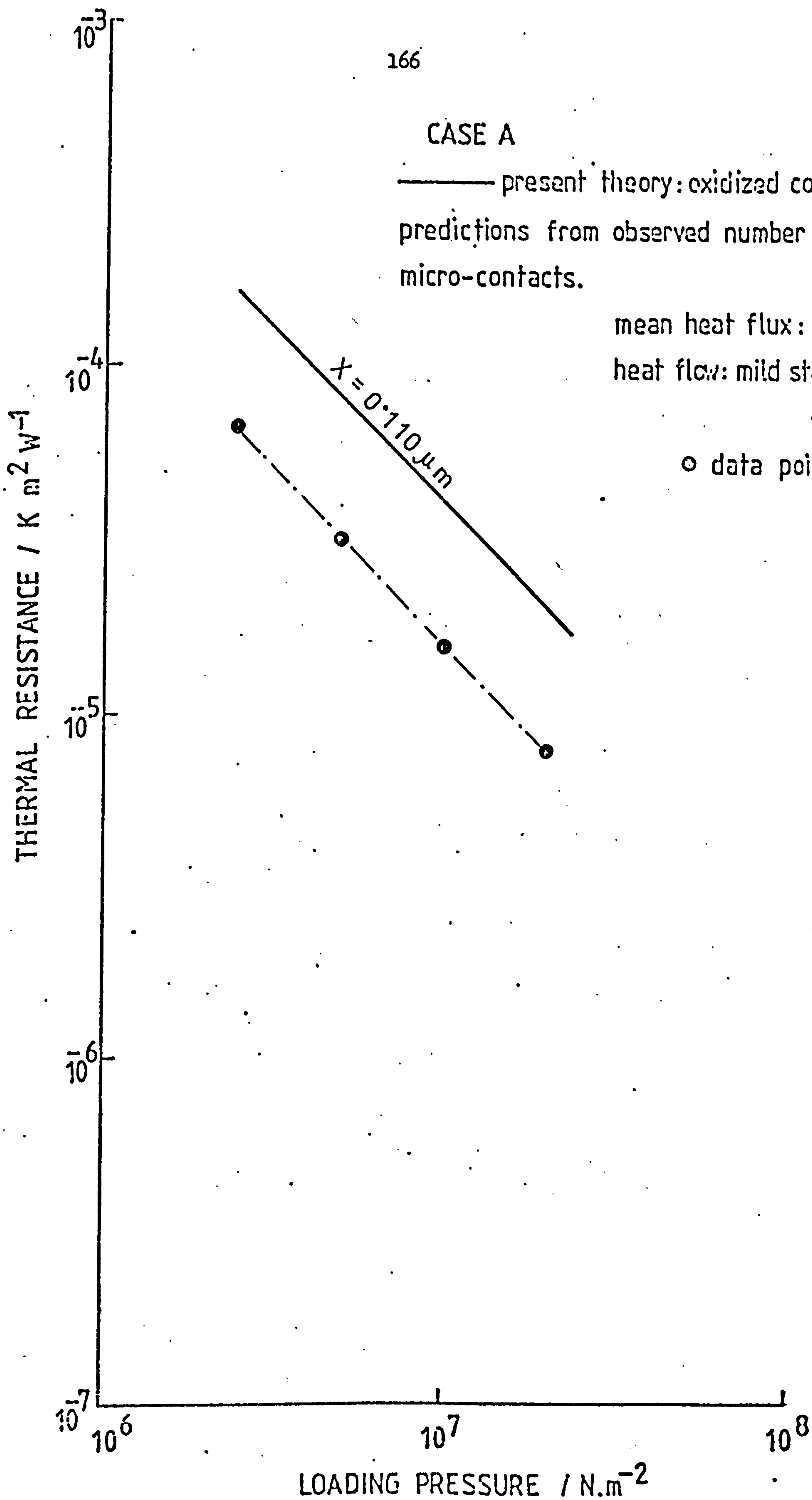


FIG. 7.1.1

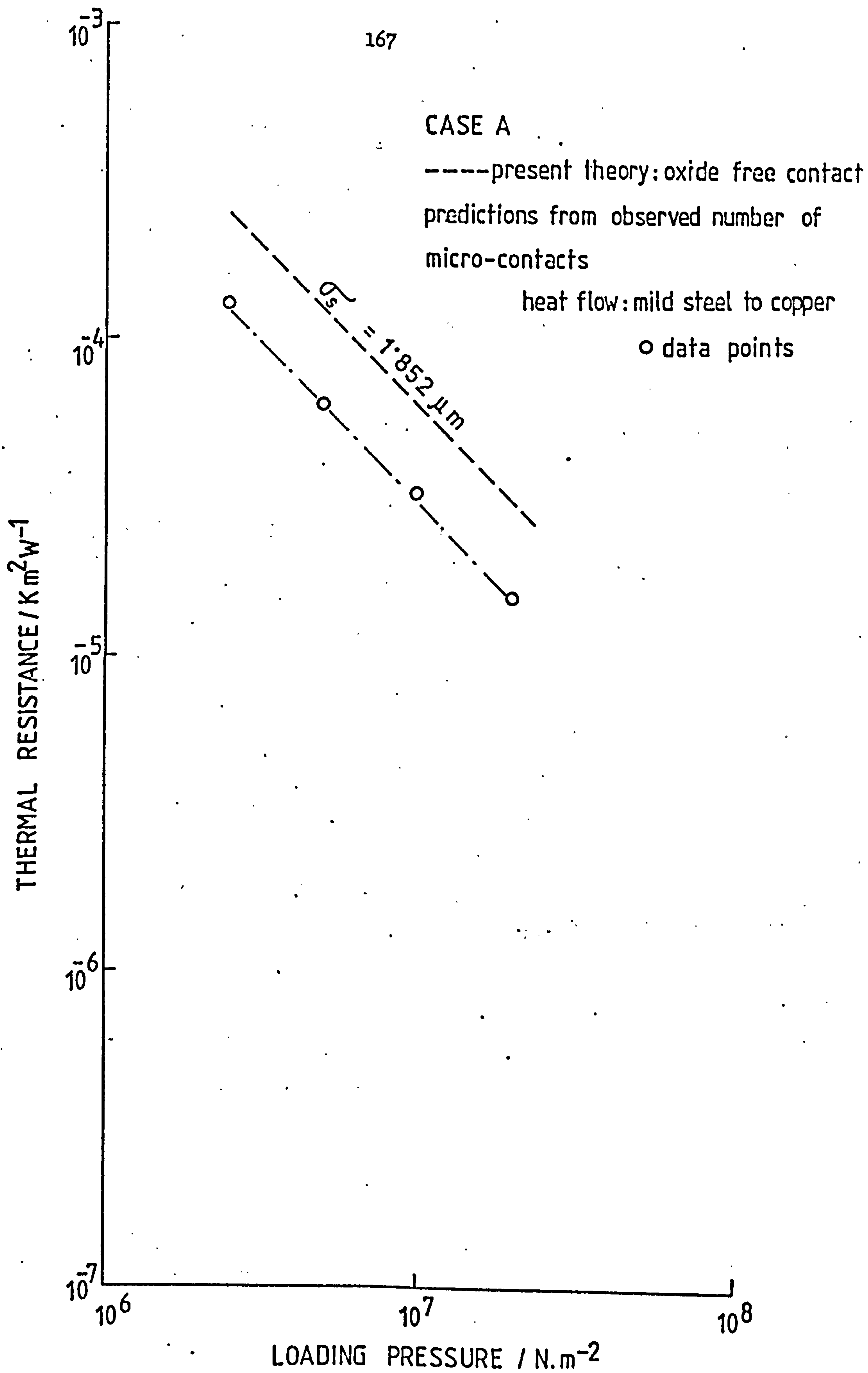


FIG. 7,12

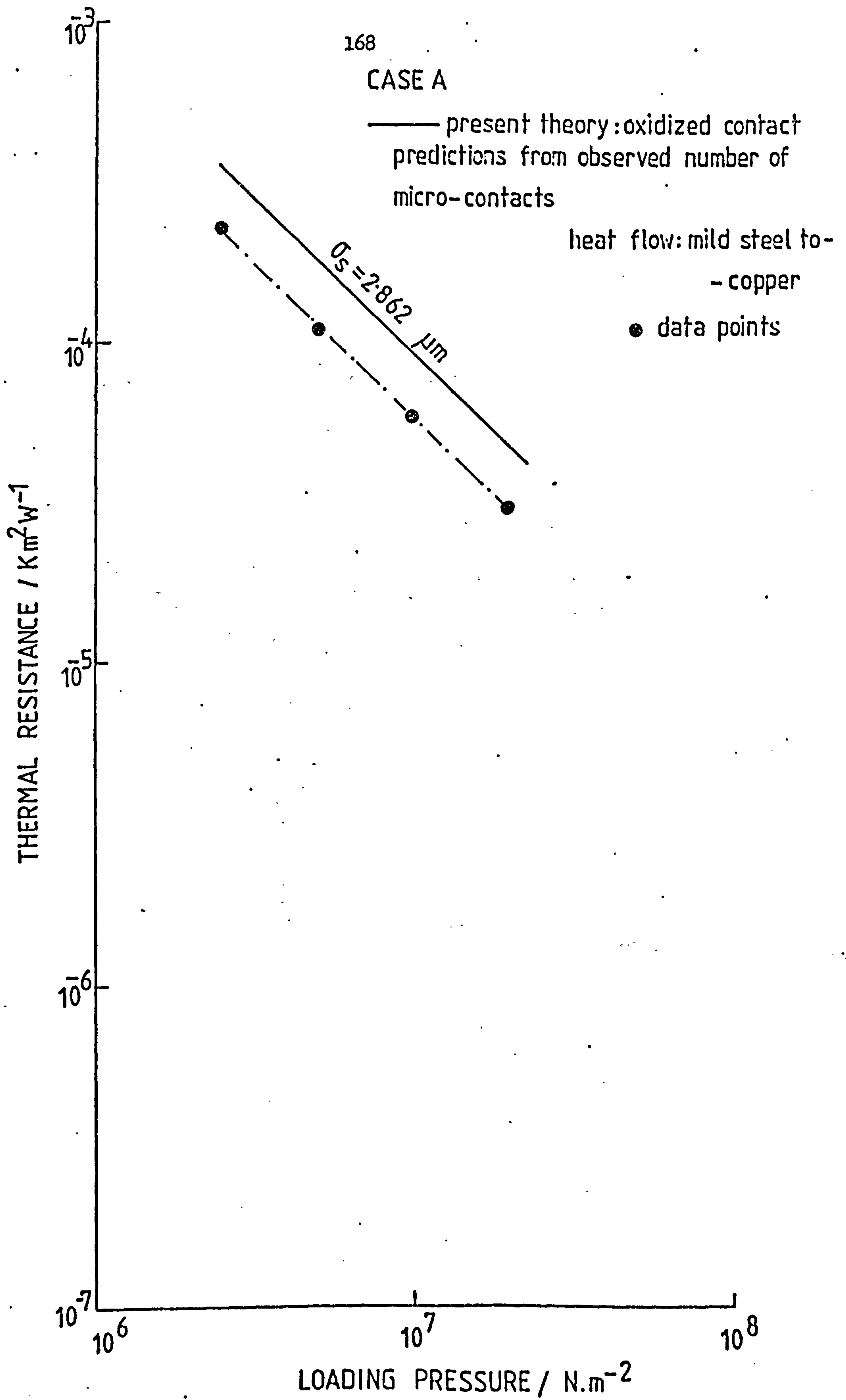


FIG. 7.13

CASE A

— present theory: oxidized contact

mean heat flux : 4.0–5.0 W

● heat flow from mild steel to copper

$$X = 0.400 \mu\text{m}$$

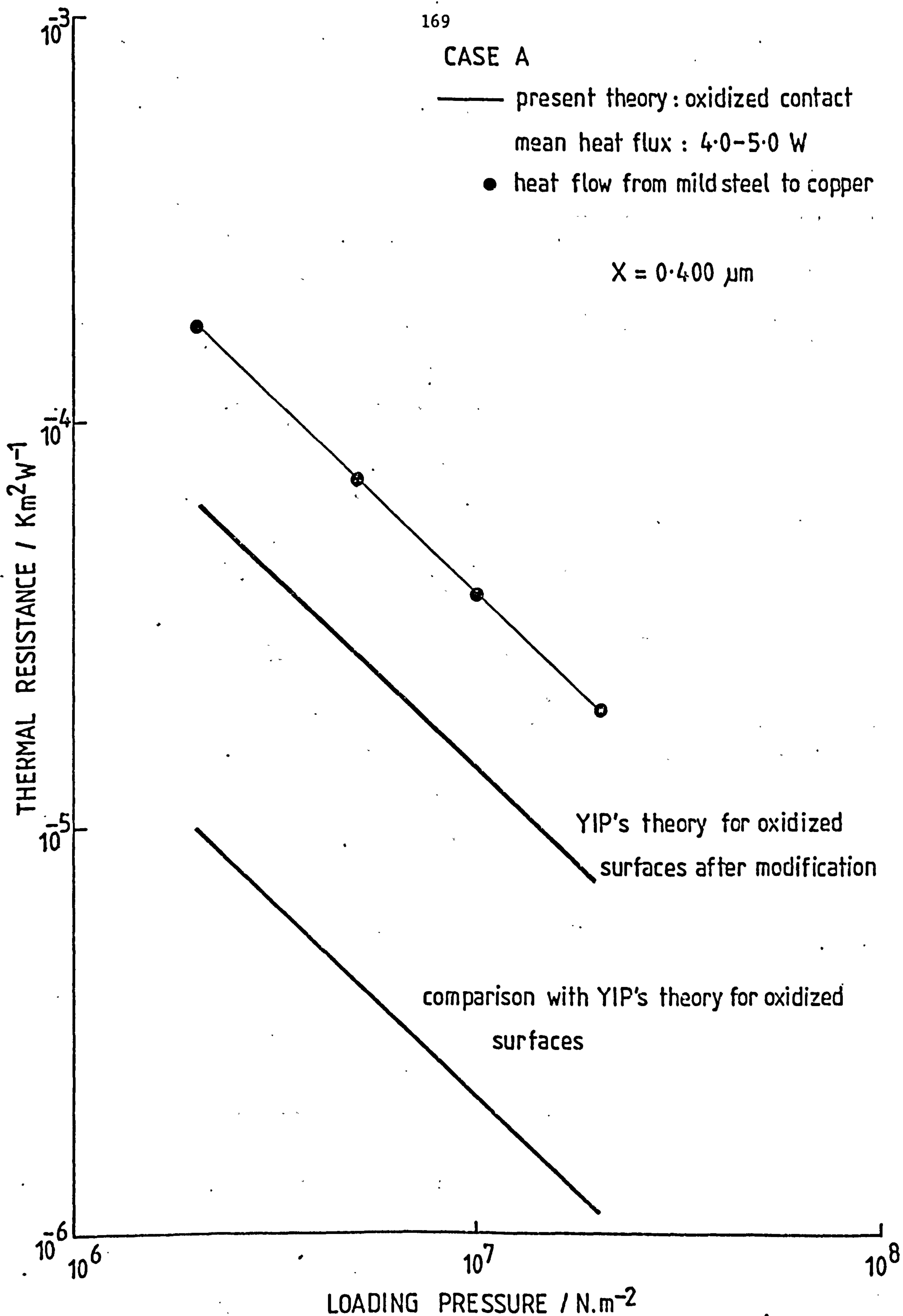


FIG. 7.14

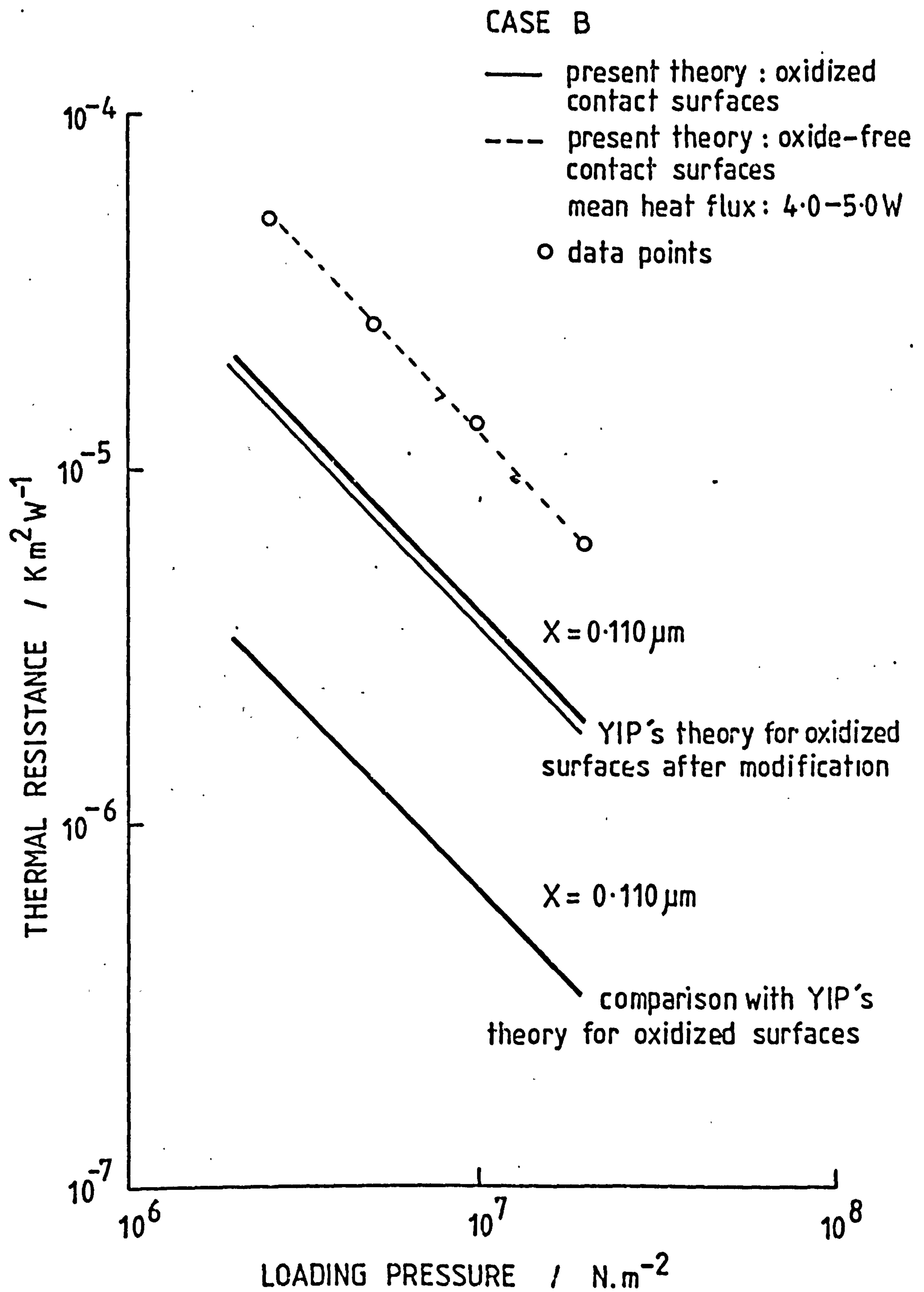


FIG. 7.15

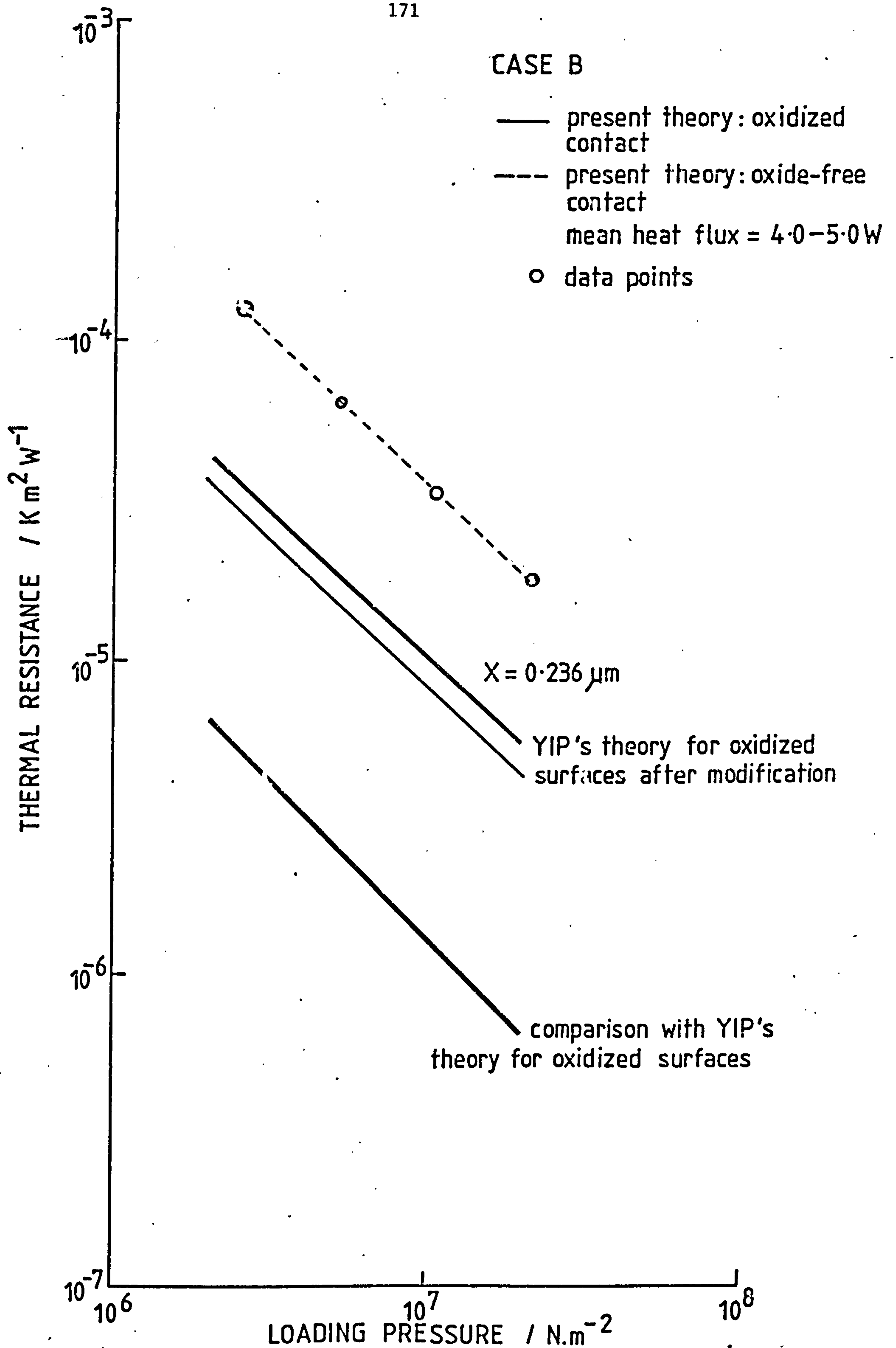


FIG. 7.16

A thin film softer than the softer contacting surfaces depending upon its thermal conductivity would affect the contact and consequently the contact resistance.

7.3.3 CASE C (Soft Thin Oxide Coatings)

The predicted contact resistance of the oxidized contact Fig. 7.17 and Fig. 7.18 would decrease compared with the oxide-free contact. This could be expected because soft and thin films sandwiched between contacting surfaces improve conductance upon contact.

7.3.4 CASE D (Insulated Surface Films)

The resistance which can be calculated from the ratio of the film thickness to thermal conductivity can be expected to increase. The theory has a limitation to be applicable to thick films.

7.3.5 Resistance Between Similar Materials

Figs. (7.19 - 7.22) in which thermal contact resistance is plotted as a function of applied loading show that the experimental resistance dropped considerably for the oxidized copper-to-copper contact compared with that of the oxidized mild steel-to-mild steel contact.

(Figs. 7.23 - 7.25 and Fig. 7.27) indicate that the thermal resistance increased with the thickness of oxide film and decreased with ascending loads.

Tsao and Heimbarg (99), during a study of the effect of surface films, observed that physically-absorbed gases led to a decrease in the thermal contact conductance by 10% and that this became more apparent, the smoother the surfaces.

Decreasing the applied load resulted in a slight hysteresis (Fig. 7.25) which also illustrated that some plastic deformation had occurred.

Figs. 7.26 and 7.27 in which the non-dimensional resistance is plotted for various ratios of film thickness ($x_1 + x_2$) to mean surface roughness of the two contacting surfaces and as a function of pressure respectively, showed that the thermal contact resistance increased with the ratio of film thickness to surface roughness. For EN3B mild steel the contact resistance was about twice that for a clean (i.e. oxide free) contact when the oxide film thickness was approximately four and a half times the surface roughness. Further increments in the ratio of film thickness to surface roughness led to only slight enhancements of the thermal contact resistance. Throughout the observations, the film thickness was the dominant variable rather than surface roughness in dictating the contact resistance.

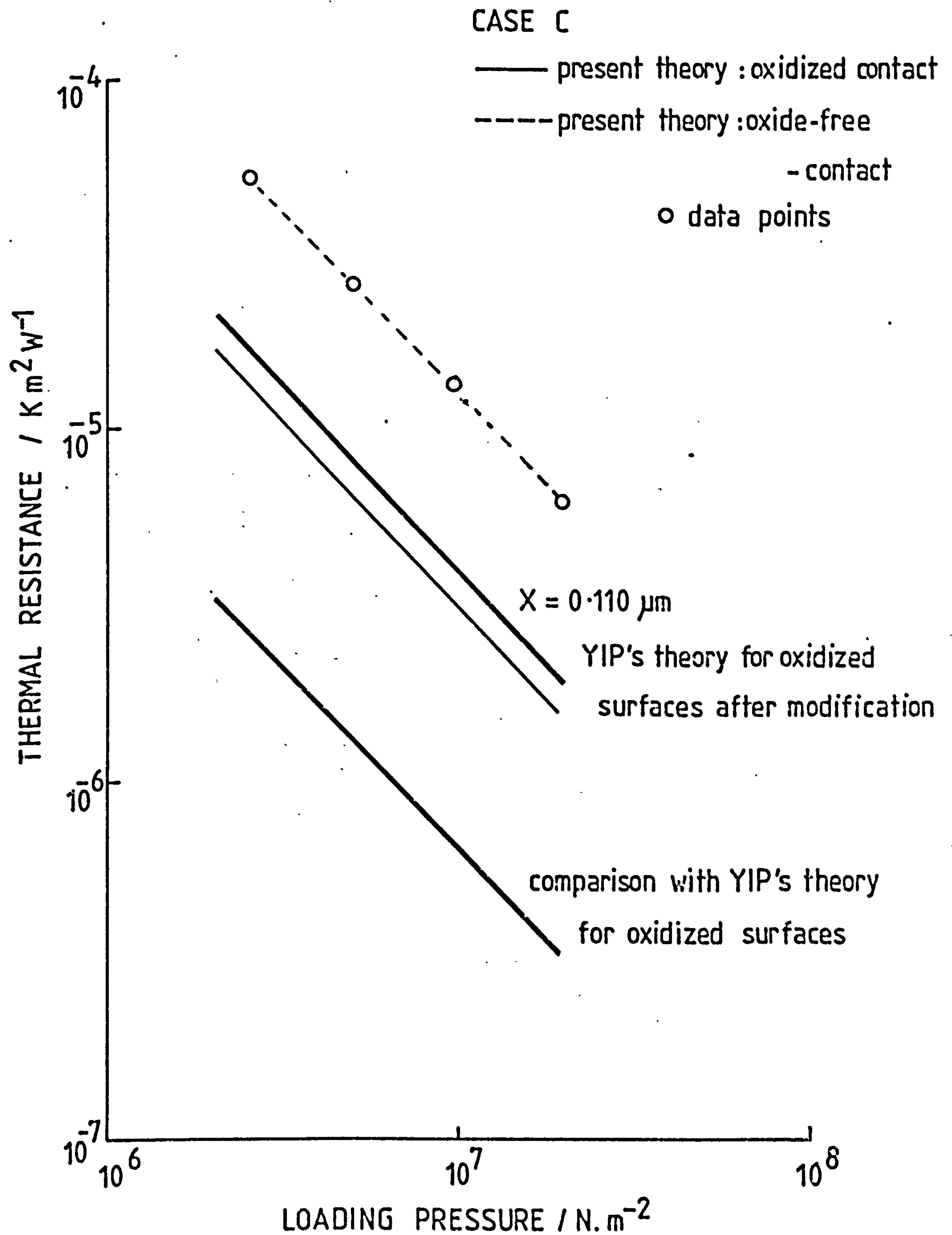


FIG. 7.17

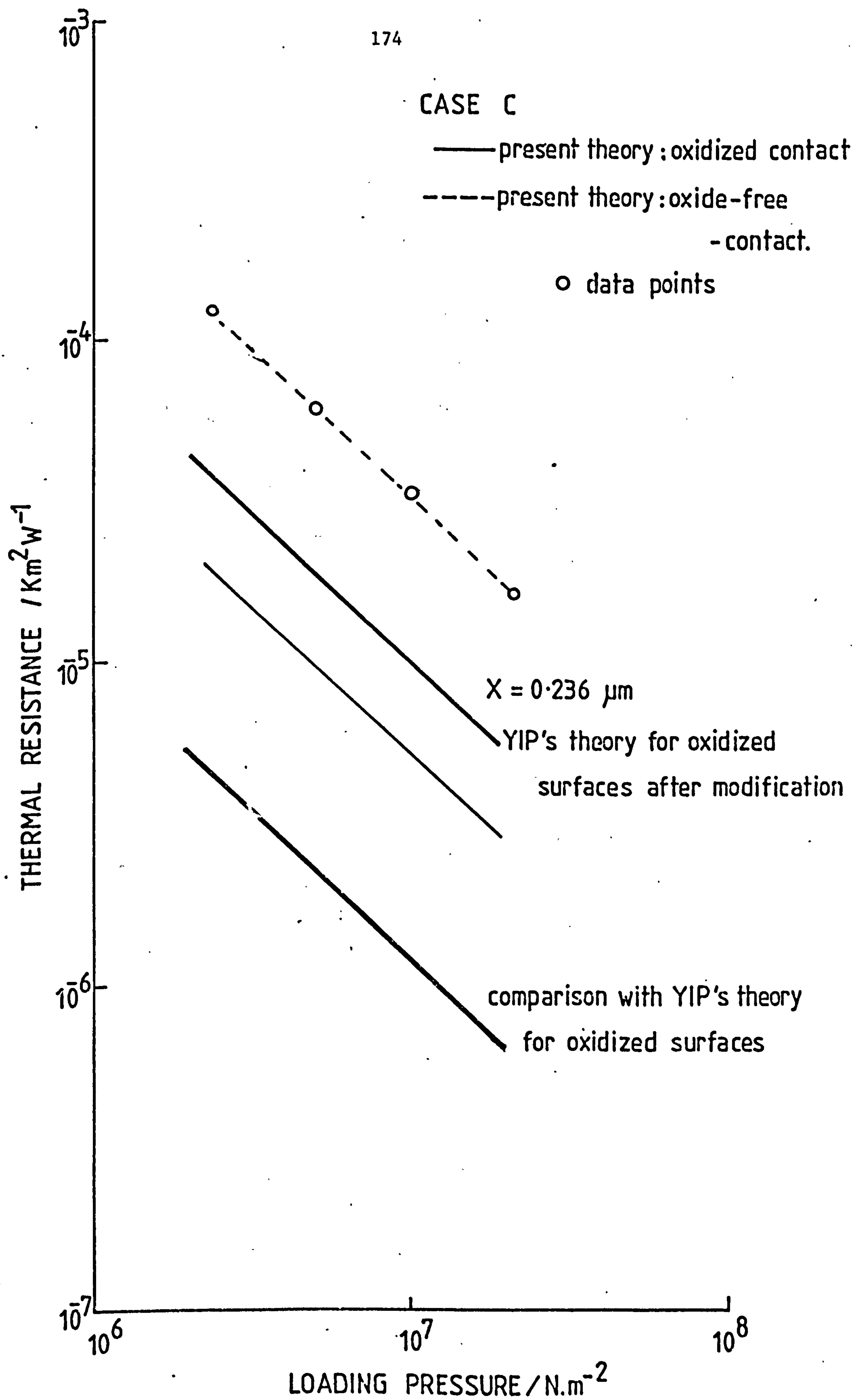


FIG. 7.18

CASE A

- present theory: oxidized contact
 --- present theory: oxide free contact

mean heat flux : 4.0-5.0 W

mild steel-to-mild steel

○ oxide free contact

● oxidized contact

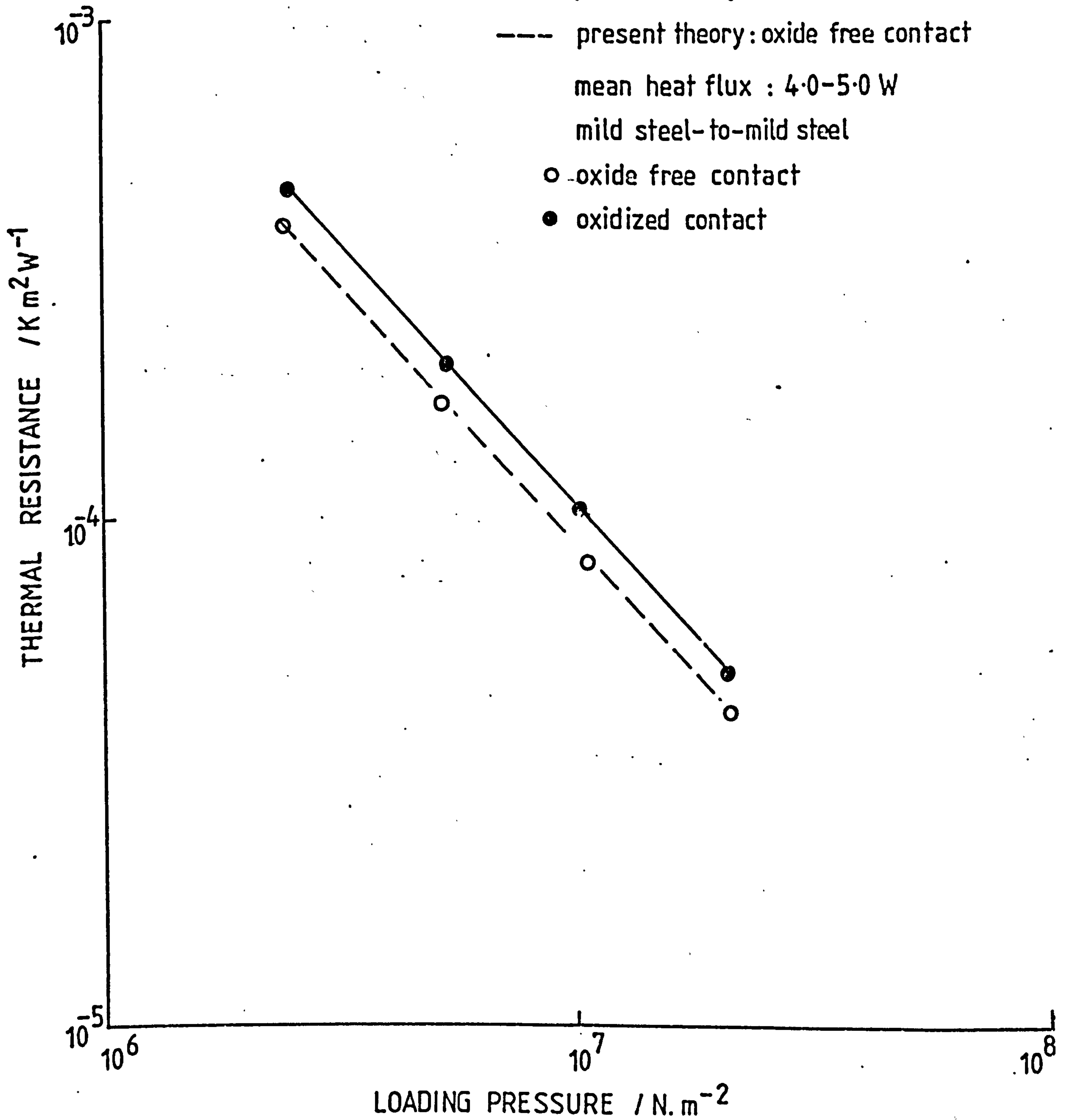


FIG. 7.19

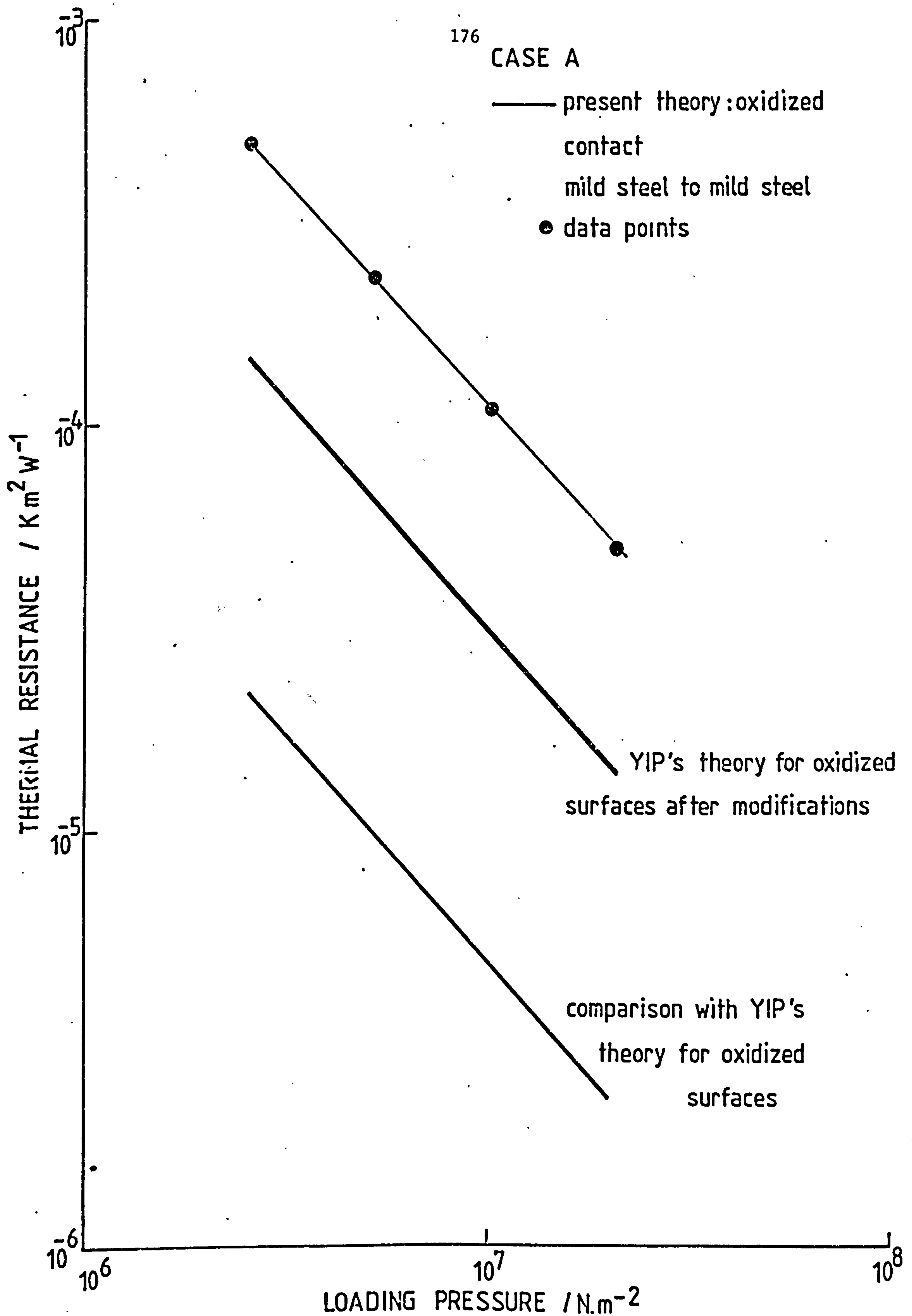


FIG. 7, 20

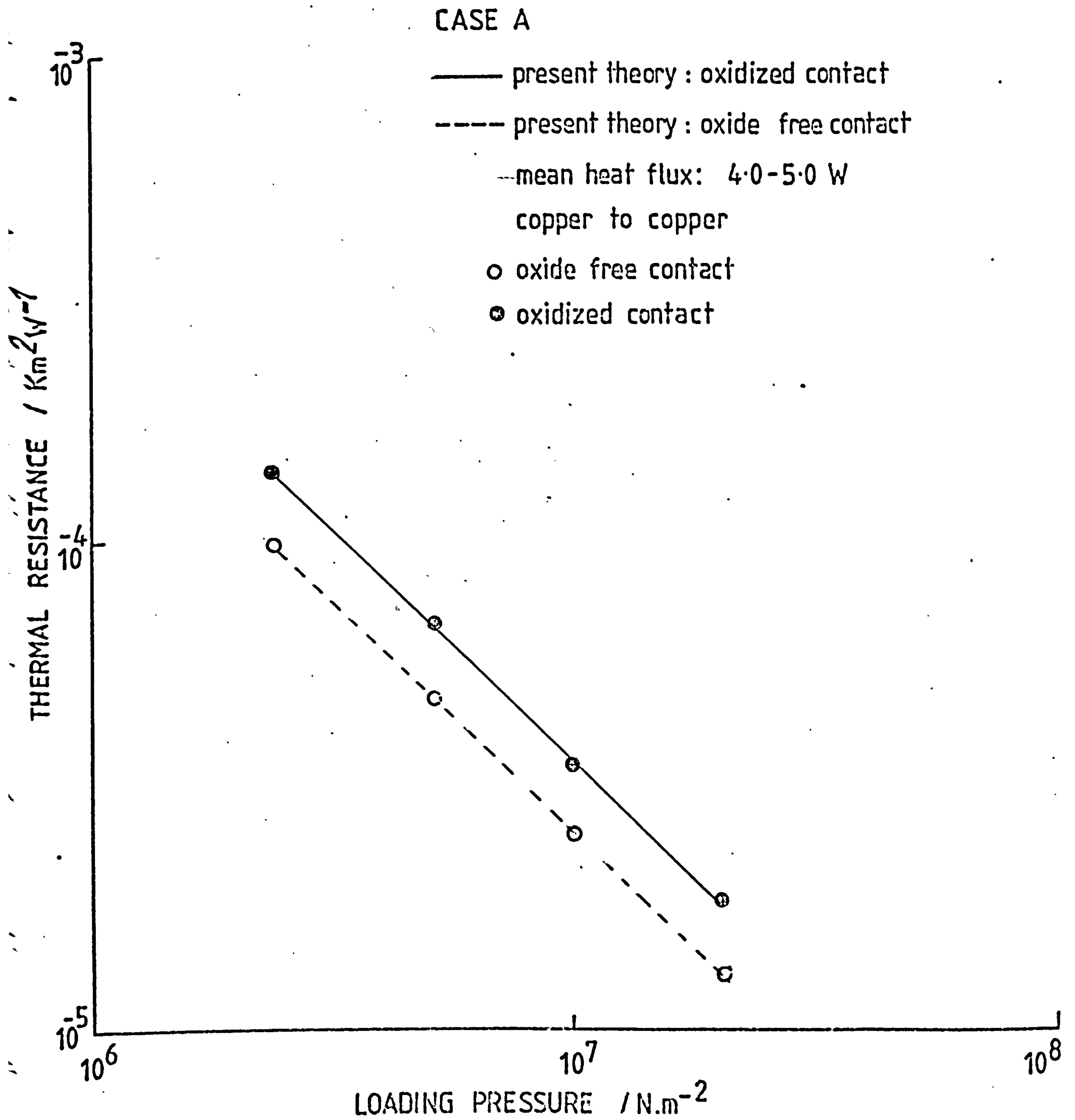


FIG. 7.21

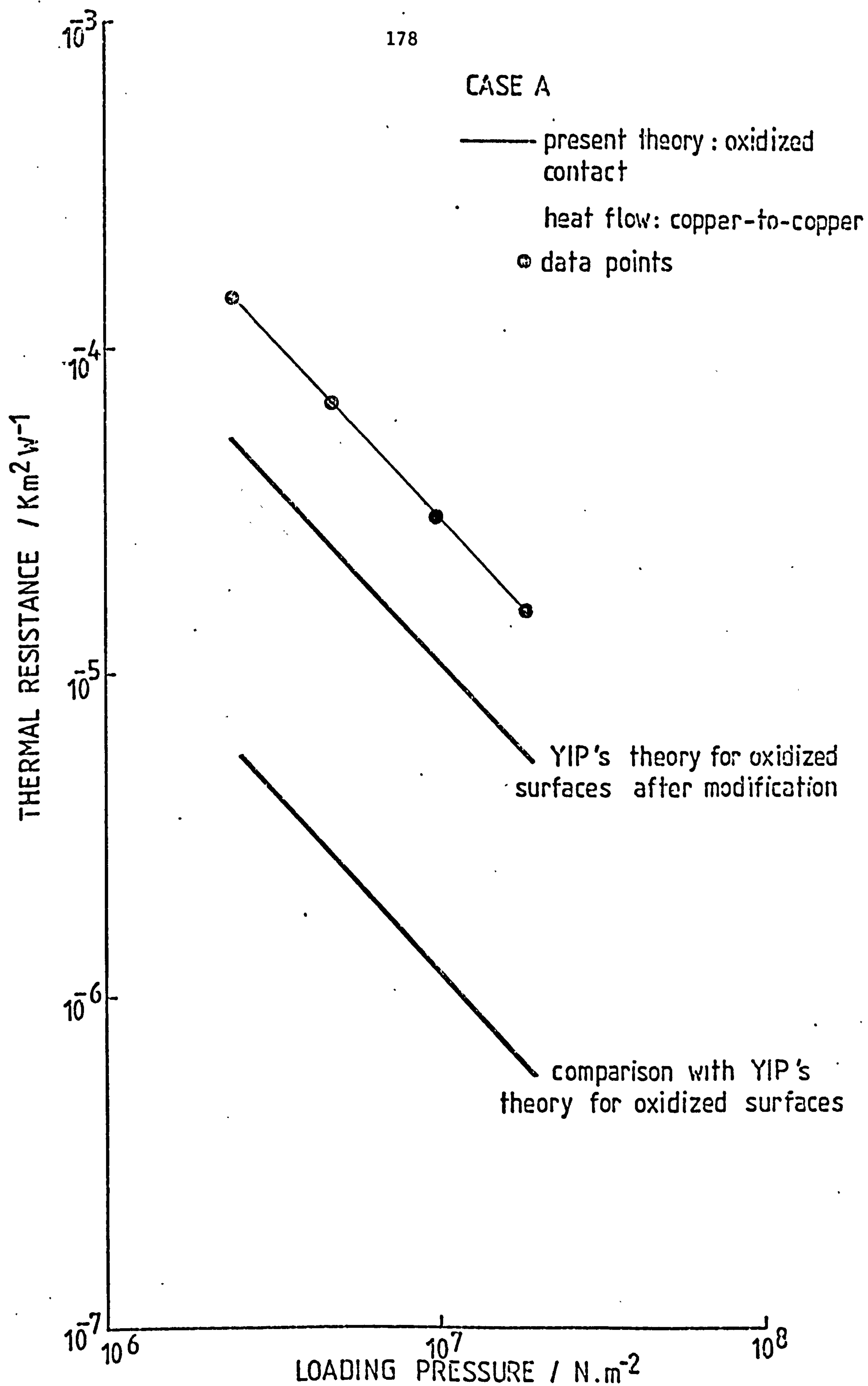


FIG. 7.22

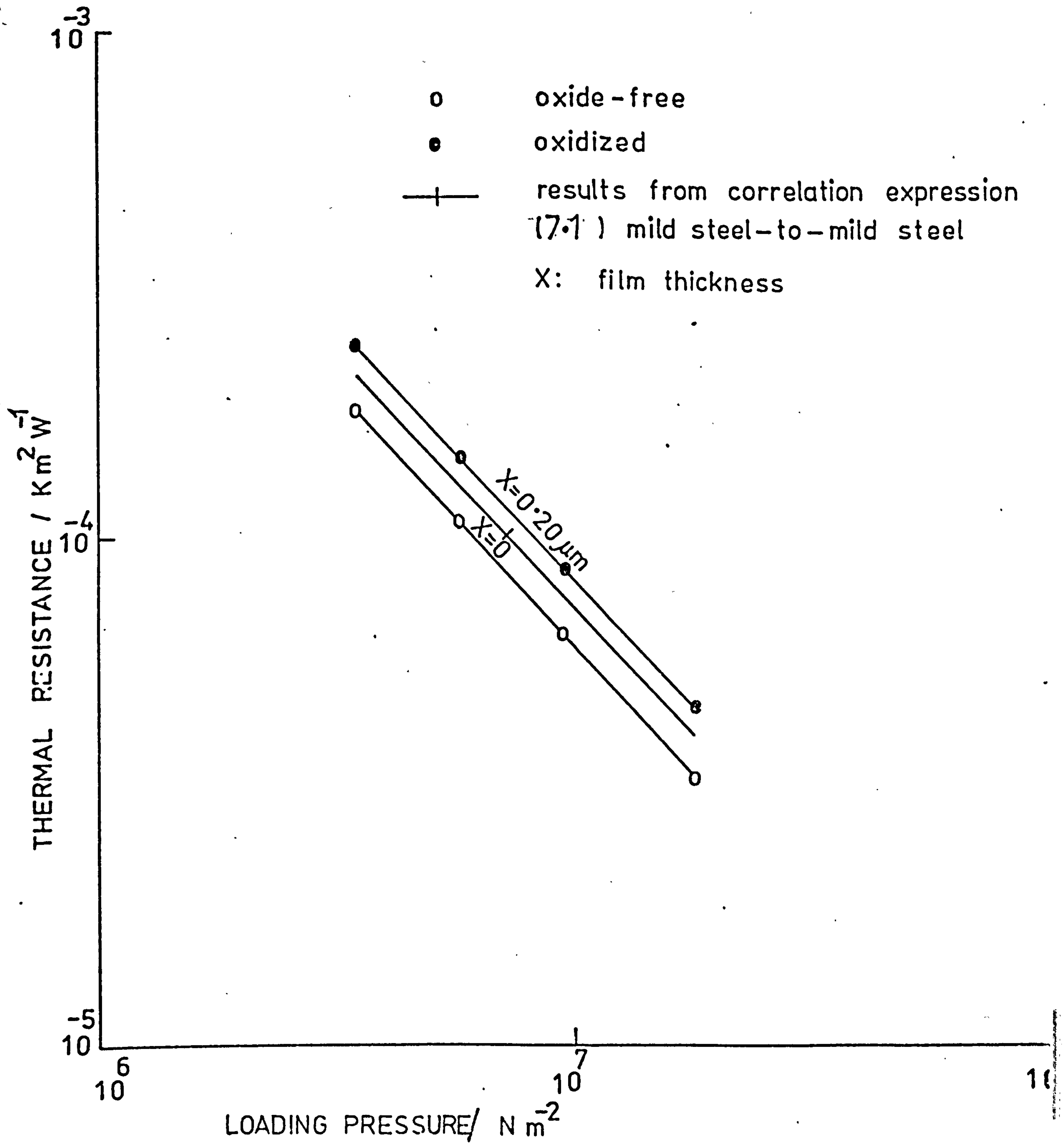


FIG.7.23

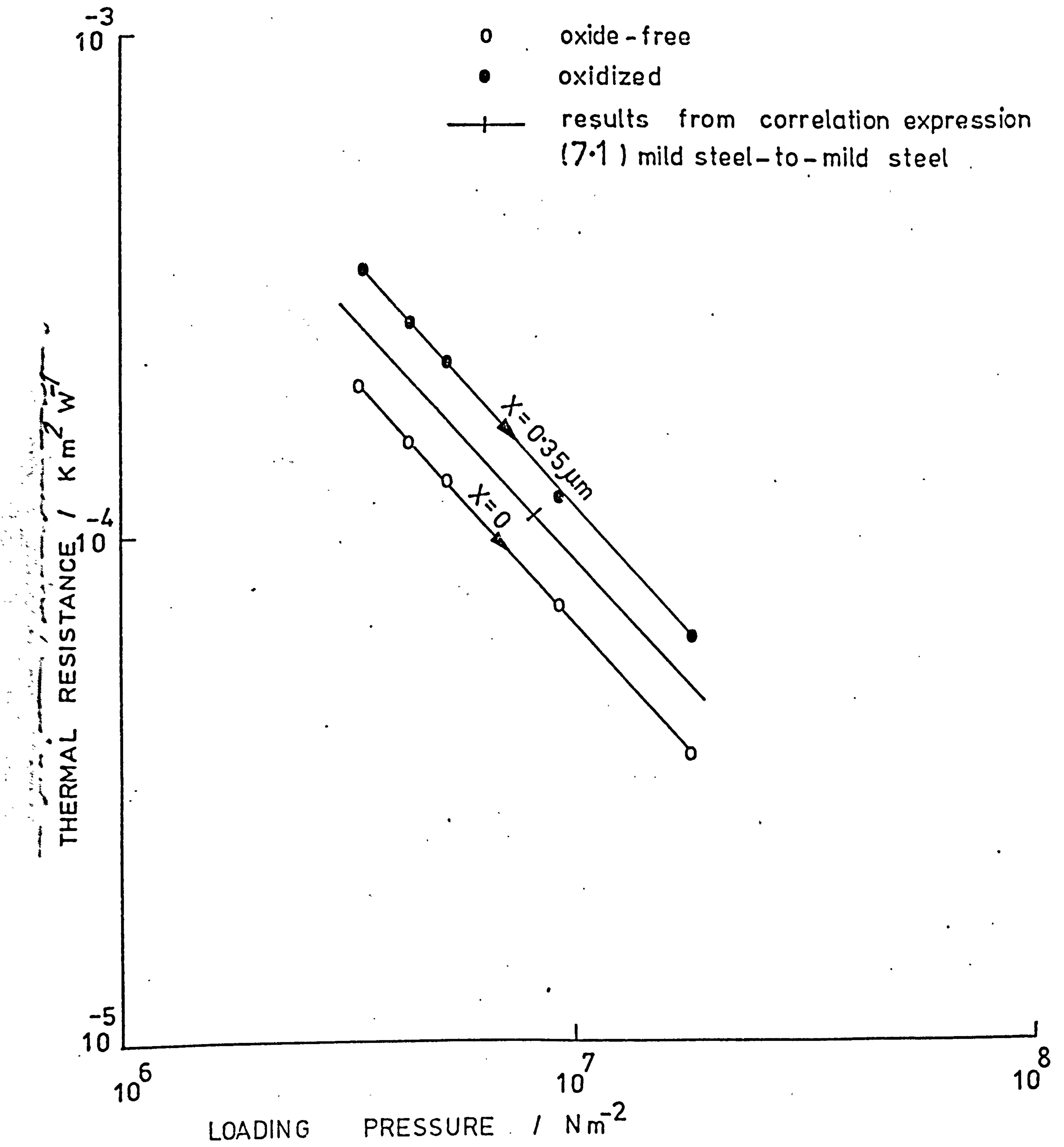


FIG. 7.24

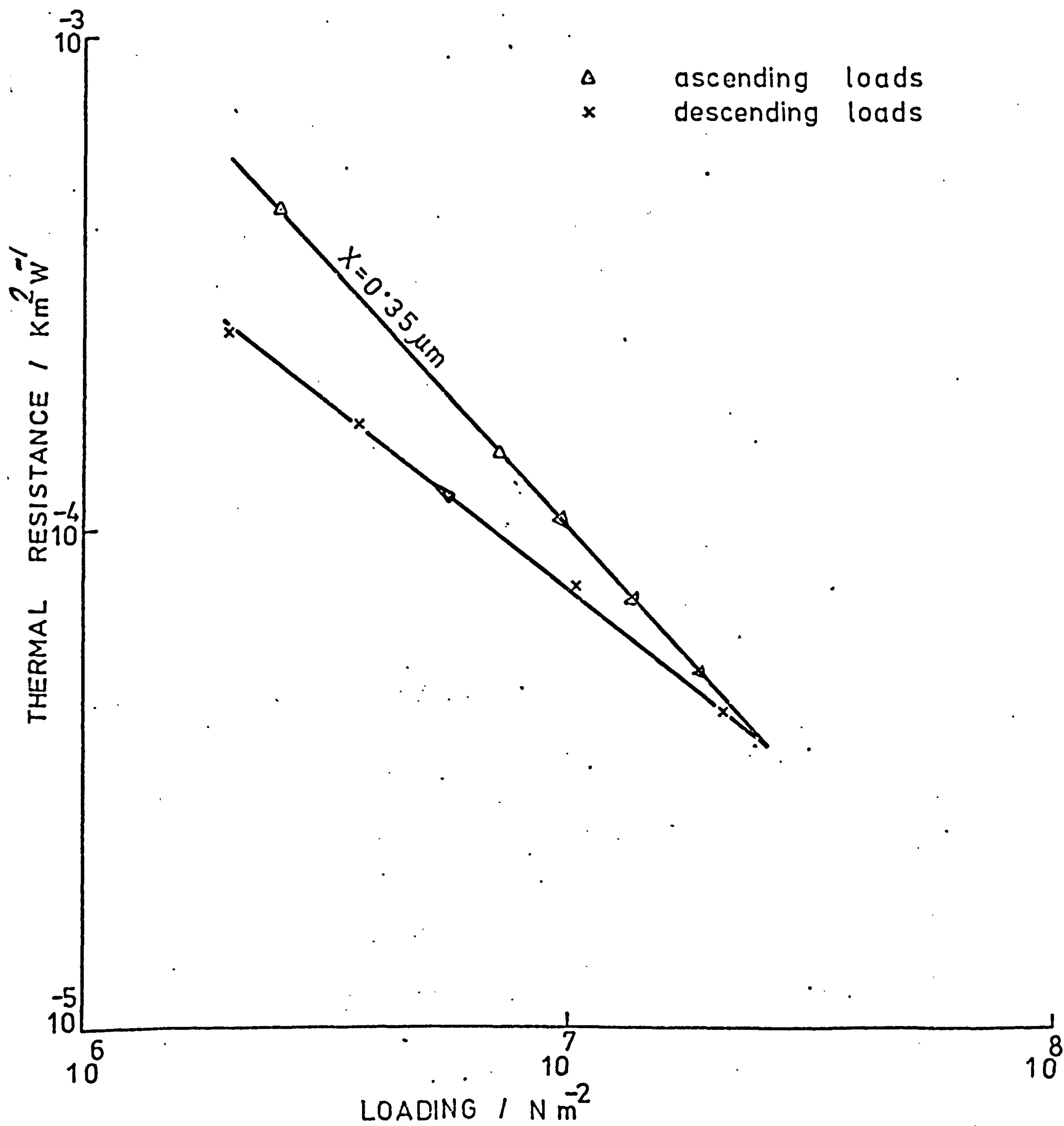


FIG.7,25

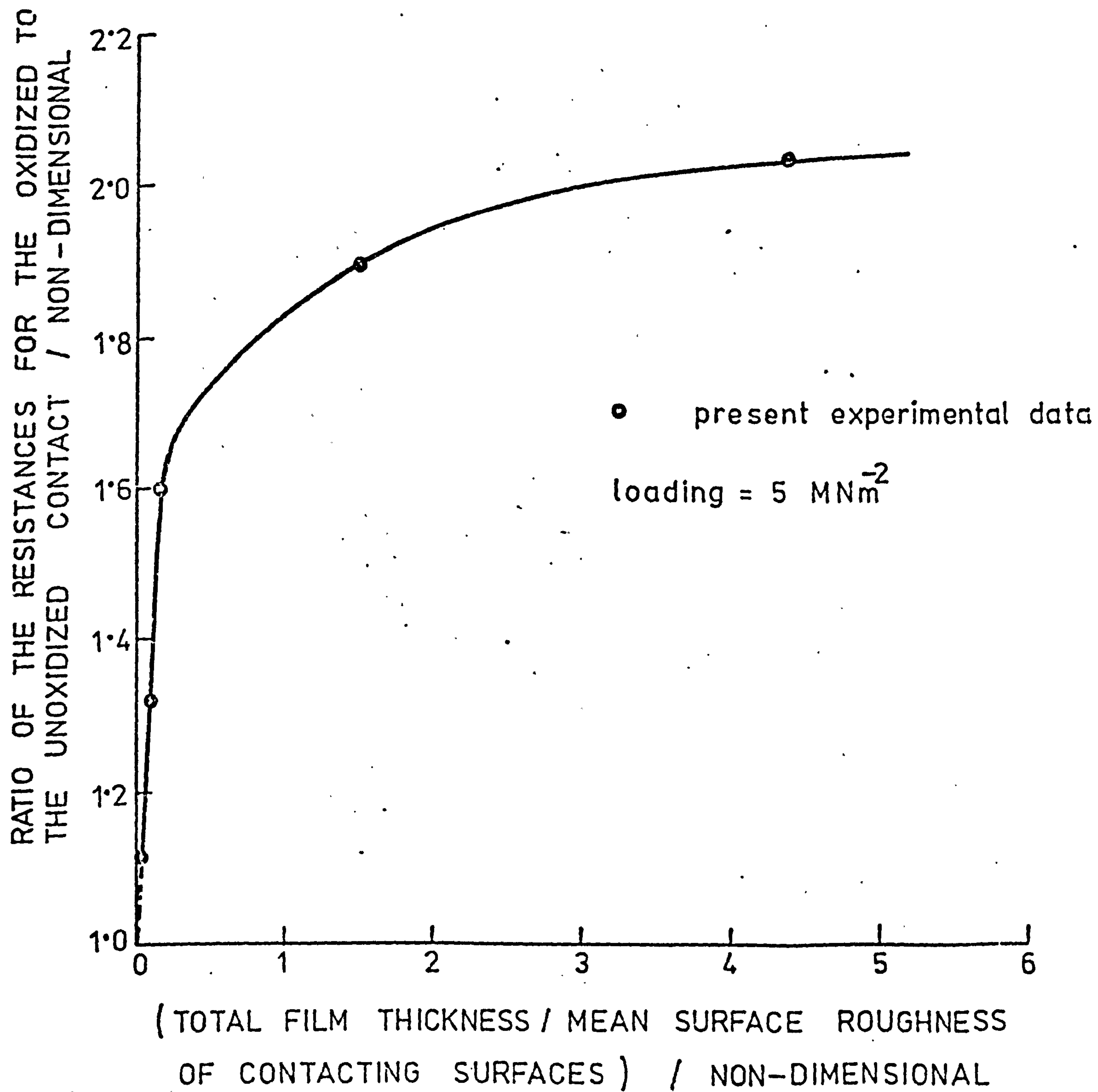


FIG.7,26

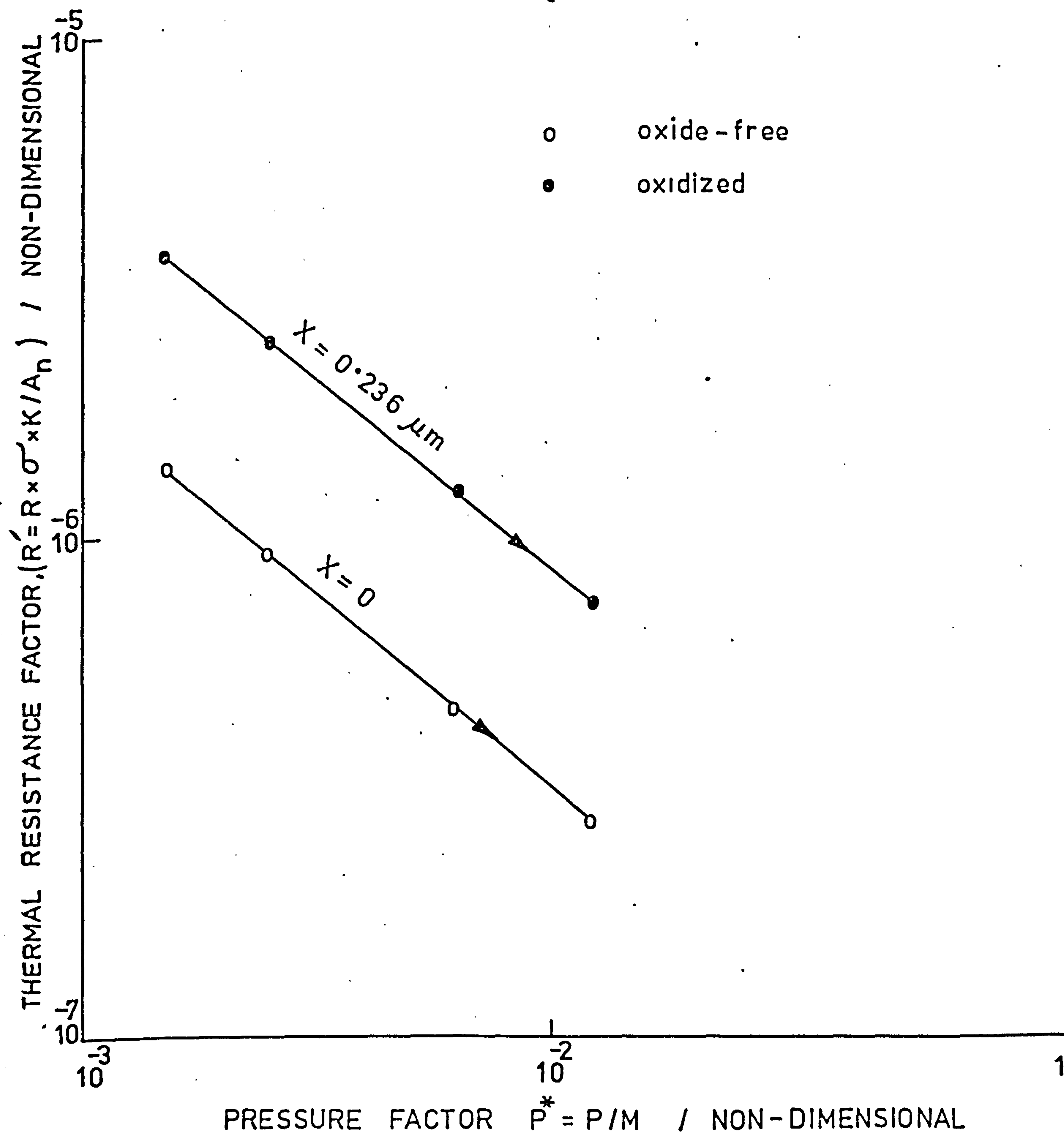


FIG. 7,27

The increase of the thermal contact resistance with the increase in the ratio of film thickness to surface roughness for similar contacting surfaces corroborates the conclusions of Yovanovich (140). Investigating the effects of metallic foils upon the joint resistance he concluded that there was an optimal foil thickness, which yielded a minimum joint resistance and any increase beyond the optimal thickness increased the thermal resistance.

The entire present experimental data was correlated using a multivariate analysis and a computer program was developed. (See Appendix III for details). This resulted in the following expression :-

$$R = 66.0 P^{-0.945} \sigma^{-0.128} X^{0.0346} \dots (7.1)$$

with a correlation coefficient of 0.85. The load exponent (-0.945) is similar to that found for oxide-free contacts (101).

Fig. 7.28 shows the scatter of the experimental data and the values calculated from equation (7.1).

To demonstrate the validity of the correlation, values of the thermal contact resistance were predicted (Figs. 7.23, 7.24, 7.29) from the constriction theory developed by Yip (6), and superimposed upon the values calculated from equation (7.1) (see Fig. 7.29). The results are in reasonable qualitative agreement, so emphasizing the relevance of the physical parameters adopted in the present analysis. A comparison with previous experimental data for thermal contact conductance is shown in Table 7.1. The experimentally measured thermal contact resistance of the ground surface (Fig. 7.30) was higher than that of the fine-turned surface (Fig. 7.31).

7.3.6 Mean Interfacial Temperature

The thermal resistance of the contacts decreased slightly with the mean contact temperature. However this decrease could be regarded as negligible.

7.3.7 Period of Heating

A slight decrease of the contact resistance with the period of heating was observed. This was expected due to the decrease in the hardness.

7.3.8 Reversal of Heat Flux

Reversal of heat flux may cause differing expansions and contractions of the contacting surfaces, thereby aiding the bedding-in process and an increase in the area of actual contact. This affects the contact resistances. The mean heat flux applied varied between 4-5 watts and no

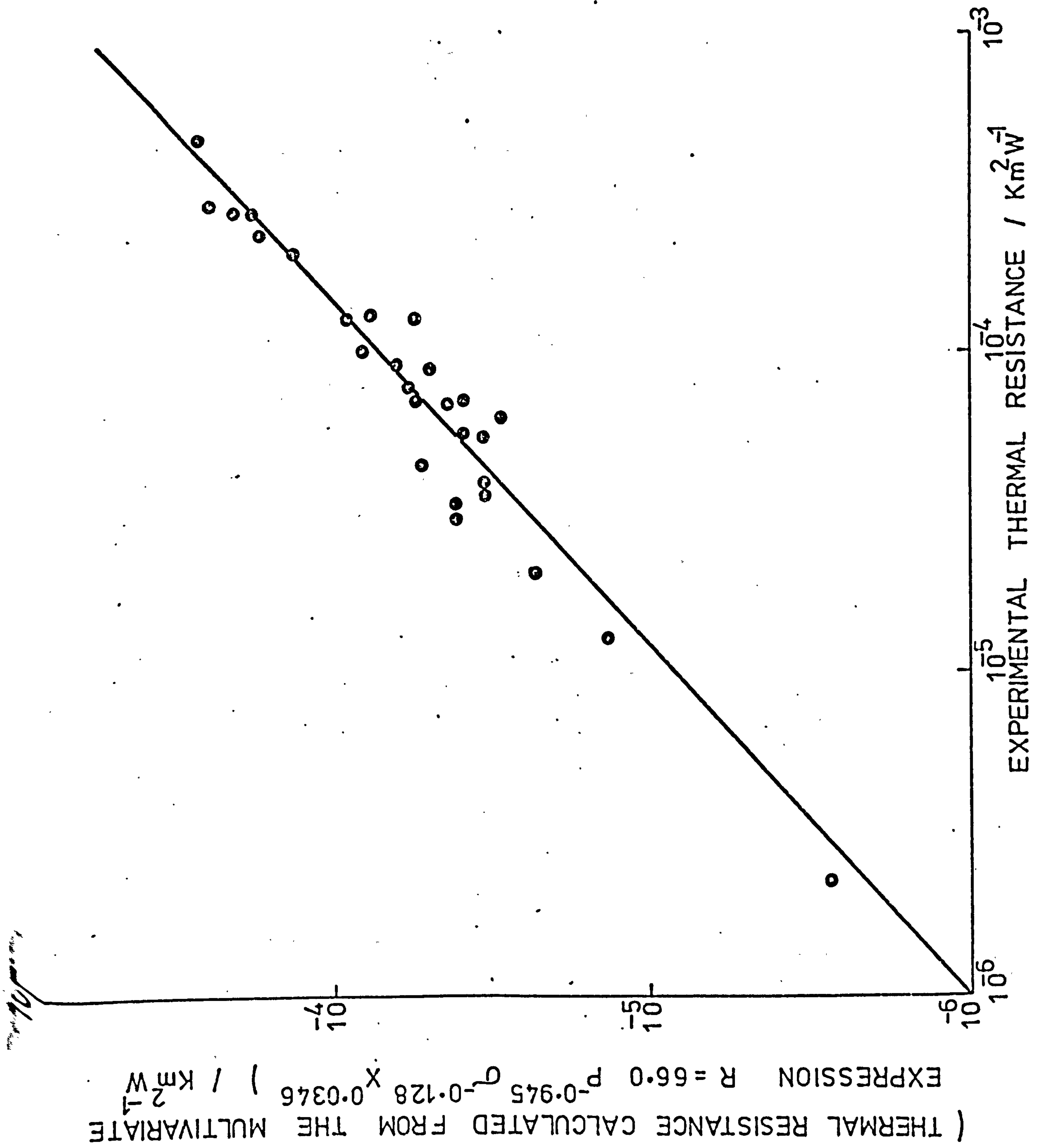


FIG. 7.28

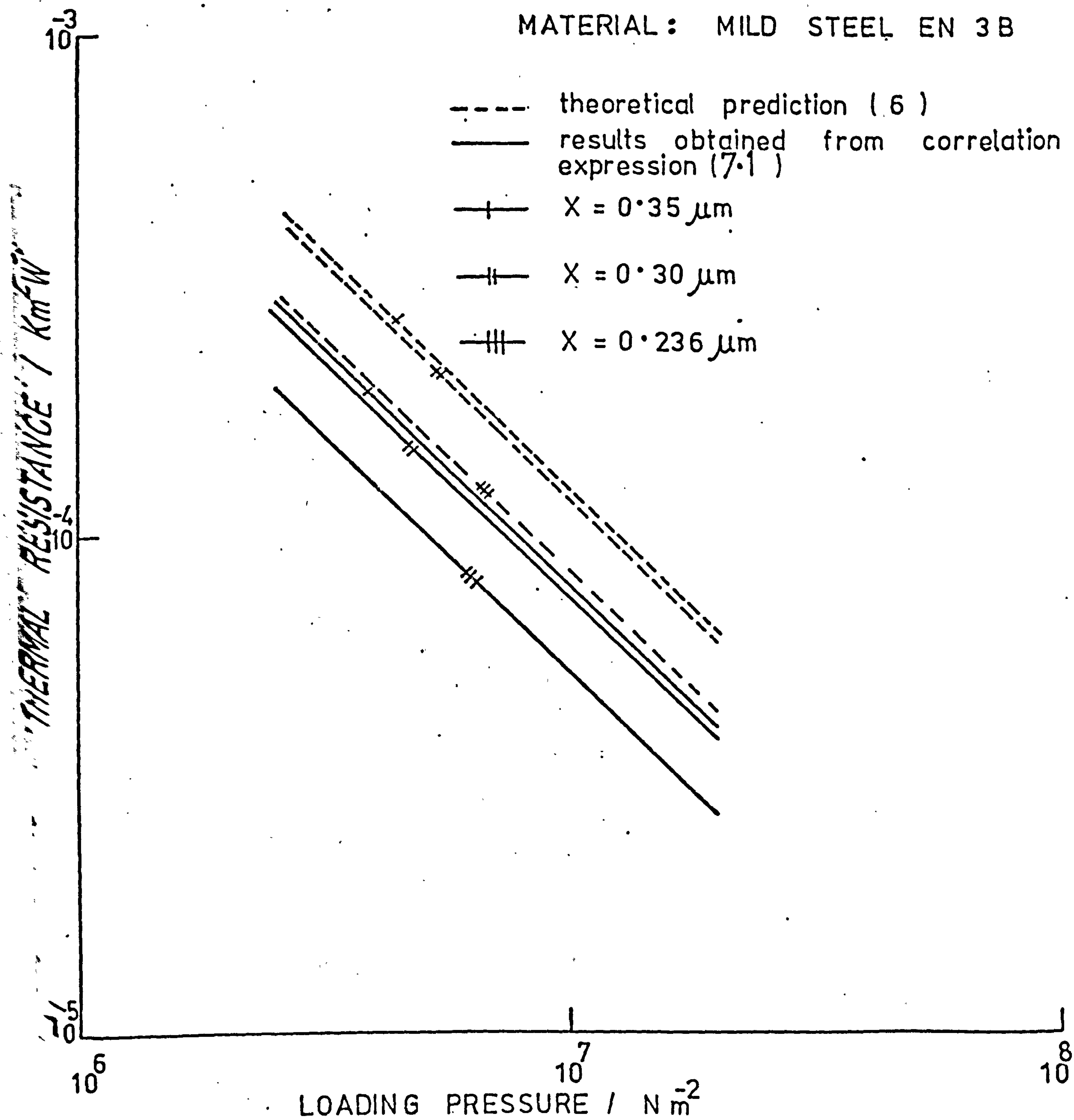


FIG. 7, 29

Table 7.1 Comparison of the Results

Researchers	Surface Characteristics	Loading on Contact MN m ⁻²	Thermal Contact Conductance W m ⁻² K ⁻¹
FRIED (56)	Roughness = 4.06 → 4.31 μm (RMS) deviation from flatness 5.34 → 6 μm	1.62	2.38 × 10 ²
		3.56	4.12 × 10 ²
		3.86	8.51 × 10 ²
	Roughness < 0.1016 μm (RMS), deviation from flatness = 0.1524 μm	3.68	7.06 × 10 ³
		5.27	1.31 × 10 ⁴
		8.38	1.31 × 10 ⁴
BLOOM (141)	Roughness = 1.27 → 1.53 μm (RMS), deviation from flatness 5 → 7.6 μm	0.28	7.04 × 10 ²
		0.28	1.32 × 10 ³
		1.73	3.85 × 10 ³
	Roughness = 0.07 → 1.4 μm (RMS), deviation from flatness 2.5 → 5 μm	0.37	1.39 × 10 ³
		0.57	8.92 × 10 ²
		1.93	2.64 × 10 ³
TSAO and HEIMBURG (99)	Allegedly flat surface	0.3	3.14 × 10 ³
		0.6	4.13 × 10 ³
		2.0	7.34 × 10 ³
* PRESENT WORK	Roughness < 3 μm (RMS)	2.0	2.54 × 10 ³
		4.0	4.90 × 10 ³
		6.0	7.18 × 10 ³
	Optically Flat, deviation from flatness < 0.1 μm	2.0	1.68 × 10 ³
		4.0	3.24 × 10 ³
		6.0	4.75 × 10 ³

* VALUES CALCULATED FROM EXPRESSION (7.1)

For total film thickness of 10⁻¹⁰ m.

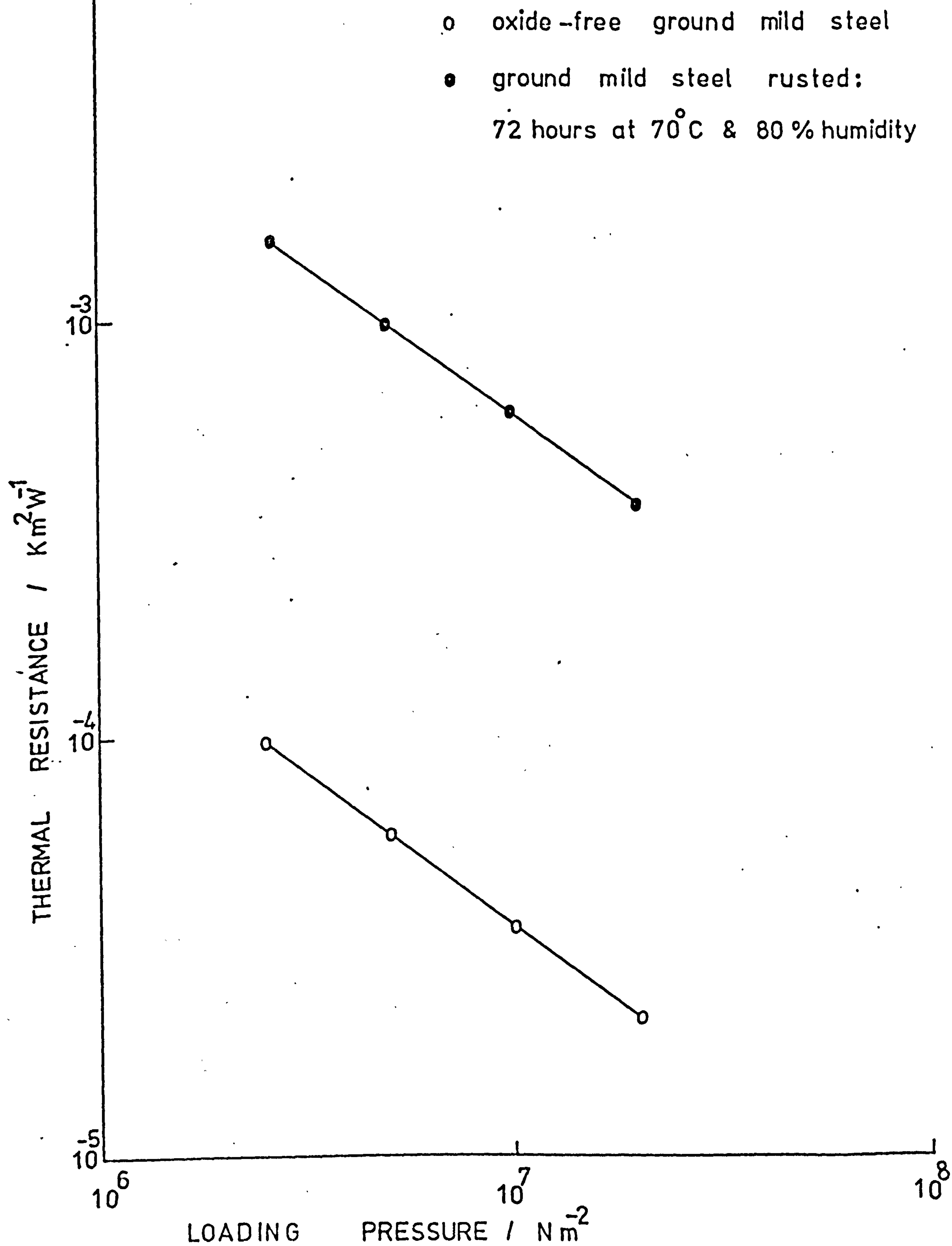


FIG.7,30

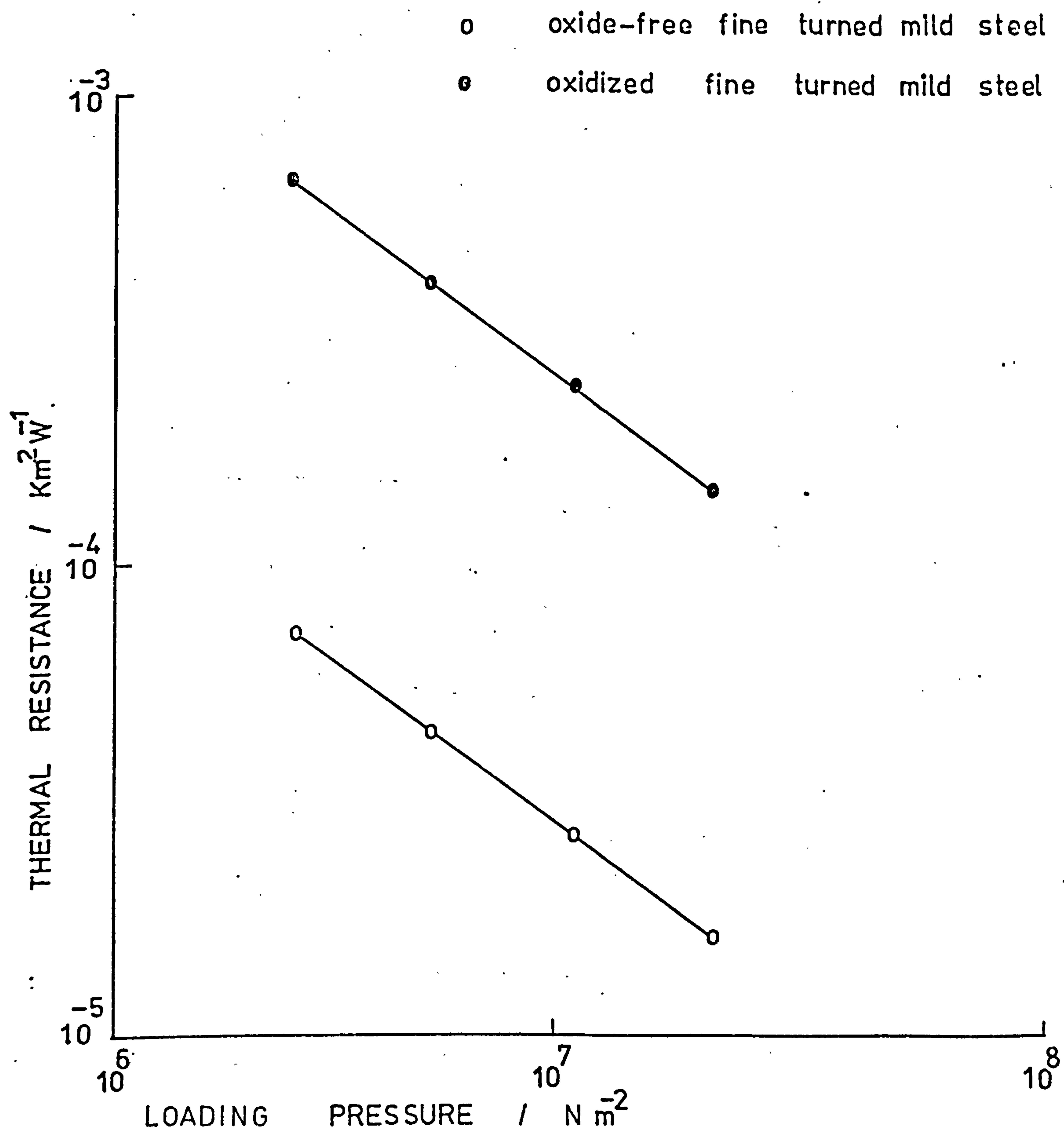


FIG. 7,31

appreciable variation of the thermal contact resistance within this range was observed.

7.4 COMPARISONS OF THEORIES

Yip's theory (6) was compared with the present theory and the experimental observations; using the same surface roughness, film thickness, mean surface slope, applied loading and nominal area of the specimen assembly. This predicted lower thermal contact resistances by orders of magnitude. The reasons for lower predictions are the assumptions of Yip which predict higher contact parameters, i.e. low mean plane separation, higher contact pressures as compared with the predictions of the present theory and higher number of micro-contacts (see Fig. 7.6 and Fig. 7.7) resulting in low thermal contact resistance. (See Figs. 7.8, 7.9, 7.14 - 7.18, 7.20, 7.32 - 7.33). Figs. 7.32 and 7.33 show the thermal contact resistance predicted from analytical solution and its comparison with the theories.

This suggested a modification of Yip's theory which was accomplished basing the theory on the intersection of asperities rather than level crossing. The theory after modification gave better predictions, i.e. lower number of micro-contacts giving rise to higher contact resistances relatively closer to the experimental results.

7.5 CONCLUSIONS

The presence of the oxides improved compliance between the contacting surfaces and increased the area of contact but as the conductivity of the oxides was less than that of the base metal, therefore, the thermal contact resistance increased.

The theoretical resistance was higher when predicted from the observed number of micro-contacts.

The thermal contact resistance increased with increases in film thickness and decreased with loading.

Increasing and decreasing the applied load revealed a slight hysteresis effect.

The initial thickness of the oxide film caused a considerable rise of the thermal resistance of the contact but further equal thicknesses of oxide led to smaller increments of resistance.

For the similar materials in contact, the thermal contact resistance of the oxide-free as well as the oxidized copper-to-copper contact dropped considerably compared with that of the mild steel-to-steel contact. The variation of the predicted resistances from Yip's theory and its modified form is due to the assumptions employed.

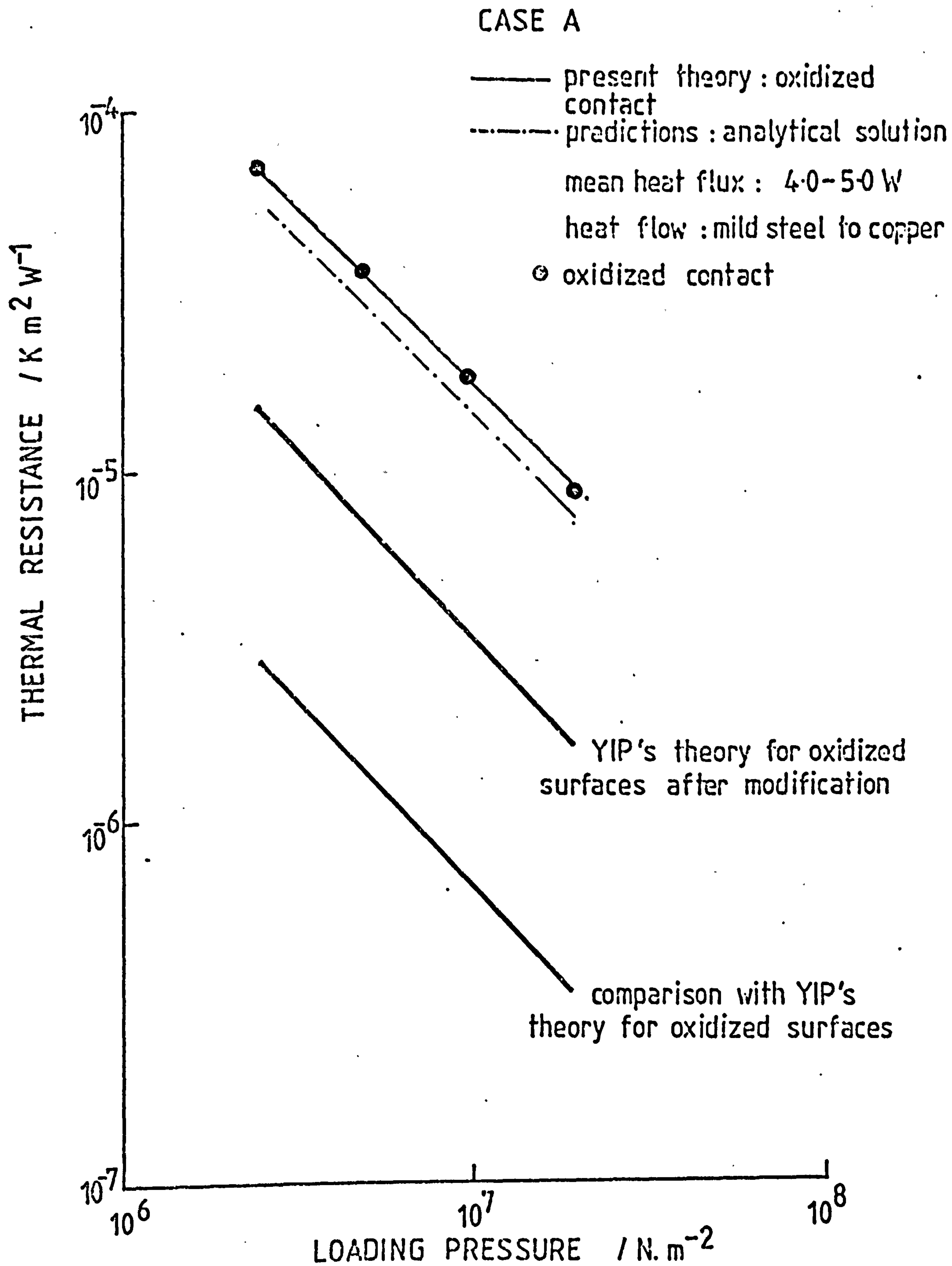


FIG. 7.32

CASE A

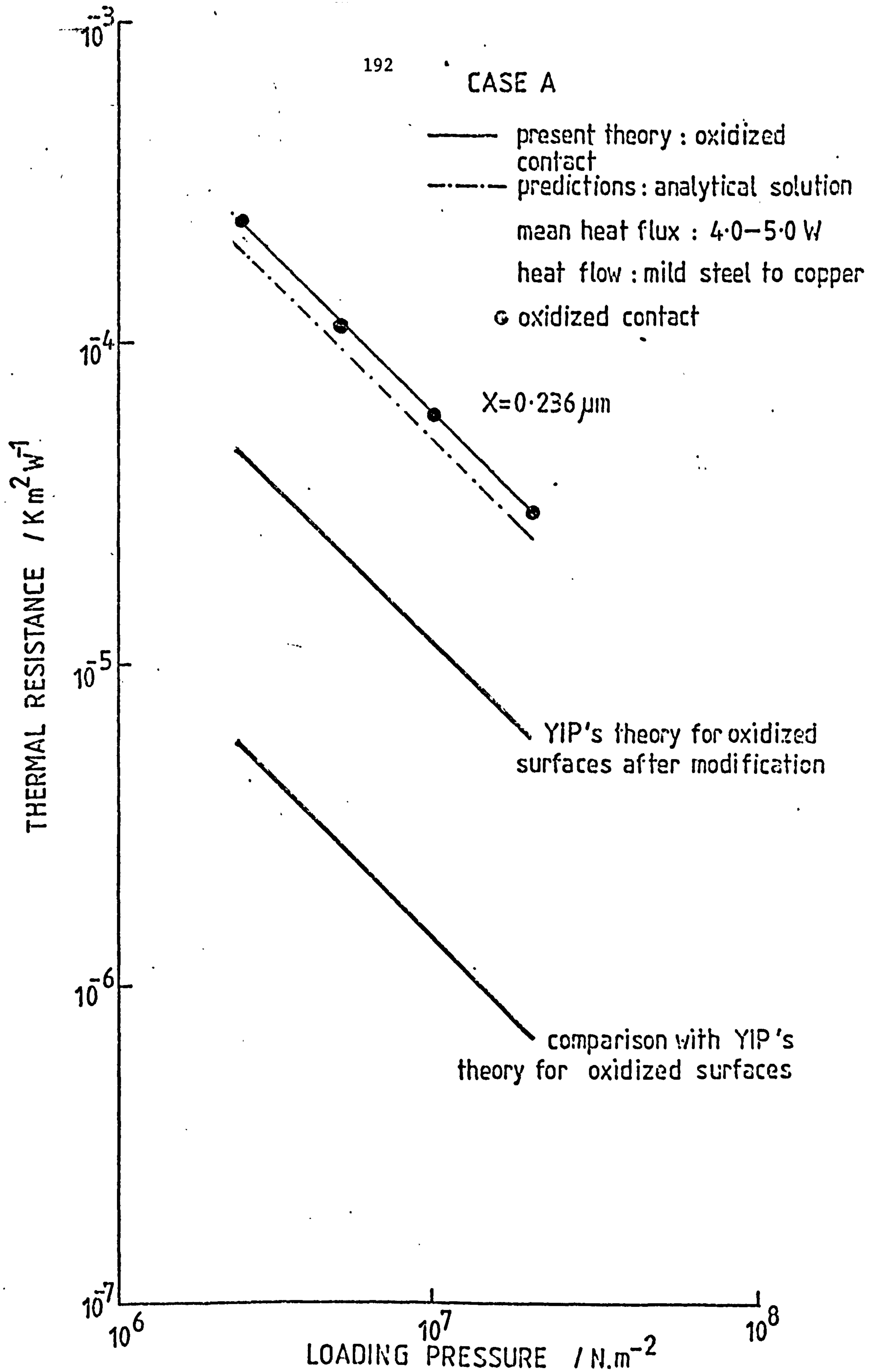


FIG. 7.33

A multivariable correlation has been developed for freshly-assembled oxidized contacts relating the loading pressure, mean roughness of the two surfaces and oxide film thicknesses to the thermal resistance of the contacts in high vacua. This may be used as a first approximation when predicting the thermal contact resistances.

From measurements of the oxide film thickness and surface topography observations, the thermal resistance of pressed contacts between freshly assembled surfaces can be predicted, provided that (i) the contact between the two contacting surfaces remains undisturbed and (ii) the values of the surface parameters are established. The predictions apply to the oxide-free surfaces if the film thickness be assumed zero.

CHAPTER EIGHT

CONCLUSIONS

8.1 INTERFACIAL CONTACT AND COMPLIANCE

The presence of the oxides improved compliance between the contacting surfaces and increased the area of contact but as the conductivity of the oxides was less than that of the underlying metal, therefore, as an overall effect, the thermal contact resistance increased.

The number of micro-contacts exhibited discrepancies with the predictions. This was due to the limitation of the experimental technique to detect the micro-contacts less than 1 μm diameter. The smallest micro-contacts became lost in the very fine surface irregularities not removable by polishing technique.

Well over 70% of the micro-contacts were observed to be non-circular. Theoretical predictions assume the shape of the micro-contacts to be circular and were therefore in excess of the experimental observations.

8.2 INTERFACIAL CONTACT RESISTANCE

The thermal contact resistance increased with film thickness and decreased with loading. Decreasing the applied loading revealed a slight hysteresis effect which also illustrated that the plastic deformation had occurred.

The thermal resistance of the contacts decreased slightly with the mean contact temperature. However this decrease could be regarded as negligible compared with the heat transfer of high emissivity surfaces (102) at elevated temperatures which is due to the increase in radiant heat transmission.

A slight decrease of the contact resistance with the period of heating was observed as expected due to the decrease in the hardness of the metals with time. This is in agreement to (10, 101).

The entire population of the experimental data for freshly-assembled oxidized contacts relating the loading pressure, the mean roughness of the two surfaces and oxide film thickness to the thermal resistance was correlated using a multivariate analysis and resulted in the following expression

$$R = 66.0 P^{-0.945} \sigma^{-0.128} X^{0.0346}$$

with a correlation coefficient of 0.85.

Throughout the measurements of the thermal contact resistance a reading was regarded as meaningful only if the heat flux in the cooler specimen was less than 5% smaller than that in the higher temperature contacting specimen.

8.2.1 How to Produce Joints with Low Thermal Resistance

In order to produce such joints the contacting conditions are :

- i) Higher interfacial pressures.
- ii) Higher thermal conductivity of the contacting material.
- iii) Low hardness.
- iv) No waviness component.
- v) High thermal conductivity of the fluid contained in the interface (i.e. liquid metal is preferable if possible).

The reverse conditions apply to the contact with higher thermal resistance.

8.2.2 Comparisons of Theories

A comparison of Yip's theory (6) with the developed theory and the experimental observations; using the same surface roughness, film thickness, mean surface slope, applied loading and nominal area of the specimen assembly predicted lower thermal contact resistances. The reason for lower predictions are the assumptions of Yip which predict higher contact parameters, i.e. low mean plane separation, higher contact pressures as compared with the predictions of the present theory and higher number of micro-contacts resulting in low thermal contact resistance.

A modification of Yip's theory (6) was carried out basing the theory on the intersection of asperities rather than level crossing. The theory after modification gave predictions closer to the experimental results.

Despite the existence of many theories relating the contacting surface topographies and applied static loads to the thermal contact resistance (45, 46) there are insufficient experimental data to corroborate the predictions (46). Factors like the constriction and spreading of heat flows in the oxide layers near the true contacts, the particular shape of micro-contacts as dictated by the history of the surfaces, the isotropy of the surface roughness and the degree of waviness of each surface have a combined and complicated effect on the rates of heat transfer crossing the contact. If the two contacting surfaces have an oxide layer between

them, studies of oxide film rupture, local yielding regions and fracture stresses are needed for a comprehensive understanding of behaviour. No attempt has been made here to measure fracture stresses, but it appears reasonable to assume that the film, though broken, would still be present and would thus affect the thermal contact resistance.

This study is more suitable for thin films of the order of naturally occurring oxides and will be useful at the design stages of many systems.

REFERENCES

1. JACOBS, R.B.
STARR, C Rev. Sci. Instr. 10, 140, 1939.
2. O'CALLAGHAN, P.W.
PROBERT, S.D. Real area of contact between a rough
 surface and a softer optically flat
 surface.
 J.Mech.E.g.Sci. Vol.12, No.4, 1970,
 pp.259-267.
3. JONES, A.M.,
O'CALLAGHAN, P.W.
PROBERT, S.D. Prediction of contact parameters
 from the topographies of contacting
 surfaces.
 WEAR, 31, 1975, pp.89-107.
4. KIMURA, Y. Estimation of the number and the
 mean area of real contact points on
 the basis of surface profiles.
 Wear, 15, 1970, pp.47-55.
5. YIP, F.C. Thermal contact resistance theory:
 application to bolted joints.
 AIAA Progress in Astronautics and
 Aeronautics: Thermal Control and
 Radiation, Vol.31, edited by
 C.L. Tien, The MIT Press, Cambridge,
 Mass., 1973, pp.177-192.
6. YIP, F.C. Effects of oxide films on thermal
 contact resistance.
 Presented as Paper 74-693 at AIAA/
 ASME Thermophysics and Heat Transfer
 Conference, Boston, Mass., July 1974,
 pp.45-64.
7. TOZER, B. Private communication Marchwood
 Engineering Laboratories, Central
 Electricity Generating Board, U.K.
 1977.
8. FRANKLIN, C.A.
DAVISON, E.H. A high power communication satellite
 for the 12 & 15 GHz bands.
 AIAA Progress in Astronautics and
 Aeronautics. Communication Satellite
 System, Vol.32, edited by P.L.
 Bargellini, The M.I.T. Press,
 Cambridge, Mass., 1974, pp.87-121.

9. DYBAN, E.P., SKVETS, I.T. Contact heat exchange in Turbine Parts (In Russian), Air Cooling of Gas Turbine Motors University of J. Kieve, 1959, English Translation Technical Documents, Liaison Office, U.S.A., MCL-1406 , 1962, pp.191-233

10. BARZELAY, M.E. Range of interface thermal conductance for aircraft joints. NACA TN D-526, 1960.

11. CLAUSING, A.M. Thermal Contact resistance in a vacuum environment. Ph.D. Thesis, 1963, Department of Mechanical Engineering, University of Illinois Urbana 111.

12. HOLM, R. Electric contacts - Theory and application. 4th ed., Springer-Verlag New York, 1967.

13. RAPIER, A.C., JONES, T.M., McINTOSH, J.E. The thermal conductance of Uranium dioxide/stainless steel interface. Int. J. Heat mass transfer, 6, 1963, pp.397-416.

14. BAKKER, G. Handbook exp. physik, Leipzig, 1930.

15. O'CALLAGHAN, P.W., JONES, A.M., PROBERT, S.D. Thermal resistance of stacks of transformer laminations. Applied Energy (3), 1977, pp.13-22.

16. JONES, F.L. The physics of electrical contacts. Clarendon Press, Oxford, U.K., 1957.

17. KUBACHEWSKI, O. BRASHER, D.M. Trans. Faraday Soc. 55 (1959), 1200.

18. HARPER, C.A. Handbook of wiring, cabling and inter-connecting for electronics. McGraw-Hill, New York, 1972.

19. DAVIES, M.H., SIDNAD, M.T., BIRCHENALL, C.E. On the mechanism and kinetics of scaling of iron. J. Metals, vol.3, 10 Oct.1951, pp.889-896

20. LAUKONIS, J.V. Fifth International Congress for electron microscopy. Academic Press, New York, Vol.1, C - 911961.
21. GULBRANSON, E.A.,
McMILLAN, W.R. J. Electrochemical. Soc. 1952.
22. STANLEY, J.K.,
VAN HOENE, J.,
HUNTOON, R.T. The oxidation of pure iron. Trans. A.M.S., Vol.43, 1951, pp.426-453.
23. WAGNER, C. Theorie der geordneten Mischphasen. Zeit. fur Phys. Chem. B22, 1931, pp.177-186.
24. WAGNER, C. Beitrag zur theorie des Anlaufvorgangs. 1 Zeit. fur Phys. Chem. B21, 1933, pp.25-41.
25. WAGNER, C. Beitrag zur theorie des Anlaufvorgangs. 2 Zeit. fur Phys. Chem. B32, 1936, pp.447-462.
26. PAIDASSI, J. The kinetics of air oxidation of iron in the range 700° - 1250°C. Acta. Met., Vol.6, 1958, pp.184-194.
27. HOLMES, D.R. New corrosion resistant high temperature heat exchanger materials. Corrosion Sci., Vol.8, 1968, pp.603-622.
28. BERNARD, J. The oxidation of metals and alloys. Met. Reviews, Vol.9, 36, 1964, pp.473-503.
29. LAWLESS, K.R. The oxidation of metals. Energetics in metallurgical phenomena. Vol.1, University of Denver, 1962.
30. GRONLUND, F. J. Chim. Physics. 53, 1956, p.660.

31. JOST, W. Diffusion und Chemische Reaktion in
fasten
Stoffen 1937.
32. WAGNER, C. Handbuch der Metallphysik.
Vol.1, Part 2, 1940.
33. VALESI, G. Pittsburg International Conference
on Surface Reactions.
Pittsburg, Corrosion Publishing
Co. , 1948.
34. MATYAS, M. Czechoslovak J. Phys. 4, 1954.
35. MATYAS, M. Czechoslovak J, Phys. 5, 1955.
36. TYLECOTE, R.F. Metallurgia 53, 1956.
37. HANCOCK, P.,
HURST, R.C. The mechanical properties and
breakdown of surface oxide films
at elevated temperatures.
Advances in Corrosion Science
and Technology, 1973.
38. JAENICKE, W.,
LEISTIKOW, S.,
STADLER, A. Mechanical stresses during the
oxidation of copper, and their
influence on oxidation kinetics.
J. Electrochem. Soc., Vol.111,
1964, pp.1031-1037.
39. STRINGER, J. Stress generation and relief in
growing oxide films.
Corrosion Science, Vol.10, 1970,
pp.513-543.
40. HOWES, V.R.,
RICHARDSON, C.N. The initial stresses developed
during oxidation of Fe-Cr alloys.
Corrosion Science, Vol.9, 1969,
pp.385-394.
41. GERMAN, P.A.,
MAXWELL, D. Some observations on dilute iron
alloys.
Werkstoffe und Korrosion, Vol.22,
1971, pp.382-355.

42. CATCHCART, J.V.,
PETERSEN, G.F.,
SPARKS, C.J. Oxidation rate and oxide
structural defects.
Surfaces and Interfaces, 1 -
Chemical and Physical
characteristics. Syracuse
University Press, 1967, pp.333-346.

43. PEKLENIK, J. New developments in surface charac-
terisation and measurements by means
of random process analysis, from
properties and metrology of surfaces.
Proc. Instn. Mech. Engrs., 182 (3K),
1967.

44. UPPAL, A.H.,
PROBERT, S.D. Topographical changes resulting
from surfaces being in contact under
static and dynamic loads.
Wear, 16, 1972, pp.381-400.

45. TSUKIZOE, T.,
HISADADO, T. On the mechanism of contact between
metal surfaces - Part 1.
Trans. ASME, 87D, pp.666-674.

46. TSUKIZOE, T.,
HISAKADO, T. On the mechanism of contact between
metal surfaces - Part II.
Trans. ASME, 90F, 1968, pp.81-88.

47. O'CALLAGHAN, P.W. Some aspects of contact between
solids.
Ph.D. Thesis, University of Wales,
1971.

48. GREENWOOD, J.A.,
WILLIAMSON, J.B.P. The contact of nominally flat
surfaces.
Proc. Roy. Soc. (London), A295
(1966), pp.300-319.

49. GREENWOOD, J.A. The real area of contact between a
rough surface and a plane.
ASME-ASLE Lubrication Conf., 1965.

50. GREENWOOD, J.A. The area of contact between rough
surfaces and flats.
J. Lubr. Technol., 89, 1967.

51. ARCHARD, J.F. Single contacts and multiple encounters.
J. Appl. Phys., 32 (8), 1961, pp. 1420-1425.

52. THOMAS, T.R., Establishment of contact parameters from surface profiles.
PROBERT, S.D. Brit. J. Apply. Phys., 3, 1970, pp.277-291.

53. THOMAS, T.R. Thermal resistance of pressed contacts.
Ph.D. Thesis, University of Wales, 1968.

54. THOMAS, T.R., UPPAL, A.H., Hardness of rough surfaces.
PROBERT, S.D. Nature Phys. Sci., 229, 1971, pp.86-87.

55. UPPAL, A.H., Topography changes resulting from surfaces being in contact under static and dynamic loads.
PROBERT, S.D. Wear, 16, 1970, pp.261-271.

56. FRIED, E. Study of interface thermal contact conductance.
Summary Rept. Contr. No. NAS8-11247, GE Doc. No. 655D 4395, 1965.

57. FRIED, E. Metallic interface thermal conductance.
Thermal Conductivity Conference, N.P.L., Teddington, England, 1964.

58. HOWELLS, R.I., Deformations of stacks of thin layers under normal compressive loads.
PROBERT, S.D. J. Stress Anal., 4 (2), 1969, pp.115-120.
JENKINS, J.H.

59. MOLGAARD, J. A coefficient of friction which increases with increasing load.
Proc. Phys. Soc. 79, 1962, pp.516-534.

60. MOLGAARD, J., The thermal contact resistance at gold foil surfaces.
SMELTZER, W.W. Intern. J. Heat Mass Transfer, 13, 1970, pp.1153-1162.

61. REASON, R.E. Some approaches to the measurement of waviness.
Sixth Intern. Machine Tool Design and Research Conf., Manchester, England, 1965.

62. REASON, R.E. The bearing parameters of surface topography.
Fifth Intern. Machine Tool Design and Research Conf., Birmingham, England, 1964.

63. HALLING, J. A reflectometer for the assessment of surface finish.
J. Sci. Instrum., 31, 1954, pp.318.

64. HALLIDAY, J.S. Surface examination by reflection electron microscopy.
Proc. Inst. Mech. Engrs., 169, 1955, pp.777.

65. GREENWOOD, J.A. Surface measurement.
In: Experimental Methods in Tribology, Proc. Inst. Mech. Engrs., 182, 1968, 3G.

66. GREEN, E. Review of surface texture measurements and the associated metrological problems.
Properties and Metrology of Surfaces, Proc. Inst. Mech. Engrs., 182 (3K), 1967, pp.330-343.

67. EBERLE, O.A. Graphical method for statistical assessment of surface roughness comparison specimens.
Properties and Metrology of Surfaces, Proc. Inst. Mech. Engrs., 182 (3K), 1967, pp.368-396.

68. TIPTON, H.,
 ROBERTS, J.I. New optical method of assessing surface geometries.
Properties and Metrology of Surfaces, Proc. Inst. Mech. Engrs., 182 (3K), 1967, pp.274-278.

69. WHITEHOUSE, D.J.,
ARCHARD, J. The properties of random surfaces
of significance in their contact.
Proc. Roy. Soc. 316A, 1970, pp.97-121.

70. HERTZ, H. Reigne Angew Math. 92, 1881 (Quoted
from Timoshanko, S. and Goodier, J.N.
Theory of elasticity.
McGraw-Hill, New York, 1951.

71. BOWDEN, F.P., TABOR, D. Friction and lubrication of solids.
Part 1.
Claredon Press, Oxford, 1964.

72. BOWDEN, F.P., TABOR, D. Friction and lubrication of solids,
Part II.
Claredon Press, Oxford, 1964.

73. TABOR, D. The hardness of metals,
Oxford University Press, 1951.

74. FENECH, H.,
ROHSENOW, W.M. Thermal conductance of metallic surfaces
in contact.
Heat Transfer Laboratory, Massachu-
setts Institute of Technology,
Report NYO 2136, 1959, pp.77.

75. MIKIC, B.M., YOVANOVICH, M.M.
ROHSENOW, W.M. The effect of surface roughness and
waviness upon the overall thermal
contact resistance.
Report 76361-42, 1966, Dept. of
Mechanical Engineering, Massachusetts
Institute of Technology, Cambridge,
Mass.

76. D'YACHENKO, P.E.D.,
TOKACHEVA, N.N.,
ANDREW, G.A.,
CARPOVA, T.M. Actual contact area between touching
surfaces.
Consultants Bureau Enterprises,
New York, 1964.

77. GREENWOOD, J.A.,
TRIPP, J.H. The elastic contact of rough spheres.
Burndy Corp. Report, 1965.

78. WILLIAMSON, J.B.P.,
PULLEN, J.,
HUNT, R.T. Plastic contact of surfaces.
Burndy Research Report No.78 and 79,
1970.

79. MOORE, A.J.W. Deformation of metals in static and sliding contact,
Proc. Roy. Soc., A195, 231, 1948.

80. KRAGELSKY, I.V., Contact area of rough surfaces.
DEMGIN, N.B. Wear, 15, 1970, pp.170-187.

81. FENECH, H., HENRY, J.J., Thermal contact resistances from
ROHSENOW, W.H. developments in heat transfer.
Edited by Rohsenow, W.M.,
Edward Arnold, London, 1964.

82. ANON Description of methods for deter-
mining geometric parameters for
surfaces in contact.
. USAEC Report N-70 9456/7, 1961.

83. HILL, R. The mathematical theory of
plasticity.
Oxford University Press, London,
1950, p.215.

84. JONES, M.H., HOWELLS, R.I.L. Solids in static contact.
PROBERT, S.D. Wear 12. 1968, pp.225-240.

85. WILLIAMSON, J.B.P. Microtopography of surfaces.
Properties and Metrology of Surfaces,
Proc. I, Mech. E., 182, (Pt 3K),
1967, pp.21-30.

86. LING, F.F. Some factors influencing the area-
load chracteristics for semi-smooth
contiguous surfaces under static
loading.
Tran. Am. Soc. Mech. Engrs. 80, 1958,
1113.

87. MUSTACCHI, C., Thermal and mechanical studies of
GIULIANI, S. solid-solid contact.
Euratom report EUR 2486e, 1965.

88. SCHNEIDER, G.E. Thermal resistance due to arbitrary
dirichlet contacts on a half-space.
Presented as Paper 78-870 at the 2nd
AIAA/ASME Thermophysics and heat
transfer conference. Palo Alto,
California, 1978, pp.103-119.

89. THOMAS, T.R.,
PROBERT, S.D. Thermal resistance of some multi-layer contacts under static loads. Int. Journal Heat Mass Transfer, 9, 1966, pp.739-754.
90. ABBOTT, E.J.
FIPESTONE, F.A. Specifying surface quality. Trans. ASME, 55, 1933, pp.569-572.
91. ARCHARD, J.F. Contact and rubbing of flat surfaces. J. Appl. Phys., 24, 8, 1953, pp.981-988.
92. DYSON, J., HIRST, W. The true contact area between solids. Proc. Physics. Soc. 67, 1954, pp.309-312.
93. THOMAS, T.R.,
PROBERT, S.D. Thermal resistance of pressed contacts. UKAEA report TRG 1013 (R/X) HMSO, 1965.
94. HENRY, J.J. Thermal conductance of metallic surfaces in contact. USAEC report NYO-9459, 1953.
95. FENECH, H.,
ROHSENOW, W.M. Prediction of the thermal conductance of metallic surfaces in contact. Journal of Heat Transfer, vol.85, no.1, Feb.1963, pp.15-24.
96. FRIED, E., COSTELLO, F.A. Interface thermal contact resistance problems in space vehicles. ARS Journal Vol.32, no.2, 1962, pp.237-243.
97. GALE, E.H. Jr. Effect of surface films on thermal contact conductance, Part I. Microscopic Experiments. Proc. of Space Technology and Heat Transfer Conference, ASME, 1970, pp.1-7.
98. SANOKAWA, K. Heat transfer between metallic surfaces in contact. The effect of the shape of surface roughness and the waviness and the approximate method of calculating thermal contact resistance. Bull, JSME, Four Reports, 11, 44, 1968.

99. TSA, Y.H., HEIMBURG, R.W. Effects of surface films on thermal contact conductance: Part 2. Macroscopic Experiments. Procs. of Space Technology and Heat Transfer Conference, ASME, Los Angeles, Calif., 1970.

100. HEIMBURG, R.W.,
TONG, K.N. The effect of physically absorbed gases on thermal contact resistance. Dept. of Mechanical and Aerospace Engineering, Syracuse University, New York, Proc. of the Eighth Conf. on Thermal Conductivity, 1969, p.527.

101. SKIPPER, R.G.S.,
WOOTTON, K.J. Thermal resistance between Uranium and Can. Proc. 2nd UN Int. Conf. on Peaceful Uses of Atomic Energy, 7, 1958, p.658.

102. BAZELAY, M.E.,
TONG, K.N., HOLLO, G. Thermal conductance of contacts in aircraft joints. NACA TN-3167, 1954.

103. WADHWA, S.K. Thermal contact conductance due to plane layer of adsorbed gases at the interface of smooth metallic contacts. Syracuse University, Ph.D. Dissertation, 1969.

104. CLAUSING, A.M.,
CHAO, B.T. Thermal contact resistance in a vacuum environment. National Aeronautics and Space Admin., University of Illinois; M.E. TN 242-1, 1963.

105. KOTTLER, F. Elektrostatik der leiter Handbuch der physik. Springer, Berlin, 1927.

106. ROESS, L.C. Thermal resistance measurements on joints formed between stationary metal surfaces. Paper presented at semi-annual meeting, ASME, Heat Transfer Division, Milwaukee, U.S.A., 1948.

107. YIP, F.C., VENART, J.E.S. Surface topography effects in the estimation of thermal and electrical contact resistance.
Inst. Mech. Engrs., London Int. Conf. on Properties and Metrology of Surfaces, paper No.2, 1968.
108. EDMONDS, M.J. The effect of surface configuration on thermal energy transfer, across pressed contacts.
Ph.D. Thesis, Cranfield Institute of Technology, U.K., 1978.
109. JONES, A.M. Thermal contact resistance.
Ph.D. Thesis, University of Wales, 1975.
110. THOMAS, T.R. Surface topography program.
ST P6 Avon Technology, 1971.
111. DAVIES; D.E.,
EVANS, U.R.,
AGARD, J.N. Proc. Royal Society, (A),
225, 1954, p.443.
112. KUBACHEWSKI, O.,
HOPKINS, B.E. Oxidation of metals. Second
edition.
Butterworths, London, 1962.
113. GULBRANSON, E.A.,
WYSONG, W.S. Trans. Amer. Inst. Min. (Metall)
Engrs. 175, 1948, pp.611-621.
114. BENARD, J. Metallurg, Ital. 42, 1950, p.3.
115. WINTERBOTTOM, A.B. J. Iron St. Inst., Vol.165,
1950, p.9.
116. TYE, R.P. Thermal conductivity.
Academic Press, Vol.1, 1969.
117. TYE, R.P. Thermal conductivity.
Academic Press, Vol.2, 1969.
118. SHLYKOV, Y.P.,
GANIN, Y.A. Thermal contact resistance,
Atomnaya, Energiya, 9, 6, 1960,
pp.496-498.

119. BENNETT, H.E.,
PORTEUS, J.O. Relation between surface roughness
and specular reflectance at normal
incidence.
J. Opt. Soc. Amer. 51, 2, 1961,
pp.123-129.

120. COULBERT, C.D.,
LIU, C. Thermal resistance of aircraft
structure joints.
WADC Technical Note, June 1963,
pp.50-53.

121. SHVETSOVA, E.M. Determination of the actual contact
areas of surfaces by means of trans-
parent models.
Sobornik i Trenie i Iznos, i Mashinak
(Collection; friction and wear of
machines), vol.7, 1953, pp.12-33.

122. MITCHELL, L.D.,
ROWE, M.D. Assessment of face seal performance
based on the parameters of a
statistical representation of surface
roughness.
Paper 6, Properties and Metrology
of Surfaces. Proc. I. Mech. E.,
182, part 3K, 1967, pp.101-107.

123. O'CALLAGHAN, P.W.,
PROBERT, S.D. Effect of static loading on surface
parameters.
WEAR, 24, 1973, pp.133-145.

124. GREENWOOD, J.A. Constriction resistance and the
real area of contact.
J. Appl. Phys., Vol.17, 1966,
pp.1621-1632.

125. HOWELLS, R.I.L.,
PROBERT, S.D. Contact between solids.
UKAEA Report 1701 R/X HMSO, 1968.

126. MIKIC, B.B. Effect of previous loading on thermal
contact conductance.
Internal Report, MIT, Cambridge,
Mass., 1969.

127. EUBANKS, A.G., MOORE, D.G.,
PENNINGTON, W.A. Effect of surface roughness on the
oxidation rate of iron.
Jour. Electrochem. Soc., Vol.109,
no.5, 1962, pp.382-389.

128. MURPHY, J.A. Surface preparation and finishes for metals: A manual of the Society of Manufacturing Engineers. McGraw-Hill, 1971.
129. MIAN, M.N.,
AL-ASTRABADI, F.R.,
O'CALLAGHAN, P.W.,
PROBERT, S.D. Thermal resistance of pressed contacts between steel surfaces - influence of oxide films. J. Mech. Eng. Sci., Vol.21, No.3, 1979. pp.159-166.
130. MIAN, M.N.,
O'CALLAGHAN, P.W.,
PROBERT, S.D. Thermal resistance of the freshly-pressed contacts between oxidized materials. To be published.
131. MIAN, M.N.,
O'CALLAGHAN, P.W.,
PROBERT, S.D. Thermal resistance of freshly-pressed contacts between oxidized surfaces of the same material. To be published.
132. MIAN, M.N.,
O'CALLAGHAN, P.W.,
PROBERT, S.D. The electrical and thermal resistance of the multi-layer systems. To be published.
133. GODARD, H.P.,
JEPSON, W.B.,
BOTHWELL, M.R.,
KANE, R.L. The corrosion of light metals. Wiley, New York, 1967.
134. Tables of error function and of its first twenty derivatives. Staff of the Computer Laboratory, Cambridge, Mass., Harvard University Press, 1952.
135. WEILLS, N.D.,
RYDER, E.A. Thermal resistance measurements on joints formed between stationary metal surfaces, Paper presented at Semi-Annual Meeting ASME Heat Transfer Division, Milwaukee, U.S.A., 1948.
136. ROESS, L.C. Theory of spreading resistance. Appendix to Ref. 135.

137. BRITISH STANDARDS
INSTITUTION

Methods of test for metallic and related coatings. Part 2. Review of methods for the measurement of thickness.
BSI 5411, Part 2, 1978.

138. SAMSONOV, G.V.

The oxide handbook.
Institute of Cermets and Special Alloys, Academy of Sciences of the Ukranian SSR Kiev, U.S.S.R.

139. ROGERS, G.F.C.

Heat transfer at the interface of the dissimilar materials.
Int. Journal Heat Mass. Transfer 2, 1961, pp.150-154.

140. YOVANOVICH, M.M.

Effect of foils upon joint resistance. Evidence of optimum thickness. Presented as Paper No.72-282 at the AIAA 7th Thermophysics Conference San Antonio Texas, 1972, pp.227-243.

141. BLOOM, M.F.

Thermal contact conductance in a vacuum environment.
Douglas Aircraft Corporation Report No. SM-47700, 1974.

142. YOVANOVICH, M.M.,
MARTIN, K.A.,
SCHNEIDER, G.E.

Constriction resistance of doubly-connected areas under uniform flux
AIAA 14th Thermophysics Conference, June 1979, Orlando, Florida, U.S.A., pp.1-5.

143. YOVANOVICH, M.M.,
SCHNEIDER, G.E.

Thermal constriction resistance due to circular annular contact.
Progress in Astronautics and Aeronautics. Thermophysics of Space-craft and outer plant entry probes., vol.56, edited by A.M. Smith, New York, 1977, pp.141-154.

APPENDIX I
ELECTRICAL RESISTANCE

APPENDIX IMEASUREMENT OF THE ELECTRICAL AND THERMAL RESISTANCES IN VACUUM

The electrical resistances were measured directly using copper contact rings on either side of the specimens as shown in Fig. 1 and plate 1.

Table 1 and Table 2 present respectively the measurements for the oxide-free as well as for the oxidised copper-to-copper static contact. The observations for the electrical and thermal resistance were taken simultaneously in high vacua better than 10^{-4} torr. In the absence of a more rigorous correlation, the electrical resistances have been related with the thermal resistances through the Wiedemann-Franz law (16) i.e.

$$\frac{R_e}{R} = LT \quad (1)$$

where R_e = electrical resistance, Ω

R = experimentally measured thermal resistances, KW^{-1}

L = Lorenz's constant, $2.48 \times 10^{-8} \text{ W}\Omega/\text{degree}^2$

T = the interface temperature, $^{\circ}\text{K}$

% age electronic contribution

$$= \frac{\text{electrical resistance via the Wiedemann-Franz law}}{\text{experimentally measured electrical resistance}} \quad (2)$$

The measured electrical resistance was higher than the one calculated from Wiedemann-Franz law. There was a very little correlation between the electrical and thermal contact resistances. The Wiedemann-Franz law used for relating the resistances considers the thermal conductivity and the electrical resistivity of the contacting materials to be functions of temperature only. The variations between the experimental and the calculated resistances through the Wiedemann Franz law could be associated to the phenomenon of the flow of electrical and thermal current. An electrical current flows through the constrictions of the micro-contacts only (12) whereas the heat transfers across the interface by the constriction of the micro-contacts; by jumping across the gap between the contacting asperities and by a small amount of direct radiation.

In electrical analogy, an electron flow is considered (16); (the maximum percentage electronic contribution in this case was 6%) while heat flow is a combination of electron and phonon effects. Other reasons for the lack of correlation were the contact rings at a macroscopic distance from the interface and the resistance of the leads carrying potential.

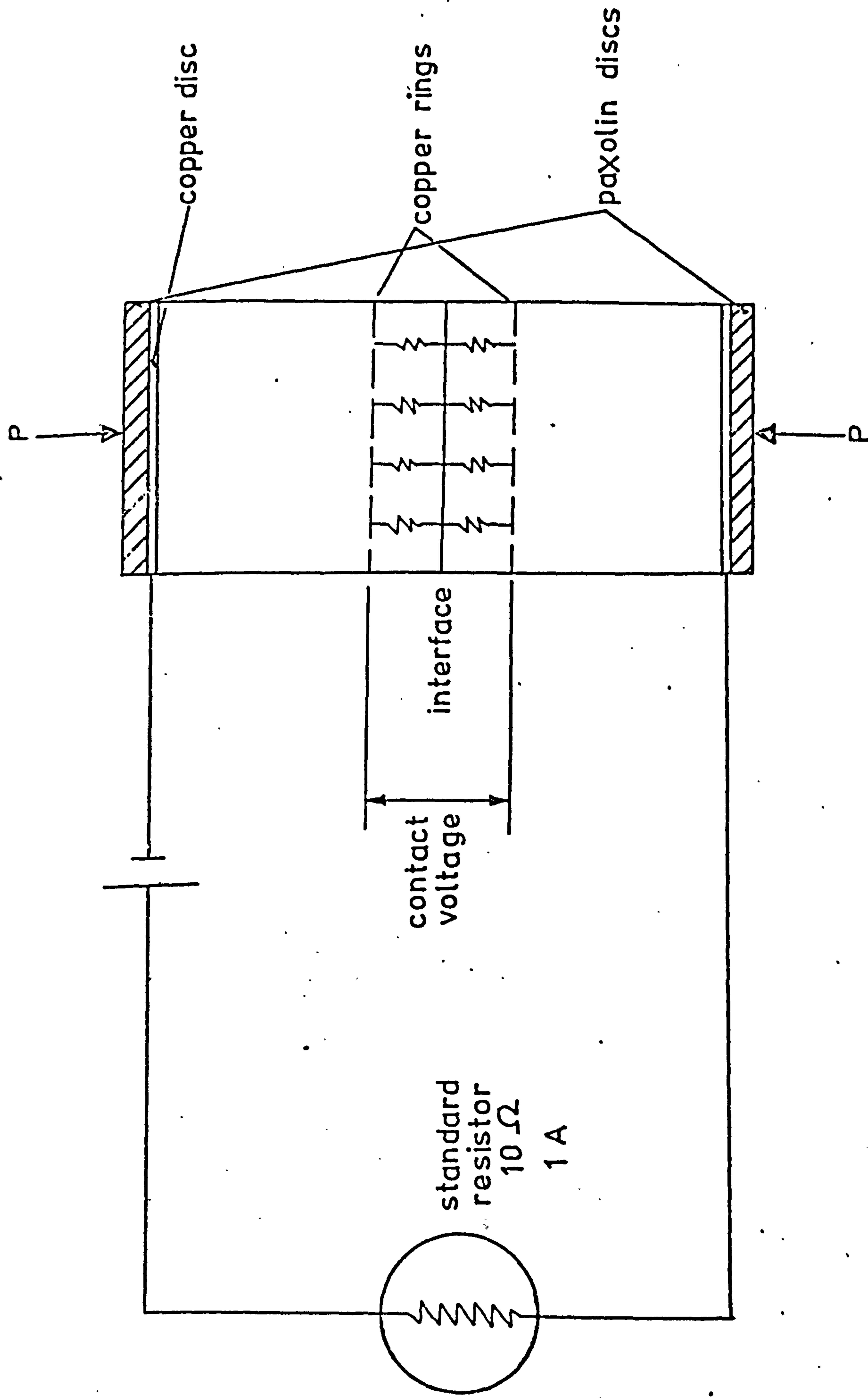


FIG.1 SCHEMATIC ARRANGEMENT OF ELECTRICAL RESISTANCE MEASURING EQUIPMENT

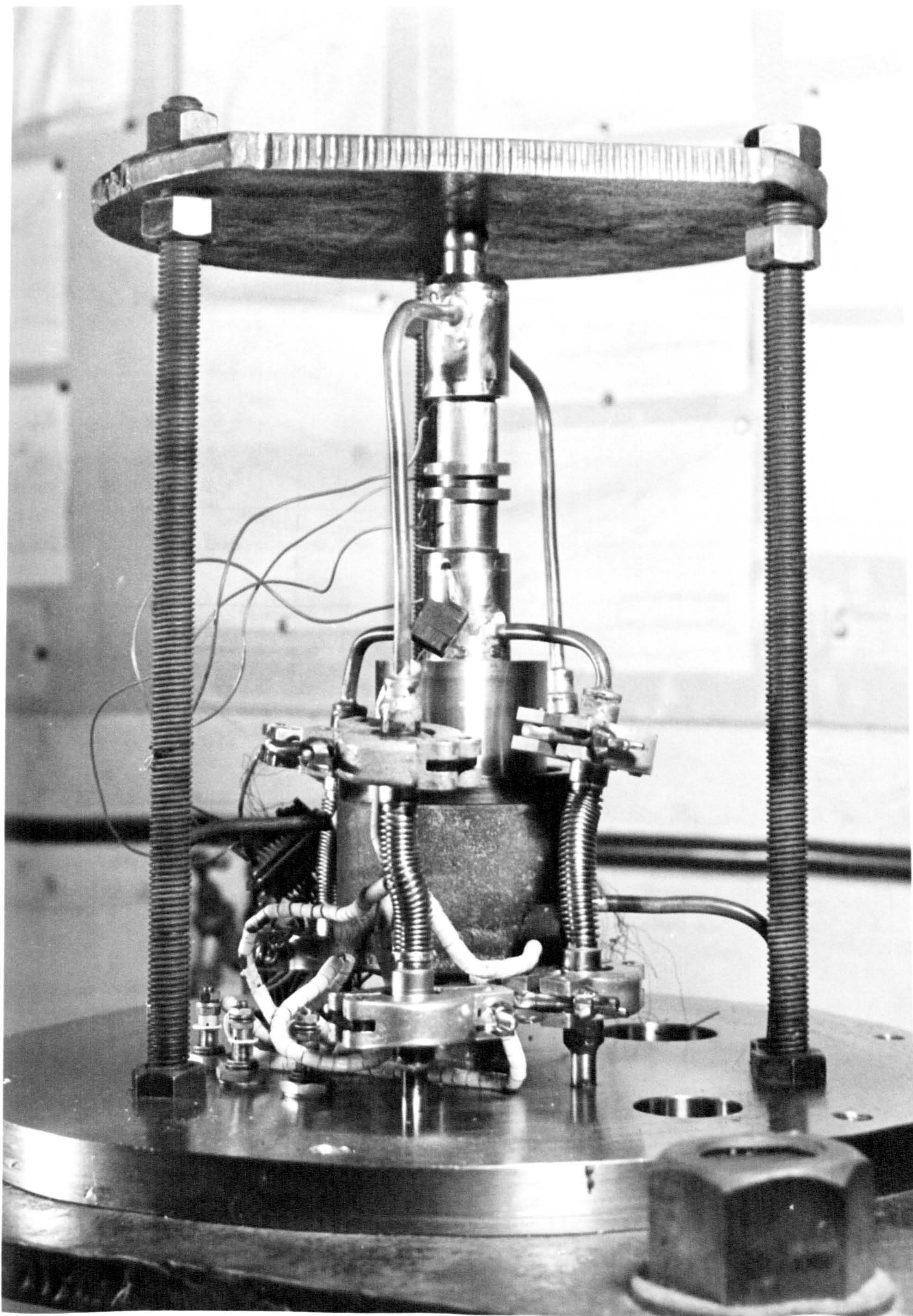


Plate 1 Test rig showing the central module and the contact rings to measure the interfacial Voltage drop.

Table 1OBSERVATIONS OF THE ELECTRICAL AND THERMAL RESISTANCES

oxide-free, copper-to-copper contact

Electrical wattage = 0.57 W

Heat input = 5.92 W

Load, N	Voltage drop across the interface 10^{-3} V	R_e $10^{-3} \Omega$	R Km^2W^{-1}	R_e W-F law Ω	R W-F law Km^2W^{-1}
0	0.046	0.23	1.2×10^{-4}	1.79×10^{-6}	1.53×10^{-2}
1250	0.034	0.17	0.812×10^{-5}	1.21×10^{-7}	1.135×10^{-2}
3650	0.022	0.11	0.635×10^{-5}	9.47×10^{-8}	7.39×10^{-3}
5850	0.020	0.10	0.594×10^{-5}	8.86×11^{-8}	6.6×10^{-3}

Table 2OBSERVATIONS OF THE ELECTRICAL AND THERMAL RESISTANCES

oxide-free copper to oxidised copper contact

Electrical wattage = 0.57 W

Heat input = 5.92 W

Load	Voltage drop 10^{-3} V	R_e $10^{-3} \Omega$	R $\text{Km}^2 \text{W}^{-1}$	R_e w-F law Ω	R w-F law
0	0.062	0.310	4.58×10^{-4}	6.98×10^{-6}	2.03×10^{-2}
1250	0.052	0.260	1.02×10^{-4}	1.57×10^{-6}	1.707×10^{-2}
3650	0.023	0.115	1.9×10^{-5}	2.89×10^{-7}	7.55×10^{-3}
5850	0.021	0.105	1.2×10^{-5}	1.829×10^{-7}	6.89×10^{-3}

APPENDIX II

COMPUTER PROGRAM FOR THE EVALUATION OF SURFACE
PARAMETERS AND NUMERICAL RESULTS FOR THE ORDINATE HEIGHT
DISTRIBUTION OF SPECIMEN SURFACES.

SPECIMEN CALCULATIONS.

APPENDIX IICOMPUTER PROGRAM FOR THE EVALUATION OF SURFACE PARAMETERS
PROGRAM NOTES (109) :-

This program (69) calculates the RMS and CLA roughness of a surface profile, identifies the peaks and valleys, calculates the number of contacts per unit length and the average land length over a range of surface heights. Also evaluates the peak radii of curvature and slopes of the asperities. A subroutine selects the highest and lowest values, produced distributions and calculates statistical parameters for all ordinates, valleys, peaks, radii of curvature and slopes. The program simulates data being sampled at different intervals by selecting sampled ordinates for computation at various separations.

In this way all the above mentioned parameters could be evaluated over a complete range of sampling interval. In addition, the surface auto-correlation is evaluated over the range of sampling intervals.

The data logger output is a list of consecutive ordinates punched on paper tape. The vertical magnification and number of ordinates are read from punched cards. The same stylus traverse speed and sampling rate are used for all tapes, the ordinate spacing is therefore set at 2.822 μm .

Previous to the calculation of parameters, the program fits a least-squares mean line to the surface ordinates, recalculates them relative to this line, and evaluates the RMS and CLA roughness. A slight mechanical misalignment of the measuring system is therefore unimportant provided all profile information is present, i.e. no peaks or valleys are truncated. The detail of the evaluation of the surface parameters is as below:-

i) RMS and CLA roughness

The evaluation of the root-mean-square (RMS) roughness of the profile is based on the expression

$$\sigma = \left(\frac{1}{d} \sum_{i=1}^{i=d} y_i^2 \right)^{1/2} \quad (1)$$

and the centre-line-average (CLA) is evaluated using

$$\text{CLA} = \frac{1}{d} \sum_{i=1}^{i=d} |y_i| \quad (2)$$

where d is the number of ordinates sampled.

ii) Subroutine DIST

The subroutine DIST calculates the maximum, minimum, mean and standard deviation of lists of parameters computed at various points. A table of frequency distributions is also compiled.

The frequency table is computed in 100 rows each of 0.1 standard deviation, starting at five standard deviations below the mean of the distribution.

iii) Peaks and valleys

The program defines a peak as a point higher than its j^{th} nearest neighbours. The value of j is 1 for the data as sampled by the stylus instrument. As j is increased to higher positive integer values, the effective sampling interval is increased in multiples of 2.822 μm , and the number of peaks detected per unit length becomes less. The ratio of peaks to ordinates is computed. The detection of valleys is performed in a similar manner. When the list of peaks or valleys has been prepared, the subroutine DIST is called and the various statistical parameters evaluated.

iv) Peak and valley curvature

Having identified a peak in the profile, the program calculates its curvature from a central difference formula for the second differential

$$\rho = (2y_i - y_{i-j} - y_{i+j}) / (xj)^2 \quad (3)$$

where x is the horizontal ordinate separation (2.822 μm).

The curvature, and not the radius of curvature, is computed since the upper limit of the radius of curvature distribution tends to infinity, whereas the corresponding limit of the curvature distribution tends to zero; the latter is obviously simpler for subroutine DIST to handle. The curvatures of the valleys are computed in a similar manner. Subroutine DIST is called to statistically analyse the lists computed. The procedure is repeated for different sampling intervals by incrementing j .

v) Profile slope

The program assumes that the slope at a point could be represented by straight line between its nearest neighbours i.e.

$$\left(\frac{dy}{dx}\right)_i = (y_{i+j} - y_{i-j}) / 2xj \quad (4)$$

If the slopes of both signs are counted, the mean slope generally becomes zero. The program therefore calculates the mean absolute slope as given by

$$\psi = \frac{1}{d - 2j} \sum_{i=j+1}^{d-j} |y_{i+j} - y_{i-j}| / 2xj \quad (5)$$

The output is the tangent of the slope angle, but since this angle rarely exceeded 10° the output is to a good approximation the slope angle in radians.

vi) Auto-correlation function

The degree of correlation between points on a profile, separated by a certain horizontal distance, depends on the structure of the surface of which the profile is a section. A measure of this correlation function defined by:

$$F_j = \frac{1}{\sigma L} \int_0^L y(x) y(x + j) dx \quad (6)$$

The maximum lag interval, $j_{\max}$, is set at less than a tenth of the total length of the profile to avoid the computation of meaningless data. This, however, means that it is not possible to detect periodic components of the surface irregularities whose wavelength is greater than 1/20 of the profile length.

The digital computation of the normalised auto-correlation is performed using:

$$F_j = \frac{1}{\sigma(d - j)} \sum_{i=1}^{i=d-j} y_i y_{i+j} \quad (7)$$

JOB ME167S, H.N.HIAN
MAXTIME 2000
CCFORTRAN R68A, LIST, 2000, N
VOLUME 5000
IN ED(PROGRAM JOBA)
LOAD #R68A
IN /O(DATA-R68A)
IN TR0(DATATAPE)
ENTER0

FORTRAN COMPILATION BY #XFAT HK 5A DATE 11/11/77 TIME 13/37/35

LIST

SEND TO(EN,SEMICOMPJOBA.STORE)
DUMP ON(ED,PROGRAM JOBA)
WORK(ED,PROGRAM WRKA(0))
LIBRARY(SUBGROUPCRAN)
PROGRAM(R68A)
INPUT1=CR0
INPUT3=TR0
OUTPUT2,(MONITOR)=LP0
COMPRESS INTEGER AND LOGICAL
END

MASTER STP6
DOUBLE PRECISION DA,DB,DC
DIMENSION Y(6000),Z(6000),RN(2000),SDPD(2000),YBAR(2000),
1CURV(2000),SLOPE(2000),NSW(13)

COMMON NDIST
WRITE(2,199)
WRITE(2,199)
WRITE(2,189)

READ(1,192)(NSW(I),I=1,13),JX,JY,JZ
NDIST=NSW(11)
2 READ(1,193)NRECOR,K,VMAQ,HSEP
WRITE(2,199)

WRITE(2,199)
READ(3,521)(Y(I),I=1,K)
521 FORMAT(4D00FD,D)

0001
0002
0003
0004
0005
0006
0007
0008
0009
0010
0011
0012

0013
0014
0015
0016
0017
0018
0019
0020

0021
0022
0023
0024
0025
0026
0027

0028
0029


```

0072 WRITE(2,199)
0073 WRITE(2,108)
0074 WRITE(2,128)
0075 CALL DIST(Y,K)
0076
0077
0078
0079
0080
0081
0082
0083
0084
0085
0086
0087
0088
0089
0090
0091
0092
0093
0094
0095
0096
0097
0098
0099
0100
0101
0102
0103
0104
0105
0106
0107
0108
0109
0110
0111
0112
0113

IF(NSW(7).NE.1)GOTO72
WRITE(2,199)
WRITE(2,108)
WRITE(2,128)
CALL DIST(Y,K)
UPCROSSINGS PER UNIT LENGTH
92 IF(NSW(9).NE.1)GOTO72
WRITE(2,199)
K9=0
KH1=K-1
DO 90 I=2,KH1
IF(Y(I-1).LT.0..AND.Y(I).GT.0.)K9=K9+1
90 CONTINUE
UPCROS=FLOAT(K9)/HSEP/(FK-1)
WRITE(2,109)UPCROS
C
C
C
LAND LENGTHS AND BEARING LENGTH
72 IF(NSW(7).NE.1)GOTO82
WRITE(2,199)
WRITE(2,113)
WRITE(2,128)
WRITE(2,122)
WRITE(2,107)
DO 71 I=1,K
IF(YMAX.LT.Y(I+1))YMAX=Y(I+1)
IF(YMIN.GT.Y(I+1))YMIN=Y(I+1)
71 CONTINUE
T7B=0.01*(YMAX-YMIN)
T7=YMIN-T7B
70 I=1
T7=T7+T7B
N=0
L=0
IF(T7-YMAX)74,82,82
IF(Y(I)-T7)75,76,76
74 I=I+1
75 IF(K-I)79,79,74
76 N=N+1
77 L=L+1
I=I+1

```



```

      IF(Y(1)-T7)75,77,77
      IF(N.EQ.0)GOTO70
      EL=FLOAT(L)*HSEP/LOAT(N)
      ELA=FLOAT(L)/((FK-1.))
      FN=FLOAT(N)/FK/HSEP
      WRITE(2,117)T7,FN,EL,ELA
      GOTO70

```

AUTOCORRELATION FUNCTION

```

82 IF(NSU(12).NE.1)GOTO501

```

```

      WRITE(2,199)

```

```

      WRITE(2,171)

```

```

      WRITE(2,124)

```

```

      WRITE(2,122)

```

```

      WRITE(2,210)

```

```

      WRITE(2,122)

```

```

      WRITE(2,140)

```

```

      K12=K/20

```

```

      DO 301 KK=1,K12

```

```

        SA=0.

```

```

        KMK=K-KK

```

```

        DO 300 I=1,KMK

```

```

          SA=SA+Y(I)*Y(I+KK)

```

```

          Z(KK)=SA/LOAT(K-KK)/RMS/RMS

```

```

          IF(Z(KK).GT.0.000)GOTO302

```

```

          WRITE(2,172)KK,Z(KK)

```

```

          FORMAT(16X,14,3X,F12.5)

```

```

          GOTO 301

```

```

302 FKK=LOAT(KK)*HSEP

```

```

      RN(KK)=ATAN(((3.0-Z(KK))/(1.0+Z(KK)))*0.5)/3.142

```

```

      SDPD(KK)=RMS*(1.0-(1.0+Z(KK))*0.5)/(2.0*3.142*RN(KK)*

```

```

      1(TAN(RN(KK)*3.142))*2.0)-((1.0-Z(KK))/(4.0*3.142*RN(KK))*2.0))

```

```

      YBAR(KK)=(RMS*((1.0-Z(KK))/3.142)*0.5)/(2.0*RN(KK))

```

```

      CURV(KK)=(RMS*(3.0-Z(KK))*((1.0-Z(KK))*0.5)/((FKK)*2.0*RN(KK)

```

```

      1*2.0*1.772)

```

```

      SLOPE(KK)=(RMS*((1.0-Z(KK))*2.0)/3.142)*0.5/(FKK)

```

```

      WRITE(2,170)KK,Z(KK),RN(KK),SDPD(KK),YBAR(KK),CURV(KK),SLOPE(KK)

```

```

      170 FORMAT(16X,14,3X,F12.5,1X,F12.5,1X,F12.5,1X,F12.5,1X,

```

```

      1F12.5,1X,F12.5)

```

```

301 CONTINUE

```

```

      DO 502 J=JX,JY,JZ

```

```

      FJ=LOAT(J)*HSEP

```



```

0100 WRITE(2,199)
0164 WRITE(2,101)
0165 WRITE(2,131)J
0166 WRITE(2,128)
0167 K1=0
0168 JP1=J+1
0169 KMJ=K-J
0170 DO 10 I=JP1,KMJ
0171 IF(Y(I).GT.Y(I-J).AND.Y(I).GT.Y(I+J))GOTO11
0172 GO TO 10
0173 11 K1=K1+1
0174 Z(K1)=Y(I)
0175 10 CONTINUE
0176 CALL DIST(Z,K1)
0177 FPEAK=FLOAT(K1)/FK
0178 WRITE(2,111)FPEAK
0179
0180 C
0181 C
0182 VALLEYS
0183
0184 22 IF(NSW(2).NE.1)GO TO 32
0185 WRITE(2,199)
0186 K2=0
0187 DO 20 I=JP1,KMJ
0188 IF(Y(I).LT.Y(I-J).AND.Y(I).LT.Y(I+J))GOTO21
0189 GO TO 20
0190 21 K2=K2+1
0191 Z(K2)=Y(I)
0192 20 CONTINUE
0193 WRITE(2,102)
0194 WRITE(2,131)J
0195 WRITE(2,128)
0196 CALL DIST(Z,K2)
0197 FVALL=FLOAT(K2)/FK
0198 WRITE(2,112)FVALL
0199
0200 C
0201 C
0202 PEAK CURVATURE
0203 32 IF(NSW(3).NE.1)GO TO 42
0204 WRITE(2,199)
0205 K3=0
0206 DO 30 I=JP1,KMJ
0207 IF(Y(I).GT.Y(I+J).AND.Y(I).GT.Y(I-J))GOTO31
0208 GO TO 30
0209 31 K3=K3+1
0210 Z(K3)=(2.*Y(I)-Y(I-J)-Y(I+J))/FJ/FJ

```


30 CONTINUE

WRITE(2,103)

WRITE(2,131)J

WRITE(2,125)

CALL DIST(Z,K3)

VALLEY CURVATURE

42 IF(NSW(4).NE.1)GO TO 52

WRITE(2,199)

K4=0

DO 40 I=JP1,KMJ

IF(Y(I).LT.Y(I-J).AND.Y(I).LT.Y(I+J))GOTO 41

GO TO 40

41 K4=K4+1

Z(K4)=(2.*Y(I)-Y(I-J)-Y(I+J))/FJ/FJ

40 CONTINUE

WRITE(2,104)

WRITE(2,131)J

WRITE(2,125)

CALL DIST(Z,K4)

PROFILE CURVATURE

52 IF(NSW(5).NE.1)GO TO 62

WRITE(2,199)

K5=K-2+J

DO 50 I=JP1,KMJ

50 Z(I-J)=(2.*Y(I)-Y(I-J)-Y(I+J))/FJ/FJ

WRITE(2,105)

WRITE(2,131)J

WRITE(2,125)

CALL DIST(Z,K5)

PROFILE SLOPE

62 IF(NSW(6).NE.1)GOTO 402

WRITE(2,199)

SABSLO=0.

K6=K-2+J

DO 60 I=JP1,KMJ

Z6=(Y(I+J)-Y(I-J))/2./FJ


```

SABSLO=SABSLO+ABS(Z6)
60 7(I-J)=76
ABSLOP=57.296+ATAN(SABSLO/FLOAT(K6))
WRITE(2,106)
WRITE(2,131)J
WRITE(2,127)
CALL DIST(Z,K6)
WRITE(2,122)
WRITE(2,120)ABSLOP
402 CONTINUE
502 CONTINUE
1 READ(1,191)NEND
IF(NEND.EQ.1)GO TO 2
WRITE(2,199)
WRITE(2,110)

```

FORMAT STATEMENTS

```

101 FORMAT(40X,26H PEAK DISTRIBUTION FOLLOWS)
102 FORMAT(40X,28H VALLEY DISTRIBUTION FOLLOWS)
103 FORMAT(40X,36H PEAK CURVATURE DISTRIBUTION FOLLOWS)
104 FORMAT(40X,38H VALLEY CURVATURE DISTRIBUTION FOLLOWS)
105 FORMAT(40X,39H PROFILE CURVATURE DISTRIBUTION FOLLOWS)
106 FORMAT(40X,35H PROFILE SLOPE DISTRIBUTION FOLLOWS)
107 FORMAT(10X,15H DISTANCE FROM,10X,15H NO. OF LANDS ,10X,
115H MEAN LAND ,10X,15H BEARING LENGTH,/10X,15H MEAN LINE
2,10X,15H PER UNIT LENGTH,10X,15H LENGTH ,10X,15H FRACTION
3 ,/)
108 FORMAT(40X,30H ORDINATE DISTRIBUTION FOLLOWS)
109 FORMAT(//,10X,10H THERE ARE,612.4,36H UPCROSSINGS PER UNIT PROFILE
1 LENGTH)
110 FORMAT(40X,14H END OF OUTPUT)
111 FORMAT(//,10X,612.4,27H OF ALL ORDINATES ARE PEAKS)
112 FORMAT(//,10X,612.4,29H OF ALL ORDINATES ARE VALLEYS)
113 FORMAT(40X,39H LAND LENGTHS AND BEARING LENGTH FOLLOW)
117 FORMAT(9X,4(615.4,10X))
120 FORMAT(20X,31H PROFILE MEAN ABSOLUTE SLOPE IS,6.3,10H DEGREES )
121 FORMAT(/)
122 FORMAT(//)
123 FORMAT(//1111)
124 FORMAT(20X,73H TABLE GIVES CORRELATION AUT BETWEEN ORDINATES AND T
1 THEIR KK-TH SUCCESSORS)
125 FORMAT(40X,26H UNITS - RECIPROCAL LENGTH)
126 FORMAT(20X,30H VERTICAL MAGNIFICATION FACTOR,612.4,10X,20H ORDINAT
1E SEPARATION,612.4)

```


LINE	ADDRESS	INSTRUCTIONS	OPERANDS	OPERATION	STATUS
0295	127	FORMAT(40X,16H UNITS - RADIANS)			
0296	128	FORMAT(40X,15H UNITS - LENGTH)			
0297	130	FORMAT(40X,40H LIST OF ORDINATES REFERRED TO MEAN LINE, //			
0298	15000(2X,610.3))				
COMMENT 178		IS THIS LARGE A REPEAT COUNT INTENDED AT ABOUT COLUMN 9, LINE 0298			
0299	131	FORMAT(40X,32H BASED ON A SAMPLING INTERVAL OF,14,10H ORDINATES)			
0300	140	FORMAT(16X,3H KK,11X,2H 2,10X,3H RN,9X,5H SPPD,8X,			
0301	16H Y BAR,5X,10H CURVATURE,5X,6H SLOPE, //)				
0302	171	FORMAT(20X,70H VARIATION OF AUTOCORRELATION FUNCTION WITH SAMPLING			
0303	1	INTERVAL FOLLOWS)			
0304	180	FORMAT(20X,11H RECORD NO.,15,11H CONTAINING,15,10H ORDINATES)			
0305	181	FORMAT(//,10X,16H RMS ROUGHNESS =,612.4,10X,16H CLA ROUGHNESS =,61			
0306	12.4)				
0307	182	FORMAT(40X,27H LIST OF ORDINATES AS INPUT, //5000(2X,610.3))			
COMMENT 178		IS THIS LARGE A REPEAT COUNT INTENDED AT ABOUT COLUMN 53, LINE 0307			
0308	189	FORMAT(40X,32H SURFACE TOPOGRAPHY PROGRAM STEP, //)			
0309	190	FORMAT(26F3.0)			
0310	191	FORMAT(11)			
0311	192	FORMAT(1311,14,14,14)			
0312	193	FORMAT(214,2F10.0)			
0313	199	FORMAT(//, //, //, //, //, //)			
0314	210	FORMAT(20X,55H KK - SAMPLING INTERVAL IN TERMS OF ORDINATE SEPERAT			
0315	110N, /20X,29H Z - AUTOCORRELATION FUNCTION, /				
0316	220X,33H RN - RATIO OF PEAKS TO ORDINATES, /				
0317	320X,47H SPPD - STANDARD DEVIATION OF PEAK DISTRIBUTION, /				
0318	420X,41H YBAR - MEAN PEAK HEIGHT ABOVE CENTERLINE, /				
0319	520X,32H CURVATURE - MEAN PEAK CURVATURE, /				
0320	620X,28H SLOPE - MEAN ABSOLUTE SLOPE)				
0321	220	FORMAT(20X,18H SAMPLING INTERVAL,2X,14,2X,3H TO,2X,			
0322	114,2X,12H IN STEPS OF,14,2X,21H ORDINATE SEPERATIONS)				
0323	STOP				
0324	END				
END OF SEGMENT, LENGTH 1445, NAME STEP6 - COMMENTS					
0325		SUBROUTINE DIST(X,K)			
0326					
0327		FINDS MAXIMUM, MINIMUM, MEAN, STANDARD DEVIATION AND FREQUENCY			
0328		DISTRIBUTION OF LIST X			
0329					
0330		DIMENSION X(5000), NS(100)			
0331		COMMON UNIT			

HIGHEST AND LOWEST VALUES

XMAX=X(1)
XMIN=X(1)

KM1=K-1

DO 10 I=1,KM1

IF(XMAX.LT.X(I+1))XMAX=X(I+1)

IF(XMIN.GT.X(I+1))XMIN=X(I+1)

10 CONTINUE

WRITE(2,100)K,XMAX,XMIN

MEAN AND STANDARD DEVIATION

FK=FLOAT(K)

SUMX=0.

SUMR=0.

DO 40 I=1,K

40 SUMX=SUMX+X(I)

XMEAN=SUMX/FK

DO 46 I=1,K

46 SUMR=SUMR+(XMEAN-X(I))*(XMEAN-X(I))

SIGMA=SQRT(SUMR/FK)

WRITE(2,101)XMEAN,SIGMA

SORT FOR DISTRIBUTION

IF(NDIST.NE.1)RETURN

PHI=SIGMA/10.

BOUND=5.0+SIGMA

DO 50 I=1,99

50 MS(I)=0

DO 47 I=1,K

47 IF(ABS(XMEAN-X(I))-BOUND)43,45,45

45 WRITE(2,143)X(I)

GO TO 47

43 L=(X(I)-XMEAN+BOUND)/PHI+1.

MS(L)=MS(L)+1

47 CONTINUE

OUTPUT

WRITE(2,103)

ALEVEL=-5.1


```

0376
0377
0378
0379
0380
0381
0382
0383
0384
0385
0386
0387
0388
0389
0390
0391
0392
0393
0394
0395
0396
0397

END OF SEGMENT, LENGTH 276, NAME DIST
0398
FINISH

END OF COMPILATION = NO ERRORS 3 COMMENTS

S/C SUBFILE: 42 BUCKETS USED

```

FS=0.
NO 20 I=1,99
ALEVEL=ALEVEL+0.1
IF(MS(I).EQ.0)GOTO20
FMS=FLOAT(MS(I))/FK*100.
FS=FS+FMS
ALEVSI=ALEVEL+SIGMA+XMEAN
WRITE(2,102)ALEVSI,ALEVEL,MS(I),FMS,FS
20 CONTINUE

FORMAT STATEMENTS

100 FORMAT(/1X,11H HIGHEST OF,15,10H VALUES 15,612.4,10X,10H LOWEST 1
15,612.4)
101 FORMAT(/10X,6H MEAN=,612.4,10X,20H STANDARD DEVIATION=,612.4,/))
143 FORMAT(10X,32H VALUE OUTSIDE TABULATED LIMITS,612.4)
102 FORMAT(1X,620.4,F15.1,120.5X,2620.4)
103 FORMAT(/10X,10H LEVEL 10X,10H NORMALIZED,10X,10H NUMBER OF,10
1X,10H PER CENT,10X,10HCUMULATIVE,130X,10H LEVEL 10X,10H VALUE
2S 10X,10H OF TOTAL,10X,10H PER CENT,/))
RETURN
END

TABLE A Numerical Results for the Ordinate Distribution of the Sand-Blasted Stainless Steel Specimen M6. Surface Roughness, 2.558 μm (RMS), Fig. 5.1

HIGHEST OF 3200 VALUES IS 7.502

LOWEST IS -8.837

MEAN = -0.3998E+10

STANDARD DEVIATION = 2.558

ORDINATE DISTRIBUTION ON FOLLOWS
UNITS - LENGTH

LEVEL	NORMALIZED LEVEL	NUMBER OF VALUES	PER CENT OF TOTAL	CUMULATIVE PER CENT
-8.951	-3.5	2	0.6250E-01	0.6250E-01
-8.696	-3.4	2	0.9375E-01	0.1563
-8.440	-3.3	2	0.6250E-01	0.2188
-8.184	-3.2	2	0.6250E-01	0.2813
-7.928	-3.1	1	0.3125E-01	0.3125
-7.673	-3.0	5	0.1563	0.4688
-7.417	-2.9	5	0.1563	0.6250
-7.161	-2.8	7	0.2188	0.8438
-6.905	-2.7	3	0.9375E-01	0.9375
-6.650	-2.6	10	0.3125	1.250
-6.394	-2.5	9	0.2813	1.531
-6.138	-2.4	10	0.3125	1.844
-5.882	-2.3	17	0.5313	2.375
-5.627	-2.2	13	0.4062	2.781
-5.371	-2.1	19	0.5938	3.375
-5.115	-2.0	11	0.3438	3.687
-4.859	-1.9	16	0.5000	4.187
-4.604	-1.8	27	0.8438	5.031
-4.348	-1.7	28	0.8750	5.906

-5.4350	-7.5	31	0.9488	7.875
-3.581	-1.4	45	1.406	9.281
-3.325	-1.3	53	1.656	10.94
-3.069	-1.2	58	1.812	12.75
-2.813	-1.1	58	1.812	14.56
-2.558	-1.0	80	2.500	17.06
-2.302	-0.9	91	2.844	19.91
-2.046	-0.8	92	2.875	22.78
-1.790	-0.7	102	3.187	25.97
-1.535	-0.6	104	3.250	29.22
-1.279	-0.5	131	4.094	33.31
-1.023	-0.4	106	3.312	36.62
-0.7673	-0.3	124	3.875	40.50
-0.5115	-0.2	122	3.812	44.31
-0.2558	-0.1	128	4.000	48.31
-0.2540E-09	-0.0	129	4.031	52.34
0.5115	0.1	129	4.031	56.37
0.7673	0.2	144	4.500	60.87
1.023	0.3	122	3.812	64.69
1.279	0.4	148	4.625	69.31
1.535	0.5	123	3.844	73.16
1.790	0.6	113	3.531	76.69
2.046	0.7	101	3.156	79.84
2.302	0.8	98	3.062	82.91
2.558	0.9	105	3.281	86.19
2.813	1.0	71	2.219	88.41
3.069	1.1	65	2.031	90.44
3.325	1.2	47	1.469	91.91
3.581	1.3	39	1.219	93.13
3.836	1.4	32	1.000	94.12
4.092	1.5	31	0.9488	95.09
4.348	1.6	26	0.8125	95.91
4.604	1.7	18	0.5425	96.47
4.859	1.8	18	0.5425	97.03
5.115	1.9	14	0.4775	97.47
5.371	2.0	13	0.4062	97.87
5.627	2.1	14	0.4775	98.31
5.882	2.2	9	0.2813	98.59
6.138	2.3	7	0.2188	98.81
6.394	2.4	7	0.2188	99.03
6.650	2.5	11	0.3438	99.37
6.905	2.6	10	0.3125	99.69
7.161	2.7	7	0.2188	99.91
7.417	2.8	2	0.6250E-01	99.97
	2.9	1	0.3125E-01	100.0

TABLE B. Numerical Results for the Ordinate Distribution of the Commercially Pure Copper Specimen Surface M7. Surface Roughness, 0.0828 μm (RMS), Fig. 5.2

ORDINATE DISTRIBUTION FOLLOWS
UNITS - LENGTH

HIGHEST OF 3200 VALUES IS 0.4049

LOWEST IS -0.3844

MEAN = -0.1512E-10

STANDARD DEVIATION = 0.8285E-01

A.21

LEVEL	NORMALIZED LEVEL	NUMBER OF VALUES	PER CENT OF TOTAL	CUMULATIVE PER CENT
-0.3894	-4.7	1	0.3125E-01	0.3125E-01
-0.3728	-4.5	1	0.3125E-01	0.6250E-01
-0.35231	-3.9	1	0.3125E-01	0.9375E-01
-0.2900	-3.5	2	0.6250E-01	0.1563
-0.2817	-3.4	1	0.3125E-01	0.1875
-0.2734	-3.3	1	0.3125E-01	0.2188
-0.2651	-3.2	2	0.6250E-01	0.2813
-0.2568	-3.1	1	0.3125E-01	0.3125
-0.2485	-3.0	3	0.9375E-01	0.4063
-0.2403	-2.9	2	0.6250E-01	0.4688
-0.2320	-2.8	5	0.1563	0.6250
-0.2237	-2.7	5	0.1563	0.7813
-0.2154	-2.6	1	0.3125E-01	0.8125
-0.2071	-2.5	3	0.9375E-01	0.9063
-0.1988	-2.4	14	0.4375	1.344
-0.1906	-2.3	10	0.3125	1.656
-0.1823	-2.2	13	0.4062	2.062
-0.1740	-2.1	17	0.5313	2.594
-0.1657	-2.0	21	0.6563	3.250
-0.1574	-1.9	12	0.3750	3.625
-0.1491	-1.8	24	0.7500	4.375
-0.1408	-1.7	33	1.031	5.406
-0.1326	-1.6	32	1.000	6.406
-0.1243	-1.5	48	1.500	7.906
-0.1160	-1.4	46	1.437	9.344

-0.8285E-01
-0.7456E-01
-0.6628E-01
-0.5799E-01
-0.4771E-01
-0.4142E-01
-0.3314E-01
-0.2485E-01
-0.1657E-01
-0.8285E-02
-0.2705E-10
0.8285E-02
0.1657E-01
0.2485E-01
0.3314E-01
0.4142E-01
0.4771E-01
0.5799E-01
0.6628E-01
0.7456E-01
0.8285E-01
0.9113E-01
0.9742E-01
0.1177
0.1160
0.1243
0.1326
0.1408
0.1491
0.1574
0.1657
0.1740
0.1823
0.1906
0.1988
0.2071
0.2154
0.2237
0.2320
0.2403
0.2485
0.2568
0.2651
0.2734
0.2817
0.2899
0.2982
0.3065
0.3148
0.3231
0.3314
0.3397
0.3480
0.3563
0.3646
0.3729
0.3812
0.3895
0.3978
0.4061
0.4144
0.4227
0.4310
0.4393
0.4476
0.4559
0.4642
0.4725
0.4808
0.4891
0.4974
0.5057
0.5140
0.5223
0.5306
0.5389
0.5472
0.5555
0.5638
0.5721
0.5804
0.5887
0.5970
0.6053
0.6136
0.6219
0.6302
0.6385
0.6468
0.6551
0.6634
0.6717
0.6800
0.6883
0.6966
0.7049
0.7132
0.7215
0.7298
0.7381
0.7464
0.7547
0.7630
0.7713
0.7796
0.7879
0.7962
0.8045
0.8128
0.8211
0.8294
0.8377
0.8460
0.8543
0.8626
0.8709
0.8792
0.8875
0.8958
0.9041
0.9124
0.9207
0.9290
0.9373
0.9456
0.9539
0.9622
0.9705
0.9788
0.9871
0.9954
1.0037
1.0120
1.0203
1.0286
1.0369
1.0452
1.0535
1.0618
1.0701
1.0784
1.0867
1.0950
1.1033
1.1116
1.1199
1.1282
1.1365
1.1448
1.1531
1.1614
1.1697
1.1780
1.1863
1.1946
1.2029
1.2112
1.2195
1.2278
1.2361
1.2444
1.2527
1.2610
1.2693
1.2776
1.2859
1.2942
1.3025
1.3108
1.3191
1.3274
1.3357
1.3440
1.3523
1.3606
1.3689
1.3772
1.3855
1.3938
1.4021
1.4104
1.4187
1.4270
1.4353
1.4436
1.4519
1.4602
1.4685
1.4768
1.4851
1.4934
1.5017
1.5100
1.5183
1.5266
1.5349
1.5432
1.5515
1.5598
1.5681
1.5764
1.5847
1.5930
1.6013
1.6096
1.6179
1.6262
1.6345
1.6428
1.6511
1.6594
1.6677
1.6760
1.6843
1.6926
1.7009
1.7092
1.7175
1.7258
1.7341
1.7424
1.7507
1.7590
1.7673
1.7756
1.7839
1.7922
1.8005
1.8088
1.8171
1.8254
1.8337
1.8420
1.8503
1.8586
1.8669
1.8752
1.8835
1.8918
1.9001
1.9084
1.9167
1.9250
1.9333
1.9416
1.9499
1.9582
1.9665
1.9748
1.9831
1.9914
2.0000
2.0080
2.0160
2.0240
2.0320
2.0400
2.0480
2.0560
2.0640
2.0720
2.0800
2.0880
2.0960
2.1040
2.1120
2.1200
2.1280
2.1360
2.1440
2.1520
2.1600
2.1680
2.1760
2.1840
2.1920
2.2000
2.2080
2.2160
2.2240
2.2320
2.2400
2.2480
2.2560
2.2640
2.2720
2.2800
2.2880
2.2960
2.3040
2.3120
2.3200
2.3280
2.3360
2.3440
2.3520
2.3600
2.3680
2.3760
2.3840
2.3920
2.4000
2.4080
2.4160
2.4240
2.4320
2.4400
2.4480
2.4560
2.4640
2.4720
2.4800
2.4880
2.4960
2.5040
2.5120
2.5200
2.5280
2.5360
2.5440
2.5520
2.5600
2.5680
2.5760
2.5840
2.5920
2.6000
2.6080
2.6160
2.6240
2.6320
2.6400
2.6480
2.6560
2.6640
2.6720
2.6800
2.6880
2.6960
2.7040
2.7120
2.7200
2.7280
2.7360
2.7440
2.7520
2.7600
2.7680
2.7760
2.7840
2.7920
2.8000
2.8080
2.8160
2.8240
2.8320
2.8400
2.8480
2.8560
2.8640
2.8720
2.8800
2.8880
2.8960
2.9040
2.9120
2.9200
2.9280
2.9360
2.9440
2.9520
2.9600
2.9680
2.9760
2.9840
2.9920
3.0000
3.0080
3.0160
3.0240
3.0320
3.0400
3.0480
3.0560
3.0640
3.0720
3.0800
3.0880
3.0960
3.1040
3.1120
3.1200
3.1280
3.1360
3.1440
3.1520
3.1600
3.1680
3.1760
3.1840
3.1920
3.2000
3.2080
3.2160
3.2240
3.2320
3.2400
3.2480
3.2560
3.2640
3.2720
3.2800
3.2880
3.2960
3.3040
3.3120
3.3200
3.3280
3.3360
3.3440
3.3520
3.3600
3.3680
3.3760
3.3840
3.3920
3.4000
3.4080
3.4160
3.4240
3.4320
3.4400
3.4480
3.4560
3.4640
3.4720
3.4800
3.4880
3.4960
3.5040
3.5120
3.5200
3.5280
3.5360
3.5440
3.5520
3.5600
3.5680
3.5760
3.5840
3.5920
3.6000
3.6080
3.6160
3.6240
3.6320
3.6400
3.6480
3.6560
3.6640
3.6720
3.6800
3.6880
3.6960
3.7040
3.7120
3.7200
3.7280
3.7360
3.7440
3.7520
3.7600
3.7680
3.7760
3.7840
3.7920
3.8000
3.8080
3.8160
3.8240
3.8320
3.8400
3.8480
3.8560
3.8640
3.8720
3.8800
3.8880
3.8960
3.9040
3.9120
3.9200
3.9280
3.9360
3.9440
3.9520
3.9600
3.9680
3.9760
3.9840
3.9920
4.0000
4.0080
4.0160
4.0240
4.0320
4.0400
4.0480
4.0560
4.0640
4.0720
4.0800
4.0880
4.0960
4.1040
4.1120
4.1200
4.1280
4.1360
4.1440
4.1520
4.1600
4.1680
4.1760
4.1840
4.1920
4.2000
4.2080
4.2160
4.2240
4.2320
4.2400
4.2480
4.2560
4.2640
4.2720
4.2800
4.2880
4.2960
4.3040
4.3120
4.3200
4.3280
4.3360
4.3440
4.3520
4.3600
4.3680
4.3760
4.3840
4.3920
4.4000
4.4080
4.4160
4.4240
4.4320
4.4400
4.4480
4.4560
4.4640
4.4720
4.4800
4.4880
4.4960
4.5040
4.5120
4.5200
4.5280
4.5360
4.5440
4.5520
4.5600
4.5680
4.5760
4.5840
4.5920
4.6000
4.6080
4.6160
4.6240
4.6320
4.6400
4.6480
4.6560
4.6640
4.6720
4.6800
4.6880
4.6960
4.7040
4.7120
4.7200
4.7280
4.7360
4.7440
4.7520
4.7600
4.7680
4.7760
4.7840
4.7920
4.8000
4.8080
4.8160
4.8240
4.8320
4.8400
4.8480
4.8560
4.8640
4.8720
4.8800
4.8880
4.8960
4.9040
4.9120
4.9200
4.9280
4.9360
4.9440
4.9520
4.9600
4.9680
4.9760
4.9840
4.9920
5.0000
5.0080
5.0160
5.0240
5.0320
5.0400
5.0480
5.0560
5.0640
5.0720
5.0800
5.0880
5.0960
5.1040
5.1120
5.1200
5.1280
5.1360
5.1440
5.1520
5.1600
5.1680
5.1760
5.1840
5.1920
5.2000
5.2080
5.2160
5.2240
5.2320
5.2400
5.2480
5.2560
5.2640
5.2720
5.2800
5.2880
5.2960
5.3040
5.3120
5.3200
5.3280
5.3360
5.3440
5.3520
5.3600
5.3680
5.3760
5.3840
5.3920
5.4000
5.4080
5.4160
5.4240
5.4320
5.4400
5.4480
5.4560
5.4640
5.4720
5.4800
5.4880
5.4960
5.5040
5.5120
5.5200
5.5280
5.5360
5.5440
5.5520
5.5600
5.5680
5.5760
5.5840
5.5920
5.6000
5.6080
5.6160
5.6240
5.6320
5.6400
5.6480
5.6560
5.6640
5.6720
5.6800
5.6880
5.6960
5.7040
5.7120
5.7200
5.7280
5.7360
5.7440
5.7520
5.7600
5.7680
5.7760
5.7840
5.7920
5.8000
5.8080
5.8160
5.8240
5.8320
5.8400
5.8480
5.8560
5.8640
5.8720
5.8800
5.8880
5.8960
5.9040
5.9120
5.9200
5.9280
5.9360
5.9440
5.9520
5.9600
5.9680
5.9760
5.9840
5.9920
6.0000
6.0080
6.0160
6.0240
6.0320
6.0400
6.0480
6.0560
6.0640
6.0720
6.0800
6.0880
6.0960
6.1040
6.1120
6.1200
6.1280
6.1360
6.1440
6.1520
6.1600
6.1680
6.1760
6.1840
6.1920
6.2000
6.2080
6.2160
6.2240
6.2320
6.2400
6.2480
6.2560
6.2640
6.2720
6.2800
6.2880
6.2960
6.3040
6.3120
6.3200
6.3280
6.3360
6.3440
6.3520
6.3600
6.3680
6.3760
6.3840
6.3920
6.4000
6.4080
6.4160
6.4240
6.4320
6.4400
6.4480
6.4560
6.4640
6.4720
6.4800
6.4880
6.4960
6.5040
6.5120
6.5200
6.5280
6.5360
6.5440
6.5520
6.5600
6.5680
6.5760
6.5840
6.5920
6.6000
6.6080
6.6160
6.6240
6.6320
6.6400
6.6480
6.6560
6.6640
6.6720
6.6800
6.6880
6.6960
6.7040
6.7120
6.7200
6.7280
6.7360
6.7440
6.7520
6.7600
6.7680
6.7760
6.7840
6.7920
6.8000
6.8080
6.8160
6.8240
6.8320
6.8400
6.8480
6.8560
6.8640
6.8720
6.8800
6.8880
6.8960
6.9040
6.9120
6.9200
6.9280
6.9360
6.9440
6.9520
6.9600
6.9680
6.9760
6.9840
6.9920
7.0000
7.0080
7.0160
7.0240
7.0320
7.0400
7.0480
7.0560
7.0640
7.0720
7.0800
7.0880
7.0960
7.1040
7.1120
7.1200
7.1280
7.1360
7.1440
7.1520
7.1600
7.1680
7.1760
7.1840
7.1920
7.2000
7.2080
7.2160
7.2240
7.2320
7.2400
7.2480
7.2560
7.2640
7.2720
7.2800
7.2880
7.2960
7.3040
7.3120
7.3200
7.3280
7.3360
7.3440
7.3520
7.3600
7.3680
7.3760
7.3840
7.3920
7.4000
7.4080
7.4160
7.4240
7.4320
7.4400
7.4480
7.4560
7.4640
7.4720
7.4800
7.4880
7.4960
7.5040
7.5120
7.5200
7.5280
7.5360
7.5440
7.5520
7.5600
7.5680
7.5760
7.5840
7.5920
7.6000
7.6080
7.6160
7.6240
7.6320
7.6400
7.6480
7.6560
7.6640
7.6720
7.6800
7.6880
7.6960
7.7040
7.7120
7.7200
7.7280
7.7360
7.7440
7.7520
7.7600
7.7680
7.7760
7.7840
7.7920
7.8000
7.8080
7.8160
7.8240
7.8320
7.8400
7.8480
7.8560
7.8640
7.8720
7.8800
7.8880
7.8960
7.9040
7.9120
7.9200
7.9280
7.9360
7.9440
7.9520
7.9600
7.9680
7.9760
7.9840
7.9920
8.0000
8.0080
8.0160
8.0240
8.0320
8.0400
8.0480
8.0560
8.0640
8.0720
8.0800
8.0880
8.0960
8.1040
8.1120
8.1200
8.1280
8.1360
8.1440
8.1520
8.1600
8.1680
8.1760
8.1840
8.1920
8.2000
8.2080
8.2160
8.2240
8.2320
8.2400
8.2480
8.2560
8.2640
8.2720
8.2800
8.2880
8.2960
8.3040
8.3120
8.3200
8.3280
8.3360
8.3440
8.3520
8.3600
8.3680
8.3760
8.3840
8.3920
8.4000
8.4080
8.4160
8.4240
8.4320
8.4400
8.4480
8.4560
8.4640
8.4720
8.4800
8.4880
8.4960
8.5040
8.5120
8.5200
8.5280
8.5360
8.5440
8.5520
8.5600
8.5680
8.5760
8.5840
8.5920
8.6000
8.6080
8.6160
8.6240
8.6320
8.6400
8.6480
8.6560
8.6640
8.6720
8.6800
8.6880
8.6960
8.7040
8.7120
8.7200
8.7280
8.7360
8.7440
8.7520
8.7600
8.7680
8.7760
8.7840
8.7920
8.8000
8.8080
8.8160
8.8240
8.8320
8.8400
8.8480
8.8560
8.8640
8.8720
8.8800
8.8880
8.8960
8.9040
8.9120
8.9200
8.9280
8.9360
8.9440
8.9520
8.9600
8.9680
8.9760
8.9840
8.9920
9.0000
9.0080
9.0160
9.0240
9.0320
9.0400
9.0480
9.0560
9.0640
9.0720
9.0800
9.0880
9.0960
9.1040
9.1120
9.1200
9.1280
9.1360
9.1440
9.1520
9.1600
9.1680
9.1760
9.1840
9.1920
9.2000
9.2080
9.2160
9.2240
9.2320
9.2400
9.2480
9.2560
9.2640
9.2720
9.2800
9.2880
9.2960
9.3040
9.3120
9.3200
9.3280
9.3360
9.3440
9.3520
9.3600
9.3680
9.3760
9.3840
9.3920
9.4000
9.4080
9.4160
9.4240
9.4320
9.4400
9.4480
9.4560
9.4640
9.4720
9.4800
9.4880
9.4960
9.5040
9.5120
9.5200
9.5280
9.5360
9.5440
9.5520
9.5600
9.5680
9.5760
9.5840
9.5920
9.6000
9.6080
9.6160
9.6240
9.6320
9.6400
9.6480
9.6560
9.6640
9.6720
9.6800
9.6880
9.6960
9.7040
9.7120
9.7200
9.7280
9.7360
9.7440
9.7520
9.7600
9.7680
9.7760
9.7840
9.7920
9.8000
9.8080
9.8160
9.8240
9.8320
9.8400
9.8480
9.8560
9.8640
9.8720
9.8800
9.8880
9.8960
9.9040
9.9120
9.9200
9.9280
9.9360
9.9440
9.9520
9.9600
9.9680
9.9760
9.9840
9.9920
10.0000
10.0080
10.0160
10.0240
10.0320
10.0400
10.0480
10.0560
10.0640
10.0720
10.0800
10.0880
10.0960
10.1040
10.1120
10.1200
10.1280
10.1360
10.1440
10.1520
10.1600
10.1680
10.1760
10.1840
10.1920
10.2000
10.2080
10.2160
10.2240
10.2320
10.2400
10.2480
10.2560
10.2640
10.2720
10.2800
10.2880
10.2960
10.3040
10.3120
10.3200
10.3280
10.3360
10.3440
10.3520
10.3600
10.3680
10.3760
10.3840
10.3920
10.4000
10.4080
10.4160
10.4240
10.4320
10.4400
10.4480
10.4560
10.4640
10.4720
10.4800
10.4880
10.4960
10.5040
10.5120
10.5200
10.5280
10.5360
10.5440
10.5520
10.5600
10.5680
10.5760
10.5840
10.5920
10.6000
10.6080
10.6160
10.6240
10.6320
10.6400
10.6480
10.6560
10.6640
10.6720
10.6800
10.6880
10.6960
10.7040
10.7120
10.7200
10.7280
10.7360
10.7440
10.7520
10.7600
10.7680
10.7760
10.7840
10.7920
10.8000
10.8080
10.8160
10.8240
10.8320
10.8400
10.8480
10.8560
10.8640
10.8720
10.8800
10.8880
10.8960
10.9040
10.9120
10.9200
10.9280
10.9360
10.9440
10.9520
10.9600
10.9680
10.9760
10.9840
10.9920
11.0000
11.0080
11.0160
11.0240
11.0320
11.0400
11.0480
11.0560
11.0640
11.0720
11.0800
11.0880
11.0960
11.1040
11.1120
11.1200
11.1280
11.1360
11.1440
11.1520
11.1600
11.1680
11.1760
11.1840
11.1920
11.2000
11.2080
11.2160
11.2240
11.2320
11.2400
11.2480
11.2560
11.2640
11.2720
11.2800
11.2880
11.2960
11.3040
11.3120
11.3200
11.3280
11.3360
11.3440
11.3520
11.3600
11.3680
11.3760
11.3840
11.3920
11.4000
11.4080
11.4160
11.4240
11.4320
11.4400
11.4480
11.4560
11.4640
11.4720
11.4800
11.4880
11.4960
11.5040
11.5120
11.5200
11.5280
11.5360
11.5440
11.5520
11.5600
11.5680
11.5760
11.5840
11.5920
11.6000
11.6080
11.6160
11.6240
11.6320
11.6400
11.6480
11.6560
11.6640
11.6720
11.6800
11.6880
11.6960
11.7040
11.7120
11.7200
11.7280
11.7360
11.7440
11.7520
11.7600
11.7680
11.7760
11.7840
11.7920
11.8000
11.8080
11.8160
11.8240
11.8320
11.8400
11.8480
11.8560
11.8640
11.8720
11.8800
11.8880
11.8960
11.9040
11.9120
11.9200
11.9280
11.9360
11.9440
11.9520
11.9600
11.9680
11.9760
11.9840
11.99

TABLE C Numerical Results for the Ordinate Distribution of the Sand-blasted Stainless Steel Specimen M22. Surface Roughness, 2.829 μm (RMS), Fig. 5.3

ORDINATE DISTRIBUTION FOLLOWS
UNITS - LENGTH

HIGHEST OF 3200 VALUES IS 10.99 LOWEST IS -7.507

MEAN = 40.9618E+10 STANDARD DEVIATION = 2.829

LEVEL	NORMALIZED LEVEL	NUMBER OF VALUES	PER CENT OF TOTAL	CUMULATIVE PER CENT
-7.638	-2.7	21	0.6563	0.6563
-7.355	-2.6	3	0.9375E-01	0.7500
-7.072	-2.5	9	0.2813	1.031
-6.789	-2.4	14	0.4375	1.469
-6.506	-2.3	8	0.2500	1.719
-6.223	-2.2	11	0.3438	2.062
-5.940	-2.1	11	0.3438	2.406
-5.657	-2.0	15	0.4688	2.875
-5.375	-1.9	24	0.7500	3.625
-5.092	-1.8	32	1.000	4.625
-4.809	-1.7	23	0.7188	5.344
-4.526	-1.6	33	1.031	6.375
-4.243	-1.5	40	1.250	7.625
-3.960	-1.4	43	1.344	8.969
-3.677	-1.3	63	1.069	10.034
-3.394	-1.2	60	1.875	12.81
-3.112	-1.1	71	2.219	15.03
-2.829	-1.0	82	2.562	17.59
-2.546	-0.9	78	2.437	20.03
-2.263	-0.8	106	3.212	23.34
-1.980	-0.7	105	3.281	26.62
-1.697	-0.6	96	2.937	29.56
-1.414	-0.5	115	3.594	33.16

-0.3329E-09
0.2829
0.5657
0.8486
1.1331
1.4114
1.697
1.680
2.263
2.546
2.829
3.112
3.394
3.677
3.960
4.243
4.526
4.809
5.092
5.375
5.657
5.940
6.223
6.506
6.789
7.072
7.355
7.638
7.920

-0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8

156
153
125
142
112
110
103
100
68
76
60
61
43
42
37
25
26
15
29
25
21
16
10
12
7
3
1
1
3

4.875
4.781
3.006
4.437
3.500
3.438
3.219
3.125
2.125
2.375
2.156
1.006
1.444
1.312
1.156
0.7913
0.8125
0.4688
0.9663
0.7813
0.6563
0.5000
0.3125
0.3750
0.2488
0.9375E-01
0.3125E-01
0.3125E-01
0.9375E-01

54.56
59.34
63.23
67.69
71.19
74.62
77.84
80.97
83.09
85.47
87.62
89.53
90.87
92.19
93.34
94.12
94.94
95.41
96.31
97.09
97.75
98.25
98.56
98.94
99.16
99.25
99.28
99.31
99.41

TABLE D Numerical Results for the Ordinate Distribution of the Sand-blasted Stainless Steel Specimen M23. Surface Roughness 3.460 μ m (RMS). Fig. 5.4

ORDINATE DISTRIBUTION FOLLOWS
UNITS - LENGTH

HIGHEST OF 3200 VALUES IS 10.33 LOWEST IS 10.55

MEAN = 10.3101E+10 STANDARD DEVIATION = 3.460

LEVEL	NORMALIZED LEVEL	NUMBER OF VALUES	PER CENT OF TOTAL	CUMULATIVE PER CENT
-10.73	3.1	1	0.3425E-01	0.3125E-01
-10.38	3.0	3	0.9375E-01	0.1250
-10.03	2.9	8	0.2500	0.3750
-9.688	2.8	3	0.9775E-01	0.4688
-9.342	2.7	2	0.6250E-01	0.5313
-8.996	2.6	4	0.1250	0.6563
-8.650	2.5	5	0.1563	0.8125
-8.304	2.4	9	0.2813	1.094
-7.958	2.3	12	0.3750	1.469
-7.612	2.2	15	0.4688	1.937
-7.266	2.1	16	0.5000	2.437
-6.920	2.0	25	0.7813	3.219
-6.574	1.9	32	0.6875	3.906
-6.228	1.8	34	1.062	4.969
-5.882	1.7	26	0.8125	5.781
-5.536	1.6	43	1.344	7.125
-5.190	1.5	36	1.125	8.250
-4.844	1.4	43	1.344	9.594
-4.498	1.3	60	1.875	11.47
-4.152	1.2	69	2.156	13.62
-3.806	1.1	80	2.781	16.41
-3.460	1.0	71	2.219	18.63
-3.114	0.9	93	2.906	21.53
-2.768	0.8	108	3.375	24.91
-2.422	0.7	90	2.812	27.73
-2.076	0.6	101	3.156	30.89

-1.730	0.5	117	3.656	34.53
-1.384	0.4	115	3.594	38.12
-1.038	0.3	107	3.324	41.47
-0.6920	0.2	90	3.094	44.56
-0.3460	0.1	125	3.906	48.47
-0.3205E-09	0.0	144	4.500	52.97
0.3460	0.1	127	3.969	56.94
0.6020	0.2	127	3.069	60.91
1.038	0.3	118	3.687	64.59
1.384	0.4	106	3.912	67.91
1.730	0.5	124	3.875	71.78
2.076	0.6	117	3.456	75.44
2.422	0.7	113	3.531	78.97
2.768	0.8	103	3.219	82.19
3.114	0.9	80	2.781	84.97
3.460	1.0	87	2.719	87.49
3.806	1.1	57	1.781	89.47
4.152	1.2	65	2.631	91.50
4.498	1.3	45	1.406	92.91
4.844	1.4	42	1.312	94.22
5.190	1.5	24	0.7500	94.97
5.536	1.6	27	0.8438	95.81
5.882	1.7	23	0.7488	96.53
6.228	1.8	21	0.6563	97.19
6.574	1.9	15	0.4688	97.66
6.920	2.0	14	0.4775	98.09
7.266	2.1	11	0.3438	98.44
7.612	2.2	10	0.3125	98.75
7.958	2.3	4	0.1250	98.87
8.304	2.4	4	0.1250	99.00
8.650	2.5	6	0.1875	99.19
8.996	2.6	7	0.2188	99.41
9.342	2.7	8	0.2500	99.66
9.688	2.8	5	0.1562	99.81
10.03	2.9	6	0.1875	100.0

TABLE L Numerical Results for the Ordinate Distribution of the Commercially Pure Aluminium Specimen Surface M38. Surface Roughness, 0.0882 μm , Fig. 5.5

ORDINATE DISTRIBUTION FOLLOWS
UNITS - LENGTH

HIGHEST OF 3200 VALUES IS 0.3335

LOWEST IS -0.2999

MEAN= 0.6138E-12

STANDARD DEVIATION= 0.8822E-01

A.27

LEVEL	NORMALIZED LEVEL	NUMBER OF VALUES	PER CENT OF TOTAL	CUMULATIVE PER CENT
-0.3000	-3.4	2	0.6250E-01	0.6250E-01
-0.2647	-3.0	1	0.3125E-01	0.9375E-01
-0.2558	-2.9	2	0.6250E-01	0.1563
-0.2382	-2.7	3	0.9375E-01	0.2500
-0.2294	-2.6	5	0.1563	0.4063
-0.2206	-2.5	6	0.1875	0.5938
-0.2117	-2.4	9	0.2813	0.8750
-0.2029	-2.3	16	0.5000	1.375
-0.1941	-2.2	21	0.6563	2.031
-0.1853	-2.1	20	0.6250	2.656
-0.1764	-2.0	18	0.5625	3.219
-0.1676	-1.9	20	0.6250	3.844
-0.1588	-1.8	30	0.9375	4.781
-0.1500	-1.7	41	1.281	6.062
-0.1412	-1.6	42	1.312	7.375
-0.1323	-1.5	45	1.406	8.781
-0.1235	-1.4	61	1.906	10.69
-0.1147	-1.3	61	1.906	12.59
-0.1059	-1.2	58	1.812	14.41
-0.9704E-01	-1.1	44	2.000	16.41
-0.8822E-01	-1.0	78	2.437	18.84
-0.7940E-01	-0.9	80	2.500	21.34
-0.7058E-01	-0.8	45	2.456	24.00

-0.2647E-01	-0.3	122	3.817	41.78
-0.1764E-01	-0.2	113	3.531	45.31
-0.8322E-02	-0.1	115	3.594	48.91
-0.6768E-11	-0.0	129	4.031	52.94
0.8322E-02	0.1	129	4.031	56.97
0.1764E-01	0.2	126	3.037	60.91
0.2647E-01	0.3	119	3.719	64.62
0.3529E-01	0.4	106	3.712	67.94
0.4411E-01	0.5	107	3.744	71.28
0.5293E-01	0.6	116	3.625	74.91
0.6176E-01	0.7	101	3.156	78.06
0.7058E-01	0.8	114	3.562	81.62
0.7940E-01	0.9	96	3.000	84.62
0.8322E-01	1.0	81	2.531	87.16
0.9704E-01	1.1	64	2.000	89.16
0.1059	1.2	41	1.281	90.44
0.1147	1.3	56	1.750	92.19
0.1235	1.4	36	1.062	93.25
0.1323	1.5	40	1.250	94.50
0.1412	1.6	28	0.8750	95.37
0.1500	1.7	28	0.8750	96.25
0.1588	1.8	31	0.9668	97.22
0.1676	1.9	25	0.7813	98.00
0.1764	2.0	20	0.6250	98.62
0.1853	2.1	15	0.4688	99.09
0.1941	2.2	12	0.3750	99.47
0.2029	2.3	6	0.1250	99.59
0.2117	2.4	4	0.1250	99.72
0.2206	2.5	3	0.9375E-01	99.81
0.2294	2.6	1	0.3125E-01	99.84
0.2470	2.8	2	0.6250E-01	99.91
0.2647	3.0	1	0.3125E-01	99.94
0.2735	3.1	1	0.3125E-01	99.97
0.3264	3.7	1	0.3125E-01	100.0

SAMPLE CALCULATIONS FOR THE NUMBER AND AREA OF ACTUAL CONTACT.

$$\frac{P}{M} = 0.0366 \text{ (from Figure 5.16)}$$

$$|\bar{\psi}| = 0.1738 \text{ radian obtained by computer search.}$$

For dissimilar materials using equation (6.3)

$$\psi_s = 9.6051 \times 10^4$$

now by substituting in equation (5.3)

$$\begin{aligned} \phi(t_m) &= \frac{1}{2} - \frac{P}{M} \\ &= 0.5 - 0.0366 = 0.4634 \end{aligned}$$

From statistical tables of error functions (134)

$$t_m = 1.792 \text{ and its corresponding probability function } \phi(t_m) = 0.08009$$

By substituting in equation (5.5)

$$\bar{N}_m = \frac{\pi t_m \phi(t_m) \psi_s^2}{8}$$

$$= \frac{\pi \times 1.792 \times 0.08009 \times (9.6051 \times 10^4)^2}{8}$$

$$= 5.2 \times 10^8$$

By substituting in equation (5.4)

$$\bar{a}_m = \frac{2}{\pi \psi_s t_m}$$

$$= \frac{2}{\pi \times 9.6051 \times 10^4 \times 1.792}$$

$$= 3.69 \mu\text{m}$$

By substituting in equation (5.6), the area of actual contact per unit nominal area can be calculated i.e.

$$\bar{A}_{rm} = \pi (\bar{a}_m)^2 \bar{N}_m$$

$$= \pi \times (3.69)^2 \times 5.2 \times 10^8$$

$$= 2.234 \times 10^{-2}$$

Similarly other values of the area of actual contact relating to Fig. 5.11 can be obtained as given in Table F.

SAMPLE CALCULATIONS FOR THE THERMAL RESISTANCE
OF THE OXIDISED CONTACT

$$P = 2.5 \times 10^6 \text{ Nm}^{-2} \quad (\text{from Figure 7.8})$$

$$M = 0.99 \text{ GN m}^{-2}$$

By substituting in equation (6.16)

$$\bar{\phi}(t_m) = \frac{1}{2} - \frac{P}{M}$$

$$= \frac{1}{2} - 2.52 \times 10^{-3} = 0.49748$$

Table F Calculations of the area of actual contact.

Loading pressure,	Mean plane of metallic contact	probability function of metallic contact roughness	Effective surface	Mean surface slope from computer	Effective surface slope	Calculated number of micro-contacts per unit nominal area	Observed number of micro-contacts per unit nominal area	Calculate actual area
P/M (Dimensionless)	t_m (Dimensionless)	$\rho(t_m)$ (Dimensionless)	$\sigma_s \times 10^{-6}$ (m)	$ \bar{\psi} $ (radians)	$\psi_s \times 10^4$ (m^{-1})	$\bar{N}_m \times 10^8$ (Dimensionless)	(Dimensionless)	(Dimensionless)
3.66x10 ⁻²	1.792	0.080093	2.5593	0.1728	9.6051	5.2	2.21	2.234x10 ⁻²
5.49x10 ⁻²	1.600	0.110921	2.5593	0.1900	10.5	7.8	3.62	3.518x10 ⁻²
7.32x10 ⁻²	1.452	0.139027	2.5593	0.2081	11.5	10.5	4.22	4.794x10 ⁻²
9.15x10 ⁻²	1.330	0.164502	2.5593	0.2242	12.39	13.2	5.5	6.184x10 ⁻²

from statistical table (134)

$$t_m = 2.804$$

$$\phi(t_m) = 0.00783$$

From equation (6.18)

$$t_o = 2.149, \text{ its corresponding probability function, } \phi(t_o) = 0.0396$$

$$|\bar{\psi}| = 0.060 \text{ radian obtained by computer search.}$$

For dissimilar contacting materials using equation (6.3)

$$\bar{\psi}_s = 0.458 \times 10^5$$

By substituting in equation (6.19)

$$\bar{a}_m = \frac{2}{\pi \bar{\psi}_s t_m}$$

$$\bar{a}_m = \frac{2}{\pi \times 0.458 \times 10^5 \times 2.804} = 4.957 \mu\text{m}$$

and from equation (6.20)

$$\bar{a}_o = \bar{a}_m + X$$

$$= 4.957 + 0.925 = 5.882 \mu\text{m}$$

Using equation (6.23)

$$\bar{N}_m = \frac{\pi \bar{\psi}_s^2 t_m \phi(t_m)}{8}$$

$$\bar{N}_m = \frac{\pi \times (0.458^2) \times 10^{10} \times 2.804 \times 0.00783}{8}$$

$$= 1.808 \times 10^7$$

By substituting in equation (6.24)

$$\bar{N}_T = \frac{\pi \times (0.458)^2 \times 10^{10} \times 2.149 \times 0.0396}{8}$$

$$= 7.009 \times 10^7$$

From equation (6.25)

$$N_O = N_T - N_m$$

$$= 2.5529 \times 10^4$$

By substituting in equation (6.21)

$$\begin{aligned} A_{rm} &= \pi \bar{a}_m^2 N_m \\ &= \pi \times (4.957)^2 \times 10^{-12} \times 8.876 \times 10^3 \\ &= 6.85 \times 10^7 \text{ m}^2 \end{aligned}$$

Similarly

$$\begin{aligned} A_{rT} &= \pi \bar{a}_O^2 N_T = \pi \times (5.882)^2 \times 10^{-12} \times 3.4405 \times 10^4 \\ &= 3.739 \times 10^{-6} \end{aligned}$$

By substituting in equation (6.22)

$$\begin{aligned} \bar{a}_{OO}^2 &= (\bar{a}_O^2 N_T - \bar{a}_m^2 N_m) / N_O \\ &= \frac{[(5.882)^2 \times 3.4405 \times 10^4 - (4.957)^2 \times 8.876 \times 10^3]}{2.552 \times 10^4} \end{aligned}$$

$$\therefore \bar{a}_{OO} = 6.17 \text{ } \mu\text{m}$$

Now the total area of contact using equation (6.21) is:

$$\begin{aligned} A_{TT} &= 3.739 \times 10^{-6} + 1.39 \times 10^{-3} + 3.055 \times 10^{-6} \\ &= 1.3967 \times 10^{-3} \text{ m}^2. \end{aligned}$$

By substituting in equations (6.37 - 40); the thermal conductivity for the oxide-to-oxide contact is:

$$\frac{4}{k_{so}} = \frac{1}{47} + \frac{1}{43} + \frac{1}{385} + \frac{1}{300}$$

$$\text{or } k_{so} = 79.2 \text{ Wm}^{-1} \text{ K}^{-1}$$

For the metal-to-metal contact for the oxidised contacting surfaces

$$k_s = 83.77 \text{ Wm}^{-1} \text{ K}^{-1}$$

Similarly k_{so} from equation (6.39) for this case is

$$= 75.21 \text{ Wm}^{-1} \text{ K}^{-1}$$

Now by substituting in equation (6.40)

$$\begin{aligned} k_{TO} &= \% k_s + \% k_{so} \\ &= 0.14 \times 83.77 + 0.86 \times 75.21 = 76.41 \text{ Wm}^{-1} \text{ K}^{-1} \end{aligned}$$

From equations (6.41 and 6.42) the thermal contact resistance is:

$$\begin{aligned} R_{mo} &= \frac{1}{2 \times 5.882 \times 10^{-6} \times 8.876 \times 10^3 \times 76.41} \\ &= 1.25 \times 10^{-1} \text{ K}^\circ \text{ W}^{-1} \end{aligned}$$

$$\begin{aligned} \text{and } R_{oo} &= \frac{1}{2 \times 6.17 \times 10^{-6} \times 2.5529 \times 10^4 \times 75.21} \\ &= 4.22 \times 10^{-2} \text{ K}^\circ \text{ W}^{-1} \end{aligned}$$

From equations (6.43) the total resistance

$$\begin{aligned}
 R_T &= (R_{mo} + R_{oo}) A_n \\
 &= 1.672 \times 10^{-1} \times 4.908 \times 10^{-4} \\
 &= 8.206 \times 10^{-5} \text{ Km}^2 \text{ W}^{-1}
 \end{aligned}$$

By substituting into equation (6.13)

$$g(\gamma) = 1 - 1.409\gamma + 0.296\gamma^3$$

where $\gamma = \frac{\bar{a}}{\bar{b}}$

and $\bar{b} \left(\frac{A_n}{\pi N} \right)^{\frac{1}{2}} = 6.73 \times 10^{-5}$

and $\gamma = 8.73 \times 10^{-2}$

and from equation (6.14) the modified contact resistance

$$\begin{aligned}
 R_{mod} &= R_T \cdot g(\gamma) \\
 &= 8.206 \times 10^{-5} \times 0.877 \\
 &= 7.196 \times 10^{-5} \text{ Km}^2 \text{ W}^{-1}
 \end{aligned}$$

Similarly calculations for other observations can be made. The calculated values are given in Table G. The theoretical resistance from YIP's theory (6) and its modification obtained using computer program are also presented.

1000

$$M = 0.99 \text{ Gm}^{-2}$$

Loading pressure	Mean plane of metallic contact,	Mean plane of oxidized contact,	Probability function of metallic contact	Probability function of oxidized contact	Effective surface roughness	Mean surface slope from Computer	Effective surface slope	Theoretical thermal resistance of the oxide free contact	Theoretical thermal resistance of the oxidized contact	Theoretical thermal resistance from Yip's theory(6)	Theoretical thermal resistance from the modification of Yip's theory(6)
P/M,	t_m	t_o	$\rho(t_m)$	$\rho(t_o)$	$\sigma_s \times 10^{-5}$ (m)	$ \psi $ (radians)	$\psi_s \times 10^5$ (m^{-1})	$km^2 W^{-1}$	$km^2 W^{-1}$	$km^2 W^{-1}$	$km^2 W^{-1}$
Dimensionless	Dimensionless	Dimensionless	Dimensionless	Dimensionless							
2.52×10^{-3}	2.804	2.149	0.00783	0.0396	0.1852	0.060	0.458	5.4×10^{-5}	7×10^{-5}	2.85×10^{-6}	1.5×10^{-5}
5.1×10^{-3}	2.572	1.917	0.01460	0.0638	0.1852	0.070	0.534	2.7×10^{-5}	3.6×10^{-5}	1.4×10^{-6}	7.0×10^{-6}
1×10^{-2}	2.320	1.665	0.02705	0.0997	0.1852	0.075	0.572	1.4×10^{-5}	1.8×10^{-5}	6.8×10^{-7}	3.4×10^{-6}
2×10^{-2}	2.048	1.393	0.04898	0.1511	0.1852	0.080	0.610	7×10^{-6}	1.0×10^{-5}	3.4×10^{-7}	1.7×10^{-6}

APPENDIX III

COMPUTER PROGRAM FOR THE PREDICTION OF
THERMAL CONTACT RESISTANCE

COMPUTER PROGRAM FOR MULTIPLE REGRESSION
AND CORRELATION

APPENDIX IIICOMPUTER PROGRAM FOR THE PREDICTION OF THERMAL RESISTANCEPROGRAM NOTES (47)

Program PRG5 corrects thermocouple readings in accordance with the calibration curves, converts them to temperatures, fits the best straight line to the temperature data for each pair of specimens, and extrapolates these lines to the contacting faces. The program then calculates and outputs: the contact pressure, total load, dimensionless loading, the interfacial temperature drop, the heat fluxes in each specimen, the mean heat flux crossing the interface, the interface conductance and resistance, the mean interfacial temperature, the standard errors in all these quantities, and the effectiveness parameters. 95% of all estimates of thermal resistance lie within two standard errors from the mean.

The input first is an array TT(1), V(1) which represents the thermocouple tables. This is followed by the polynomial coefficients B(1), C(1) and F(1), representing the calibration coefficients for the thermocouples, the thermal conductivity of the metals used with respect to temperature, and the load-microstrain characteristic. ISTOP is a trip to stop the program when all sets of data have been analysed. Next fed in are the numbers of thermocouples in upper and lower specimens, JAU and JAL, the length of the upper specimen ELU, the distance between the upper heater and the lower contact face, ELL, the constants, REF1, REF2, (which are respectively the temperature (°C) to which measurements are referred, and the EMF corresponding to this temperature in the tables), and the diameters, DIAMU, DIAML, of the specimens. The array D(1) gives the distance to each thermoprobe site with respect to the source of heating. All these parameters are output for an immediate echo check. Lastly, the input wattage and the thermocouple readings, VJAU, VJAL, are fed in.

The program proceeds to calculate the contact pressure, total load, and dimensionless load (having selected the smaller of the two nominal areas in contact). Thermocouple readings are first calibrated and then converted to temperature in subroutine TEMPEMF, in which polynomial interpolation via subroutine POLY1 is performed upon the 5 pairs of values TT(1), V(1) nearest to the value of EMF considered. Two arrays, TEMPJauc(1) and TEMPJalc(1) are then filled in the main program and distances EMFS and temperatures output. The subroutine FIT is then called-up which calculates the best straight line of temperature on distance by least squares for each set of data, and extrapolates to the interface. FIT returns correlation coefficients, the smoothed values of temperature and associated errors (2 x standard error) to the main program. This then calculates and outputs the mean interfacial temperature drop, DELTATINT, the heat flux in each specimen, QU, QL, the arithmetic mean value of heat flux crossing the interface, QM1, and the mean interfacial temperature, TM1, together with their respective errors. For this purpose the estimated error in the measurement of geometrical dimensions was input as 0.5%.

The total conductance, TOTCON, that per unit area, XINTCON, and their reciprocals are then calculated together with the overall errors. Finally the three effectiveness parameters are calculated.

NOTES ON OTHER PROGRAMSProgram SALM

This program 'SALM' calculates the surface parameters; the effective surface roughness, the effective mean surface slope, the number and radius of the micro-contacts and the interfacial resistance of the oxidised contact.

The input to the program is the oxide film thickness, the surface roughness of the contacting specimens, an arbitrary value of the mean surface slope, the thermal conductivities of the oxide-free as well as oxidised specimens, the micro-hardness of the softer of the contacting materials and the value of the mean plane separation (supplied from tables of error functions (134))

The program proceeds to calculate the probability function SYFM and SYFO for the oxide-free and the oxidised contact respectively. It calculates the effective surface roughness (ESRO), the effective mean surface slope (ESSL), the number of micro contacts and the resistance of the oxidised contact for one value of slope. The program selects the next value of the slope and the procedure is repeated until the surface parameters are established to match the theory with the experimental measurements.

Program TALK

The program 'TALK' has been developed from the constriction resistance theory (6). The input and output to the program is essentially the same as that for the previous program. In addition, the sub-routines S15AEF and S17ABF are called for the evaluation of the error functions and Bessel's functions respectively.

Program CORE

This program has been written to develop a statistical expression for the prediction and relation of the thermal contact resistance with the oxide film buildup. The input to the program are arrays P(N), AS(N), F(N) and R(N) which represent the pressure, RMS surface roughness, film thickness and the experimentally measured thermal contact resistance respectively. The program calculates the standard error of estimate; SEE, the correlation coefficient; cc and the values of the variables of an expression for the prediction of the thermal resistance.

LIST

```

0001
0002
0003 SEND TO(ED,SEMITOMPGSTF,STORE)
0004 NUNP ON(ED,PROGRAM JOB8)
0005 WORK(ED,PROGRAM WK8(0))
0006 LIBRARY (SUBGROUPNAGF)
0007 PROGRAM(PRG5)
0008 INPUT 1=CR0
0009 OUTPUT 2=LPO
0010 TRACE 2
0011 END

```

C PROGRAM TO CALCULATE THERMAL RESISTANCE PARAMETERS.

```

0012 MASTER POC9
0013 REAL MS
0014 DIMENSION TT(300),V(300),B(3),C(3),F(5),D(8),VJAU(4),VVV(5),
0015 1TT(5),TEMPJAU(4),VJAL(4),TEMPJALC(4),
0016 2TEMPJAU(4),DL(4),ETEMPJALC(4),DU(4),
0017 3PETEMPJALC(4),PETEMPJAU(4),EDL(4),EDU(4)
0018
0019

```

C TEMPERATURE-FMF TABLES

```

0020
0021 READ(1,351)(TT(1),V(1),I=1,280)
0022
0023 851 FORMAT(5000F0.0)
0024

```

C POLYNOMIAL COEFFICIENTS

IS THIS LARGE A REPEAT COUNT INTENDED AT ABOUT COLUMN 16, LINE 0022

```

0025 PEAD(1,0)(B(1),I=1,3)
0026 READ(1,0)(C(1),I=1,3)
0027 9 FORMAT(3E20.13)
0028 WRITE(2,33) (B(1),I=1,3)
0029 33 FORMAT( 39H THERMOCOUPLE CALIBRATION COEFFICIENTS,/(3E30.14))
0030 WRITE(2,34)(C(1),I=1,3)
0031 34 FORMAT(10X,50H POLYNOMIAL COEFFICIENTS FOR THERMAL CONDUCTIVITY ,/
0032 11UX,28H OF STEFL VERSUS TEMP DEG ,3E22.14)
0033
0034
0035
0036

```

C 392 CONTINUE

```

0037 READ(1,098)1STOP
0038
0039

```


A.41

```
0038 READ(1,8) JAU,JAL,ELU,ELI,REF1,REF2,DIAMU,DIAML
0039 8 FORMAT(210,6F0.0)
0040 JA=JAU+JAL
0041 WRITE(2,32)JAU,JAL,ELU,ELI,REF1,REF2,DIAMU,DIAML
0042 32 FORMAT(10X,40H NO OF AXIAL TCS IN UPPER SPECIMEN = ,13.1,
0043 140X,40H NO OF AXIAL TCS IN LOWER SPECIMEN = ,13.1,
0044 210X,26H LENGTH OF UPPER SPECIMEN=,F8.4,5H M ,.1,
0045 310X,26H LENGTH OF LOWER SPECIMEN=,F8.4,5H M ,.1,
0046 410X,41H MILLIVOLTS CORRESPONDING TO DATUM TEMPE ,F12.6,5H MVS.,.1,
0047 510X,19H DATUM TEMPERATURE=,F12.6,6H DEG C,1,6H DIAM=,F12.6,4H M ,
0048 1/,
0049 610X,26H DIAM OF UPPER SPECIMEN= ,F8.4,5H M ,.1,
0050 710X,26H DIAM OF LOWER SPECIMEN= ,F8.4,5H M )
0051 WARNING 186 SEPARATOR OMITTED AT ABOUT COLUMN 38, LINE 0049 , COMMA ASSUMED
0052 WARNING 186 SEPARATOR OMITTED AT ABOUT COLUMN 38, LINE 0050 , COMMA ASSUMED
0053 0051 READ(1,14)(D(I),I=1,JA)
0054 14 FORMAT( 8F0.0)
0055 37 WRITE(2,37)(D(I),I=1,JA)
0056 37 FORMAT( 20H AXIAL DISTANCE( M)= , 8F9.4)
0057 40 CONTINUE
0058 C
0059 C AXIAL PRESSURE APPLIED
0060 C
0061 READ(1,4)NO
0062 4 FORMAT(10)
0063 WRITE(2,393)NO
0064 393 FORMAT(//,30X,13,1//)
0065 IF(40 .EQ.999.0)GO TO 999
0066 AU=3.142*(DIAMU**2)/4.0
0067 AL=3.142*(DIAML**2)/4.0
0068 IF(ALL.GT.AL)GO TO 38
0069 A=ALL
0070 GO TO 391
0071 38 A=AL
0072 391 CONTINUE
0073 READ(1,395) ALOAD
0074 395 FORMAT(F0.0)
0075 IF(ALOAD.EQ.416.0) STOP
0076 P=ALOAD/A
0077 WRITE(2,396) ALOAD,P
0078 396 FORMAT(10X,7H ALOAD=,F8.4,3H NO,40X,18H APPLIED PRESSURE=,F8.4,8H N
1/5Q M )
```

-----END OF DATA-----LINE 0074 - COMMA ASSUMED


```

0080 1 FORMAT(10)
0081 IF(K.EQ.0.0) GOTO 6
0082 WRITE(2,3)
0083 3 FORMAT(10X,16H LOWER HEATER-CH)
0084 GO TO 7
0085 6 WRITE(2,2)
0086 2 FORMAT(10X,16H UPPER HEATER ON)
0087 7 CONTINUE
0088 100 CONTINUE
0089
0090 HEAT SUPPLIED TO SPECIMEN
0091
0092 READ(1,15)WIN
0093 15 FORMAT(F0.0)
0094 WRITE(2,101)WIN
0095 101 FORMAT(40X,13H INPUT WATTS=,F8.4,6HWATTS )
0096
0097 CALIBRATE THERMOCOUPLES AND CONVERT EMF TO TEMPERATURE
0098
0099 UPPER SPECIMEN
0100 READ(1,851)(VJAU(I),I=1,JAU)
0101 DO 222 I=1,JAU
0102 X=VJAU(I)
0103 CALL TEMPEMF(V,TT,JAU,X,B,REF1,Y)
0104 TEMPJAU(I)=Y
0105
0106 222 CONTINUE
0107
0108 WRITE(2,221)((D(I),I=1,JAU),(VJAU(I),I=1,JAU),(TEMPJAU(I),I=1,
0109 1JAU))
0110 221 FORMAT(10X,15H UPPER SPECIMEN,/,10X,17H AXIAL DIST(M),,4F9.4,
0111 15H MS,/,10X,17H EMF AT D ,4F9.4,11H MILLIVOLTS,/,
0112 210X,13H TEMP AT D ,4F9.4,7H DEG C )
0113
0114 LOWER SPECIMEN
0115 READ(1,851)(VJAL(I),I=1,JAL)
0116 DO 249 I=1,JAL
0117 X=VJAL(I)
0118 CALL TEMPEMF(V,TT,JAU,X,B,REF1,Y)
0119 TEMPJAL(I)=Y
0120 249 CONTINUE
0121 WRITE(2,251)((D(I),I=JAU+1,JA),(VJAL(I),I=1,JAL),(TEMPJAL(I),
0122 1I=1,JAL))

```

251 FORMAT(10X,16H LOWER SPECIMEN,/,10X,17H AXIAL DIST(M),


```

0126 C FIT BEST STRAIGHT LINE TO AXIAL TEMPERATURES AND EXTRAPOLATE TO IN
0127 C TERFACE
0128 C
0129 C
0130 C UPPER SPECIMEN
0131 DU(1)=D(1)
0132 DO 233 I=1,JAU
0133 C CONTINUE
0134 233 CALL FIT(DU,TEMPJALC,TEMPCUINT,ETEMPJALC,ETEMPCUINT,ELU,JAU)
0135 WRITE(2,501) TEMPCUINT,ETEMPCUINT
0136 501 FORMAT(10X,37H TEMP OF UPPER SPECIMEN AT INTERFACE =
0137 1F9.4,7H DEG C ,15H PLUS OR MINUS ,F9.4,7H DEG C )
0138 C
0139 C LOWER SPECIMEN
0140 DO 234 I=JAU+1,JA
0141 DL(I-JAU)=D(I)
0142 234 CONTINUE
0143 C
0144 CALL FIT(DL,TEMPJALC,TEMPCLINT,ETEMPJALC,ETEMPCLINT,ELL,JAL)
0145 WRITE(2,502) TEMPCLINT,ETEMPCLINT
0146 502 FORMAT(10X,37H TEMP OF LOWER SPECIMEN AT INTERFACE =
0147 1F9.4,7H DEG C ,15H PLUS OR MINUS ,F9.4,7H DEG C )
0148 C
0149 C INTERFACIAL TEMPERATURE DROP
0150 IF(K.EQ.1)GO TO 510
0151 DELTATINT=TEMPCLINT-TEMPCUINT
0152 GO TO 511
0153 510 DELTATINT=TEMPCUINT-TEMPCLINT
0154 511 CONTINUE
0155 FDELTATINT=SQRT((ETEMPCUINT**2.0)+(ETEMPCLINT**2.0))
0156 WRITE(2,503) DELTATINT,FDELTATINT
0157 503 FORMAT(10X,30H INTERFACIAL TEMPERATURE DROP=F,F9.4,7H DEG C ,/,
0158 115H PLUS OR MINUS ,F9.4,7H DEG C )
0159 C
0160 C HEAT FLUX
0161 TML=(TEMPJALC(1)+TEMPJALC(4))/2.0
0162 AKL=C(1) + C(2)*TML + C(3)*TML*TML
0163 TDIFFL = ABS(TEMPJALC(1)-TEMPJALC(4))
0164 DO 504 I=1,JAL
0165 PETEMPJALC(I)=ETEMPJALC(I)/TEMPJALC(I)
0166 FDL(I)=0.005
0167 504 CONTINUE
0168 FTDIFFL = SQRT(PETEMPJALC(1)**2+PETEMPJALC(4)**2)
0169 HDL=ABS(DL(1)-DL(4))
0170 FEOL=SQRT(FDL(1)**2+EDL(4)**2.0)
0171 EAKI=0.00

```


0219 P=1.0/XINTCON
 0220 FRRR=R*FINTCON/XINTCON
 0221 WRITE(2,1001)R,FRRR
 0222 FORMAT(19H INTERFACE RES. IS,F12.6,15H PLUS OR MINUS,F12.6)
 WARNING 186 SEPARATOR OMITTED AT ABOUT COLUMN 34, LINE 0222 , COMMA ASSUMED

WARNING 186 SEPARATOR OMITTED AT ABOUT COLUMN 58, LINE 0222 , COMMA ASSUMED

0223 TCTR=1.0/TOTCON
 0224 FTCTR=ERRR/A
 0225 WRITE(2,1020)TOTR,ETOTR
 0226 FORMAT(40X,19H TOTAL RESISTANCE =,F8.4,15H PLUS OR MINUS ,F8.4,
 0227 15H K/U)
 0228 IF(K.EQ.1)GO TO 1701
 0229 QIN=QL
 0230 QOUT=QU
 0231 GO TO 1702
 0232 QI1=QU
 0233 QOUT=QL
 0234 1702 CONTINUE
 0235 ETAS=QIN/WIN
 0236 ETASS=QOUT/WIN
 0237 ETASSS=QOUT/QIN
 0238 WRITE(2,1704)ETAS,ETASS,ETASSS
 0239 1704 FORMAT(10X,23H SOURCE EFFECTIVENESS =,F12.6,/,
 0240 110X,20H SINK EFFECTIVENESS =,F12.6,/,
 0241 210X,38H SPECIMEN SOURCE SINK EFFECTIVENESS =,F12.6)
 0242 C
 0243 999 CONTINUE
 0244 C RETURN FOR NEXT LOAD
 0245 GOTO 391
 0246 C
 0247 C RETURN FOR NEXT CONFIGURATION
 0248 C
 0249 1000 STOP
 0250 END

END OF SEGMENT; LENGTH 1299, NAME POC9 - WARNINGS

0251 SUBROUTINE TEMPEMF(V,T,MM,AMV,R,REF1,TEMPC)
 0252 DIMENSION V(300),T(300),B(3),VVV(5),TT(5)
 0253 AMV=((AMV*(1.0+R(1))+R(2)*AMV+B(3)*(AMV**2))+REF1)*1000.0)
 0254 KK=1
 0255 13 IF(V(KK)-AMV)11,11,12
 0256 11 XX=XX+1


```

0258      12 CONTINUE
0259      DO 15 N=1,5
0260          VV(N)=V(KK+N-3)
0261          TT(N)=TT(KK+N-3)
0262      15 CONTINUE
0263      CALL POLY1(VV,AV,TEMPC,TT)
0264      RETURN
0265      END

```

END OF SEGMENT; LENGTH 159, NAME TEMPEMF

```

0266      SUBROUTINE POLY1(X,XX,YY,Y)
0267      DIMENSION X(5),V(5),A(16,16),SUMX(3),SUMY(45)
0268      COMMON/NRB/REF2
0269      N=5
0270      TOL=0.001
0271      LAST=3
0272      SUMX(1),SUMX(2),SUMX(3),SUMY(1),SUMY(2)=0.
0273      DO 90 I=1,N
0274          SUMX(1)=SUMX(1)+1.
0275          SUMX(2)=SUMX(2)+
0276              SUMX(3)=SUMX(3)+
0277              SUMY(1)=SUMY(1)+
0278              SUMY(2)=SUMY(2)+
0279              NORD=1
0280      91 L=NRBL+1
0281          KK=L+1
0282          DO 101 I=1,L
0283              DO 100 J=1,L
0284                  IK=J+1+I
0285                  A(I,J)=SUMX(IK)
0286      101 A(I,KK)=SUMY(IK)
0287          DO 140 I=1,L
0288              A(KK,I)=-1.
0289              KKK=I+1
0290              DO 110 J=KKK,KK
0291                  A(KK,J)=0.
0292      110 C=1./A(1,I)
0293          DO 120 II=2,KK
0294              DO 120 J=KKK,KK
0295                  A(II,J)=A(II,J)-A(1,J)+A(II,I)+C
0296          DO 140 II=1,L
0297              DO 140 J=KKK,KK
0298      140 A(II,J)=A(II+1,J)

```



```

0301  S1=0
0302  S1=S1+A(1,KK)
0303  DO 150 I=1,NORD
0304  S1=S1+A(I+1,KK)*X(J)*+I
0305  S2=S2+(S1-Y(J))*(S1-Y(J))
0306  R=R-L
0307  S2=SQRT(S2/R)
0308  IF(NORD-LAST)162,163,162
0309  IF(S2-TOL)111,111,171
0310  IF(S2-TOL)111,111,171
0311  IF(S2-TOL)111,111,171
0312  WRITE(2,222)S2
0313  FORMAT(4H S2=,G20.14)
0314  GOT0111
0315  NORD=NORD+1
0316  J=2+10RN
0317  SUMX(J)=0
0318  SUMX(J+1)=0
0319  SUMY(NORD+1)=0
0320  DO 172 I=1,N
0321  SUMX(J)=SUMX(J)+X(I)*+(J-1)
0322  SUMX(J+1)=SUMX(J+1)+X(I)*+J
0323  SUMY(NORD+1)=SUMY(NORD+1)+Y(I)*X(I)*+NORD
0324  GO TO 91
0325  111 Y=A(1,KK)+A(2,KK)*XX+A(3,KK)*XX*XX+REF2
0326  RETURN
0327  END

```

END OF SEGMENT' LENGTH' 685, NAME POLY1

SUBROUTINE FIT(NIST,TEMP,TEMPS,ETEMP,ETEMPS,DISTS,N)
 DIMENSION DIST(4),TEMP(4),ETEMP(4)

 C
 C FIND BEST STRAIGHT LINE

 C
 A,B,C,D,E=0.0
 DO4 I=1,N
 A=A+DIST(I)
 B=B+TEMP(I)
 C=C+DIST(I)*TEMP(I)
 D=D+(DIST(I)*+2.0)
 E=E+(TEMP(I)*+2.0)


```

0341 N=FLOAT(N)
0342 SIGMAX=SQRT(D/N-(A/H)**2.0)
0343 SIGMAY=SQRT(E/N-(B/H)**2.0)
0344 COCO=(C/H-(A*B)/N**2.0)/(SIGMAX*SIGMAY)
0345 WRITE(2,25) COCO
0346 25 FORMAT(10X,26H CORRELATION COEFFICIENT= ,F8.4)
0347
0348 C
0349 C PEGRESSION EQUATION OF TEMPERATURE ON DISTANCE
0350 C
0351 AH=COCO*SIGMAY/SIGMAX
0352 C=B/H-AH*A/H
0353
0354 C
0355 C STANDARD ERROR OF ESTIMATE OF TEMP FROM DISTANCE
0356 C
0357 SY=SIGMAY*((1.0-COCO**2)**0.5)
0358 TSY=2.0*SY
0359 DO 30 I=1,N
0358 TEMP(I)=(AH*DIST(I))+C
0359 FTEMP(I)=TSY*TEMP(I)/100.0
0360 30 CONTINUE
0361 TEMPS=AH*DISTS+C
0362 FTEMPS=TSY*FTEMPS/100.0
0363 0363 WRITE(2,40)((DIST(I),I=1,N),(TEMP(I),I=1,N),(FTEMP(I),I=1,N),DIST
0364 1S,TEMPS,FTEMPS)
0365
0366 40 FORMAT(10X,38H TEMPS CORRECTED TO STRAIGHT LINE FIT ./,
0367 110X,10H DISTANCE ,4F9.5,/,10X,10H TEMP ,4F9.4,/,10X,
0368 212H PLUS OR MINUS ,/,21X,4F9.4,/,10X,21H DISTANCE TO SURFACE ,
0369 33X,F9.4,5H MS ,/,10X,24H TEMPERATURE AT SURFACE ,F9.4,
0370 415H PLUS OR MINUS ,F9.4,7H DEG K )
0371 RETURN
0372 FND

```

END OF SEGMENT, LENGTH 318, NAME FIT

0373

FINISH

END OF COMPILATION - NO ERRORS 5 WARNINGS : COMMENT

S/C SUBFILE1

56. NUCLIFTS USPO

THIS IS MAXIMOP (MARK 5D)

TYPE JOB NUMBER- ME167S

DATE: 13/07/79 CHANNEL: 18

TP OUTPUT HAS BEEN RESTRICTED FROM SOF

20.32.05- OPEN UME167-76

20.32.27- NLIST SALM

```

1      PROGRAM(PRG5)
2      INPUT 1=CR0
3      OUTPUT2=LP0
4      TRACE 2
5      END
6      MASTER MAIN
7 C
8 C      PROGRAM M.N.MIAN FOR THERMAL RESISTANCE OXIDE THEORY.
9          DIMENSION P(4)
10         TF1=2200E-10
11         TF2=2200E-10
12         SIG1=4.E-6
13         SIG2=.12E-6
14         PYE=3.142
15         SLOP1=.03
16         AN=4.9037E-04
17         AK1=43
18         N=1
19         AK2=300
20         CK1=47.
21         CK2=385.
22         TF1=TF1/SIG1
23         TF2=TF2/SIG2
24         HM=9.9E3
25         READ(1,3) P(N)
26     3      FORMAT(1F0.0)
27 C
28     1      SLOP2=SLOP1
29 C      INVERSE INTERPOLATE
30 C      CALCULATE THE VALUE OF THE PROBABILITY FUNCTION FOR
31 C      METALLIC CONTACT.
32         TM=2.840
33         SFYM=EXP(-(TM**2/2.0))/SQRT(2.*PYE)
34         TD=TM-(TF1+TF2)
35 C      EVALUATE PROBABILITY FUNCTION FOR OXIDE CONTACT.
36         SFYD=EXP(-(TD**2/2.0))/SQRT(2.*PYE)
37 C      CALCULATE EFFECTIVE SURFACE ROUGHNESS
38         ESRO=SQRT((SIG1**2)+(SIG2**2))
39 C      CALCULATE EFFECTIVE MEAN SURFACE SLOPE
40         ESSL=SQRT(SLOP1**2+SLOP2**2)/ESRO
41 C      CALCULATE THE TOTAL NUMBER OF MICRO-CONTACTS FOR
42 C      METALLIC CONTACT.
43         ANM=PYE*(ESSL**2)*TM*SFYM*AN/3.0
44 C      CALCULATE THE TOTAL NUMBER OF MICRO-CONTACTS FOR
45 C      OXIDE CONTACT.
46         ANTO=PYE*(ESSL**2)*TD*SFYD*AN/3.
47
48         AND=ANTO-ANM
49 C      CALCULATE MEAN CONTACT SPOT RADIUS FOR OXIDE CONTACT.
50         ABAR=2./(PYE*ESSL*TD)
51         ABMT=2./(PYE*ESSL*TM)
52         WRITE(2,4) TD,ANTO,ABAR,ESRO,ANM,TM,ESSL
53     4      FORMAT(7,4X,7E15.6)

```



```

54 AKS=(2.*AKT*ANM)/(AKT+ANM)
55 AKMT=(2.*CK1*CK2)/(CK1+CK2)
56 RMET=AN/(2.*ABMT*ANM*AKS)
57 CBAR=SQRT(AN/(PYE*ANM))
58 GY=ABMT/CBAR
59 RCLN=RMET*AKS/AKMT
60 C CALCULATE THE TOTAL CONSTRICTION RESISTANCE
61 R=1./(2.*ABAR*ANM*AKS)
62 BBAR=SQRT(AN/(PYE*ANM))
63 AMOR=RCLN*GY
64 R=R*AN
65 TOTR=RMET+R
66 C APPLY CONSTRICTION ALLEVIATION FACTOR.
67 X=ABAR/BBAR
68 GX=1.0-(1.409*X)
69 C MODIFY CONSTRICTION RESISTANCE FOR OXIDE CONTACT.
70 RMJD=TOTR*GX
71 WRITE(2,5) ABMT, RMET, R, TOTR, RMJD, RCLN, AMOR
72 5 FORMAT(//,4X,7E16.6)
73 SLOP1=SLOP1+.01
74 IF(SLOP1.LE.0.14) GOTO1
75 STOP
76 END
77 FINISH
20.36.07- LOGO
CONNECTED FOR 6 MINS
MILL TIME USED 2 SECS
SESSION COST .30

```


THIS IS MAXINOP (MARK 5D)

TYPE JOB NUMBER- ME1675

DATE: 13/07/79 CHANNEL: 18

TP OUTPUT HAS BEEN RESTRICTED FROM SOF

20.47.00- ME1---OPEN UME167-76

20.47.33- NLIST TALK

1 LIBRARY (SUBGROUPNAGF)

2 PROGRAM(PRG5)

3 INPUT 1=CR0

4 OUTPUT 2=LP0

5 TRACE 2

6 END

7 MASTER MAIN

8 C

9 C PROGRAM M.N.MIAN FOR THE PREDICTION OF THERMAL

10 C RESISTANCE FROM CONSTRICTION RESISTANCE THEORY.

11 C

12 DIMENSION BETA(20),Z(3),Y(3),GAM(3),SUM(21),ALPHA(2),RUM(21)

13 READ(1,5) (BETA(N),N=1,20)

14 5 FORMAT(20 F0.0)

15 HQ=17.324339E+08

16 AA=4.908733516E-04

17 BM1=0.01

18 SIG1=1.85E-06

19 SIG2=.083E-06

20 AKM1=47.0

21 AKM2=385.

22 HM=9.0E+03

23 AKJ1=43

24 AKJ2=300

25 PYE=3.14159265

26 RD=1.41421356

27 C D,TF1,TF2 ARE NON-DIMENSIONAL

28 D=1.6

29 TF1=.029729

30 TF2=.625

31 SUM(1)=0.0

32 RUM(1)=0.0

33 1 I=1

34 K=1

35 N=1

36 BM2=BM1

37 Z(I)=(D+TF1)/RD

38 Z(I+1)=(D+TF2)/RD

39 Z(I+2)=D/RD

40 DO 4 I=1,3

41 Y(I)=S15AEF(Z(I),IFAIL)

42 GAM(I)=0.25*(1.-Y(I))*2

43 C RT=GAM(3).

44 C

45 4 CONTINUE

46 ASUM= GAM(1)+GAM(2)

47 DIFFA=GAM(3)-GAM(1)

48 DIFFB=GAM(3)-GAM(2)

49 DIVA=HQ/HM

50 C TA/HM IS A RATIO

51 RATIO=ASUM+(DIFFA+DIFFB)*DIVA

52 APP=HM/RATIO


```

53      ALDAD=APP*AA      A.52
54 C    TWO SOLUTIONS ARE POSSIBLE
55 C    CALCULATE THE CORRECT VALUE OF D
56      ALAN=EXP(-(D+TF1)**2)
57      GAL1=BM1**2
58      GAL2=3.*PYE*(SIG1**2)
59      ANM1=(GAL1*AA/GAL2)*ALAN
60      PAUL=EXP(-(D+TF2)**2)
61      GAL3=BM2**2
62      GAL4=3.*PYE*(SIG2**2)
63      ANM2=(GAL3*AA/GAL4)*PAUL
64      ASIM=EXP(-(D**2))
65      ANT1=(GAL1*AA/GAL2)*ASIM
66      ANT2=(GAL3*AA/GAL4)*ASIM
67      AND1=ANT1-ANM1
68      AND2=ANT2-ANM2
69      AM1 =SQRT(AA*GAM(1)/(ANM1*PYE))
70      AN2 =SQRT(AA*GAM(2)/(ANM2*PYE))
71      AD1= SQRT((AA*GAM(3))/(ANT1*PYE))
72      AD2= SQRT((AA*GAM(3))/(ANT2*PYE))
73 C    CALCULATE THE VALUE OF F1.
74      J=1
75      ALPHA(J)=(AD1-AM1)/AD1
76      ALPHA(J+1)=((AD1-AM1)+(AD2-AN2))/(AD1+AD2)
77      X=SQRT( 2.*GAM(3))
78      WRITE(2,14) RATIO,ALDAD,APP
79      14  FORMAT(/,4X,3E20.5)
80      36  DUM=X*(ALPHA(J)**2)*((2.-ALPHA(J))**2)
81 C
82      2  AZ=X*BETA(N)
83 C    CALCULATE J1(X)
84      AY=S17ABF(AZ)
85      ANUM1=AY
86      ZZ=AZ*(1.-ALPHA(J))
87      AY=S17ABF(ZZ)
88      ANUM2=AY
89      AZ=BETA(N)
90 C    CALCULATE J2(X)
91      AY=S17AAF(AZ)
92      ANUM3=AY
93      ANUM4=ANUM3**2
94      DUM1=ANUM1-(1.-ALPHA(J))*ANUM2
95      DUM2=DUM1**2
96      DUM3=(BETA(N)**3)*ANUM4
97      DUMY=DUM2/DUM3
98 C    EVALUATE TERM OF SERIES.
99      IF(J.EQ.2) GOTO 22
100     SUM(N+1)=SUM(N)+DUMY
101     DEUG=SUM(N+1)
102     IF(ABS(SUM(N+1)-SUM(N)).LT.1E-07) GOTO 30
103     22  RUN(K+1)=RUN(K)+DUMY
104     DD=RUN(K+1)
105     IF(ABS(RUN(K+1)-RUN(K)).LT.1E-07) GOTO 40
106 C    SUM THE SERIES
107     30  FSUM=DEUG
108 C
109 C    CALCULATE THE VALUE OF CONSTRICTION FACTOR.
110 C    CALCULATE F1& F2.
111     IF(J.EQ.2) GOTO 20
112     F1=FSUM/DUM
113     20  CONTINUE
114     J=J+1
115     IF(J.EQ.2) GOTO 36
116     40  F2=DD/DUM
117 C
118 C    CALCULATE THE VALUE OF CONSTRICTION FACTOR FOR UPPER HALF OF I
INTERFACE.

```



```

119 C      CALCULATE THE VALUE OF CONSTRICTION FACTOR FOR LOWER HALF OF I
INTERFACE.
120      DUM4=AKM1*AM1*ANM1
121      DUM5=AKM1*AM2*ANM2
122      DUM6=AKD1*AD1*AND1
123      DUM7=AKD1*AD2*AND2
124      DUM8=AKD1*AD1*ANM1
125      DUM9=AKD1*AD2*ANM2
126      RES1=(PYE/(4.*F1))*(DUM4+DUM5+DUM6+DUM7)+(PYE/(4.*F2))*(DUM8+D
UM9)
127      RMD1=1./RES1
128      RMD1=RMD1*AA
129      DUM10=AKM2*AM1*ANM1
130      DUM11=AKM2*AM2*ANM2
131      DUM12=AKD2*AD1*AND1
132      DUM13=AKD2*AD2*AND2
133      DUM14=AKD2*AD2*ANM1
134      DUM15=AKD2*AD2*ANM2
135      RES2=(PYE/(4.*F1))*(DUM10+DUM11+DUM12+DUM13)+(PYE/(4.*F2))*
1 (DUM14+DUM15)
136      RMD2=1./RES2
137      RMD2=RMD2*AA
138      TOTRES=RMD1+RMD2
139      WRITE(2,9) D,TOTRES,BM1
140      9      FORMAT(/,4X,F5.2,2X,E14.6,2X,F6.4)
141      N=N+1
142      K=K+1
143      J=1
144      IF(N.LE.6) GOTO 2
145      WRITE(2,15) ANM1,ANM2,ANT1,ANT2
146      15      FORMAT(/,4X,4E16.6)
147      BM1=BM1+0.01
148      IF(BM1.LE.0.14) GOTO 1
149      BM1=.01
150      D=D+0.2
151      IF(D.LE.2.0) GOTO 1
152      STOP
153      END
154      FINISH
20.54.53- LESS
CONNECTED FOR      9 MINS
MILL TIME USED      4 SECS
SESSION COST      .53

```


THIS IS MAXIMOP (MARK 5D)

TYPE JOB NUMBER- ME167S

DATE: 19/09/79 CHANNEL: 13

NEW GINO-F, SURF SUBROUTINE LIBRARIES FROM 5/9/79.

ANY QUERIES TO S. INGHAM OR C. WHITAKER

20.21.25- OPEN UME167-76

20.21.50- NLIST CORE

```

1
2
3      PROGRAM(PRG5)
4      INPUT 1=CR0
5      OUTPUT 2=LP0
6      TRACE 2
7      END
8      MASTER MAIN
9 C
10 C      PROGRAM M.N.MIAN FOR MULTIPLE REGRESSION AND
11 C      CORRELATION OF THERMAL RESISTANCE PARAMETERS.
12 C
13      DIMENSION AX(27),BX(27),CX(27),DX(27),YEST(27)
14      1 ,R(27),P(27),AS(27),VAL(27),F(27)
15      AN=13.
16      Y=0.
17      N=1
18      SUM1=0.
19      SUM2=0.
20      DJM=0.
21      SUM3=0.
22      SAX=0.
23      SBX=0.
24      SCX=0.
25      SDX=0.
26      SUM5=0.
27      SUM6=0.
28      SUM7=0.
29      SUM8=0.
30      SUM9=0.
31      SUM10=0.
32      SUM11=0.
33      READ(1,10)AX
34      10 FORMAT(13F0.0)
35      READ(1,11)BX
36      11 FORMAT(13F0.0)
37      READ(1,12)CX
38      12 FORMAT(13F0.0)
39      READ(1,13)DX
40      13 FORMAT(27F0.0)
41      1 Y=Y+AX(N)
42      A1=AX(N)*BX(N)
43      A2=AX(N)*CX(N)
44      A3=AX(N)*DX(N)
45      A5=AX(N)**2
46      A6=BX(N)**2
47      A7=CX(N)**2
48      A8=DX(N)**2
49      A9=BX(N)*CX(N)
50      A10=BX(N)*DX(N)
51      A11=CX(N)*DX(N)
52      SAX=SAX+AX(N)
53      SBX=SBX+BX(N)
54      SCX=SCX+CX(N)
55      SDX=SDX+DX(N)
56      SUM1=SUM1+A1
57      SUM2=SUM2+A2
58      SUM3=SUM3+A3

```



```

60 SUM5=SUM5+A5
61 SUM6=SUM6+A6
62 SUM7=SUM7+A7
63 SUM3=SUM3+A3
64 SUM9=SUM9+A9
65 J=1
66 IF(J.EQ.1)GOTO 20
67 YEST(N)=4.189-0.9443*BX(N)-0.128*CX(N)+0.03455*DX(N)
68 DIFF1=AX(N)-YEST(N)
69 DIFF2=DIFF1**2
70 SUM10=SUM10+A10
71 DUM=DUM+DIFF2
72 SUM11=SUM11+A11
73 R(N)=EXP(AX(N))
74 P(N)=EXP(BX(N))
75 AS(N)=EXP(CX(N))
76 F(N)=EXP(DX(N))
77 VAL(N)=EXP(YEST(N))
73 20 CONTINUE
79 N=N+1
80 IF(N.LE.13) GOTO 1
81 SD=SQRT((SUM5/AN)-((Y/AN)**2))
82 WRITE(2,2) SUM1, SUM2, SUM3, SUM5, SUM6, SUM7, SUM3, SUM9
83 2 FORMAT(4X, 3E12.5)
84 WRITE(2,3) SUM10, SUM11, SD
85 -3 FORMAT(/,4X,3E13.5)
86 WRITE(2,7) ((R(N),P(N),AS(N),F(N))N=1,27)
87 7 FORMAT(/,4X,4E16.5)
88 SEE=SQRT(DUM/AN)
89 CC=SQRT(1.-(SEE**2/SD**2))
90 WRITE(2,8) SEE, CC
91 22 CONTINUE
92 WRITE(2,6) SAX, SBX, SCX, SDX
93 6 FORMAT(/,4X,4E20.5)
94 IF(J.EQ.1) GOTO 23
95 8 FORMAT(/,4X,2E20.6)
96 WRITE(2,9) ((YEST(N),VAL(N))N=1,27)
97 9 FORMAT(4X,2E16.5)
98 23 STOP
99 END
100 FINISH

```