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H N Gouveia

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The Coupling Mechanisms in the CO₂ Laser

Welding of Copper

School of Industrial and Manufacturing Science

Ph.D Thesis

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The Coupling Mechanisms in the CO₂ Laser Welding of Copper

Supervisor:

John Norrish

ABSTRACT

The CO₂ laser is a potentially powerful tool for welding, allowing high integrity joints to be produced with minimal thermal damage and high joint completion rates. Its use in the joining of reflective, high conductivity materials, such as copper is, however, limited.

The current work examined the high power CO₂ laser welding of oxygen free high conductivity copper and in particular the coupling mechanisms which appear to control the consistency of the process.

The role of the plasma control jet was found to have a fundamental influence on the coupling behaviour.

Due to the practical problems of direct observation of the jet gas flow during welding, the process was modelled using a flow simulation package.

The results of the simulation enabled a satisfactory theory for the coupling mechanism to be developed.

Plasma plume formation and maintenance during the welding process appeared to be responsible for coupling and to occur by a non-conventional mechanism.

The theory explains the anomalies in previous work and indicates how the process consistency may be improved.

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TO MY CHILDREN PEDRO AND RUI

THE COUPLING MECHANISMS IN THE CO₂ LASER WELDING OF COPPER

CONTENTS

ABSTRACT

ACKNOWLEDGEMENTS

CONTENTS

NOTATION

CHAPTER I - INTRODUCTION	1
1.1 INTRODUCTION	1
1.2 BACKGROUND	2
1.3 OUTLINE OF THE RESEARCH	3
1.4 OUTLINE OF THE PRESENTATION	4
CHAPTER II - CO₂ LASER BEAM WELDING - SURVEY	5
2.1 INTRODUCTION	5
2.2 INTRODUCTION TO LASERS	6
2.2.1 The Optical Resonator (Optical Cavity)	8
2.2.2 Beam Transmission Systems	9
2.2.3 The Carbon Dioxide Laser	10
2.2.3.1 Types of CO ₂ lasers	12
■ Sealed Tube Lasers	12
■ Waveguide Lasers	12
■ Longitudinal (or Axial) Slow Flow Lasers	13
■ Fast Axial Flow Lasers	13
■ Transverse Flow Lasers	13
■ Gas Dynamic Lasers (GDL)	14
■ Transverse Excitation Atmospheric Pressure Laser (TEA)	15
2.3 CO ₂ LASER BEAM WELDING	15
2.3.1 Process Fundamentals	15
2.3.2 CO ₂ Laser Welding Parameters	16
2.3.2.1 Beam and transport properties	16
2.3.2.2 Gas shielding properties	18
2.3.2.3 Material properties	19
2.3.3 Plasma Effects	20
2.3.3.1 Plasma Control Techniques	20
■ Plasma control using a gas jet	20
■ Plasma control by mechanical or electrically pulsing the beam	22
■ Plasma control by a combination of a gas jet and linear beam oscillation - "Laser Spike Seam welding" method	23

THE COUPLING MECHANISMS IN THE CO₂ LASER WELDING OF COPPER

2.4	CO ₂ LASER WELDING OF HIGH REFLECTIVITY MATERIALS	23
	FIGURES	25

CHAPTER III - INTERACTION OF LASER RADIATION WITH METALS - REVIEW

3.1	INTRODUCTION	41
3.2	ABSORPTION OF LASER RADIATION	42
3.2.1	Free Electron Theory of Metals (Drude model)	43
3.2.2	Optical Behaviour of Metals	47
3.2.2.1	Temperature dependence	48
3.3	COUPLING IN THE LOW INTENSITY RANGE	49
3.3.1	Influence of the Metal Optical Properties	49
3.3.1.1	Surface condition	49
	• <i>Surface roughness</i>	50
	• <i>Defects and impurities</i>	51
	• <i>Oxides</i>	51
	• <i>Surface Coating</i>	51
3.3.2	Laser Beam Characteristics	52
3.4	COUPLING IN THE HIGH INTENSITY RANGE	52
3.4.1	Plasma Generation	54
3.4.2	Plasma Model	56
3.4.3	"Enhanced Coupling" Models	58
3.4.3.1	Multiple reflections and integrated absorption at the keyhole walls	58
3.4.3.2	Laser induced plasma	59
3.4.3.3	Multiple reflection/laser induced plasma	60
3.4.4	Materials Processing Involving the Laser Induced Plasma	60
	FIGURES	63

CHAPTER IV - RESEARCH PROGRAMME - CO₂ LASER WELDING OF COPPER

4.1	INTRODUCTION	73
4.2	PRELIMINARY WORK	74
4.3	RESEARCH PROGRAMME	74
4.3.1	Experimental Set-Up	74
4.3.1.1	Material and preparation	74
4.3.1.2	Equipment	75
4.3.1.3	Assist gases	75
	■ <i>Determination of the welding parameters</i>	75
	■ <i>Optimization of the welding process</i>	76
4.3.1.4	Experimental welding parameters	76
	■ <i>Determination of the welding parameters</i>	76
	■ <i>Optimization of the welding process</i>	76
4.3.1.5	Assessment	76
4.3.2	Results	77
4.3.2.1	Welding behaviour	77
4.3.2.2	Dimensional analysis of the weld beads	78

THE COUPLING MECHANISMS IN THE CO₂ LASER WELDING OF COPPER

4.3.2.3	Influence of beam power, focus position and welding speed on weld bead characteristics	78
4.3.2.4	Influence of the gas jet composition and flow rate	78
	■ <i>pure gases: N₂ and Ar</i>	78
	■ <i>gas mixtures: N₂ + O₂ and Ar + N₂</i>	79
4.3.2.5	Effect of the use of a gas lens on plasma control	79
	■ <i>Determination of the welding parameters</i>	79
	■ <i>Optimization of the Welding Process</i>	80
4.3.2.6	Influence of plasma control device setting - up on the coupling behaviour	80
4.3.3	Discussion	81
4.3.3.1	Coupling phenomena	81
4.3.3.2	Welding behaviour	82
4.3.3.3	Porosity	82
4.3.3.4	Plasma control device performance	83
4.3.4	Conclusions	83
FIGURES		85

CHAPTER V - RESEARCH PROGRAMME - PLASMA CONTROL GAS FLOW VISUALISATION 108

5.1	INTRODUCTION	108
5.2	FLOW VISUALISATION TECHNIQUES	109
5.2.1	General survey	109
5.2.1.1	Schlieren Method	109
5.2.1.2	Shadow System	111
5.2.1.3	Smoke Method	111
5.2.1.4	Holographic Interferometry	112
5.3	EXPERIMENTAL PROGRAM	113
5.3.1	Visualisation of gas jet flow using the Schlieren technique	113
5.3.1.1	Set - up	114
5.3.1.2	Results	114
5.3.1.3	Conclusions	115
5.3.2	Visualisation of gas jet flow pattern using the smoke technique	115
5.3.2.1	General	115
5.3.2.2	Set-up	115
5.3.2.2	Results and Conclusions	116
5.3.3	Conclusions	116
FIGURES		118

CHAPTER VI - RESEARCH PROGRAMME - PLASMA CONTROL GAS FLOW SIMULATION 127

6.1	INTRODUCTION	127
6.2	SIMULATION PROGRAM: FLUENT V 3.0	128
6.2.1	General Introduction	128
6.2.2	Solution of the Continuous Phase Equations	129
6.3	SIMULATION CONDITIONS	130

THE COUPLING MECHANISMS IN THE CO₂ LASER WELDING OF COPPER

6.3.1	Assumptions	130
6.3.2	Gas Jet Nozzle Set-up	131
6.3.3	Gas Lens Set-up	132
6.3.4	Gas Jet Composition and Flow Rate	132
6.3.5	Gas Lens Composition and Flow Rate	132
6.3.6	Gas Velocity Distribution Profile	132
6.4	RESULTS	133
6.4.1	Effect of the Nozzle Tip Geometry on the Gas Jet Flow Pattern	133
6.4.2	Effect of Increasing /Decreasing the Nozzle Length	133
6.4.3	Effect of the Use of a Gas Lens	133
6.4.4	Particle/Droplet Trajectory	133
6.4.5	Gas Velocity Distribution Profile	133
6.5	DISCUSSION	134
6.6	CONCLUSIONS	136
	Nomenclature used to designate the simulation experiments	137
	FIGURES	138
	CHAPTER VII - DISCUSSION	167
7.1	INTRODUCTION	167
7.2	MODEL FOR THE COUPLING PROCESS IN THE LASER WELDING OF COPPER	169
7.2.1	Outline of the Coupling Mechanism	169
7.2.2	Mechanism of Formation of the "Seed" Particles	170
7.2.2.1	Theoretical considerations	170
7.2.3	Copper Behaviour in the Interaction with a Laser Beam	172
7.2.4	Copper Behaviour in the Interaction with a High Intensity CO ₂ Laser Beam	174
7.2.4.1	Coupling mechanism	178
	■ <i>Onset of interaction</i>	178
	■ <i>Maintenance of the process</i>	181
7.3	FINAL REMARKS	183
	CHAPTER VIII - CONCLUSIONS	189
	REFERENCES	192
	APPENDICE A	204
	PART I - Electromagnetic waves	205
	PART II - Optical properties (macroscopic approach)	208
	APPENDICE B - Simulation assumptions	211

NOTATION

● Abbreviations

Al	-	aluminium
Ar	-	argon
Bw	-	bottom (root) weld bead width
CO ₂	-	carbon dioxide
Cu	-	copper
cw	-	continuous wave
FA	-	fusion area
He	-	helium
N ₂	-	nitrogen
O ₂	-	oxygen
OFHC	-	oxygen free high conductivity
R ₁	-	gas jet flow rate
R ₂	-	gas lens flow rate
R ₃	-	gas shroud flow rate
RF	-	radio frequency
TEM	-	transverse electromagnetic mode
Tw	-	top (face) weld bead width

● Nomenclature

α	-	absorption coefficient
ϵ	-	average electron energy
Γ	-	damping frequency
δ	-	skin depth
ϵ	-	permittivity
ϵ_0	-	free space permittivity
ϵ_1	-	real part of the complex permittivity
ϵ_2	-	imaginary part of the complex permittivity
ϵ_r	-	relative permittivity
κ	-	extinction coefficient
K	-	propagation constant
λ	-	wavelength
μ	-	permeability
μ_0	-	free space permeability
ν_p	-	threshold frequency
ξ	-	emissivity
ρ	-	free charge density
σ	-	conductivity
σ_0	-	dc conductivity
τ	-	mean free time between collisions
ω	-	angular frequency
ω_p	-	plasma frequency

THE COUPLING MECHANISMS IN THE CO₂ LASER WELDING OF COPPER

A	-	absorptivity
B	-	magnetic field intensity
c	-	velocity of light in free space
c_p	-	heat capacity
e	-	electron charge
E	-	electric field intensity
h	-	Planck's constant
I	-	laser intensity
I_B	-	threshold intensity for gas breakdown
I_D	-	detonation threshold intensity
I_v	-	threshold intensity for vaporisation
J	-	free current density
K	-	thermal conductivity
L_f	-	latent heat of fusion
L_v	-	latent heat of vaporisation
m	-	electron mass
n	-	index of refraction
N_e	-	electron density
n_M	-	vapour density
P	-	power
R	-	reflectivity
r_F	-	focus radius
t	-	time
T_e	-	electron temperature
T_m	-	melting temperature
T_v	-	vaporisation temperature
v	-	welding speed
v_p	-	phase velocity
z	-	effective ion charge

CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

The usefulness of the laser as a processing tool has been proved over the last 3 decades, during which the laser has established an important place in materials processing by offering impressive technical advantages over conventional processes.

Although, laser welding of materials such as carbon and stainless steels is well established in industry, it still remains a complex process for the joining of high reflectivity and conductivity materials (i.e. copper and aluminium). This is due, not only to the thermo-physical properties of these materials but also to the lack of a complete understanding about the mechanisms that control the welding process.

The joining of copper using conventional welding processes generally presents some problems (e.g. porosity, cracking) which make it difficult to produce high integrity copper joints, and limit its use for particular applications. The use of high energy density beams, i.e. electron and laser beam processes for the welding of copper can be regarded as technological alternatives, which combine better performances with an innovative approach to the fabrication of high quality components in copper.

Electron beam welding has proved to be a reliable technological alternative for the joining of copper. However, the need for a vacuum chamber and its lower flexibility when compared with the laser welding process makes the later more attractive. The development of the laser beam process as a reliable process for the welding of copper is the primary motivation behind the present investigation work.

The development of a predictable and reliable process demands that an in depth knowledge of all the mechanisms involved is achieved. Strict control of the process is also needed to attain high efficiencies, which are of prime importance for a high cost related process.

Both the lack of a full understanding of the mechanisms involved in the laser welding of high reflectivity and conductivity materials and the scattered published data concerning the interaction of laser beams with these materials have limited the application of the laser technology to their processing.

Thus, the primary aim of this work is to provide a better understanding of the key mechanisms involved in the laser welding of copper and particularly of those that assist the coupling process, thus providing a fundamental contribution to the development of a reliable technological alternative for the welding of copper and all other high reflectivity and conductivity materials. In addition, the work aims to contribute to the clarification of the complex phenomena that occur in the interaction of high density power beams and materials, making improved control of the process possible. This is particularly important when automation of the process is envisaged.

1.2 BACKGROUND

Early work on the use of a carbon dioxide (CO_2) laser for the welding of copper was reported in 1985 by Dell'Erba. The welding of uncoated copper plates was achieved using helium (He) and oxygen (O_2) as assist gases. Helium was provided coaxially to the laser beam, while O_2 was supplied to the laser beam/material interaction point through a nozzle placed at an angle of 45° relatively to the laser beam axis. The need for O_2 assistance in the laser welding of copper was later outlined in subsequent work developed by this researcher et al. [1986a-b].

The relatively successful coupling of the laser radiation into copper was attributed by Dell'Erba et al., to a laser induced oxidation process as described by Ursu et al. [1983-84a]. According to the later the oxidation rate of a copper surface exposed to the simultaneous action of a continuous wave CO_2 laser and an O_2 gas jet is some orders of magnitude greater than in non laser conditions, giving rise to the growth of oxide layers of both cuprous and cupric oxides, Cu_2O and CuO , respectively. At temperatures close to the melting point, T_m , a significant increase in the absorptivity of the copper surface (to about 50%) occurs and an enhanced coupling caused by an interference phenomena in the metal-oxide layer systems results.

There is, however, experimental evidence in the work of Dell'Erba et al. [1986a-b], that shows that the above mechanism does not completely describe the phenomena occurring in the interaction of a CO_2 laser radiation and an uncoated copper surface. Actually, whenever the oxygen gas jet was removed or replaced by another gas during the welding process, the process was immediately interrupted and extinguished with the incident laser radiation being completely reflected, independently of either the sample temperature or the extent of oxide layers already formed on the beam exposed surface. Even in the case of a pre-oxidised copper sample if the assist gas is either an inert gas or compressed air but not oxygen, welding did not occur.

An interesting feature of the conditions under which welding occurred, (i.e., with oxygen assistance) was the reported presence of a green plume over the interaction zone, whose composition was not disclosed in the Dell'Erba work (e.g., 1986a), although it has been suggested that it can be due to the presence of excited copper atoms.

Despite the apparently successful results, the need for O_2 to initialise and run the whole welding process, raises some doubts about the quality of the welds produced, since O_2 is known as having a detrimental effect on copper welding.

Another approach to coupling was reported by Daurelio et al. [1988, 1991]; this consisted of the use of different pre coatings on copper surfaces, namely: titanium oxide, glossy chromium, colloidal graphite dispersion in a volatile solvent and black chromium. Different covering gases were used (N_2 , O_2 , He and compressed air). Quite good results were obtained, although the black chromium coating gave the best results. The only drawback of this approach seemed to be the limit of 1 mm as the maximum thickness weldable.

The idea of using thermochemical surface reactions to increase the efficiency of the thermal processing of metals under the action of continuous wave CO_2 lasers was suggested by Sullivan et al. [1967]. The use of oxygen mixed with inert gases to enhance the coupling of laser radiation into materials, has also been reported by other researchers [Ohmine et al., 1988; Jorgensen, 1980], for the cases of the aluminium and stainless steel, respectively. In both cases enhanced coupling, and therefore, improved penetration was attributed to the formation of oxides, which by improving the material's surfaces absorptivities, improved the process performance. Ohmine et al. [1988] have also described for nitrogen a role similar to that of oxygen when welding aluminium (i.e, better coupling due to the formation of nitrides).

Nitrogen was also used quite satisfactory by Stares [1987] to weld copper. In his study nitrogen and helium were tested as assist gases to control the plasma, which is formed as a result of the interaction of the high CO_2 power beam with materials. The plasma control gas was delivered to the interaction zone through a nozzle placed at an angle of about 45° relatively to the laser beam axis. Stable and penetrating welds were reported to be produced on uncoated copper plates.

This latter result appears to be in contradiction with the others described above, in terms of the mechanisms responsible for the interaction and welding processes.

1.3 OUTLINE OF THE RESEARCH

The previous results on the CO_2 laser welding of copper, although contradictory in the way they were justified, have provided evidence for the beneficial role of gases other than argon and helium.

Although, the research work on the CO_2 laser welding of copper reported by Stares [1987] was only exploratory, it has shown the potential for N_2 as assist gas in the laser welding of copper.

Nitrogen is a commonly used gas (alone or mixed with argon) in the welding of copper by conventional processes and specially in TIG (tungsten inert gas) welding. It is a low cost gas when compared to argon and helium, and is thus able to affect significantly the overall costs of the welding process. Notwithstanding these features, no reference in literature, except for the concise work from Stares [1987], was found concerning the use of this gas in the laser welding of uncoated copper.

The aim of this research project was to provide a practical industrial oriented process option and for this reason it was decided to explore the use of nitrogen as the assist gas in the laser welding of copper and to attempt to develop an understanding of its role.

Preliminary work was undertaken in order to explore the potential on N_2 in the welding of copper with a CO_2 laser, and to obtain an overview of all the relevant parameters and of their influence in the welding process. It was aimed at this stage to develop a model, which would describe the CO_2 laser welding of copper.

The experimental work was initially directed at providing data for the modelling, but it was clearly shown that the CO_2 laser welding of copper was not a reliable process, even when the reported techniques were adopted.

All the variables and parameters related to the process were carefully and exhaustively controlled in order to understand the sources of process instabilities.

It was established that process instabilities were related to the N_2 flow patterns over the laser/copper interaction zone. Therefore, the remainder of the research programme was designed to explain the behaviour of gases, in order to be able to understand their influence on the coupling and welding processes.

In view of the results obtained a theoretical model was developed to explain the interaction mechanisms in the CO_2 laser welding of copper, giving an insight in the complex mechanisms that control the process.

1.4 OUTLINE OF THE PRESENTATION

The thesis is presented in eight chapters, with a literature survey following this Introduction.

The experimental work is presented in chapters IV, V and VI. Chapter IV gives a detailed description of the CO_2 laser welding experiments, the results, discussion of results and the main conclusions. Chapter V describes the gas flow visualisation studies. The results of this study and the main conclusions are also included in this chapter. The visualisation of the gas flow patterns was finally achieved through simulation, which is fully described in chapter VI.

The discussion of the overall results is presented in chapter VII where an attempt is made to develop a general interpretation of the response of copper to its interaction with a high intensity CO_2 laser beam. Finally, specific conclusions are presented in chapter VIII.

CHAPTER II

CO₂ LASER BEAM WELDING

- SURVEY -

2.1 INTRODUCTION

The laser has gained as a material processing tool general acceptance. This results from it being a unique source of thermal energy, precisely controllable in intensity and position, allowing high quality performances to be achieved.

Intensive and exhaustive research has been dedicated either to the development of higher power lasers with better performances and to the study of the processing of materials by lasers in order to improve the reliability and repeatability of the processes.

No attempt is made here to give a complete account of all the literature reported on this subject, but the survey is intended to put into perspective aspects considered relevant to the present work.

The survey is divided into 2 main parts: in the first part, a description of the main features of the radiation produced by a laser is given, with special emphasis on the CO₂ laser; and in the second part laser beam welding is described; outlining its essential aspects, including those most relevant to processing with high power laser beams.

2.2 INTRODUCTION TO LASERS

The word **laser** is an acronym for "Light Amplification by Stimulated Emission of Radiation", a phrase that covers most, though not all, of the key physical processes inside the laser.

A laser is a device that amplifies, or increases, the intensity of light, producing a strong, highly directional or parallel beam of light of a particular wavelength [Silfvast, 1991].

From an engineering viewpoint a laser may be considered as an energy conversion device, in which energy from a primary source (electrical, chemical, thermal, optical, nuclear) is transformed into a beam of coherent electromagnetic radiation whose wavelengths span the spectrum from the far infrared to the near infrared, the visible to the ultraviolet, and the vacuum ultraviolet to the soft X-ray region (fig. 2.1).

A general laser device (fig. 2.2) consists of (1) an active medium (lasing material), constituted by the atomic species¹ that actually emit the light, (2) an excitation system, to pump energy into the active medium, thus exciting the active species and rendering amplification possible and (3) an optical resonator or mirror arrangement for providing positive feedback into the system to produce oscillation.

The lasing medium (or lasant) can consist of a range of different materials in different matter states such as gases, metal vapours, plasmas, liquids (dyes), semiconductors and solids. In the latter case, the laser species are implanted within an host material such as a crystal or a glass in a proportion ranging from approximately 1 part in 100 to 1 part in 10.000.

All the atomic species possess discrete energy levels; at the lowest energy level (ground level) electrons are found in an equilibrium condition, but they "jump" to higher energy levels when energy is pumped into the species either by heating or irradiating it with light or energetic particles such as fast electrons or fast atomic particles. When electrons jump or decay from some of these high lying or excited energy levels to lower lying energy levels, light is produced. Light emitted when an electron decays can occur either spontaneously, due to inherent interactions of the atomic structure or by stimulated emission whereby the electron is forced or driven to radiate by an approaching photon of the appropriate energy or wavelength (fig. 2.3).

Stimulated emission is a natural process, first recognized by Einstein in 1917, that occurs when a beam of light passes through a medium and stimulates atoms (already excited) of that medium to radiate more light in the same direction and at the same wavelength as that of the original beam. It is the ability of light to stimulate the emission of light that creates the situation in which light can be amplified. Stimulated emission is the key process in laser emission but it only yields to a net increase in the number of photons if a condition known as population inversion is satisfied. This means that when a beam of light passes through the

¹Atomic species include: (i) individual atoms or ions; (ii) small uniquely group of atoms (molecules); (iii) periodically arranged groups of atoms (semiconductors or crystalline solids); (iv) randomly arranged group of atoms (liquids and amorphous solid structures)

lasing medium it is necessary that the higher energy levels are more populated than the lower ones, in order that more photons were stimulated rather than absorbed.

The population inversion is, therefore, to be a fundamental condition which is achieved if energy is fed to the lasing material in order to produce the excited states.

The energy for this process can be provided in the form of highly energetic electrons or heavier particles such as protons, neutrons or even other atoms or electromagnetic radiation (light) in the form of [Silfvast, 1991]: (i) broad frequency spectrum of emission such as a flash lamp, (ii) narrow frequency spectrum provided by another laser. The most common excitation source is that provided by energetic electrons since they are easily accelerated by applying an electric field or voltage drop to an amplifier. Electron excitation sources are also the most efficient, since flash lamps are themselves generally excited by electrons before they are used to pump lasers. Electrons are typically used in most gas, metal vapour, plasma and semiconductors lasers, whereas light (optical excitation) is most often used in liquid (dye) lasers and crystalline solid state lasers.

The net increase in the number of photons resultant from the process of stimulated emission will not produce laser emission if amplification of the light does not occur. Amplification of light occurs in the optical cavity or optical resonator, which typically comprises a mirror at each end of the gain region (fig. 2.2), thus allowing the growing beam to bounce back and forth (oscillate) between the mirrors. A useful beam emerges from the laser either by making one of the laser mirrors partially transmitting or by using a mirror with a small hole in it.

The laser produces light with unique properties, which include [Luxon et al., 1985]:

- high monochromaticity,
- high brightness,
- high degree of both spatial and temporal coherence,
- ability of very low (mW) to very high (kW) continuous power output from different type of lasers,
- high peak power (kW) and large energies (hundreds of Joules) per pulse in pulsed output lasers,
- possibility of being focused to a small diffraction limited spot size (of the order of the light wavelength).

The accurate focusing capability of the laser, allowing the concentration of a high power into a small area, makes it a natural device for the processing of materials.

The important characteristics from the material processing viewpoint are linewidth, divergence, coherence and focusability.

Describing a laser beam as monochromatic means that its output has a very narrow spectral width, i.e., all the output power of the laser is concentrated in a single wavelength or in a very narrow range of wavelengths.

The output from most lasers is in the form of an almost parallel beam. The beam divergence angle is in the order of few milliradians, meaning that the beam can travel long distances without significant spreading. The high directionality of the laser beam makes possible to collect it by a lens and focus it to a small area.

As a result of the directionality and coherence of the laser beam, the laser is a source of energy that can be concentrated at the surface of a material by a lens to achieve extremely high power density.

2.2.1 The Optical Resonator (Optical Cavity)

The optical cavity is usually formed by placing mirrors (either plane or curved) perpendicularly to the axis along which the laser light will oscillate. This structure tends to maintain particular electromagnetic field configurations with sufficiently low loss, so that it may be compensated by the gain attained through stimulated emission. These configurations are referred to as the modes of the cavity. The development of modes involves an attempt by competing light beams of similar wavelengths to fit an exact number of their waves into the optical cavity with the constraint that the oscillating electric field of the light beam is zero at each of the mirrors.

There are two different types of optical resonator designs: stable and unstable ones. These two types have different advantages and different mode patterns. The stable resonator refers to a mirror arrangement (usually one with a mirror at each end of the elongated cavity) (fig.2.2) where light concentrates along the laser axis, extracting energy efficiently from that region, but not from the outer regions far from the axis. The beam has an intensity peak in the centre, and a gaussian drop in intensity with increasing distance from the axis. It is the commonly used with low gain and continuous wave lasers. Several resonator mirror configurations are shown in fig. 2.4a, along with the approximate mode volume for each. Whether a stable resonator configuration laser operates in the lowest order mode or higher mode largely depends on the size of the effective aperture in relation to the cavity length [Luxon et al, 1985].

An unstable resonator is a mirror arrangement (fig. 2.4b) where the light rays "walk-off" the axis and they have to be intercepted by a third mirror called the scraping mirror [Luxon, 1986]. In most cases the beam has an annular profile with peak intensity in a ring around the axis but nul on axis. This design collects laser energy from more of the volume in the laser cavity, typically leading to higher overall energy conversion efficiency than with a stable resonator. These type of optical resonators are frequently used in high power, high gain lasers.

Two distinct types of modes exist in the optical resonators: the longitudinal and transverse. Longitudinal modes involve many light beams travelling along a distinct path between the mirrors and having an exact integral number of wavelengths along that path, but differing in wavelength by an amount determined by the total number of wave cycles that fit between the mirrors. Transverse modes are represented by slightly different optical paths as they travel through the amplifier (fig. 2.5) [Silfvast, 1991]. Thus each transverse mode travelling over its unique path could consist of several longitudinal modes oscillating along that path.

Light distribution is therefore determined by the resonance modes of the laser and has a characteristic pattern depending on the dominant transverse electromagnetic mode(s) -TEM_{mn}. The subscripts m and n specify the integral number of transverse nodal lines across the emerging beam. They are related to the number of nulls in the beam pattern in two directions.

The notation TEM₀₀, is representative of the lowest order mode which is the fundamental mode and which possesses a gaussian distribution with the an intensity which is maximum along the laser axis gradually diminishing in the lateral direction. The gaussian beam mode and other multimode beams are illustrated in fig. 2.6. The beam intensity distribution can be rather complex, with non uniform distributions which are likely to affect the laser processing operation.

Unstable resonators are capable of producing a variety of transverse modes, just as stable resonators do. However, lasers fitted with unstable resonators nearly always operate in their lowest order transverse mode. This mode can result in a divergence angle and focusing capability approximately equal to the gaussian mode [Luxon et al., 1985].

The transverse mode of a laser beam is extremely important in materials processing. The order of the mode relates to beam size, divergence angle, focused spot size and depth of focus [Luxon, 1986]. The beam TEM and the aberrations and divergence introduced by the optics determine the laser beam quality² [Welding Handbook, 1991].

At laser output powers in the multikilowatt range, the ability to generate a high quality output beam can be limited by several factors. Non uniformities in the lasing media and thermally induced changes of diffraction in materials used as output couplers and windows can significantly affect the output beam quality.

The most significant unstable resonator parameter affecting beam quality, is its magnification M, which is defined as the ratio of the near field annular output beam's outer diameter, (OD), to inner diameter, (ID) (fig.2.4b). Focusability increases with increased magnification [Banas, 1986].

2.2.2 Beam Transmission Systems

The purpose of the beam transmission system is to transfer the high power beam from the laser generator to the workpiece in a manner which is appropriate for the application. The efficiency and success of an application depends on a large extent on the efficiency of the transmission [Crafer et al., 1993].

In a stable resonator, the beam is extracted through a partially reflecting transparent plane window. In the case of solid state lasers the material of the window is glass, whereas for carbon dioxide lasers a yellow transparent material called zinc selenide is used. The thermal lensing that can result from the heating of this material leads to a degradation of the beam and in extreme cases to mechanical failure.

² Laser beam quality is a measure of focusability.

In an unstable resonator, which is fitted to high power CO₂ lasers (beam power > 5 kW) the transmission of the beam from the generator environment to the working environment is achieved through some sort of window. Some multikilowatt lasers employ an aerodynamic window³ instead of transmissive components to avoid "thermal focusing" phenomena and therefore preserve beam quality. The aerodynamic window involves a design in which the beam is brought to a preliminary focus through a series of differentially apertures and subsequently reformed, using off-axis optics [Crafer et al., 1993; Megaw et al., 1986].

Having extracted the beam from the laser, it must be delivered to the workpiece. Low power solid state laser systems usually employ transmissive optics (lenses) and optical fibres to deliver the beam to the workpiece, while the higher power gas lasers generally use reflective optics (mirrors) for the same purpose. The fibre optic delivery of multi-kilowatts CO₂ power is already at laboratorial level [Harrington, 1993].

Once in the vicinity of the workpiece, lenses are commonly used to bring the beam to a focus. In the high power CO₂ lasers mirrors are usually employed. These mirrors are usually made of metal and are water cooled to withstand high incident powers. Several different types of laser focusing heads for high power beam welding are shown in fig. 2.7 [Welding handbook, 1991].

2.2.3 The Carbon Dioxide Laser

The carbon dioxide (CO₂) laser was first reported in 1964 by Patel but only became commercially available in 1966. In this type of device laser emission occurs between 9 and 11 μm in the infrared, either at a single line or on the strongest lines in untuned cavities.

Although, the infrared region of the spectrum may not be ideal for applications in the processing of materials (due to the high reflectance of metals in this region) high efficiencies are generally achieved (up to 30%) [Silfvast, 1991; Smith, 1980]. The CO₂ laser is one of the most versatile types on the market and one of the most powerful, producing output powers ranging from a few milliwatts to many kilowatts in a continuous or pulsed mode (energy > 10.000 J or several kW peak power) [Kestenbaum, 1972].

The CO₂ laser versatility results from the possibility of having several distinct designs. While they share the same active medium and its primary excitation is always electrical, the latter may involve either microwave, RF [Schock et al., 1986; Windgasse, 1986], AC or DC, high frequency [Wester et al., 1985], ultra high frequency [Schmitt et al., 1985]. These present correspondingly important differences in the internal structure (e.g. optical resonator, optical extraction geometries, etc.) and in functional characteristics. In practice, there are some distinct configurations that meet most user needs, namely [Hecht, 1992]: waveguide lasers, sealed tube lasers, flowing gas lasers of various power levels, and pulsed transversely excited atmospheric (TEA) lasers.

³ Aerodynamic windows are used to transmit the beam from the reduced pressure environment in the laser cavity to atmospheric pressure.

The active medium in a CO₂ laser is typically a mixture of carbon dioxide, nitrogen (N₂) and an inert gas, generally helium (He), where each gas plays a different role in the lasing process.

The carbon dioxide is the light emitter. Since CO₂ is a triatomic linear molecule, it has three possible vibrational modes in the lowest electronic state, ν_1 , ν_2 , ν_3 as shown in fig. 2.8. ν_1 is a symmetric stretching vibration (expansion and contraction), ν_2 is a doubly degenerate bending vibration and ν_3 is an asymmetrical stretching vibration. The ground vibrational state (000) and the relevant energy levels in the CO₂ laser are shown in fig. 2.9a. When a gas discharge is established, the CO₂ molecules are first excited into higher electronic levels so they vibrate in an asymmetrical stretching mode. The molecules then lose part of the excitation energy by dropping to one or two other, lower energy vibrational states. These two decay paths are the two principal laser transitions leading to the most important lasing emissions: a shift to a symmetrical stretching mode accompanied by emission of a 10.6 μ m (10.4 μ m in, e.g., Duley [1983]) photon, or a shift to a bending mode accompanied by emission of a 9.6 μ m (9.4 μ m in, e.g., Duley [1983]) photon (fig. 2.9a). Although the nominal vibrational transitions are at 10.6 and 9.6 μ m, respectively, the occurrence of simultaneous rotational transitions create large families of laser lines. Frequencies and wavelengths of the corresponding emission lines have been tabulated by Duley [1976].

Carbon dioxide molecules can reach the upper laser level in a variety of ways. The nitrogen molecule is able to help in this process. The excited vibrational state of N₂ is metastable and its energy is very close to that of the ν_3 vibrational state of CO₂; thus, resonant energy transfer takes place and an enhanced excitation is obtained (fig. 2.9b). An alternative way is the CO₂ molecules directly absorbing energy by inelastic collision with low energy electrons inserted into the gas by a discharge or electron beam.

The role of helium in the laser mixture is, in part, to quench the population that builds up at the lower levels (100/020) of the CO₂ molecule after laser emission has occurred, thus maintaining the population inversion needed for laser operation. Helium atoms are translationally excited during such process and this heat must be removed from the laser gas for efficient operation. Being a good thermal conductor, helium helps to remove the waste heat from the medium and also promotes uniform discharge.

The optimum composition and pressure for the gas in a CO₂ laser depends on the mode of excitation. In general, the concentrations of N₂ and CO₂ are comparable but much lower than that of helium. Low pressures are needed for continuous operation, but pressures well above 1 atm are generally required to operate pulsed CO₂ lasers.

Different combinations of the several key parameters involved, including gas pressure, gas flow, type of laser cavity, and excitation method lead to different CO₂ laser devices operating either in continuous wave and pulsed modes. A general, concise overview of the main types of carbon dioxide lasers is given below.

2.2.3.1 Types of CO₂ lasers

■ *Sealed Tube Lasers*

The simplest form of a CO₂ laser is one in which the laser gas mixture is contained in a sealed tube (fig. 2.10a). It does not require input of gas during operation, as a consequence the heat generated in the gas mixture has to be removed by conduction through the walls of the laser tube. This conduction process limits the output power to around 50W per meter of tube length, to a maximum output of 100W. Outputs in the range of 25-100 W are generated using a laser design in which the discharge for excitation is provided by high voltage electrodes located near the ends of the tube. Sealed lasers with power levels up to 240 W continuous wave have been reported [Laakman, 1993].

A newer alternative design [Hecht, 1992] utilises a radio frequency (RF) discharge perpendicularly to the tube axis for excitation. The main advantages of this design include electronic modulation at up to 10 kHz, lower operating voltage, excitation of a larger gas volume in the tube, and potentially lower tube cost. Disadvantages of this design, is the more complex nature of the RF power supplies and their lower efficiency compared to the dc ones.

The laser tubes are usually long and narrow to keep the gas in contact with the walls of the tube and therefore the output beam from this type of laser has generally a low order stable transverse mode structure.

The main problem involved in the operation of a closed CO₂ laser is in providing a reaction path whereby the products of the dissociation of CO₂ can be regenerated to form CO₂. These dissociation products are mainly carbon monoxide (CO) and oxygen (O₂). Two solutions are generally employed to overcome the decomposition problem. Small amounts of hydrogen or water are added to the gas mixture, which by reacting with the decomposition products will regenerate the CO₂. Alternatively, a 300°C nickel cathode can act as a catalyst to stimulate the recombination reaction. These solutions allow the sealed CO₂ lasers to operate for several thousand hours before their output becomes degraded to require refurbishment or replacement.

■ *Waveguide Lasers*

The configuration of a waveguide laser derives from that of the sealed tube, where the inner diameter of the CO₂ laser tube is reduced to a few millimetres and the tube is made in the form of a dielectric waveguide (fig. 2.10b). The waveguide design limits diffraction losses. The tube is normally sealed, with a gas reservoir separated from the waveguide itself, but it can also allow for flowing gas. The gas can be excited by an electrical discharge or by an intense RF field. The waveguide may be made from metal, dielectric or a combination of both [Hecht, 1992].

The waveguide laser provides a good quality beam, can be operated cw or pulsed and can readily be tuned to many discrete CO₂ lines. In addition, it is a compact size device (comparable to the HeNe laser) which is able to produce watts instead of milliwatts, although it usually needs water or forced air cooling.

■ *Longitudinal (or Axial) Slow Flow Lasers*

The slow axial flow or conventional cw CO₂ laser is basically constituted by a water cooled tube with mirrors on both ends (fig.2.10c) through which the laser mixture flows and it is excited electrically. In slow flow devices heat is removed by conduction through the walls of the laser tube, with which gas molecules collide. Therefore, the cw output of slow axial flow CO₂ lasers increases linearly with tube length with the most powerful lasers generating 80 Wm⁻¹ [Hecht,1992].

Instead of using the gas or electrodes to remove the decomposition products, the gas mixture flows slowly along the tube axis, generally in the same direction as the discharge and is exhausted, thus removing the decomposition products before a significant concentration builds up.

As in the case of the sealed CO₂ lasers, the need to keep the gas in close contact with the tube walls results in a laser with long narrow tubes, and hence the output beam has a low order stable transverse mode structure. A recent advance is the use of many parallel thin tubes in a flat or annular array (fig. 2.11) [Hecht,1992]. The surfaces are cooled to keep the laser gas temperature low. The maximum power per channel is 50 Wm⁻¹, so the laser output is obtained by multiplying that value by the number of parallel channels, although with a degradation in the beam quality.

■ *Fast Axial Flow Lasers*

Increasing gas flow to the point where convective cooling occurs, also significantly increases the efficiency of the axial flow lasers, and the overall size of the laser may be reduced while maintaining a high output power : 800 Wm⁻¹ of tube length. The output beam has a low order stable transverse mode structure.

The excitation is usually with a longitudinal discharge as in slow axial flow lasers but some fast axial flow lasers are powered with RF discharges.

Laser tubes are typically 0.5 m long with gas flows a few hundred meters per second and power outputs of up 1 kWm⁻¹ [Crafer et al.,1981]. Higher powers need larger tubes and higher pressures which cause problems of discharge instabilities.

A typical design might include four to eight parallel flow tubes, optically in series for each kilowatt of output [Hecht, 1992]. Its lower resonator dimensions associated to lower space requirements made this laser the most common for operating powers in the range 500 W to 5 kW.

■ *Transverse Flow Lasers*

An alternative design has the gas flow transverse to the laser resonator (fig. 2.10d). Therefore, heat is removed by flowing the gas mixture transverse to the discharge direction. This gas flow and excitation mode are now used in high power (5-20 kW) commercially cw CO₂ lasers.

The gas flows a shorter distance across a much wider region than in the fast axial flow laser, easing pumping requirements. The gas is generally recycled by passing it through a system which regenerates CO₂ and adds some new air to the mixture. The cavity length is comparatively shorter and this can lead to beam quality problems, i.e., both beam mode structure and beam symmetry are considerably poorer than in fast and slow axial flow lasers.

The output beam consists of either a combination of several low order stable transverse modes or a combination of low order unstable transverse modes, characterized by a power distribution surrounding a large hollow centre. Quoted efficiencies are generally lower than for the axial flow lasers, 5-10% compared with 10-15% , but the maximum powers available are higher.

Some features of the continuous wave CO₂ lasers are summarized in table 2.1 [Duley,1991]

Table 2.1 - Output characteristics of cw CO₂ lasers

CONFIGURATION	OUTPUT POWER(W)	BEAM DIAMET.(mm)	BEAM DIVERGENCE(mrad)	FEATURES
WAVEGUIDE	≤25	1.5-3	10	SEALED TUBE
LONGITUDINAL EXCITATION	≤75	5	3	SEALED TUBE
SLOW AXIAL FLOW - LONGIT. EXCITATION	100-1000	5-30	1.5-3	PULSED, LINE TUNABLE
FAST AXIAL FLOW - LONGIT. EXCITATION	500-3000	10-20	1.5-3	COMPACT SIZE
TRANSVERSE FLOW - TRANSV. DISCHARGE	5000-15000	>15	>3	HIGH POWER

In general, except for waveguide lasers, beam diameter and divergence in single mode operation are 20 to 50 percent of the values for multimode output [Hecht, 1992]

■ *Gas Dynamic Lasers (GDL)*

The GDL is a transverse flow laser. In the gas dynamic laser CO₂, N₂, and various additives are heated and compressed in thermal equilibrium to temperatures exceeding 1000K, so that the upper vibrational level of the CO₂ and N₂ become thermally populated [Spalding, 1978]. The gases are then rapidly cooled, by expansion through a nozzle into a low pressure chamber (fig. 2.12), so that most of the CO₂ levels become depopulated by collisions. The N₂ molecule is, however, relatively long lived and transfers its energy to the CO₂ (001) level by collision, thus providing the population inversion. A laser beam is extracted from the gas by placing a pair of mirrors on opposite sides of the expansion chamber. This type of laser is capable of power levels as high as 100 kW and even more. It is of interest for military applications and it has never become commercially available.

■ *Transverse Excitation Atmospheric Pressure Laser (TEA)*

Discharge instabilities prevent cw CO₂ laser operation at pressures greater than about 100 torr. Many cw CO₂ lasers can also be pulsed electrically or in Q-switching mode to obtain output pulses with peak powers approximately 10² larger than the cw power. Pulse duration can extend from less than 1 microsecond to milliseconds with intracavity modulation or mode locking pulse technique [Duley, 1983]. Pulse lengths as short as few nanoseconds are obtained in a high pressure CO₂ laser.

The transverse excited atmospheric pressure (TEA) laser exploits a transverse excitation geometry to induce a uniform self sustained avalanche discharge by electrical pulsing. The result is the emission of an intense gain switched pulse lasting about 100-200 ns. This is followed by emission of a broader (1-10 μ s) pulse of comparable energy. The TEA can be operated at pulse repetition frequency of up to 300-400 Hz with pulse energies of few hundred millijoules. At lower repetition rates, output pulse energies can be as high as 2000-3000 Joules [Duley, 1989].

2.3 CO₂ LASER BEAM WELDING

2.3.1 Process Fundamentals

The Laser Beam Welding (LBW) is defined as a joining process where the coalescence of materials is produced by the heat generated from the application of a concentrated coherent light beam impinging upon the surfaces to be joined [ASM, 1983].

For welding, the laser beam must be focused to a small spot size to produce a high power density. This controlled power density melts the material and in most cases vaporizes part of it. When solidification occurs, a fusion zone or weld joint results.

In the CO₂ laser beam welding, a CO₂ laser emitting in the infrared with a wavelength of 10.6 μ m is used. This is the most efficient laser currently available for material processing applications, and can be used in both the high power continuous wave and pulsed operating modes. A wide range of powers are available with the CO₂ lasers and these determine the type of weld produced, i.e., conduction limited or deep penetration (fig. 2.13).

In conduction limited laser beam welding, the laser energy is absorbed by the material at its surface, and transferred to the underlying material by thermal conduction, leading to its heating and melting. Lasers with low average power (≤ 1 kW) are normally used.

Deep penetration laser beam welding requires higher powered CO₂ lasers and is accomplished by a keyhole energy transfer mechanism. The laser beam energy is so intense that it cannot be transferred by normal conduction, convection or radiation processes. Thus, it is delivered to the material through the depth of the weld, and not just to its surface.

When the material at the interaction point melts and vaporizes, the vapour recoil pressure creates a deep cavity or keyhole. This keyhole is a vapour column surrounded by a thin cylinder of molten metal.

The potential advantages of the laser beam welding can be enumerated [e.g, Mazumder, 1982; ASM, 1983; Crafer et al, 1993; Dawes, 1983]:

- LBW is a non contact process
- focused laser light can produce high energy density,
- low heat inputs to the material, thus minimizing distortion,
- the beam produces localised heating, melting and vaporisation,
- formation of narrow deep welds,
- high welding speeds can be achieved,
- high integrity joints can be produced,
- flexibility of beam transmission,
- filler material is not required for most joint preparations.

2.3.2 CO₂ Laser Welding Parameters

The major process parameters include the following (fig. 2.14) [Steen, 1990]:

- | | |
|----------------------------|---|
| • Beam properties | power, pulsed or continuous
spot size and mode
polarization |
| • Transport properties | speed
focal position
joint geometries
gap tolerance |
| • Shielding gas properties | composition
shielding design
pressure/velocity |
| • Material properties | composition
surface condition |

2.3.2.1 Beam and transport properties

The type of laser used for a particular application dictates variables such as the wavelength of the beam, and its intensity distribution. The penetration depth during laser welding is directly related to the power density of the laser beam and thus is a function of incident beam power and beam diameter. For a constant beam diameter, penetration depth increases with increasing beam power, in an almost linear fashion as reported by Banas [1986], Willgoss [1979], Locke et al. [1972], etc.. The continuous and pulsed modes of operation of a laser yield to different trends in the behaviour of the relation penetration depth-power (fig. 2.15).

In the pulsed mode of operation of a laser, besides the peak and average power or energy, other parameters must be considered as the pulse shape and length and the pulse repetition rate. An increase in the later parameter (considering all the other parameters constant) leads to a decrease in the penetration depth, provided that a lower average power is attained by pulse (fig. 2.16).

The laser intensity distribution depends on the transverse mode of the laser beam, which in turn is related to the beam size, divergence angle and focused spot size. The magnification, M , of an unstable resonator (pt.2.2.1) affects welding performance, namely the penetration depth (fig. 2.17) as a consequence of its influence in the beam quality (i.e., focusability) [Welding Handbook, 1991].

The angle of incidence of the laser beam at the material surface and the polarisation characteristics of the beam are parameters that influence the absorption of the laser radiation by the material. In deep penetration welding, it was thought that beam polarisation had no effect on welding, since the beam was absorbed inside the keyhole. However, Beyer et al. [1988] have verified in the welding of steels⁴, that the penetration depth was affected by the polarisation state of the beam, and that this effect became particularly important at high welding speeds (fig. 2.18).

The influence of the beam polarisation on the welding speed is also reported in the Welding Handbook [1991]. Highest welding speeds with the narrowest weld bead geometries result when the polarisation plane is coincident with the direction of welding. The output of a laser is frequently characterised as being either "randomly polarised". Welds made with such lasers generally do not exhibit any polarisation effects.

For a given beam mode, focal spot size and power, the penetration depth and weld width are inversely proportional to the welding speed (fig.2.18) [Ready, 1972].

The size of the focused spot controls the laser beam power density on the work. The spot size is dependent on, and increases with, the f/number ⁵ of the focusing system (fig 2.19). Low f/number optics are characterised by a relatively short depth of focus requiring precise control of beam to workpiece distance. Notwithstanding, the smaller the f/number the higher the maximum speed for a given joint [Dawes, 1983].

The effect of the variation of the focal position on the weld geometry is illustrated in fig.2.20a. The maximum penetration is obtained with the focal point positioned slightly below the surface. The optimum focus position was also found to be approximately 1 mm below the workpiece surface, according to Willgoss et al. [1979]. This produced welds with little or no "nail head" and nearly parallel sides. The theoretical variation in the optimal position of focus within the workpiece for maximum penetration, for a given power is illustrated in fig. 2.20b. It is general agreed that the optimum position of the focal point is below the surface but the exact distance is dependent on the thickness of the workpiece and the laser power used.

⁴No beam polarisation effect was detected in the welding of aluminium [Beyer et al., 1988]

⁵ The f - number is obtained by dividing the focal length of the focusing system by the laser beam diameter incident on the system.

Shorter focal lengths imply much reduced depth of focus (fig.2.21). Short focal lengths (< 150 mm with a 30 mm diameter beam) are therefore more suited to the welding of thin materials (< 4 mm) at high welding speeds. On the contrary, longer focal length systems with greater depth of focus are more efficient to weld thicker materials at comparatively lower speeds [Crafer et al., 1993].

Joint geometry also influences the thickness that can be welded. Due to the high welding speeds attained in laser welding there is little time for material flow and a relatively small amount of molten material, thus the process will almost always require close fitting joints. Fig. 2.22 illustrates several common types of joints that are used in laser welding [Gagliano et al., 1972].

Because laser welds are narrow, good fit-up is required for autogenous welds. When welding sheet material, both joint face gap and surface fit-up have to be considered. In butt joints the face gap must be small enough not to allow the beam to pass straight through the joint. Larger gaps are allowed in thicker material. The joint configuration also influences the gap that can be used. As rules of thumb the fit-up tolerances are stated in terms of material thickness t . The joint face gap should not be larger than $0.15 t$ and the misalignment should be less than $0.25 t$, as illustrated in fig. 2.23 [Ready, 1972].

2.3.2.2 Gas shielding properties

Gases are commonly used in welding to protect the welding zone against the contamination from the ambient atmosphere and therefore to prevent the occurrence of detrimental results in the welds produced. However, their function can be extended, in laser welding, to control the laser induced plasma, which is formed as a consequence of the interaction of a high power beam with a material. The presence of this plasma is harmful because it tends to absorb and attenuate the laser beam. In addition, the shielding gas protects optical components from fume and spatter and ensures effective transmission of the beam through the hot region of gas just above the workpiece.

Helium, argon, nitrogen and carbon dioxide have been reported as suitable shielding gases for laser welding. The effect of the shielding gas on weld penetration depends on its composition and flow rate as well as on the laser power density and welding speed, as illustrated in fig. 2.24 [Rosen, 1986; Terai et al., 1988]. This effect becomes more dominant at higher power densities and lower welding speeds. This range appears to define the domain where plasma effects become particularly important.

The influence of the shielding gas flow rate and composition on the weld penetration is illustrated in fig. 2.25. A significant variation on the weld penetration is seen to occur with helium and argon, although with nitrogen no variation is detected over a large range of gas flow rates.

The influence of the gas composition on the shielding function depends on its activity towards the material and on its ionisation potential [Seaman, 1977]. A gas with an higher ionisation potential will remain essentially neutral at the high temperatures involved in the laser welding, thus inhibiting ionisation and minimizing the plasma effect [Locke et al., 1972; Marchand et

al., 1991]. Helium, is the gas that provides better performances (figs 2.24-2.25) due to its high ionisation potential and high thermal conductivity [Marchand et al., 1991], in spite of its high cost compared to the other gases.

The activity of the gas relatively to the material to be welded was used by Jörgensen [1980], through the use of a mixture of argon with a small amount of oxygen in the welding of mild steel. An increase in the weld penetration has been observed. An increase in the welding speed can be obtained by the same means, due to the higher absorption of the laser energy by the material. This may be, however, unacceptable for some materials.

The mechanism of the shielding gas in plasma control relies on its ability to "blow away" the material vapour ejected from the beam/material interaction point, thus allowing the laser beam to reach the material, or dilute the plasma through its diffusion on it [Ducharme et al., 1993b]. Helium shows the best performance since helium atoms are more mobile than the other gas shielding atoms and so they are able to more rapidly diffuse into a partially ionised plasma.

Plasma effects and control techniques based on the use of gas jets directed to the top of the weld to blow away the plasma will be discussed later in this chapter.

2.3.2.3 Material properties

The efficiency of the laser welding depends primarily on how much energy is absorbed by the material. The coupling of the laser beam into the material depends, to a large extent, on the material surface itself. The surface condition, in terms of topography, oxidation and cleanliness has a fundamental influence on the interaction of a laser beam with a material, since they will modify the reflectivity of the surface to the impinging laser beam.

The optical and thermal properties of materials are therefore relevant from the laser processing point of view. Whereas the optical properties determine the way the material's surface responds to the interaction with a laser beam, thus depending strongly on its condition, the thermal properties determine how the absorbed energy will be used in the rise of material temperature and attainment of the required phase changes.

Fig. 2.26a schematically illustrates the absorption rate of different types of materials as a function of the wavelength, whereas fig. 2.26b shows in more detail the reflectance variation of a group of metals. The data are for normally incident light on specular surfaces at room temperature. It is seen that for metals the absorptivity is very low at the CO₂ laser wavelength. However, any departure of the metal's surface from the specular condition will increase its absorptivity. On the other hand, as the temperature of the surface increases, reflectivity often decreases with a corresponding increase in absorptivity [Gagliano et al., 1972].

The effects of different surface conditions on the metal absorptivity and on the efficiency of its processing will be extensively covered in next chapter which deals with the interaction of laser beams with metals.

The composition of the material is another relevant parameter, since it determines its physical, thermal and chemical properties.

2.3.3 Plasma Effects

A consequence of the high power densities associated with the laser keyhole welding is the formation of a beam absorbing plasma at the beam/material interaction point. This plasma results from the ionization of the vaporized workpiece material as a consequence of its interaction with the laser radiation.

The role of the laser induced plasma during high power density laser beam welding is a quite controversial subject, due to the different effects that plasma could have on the welding performance. This plasma has been described both as an energy beam absorber [Banas, 1986; Rockstroh et al., 1987] responsible for an attenuation of the beam power reaching the material and as an magnifier of the coupling of the beam power to the material due to the reradiation of the laser energy that it has absorbed [Banas, 1986; Dixon et al., 1985; Lewis et al., 1985].

The contradictory effects of the laser induced plasma on welding performance are depicted in fig. 2.27. Furthermore, in addition to absorption and attenuation, the plasma can degrade welding efficiency by distorting beam optical characteristics and reducing focusability [Fowler et al., 1975]. A detailed analysis on the mechanisms of plasma formation are given in chapter III.

The presence of plasma and of its interference in the coupling of the laser radiation into a material can be detected by the "wine glass" shape profiles of the weld beads. This plasma is usually eliminated or at least reduced by the utilization of a suitable plasma suppression means as discussed in the following.

2.3.3.1 Plasma Control Techniques

The problem of the plasma interaction with a laser beam was first reported in 1972 [Locke et al., 1972], when attempting to weld in air. To minimise the beam attenuation caused the presence of plasma, this must be removed from the beam path or its formation should be prevented. A number of different techniques have been investigated to control the plasma formation and, hence, to improve the laser's penetration capability.

■ *Plasma control using a gas jet*

One of the first techniques used to control the plasma, was via an argon jet introduced above the weld and directed to the interaction point [Locke et al., 1972]. Deep penetration welds were then achieved although the welds were not uniform with less penetration in some locations. In addition, the weld pool was blown away if the molten material was disturbed by the gas stream.

An alternative method was to direct the argon jet parallel to the surface of the workpiece and offset a little above the surface [Locke et al., 1972]. Uniform welds were then obtained although the penetration was slightly reduced, relatively to the above setting.

Soon, it was realized that helium could be more effective in plasma control than argon. Helium, having a higher ionization potential and a lower density, provides a better plasma control, due to its smaller tendency to thermal ionization and plasma formation, and to its ability to quickly disperse upward the metal vapour generated. Increased depth penetrations result [Shinada et al., 1981]. It has been shown [Rein et al., 1972; Seaman, 1977] that adding hydrogen, sulphur hexafluoride or carbon dioxide to the helium improves the beam transmission even more.

Another technique, developed in the Culham Laboratories and reported by Megaw et al. [1981], is based on the disruption of the plasma formed above the keyhole, by a high velocity helium jet. This technique uses a special device in which the jet and shield gas are incorporated in the same system. The plasma control device was later improved, resulting in the comprehensive system shown in fig. 2.28. A similar system was later reported by The Welding Institute [Watson et al., 1983].

In the above systems the plasma control gas jet is directed by a nozzle, set at a position some millimetres above the workpiece surface, towards the laser beam/material intersection point, and it has been found that the best angle of the nozzle relative to the beam is generally in the range of 25°-50°, dependent on the material's thickness.

Recent improvements in The Welding Institute system, show that a most effective control is achieved when the nozzle is positioned so that, the plasma control jet impingement point is 1mm ahead of the centreline of the beam at the workpiece surface [Norris, 1988].

Most efforts on the development of deep penetration techniques have emphasized the nozzle position and the pressure produced from the gas jet. The importance of the relative position of the nozzle suggests that the mechanism for plasma control is based on the two velocity components of the jet gas flow [Norris, 1988]: the horizontal component, which blows away the metallic vapour from the top of the keyhole and out of the beam path, and the vertical component which disrupts the plasma formed on the top of the keyhole. Moreover, the latter assists the recoil pressure of the metal vapour in holding the keyhole open and, thus, allows the beam to penetrate further into the workpiece.

Improvements in the welding performance, using a different control technique were reported by Minamida et al. [1982]. This work was based on the effective utilisation of plasma. In this method an assist gas jet flowing coaxially with the laser beam causes the plasma control gas, set at an angle to the laser beam and directed to the impingement point, to be blown towards the keyhole and, therefore, the plasma is pushed into the keyhole, to ensure that its thermal energy is effectively used.

The technique of removing or suppressing the laser plasma by means of a gas jet has its drawbacks. One of the problems concerns the frequent blocking of the nozzle with metal spatter from the weld pool. The reproducibility of welding depends on an accurate positioning of the nozzle in respect to the weld zone, which, besides, being a little difficult to achieve could be modified by the rapid wear of the nozzle's tip which changes the gas flow. Recent developments reported by Norris [1988] show that, when a multimode beam is used, an increased tolerance in the set up of the plasma control device results. Increased tolerances in

terms of gas nozzle diameters and flow rates were reported for helium by Dawes et al. [1989].

Another limitation of the process, often reported concerns the need for an accurate control of gas flow rates [Watson et al., 1983; Arata et al., 1983a-b]. This seems to be a limitation, only for low order mode beam lasers, since according to Norris' [1988] results, large tolerances exist for plasma control flow rates, in multimode beam lasers.

The limitations of the methods for plasma control by a gas jet could limit their applicability in production applications, but in spite of these potential limitations the method has gained general acceptance, being industrially used.

Some improvements could be achieved by monitoring the plasma control gas and also by research into new materials for the nozzles, more resistant to the actual laser welding conditions.

■ *Plasma control by mechanical or electrically pulsing the beam*

This method has been developed and patented by Banas [1979]. It relies on the knowledge that the generation of a plasma above the keyhole is not instantaneous but takes a certain time to form under keyhole welding conditions. Thus, if a pulsed beam is used and controlled in a way that the pulse repetition rate is faster than the thermal response time of the material (typically > 1 kHz) and the pulse duration shorter than the plasma generation time, there is a complete elimination of vapour breakdown, and therefore of plasma formation and the laser energy is able to efficiently penetrate the material.

Typical values for pulse frequencies lying in the range of 6-24 kHz have been reported in the literature, as being very effective in reducing the plasma formation [ASM, 1983].

Narrower and relatively straight sided welds are obtained with this technique, when compared with those obtained with a continuous laser output using a gas jet for plasma control. This is evidence of the effectiveness of the method for the complete elimination of the plasma. Nevertheless, the complete extinction of the plasma is not accompanied by an increase in the maximum penetration depth, though an increase in welding speed has been reported [ASM, 1983].

High frequency pulsing of the laser beam can be achieved both by simple mechanical chopping of the relatively low power beam from a laser oscillator, before it reaches the amplification stage in an oscillator/amplifier system [ASM, 1983], or by simple switching of the high voltage circuitry using series valves controlled via a suitable pulse generator [Norris, 1987].

Although, the beam pulsing technique has been recognized as very effective in reducing plasma formation during laser welding, it presents some limitations mainly related to the fitting of the required devices for pulsing the beam into lasers and with the sensitivity of the technique to changes in the joint type and material thickness. Thus, albeit the pulsing technique appears very attractive for use in production, with significant advantages over other plasma suppression techniques as the gas jet, no references to its use were found in the

literature available.

- *Plasma control by a combination of a gas jet and linear beam oscillation - "Laser Spike Seam welding" method*

This technique was developed and patented by Arata et al. [1985a].

For removing the plasma formed above the keyhole, this method employs an inert gas jet directed to the weld zone and the simultaneous linear oscillation of the beam along the joint in the welding direction (fig. 2.29). The gas jet removes the vapour metal formed above the keyhole avoiding its thermal ionization, and the beam oscillation led to a higher interaction time with the material with achievement of higher penetrations. The beam interacts with the material for sufficient time to form a keyhole, and then moves forward avoiding the plasma formed above the keyhole, which is then disrupted by the gas flow.

No reference was found in literature concerning the industrial applicability of this method.

- *In vacuum plasma control*

A solution for plasma suppression has been given by Arata et al. [1985b].

This technique uses a vacuum chamber similar to those used in EBW (Electron Beam Welding) and it was observed that at a pressure below 5 Torr the laser plasma is almost suppressed, allowing deep penetration, even at very slow welding speeds. The pressure dependence of penetration is illustrated in fig. 2.30 for laser and electron beam welding.

This method solves completely the problem of laser plasma suppression. However, its industrial application is restricted due to the need for a vacuum chamber. In this respect the process becomes similar to EBW, which often has lower equipment cost and better penetration capability.

The welding of magnetic materials is probably the only area where this technique can be used with advantage over the EB process.

2.4 CO₂ LASER WELDING OF HIGH REFLECTIVITY MATERIALS

The high welding speed and low heat input characteristics of the laser welding process make it very attractive for industrial applications and led to its general acceptance as an important manufacturing tool. Although, this process has been used quite successfully in industry for the carbon and stainless steels, it still remains a difficult process for the joining of high reflectivity and high thermal conductivity materials. In the later group, copper and aluminium are from the industrial point of view the most important materials.

To date, very limited data related to the welding of these materials by laser are available in the open literature. The properties of both materials raise some problems even when processed by the conventional welding processes. The high beam power densities provided by a laser

seem more appropriate to overcome the high thermal conductivity barrier presented by these materials. However, the high surface reflectivity to the CO₂ laser radiation (fig. 2.27) constitutes a significant hindrance to the welding initiation and most of the problems are found in this area.

Some successful results in welding aluminium by a CO₂ laser have been reported [Jones et al., 1992; Thorstensen, 1990; Ohmine et al., 1988]. Thorstensen [1990] presents a very comprehensive study on the identification of the main problems that accompany the welding of aluminium, which are: the difficulty in coupling the laser radiation to the workpiece to start the welding process, porosity and lack of alloying elements that could result from the welding operation.

For copper only few results exist [Dell'Erba et al., 1985; 1986a-b; Stares, 1987], which besides demonstrating that the laser welding of copper is a viable process, also show that much more work is required both on the fundamental and processing side to develop the laser process as a real alternative to be used in production.

The key problem in the processing of copper and aluminium by laser is the coupling of the laser radiation to the materials. Techniques to increase initial surface absorptivity have been reported in literature: surface roughening, coating with graphite or paints, pre-oxidation and machining of a V groove [Hunting et al., 1983], etc.. These techniques will be discussed in detail in chapter III. Another approach, which entailed the use of reactive gases has been also reported, both for aluminium [Ohmine et al., 1988] and copper [Ursu et al., 1984; Dell'Erba, 1985].

Once the coupling has been achieved and a keyhole has been formed, no additional problems were to be expected since the increase in temperature is expected to assist the welding process. However, process instabilities and breakdowns are currently reported along with lack of reliability and reproducibility.

CHAPTER II

FIGURES

- 2.1 - The laser operating region in the electromagnetic spectrum
 - 2.2 - The main components of a laser device [From: Silfvast, 1991]
 - 2.3 - Electronic emissions between energy levels [From: Silfvast, 1991]
 - 2.4a - Stable resonator configuration [From: Luxon and Parker, 1988]
 - 2.4b - Unstable resonator configuration commonly used in multikilowatt CO₂ lasers [From: Luxon and Parker, 1988]
 - 2.5 - Longitudinal and transverse modes of the optical cavity [From: Silfvast, 1991]
 - 2.6 - Beam cross sections for four different TEM modes [From: Welding Handbook, 1991]
 - 2.7 - Multikilowatt laser beam focusing heads [From: Welding Handbook, 1991]
 - 2.8 - Vibrational motions of CO₂ molecule [From: Kentenbaum, 1972]
 - 2.9 - Vibrational energy levels involved in CO₂ molecule laser action [From: Kentenbaum, 1972 (a); Spalding, 1980 (b)]
 - 2.10 - CO₂ lasers: a) sealed tube conventional laser with dc discharge excitation; longitudinal flowing gas laser: b) slow flow, c) fast flow; d) fast transverse flow; e) waveguide laser with RF excitation [From: Hecht, 1992]
 - 2.11 - Slow axial flow tubes arrangement in parallel, either in a flat surface or on a ring [From: Hecht, 1992]
 - 2.12 - Basic structure of a gas dynamic laser [From: Hecht, 1986]
 - 2.13 - The two types of laser welding [From: Sona, 1987]
 - 2.14 - Laser welding: the main process parameters [From: Steen, 1990]
 - 2.15 - Relation penetration depth/power for continuous and pulsed modes of operation [From: Coherent, 1978]
 - 2.16 - The variation of the beam energy with the pulse length for various repetition rates [From: Coherent, 1978]
 - 2.17 - Influence of M (unstable resonator) on weld performance (penetration depth) [From: Terai et al., 1988]
 - 2.18 - Welding speed vs penetration for a fast axial flow CO₂ laser [From: Steen, 1990]
-

CHAPTER II

- 2.19** - Variation of the spot size with the f number [From: Steen, 1990]
 - 2.20a** - Influence of the focal position on the penetration depth [From: Terai et al., 1988]
 - 2.20b** - Theoretical variation in the optimal position of the focus within the workpiece for maximum penetration, for a given power [From: Steen, 1990]
 - 2.21** - Focal length, spot size and power density relationships [From: Coherent, 1978]
 - 2.22** - Some joint designs for laser welding [From: Crafer et al., 1993]
 - 2.23** - Tolerances in the fit-up of joints for laser welding
 - 2.24** - Influence of shielding gases on penetration depths [From: Rosen, 1986]
 - 2.25** - Relation between gas flow rates and welding depth [From: Beyer et al., 1986]
 - 2.26a** - Room temperature absorption of different group of materials at various wavelengths [From: Dausinger, 1990]
 - 2.26b** - Room temperature reflectance of different metals [From: Gagliano et al., 1972]
 - 2.27** - Effects of the plasma plume in high power density laser beam welding [From: Chiang et al, 1991]
 - 2.28** - Plasma control and gas shielding arrangement [From: Hill et al., 1985]
 - 2.29** - Mechanisms of Laser Spike Seam welding [From: Arata et al., 1985]
 - 2.30** - Pressure dependence of penetration depth is compared for laser and electron beam welding [From: Arata, 1990]
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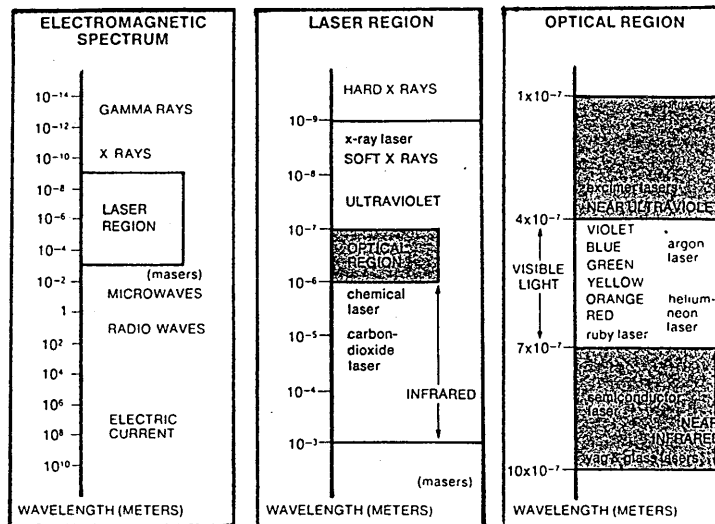


Fig. 2.1 - The laser operating region in the electromagnetic spectrum

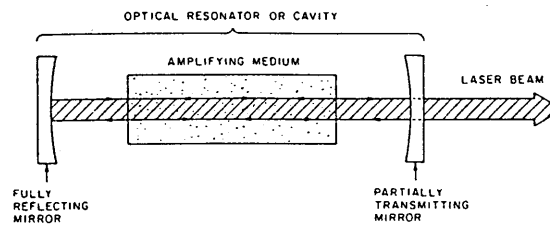


Fig. 2.2 - The main components of a laser device [From: Silfvast, 1991]

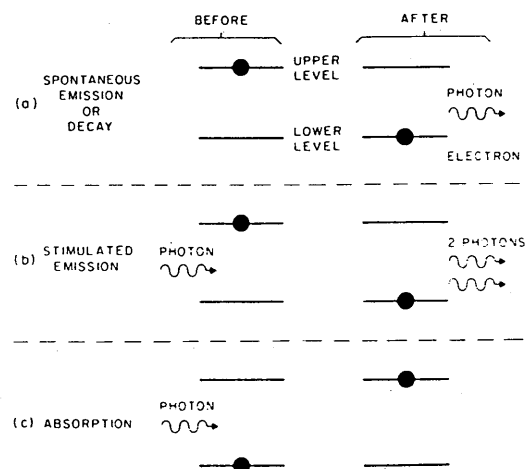


Fig. 2.3 - Electronic emissions between energy levels [From: Silfvast, 1991]

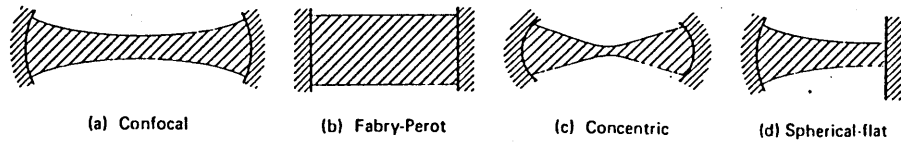


Fig. 2.4a - Stable resonator configuration [From: Luxon and Parker, 1988]

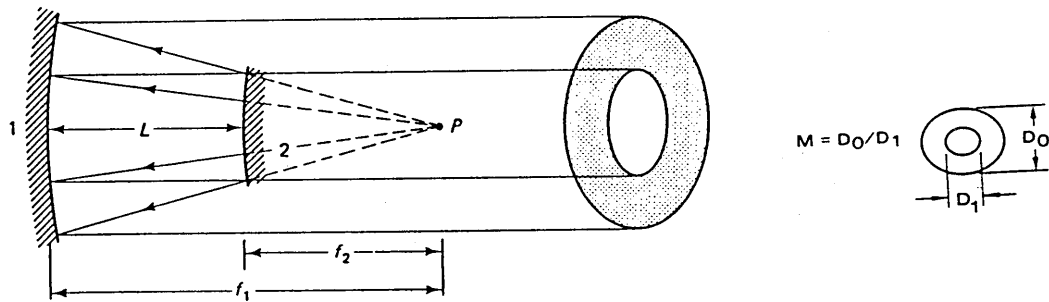


Fig. 2.4b - Unstable resonator configuration commonly used in multikilowatt CO₂ lasers [From: Luxon and Parker, 1988]

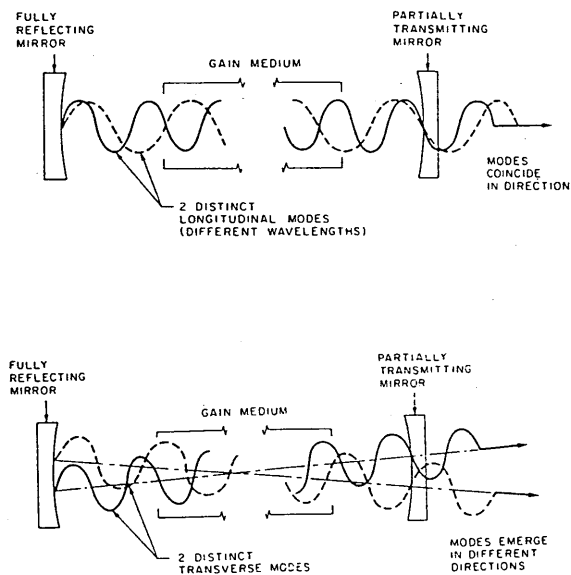


Fig. 2.5 - Longitudinal and transverse modes of the optical cavity [From: Silfvast, 1991]

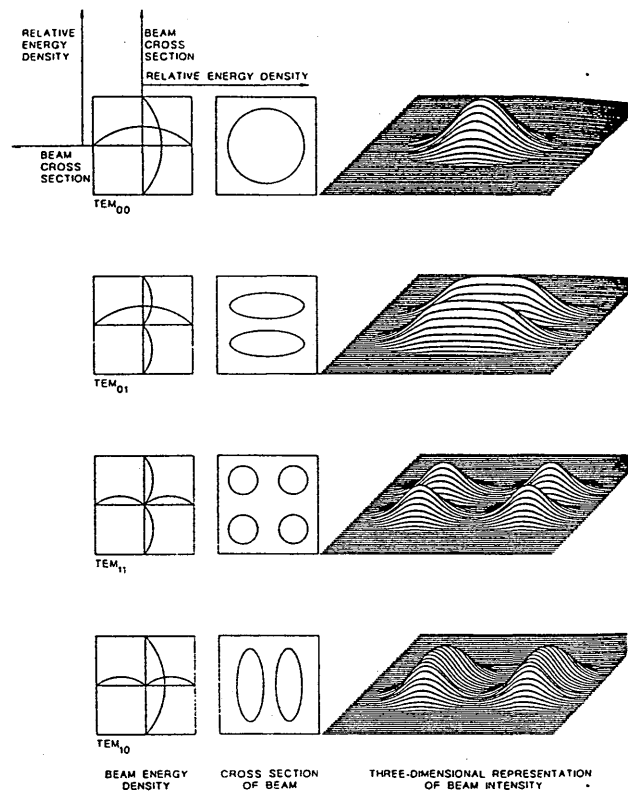


Fig. 2.6 - Beam cross sections for four different TEM modes [From: Welding Handbook, 1991]

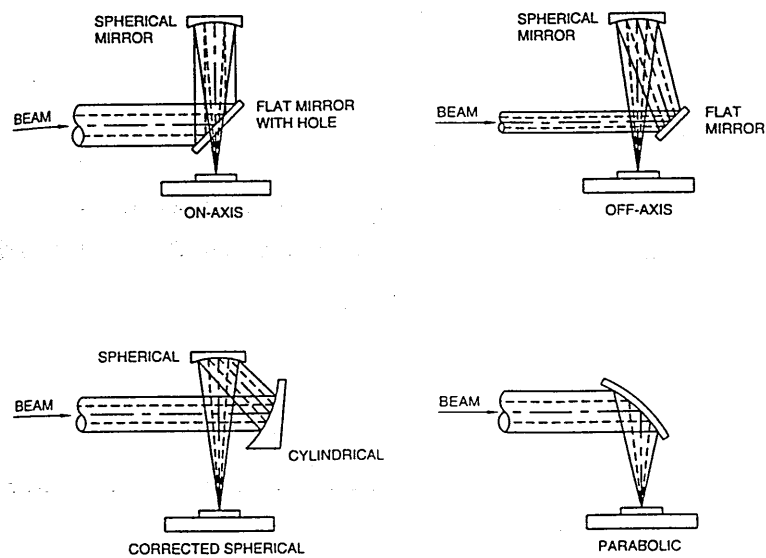


Fig. 2.7 - Multikilowatt laser beam focusing heads [From: Welding Handbook, 1991]

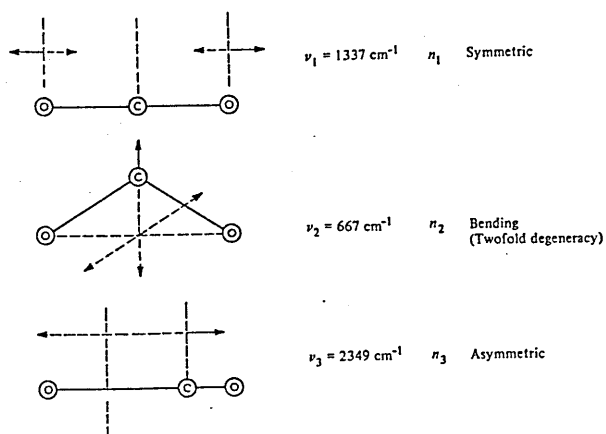


Fig. 2.8 - Vibrational motions of CO₂ molecule [From: Kantenbaum, 1972]

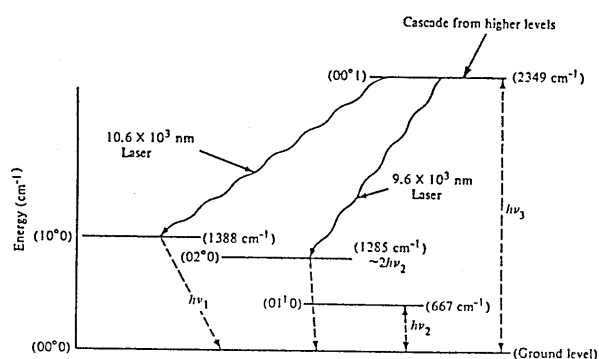
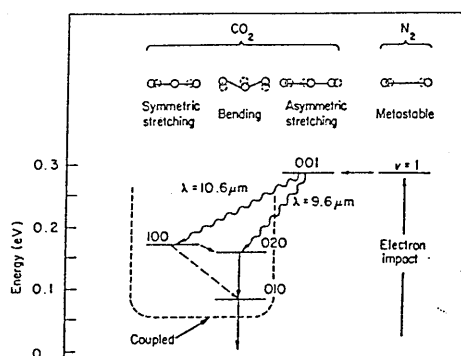


Fig. 2.9 - Vibrational energy levels involved in CO₂ molecule laser action [From: Kentenbaum, 1972 (a); Spalding, 1980 (b)]

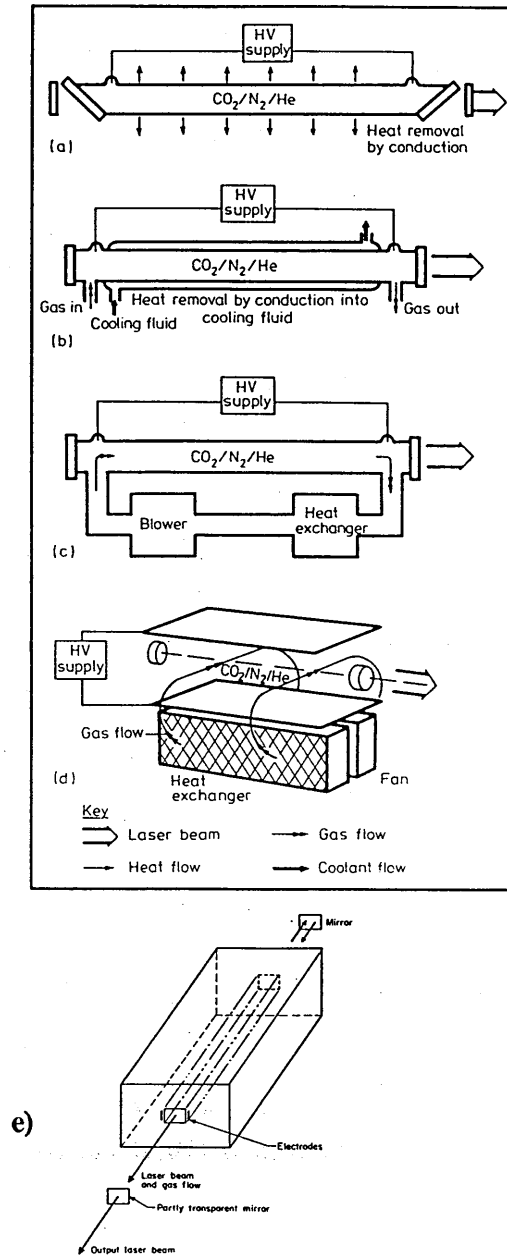


Fig. 2.10 - CO₂ lasers: a) sealed tube conventional laser with dc discharge excitation; longitudinal flowing gas laser: b) slow flow, c) fast flow; d) fast transverse flow; e) waveguide laser with RF excitation [From: Hdt, 1992]

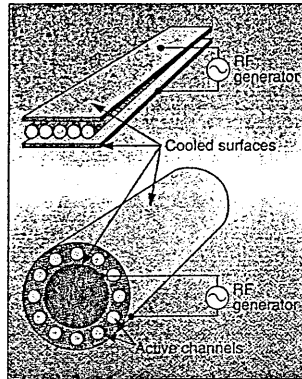


Fig. 2.11 - Slow axial flow tubes arrangement in parallel, either in a flat surface or on a ring [From: Hecht, 1992]

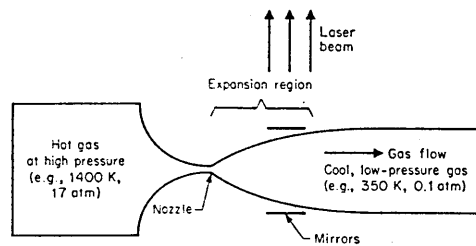


Fig. 2.12 - Basic structure of a gas dynamic laser [From: Hecht, 1986]

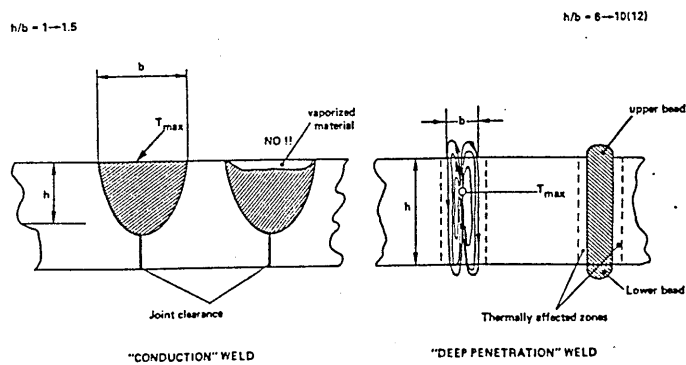


Fig. 2.13 - The two types of laser welding [From: Sona, 1987]

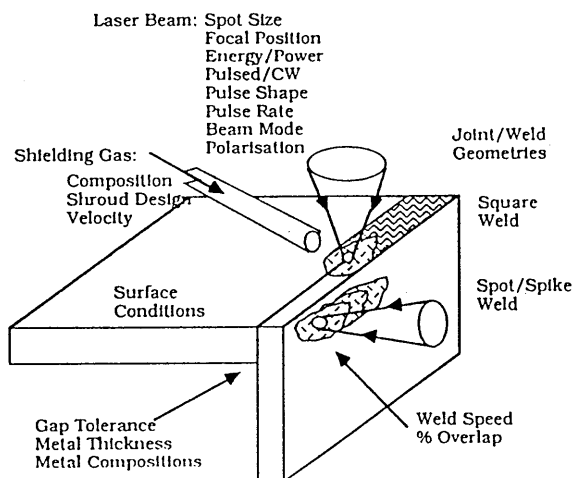


Fig. 2.14 - Laser welding: the main process parameters [From: Steen, 1990]

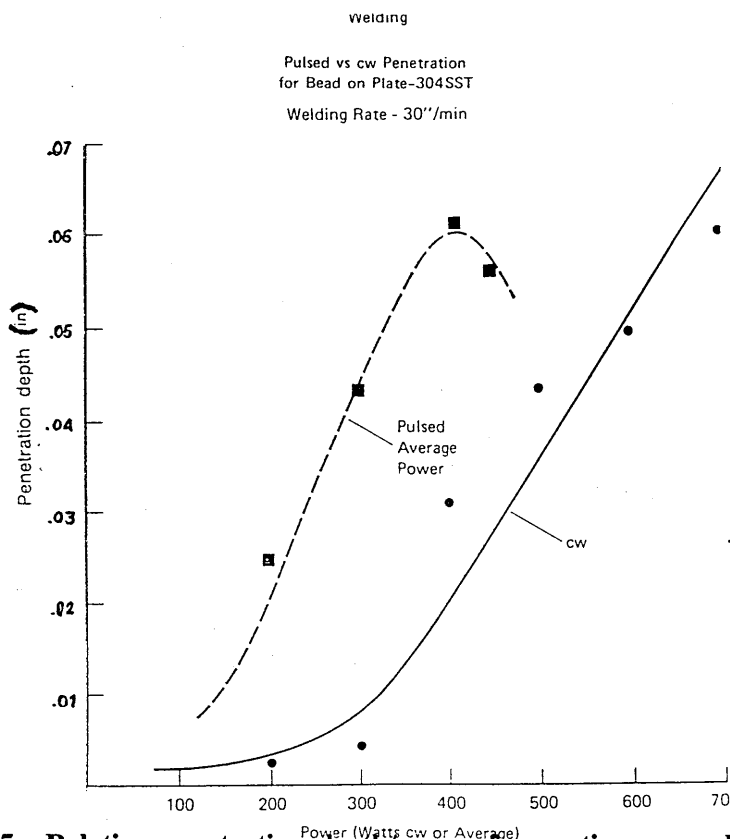


Fig. 2.15 - Relation penetration depth/power for continuous and pulsed modes of operation [From: Coherent, 1978]

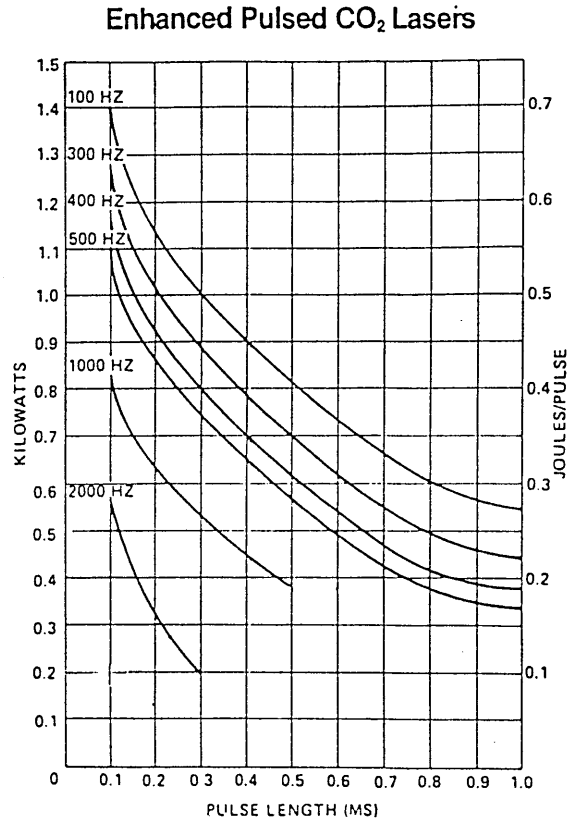


Fig. 2.16 - The variation of the beam energy with the pulse length for various repetition rates [From: Coherent, 1978]

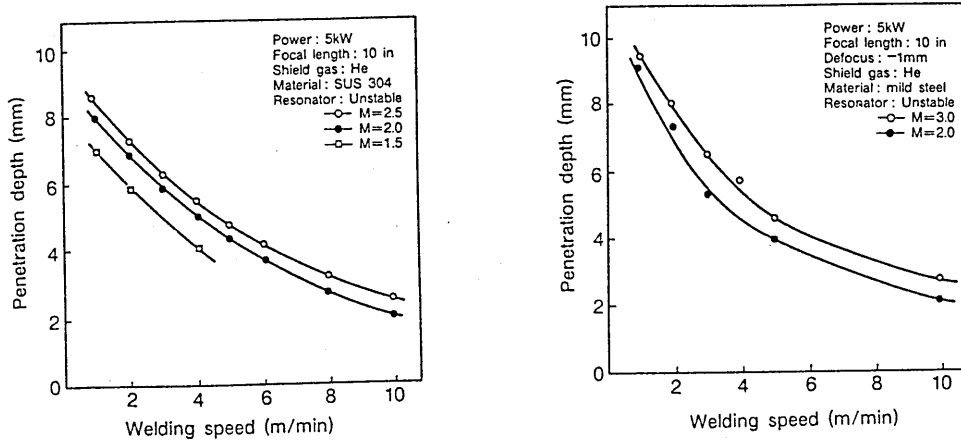


Fig. 2.17 - Influence of M (unstable resonator) on weld performance (penetration depth) [From: Terai et al., 1988]

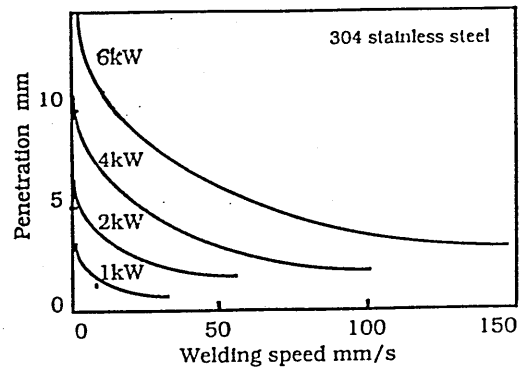


Fig. 2.18 - Welding speed vs penetration for a fast axial flow CO₂ laser [From: Steen, 1990]

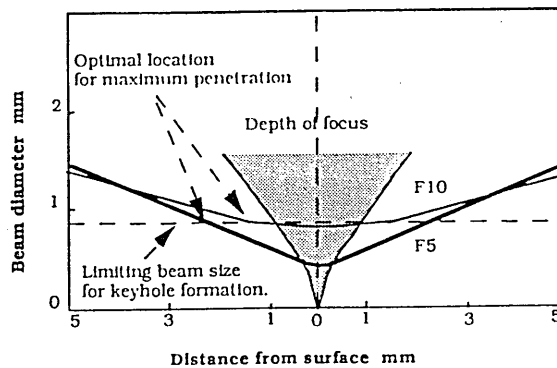


Fig. 2.19 - Variation of the spot size with the f number [From: Steen, 1990]

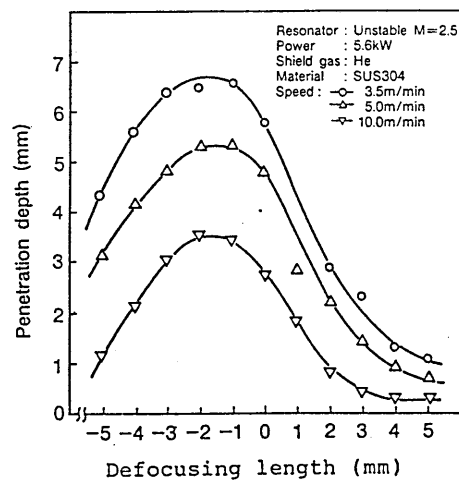


Fig. 2.20a - Influence of the focal position on the penetration depth [From: Terai et al., 1988]

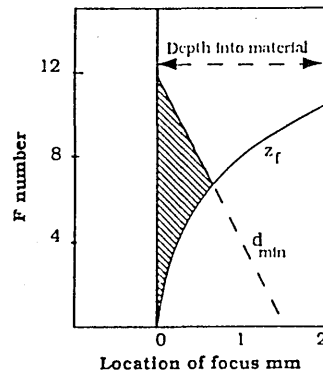


Fig. 2.20b - Theoretical variation in the optimal position of the focus within the workpiece for maximum penetration, for a given power [From: Steen, 1990]

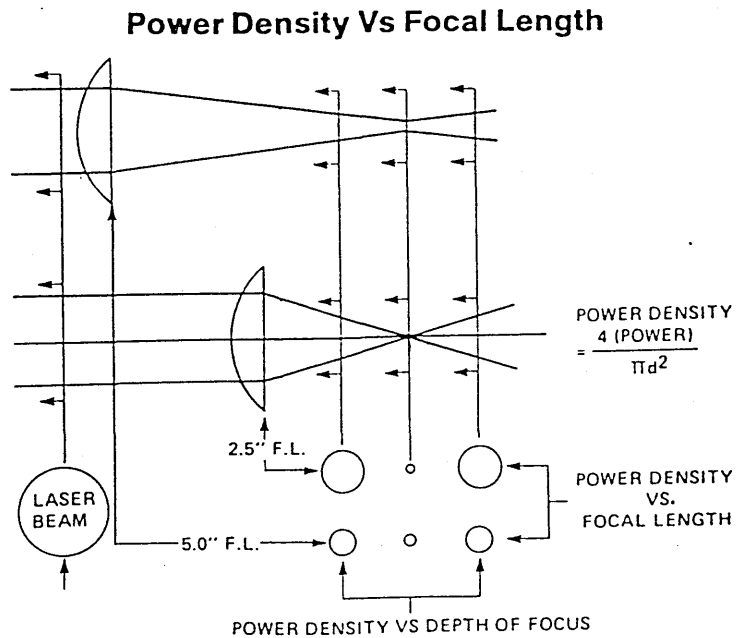


Fig. 2.21- Focal length, spot size and power density relationships [From: Coherent, 1978]

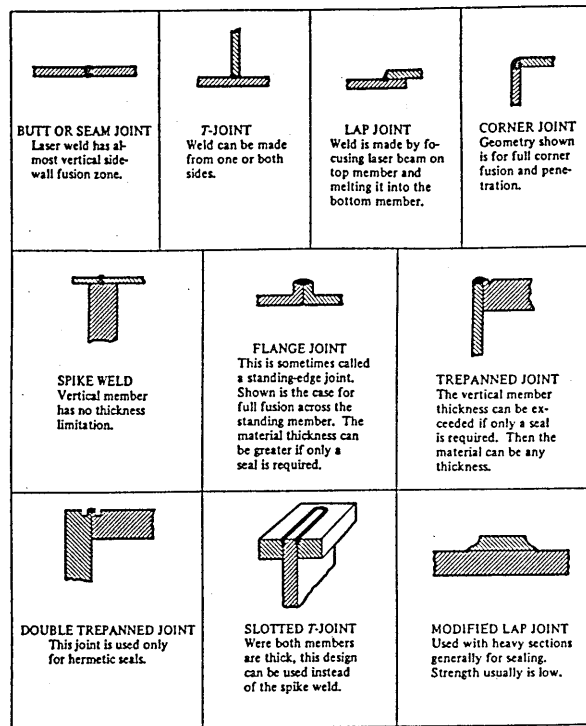


Fig. 2.22 - Some joint designs for laser welding [From: Crafer et al., 1993]

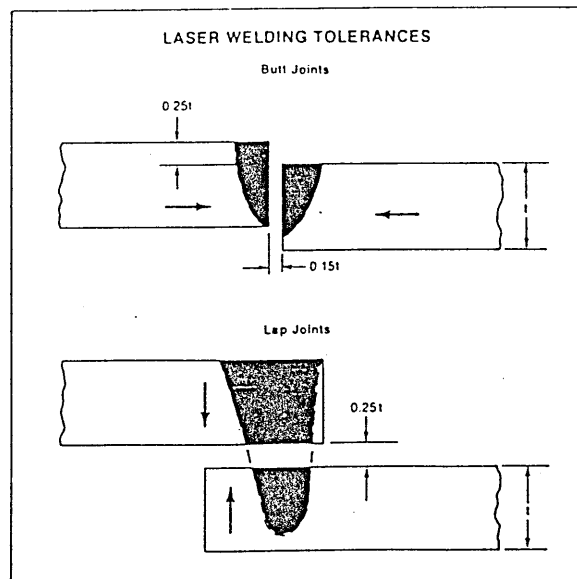


Fig. 2.23 - Tolerances in the fit-up of joints for laser welding

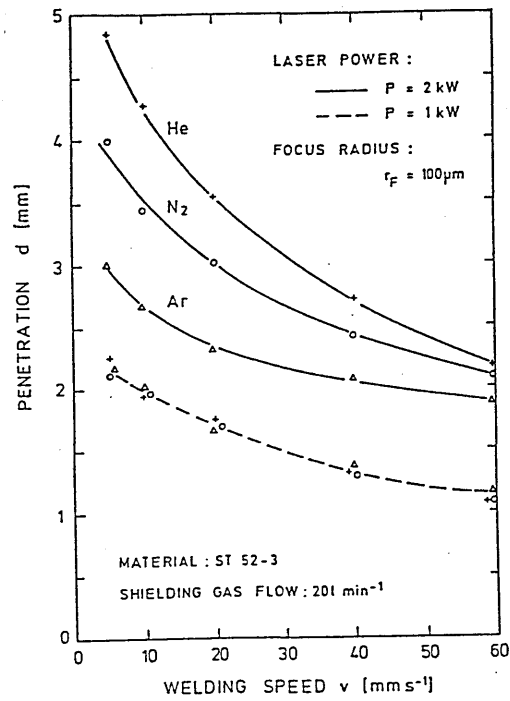


Fig. 2.24 - Influence of shielding gases on penetration depths [From: Rosen, 1986]

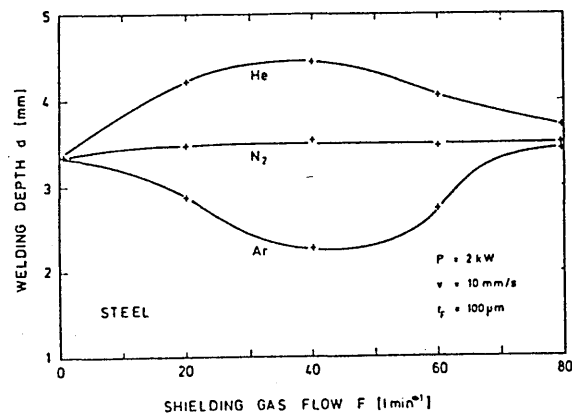


Fig. 2.25 - Relation between gas flow rates and welding depth [From: Beyer et al., 1986]

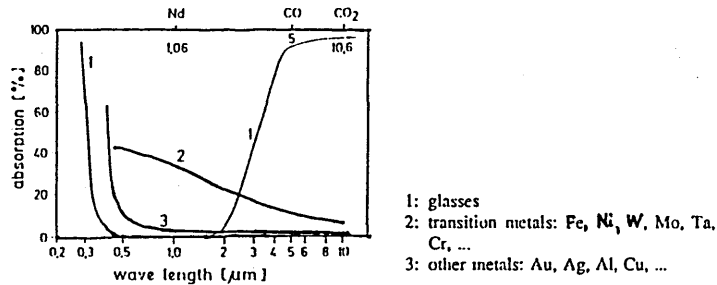


Fig. 2.26a - Room temperature absorption of different group of materials at various wavelengths [From: Dausinger, 1990]

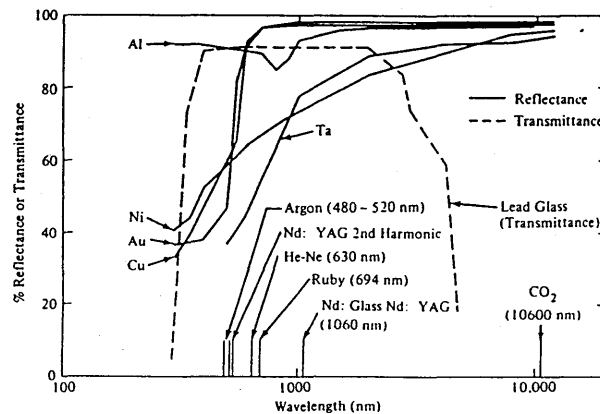


Fig. 2.26b - Room temperature reflectance of different metals [From: Gagliano et al., 1972]

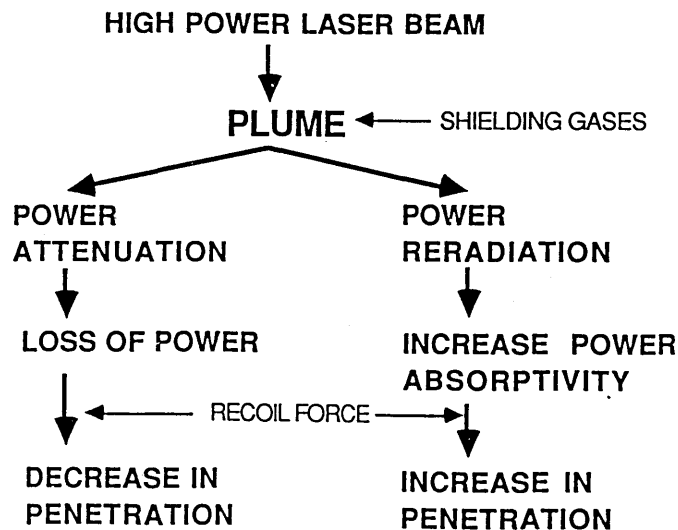


Fig. 2.27 - Effects of the plasma plume in high power density laser beam welding [From: Chiang et al, 1991]

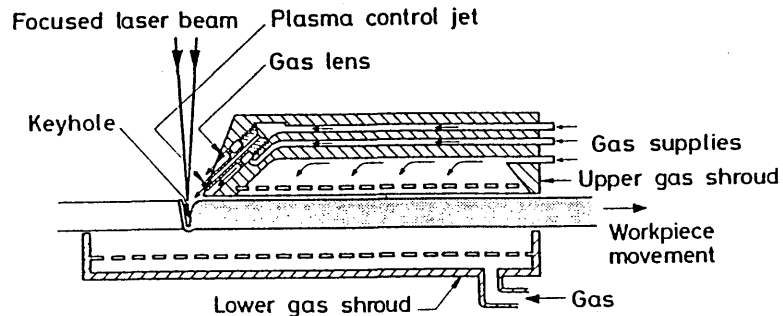


Fig. 2.28 - Plasma control and gas shielding arrangement [From: Hill et al., 1985]

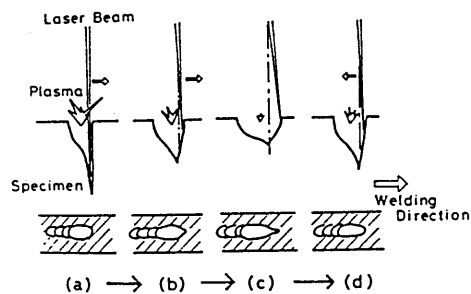


Fig. 2.29 - Mechanisms of Laser Spike Seam welding [From: Arata et al., 1985]

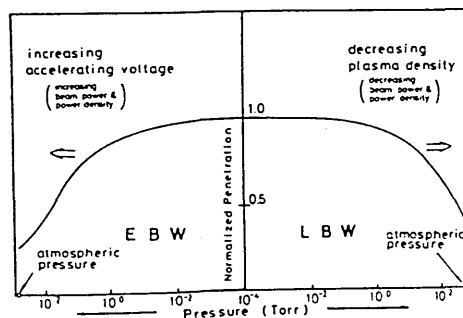


Fig. 2.30 - Pressure dependence of penetration depth is compared for laser and electron beam welding [From: Arata, 1990]

CHAPTER III

INTERACTION OF LASER RADIATION WITH METALS

- REVIEW -

3.1 INTRODUCTION

Research in the field of the interaction of laser beams with materials has been intensively pursued since lasers were first applied to the processing of materials.

This research has allowed a better understanding of the phenomena involved to be developed. Despite the progress in this field some mechanisms are still not understood, in particular when working with high intensity beams where non linear effects are expected to result from the interaction beam/material.

The interaction of laser radiation with materials can produce a number of effects, such as heating, melting and vaporisation of solid materials, emission of charged particles and plasmas, electrical discharges in gases, etc.. The occurrence of these different effects depends on the laser beam intensity as well as on the beam energy absorbed by the material in the interaction.

The beam energy absorption, is part of a more global process, the coupling of the laser energy into the material. This rather complex phenomena, that does not merely involve the physical process of absorption, but the whole process of conversion of a certain fraction of laser power into heat used to heat and melt (and vaporise) the material. The efficiency of the laser materials processing strongly depends on this coupling mechanisms. On the basis of

the predominant physical phenomena, two regimes may be considered, the low and high intensity, respectively.

In the low intensity range, i.e. below a critical intensity I_c , the efficiency of the laser processing operation depends on the fraction of the laser power absorbed by the material surface, which is in turn governed by the optical properties of the material and characteristics of laser radiation. To date, classical and quantum mechanical theories have been successful in explaining the phenomena observed at low intensities. An acceptable mechanism of intensity independent energy coupling is given by the temperature dependent optical properties of the material.

In the high intensity regime, i.e., above a critical intensity I_c , the effects and mechanisms involved in the interaction are not as well understood as they are in the low intensity regime. This is due to the more complex phenomena that occur during the interaction. Intensity dependent energy coupling has been observed for a large number of materials independent of the beam wavelength, which is governed by the evaporation of the material and generation of a laser induced plasma in combination with the dynamics of the molten and vaporised material within the interaction zone.

This chapter presents a comprehensive discussion of the main phenomena observed during the interaction of laser beams of different intensities with metals, and the main aspects for the present work will be outlined. The chapter is divided into three sections: the first presenting the optical properties of metals, the second the main features of coupling in the low intensity range and the third the phenomena related with the coupling in the high intensity range with particular emphasis for the plasma formation and influence on laser processing.

3.2 ABSORPTION OF LASER RADIATION

In the interaction of a laser beam with a metal, any lasting effects on the metal will depend on the laser radiation absorbed by the metal. Absorption of the laser radiation is the first step and often the most critical in laser processing.

The absorption of laser radiation by a metallic surface is a process that depends not only on the characteristics of the radiation itself (wavelength, angle of incidence, polarization, ...) but also on the material properties, primarily its optical properties.

The interaction between laser light (a form of electromagnetic energy) and materials takes place between the optical electric field and the most nearly free electrons in the medium according to the classical treatment of the optical behaviour of materials, or between photons and electrons in the presence of the lattice of nuclei in quantum mechanical terms.

The description of a laser beam as an electromagnetic wave is presented in appendix A - part I, following a classical approach, provided by the Maxwell's equations, i.e., electromagnetic radiation is described as a wave phenomena.

A macroscopic approach to the optical behaviour of a material is presented in appendix A - part II. This behaviour was derived from the classical formulation of Maxwell.

In the interaction of a laser beam with a material the macroscopic approach to describe the material response seems to be adequate, since the light wavelengths are much longer than the material interatomic distances. However, a microscopic approach appears to be necessary, since the dielectric function, which describes the response of a material to a weak electromagnetic radiation, depends on the light frequency in a way determined by the microscopic structure of the material.

The classical theory of absorption is due mainly to Lorentz and Drude. Whereas the Lorentz model is applicable to insulators, the Drude model is applicable to free electron metals.

3.2.1 Free Electron Theory of Metals (Drude model)

A rather simple picture of metals was given by Drude, who assumed that in a metal electrons are free to move, and the energy absorption proceeds through the intermediary electrons which further transmit, through collisions their energy to the crystalline lattice, thus experiencing damping in its motion [Prokhorov et al., 1990].

The optical response of a metal is dominated by the conduction electrons.

The complex permittivity due to the free electrons and lattice is then given by

$$\epsilon_r = 1 + \left(\frac{N_e e^2}{m \epsilon_0} \right) \frac{1}{-\omega^2 - i\Gamma\omega} \quad (1)$$

where, the term

$$\omega_p^2 = \frac{N_e e^2}{m \epsilon_0} \quad (2)$$

is defined as the plasma frequency of the free electrons. The order of magnitude of ω_p for metals at room temperature is approximately 10^6 rad s^{-1} , a small deviation from this value resulting from the volume dilation as an effect of heating [Prokhorov et al., 1990].

Introducing this term in eqn (1), equating the real and imaginary parts of the complex permittivity gives [Wooten, 1972; Allmen, 1983; Saifi, 1972]

$$Re \quad \epsilon_1 = 1 - \frac{\omega_p^2}{\omega^2 + \Gamma^2} = n^2 - \kappa^2 \quad (3)$$

and

$$\text{Im} \quad \epsilon_2 = \frac{\omega_p^2}{\omega^2 + \Gamma^2} \frac{\Gamma}{\omega} = 2 n \kappa \quad (4)$$

The optical parameters for several metals at room temperature have been calculated by several researchers [e.g., Prokhorov et al., 1990; Saifi, 1972; Ordal et al., 1983]

At $\omega = \omega_p$ (which is in the vacuum ultraviolet for most metals) both ϵ_1 and n_1 vanish. A plot of the dielectric functions and the optical constants is given in fig. 3.1. The plasma frequency is seen to separate into two regions of rather different optical properties: large R and α for $\omega < \omega_p$ and small R and α for $\omega > \omega_p$.

To relate the optical to the electrical properties of a metal, considering the conductivity given by [Myers, [1990]

$$\sigma = \frac{N_e e^2 \tau}{m(1 - i\omega\tau)} = \frac{\sigma_0}{1 - i\omega\tau} \quad (5)$$

where σ_0 is the dc conductivity given by

$$\sigma_0 = \frac{N_e e^2 \tau}{m} \quad (6)$$

Putting $\Gamma = 1/\tau$, where τ is the mean free time between collisions, eqns (3) and (4) can be rewritten

$$\epsilon_1 = 1 - \left(\frac{\sigma_0}{\epsilon_0} \right) \frac{\tau}{(1 + \omega^2 \tau^2)} \quad (7)$$

$$\epsilon_2 = \frac{\sigma_0}{\epsilon_0} \frac{1}{\omega(1 + \omega^2 \tau^2)} \quad (8)$$

The analysis of the optical behaviour of metals in the region where $\omega < \omega_p$, can be subdivided into several regions, as follows:

1) Low frequency, i.e., $\omega \ll 1/\tau$ (infrared region)

In these conditions, eqns (7) and (8) become

$$\epsilon_1 = 1 - \frac{\sigma_o \tau}{\epsilon_o} \quad (9)$$

and

$$\epsilon_2 = \frac{\sigma_o}{\epsilon_o \omega} \quad (10)$$

At such frequencies $\epsilon_2 \gg \epsilon_1$, and therefore

$$n^2 \approx k^2 = \frac{1}{2} \epsilon_2 = \frac{1}{2} \left(\frac{\sigma_o}{\epsilon_o \omega} \right) \quad (11)$$

Using eqns (22) and (28) (appendice A - part I) yields

$$\alpha \approx \sqrt{\frac{2\omega \sigma_o}{\epsilon_o c^2}} = \sqrt{\frac{2\pi \sigma_o}{\mu_o}} \quad (12)$$

and

$$R = 1 - 2 \sqrt{\frac{2\epsilon_o \omega}{\sigma_o}} \quad (13)$$

Eqn (13) was established experimentally by Hagen and Rubens and derived theoretically by Drude. This equation allows calculation of the IR reflectivity of a metal from its dc conductivity.

Experimental measurements of the variation of the emissivity $\xi_\lambda(T) = 1 - R_\lambda(T)$ of metals with the wavelength and temperature in the frequency range 10^{13} to 10^{14} Hz (i.e., in the infrared) have shown that a good agreement with eqn (13) is obtained for wavelengths down to $5 \mu\text{m}$ [Ditchburn, 1976].

According to Duley [1976] the emissivity $\xi_\lambda(T)$ for metals in the infrared ($\lambda > 2\mu\text{m}$) can be calculated from data on the temperature dependent resistivity of the metal. In the infrared $\xi \propto \lambda^{-1/2}$ (eqn 14) at constant temperature. Since $\xi \propto \rho^{1/2}$ (ρ is the electrical resistivity), while ρ increases with temperature, $\xi(\lambda)$ also increases with temperature. The emissivity can be calculated from the expression derived by Bramson [1968]

$$\xi_{\lambda}(T) = 0.365 \left[\rho_{20} \frac{(1+\gamma T)}{\lambda} \right]^{1/2} - 0.0667 \left[\rho_{20} \frac{(1+\gamma T)}{\lambda} \right] + 0.006 \left[\rho_{20} \frac{(1+\gamma T)}{\lambda} \right]^{3/2} \quad (14)$$

For the CO₂ laser wavelength, $\lambda = 10.6\mu\text{m}$, this expression becomes

$$\xi_{10.6\mu\text{m}}(T) = 11.2 [\rho_{20}(1+\gamma T)]^{1/2} - 62.9[\rho_{20}(1+\gamma T)] + 174[\rho_{20}(1+\gamma T)]^{3/2} \quad (15)$$

where, ρ_{20} is the resistivity at 20° C and γ is the coefficient of resistivity change with temperature T (°C).

Data on ρ_{20} and γ that may be used to estimate $\xi_{\lambda}(T)$ for most simple metals over a moderate range of temperature¹, was given by Bramson [1968].

- 2) Incident radiation whose frequency range is $1/\tau < \omega < \omega_p$ (near infrared and visible region for most metals).

From eqns (3) and (4), it can be seen that

$$\epsilon_1 = 1 - \frac{\omega_p^2}{\omega^2} \quad (16)$$

and

$$\epsilon_2 = \frac{\omega_p^2}{\omega^3 \tau} \quad (17)$$

Since in this frequency range $\kappa > n$, then assuming $-\epsilon_1 \approx \kappa^2$, it results

$$k \approx \frac{\omega_p}{\omega} \quad (18)$$

¹The maximum temperature should not exceed the melting temperature of the metal

$$n \approx \frac{\omega_p}{(2 \omega^2 \tau)} \approx 0 \quad (19)$$

Thus,

$$\alpha = 2 \frac{\omega_p}{c} \quad (20)$$

and

$$R = 1 - \frac{(2 \epsilon_o \omega_p)}{\sigma_o} \quad (21)$$

The electromagnetic wave decays exponentially but there is no absorption since $\omega \tau \gg 1$.

3.2.2 Optical Behaviour of Metals

Metals, due to their large density of free electrons have very small absorption lengths (skin depth, eqn (23) - appendix A - part II) over the whole optical spectrum. The reflectivity is high above a critical wavelength, which corresponds to the plasma frequency.

The threshold frequency for a typical metal can be calculated through eqn (2). Taking the electron density in a typical metal as $6 \cdot 10^{28}$ per m^3 , $\nu_p = 2.2 \cdot 10^{15}$ Hz.

Converting the above calculated frequency into wavelength, $\lambda_{cr} = c/\nu = 136nm$.

Thus, the threshold wavelength is well below the edge of the visible region (400nm). This explains why metals present lower reflectivities for radiation in the ultraviolet (below the critical wavelength) than in the visible and infrared (Table 3.1).

The optical properties predicted by fig. 3.1 are the metal's bulk properties. The metal's surface properties usually show lower reflectance than the bulk due to contamination (adsorbates, oxide layers, etc.) or macroscopic defects [Allmen, 1987].

The treatment presented above for the response of metals to the interaction with a laser beam is only valid if this is weak enough not to perturb the states of electrons and atoms significantly [Allmen, 1987]. At sufficiently high laser intensities the response of metals to the interaction is modified by a number of mechanisms. This means that **coupling** is no longer characterised by a static dielectric function but becomes a dynamic process.

According to Allmen [1987] the beam induced changes in the optical properties of solids can be ascribed in the case of metals to thermal effects, which can induce different phenomena according to the intensity of the incident beam.

Table 3.1 - Skin depth and reflectivity for some metals at different wavelengths

wavelength:	0.25 μm		0.5 μm		1.06 μm		10.6 μm	
	$1/\alpha$	R	$1/\alpha$	R	$1/\alpha$	R	$1/\alpha$	R
Ag	20nm	0.30	14nm	0.98	12nm	0.99	12nm	0.99
Al	8nm	0.92	7nm	0.92	10nm	0.94	12nm	0.98
Au	18nm	0.33	22nm	0.48	13nm	0.98	14nm	0.98
Cu		(0.1)	14nm	0.62	13nm	0.98	13nm	0.99
Ni		(0.15)	12nm	0.62	15nm	0.67	37nm	0.97
W	7nm	0.51	13nm	0.49	23nm	0.58	20nm	0.98

3.2.2.1 Temperature dependence

A significant aspect of the absorption of laser radiation by a metal, is the fact that it increases with temperature. This means that during laser irradiation, the temperature of the metal will increase and so will the absorption. The **coupling** of the laser radiation into the metal is therefore dependent on the temperature dependence of the absorption. The reduction in the reflectivity with the temperature rise for high reflectivity metals, i.e., Ag, Au, Cu and Al and light wavelength 10.6 μm is shown in figs 3.2 [Ujihara, 1972] and 3.3 [Chan et al., 1977].

The metal's reflectivity decrease with temperature increase appears to result from a decrease in the dc conductivity (eqn 14), due to the apparent reduction in the electron-lattice collision time (eqn 7). According to Ujihara [1972] the variation of reflectivity with the temperature increase was explained on the basis of the Drude theory and the theory of the electron-phonon collision. The electron-phonon collision frequency is dependent on the temperature through the temperature dependence of the phonon population. In addition, hot metals are more reactive, and chemical reactions are likely to occur, under non vacuum conditions, contributing further for the modification on the metal's reflectivity.

The absorptivity of a metal, which is $A = 1 - R$, can be considered as being composed of three contributions, due to the free electrons (fe), interband transitions (ib) and surface (surf) effects. Then

$$1-R \approx (1-R)^{(fe)} + (1-R)^{(ib)} + (1-R)^{(surf)} \quad (22)$$

The same trend on the variation of the metal's optical properties with temperature was determined by Siegel [1976] for liquid metals at and beyond their melting temperatures (fig. 3.4).

3.3 COUPLING IN THE LOW INTENSITY RANGE

In the low intensity range, i.e. radiation intensities below a critical value I_c , the interaction of a laser beam with a metal can produce different phenomena, which depend on the beam intensity and/or time of irradiation on the target surface. Two classes of effects can be produced, dependent on whether surface deformation is achieved or not. Processes that rely on surface heating without surface melting (e.g. transformation hardening), where no surface deformation is apparent but changes in material properties at the surface of the target result, belong to the 1st class of phenomena that can result from the interaction of low intensity beams with materials. On the other hand, processes that rely on surface melting can lead to different types of processing, e.g. surface treatments (surface melting, alloying) and welding. In the latter case due to the low intensity of the beam typical "conduction" welds are produced.

In this intensity range, the efficiency of the laser processing operation depends on the fraction of laser power absorbed by the metal's surface, and consequently on the optical properties of the metal [Herziger, 1986]. Absorption of light can be described by the classical Fresnel formulae where the light beam is assumed to couple to the metal electron gas which absorbs part of the intensity owing to Joule heating.

This mechanism gives an intensity independent absorption coefficient A , which essentially depends on (i) the optical properties of the material (e.g., surface condition, state of oxidation, etc.) ii) characteristics of the laser radiation (e.g., wavelength of the laser beam, its polarisation state and angle of incidence of the laser beam as measured from the surface normal).

3.3.1 Influence of the Metal Optical Properties

3.3.1.1 Surface condition

The metal's optical properties are commonly obtained on metal surfaces in the polished, clean and stress free condition.

The real surface of a material is generally different from an ideal one. The presence of impurities, microimpurities, defects (e.g., cracks, grooves, etc.) and oxides account for an important departure from "ideal" surface properties (i.e., those obtained with perfect surfaces in vacuum conditions). In addition, the performance of thermal, chemical or mechanical preparations on real surfaces can also contribute to an alteration in their properties and therefore in their behaviour in the interaction with an electromagnetic radiation.

Since the absorption depth, δ , is only a few hundred angstroms at most for metals in the visible - near infrared spectral region, the measured reflectivities of metals are very sensitive to surface condition.

Any change from the ideal condition, will lead to higher values of absorptivity of metallic surfaces to laser radiation. According to Prokhorov et al. [1990] the metal surface absorptivity will be the sum of the intrinsic metal property and the additional contributions due to surface roughness, surface defects and impurities and oxidized and adsorbed layers.

The absorptivity of a metal is given by [Prokhorov et al., 1990]:

$$A = A_i + A_{\text{ext}}$$

where, A_i and A_{ext} are the intrinsic and external absorptivities of the metal, respectively. In its turn, the external absorptivity is given by:

$$A_{\text{ext}} = A_r + A_{\text{id}} + A_{\text{ox}}$$

where, A_r represents the supplementary contribution due to radiation absorption by surface roughness, A_{id} the contribution upon absorptivity of various defects and impurities and A_{ox} that from the oxide layers and layers consisting of adsorbed substances.

Therefore absorptivity and thus the coupling efficiency can be improved by producing a surface condition diverse from the ideal one.

- *Surface roughness*

The influence of surface roughness on the absorptivity of a metallic surface can be explained in different ways [Prokhorov et al., 1990]: first, to an increase in the absorption on surface areas where the incident radiation is oblique, i.e., $\theta \neq 0$, and also in grooves and cracks which favour a waveguided propagation of radiation and secondly, to the collective effects related to the generation of surface electromagnetic waves on the periodical surface microrelief².

A rougher surface would have a greater exposed surface area for a given irradiated area on which absorbing inclusions, surface defects or trapped contamination can reside [House et al., 1977]. Therefore the increase in the effective area of interaction is also likely to influence the absorptivity of the material.

In addition, mechanical treatment such as roughening will produce a superficial deformed layer. The properties of the superficial strained amorphous layer will be entirely different from those presented by a smooth surface [Roberts, 1960]. An increase in the absorption with residual strain has been verified by Ikeda [1989].

²-The surface electromagnetic waves are launched by scattering of the incident light and subsequent interference between two electromagnetic waves.

The increase in metal absorptivity with the increase in surface roughness has also been reported for example by Arata et al. [1971], Wieting et al. [1979], Stern [1990]. At the melting point a decrease in the metal absorptivity has been detected. This is contradictory to the behaviour described above concerning the variation of reflectivity with temperature.

- *Defects and impurities*

The impurities scattered on a real surface also contribute to supplementary absorption of radiation. The most common surface microimpurities are dust particles of different shapes and sizes. Other common impurities are the abrasive particles left behind by polishing either on the surface or in the bulk of the material. The later are particularly important in soft materials, e.g. copper. Defects occurring in the bulk of metallic materials which are able to increase the absorption are for example, pores, cracks and grooves (cavities). An important role in the increase of a metal absorptivity is played by defects consisting of the metal itself, which, for some reason are thermally insulated from the rest of the material [Ursu et al., 1984 b; Smith, 1977].

The defects either metallic or non metallic, are thought to present, in general, a higher absorptivity than the metallic structure nearby, thus becoming overheated, which further increase its absorptivity due to the temperature dependence of the later.

- *Oxides*

The influence of an oxide layer on a metal's absorptivity has been observed for several metals [Ursu et al., 1983, 1984 a-b; Duley et al, 1979; Roos et al., 1983 a-b; Mallory, 1989, Arata et al., 1971]. The thickness and structure of the oxide layer depends on the preparation and history of the metal sample. Three methods have been reported to produce an oxidized layer in metals : thermal or chemical and thermo-chemical.

The effect of oxides on metal absorptivity was attributed according to different researchers to different mechanisms: different optical properties of the oxide relatively to the bulk metal with higher absorptivity, selective properties due to the interface morphology, poor adherence properties on the substrate, being therefore thermally isolated from it and interference phenomena in the metal/oxide layer system. The influence of oxide layers in absorptivity will also depend on the radiation wavelength.

It has been verified that the composition, morphology and thickness of the oxide layers have a fundamental role in the efficiency of the coupling of the laser radiation into a metal. This influence of these parameters have been shown by Ursu et al. [1983] for the case of copper and Ikeda [1989] for steel.

- *Surface Coating*

The technique of coating the metallic surfaces with paints [McLachlan et al., 1982] or some other kind of absorbing materials [McLachlan, 1986] pursues the same aim as the formation of oxide layers, that is, to cover the high reflectivity metal surface with a layer of a substance that absorbs better the laser radiation in question.

However, this technique is not always effective; the coating can be blasted off leaving the shiny metal untouched. It also presents some other drawbacks: frequently, the coating has rather poor electrical and thermal conductivities and consequently the transfer of energy absorbed by it to the underlying material has a rather low efficiency. In welding, contamination of the weld zone is likely to occur due to coating vaporisation and mixing in the weld pool.

3.3.2 Laser Beam Characteristics

Laser beam wavelength, polarisation state and angle of incidence are the most influential beam characteristics on the coupling behaviour in the low intensity range.

The effect of the beam wavelength on the absorption capacity of different materials was discussed in chapter II (pt. 2.3.2.3) and illustrated in fig. 2.26, for normally incident light.

The influence of the polarisation state of the laser beam on the reflectivity behaviour of a copper surface is shown in fig. 3.5 [Dausinger, 1990; Spalding, 1987]. If the laser beam is linearly polarized parallel to the plane of incidence, a strong increase in the absorption rate is observed at high angles of incidence. A peak value is obtained at the so called Brewster angle. The behaviour is described by the Fresnel formula. At a given angle of incidence, the absorption strongly increases with temperature.

The increase in the angle of incidence yields to a reduction in the intensity of the impinging laser light as illustrated in fig. 3.6a for a gaussian intensity distribution. In terms of absorbed energy, the main effect of increasing the angle of incidence is the broadening of the interaction zone (fig. 3.6 b) [Dausinger, 1990].

Fig. 3.7 compares the calorimetrically measured absorption rates of different wavelengths at different angles of incidence. Remarkable improvements can be achieved with shorter wavelengths.

3.4 COUPLING IN THE HIGH INTENSITY RANGE

Apart from the "intrinsic" effects produced in metals as a result of their interaction with beams with relative low intensity, other effects associated with changes in the shape of the metal can be produced with increasing intensity beams. Characteristic features of this intensity range are the evaporation of material, plasma formation and the appearance of an intensity dependent absorption.

As the intensity of the radiation at the surface of a material increases to values above a critical value of the intensity $-I_c-$ there is a transition from nearly null to nearly total absorption of the laser radiation (fig. 3.8), i.e. reflectivity decreases sharply and consequently absorptivity rises to values approaching unity, which leads to an increase in coupling efficiency. The critical

intensity is related to the condition that the surface must reach the boiling point and consequently it depends on laser beam parameters and metal's properties.

The metal's vaporisation in the impinging point laser/metal leads to the formation of a cavity through the depth of the metal. This cavity is referred to as a "keyhole" and forms the basis for deep penetration laser keyhole welding. The "keyhole" is a liquid lined cavity with a very hot ionised gas core. Beam pressure as well as vapour and recoil pressures tends to maintain the keyhole opened [Lancaster, 1984] and hold the liquid in place against gravity and surface tension pressure, thus enabling the laser radiation to penetrate deeply into the workpiece keeping the process going. A general configuration of the keyhole and its relationship with the laser beam and the workpiece is shown in fig. 3.9.

In the high intensity range different regimes may be distinguished on the basis of the predominant physical phenomena, as follows [Krokhin, 1972; Allmen, 1987]:

- In the low temperature regime, which means laser intensity radiation smaller than approximately 10^6 Wcm^{-2} , the main process is the phase transition of the metal from the condensed to the gaseous phase. The vaporisation in this regime takes place at temperatures slightly exceeding the boiling temperature of the material. Under these conditions the vaporised material, which is continuously removed from the retreating surface, is a nearly transparent gas for the incident radiation, although its refractive index is different from its surroundings, which can yield to a distortion of the incident wavefront. Condensing droplets of submicrometer size are formed, which lead to absorption and scattering [Matsunawa et al, 1984 - 1993]. Energy is effectively used in removing material (by vaporisation) and only a small amount is expended in heating the material after it leaves the surface.
 - In an intermediate temperature regime, between 10^7 and 10^{10} Wcm^{-2} (depending on wavelength), the hot vapour evolved from the surface becomes partially ionised forming a vapour plasma which can absorb a substantial fraction of energy. The vapour plasma is able to emit this energy as blackbody radiation. In this intensity range a shielding gas plasma can be also ignited with the support of the laser induced metallic vapour plasma [Beyer et al., 1986].
 - In the high temperature regime, for laser intensities higher than 10^9 Wcm^{-2} , a high temperature vapour is formed whose properties can affect further interaction with metal's surface. The temperature of the vapour generated in this regime is generally high enough to cause appreciable atomic excitation and ionisation. Then the vapour begins to absorb laser radiation, and further ionisation can make the plasma opaque and shield the surface from the laser radiation.
-

3.4.1 Plasma Generation

A particular important aspect of metal evaporation by a laser beam is the interaction of the evolving hot vapour with the beam itself. This interaction leads to strong nonlinearities in the coupling of an intense beam with a target, in addition to those that may arise in the condensed matter.

In general, vaporised material at temperatures slightly exceeding the boiling temperature of the material, does not give rise to plasma generation, because the density of the vapour does not become high enough for further interaction with the beam.

With increasing beam intensities the temperature of the vapour increases. The hot vapour represents an easily ionisable medium, due to the thermal excitation of the atoms. Further heating of the vapour occurs by absorption of the laser light by the vaporised material. The absorption would occur by the inverse Bremsstrahlung process, which involves absorption of a photon by a free electron in the presence of a heavy particle (for momentum conservation) [Mazumder et al, 1987; Ready, 1971; Allmen, 1987]. This is the primary mechanism for plasma formation and maintenance. The electrons, as a consequence of this mechanism are accelerated until they attain a kinetic energy high enough to ionize the ambient gas or the material vapour during collisions, which increases the number of electrons by avalanche ionisation, and thus the electron density.

The effective inverse bremsstrahlung absorption coefficient is given by [Rockstroh et al., 1987]:

$$\alpha(m^{-1}) = \frac{4}{3} \frac{2\pi e^6 z}{\sqrt{6\pi k m_e^3 h c^4}} \frac{N_e^2 \lambda^3}{\sqrt{T_e}} [1 - \exp(-\frac{h\omega}{kT_e})] [G_{ff} + (\frac{h\omega}{kT_e})] \quad (23)$$

where z is the effective ion charge, N_e is the electron density (cm^{-3}), λ the laser wavelength, ω the laser frequency, T_e the electron temperature (K), and G_{ff} the free-free Gaunt factor. The constants in the above equation are k , the Boltzmann constant; e the electron charge; and h , the Planck constant.

Thus, the absorption coefficient increases at high electron density, high beam wavelength and low electron temperature.

In order for the laser energy to penetrate into the plasma, the optical frequency must be higher than the plasma frequency [Herziger, 1986]

$$\omega > \omega_p = \left(\frac{e^2 N_e}{\epsilon_0 m_e} \right)^{1/2} \quad (24)$$

since for $\omega \leq \omega_p$ the incident laser radiation is reflected by the plasma.

In laser materials processing the critical intensity for the development of a laser induced plasma, is always related to the metallic vapour breakdown, since this is significantly lower than that required for air or gas breakdown. Some insight into this behaviour can be obtained by comparison of the ionisation potentials of common metals and gases, which are given in table 3. [Banas, 1986]. The ionisation potentials of metals are of the order of one half that of the gases, and because the degree of thermal ionisation is an exponential function of the energy level, ionisation at comparable temperatures differs by the order of e^2 between metals and gases.

In the continuous wave mode of operation the threshold intensity for a laser induced plasma increases with decreasing laser power (fig.3.10).

For the pulsed mode, fig. 3.11 illustrates the threshold intensity behaviour with the pulse duration. For short ones the threshold intensity is independent of the focus radius r_F , whereas for longer pulse durations, threshold intensity becomes dependent on r_F , because transverse thermal conduction becomes dominant. Thus, a beam with small r_F requires higher intensities for vaporisation.

The development of a laser induced plasma as well as the fully developed plasma (cw plasma) can be described by a model, based on the classical model of plasma generation and heating by microwaves, which approximates the energy transmission by inverse bremsstrahlung [Herziger, 1986].

TABLE 3.2 - Ionisation potentials of common gases and metals	
Material	First ionisation potential,eV
Argon (Ar)	15.68
Helium (He)	24.46
Oxygen (O ₂)	12.50
Nitrogen (N ₂)	15.54
Carbon dioxide (CO ₂)	14.41
Water vapour (H ₂ O)	12.56
Aluminium (Al)	5.96
Nickel (Ni)	7.61
Iron (Fe)	7.83
Copper (Cu)	7.72
Magnesium (Mg)	7.61
Manganese (Mn)	7.41

3.4.2 Plasma Model

The system of equations, which comprises the rate equations for electron energy, electron momentum, electron density, and metallic vapour density, to describe plasma characteristics is presented below [Beyer et al.,1984].

Assuming isotropic scattering, the momentum rate equation can be neglected.

System of Rate Equations for Laser Induced Plasma

- **Electron Density $N_e(t)$**

$$\frac{d N_e}{d t} = R_i - R_{diff} - R_{rec} \quad (25)$$

where,

R_i : ionisation rate
 R_{diff} : diffusion rate
 R_{rec} : recombination rate

The recombination rate

$$R_{rec} = R_{ee} + R_{en}$$

where,

R_{ee} : three body recombination (electron-ion-electron)
 R_{en} : three body recombination (electron-ion-atom)

are given by

$$R_{ee} = f(N_e, \bar{\epsilon}) N_e^3 \quad (26)$$

$$R_{en} = f(N_e, \bar{\epsilon}) \Sigma \left(\frac{n_g}{M_g} \right) N_e^2 \quad (27)$$

- **Average Electron Energy $\bar{\epsilon}(t)$**

$$N_e \frac{d\bar{\epsilon}}{dt} = \alpha I - P_c - P_e - R_i (E_i + \bar{\epsilon}) + R_{ee} (E_i - E_e + \bar{\epsilon}) \quad (28)$$

where,

- $\alpha (n_M, N_e)$: absorption coefficient
- I: laser intensity
- P_c : power losses by elastic collisions
- P_e : power losses by excitation
- E_i : ionisation energy
- E_e : excitation energy

- Vapour Density $n_M(t)$

$$n_M(t) = \text{const} \left[A I - \frac{\sqrt{2\pi} T_v K / r_F}{\text{arc tg} \frac{\sqrt{8 k t}}{r_F}} \right] \quad (29)$$

where,

- A: degree of absorption/absorptivity
- T_v : vaporisation temperature
- r_F : focus radius
- K: heat conductivity
- κ : thermal diffusivity

The metal vapour density is a function of the absorbed laser intensity and is given by the equation above, which is based on a model developed by Krokhin and Afanases, which has been extended to introduce power losses due to heat conduction [Herziger, 1986]. The metal vapour density is important because the plasma absorption coefficient is a function of the vapour density. This is only valid as long as collisions between electrons and atoms exceed those due to electrons and ions.

The cross-section for an electron - ion collision is greater than the cross-section for electron - atom collision, but the metallic vapour density is some order of magnitude higher than the electron density and therefore the recombination rate with a neutral atom as a third particle can be dominant [Beyer et al., 1984].

The electron density and average electron energy can be determined as a function of I [Herziger, 1986]. A numerical solution of the system of rate equations is shown in fig. 3.12 for the case of an aluminium vapour and in fig 3.13 for iron vapour with different shielding gases. The average electron energy increases rapidly to a constant value, higher in the case of higher laser intensity. The increase in electron energy is a function of laser intensity and occurs when the absorption coefficient increases due to an increase in the collision frequencies. At this value the ionisation rate in the equations becomes dominant so that an avalanche ionisation process is initiated, and as a result the electron density increases. At a critical electron density the recombination rate is dominant leading to a constant density N_e (cw plasma).

For the electron - ion recombination a more simplified relation is assumed [Beyer et al., 1984]

$$R_{\text{rec}} \approx \text{const. } N_e^2 / \epsilon^{1/2}$$

This rate determines the electron density and the absorption length of a laser induced plasma.

The plasma absorption coefficient is a linear function of electron density (eqn 23), thus the plasma shielding above the workpiece is strongly correlated with the electron density.

It can also be seen that threshold intensities for vaporisation of aluminium are significantly higher than for steel (fig. 3.14), which is expectable due to the lower absorption coefficient and higher thermal properties of aluminium.

3.4.3 "Enhanced Coupling" Models

The increase in coupling efficiency verified in the high intensity range is related to an "abnormal" absorption associated to the keyhole formation. Various models have been proposed to explain this behaviour [Beck et al., 1989], which can be roughly classified in two groups, according to the phenomenon responsible for the improvement in the coupling. In a first group (fig. 3.15) the **increased coupling** was attributed to a **laser induced plasma** generated in the evaporated target surface, which acts as a coupling media. According to the location of the plasma the following situations were described:

- Plasma above the workpiece [Peebles, 1987]
- Plasma in the keyhole volume [Herziger, 1986]
- "microplasma" on the surface of the keyhole walls [Schellhorn, 1986]

In the other proposed model the **increased coupling** was attributed to **multiple reflections and integrated absorption** at the walls of the keyhole, which is formed above the critical intensity [Banas, 1986] .

3.4.3.1 Multiple reflections and integrated absorption at the keyhole walls

The nature of the absorption inside the keyhole is still a very controversial subject, where the keyhole itself represents the key problem. Observations made by different researchers (e.g. Arata et al., [1976; 1983]) have shown that a variety of different keyhole shapes can be obtained. However, the energy interchange process involved in laser processing is extremely complicated because the conditions and physical processes in the interior of the keyhole are not known with certainty. One possibility is that the laser energy is directly absorbed by the walls of the keyhole (Fresnel absorption) [Beck et al., 1989b; Schulz et al., 1987].

Based on this assumption a model was developed to explain the "enhanced coupling" phenomenon, which appeared as a result of multiple reflections and integrated absorption of the laser beam at the walls of the keyhole, i.e. the keyhole acts as a radiation trap for the incident beam energy [Banas, 1986; Miyamoto et al., 1986; Schellhorn et al., 1987; Beck et al., 1989]. This mechanism has been supported by a theoretical model developed by

Schellhorn [1986] to simulate the formation of the vapour cavity. Assuming multiple reflections of the incident laser beam at the wall of the cavity, the time dependent variation of the total absorption was calculated and compared with experimental results obtained with steel and aluminium targets, showing a satisfactory agreement.

However, in this model effects such as absorption of radiation in the plasma or variation of the absorption coefficient with temperature, which also lead to "enhanced coupling", were neglected.

Other results, that support the multi reflection model to explain the "enhanced coupling" behaviour in deep welding, and therefore, contradict the plasma model were given by [Dausinger et al., 1988]:

- Schellhorn [1988] who was able to demonstrate experimentally that the plasma plume appeared after the increase in coupling rate had occurred.
- Peebles and Williamson [1987] who observed that the plasma plume appeared at intensity values distinctly below the threshold intensity for deep penetration welding.
- Ireland [1988] whose experimental results had showed 15mm deep weld without "nail head".

Despite the apparent contradiction between these results, they seemed to show that no reliable correlation exist between plasma formation and deep penetration welding. On the other hand, there is strong experimental evidence [e.g., Locke et al., 1972] that shows that the presence of a plasma inside and above the keyhole plays a significant role in the absorption of energy.

3.4.3.2 Laser induced plasma

According to some researchers (e.g., Beyer et al., [1984]; Herziger [1986]), the "enhanced coupling" is explained by the plasma formed at the critical intensity which would act as a power coupler absorbing the laser radiation by a process of inverse bremsstrahlung and then transmitting the absorbed power elsewhere via reradiation of shorter wavelength (usually visible and ultraviolet for infrared incident radiation), heat conduction, and pressure³. Whereas most researchers discuss this mechanism for very high intensities and short interaction times of pulsed lasers (e.g., Pirri et al., [1977]), other (e.g., Herziger [1986]; Fowler et al. [1975]) have applied the plasma coupling theory to an intensity range around 10^6 W/cm^2 and to interaction times in the ms range.

Some controversy still exists concerning the effects that explain energy transfer from plasma to material. Some authors (e.g., Pirri et al., [1978]; McKay et al., [1977]) report that the energy transfer takes place by reradiation from the plasma. The energy flux emitted from the plasma is proportional to the fourth power of the temperature (Stefan-Boltzmann law, assuming that the plasma radiates as black body). Then, as the temperature of the plasma

³In the case of the Laser Supported Combustion (LSC) waves.

increases, the maximum energy flux emitted increases and importantly shifts towards shorter wavelengths (fig. 3.16). Shorter wavelengths are more readily absorbed in a metal than the infrared laser radiation (fig. 2.26b), and this therefore leads to an overall enhancement in power coupling to the workpiece. In contrast, Rockstroh et al. [1987] have shown that reradiation from plasma in continuous wave applications is not significant.

3.4.3.3 Multiple reflection/laser induced plasma

Beck et al. [1989a] have modelled the absorption of laser energy by a keyhole for two different materials (steel and aluminium) using the two different approaches to explain the "enhanced coupling". They found that, whereas in the case of steel, this was explained by a multi-reflection mechanism as also emphasized by the good agreement with the experimental results, in the case of aluminium the plasma mechanism would dominate. Important experimental support for this theoretical modelling was provided by Schellhorn et al. [1986], where the results from time resolved absorption measurements showed different behaviours for those metals.

Ducharme et al. [1992-93] developed an integrated keyhole model where both inverse bremsstrahlung and Fresnel absorption mechanisms were included. This model predicts that at low translation speeds inverse bremsstrahlung is the dominant mechanism, whereas at high speeds the Fresnel absorption mechanism is dominant.

From the above discussion it can be concluded that, up to now, there is no theoretical and experimental evidence that makes it possible to establish which mechanism dominates nor the importance of each one if both are involved as it seems likely.

Despite the non agreement in the role of the laser induced plasma, there is sufficient experimental evidence on its importance and influence on the efficiency and quality of laser welding. Therefore, it seems appropriate to obtain some insight on the laser induced plasma effects during laser welding.

3.4.4 Materials Processing Involving the Laser Induced Plasma

Vapour breakdown and the resulting plasma formation has been investigated by high speed photography [Donati et al., 1983; Matsunawa et al., 1985; Schellhorn et al., 1986].

The interaction of laser radiation with the laser induced plasma leads to different behaviour according to the laser intensity levels. For relatively low intensities (in the high intensity range), the plasma produced forms a stationary layer close to the evaporating surface. The plasma absorbs significantly the laser radiation and the energy transfer from it to the metal underneath can take place by any of the mechanisms already discussed. Under these circumstances, the plasma improves the energy coupling into the workpiece leading to the so called "enhanced coupling" phenomenon.

With increasing intensity the degree of ionisation of the vapour is increased and thus the temperature and degree of optical thickness reached by the plasma. The energy received by

the material from the plasma is accordingly reduced, until, at a certain threshold value of intensity the primary effect of plasma is to protect the target from thermally coupling to the laser energy. In the limit the attenuation of the incident laser radiation by the laser induced plasma grows until the processing operation is interrupted. At this stage the plasma detaches from the surface and expands towards the laser.

The interaction phenomena between laser radiation and plasma may be classified in three intensity ranges [Herziger, 1983].:

- $I_v < I < I_B$, (I_v , I_B : threshold intensities for vaporisation and gas breakdown, respectively)

In this range the vaporised target material forms a vapour jet emerging towards the laser. The plasma is weakly ionized and almost transparent. Besides the plasma lensing effect in the original beam geometry, no other effect is observed in the beam - plasma interaction.

- $I_B < I < I_D$, (I_D : detonation threshold intensity)

The laser beam is partially absorbed by the material vapour, the surrounding atmosphere, or, in a mixture of vapour and atmosphere. The laser induced plasma generates the formation of an LSC (Laser Supported Combustion) wave. This wave tends to be optically thin to the laser radiation. It propagates with subsonic speed with respect to the vapour and ambient atmosphere. Propagation is limited to the channel formed by the laser beam [Allmen, 1987].

- $I > I_D$

The laser radiation is greatly absorbed in a shock wave generated by the expanding plasma. This limiting case is characterized by the formation of an LSD (Laser Supported Detonation) wave. The LSD wave moves towards the beam with supersonic velocity. Although, enhanced coupling could be present initially at a small fraction of the laser pulse, it is quickly replaced by complete shielding of the target as the strongly absorbing plasma propagates away from the surface. The enhanced coupling in the presence of such a wave is dominated by mechanical rather than thermal energy transfer [Allmen, 1987].

The LSC and LSD waves can be generally designated by Laser Supported Absorption (LSA) waves. Fig. 3.18 illustrates phenomenologically these two waves and the corresponding conditions. The plasma formed in these conditions shields the workpiece surface. As a result vaporisation stops and the processing operation is interrupted. Since the substrate no longer supplies vaporised particles and the plasma begins to dissipate, its attenuation effect is reduced. In addition, the plasma wave propagates back towards the laser to a position where the intensity is lower and the plasma heating decreases. The plasma plume then becomes transparent and the process starts again.

As seen above the generation of both these waves depend on the incident intensity range. The onset of an LSD wave can be foreseen by the following relation:

$$\alpha \lambda_c \approx 1 \quad (30)$$

where α is the absorption coefficient and λ_c is the mean free path of the vapour atoms. The processing in this region is used only for special applications (e.g. shock hardening), since it is not able to perform considerable material removal.

FIGURES

- 3.1** - Optical properties of a metal described by the equivalent pairs of parameters: ϵ_1 and ϵ_2 , n and k and R and α [From: Allmen, 1983].
- 3.2** - Reflectivity of Ag, Au, Cu and Al vs temperature at $\lambda = 10.6 \mu\text{m}$ [From: Ujihara, 1972].
- 3.3** - Reflectivities of Cu and Al at high temperatures (experimental errors are 10% for reflectivity and 20% for temperature calculation) [From: Chan et al., 1977].
- 3.4** - Reflectivity vs temperature for twenty liquid metals at $10.6 \mu\text{m}$ [Siegel, 1976].
- 3.5** - Variation of reflectivity with angle of incidence for copper at room temperature (a), (b) and 1000°C (c), (d). Curves (a) and (c) are drawn for $10.6 \mu\text{m}$ radiation linearly polarized with the electric vector E_e parallel to the surface of the workpiece; and (b), (d) with the orthogonal polarization (E_p) [From: Spalding, 1987].
- 3.6** - Intensity profile of a gaussian laser beam at different angles of incidence [Dausinger et al., 1990].
- 3.7** - Absorption of linearly polarised laser beams with different wavelengths. Results from calorimetric measurements at room temperature and from calculations based on Fresnel formula and drude theory [Dausinger et al., 1990].
- 3.8** - Intensity dependent absorption for copper [From: Herziger, 1976].
- 3.9** - Illustration of the laser keyhole welding
- 3.10** - Calculated and measured plasma thresholds intensities at different laser powers [From: Herziger, 1986].
- 3.11** - Laser intensity as function of the time to reach boiling temperature for different spot sizes [From: Beyer et al., 1984].
- 3.12** - Development of electron energy and density in Al vapour as a function of time [Beyer et al., 1984].
- 3.13** - Development of a laser induced plasma calculated with the system of rate equations with different shielding gases [Beyer et al., 1986].
- 3.14** - Calculated threshold intensity for vaporisation and critical intensity for laser induced metal vapour breakdown and free gas breakdown [Beyer et al., 1984].
- 3.15** - Different models to explain "enhanced coupling" [Schellhorn, 1986].
- 3.16** - Blackbody energy flux emitted as a function of wavelength and temperature [From: Lewis et al., 1985].
- 3.17** - Two dimensional LSC and LSD waves [From: Lewis et al., 1985].
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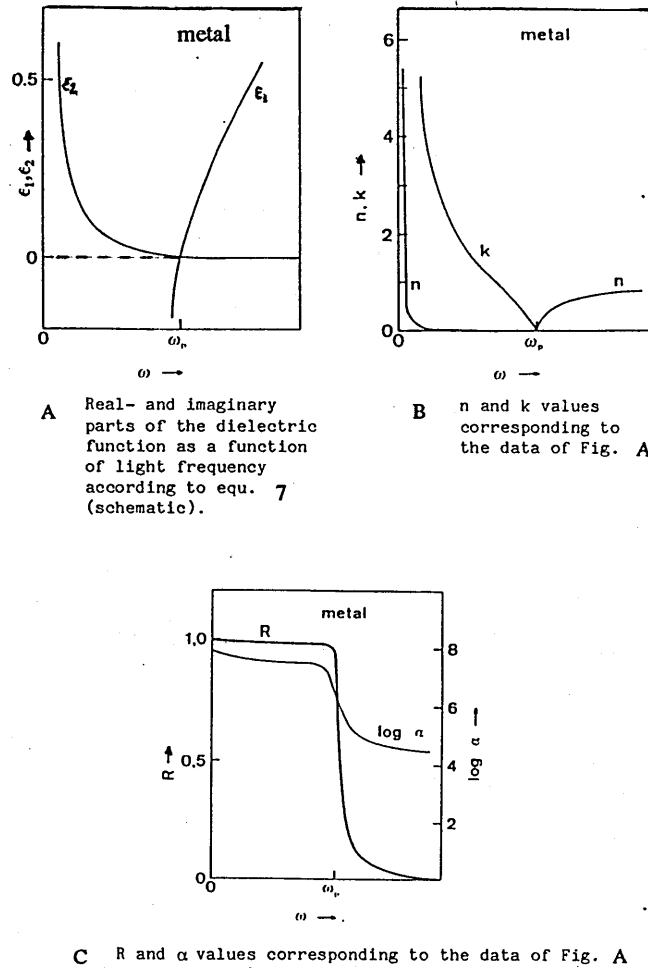


Fig. 3.1 - Optical properties of a metal described by the equivalent pairs of parameters: ϵ_1 and ϵ_2 , n and k and R and α [From: Allmen, 1983].

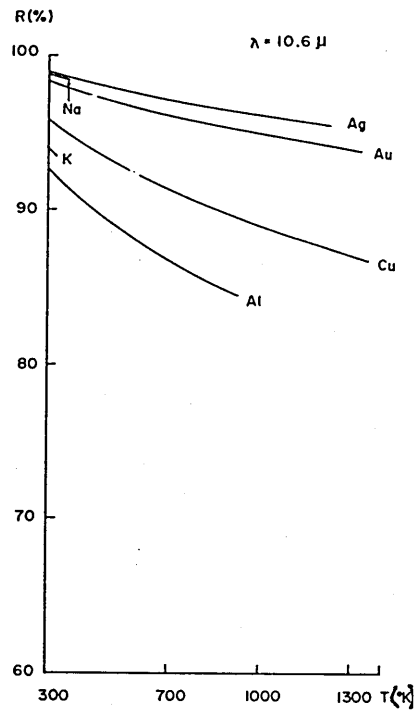


Fig. 3.2 - Reflectivity of Ag, Au, Cu and Al vs temperature at $\lambda=10.6 \mu m$ [From: Ujihara, 1972].

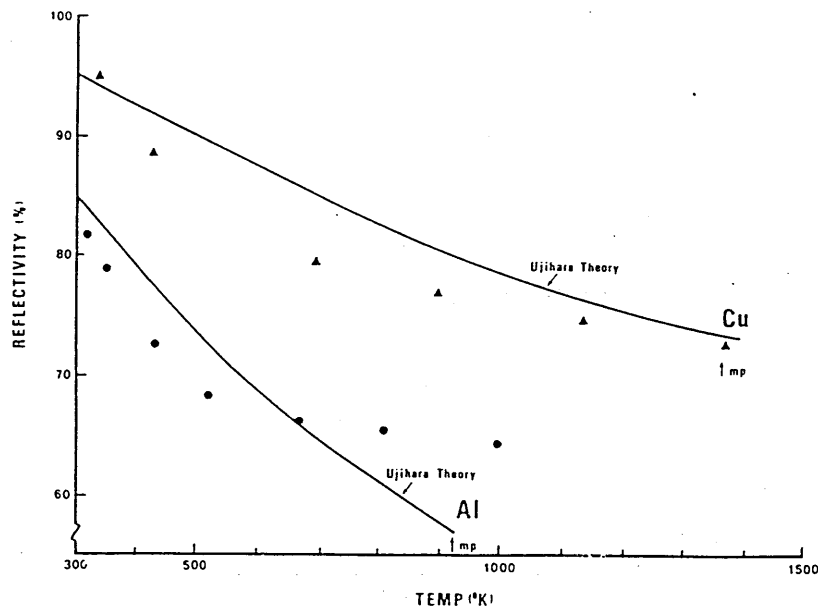


Fig. 3.3 - Reflectivities of Cu and Al at high temperatures (experimental errors are 10% for reflectivity and 20% for temperature calculation) [From: Chan et al., 1977].

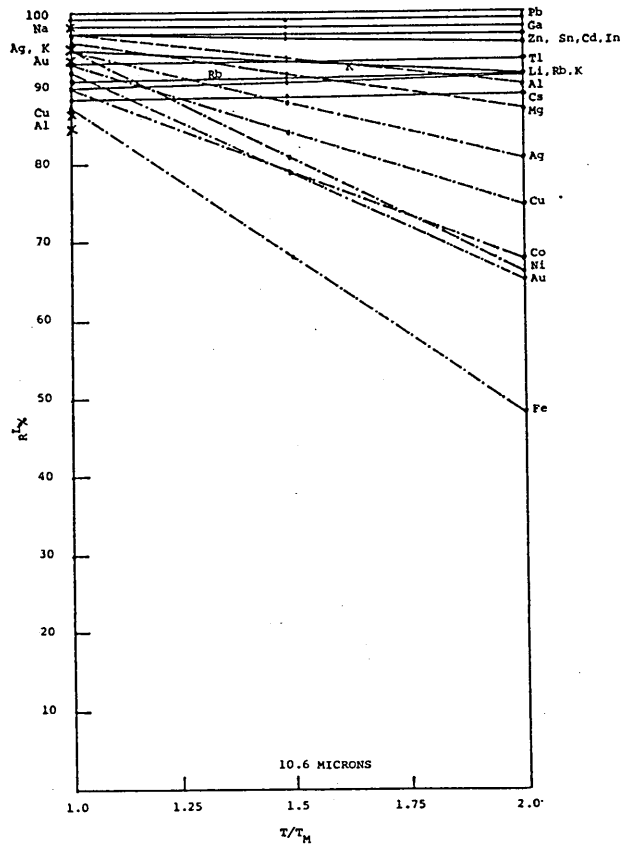


Fig. 3.4 - Reflectivity vs temperature for twenty liquid metals at 10,6 μm [Siegel, 1976].

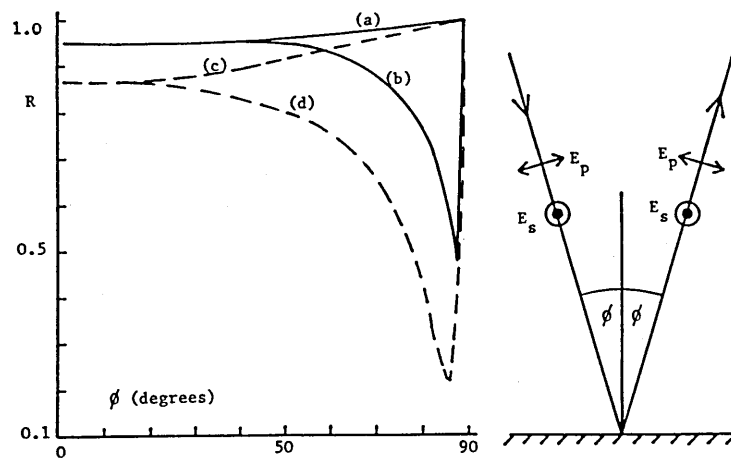


Fig. 3.5 - Variation of reflectivity with angle of incidence for copper at room temperature (a), (b) and 1000°C (c), (d). Curves (a) and (c) are drawn for 10.6 μm radiation linearly polarized with the electric vector E_s parallel to the surface of the workpiece; and (b), (d) with the orthogonal polarization (E_p) [From: Spalding, 1987].

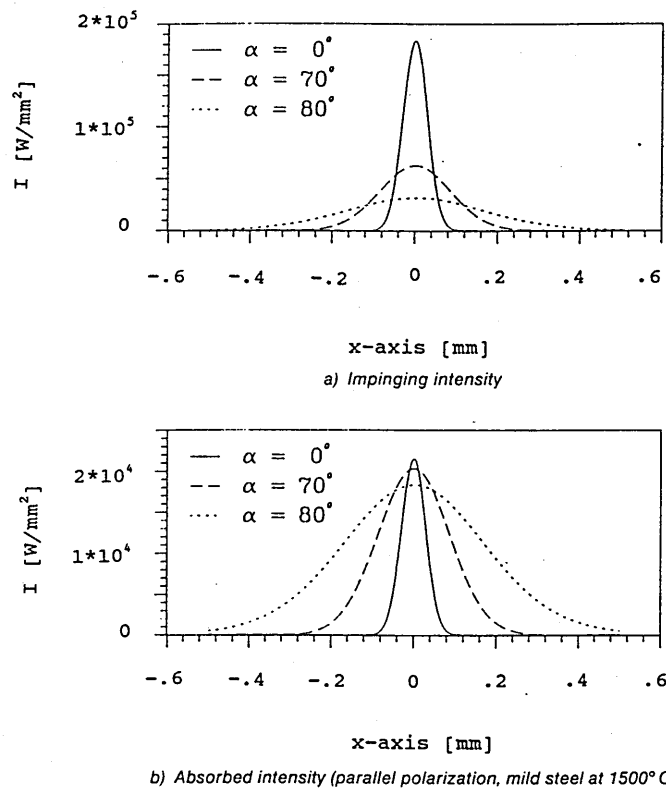
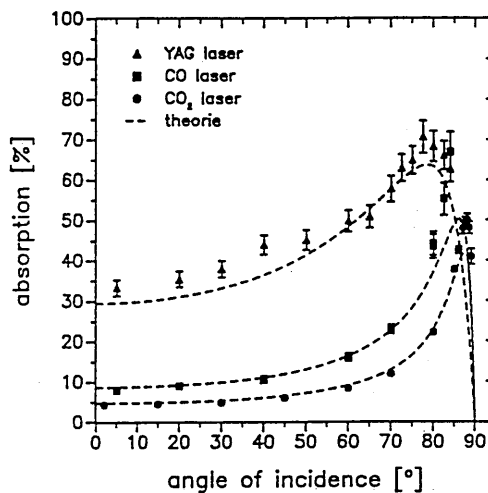


Fig. 3.6 - Intensity profile of a gaussian laser beam at different angles of incidence [Dausinger et al., 1990].



3.7 - Absorption of linearly polarised laser beams with different wavelengths. Results from calorimetric measurements at room temperature and from calculations based on Fresnel formula and drude theory [Dausinger et al., 1990].

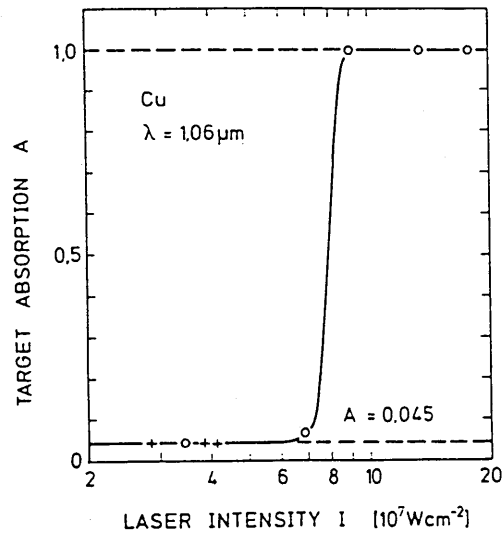


Fig. 3.8 - Intensity dependent absorption for copper [From: Herziger, 1976].

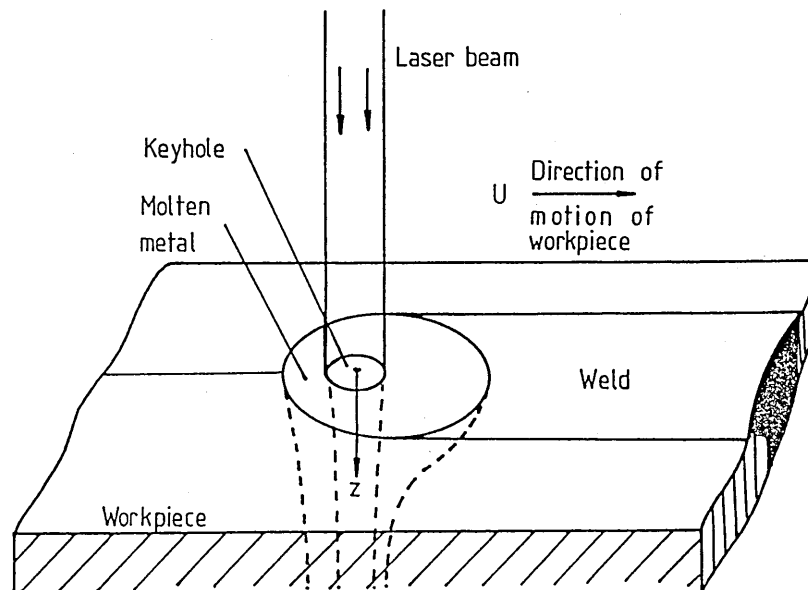


Fig. 3.9 - Illustration of the laser keyhole welding

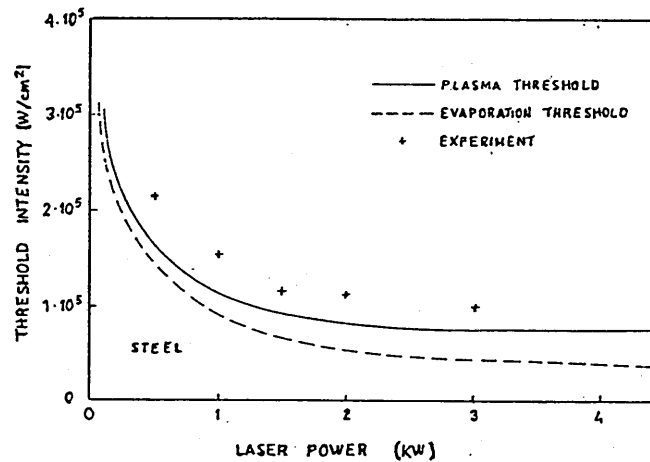


Fig. 3.10 - Calculated and measured plasma thresholds intensities at different laser powers [From: Herziger, 1986].

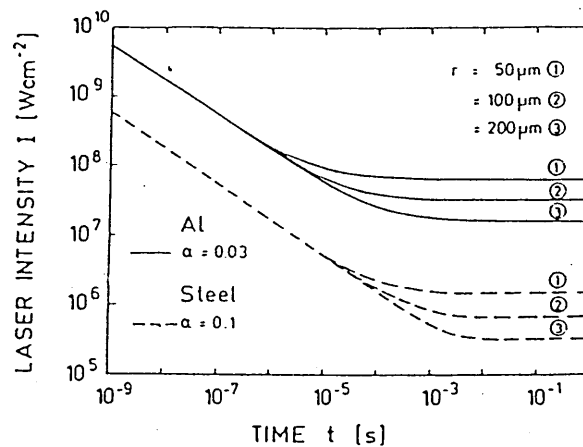


Fig. 3.11 - Laser intensity as function of the time to reach boiling temperature for different spot sizes [From: Beyer et al., 1984].

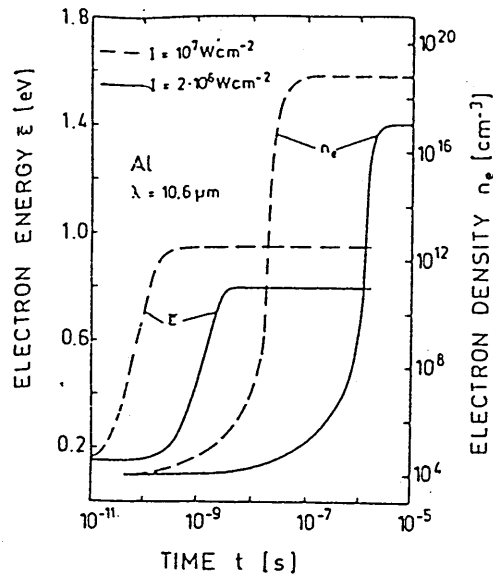


Fig. 3.12 - Development of electron energy and density in Al vapour as a function of time [Beyer et al., 1984].

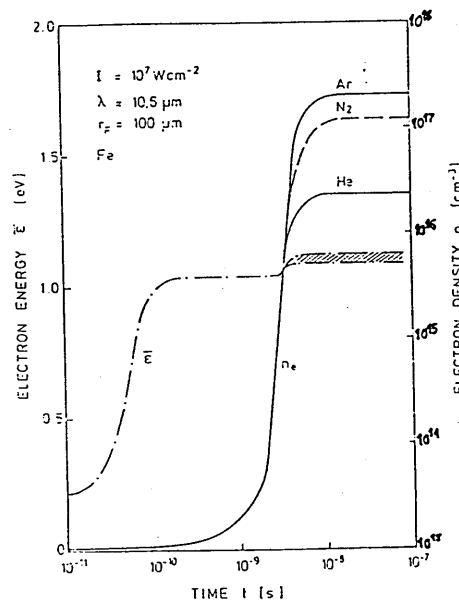


Fig. 3.13 - Development of a laser induced plasma calculated with the system of rate equations with different shielding gases [Beyer et al., 1986].

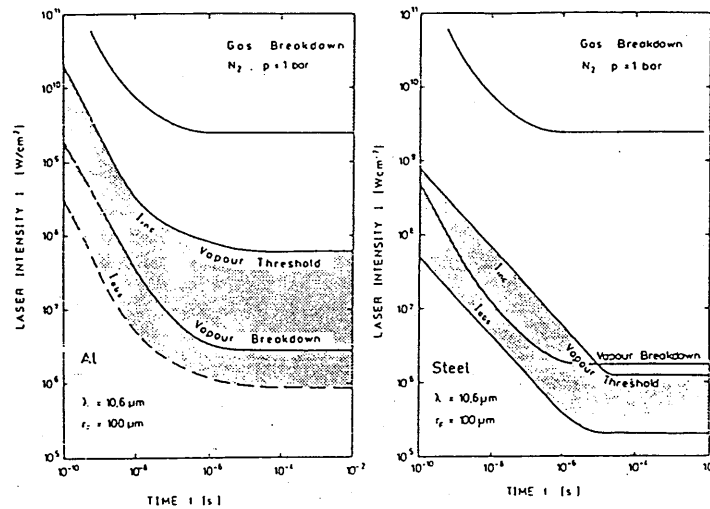


Fig. 3.14 - Calculated threshold intensity for vaporisation and critical intensity for laser induced metal vapour breakdown and free gas breakdown [Beyer et al., 1984].

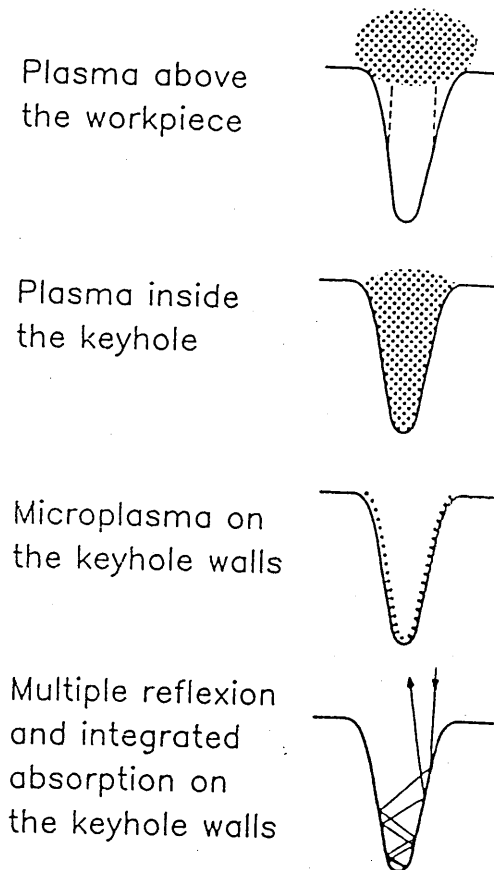


Fig. 3.15 - Different models to explain "enhanced coupling" [Schellhorn, 1989].

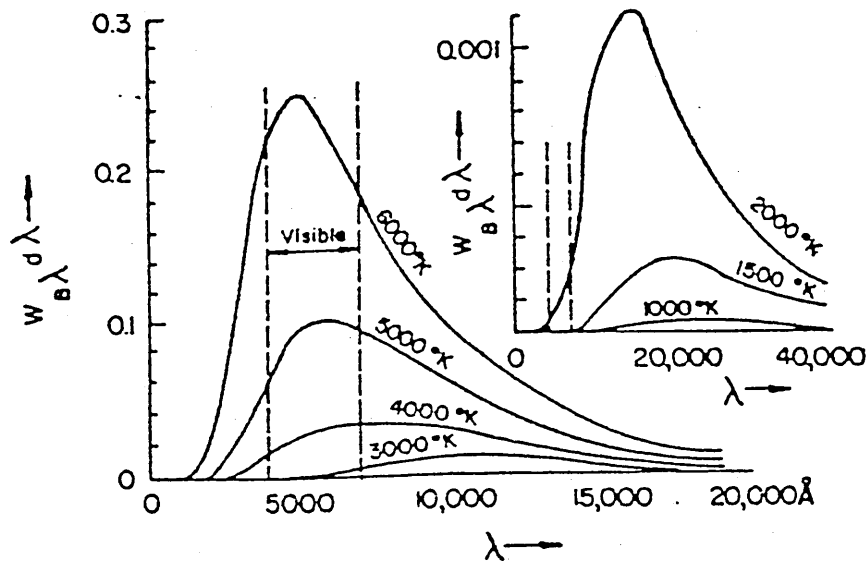


Fig. 3.16 - Blackbody energy flux emitted as a function of wavelength and temperature [From: Lewis et al, 1985].

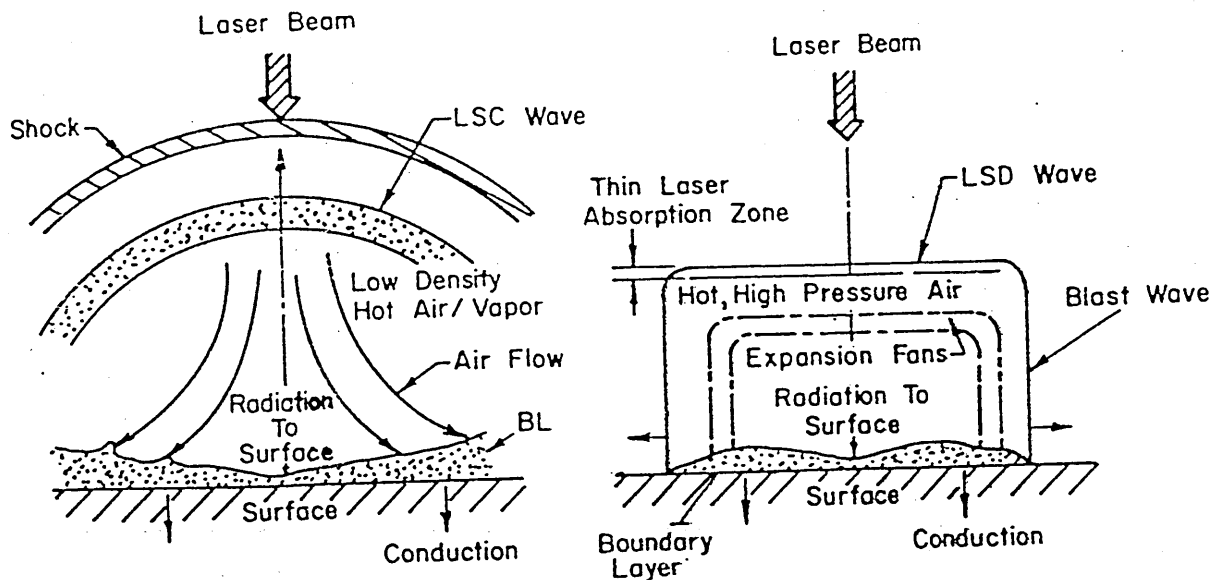


Fig. 3.17 - Two dimensional LSC and LSD waves [From: Lewis et al., 1985].

CHAPTER IV

RESEARCH PROGRAMME

- CO₂ LASER WELDING OF COPPER -

4.1 INTRODUCTION

The present chapter is the first of three directed to the description, analysis and discussion of the research work experimentally carried out.

The first step in the investigation of the CO₂ laser welding of copper was the execution of welding trials, during which the interaction behaviour was analysed.

After preliminary welding trials, the welding programme was designed to provide data to enable parametric models to be developed to optimise the laser welding of copper. However, the non-repeatability and inconsistency of the process observed during the experimental programme, led to a deviation from the initial objectives. The research focused on the interaction phenomena and more specifically on the coupling mechanism appeared to be potentially more important to the field of laser processing of high reflectivity materials. The control of this process will only be effective when a full understanding of the whole process is attained.

In this chapter a detailed description of the copper preparation, equipments used, experimental set-ups and results of the welding programme is given. In addition, a discussion of the results obtained is made and the main conclusions stressed.

CHAPTER IV

4.2 PRELIMINARY WORK

The key problem in the laser welding of copper and materials with similar properties is the **coupling** of the laser radiation into the material. The high reflectivity of copper to infrared wavelengths and its high thermal conductivity are considered to be the main obstacles to efficient copper processing.

In order to determine the best technique to overcome the expected difficulties with the coupling process, a set of preliminary tests was carried out. Blackening the copper surface and use of helium as assist gas was the first approach, but this did not produce good results. It was observed that, once coupling was achieved a plume appeared and welding took place, although rather inconsistently. Helium was also used as assist gas in trials where the copper surface was uncoated. No welds were produced due to the lack of coupling beam/copper. In view of these results other techniques were tried: they consisted of initializing the welding run on a steel plate placed close to the copper or at the interface steel/copper. The results obtained were again very inconsistent in terms of quality and reproducibility. Once again the approach was changed and this involved initialising the welding on the copper plate, whose surfaces were just roughened, and using nitrogen as the assist gas. Nitrogen was selected since it is an inert gas with respect to copper, and its use in welding of copper by the TIG (tungsten inert gas) process has been claimed to give advantage.

Good results in terms of coupling and welding behaviour were obtained, with welding operations taking place smooth and consistently.

This procedure was therefore selected for further trials which were performed to determine the best welding parameters, and to optimize the process. For determination of the best welding parameters a conventional approach was used, i.e., the effect of each parameter was studied maintaining all others fixed, whereas for the optimization of the process a factorial design was employed because it provided a more efficient means of estimating the effects of several variables simultaneously.

4.3 RESEARCH PROGRAMME

4.3.1 Experimental Set-Up

4.3.1.1 Material and preparation

Oxygen free high conductivity copper (Cu-OFHC), 3,25mm thickness was used throughout this work. The chemical composition of the copper is given in table 4.1.

Table 4.1 - Chemical composition of copper

S	P	Bi	Pb	Ag
0.0012%	0.0015%	—	0.69 ppm	1.18 ppm

Before welding all the copper surfaces were cleaned with a wire brush, to an average roughness of $1.5\mu\text{m}$ (fig. 4.1) and degreased with Genklene.

Melt runs were made across coupons approximately 140 x 50 mm in size. Butt welds were carried out on specimens 140 x 80 mm with welds being made along the long edges. Both weld specimens had their edges milled flat and square.

4.3.1.2 Equipment

The experiments were carried out on the AEA Culham - 10 kW, CL10 continuous wave, carbon dioxide - CO₂ laser (fig. 4.2), described by Kaye et al. [1983].

The laser is a transverse flow, DC electrically excited device which utilizes an unstable resonator with a magnification of 3 and a diameter of 43 mm. The laser produces an annular output beam which exits the laser cavity through an aerodynamic window, passes through a collimator which produces a near parallel beam of 43 mm diameter and propagates to the workstation. In the workstation the laser beam is focused downwards by a f/8 mirror optics system. The beam is plane polarized.

A special device, described by Hill et al. [1985], was used to provide both the plasma control and shielding gases to the welding area. This system is shown in fig. 4.3. A gas "jet" nozzle of 2 mm diameter was set at an angle of approximately 45° in relation to the laser beam axis, and the distance from the top of the nozzle to the impingement point was approximately 2 mm. In some experiments this distance was reduced to 1.5 mm as explained later.

The jet is surrounded by a coaxial gas "lens" and the cooling weld bead is protected by gas flow from a trailing "shroud".

All melt runs and welds were made in the flat position with plates clamped down onto an x-y traversing table and when necessary, aligned using a He-Ne tracer beam running through the same optical system as the CO₂ beam.

4.3.1.3 Assist gases

■ *Determination of the welding parameters*

Nitrogen (N₂), argon (Ar) and mixtures of nitrogen with oxygen and argon with nitrogen were used as jet gases. Nitrogen and argon jet gases were supplied at flow rates variable in the range 2-15 and 6-10 l/min, respectively. Nitrogen at a fixed flow rate of 10 l/min was used mixed with small amounts of oxygen up to a maximum of 10%. Mixtures of argon (6 l/min) and nitrogen were also used as gas jet.

The gas lens was nitrogen, with flow rates variable in the range 0-10 l/min.

The shroud gases were helium (He) at a 100 l/min flow rate, nitrogen and argon with variable flow rates in the ranges of 10-40 and 20-40 l/min, respectively.

CHAPTER IV

■ *Optimization of the welding process*

Nitrogen was selected and used as jet, lens and shroud gases. Two levels of flow rates for each gas function were used, as described:

- gas jet: 6 and 8 l/min
- gas lens: 5 and 10 l/min
- gas shroud: 10 and 20 l/min

4.3.1.4 Experimental welding parameters■ *Determination of the welding parameters*

Two levels of beam powers (7 and 9 kW), welding speeds in the range 15 to 40 mm/s and two different focal positions (on the surface and 5 mm below it) were used, together with variable values of gas flow rates for the jet, lens and shroud, as described in pt. 4.3.1.3 (Table 4.2 in annex 4A).

■ *Optimization of the welding process*

The sets of experiments carried out to determine the effects of the various parameters and to select the best welding parameters allowed the selection of an optimal range for variation of each parameter, whose values were used later, in the factorial design for the parameter optimization study.

The selected ranges were obtained by visual evaluation of the coupling and welding behaviour as well as of the weld bead appearance. Metallographic examination and dimensional analysis of the weld beads also contributed to the selection process.

The experimental parameters are presented in table 4.3 (annex 4A).

4.3.1.5 Assessment

The quality of the melt runs and butt welds was first assessed by visual examination taking into consideration the following factors:

- welding behaviour, in terms of coupling stability (without disruptions or intermittent interruptions);
- welding operation, smooth and consistent;
- bead geometry, top and bottom widths and reinforcement.

The visual observation of coupling and welding behaviour combined with the visual examination of the appearance of the welds produced proved to be very effective during the performance of the welding trials. The permanent assessment made to the effects of the different factors allowed continually adjustment of the experimentation to achieve the initial defined objectives.

After welding, radiographic examination was carried out in order to determine the density of porosity, its location and the influence of welding conditions on the porosity level.

Finally, metallographic sectioning (three per weld bead) and examination using the optical microscope was performed to assess the weld geometry, as well as weld porosity.

4.3.2 Results

4.3.2.1 Welding behaviour

Coupling behaviour proved to be one of the fundamental factors which determine the quality of a laser welding operation.

During the trials it was observed that before welding commences some plasma might be allowed to form. This plasma with a blue/white colour appeared to be fundamental for welding to take place. When this plasma did not form, coupling did not occur and welding did not take place either.

An apparent coupling behaviour dependence on the gas jet flow was detected. The coupling appeared to be controlled by mechanisms related with the gas jet effects in the welding zone, which in turn controlled the lack of reproducibility of the welding process.

The relationship between the coupling behaviour and the gas jet flow was established from the observed influence of the gas nozzle geometry on the coupling process. This was detected during the experimentation when it was necessary to change the gas jet nozzle after its tip was found to be melted. The copper nozzles after a certain period in use, acquire a profile such as that illustrated in fig. 4.4, which is the result of the intense heat from the welding zone. When a new nozzle (circular cross section), which will be designated hereafter "standard" nozzle, was installed, and under otherwise identical welding conditions, it became impossible to weld because the coupling of the laser beam to copper was not achieved. When the "standard" nozzle was then changed for the old one (called hereafter "modified" nozzle), the welding programme proceeded as before.

Before this relationship was established, unexpected and unexplained behaviour was observed, which led to frequent re-calibration of the equipment. When all other causes were eliminated it was concluded that the observed behaviour could only be related to the nozzle tip geometry and therefore with the influence of the gas jet flow pattern over the welding zone.

This relationship was confirmed during the experimentation, when good coupling behaviour was achieved by moving the plasma control device about 0.5mm forward, (which means that the distance between the top of the nozzle and the interaction point was reduced from the original 2mm to approximately 1.5mm). The same nozzle (which had its tip slightly worn) at the original set-up (2 mm) had not allowed coupling to be produced in this case.

The achievement of a good coupling is fundamental for welding but it is not sufficient to guarantee the prosecution of the welding operation in the proper conditions.

CHAPTER IV

In summary, during the welding programme 3 different types of welding behaviour were observed:

- no coupling, no welding
- coupling, unstable welding operation
- coupling, stable welding operation

4.3.2.2 Dimensional analysis of the weld beads

The dimensional analysis of the weld beads was undertaken by measuring the top and bottom weld widths and weld fusion area (fig. 4.5). The measurements were made on transverse metallographic sections (3 per fusion line or weld). Weld widths were measured directly on macrographs of the weld beads and the fusion areas were determined using a computer package developed for determination of areas.

The results obtained are presented in tables 4.4 and 4.5 (annex 4B).

4.3.2.3 Influence of beam power, focus position and welding speed on weld bead characteristics

The influence of the welding parameters on the dimensions of the weld beads are plotted in the graphs shown in fig. 4.6 and 4.7. The related weld profiles are shown in fig. 4.8.

Examination of figs 4.6 till 4.8 reveals that the smaller fusion areas were obtained with a power beam of 7 kW, whose focus point was made 5 mm below the copper surface. The later conditions allowed narrow root widths to be obtained, although narrow top width beads have been achieved with the focus on the copper surface.

4.3.2.4 Influence of the gas jet composition and flow rate

■ pure gases: N₂ and Ar

Nitrogen and argon were used as jet gases for plasma control. Although, nitrogen was expected to be the most suitable jet control gas, argon was also used for comparative evaluation. Few tests were made with argon, but they allowed it to be established that for flow rates similar to those used with nitrogen, a brighter plasma was formed. This means that greater argon flow rates should be used to achieve plasma control performances identical to those obtained with nitrogen.

The initial flow rate of N₂ as gas jet (6 l/min) had been selected from the preliminary trials, where it seemed to produce an adequate control of plasma.

However, in order to optimise the gas jet flow rates for plasma control and analyze the effects of different flow rates on the welding behaviour and bead characteristics, a set of trials was made over a range of N₂ flow rates, maintaining at fixed values the following parameters: power- P=7kW; welding speed- v=25mm/s; focal position-F: -5mm and helium shroud flow: R₃ = 100 l/min.

CHAPTER IV

At a jet flow rate of 2 l/min very unstable, non penetrating and wide weld beads were obtained. As the gas jet flow rate was increased up to 4 l/min, the welding behaviour remained unstable, but narrower beads were produced.

For flow rates 6 l/min up to 10 l/min, the welding behaviour became more stable and more consistent weld beads were obtained.

Further increases in the gas jet flow rate caused the welding operation to become unstable and at about 15 l/min, some disruption of the molten metal occurred, leading to weld beads with irregular profiles and intermittent penetration.

The cross sections obtained for the different gas flow conditions are presented in fig. 4.9.

The influence of gas jet flow rates on bead geometry is shown in the graphs of fig. 4.10.

From the visual assessment made during the work, a nitrogen jet flow rate of 10 l/min was selected for further experiments.

■ *gas mixtures: N₂ + O₂ and Ar + N₂*

Some trials were made in order to analyze the effect of the addition of small amounts of oxygen (up to 10%) to nitrogen in the gas jets. No gas lens was used.

As shown in the graph of fig. 4.11, a slight increase in the weld bead dimensions results as the O₂ content increases. This result is consistent with the theory (chapter III) that the oxygen promotes the oxide formation on copper surfaces, thereby enhancing energy coupling to the workpiece and, higher heat absorption yield to broader fusion zones.

An increase in the density of porosity was also obtained when O₂ was added to the N₂, and for an O₂ content of about 10%, there was also an increase in pore dimension (fig. 4.12).

The addition of small amounts of N₂ to Ar in the gas jet did not produce any particular effect on the coupling behaviour or in the dimensions of the weld beads produced. Only a few tests were made with Ar/N₂ mixtures and therefore the results are not significant.

4.3.2.5 Effect of the use of a gas lens on plasma control

The device used to provide the jet and shroud gases (fig. 4.3) to the welding zone, also allows the supply of another gas which is called lens gas. The purpose of the lens gas is to improve the performance of the gas jet in the plasma control and simultaneously to create a boundary between the latter and the ambient atmosphere.

■ *Determination of the welding parameters*

Some trials were made in order to determine the effectiveness of the lens gas on the plasma control and to assess its effect in the characteristics of the weld bead.

CHAPTER IV

In fig. 4.13 a weld bead cross section, obtained using N₂ as the lens gas with a flow rate of 10 l/min, is presented. The jet and shroud gases and flow rates were N₂ at 10 l/min and He at 100 l/min, respectively.

The comparison of these cross sections with others obtained in identical conditions but without using lens gas (fig. 4.14), shows that the former are slightly narrower, with smaller top and bottom bead widths, which suggests a more effective plasma control.

A substantial reduction in the density and dimension of porosity was observed by radiographic examination of the specimens welded with a lens gas. The radiographic results seemed to indicate a beneficial contribution of the lens gas which, by promoting more efficient shielding above the welding zone against the ambient atmosphere, would be expected to result in a lower overall gas concentration in molten weld metal.

■ *Optimization of the Welding Process*

In the factorial design for optimization of the welding process it was decided to use a lens gas in every trial, due to the good performances it exhibited in the previous trials, as described above.

The radiographic examination of the weld beads, the microscopic analysis of their cross sections as well as their dimensional results (table 4.5) showed that, although an overall reduction in the porosity level has been obtained, as expected, some inconsistency appeared in the dimensional results. For example, when higher flow rates of jet and lens gases were used (maintaining constant all the other parameters except the shroud gas), it would be expected to obtain narrower weld beads due to a more efficient plasma control (fig. 4.15). However, this was not observed in all cases. Thus the role of the lens gas, did not appear to be as clear as initially described.

It must be stressed that the use of a lens gas did result in an overall reduction of porosity density and size.

4.3.2.6 Influence of plasma control device setting - up on the coupling behaviour

The setting up of the plasma control device was described in pt. 4.3.1.2 and shown in fig. 4.3. However, during experimental trials for optimization of the welding process, the original set-up was modified, in an attempt to overcome some problems with coupling. The modification consisted in moving forward approximately 0.5 mm the plasma control device, which means that the distance from the top of the nozzle to the impingement point was reduced to about 1.5 mm. The variation in the setting-up allowed the coupling process to initiate, after it had been impossible to achieve coupling with the original set-up.

The modification needed in the plasma control set-up implied a variation in the gas flow pattern over the interaction zone. This tends to confirm the critical nature of the plasma control gas jet flow on coupling.

CHAPTER IV

4.3.3 Discussion

4.3.3.1 Coupling phenomena

The increase in coupling efficiency as a result of keyhole formation and thermal ionisation of the hot vaporised metal emerging from the keyhole, has been object of some controversy, as discussed in chapter III.

However, in the present work the required presence of some plasma above the workpiece at the beginning of the process, as described above in pt. 4.3.2.1, showed that the "enhanced coupling" is a fundamental process for a successful laser beam/copper interaction and copper welding.

In pt. 4.3.2.1 the particular conditions under which coupling of the CO₂ laser energy into copper resulted were described. The gas jet initially intended to control only the laser induced plasma appeared to have also an important influence in the coupling process, since it was observed that coupling only resulted when the gas jet was supplied to the interaction zone through a nozzle with particular tip configuration.

As far as is known, nitrogen is inert towards copper. Thus, the occurrence of some sort of thermochemical reaction which could change the superficial characteristics of copper and, consequently, its absorption properties seems very unlikely.

The behaviour of the different nozzles with respect to coupling seems in some way to be related to the gas fluid dynamics over the interaction zone. Under otherwise identical welding conditions, different gas flow behaviours will result from the different nozzle tip geometries, and the former would lead to different gas dynamic pressures and velocities over the welding zone. This mechanical effect seems to be the key for the occurrence of other phenomena, which would be effectively responsible for the "enhanced coupling" or for the lack of it.

A first hypotheses would be to consider that the gas flow from a "standard" nozzle produced excessive convective cooling, which on one hand would prevent the copper surface temperature rise, thus preventing it to attain the boiling temperature, but on the other hand, in case a keyhole succeeded to form would suppress the plasma core.

The modification of the nozzle tip reduced the downward component of the flow thereby, allowing a keyhole to be formed and permitting a plasma to be sustained, which could couple energy to the workpiece.

The hypotheses raised could lead to two effects apparently contradictory and does not permit an explanation of how plasma is formed and how the assist gases affect this process.

Nevertheless, this work is mainly focused on the coupling mechanism, i.e. on the way the laser radiation interacts with copper and is absorbed by it producing the copper's vaporisation from which plasma would develop. This plasma appears to be fundamental for the coupling and welding of copper by laser and therefore it constitutes the main question to be addressed.

CHAPTER IV

The inconsistent behaviour observed during welding appears to be related with the same phenomenon. The gas flow dynamics besides affecting the mechanism of plasma formation seem also to affect the maintenance of plasma in the convenient conditions for energy transfer to occur and welding to take place.

In the absence of the gas lens, and bearing in mind the vigorous nature of the plasma, some air could be entrained into the interaction region. The resulting ingress of oxygen, in addition to possibly augmenting coupling via oxide formation, could also contribute to the observed porosity. It should be noted that normally the effect of O₂ in a laser induced plasma is to remove electrons by attachment, i.e. it quenches rather than promotes plasma.

The lens gas flowing around the gas jet nozzle, tends to cause the gas jet to become laminar and simultaneously it forms a boundary that prevents the contamination of the gas jet by the ambient atmosphere. The results should be a more efficient control of plasma and a decrease in contamination as observed in some of the welds produced. Straighter weld beads with a significant decrease in the porosity density were obtained in the first experiments where the lens gas was used, and were also confirmed in the factorial design experiments.

Notwithstanding the restriction in oxygen entrainment resultant from the use of a gas lens, satisfactory coupling was still observed. This suggests that the presence of plasma plays a dominant role in the coupling, rather than any oxide formation.

Although a fully comprehensive picture of the mechanism of coupling in laser copper welding was not obtained from this part of experimental work, it allowed fundamental clues to be obtained and suggested that it was essential to obtain an understanding of the CO₂ laser/copper interaction and the role of gases in this interaction.

4.3.3.2 Welding behaviour

Coupling achievement did not always mean that a smooth and consistent weld would result.

The understanding of the coupling mechanism appeared to be fundamental but not sufficient to control the CO₂ laser welding of copper. As indicated above both the coupling and welding behaviour, appeared to be linked and controlled by the same mechanism. The gas flow patterns have a fundamental influence on those mechanisms, although this influence could not be "seen" and understood during this experimental work.

4.3.3.3 Porosity

The porosity level as well as its distribution, location and size seem to differ from weld to weld, but some general remarks can be made:

- In a large number of weld beads, gross porosity appeared, located essentially at the weld fusion boundaries, and upper middle of the weld bead;
 - Lower speeds lead to a higher level of porosity and bigger size of pores, generally distributed uniformly in the weld bead;
-

CHAPTER IV

- The use of a lens gas resulted in a significant reduction of the porosity level;
- The addition of oxygen to nitrogen, in the gas jet, even when a lens gas is used, results in an increased level of porosity, although, this is lower than when no lens gas is used and the gas jet is only nitrogen.

Several mechanisms have been proposed to explain the origin of porosity in laser welds, such as entrainment of atmospheric oxygen, entrapment of shielding gas, instabilities in the molten wall surrounding the keyhole resulting in momentary closure of parts of keyhole and entrapment of metal vapour, contamination of the material by rust or moisture, etc.

Under arc welding conditions nitrogen may be considered a porosity - forming gas and some of the porosity found in copper welds may be due to the nitrogen entrained in the shielding gas from the ambient atmosphere [Littleton (1974)].

However, there is good evidence in TIG welding that the main factors affecting the porosity formation are the oxygen and hydrogen from moisture in the shielding gas [Littleton et al., 1975].

In the laser copper welds, the general results in terms of porosity does not enable the causes of porosity to be clearly established. However, the results obtained do not seem to indicate a substantial contribution due to nitrogen, but an important contribution from entrained atmospheric oxygen in the welding environment.

The hypothetical contamination of the gas jet (N₂) with moisture does not appear to occur in the actual laser conditions, since when the lens gas (N₂) is used, the quantitative increase in the overall gas in the welding zone, does not lead to an increase in the porosity level, but, to a decrease.

4.3.3.4 Plasma control device performance

The plasma control device performance was discussed in Chapter II (pt. 2.3.3.1). Some of the problems pointed there were also felt during this experimental work. The blocking and melting of the gas jet nozzle tip constituted the main limitations to an effective plasma control. Variations in the nozzle tip imply variations in the set-up and in the gas flow pattern, which contribute to the difficulty in reproducing weld results.

4.3.4 Conclusions

The results obtained from the experimental welding trials programme, allow the following conclusions to be drawn:

- The key factor in the laser welding of copper is the **coupling** process;
 - Good coupling of the laser beam energy into copper was obtained, without the need of precoats and using N₂ as the plasma control gas.
-

However, some inconsistency was experienced when duplicate experiments were attempted;

- The coupling efficiency and therefore the welding behaviour appeared to depend on the morphology of the gas jet nozzle tip;
 - The nozzle tip geometry affects the gas flow pattern and dynamics over the interaction zone where it appears to exert mechanical and chemical effects, which are thought to influence the coupling behaviour;
 - It is suggested that the improved weld performance with a "modified" nozzle is due to a redirection of the gas jet, so that less convective cooling of the core of the plasma takes place with the result that is easier for plasma to be sustained, which couples energy to the workpiece;
 - Efficient coupling was only accomplished after a plasma plume was formed and seen over the interaction zone;
 - When no coupling was achieved no visible traces of the interaction of the laser beam with copper were observed on the copper surface.
 - Dependent on the conditions of coupling achievement (or not), welding occurred (or not) and the three following situations were observed:
 - no coupling (no plume), no welding;
 - coupling, unstable welding operation;
 - coupling, stable welding operation.
 - Under conditions of plume formation and welding, the use of a lens gas has provided in the most cases straighter weld beads with a lower level of porosity, which appeared to be due to a more efficient plasma control and simultaneously to a better protection against ambient atmosphere;
 - The plasma control gas device set-up appeared to affect significantly the coupling and welding behaviour;
 - The relationship between gas flow dynamics and coupling / welding behaviour must be investigated in depth, since it appears fundamental to an understanding of the mechanisms of laser beam/copper interaction.
 - The factorial design approach did not provide sufficient data for statistical analysis.
-

CHAPTER IV

FIGURES

- 4.1 - Copper surface aspect after brushing**
 - 4.2 - CL 10 laser**
 - 4.3 - Culham's standard plasma control and gas shielding device**
 - 4.4 - Profile of a "standard" and "modified" nozzles**
 - 4.5 - Weld bead dimensional parameters**
 - 4.6 - Effect of the welding speed, beam power and focal position on face bead (upper) and root bead widths**
 - 4.7 - Effect of the welding speed, beam power and focal position on fusion area**
 - 4.8 - Weld bead profiles obtained at different conditions of beam power, focal position and welding speed**
 - 4.9 - The influence of the flow rate of N₂, as plasma control gas, on the weld bead characteristics**
 - 4.10 - Effect of jet gas flow rate on the face and root widths and fusion area**
 - 4.11 - Effect of the addition of O₂ to N₂ (gas jet) on the face and root widths and fusion area**
 - 4.12 - Effect of the O₂ content mixed in the gas jet N₂ on the porosity level**
 - 4.13 - Effect of the use of a gas lens (N₂) on the weld bead morphology and porosity**
 - 4.14 - Comparision of weld bead cross sections obtained with and without lens gas**
 - 4.15 - Inconsistent results with lens gas (factorial design series)**
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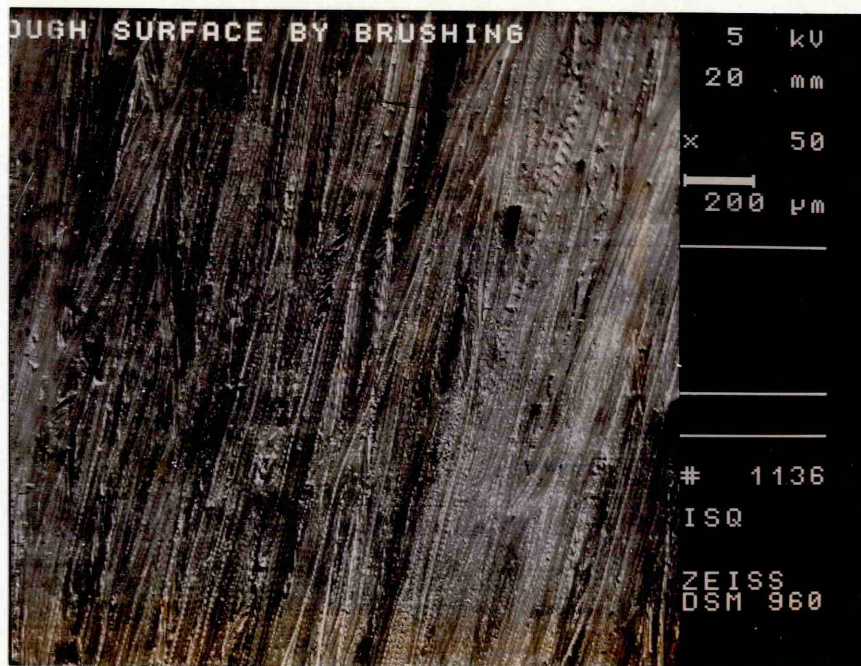


Fig. 4.1- Copper surface aspect after brushing

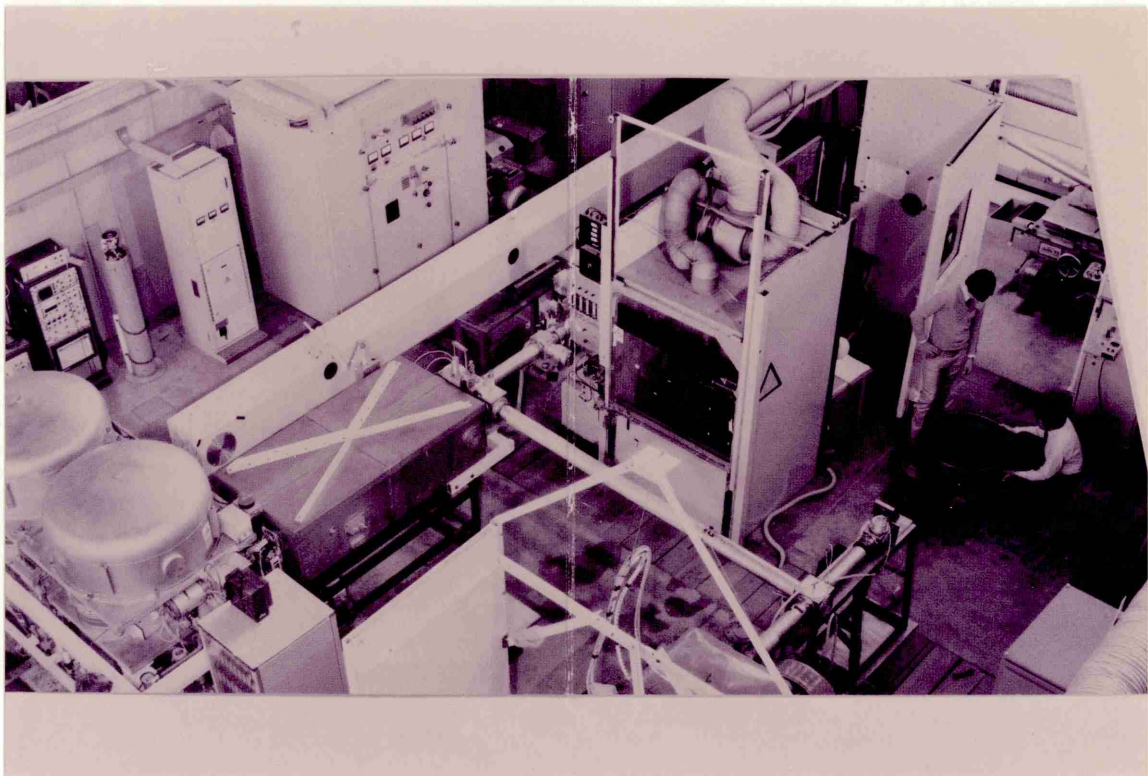


Fig. 4.2 - CL10 laser

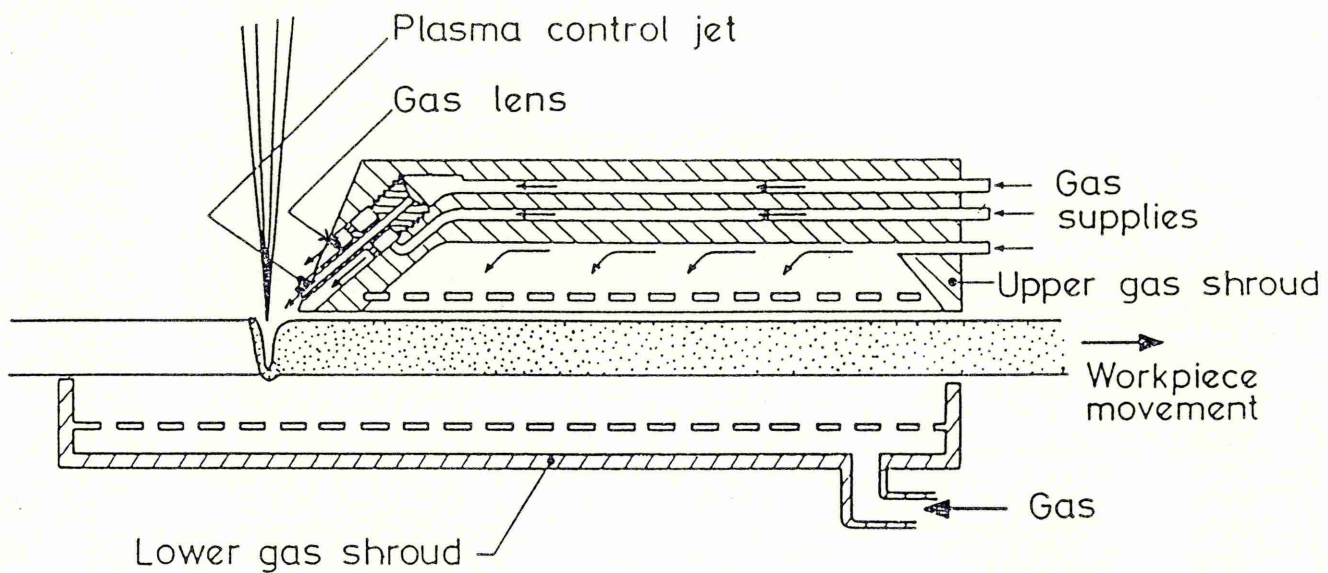


Fig. 4.3 - Culham's standard plasma control and gas shielding device

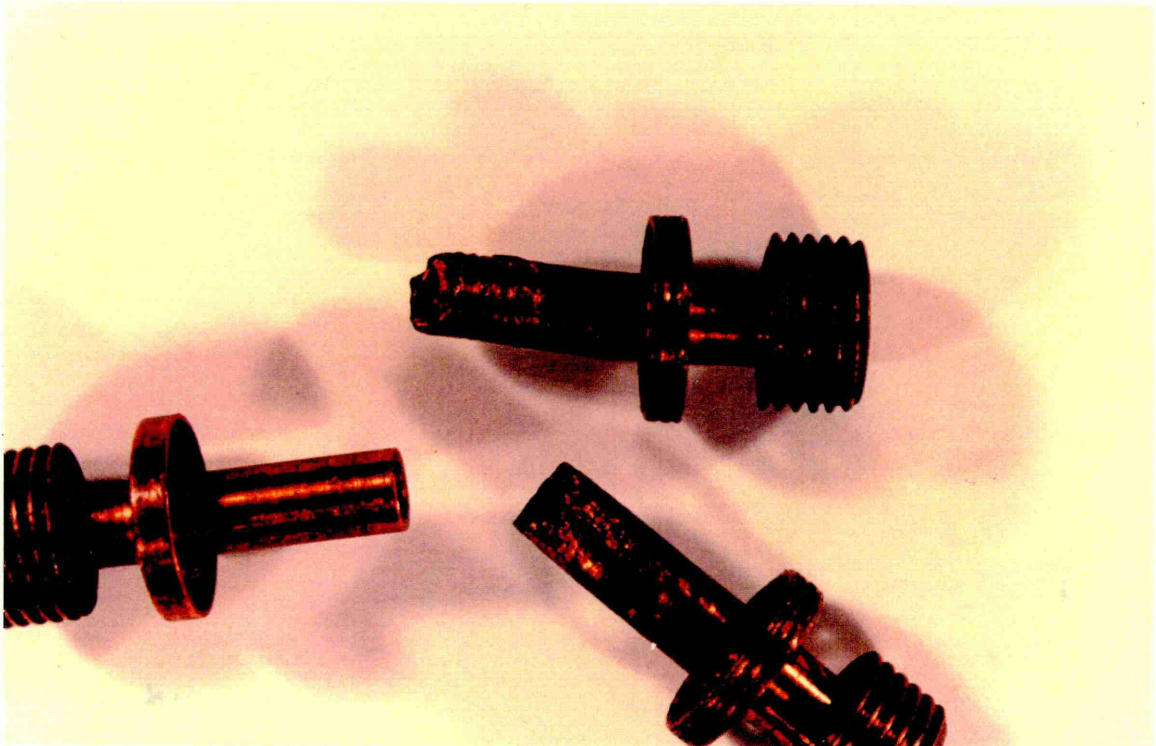


Fig. 4.4 - Profile of a standard and "modified" nozzles

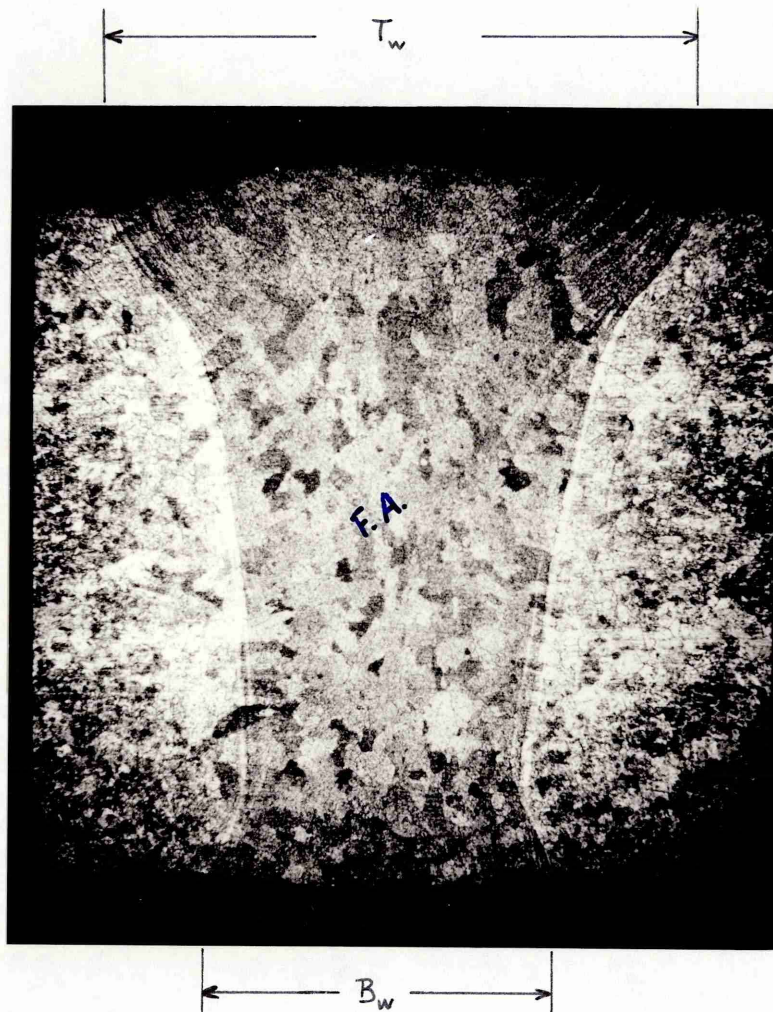
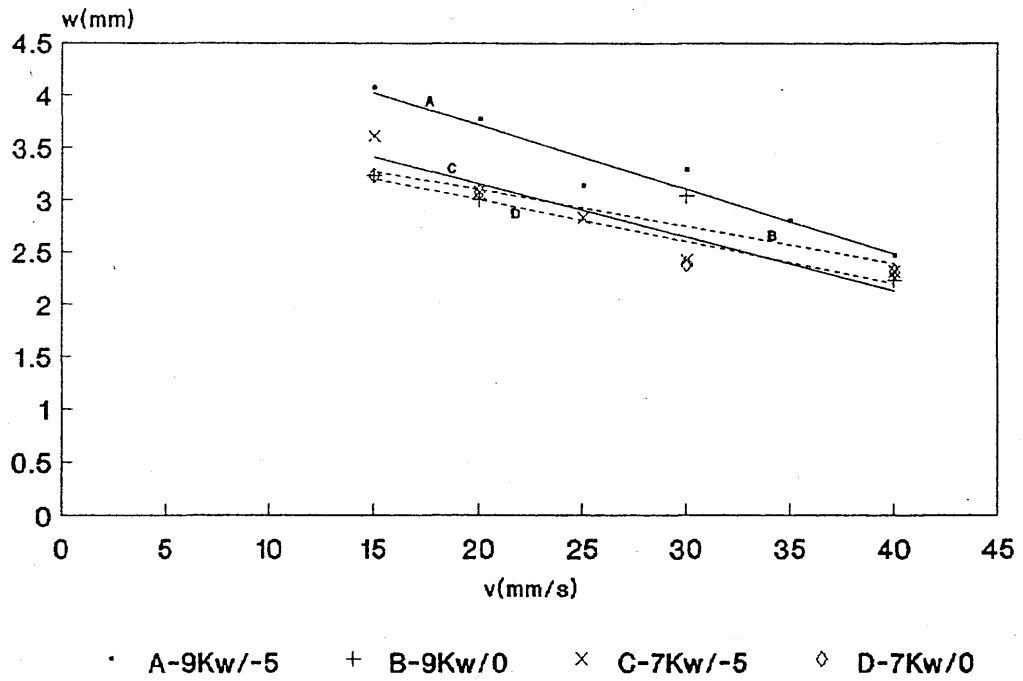


Fig. 4.5 - Weld bead dimensional parameters

COPPER WELDING BY LASER



COPPER WELDING BY LASER

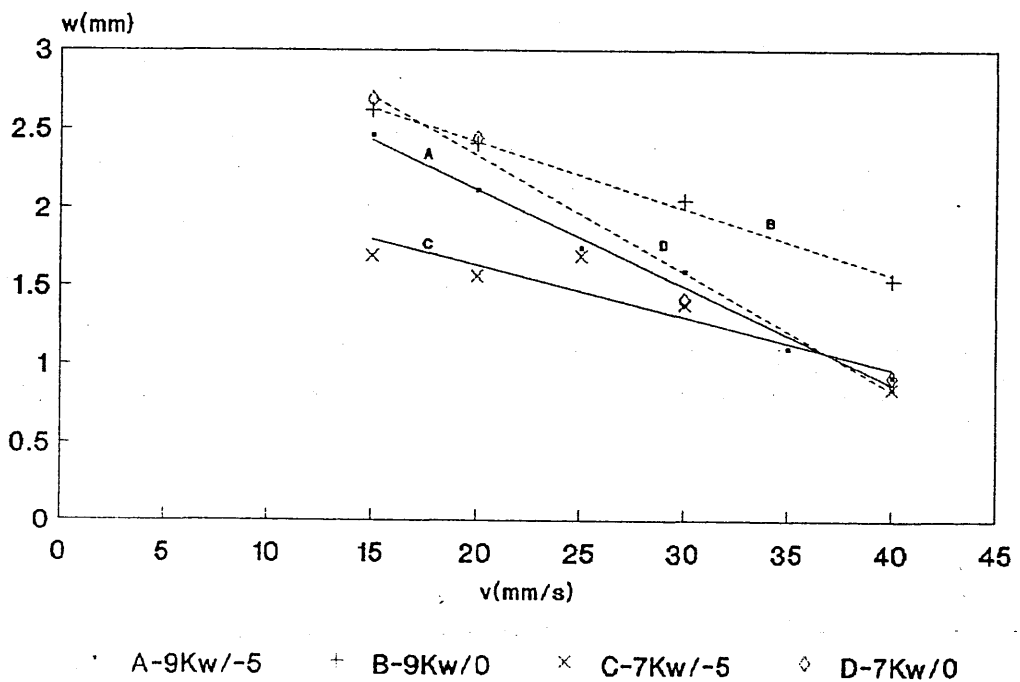


Fig. 4.6 - Effect of the welding speed, beam power and focal position on face bead (upper) and root bead widths

COPPER WELDING BY LASER

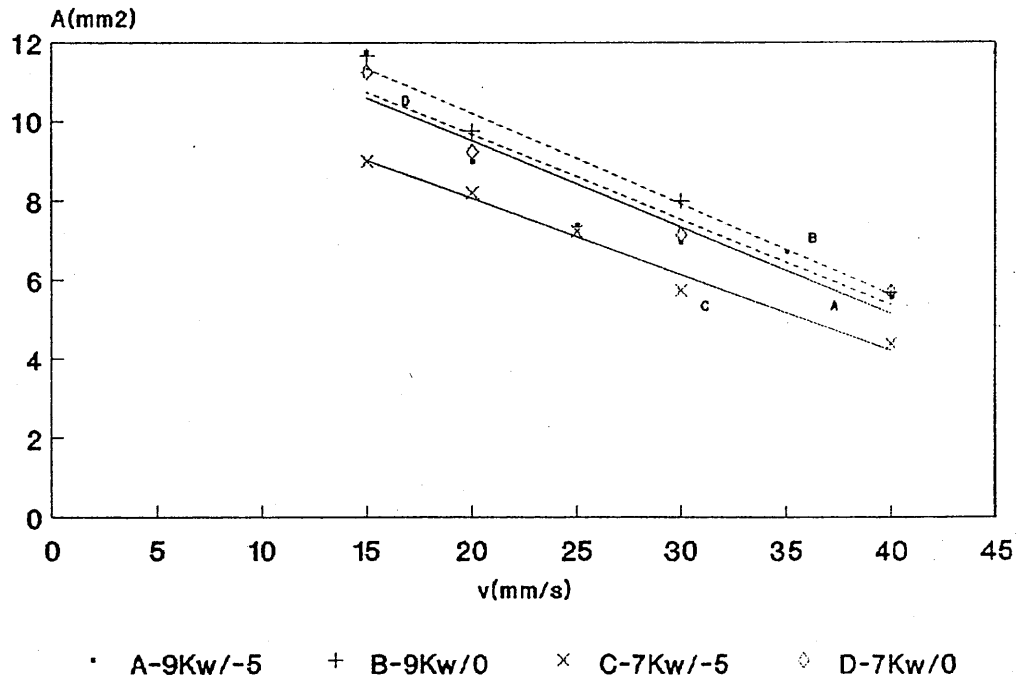


Fig. 4.7 - Effect of the welding speed, beam power and focal position on fusion area



Fig. 4.8 - Influence of beam power, focal position and welding speed on weld bead profiles

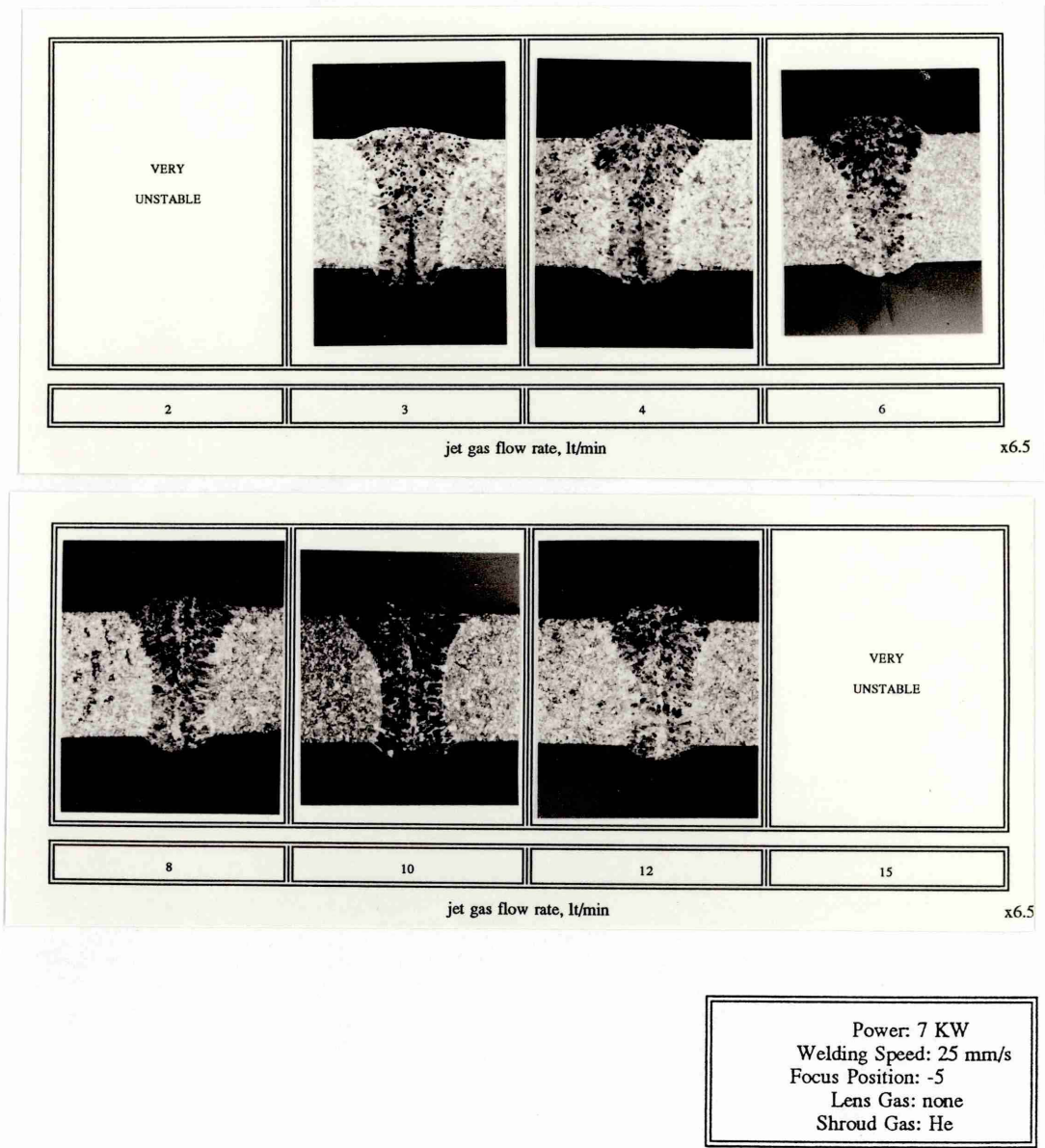
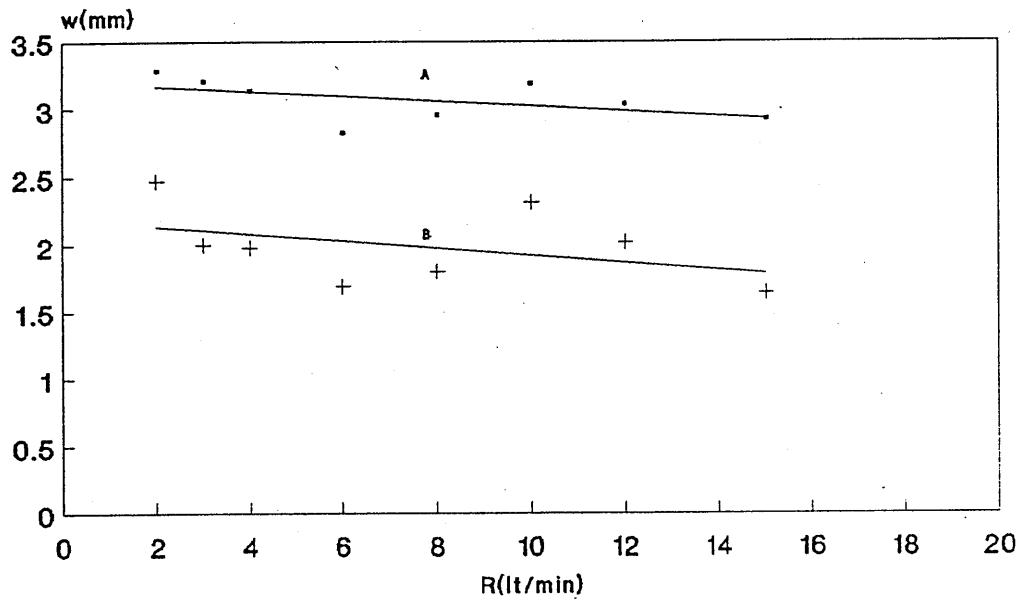


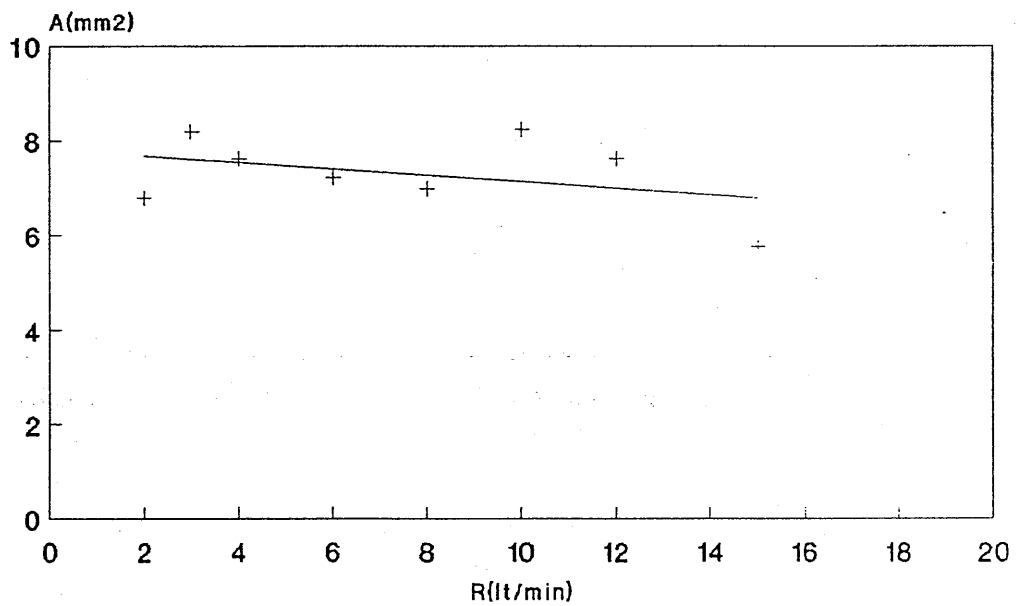
Fig. 4.9 - Influence of the flow rate of N₂ as plasma control gas on bead characteristics

COPPER WELDING BY LASER



• A-top width + B-bottom width

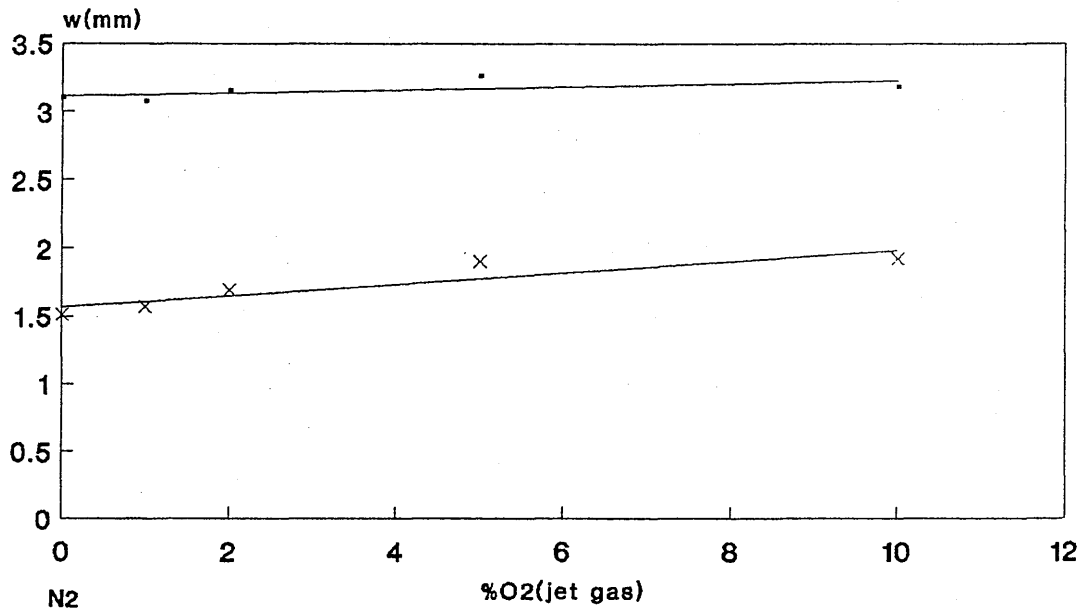
COPPER WELDING BY LASER



+ fusion area

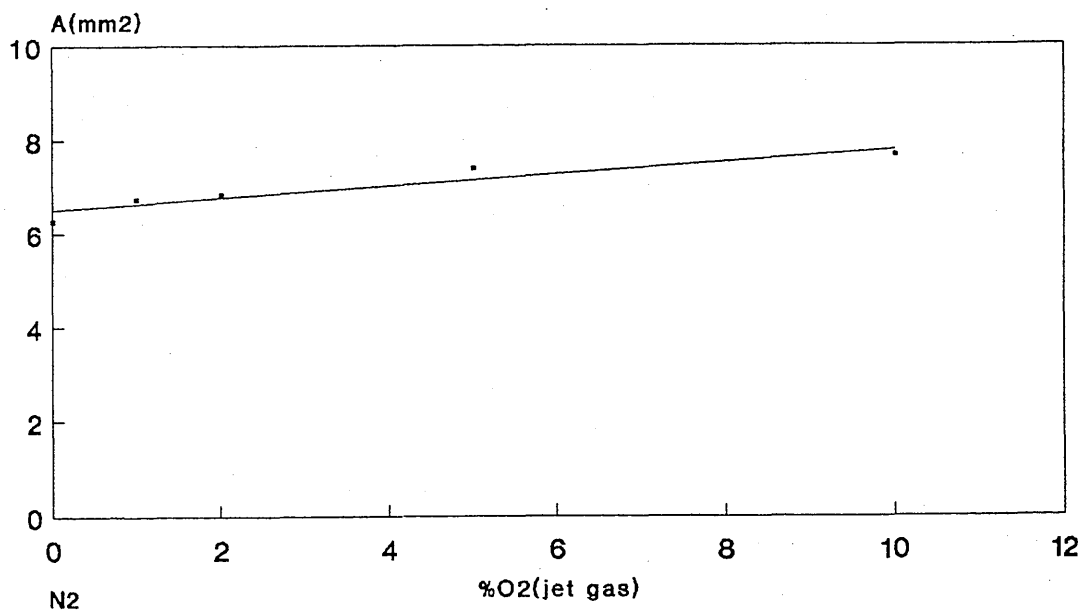
Fig. 4.10 - Effect of gas jet flow rate on the face and root bead widths and fusion area

COPPER WELDING BY LASER



• A- face width × B- root width

COPPER WELDING BY LASER



• fusion area

Fig. 4.11 - Effect of the addition of O₂ to N₂ (gas jet) on the face and root widths and fusion area

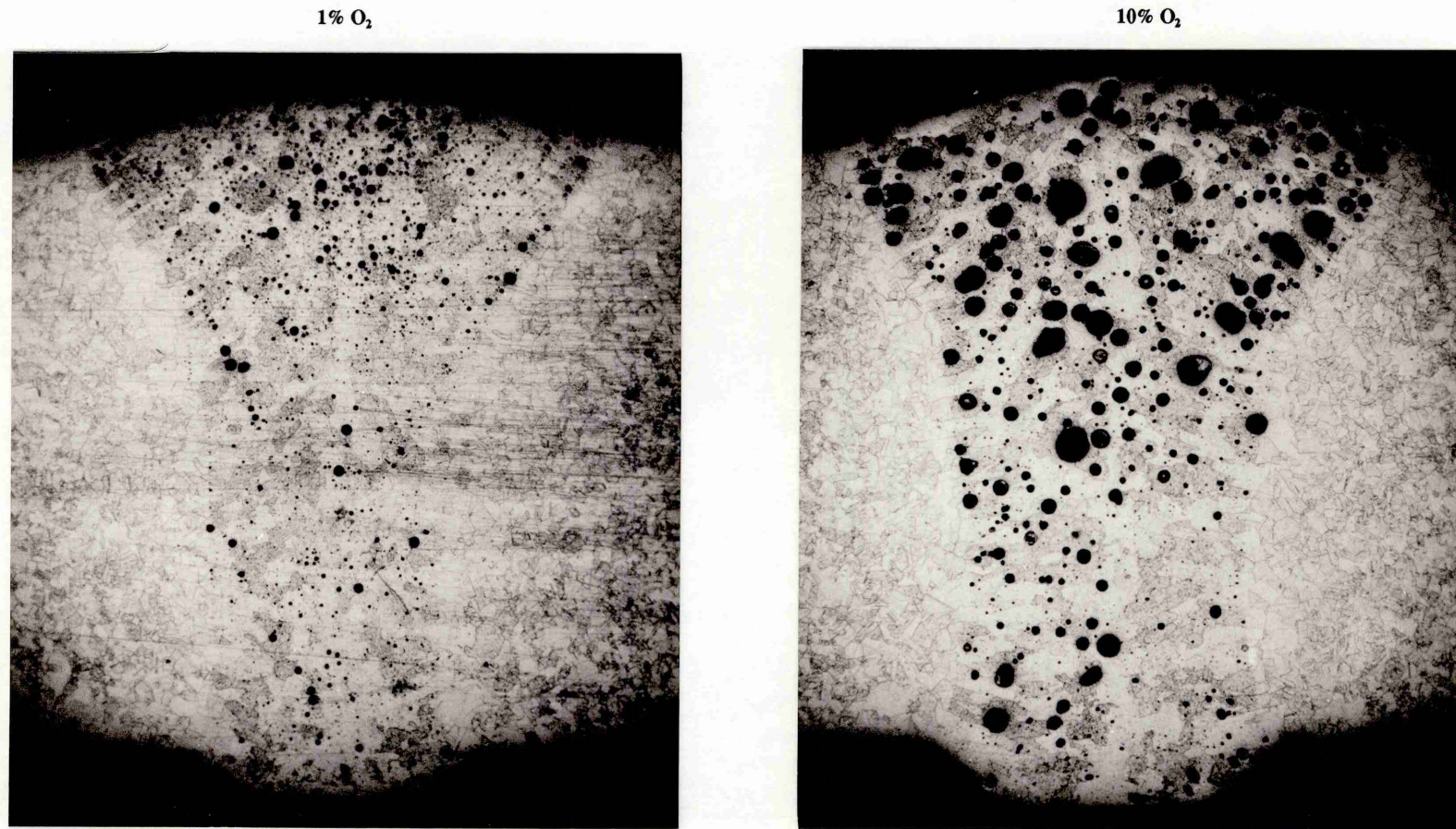
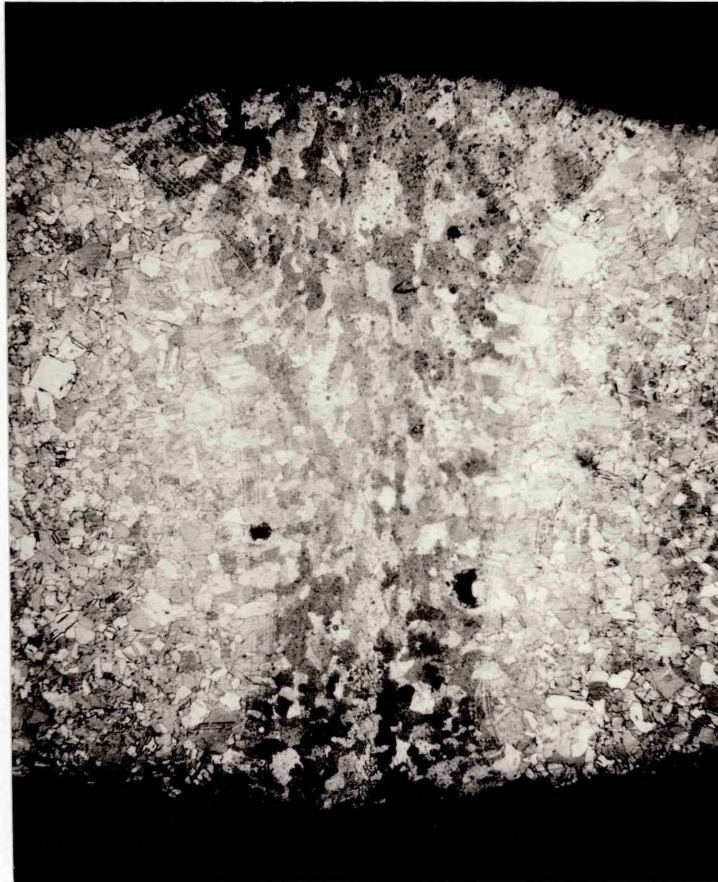


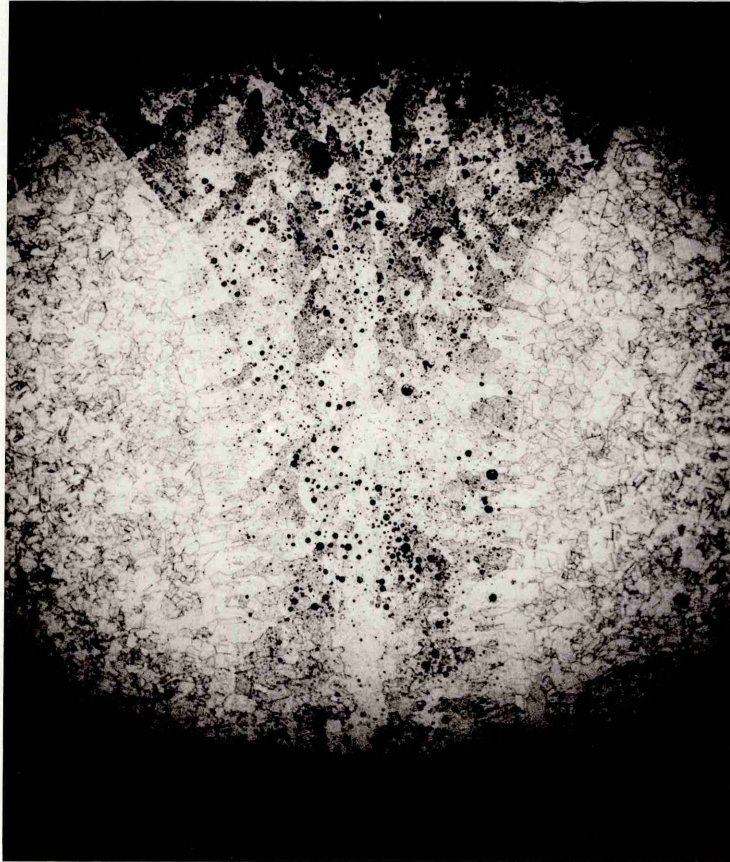
Fig. 4.12 - Effect of the O₂ content mixed in N₂ in the porosity level



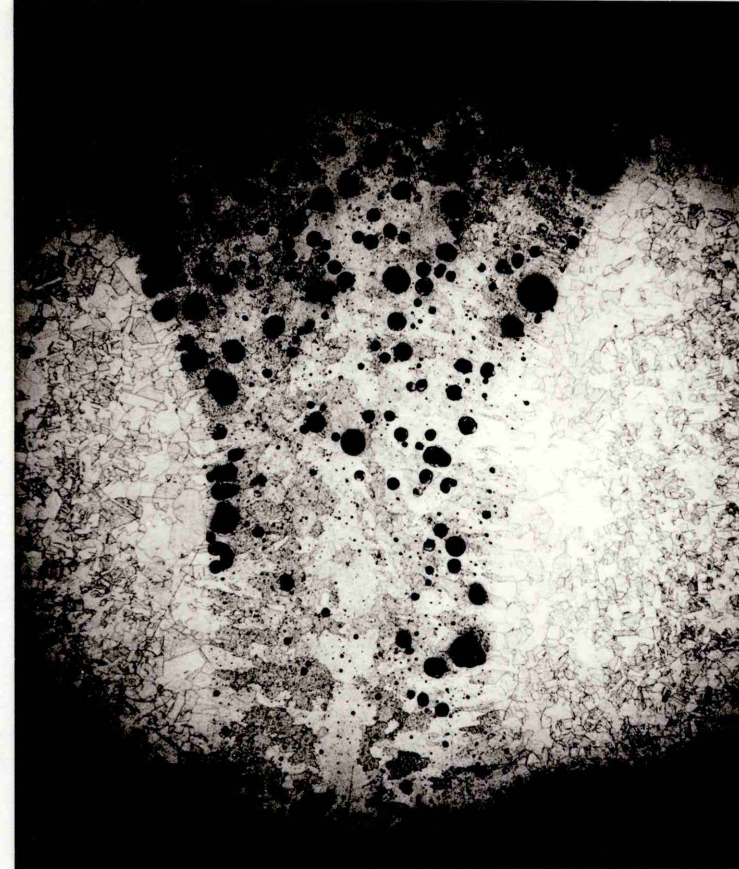
Power: 7 KW
Welding Speed: 25 mm/s
Focus Position: -5
Jet Gas: N ₂ (10 lt/min)
Lens Gas: N ₂ (10 lt/min)
Shroud Gas: He (100 lt/min)

Fig. 4.13 - Effect of the use of a gas lens (N₂) on the weld bead morphology and porosity

with gas lens



without gas lens

**Fig. 4.14 - Comparison of weld cross sections obtained with and without gas lens**

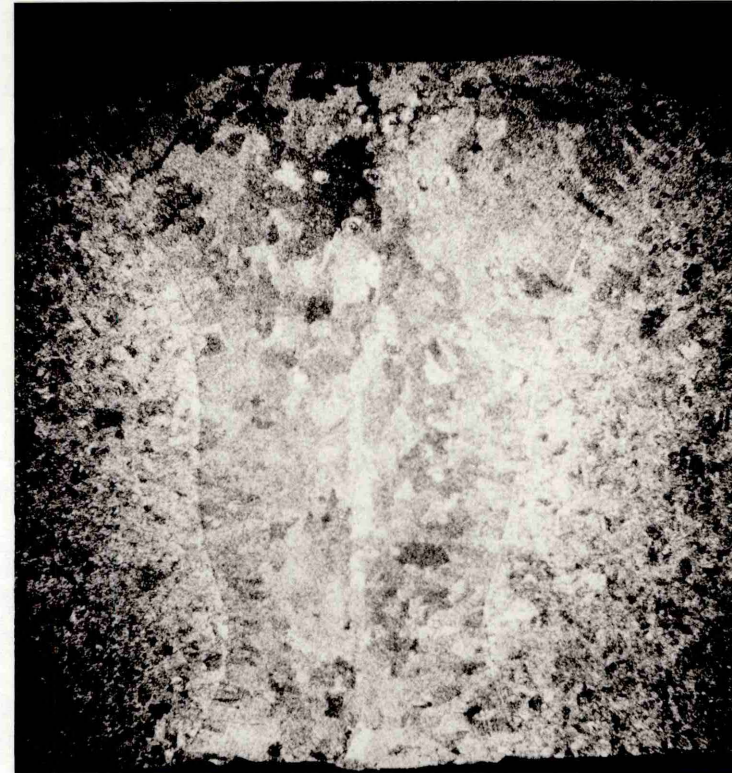
$R_1:6; R_2:10; R_3:20$ (lt/min) $R_1:6; R_2:5; R_3:10$ (lt/min)

Fig. 4.15A - Inconsistent results with gas lens (factorial design series)

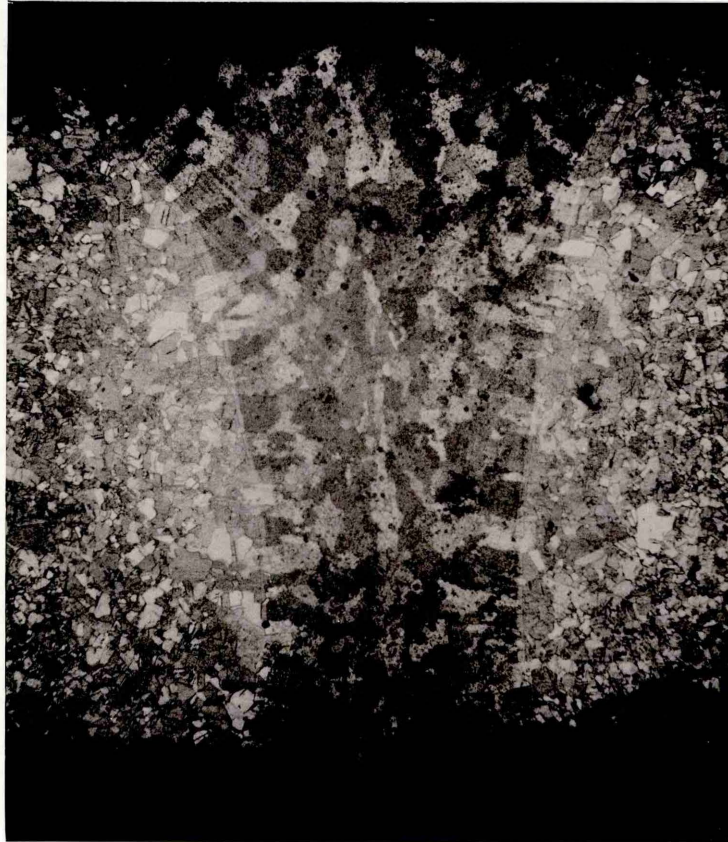
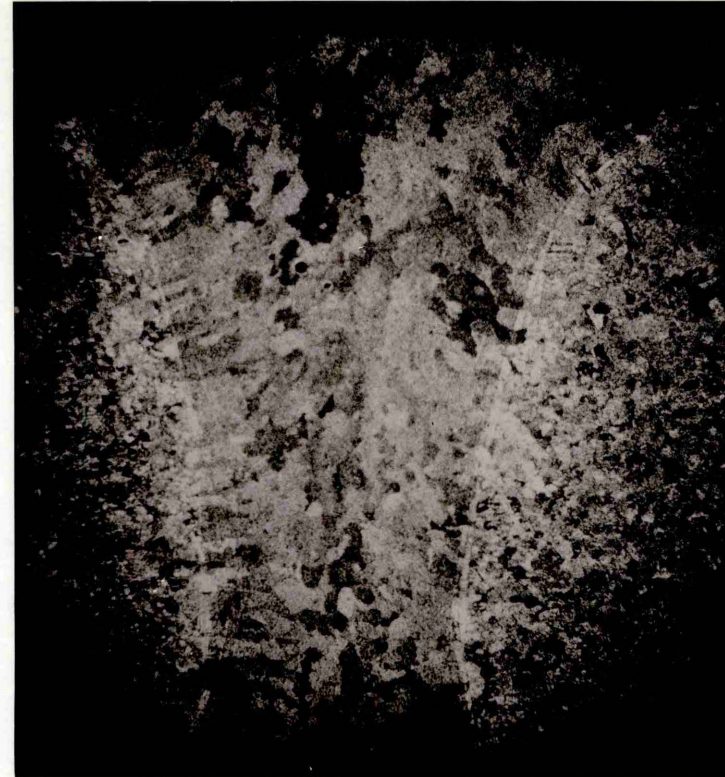
$R_1:8; R_2:5; R_3:10$ (lt/min) $R_1:8; R_2:10; R_3:10$ (lt/min)

Fig. 4.15B - Inconsistent results with gas lens (factorial design series)

TABLE 4.2 - Experimental parameters for determination of the best welding conditions

Weld	P	v	Foc	Jet gas	R1	Lens gas	R2	Shroud gas	R3
No	(Kw)	(mm/s)	(mm)	Type	(lt/min)	Type	(lt/min)	Type	(lt/min)
1	9	15	-5	N2	6	none		He	100
2	9	20	-5	N2	6	none		He	100
3	9	25	-5	N2	6	none		He	100
4	9	30	-5	N2	6	none		He	100
5	9	35	-5	N2	6	none		He	100
6	9	40	-5	N2	6	none		He	100
7	9	15	0	N2	6	none		He	100
8	9	20	0	N2	6	none		He	100
9	9	30	0	N2	6	none		He	100
10	9	40	0	N2	6	none		He	100
11	7	15	-5	N2	6	none		He	100
12	7	20	-5	N2	6	none		He	100
13	7	25	-5	N2	6	none		He	100
14	7	30	-5	N2	6	none		He	100
15	7	40	-5	N2	6	none		He	100
16	7	15	0	N2	6	none		He	100
17	7	20	0	N2	6	none		He	100
18	7	30	0	N2	6	none		He	100
19	7	40	0	N2	6	none		He	100
20	7	25	-5	N2	2	none		He	100
21	7	25	-5	N2	3	none		He	100
22	7	25	-5	N2	4	none		He	100
23	7	25	-5	N2	8	none		He	100
24	7	25	-5	N2	10	none		He	100
25	7	25	-5	N2	12	none		He	100
26	7	25	-5	N2	15	none		He	100
27	7	25	-5	N2	10	N2	10	He	100
28	7	25	-5	N2	10	N2	10	He	100
29	7	25	-5	N2	10	N2	10	He	100
30	7	25	-5	N2+1%O2	10+0.1	N2	10	He	100
31	7	25	-5	N2+2%O2	10+0.2	N2	10	He	100
32	7	25	-5	N2+5%O2	10+0.5	N2	10	He	100
33	7	25	-5	N2+10%O2	10+1.0	N2	10	He	100

TABLE 4.2 - Experimental parameters for determination of the best welding conditions (cont.)

Weld	P	v	Foc	Jet gas	R1	Lens gas	R2	Shroud gas	R3
No	(Kw)	(mm/s)	(mm)	Type	(lt/min)	Type	(lt/min)	Type	(lt/min)
34	7	25	-5	N2	10	N2	10	N2	10
35	7	25	-5	N2	10	N2	10	N2	20
36	7	25	-5	N2	10	N2	10	N2	40
37	7	25	-5	N2	10	none		N2	10
38	7	25	-5	N2	10	none		N2	20
39	7	25	-5	N2	10	none		He	100
40	7	25	0	N2	10	none		He	100
41	7	25	-5	N2	10	none		Ar	20
42	7	25	-5	N2	10	none		Ar	40
43	7	25	-5	Ar	10	none		Ar	40
44	7	25	-5	Ar	6	none		Ar	40
45	7	25	-5	Ar+10%N2	6+0.6	none		Ar	40
46	7	25	-5	Ar+20%N2	6+1.2	none		Ar	40
47	7	25	-5	Ar+20%N2	6+1.2	none		He	100
48	7	25	-5	Ar	6	none		He	100
49	7	25	-5	Ar	6	none		He	100
50	7	25	-5	Ar+20%N2	6+1.2	none		He	100
51	7	15	-5	Ar	10	none		He	100
52	7	20	-5	Ar	10	none		He	100
53	7	25	-5	Ar	10	none		He	100

TABLE 4.3 - Experimental parameters (factorial design) for optimization of the welding process

Weld No	P (Kw)	v (mm/s)	foc (mm)	Jet gas Type	R1 (lt/min)	Lens gas Type	R2 (lt/min)	Shroud gas Type	R3 (lt/min)
1	7	20	-5	N2	6	N2	5	N2	20
2	7	25	-5	N2	6	N2	5	N2	10
3	7	20	-2	N2	6	N2	5	N2	10
4	7	25	-2	N2	6	N2	5	N2	20
5	7	20	-5	N2	8	N2	5	N2	10
6	7	25	-5	N2	8	N2	5	N2	20
7	7	20	-2	N2	8	N2	5	N2	20
8	7	25	-2	N2	8	N2	5	N2	10
9	7	20	-5	N2	6	N2	10	N2	10
10	7	25	-5	N2	6	N2	10	N2	20
11	7	20	-2	N2	6	N2	10	N2	20
12	7	25	-2	N2	6	N2	10	N2	10
13	7	20	-5	N2	8	N2	10	N2	20
14	7	25	-5	N2	8	N2	10	N2	10
15	7	20	-2	N2	8	N2	10	N2	10
16	7	25	-2	N2	8	N2	10	N2	20
17	7	20	-5	N2	6	N2	5	N2	10
18	7	25	-5	N2	6	N2	5	N2	20
19	7	20	-2	N2	6	N2	5	N2	20
20	7	25	-2	N2	6	N2	5	N2	10
21	7	20	-5	N2	8	N2	5	N2	20
22	7	25	-5	N2	8	N2	5	N2	10
23	7	20	-2	N2	8	N2	5	N2	10
24	7	25	-2	N2	8	N2	5	N2	20
25	7	20	-5	N2	6	N2	10	N2	20
26	7	25	-5	N2	6	N2	10	N2	10
27	7	20	-2	N2	6	N2	10	N2	10
28	7	25	-2	N2	6	N2	10	N2	20
29	7	20	-5	N2	8	N2	10	N2	10
30	7	25	-5	N2	8	N2	10	N2	20
31	7	20	-2	N2	8	N2	10	N2	20
32	7	25	-2	N2	8	N2	10	N2	10

CHAPTER IV

RESEARCH PROGRAMME
CO₂ LASER WELDING OF COPPER

TABLE 4.4 - Dimensions of the weld beads produced in the experimental set for determination of the best welding parameters

Weld No	Tw1 (mm)	Tw2 (mm)	Tw3 (mm)	Tw(mean) (mm)	Bw1 (mm)	Bw2 (mm)	Bw3 (mm)	Bw(mean) (mm)	A1 (mm ²)	A2 (mm ²)	A3 (mm ²)	A(mean) (mm ²)
1	4.07			4.07	2.46			2.46	11.73			11.73
2	3.61	3.85	3.85	3.77	1.87	2.31	2.15	2.11	8.36	9.32	9.20	8.96
3	2.77	3.23	3.38	3.13	1.69	1.85	1.69	1.74		7.12	7.59	7.36
4	2.92	3.54	3.38	3.28	1.38	1.92	1.46	1.59	6.16	7.63	7.01	6.93
5	2.76	2.85	2.77	2.79	1.62		1.69	1.10	6.41	7.28	6.42	6.70
6	2.46			2.46	0.92			0.92	5.56			5.56
7	3.23			3.23	2.62			2.62	11.67			11.67
8	2.85	3.08	3.08	3.00	2.31	2.46	2.46	2.41	9.62	9.38	10.26	9.75
9	2.77	3.08	3.23	3.03	2.15	2.00	2.00	2.05	7.60	8.40	7.93	7.98
10	2.23			2.23	1.54			1.54	5.69			5.69
11	3.61			3.61	1.69			1.69	8.98			8.98
12	2.92	3.38	2.92	3.07	1.38	1.54	1.77	1.56	7.87	7.78	8.93	8.19
13	2.77	2.85	2.85	2.82	1.92	1.77	1.38	1.69	7.13	7.10	7.43	7.22
14	2.23	2.46	2.54	2.41	1.38	1.38	1.38	1.38	5.39	5.92	5.89	5.73
15	2.31			2.31	0.85			0.85	4.38			4.38
16	3.23			3.23	2.69			2.69	11.24			11.24
17	3.07	3.23	2.92	3.07	2.54	2.46	2.31	2.44	9.09	9.14	9.44	9.22
18	2.31	2.46	2.38	2.38	1.38	1.38	1.46	1.41	6.67	6.99	7.74	7.13
19	2.31			2.31	0.92			0.92	5.70			5.70
20	3.08	3.23	3.54	3.28		2.62	2.31	2.47	4.17	8.24	7.92	6.78
21	2.92	3.23	3.46	3.20	2.00	2.08	1.92	2.00	8.00	8.35	8.23	8.19
22	3.08	3.15	3.15	3.13	2.00	1.85	2.08	1.98	7.31	7.63	7.90	7.61
23	2.92	2.85	3.08	2.95	1.69	1.85	1.85	1.80	6.52	7.08	7.35	6.98
24	3.23	3.08	3.23	3.18	2.31	2.23	2.38	2.31	7.80	8.35	8.55	8.23
25	2.92	3.08	3.08	3.03	2.00	2.15	1.92	2.02	7.51	7.67	7.64	7.61
26	3.08	2.77	2.92	2.92	1.54	1.54	1.85	1.64	5.89	5.87	5.52	5.76
27	2.77	2.77	2.77	2.77	1.69	1.46	1.46	1.54	5.78	5.96	5.79	5.84
28	3.07	2.92	2.77	2.92	1.69	1.38	1.54	1.54	6.62	6.10	6.00	6.24
29	2.85	3.23	3.23	3.10	1.46	1.69	1.38	1.51	5.60	6.05	7.14	6.26
30	2.92	2.92	3.38	3.07	1.62	1.54	1.54	1.57	6.49	6.77	6.89	6.72
31	3.07	3.08	3.31	3.15	1.77	1.69	1.62	1.69	6.78	7.10	6.59	6.82
32	3.08	3.31	3.38	3.26	2.00	1.85	1.85	1.90	7.10	7.31	7.70	7.37
33	3.23	3.23	3.08	3.18	1.85	2.00	1.92	1.92	7.52	7.57	7.81	7.63

CHAPTER IV

RESEARCH PROGRAMME
CO₂ LASER WELDING OF COPPER

TABLE 4.4 - Dimensions of the weld beads produced in the experimental set for determination of the best welding parameters (cont.)

Weld	Tw1	Tw2	Tw3	Tw(mean)	Bw1	Bw2	Bw3	Bw(mean)	A1	A2	A3	A(mean)
No	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm ²)	(mm ²)	(mm ²)	(mm ²)
34	3.08	3.31	3.23	3.21	1.31	1.46	1.31	1.36	6.73	7.73	6.80	7.09
35	3.08	3.15	3.15	3.13	1.08	1.69	1.46	1.41	6.62	7.42	8.52	7.52
36	3.08	3.31	3.00	3.13	1.26	1.38	1.23	1.29	7.07	7.00	6.31	6.79
37	3.23	3.23	3.15	3.20	2.00	1.69	2.00	1.90	7.37	8.03	7.88	7.76
38	3.15	3.23	2.92	3.10	2.00	1.85	2.15	2.00	7.90	8.42	7.79	8.04
39	2.92	2.92	2.85	2.90	1.92	1.69	1.62	1.74	7.64	7.24	7.59	7.49
40	3.23	3.00	3.31	3.18	1.85	2.54	2.46	2.28	7.51	9.90	9.37	8.93
41	2.77	3.00	2.85	2.87	1.46	1.54	1.46	1.49	6.83	7.45	7.77	7.35
42	2.92	2.92	3.00	2.95	1.38	1.54	1.54	1.49	6.83	6.85	7.44	7.04
43	2.31	2.46	2.46	2.41	1.11	1.38	1.54	1.34	5.99	6.61	6.57	6.39
44	2.92	2.77	2.92	2.87	1.23	1.54	1.54	1.44	7.21	7.27	7.86	7.45
45	2.92	2.77	2.85	2.85	1.23	1.38	1.38	1.33	7.14	7.57	7.62	7.44
46	2.61	3.15	2.85	2.87	1.46	1.46	1.46	1.46	6.95	7.11	7.30	7.12
47	2.77	3.08	2.77	2.87	1.77	1.77	1.69	1.74	6.46	7.26	7.00	6.91
48	2.77	2.46	2.77	2.67	1.57	1.38	1.61	1.52	5.88	6.93	6.12	6.31
49	2.00			2.00	1.15			1.15	5.14			5.14
50	2.77			2.77	1.69			1.69	6.42			6.42
51	2.92			2.92	2.08			2.08	8.28			8.28
52	2.92			2.92	2.15			2.15	7.05			7.05
53	2.92			2.92	2.15			2.15	7.46			7.46

CHAPTER IV

RESEARCH PROGRAMME
CO₂ LASER WELDING OF COPPER

TABLE 4.5 - Dimensions of the weld belds produced in the set of experimentsfor optimization of the welding process

Weld	Tw1	Tw2	Tw3	Tw(mean)	Bw1	Bw2	Bw3	Bw(mean)	A1	A2	A3	A (mean)
No	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm ²)	(mm ²)	(mm ²)	(mm ²)
1	3.06	3.23	3.40	3.23	1.91	1.79	1.83	1.84	7.14	7.32	7.23	7.23
2	2.94	2.68	2.64	2.75	1.36	1.40	1.57	1.44	5.50	6.03	5.76	5.76
3	3.40	2.85	3.06	3.10	1.87	1.70	1.49	1.69	7.20	5.52	6.79	6.50
4	2.72	2.80	2.85	2.79	1.49	1.53	1.53	1.52	5.27	5.88	5.87	5.67
5	2.47			2.47	1.87			1.87				
6												
7	2.80	2.80	2.85	2.82	1.74	1.70	1.91	1.78	6.35	6.87	6.81	6.68
8	2.89	3.02	2.59	2.83	1.45	1.45	1.45	1.45	5.86	6.10	5.61	5.86
9	3.19	3.10	3.19	3.16	1.66	1.70	1.74	1.70	6.73	7.50	7.07	7.10
10	2.89	2.80	3.02	2.90	1.15	1.06	1.28	1.16	5.67	5.63	4.65	5.32
11	3.32	3.36	3.28	3.32	1.83	1.83	1.83	1.83	7.19	6.99	7.13	7.10
12	2.85	2.89	2.85	2.86	1.53	1.62	1.49	1.55	5.72	6.03	5.76	5.84
13	3.28	3.32	3.28	3.29	1.74	1.91	1.79	1.81	6.96	6.80	6.90	6.88
14	3.06	3.23	3.06	3.12	1.66	1.70	1.45	1.60	6.25	6.00	5.82	6.02
15	2.98	2.94	2.98	2.97	1.66	2.04	1.49	1.73	6.79	6.95	6.75	6.83
16	3.10	2.98	2.89	2.99	1.74	1.70	1.53	1.66	6.48	6.21	5.96	6.22
17	2.85	2.68	2.34	2.62	1.62	2.09	2.26	1.99	6.64	7.04	6.79	6.82
18	3.06	3.19		3.13	1.53	1.79		1.66	6.18	6.36		6.27
19	3.19	3.23	3.32	3.25	1.96	1.70	1.87	1.84	6.75	7.00	7.17	6.97
20	2.77	2.98	2.89	2.88	1.96	1.57	1.70	1.74	7.42	5.89	6.25	6.52
21	3.19	3.15	3.28	3.21	1.66	1.70	1.70	1.69	6.26	6.48	6.86	6.53
22	3.10	3.06	2.98	3.04	1.23	1.19	1.28	1.23	6.17	5.92	6.78	6.29
23	3.19	3.28	3.40	3.29	1.87	2.13	2.00	2.00	7.51	7.32	7.02	7.28
24	2.94	2.85	3.02	2.94	1.66	1.66	1.36	1.56	5.88	6.10	5.78	5.92
25	3.32	3.23	3.36	3.30	1.66	1.70	1.57	1.64	7.18	7.18	7.24	7.20
26	2.80	2.98	2.89	2.89	1.19	1.40	1.28	1.29	5.65	6.24	5.99	5.96
27	3.32	3.23	3.15	3.23	2.09	1.79	1.66	1.85	6.86	7.12	6.18	6.72
28	3.06	2.94	3.02	3.01	1.19	1.53	1.40	1.37	5.48	5.88	5.93	5.76
29	2.89	2.77	2.64	2.77	2.26	2.13	1.49	1.96	6.77	7.43	6.11	6.77
30												
31	3.23	3.28	3.53	3.35	1.79	1.91	1.83	1.84	6.64	7.22	7.22	7.03
32	3.06	2.98	2.85	2.96	1.14	1.53	1.49	1.39	6.25	5.89	5.70	5.95

CHAPTER V

RESEARCH PROGRAMME

- PLASMA CONTROL GAS FLOW VISUALISATION -

5.1 INTRODUCTION

The conditions under which the coupling of a CO₂ laser beam into copper took place were presented and discussed in chapter IV.

As expected, the coupling process was the key to the successful welding of copper by laser. However, it became clear from the experimental work described in chapter IV, that a relationship between the coupling and the plasma control gas flow existed.

This constituted a new feature, whose exploration seemed extremely important due to the significance of the relationship detected, and because it could be a way of finding answers for some of the questions concerning the interaction of high intensity laser beams and copper.

Some hypotheses were put forward in Chapter IV to explain this relationship; these relied on the probable effects of the fluid dynamics over the interaction zone. These effects are related with the streaming of gas after it leaves the nozzle, i.e., the gas flow patterns.

Since, it became necessary to know the behaviour of the gas, as it issued from nozzles with different tip geometries, some means of visualising the gas flow patterns (i.e., turbulence, velocity, etc.) appeared to be a logical step in the direction of the understanding of the relationship between coupling behaviour and plasma control gas flow, and therefore of the coupling phenomenon.

A gas flow visualisation study was then planned with the aim of:

- a) Visualise the path of the gas jet as it issues from the jet nozzle, in order to examine the gas flow behaviour. (The visualisation to be made using nozzles with different tip geometries as well as different gases and flow rates);
- b) Visualise the flow stream using a gas lens. (The objective being to show the effect of the use of a gas lens on the gas jet, on the final gas flow behaviour).

The aim of this 2nd experimental investigation was to acquire a clear understanding of gas flow patterns in the laser beam/copper interaction zone, which would enable determination of their relationship with the coupling behaviour and thus the best conditions for the assist gases to produce good quality welds.

5.2 FLOW VISUALISATION TECHNIQUES

5.2.1 General survey

In welding, flow visualisation techniques have been devised for research and development purposes, such as improving gas nozzle design, but they are also practical ways of assessing gas shielding efficiency; with well defined objectives, either technical and/or economical.

The gas flow patterns can be made visible by different methods, although for the study of gas shielding in welding the following experimental optical methods are widely used:

- Schlieren method
- Shadow System
- Smoke tracer methods
- Holographic Interferometry

5.2.1.1 Schlieren Method

The Schlieren method is an optical technique that relies on densities changes of a gas due to variations in either its composition, temperature or pressure.

The density changes that occur in the motion of a gas are accompanied by changes in its index of refraction, which causing deviation of light allows the pattern to be recorded photographically.

A Schlieren system can have different practical forms, as illustrated in fig. 5.1 a typical experimental arrangement for the Schlieren analysis. A slit light source located at the focal point of the first mirror (or lens), produces a parallel beam of light, which after striking the second mirror (or lens) is reflected on to a knife edge located at the focal point of this mirror and then forms an image on the receiving system, comprising a viewing screen or photographic film, which is located behind the knife edge. When the knife edge is at the correct location and is made to intercept the image of the slit light source, the field on a

screen is uniformly darkened. But if a disturbed gas, such as a nozzle issuing a gas is placed in the path of the parallel beam, then some of the previously parallel rays will be deflected because the refractive index of the disturbance is different from that of the ambient, still air. These deflected rays are no longer concentrated at the focal point, and therefore when reflected by the second mirror, will pass over, or be intercepted by the knife edge. Hence, a change in the pattern of illumination occurs in the receiving system, and dark areas appear where deviated rays have been intercepted by the knife edge, and bright areas appear where such rays have not been intercepted, resulting in an image of the gas flow pattern.

The image contrast is proportional to density changes in the gas. Greater variations in density results in sharper images. At constant temperature this method is able to detect compositional variations or areas of local turbulence in the gas, and allows visualisation of the flow characteristics.

The method has been used in welding under non arc and arc conditions to study the effect of the nozzle design on shielding gas flow patterns and shielding effectiveness [Starchenko et al., 1968 ; Stepanov, 1977; Lapteva, 1972], and also to study the fluid flow behaviour of different shielding gases in order to determine their shielding properties and enable a choice of appropriate gas from the standpoint of quality and cost [Moen et Gibson, 1952; Gibson, 1953].

The method presents some drawbacks in the visualisation and interpretation of results when the gas flow analysis is intended to be done with gases having densities or refractive indexes close to that of air (table 5.1). This is particularly critical for experimentation carried out at room temperature.

Thus the presence of an arc or an heating system for the gas is desirable not only for the assessment under realistic welding conditions but also for improvement in the clarity of the Schlieren patterns produced.

The presence of an arc also gives rise to some problems. Gas issuing from the nozzle rebounds after striking the workpiece and causes a confused flow pattern to be produced. This can be overcome by inverting the holder and maintaining the arc on the end of a 3mm diameter water cooled tube which offers a minimal degree of opposition to the gas flow [Moen et Gibson, 1952].

Heating of the workpiece and gas by an arc can also create interpretation problems because the surrounding air is indirectly heated, which causes a change in its density and, thus it becomes visible on the screen or film. In addition, the effect of the shielding gas rebounding from the workpiece or rising because of density changes, can make the results more confusing. This problem can be minimised if the nozzle is placed in a very gentle, laminar air current which carries off the rising and rebound gas [Gibson, 1953].

Improvement on the clarity and interpretation of Schlieren patterns can be achieved by the use of a laser light source [Okada et al., 1979]. The arrangement of the optical system reported by Okada et al. [1979] is shown in fig. 5.2. This experimental device utilises a He-Ne laser as a light source in combination with a band pass filter (nonmetal interference filter) which

passes a very narrow band of light ($\lambda = 632.8 \text{ nm}$) only at the focusing side, this effectively removes almost completely the arc light from the resulting image. Consequently this technique allows the direct observation of the gas flow patterns during arcing, without the difficulties found with other light sources.

Coloured Schlieren pictures can be obtained if a source of white light is used and a prism is placed in front of it so that a spectrum is produced in the focal plane of the second lens or mirror. A slit parallel to the band of the spectrum is then used instead of the knife edge, and the colour of the light passing through on the screen may be adjusted by moving the slit across the spectrum. If the light is deflected by a local gradient of refractive index in the working section, the corresponding spectrum moves across the slit and the image of the optical disturbance changes colour. This method is particularly valuable for visual observations, because the eye is more sensitive to changes of hue than illumination.

Schlieren analysis can provide real time visualisation of shielding gas behaviour under actual welding conditions, but is essentially a laboratory technique since the equipment is expensive, sensitive and requires an environment free from temperature fluctuations or external draughts.

5.2.1.2 Shadow System

The shadow system also utilizes a light source to produce a parallel beam of light which after passing through the disturbance is collected on a transparent screen. The screen is of uniform illumination if the rays do not undergo any deviation, but if the rays pass through a zone with different optical density, they undergo a deviation which changes the intensity of the light on the screen from point to point [Howarth, 1953].

Since the deviations of the rays are proportional to the first derivative of the variation of the density, and the variation of illumination is proportional to the derivative of the deviation, the result is that in the shadow system the variation of the light is proportional to the second derivative of the density (i.e. refractive index) in the same direction.

In practice, the conditions are usually more complicated than the given description suggests. For example, the deflection of the light may cause the light from several points in the disturbance to fall on a common point on the screen. Thus it is only possible to obtain quantitative results from the shadowgraph method under particular conditions. In welding this method seems not to have received acceptance since no reference to its application has been found in the literature.

5.2.1.3 Smoke Method

The introduction of a smoke tracer into the shielding gas is the most commonly used method of qualitatively assessing shielding performance by making the gas stream visible. This is mainly due to the simplicity of the equipment required, which in its most basic form comprises a container fitted with gas inlet and outlet pipes, which contains a slowly burning combustible material.

Tracer particles can be produced by a number of different techniques.

One of the methods used consist in passing the shielding gas through a cylinder containing vaporised machine oil [Gorman,1962; Belkin et al.,1969]. However, at the ambient temperature the oil vapour was found to condense inside the torch (conventional welding) and the droplets subsequently formed caused a distortion of the gas jet. The addition of two oil traps between the smoke generator and the torch reduces this limitation, allowing a number of tests to be performed before the gas jets and nozzle had to be unblocked [Lowery, 1966].

Chemical methods were employed by several researchers for colouring the shielding gas [Reiter, 1967; Dubova, 1963; Kalenskii et al., 1974]. The smoke produced by this method is actually fine particles of titanium dioxide (Ti O_2) formed from the reaction of water vapour in the air with titanium tetrachloride (Ti Cl_4), which also produces hydrogen chlorine gas fumes (which must be locally extracted).

The gas to be studied must be dried prior to entering the flask otherwise the residual moisture content will initiate the reaction, causing the welding torch to become clogged with white powder. The reaction should only take place after the shielding gas (containing Ti Cl_4 vapour) has discharged from the torch. The reaction occurs at the boundary between the shielding gas and the air, clearly revealing the mixing process.

The use of methods in which the shielding gas supply is coloured excludes the presence of an arc because of severe contamination of the gas.

The different techniques using smoke tracers are illustrated in fig. 5.3. The most useful and realistic smoke technique is known as the side flow or external probe method [Lowery, 1966; Salter, 1970]. The trace is only applied to the exterior of the gas shield. A low flow of gas is combined with smoke prior to passing into a narrow probe, the end of which is located close against the side of the shroud (fig. 5.3d). In operation, the smoke simply drifts down the shroud to be carried away on top of the shielding gas, thus highlighting the position and behaviour of the air/shielding gas interface.

The interpretation of the resulting gas flow patterns is simple, since as the smoke is now representing the external atmosphere, the presence of any smoke particles underneath the torch implies that the air has been entrained into the gas shield. On the other hand, the arc and shielding gas flow are not disturbed by the physical action of the observing flow pattern, thus providing a realistic simulation of the conditions present during welding.

5.2.1.4 Holographic Interferometry

Holography, despite being generally associated with the production of three dimensional images for recreative purpose, can also be applied to the study of shielding gas in laboratory.

This method consist in making two exposures of the interference fringes, which arise from the interaction of object and reference beams from the same laser light source, on the same photographic plate, both before and after the object has undergone a slight movement. When the resulting developed plate is illuminated, two images are created which lie so close together

that the eye perceives them as one image covered by a pattern of lines which map out surface displacement contours [Trolinger et al., 1983] (fig. 5.4).

The application of this method to welding relies on that the gas column refracts the object beam to a greater or lesser extent than still air. By making exposures of the torch and workpiece area both before and after turning on the shielding gas flow, the gas stream can be visualised by the resulting pattern of light and dark lines which are formed in the holographic image.

As with Schlieren analysis this method produces better results with gases which have refractive indexes significantly different from that of air (e.g. helium; carbon dioxide). In addition, the results from this method contain quantitative information about the density of the gas at any point between the torch and work surface, which is an advantage over the Schlieren method.

The qualitative interpretation of the interference fringes is quite simple, allowing a good distinction between the good and poor shielding arrangements.

TABLE 5.1 - DENSITIES AND REFRACTIVE INDICES
OF THE MOST COMMON SHIELDING GASES

GAS	DENSITY (kg/m ³)	REFRACTIVE INDEX
AIR	1.2045	1.000 292
ARGON (Ar)	1.6610	1.000 281
CARBON DIOXIDE (CO ₂)	1.98	1.000 451
HELIUM (He)	0.1663	1.000 036
NITROGEN (N ₂)	1.1648	1.000 297
OXYGEN (O ₂)	1.3310	1.000 272

From: Tables of Physical and Chemical Constants G.W.C. Kaye & T.H. Laby, 14th ed., 1973

5.3 EXPERIMENTAL PROGRAM

5.3.1 Visualisation of gas jet flow using the Schlieren technique

The Schlieren technique was initially selected due to its extensive use in welding applications and because it seemed the most appropriate technique for the desired analysis. Although, the density and refractive index of nitrogen were not very different from those of air, gradients on the refractive index were expected to be caused by temperature and pressure (gas flow).

The experimental work was carried out in laboratorial and non welding conditions due to the complexity of the system. The tests were made with gases at ambient temperature or slightly heated.

5.3.1.1 Set - up

For the visualisation of the gas jet flow, a Schlieren system similar to that illustrated in fig. 5.5 was used. Two mirror systems, where the main difference was the size of the mirrors, were used.

Nozzles with different bore diameters (e.g., 1, 1.5, 2, 2.5, 3, 3.8 mm) and tip geometries were placed on the Culham's plasma control device (fig. 4.3).

Tests were made using Ar and N₂ gases with flow rates varied in the range 5 to 25 l/min.

A variation of the system illustrated in fig. 5.5, which consisted in the use of a He-Ne laser for light source was also used with the aim of obtaining improved pictures of the gas jet flow patterns.

5.3.1.2 Results

The main results obtained are summarised below:

- With N₂ at the ambient temperature, it was impossible to achieve clear images of the gas flow pattern (fig. 5.6).

Heating of the gas with a heater placed in the gas bottle did not improve the clarity of the images obtained. This heating process was not adequate to cause significant variations in the gas density and therefore the images of the N₂ flow appeared quite faded (fig. 5.7) and confusing.

- With Ar, at the ambient temperature almost the same difficulties found with N₂ were experienced (fig. 5.8 and 5.9). However, when Ar was heated some improvements in flow patterns results were obtained, although the quality of the images obtained was not clear enough to interpret the gas flow patterns.
 - The Schlieren system with smaller mirrors did not allow the visualisation of the gas flow on the screen.
 - The use of a He-Ne laser light source did not improve the definition of the gas flow patterns to the levels required for analysis.
-

5.3.1.3 Conclusions

Ar has a density higher than that of air, but the difference in their refractive indices at the ambient temperature are very small (table 5.1). This makes the observation of Ar and N₂ flow patterns difficult to achieve. N₂, with a density close to that of air became even more difficult to visualise.

The heating of gases should make the differences large enough to enable the clarification of the gas flow observations. As reported, the heating of gases improved the flow patterns of Ar, although, not sufficiently to allow an accurate analysis of them.

The heating process used (heater placed at the exit of the gas bottle) did not appear adequate to heat gases to sufficiently high temperature, which would cause a significant density variation, allowing gases to become visible.

On the other hand, the complexity of the Schlieren technique makes its utilization under laser welding conditions very difficult.

It is thought that the main difficulty with this technique was due to the rather low gas flow rates tested (which are, however, those of interest for the plasma control in the laser welding). Experiments carried out using the same experimental set-up but much higher gas flow rates, allowed visible flow patterns to be produced, even in a cold condition, since turbulence and swirl effects at the exit of the nozzle were produced.

The difficulties in the plasma control gas flow visualization using the Schlieren technique led to the investigation of other techniques, such as the smoke method.

5.3.2 Visualisation of gas jet flow pattern using the smoke technique

5.3.2.1 General

The constraints of the Schlieren technique did not allow a clear visualisation of the gas jet flow patterns. Thus, to overcome the difficulties and limitations of the above method, another technique was employed, the smoke technique. There is experimental evidence of the effectiveness of this method in the qualitative analysis of gas flow patterns [Lowery, 1966].

5.3.2.2 Set-up

A smoke tracer was produced using smoke pellets from PH (trade mark).

The pellets were burnt in a container through which the gas was passed before issuing from the nozzle. The set-up is shown in fig. 5.10.

As soon as the gas flow began, its flow was recorded photographically at 1/60s.

The nozzles and gas and flow rates were the same as those used in the Schlieren technique, which are described in pt. 5.3.1.1.

5.3.2.2 Results and Conclusions

The results obtained with the shadow method were inconclusive.

The acquisition of clear and precise images of the gas flow patterns appeared to be very difficult since to obtain reliable pictures of the flow pattern, these had to be taken almost instantaneously on initiating the gas flow. Although, this initial flow was more clear allowing better pictures; it did not correspond to the gas flow in a stabilised state. However, the very short time needed to allow gas flow stabilisation is enough to produce a smoky environment, which obscures the gas flow. This difficulty is illustrated in fig. 5.11.

Gas flow patterns obtained with the same bore diameter nozzle but different tip geometry were not different enough to allow any meaningful conclusions to be drawn (figs 5.12 and 5.13).

Using the set-up shown in fig. 5.10 (upper) additional problems were found. The residues formed as a consequence of the pellet reaction mixed with the gas clogging the interior of the plasma control gas device, thus causing a distortion of the results.

The smoke method proved not to be effective for this research. The experimental apparatus, although simple, is not able to produce sufficiently accurate results for further interpretation.

5.3.3 Conclusions

From the data obtained with the experimental gas flow visualisation, the following conclusions have been drawn:

- The Schlieren technique is not adequate to visualize the gas flow patterns at room temperature;
 - The use of a laser light source did not improve the definition of the visualisation;
 - The heating of the gas with a heater placed in the exit of the gas bottle, was not sufficient to obtain more clear images of the gas flow patterns;
 - The alternative to the Schlieren technique, the smoke tracer method, also proved to be unable to produce accurate results for further analysis;
 - Although, both techniques have been reported as having an extensive use in the welding field, they appeared to be very difficult to set-up for this particular application, requiring a strict control not compensated in the quality, reproducibility and accuracy of results produced;
-

- Further consideration of enhancement of the Schlieren technique using more efficient heating was discounted since it would tend to distort the results;
 - Holographic techniques were discussed but found to be complex and impractical for this application;
 - The alternative of fluid flow modelling was therefore considered to be the most profitable approach.
-

FIGURES

- 5.1 - Typical arrangement for Schlieren optical analysis [From: Mohen & Gibson, 1952]**
 - 5.2 - Optical arrangement of Schlieren analysis using a laser light source [From: Okada et Al., 1979]**
 - 5.3 - Illustration of techniques using smoke tracers**
 - 5.4 - Conceptual "State of the Art" holographic flow visualisation system**
 - 5.5 - Illustration of the Schlieren system used in the experimental work**
 - 5.6 - Schlieren pattern from a "standard" nozzle, 4mm bore diameter, using N₂ at a flow rate of 30 lt/min**
 - 5.7 - Schlieren pattern obtained heating the gas (same set-up and conditions of fig. 5.6)**
 - 5.8 - Schlieren pattern from a "standard" nozzle, 4mm bore diameter, using Ar at a flow rate of 10 lt/min**
 - 5.9 - Schlieren pattern from a "standard" nozzle, 4mm bore diameter, using Ar at a flow rate of 25 lt/min**
 - 5.10 - Two different set-ups used with the smoke tracer method**
 - 5.11 - Smoky atmosphere which obscures the clarity of the gas jet flow**
 - 5.12 - Gas flow pattern (N₂) from "modified" nozzle, 2mm bore diameter**
 - 5.13 - Gas flow pattern (N₂) from "standard" nozzle, 2 mm bore diameter**
-

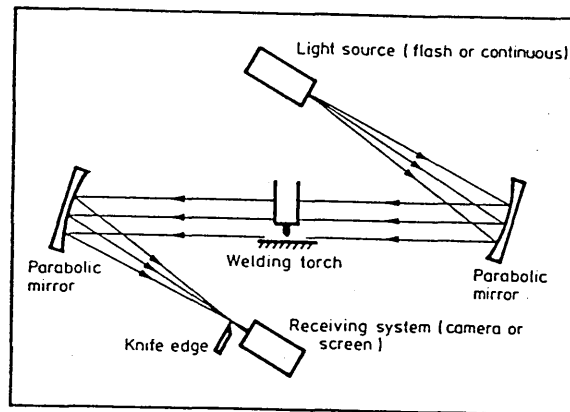


Fig. 5.1 - Typical arrangement for Schlieren optical analysis
[From: Mohen & Gibson, 1952]

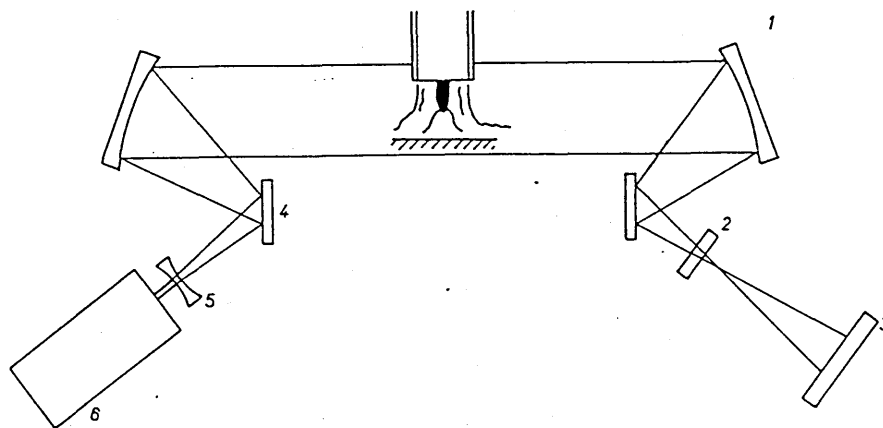


Fig. 5.2 - Optical arrangement of Schlieren analysis using a laser light source
[From: Okada et Al. 1979]

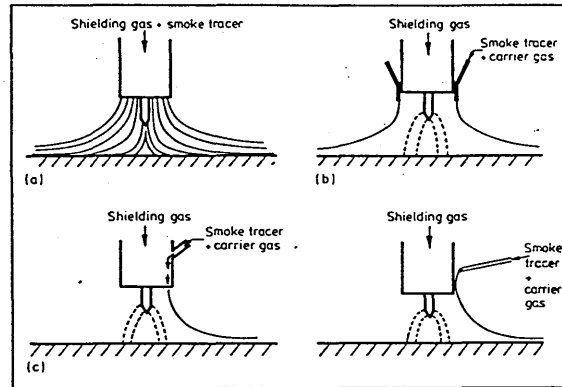


Fig. 5.3 - Illustration of techniques using smoke tracers

- a) - Full flow technique (no arc)
- b) - Side jet technique (with or without arc)
- c) - Shroud insert technique (with or without arc)
- d) - External probe technique (with or without arc)

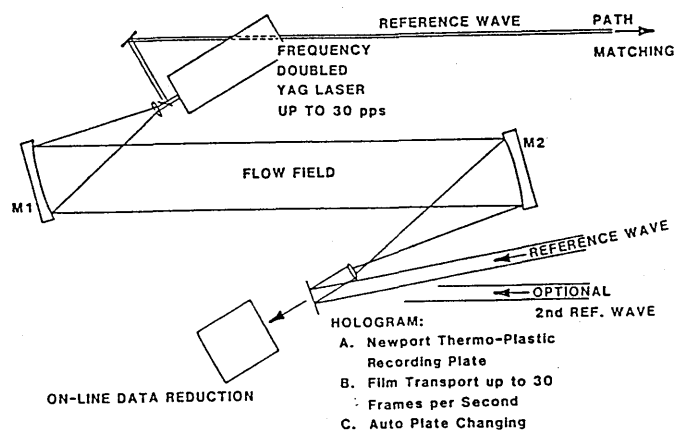


Fig. 5.4 - Conceptual "State of the Art" holographic flow visualisation system

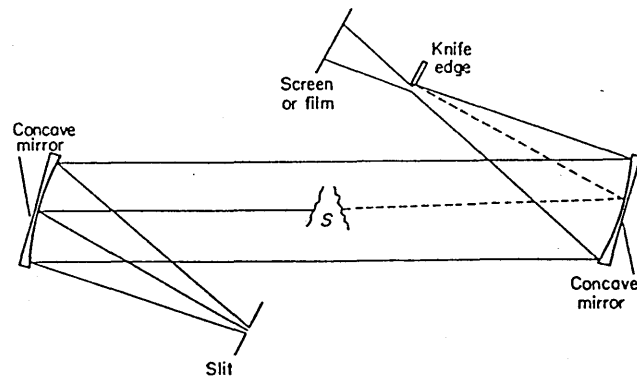


Fig. 5.5 - Illustration of the Schlieren system used in the experimental work

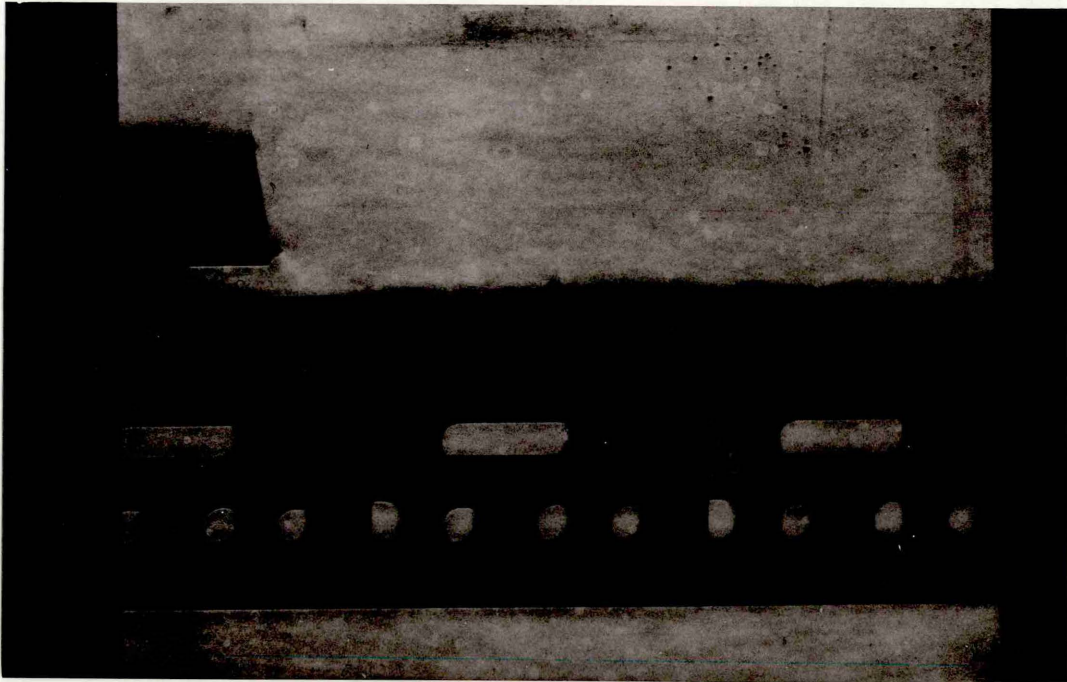


Fig. 5.6 - Schlieren pattern from a "standard" nozzle, 4mm bore diameter, using N_2 at a flow rate of 30 lt/min

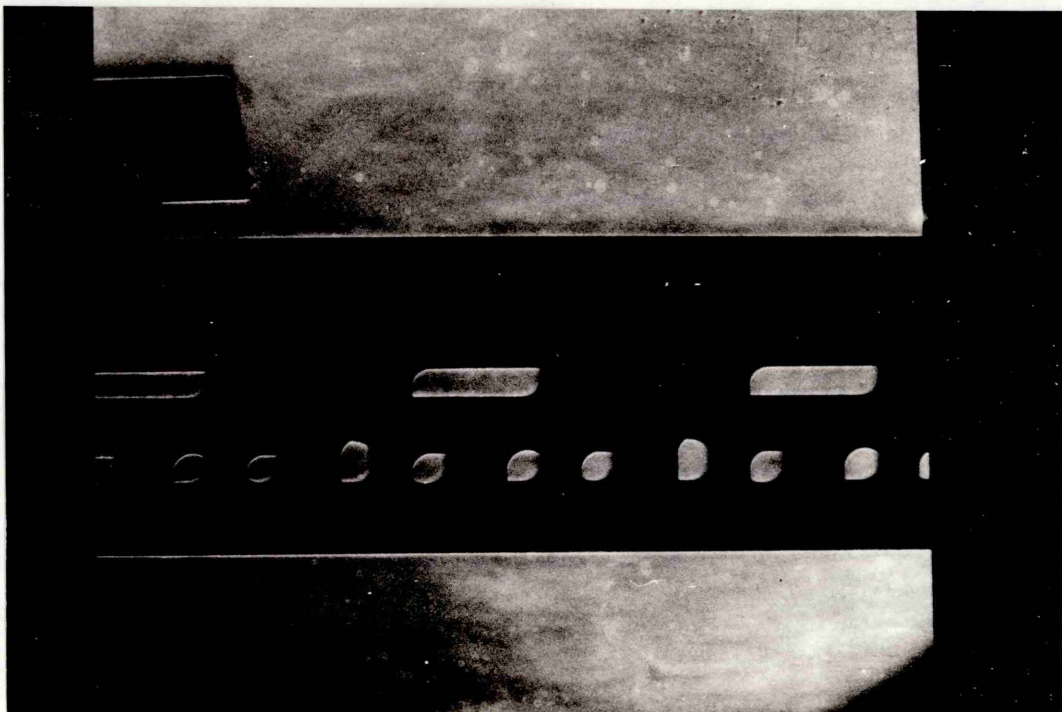


Fig. 5.7 - Schlieren pattern obtained heating the gas (same set-up and conditions of fig. 5.6)

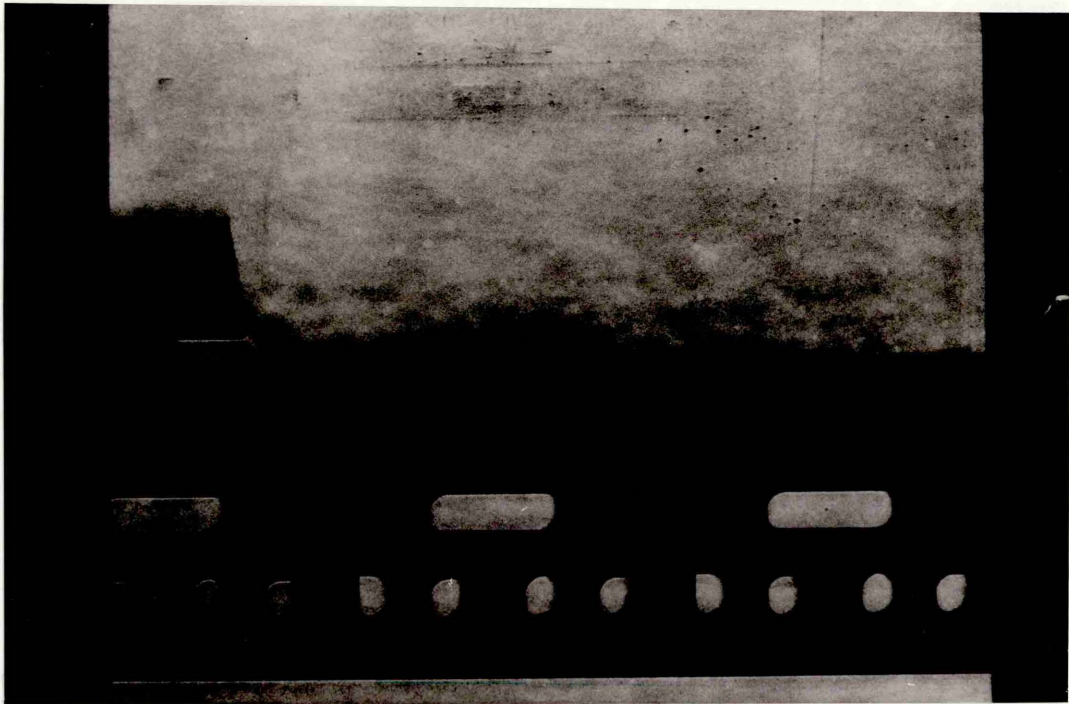


Fig. 5.8 - Schlieren pattern from a "standard" nozzle, 4mm bore diameter, using Ar at a flow rate of 10 lt/min

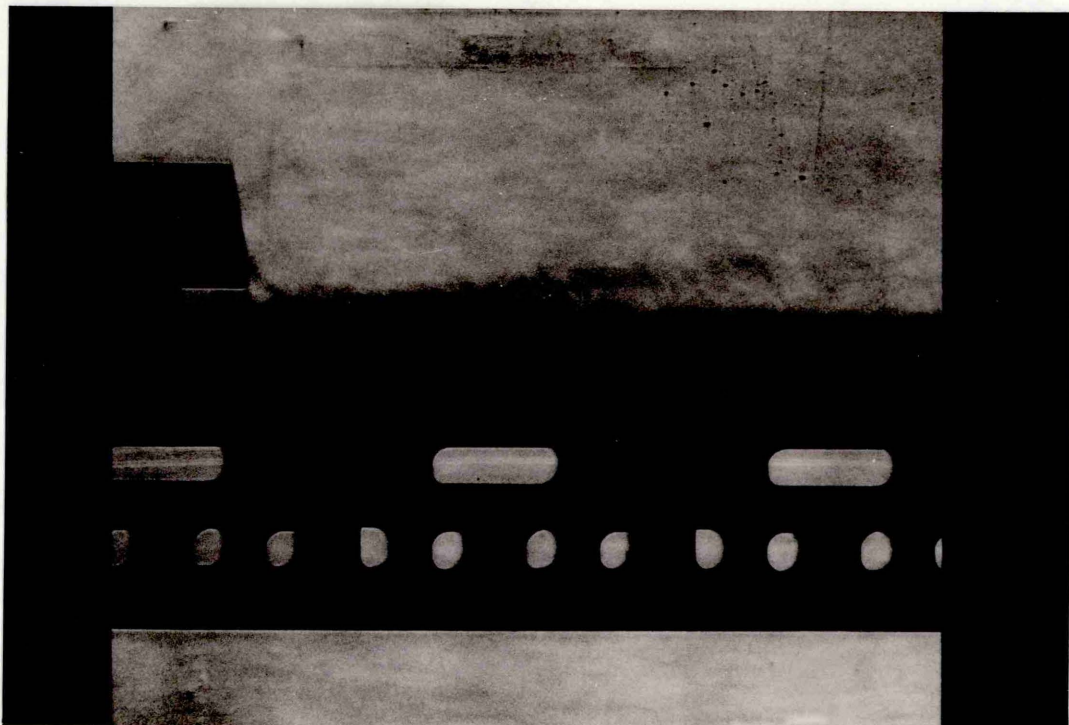


Fig. 5.9 - Schlieren pattern from a "standard" nozzle, 4mm bore diameter, using Ar at a flow rate of 10 lt/min

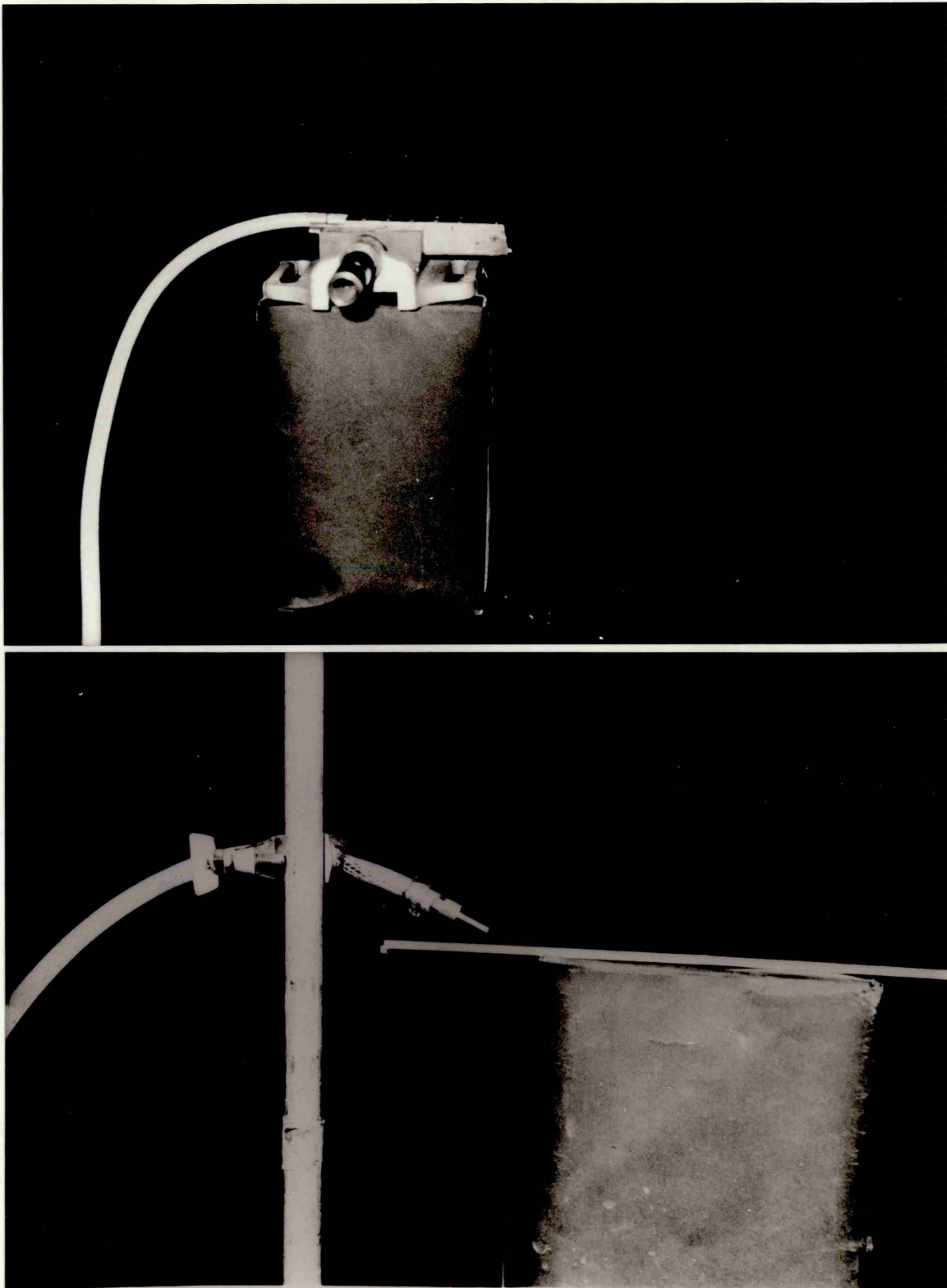


Fig. 5.10 - Two different set-ups used with the smoke tracer method

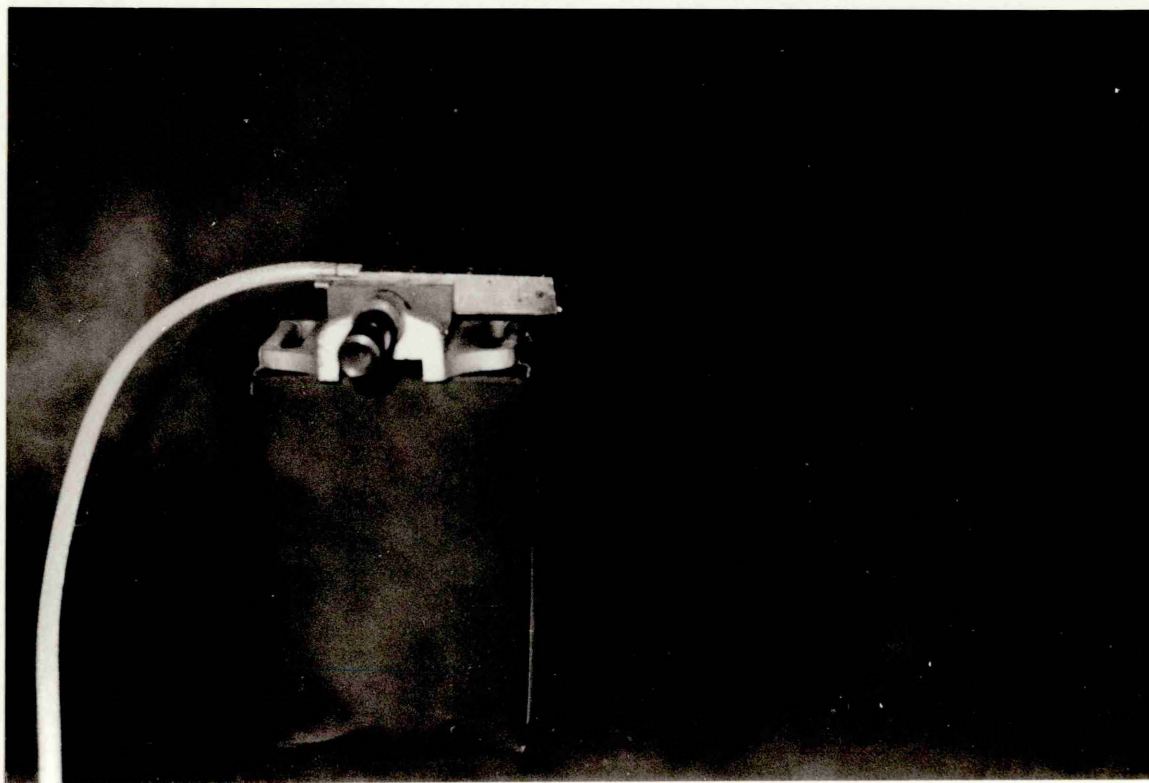


Fig. 5.11 - Smoky atmosphere which obscures the clarity of the gas jet flow

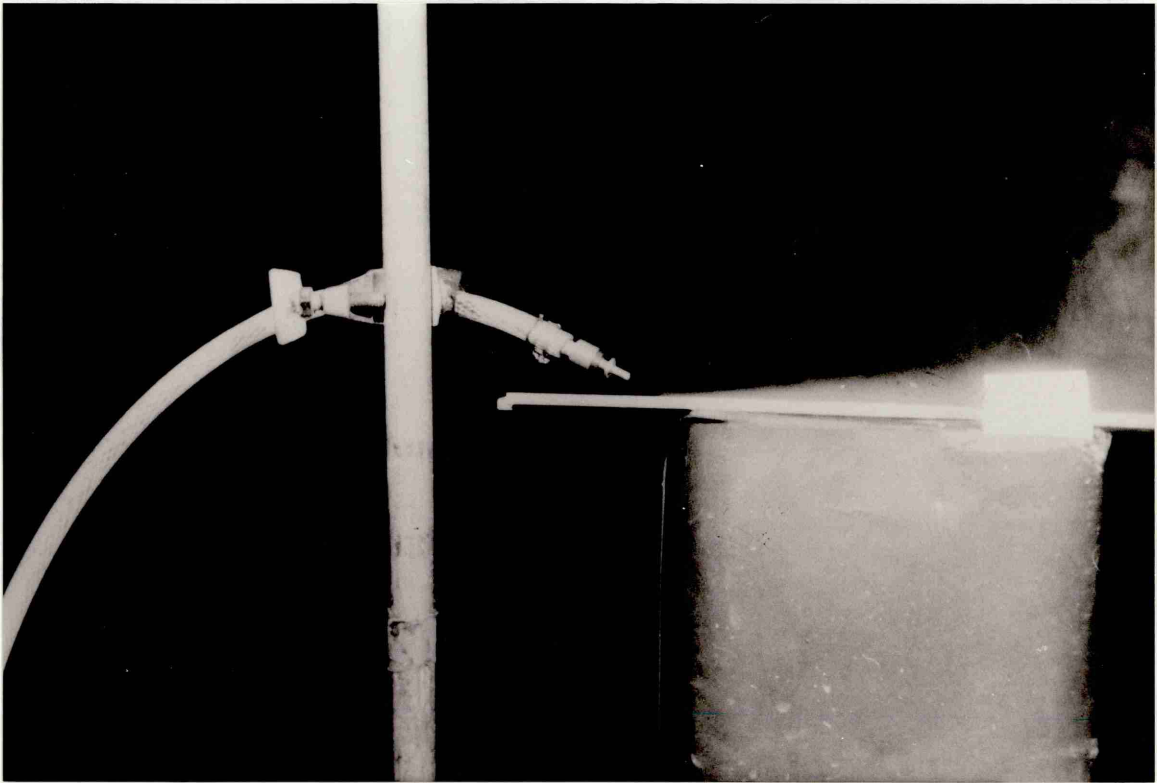


Fig. 5.12 - Gas flow pattern (N_2) from "modified" nozzle, 2mm bore diameter

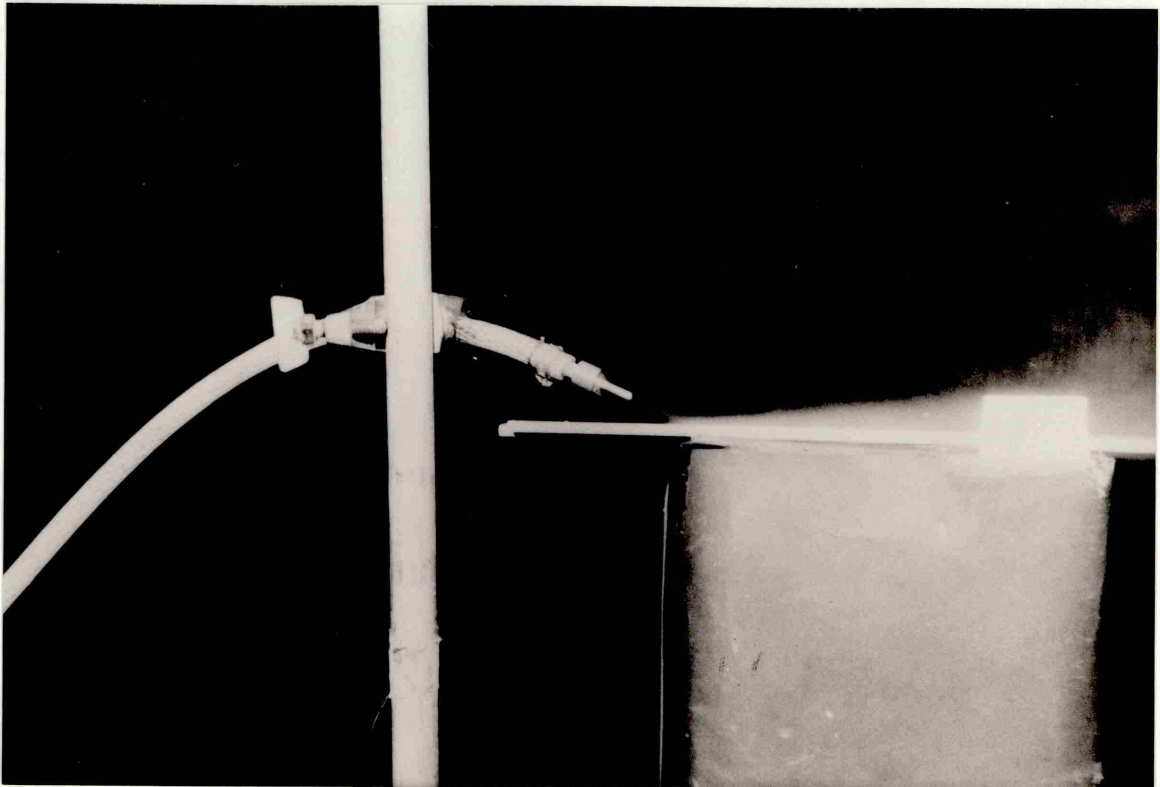


Fig. 5.13 - Gas flow pattern (N_2) from "standard" nozzle, 2 mm bore diameter

CHAPTER VI

RESEARCH PROGRAMME

- PLASMA CONTROL GAS FLOW SIMULATION -

6.1 INTRODUCTION

The experimental research programme initiated with the CO₂ laser welding of copper (chapter IV) showed that the key factor in the effectiveness of this process is the coupling of the laser radiation into the material, and this appeared to be related to the plasma control gas flow patterns over the interaction zone.

An experimental programme was designed to visualise the gas flow patterns. For the visualisation of the gas flows, optical techniques were selected.

These techniques proved, however, to be ineffective in the actual experimental conditions, mainly due to the combination of small bore diameter nozzles with relatively low gas flow velocities.

In view of the difficulty in the gas flow visualisation using optical techniques and of the need to make gas flow patterns visible (since it was believed they were the clue to explain the coupling mechanism), it was decided to carry out a simulation of the gas flow patterns, using a well known computer program, named FLUENT V 3.0. No references were found in literature concerning the use of fluid flow modelling to examine the gas flow patterns for plasma control in laser welding.

The present chapter gives a concise overview of the FLUENT software, the conditions assumed for the simulation, the results of the simulation, their discussion and the main conclusions of this 3rd step in the research programme.

6.2 SIMULATION PROGRAM: FLUENT V 3.0

6.2.1 General Introduction

FLUENT is a powerful tool addressed to the simulation of fluid flows.

FLUENT uses the basic conservation equations for laminar flow and their extensions to turbulent flow as well as the equations that describe fluid properties, to simulate the fluid flow behaviour.

The basic equations describing the laminar flow of continuous fluid are:

- conservation of mass,
- conservation of momentum,
- conservation of energy, and
- conservation of species.

The solution of these conservation equations requires a description of the fluid density and other fluid properties. FLUENT allows all fluid properties to be defined as constant or as temperature and/or composition dependent.

The more relevant fluid properties calculated by FLUENT are:

- density,
- viscosity,
- thermal conductivity,
- mass diffusion coefficients,
- specific heat capacity.

The modelling of turbulent flows requires appropriate modelling procedures to describe the effects of turbulent fluctuations of velocity and scalar quantities on the basic conservation equations quoted above. FLUENT solves the equations set via the time averaging procedures.

The conservation equations used in FLUENT for turbulent flows are obtained from those for laminar flows using a time averaging procedure commonly known as Reynolds averaging. This leads to expressions where each quantity is represented by its time averaged value and a new term containing a correlation appears.

The main task of turbulence models is to provide expressions or "solutions" that allow the evaluation of this correlation in terms of mean flow quantities. The closure models used in FLUENT V3.0 are the k - ϵ model and the Reynolds Stress Model (RSM).

The difference between the models concerns a limitation of the k - ϵ model, which assumes that the turbulent viscosity (μ_t) is isotropic. This implies that the velocity and length scales are the same in all directions. In complex flows, such as highly swirling flows, the k - ϵ model is inadequate. The k - ϵ model can be considered a simplification of the RSM model.

6.2.2 Solution of the Continuous Phase Equations

FLUENT uses a control volume based technique to convert the differential conservation equations to algebraic equations which can be solved numerically. This control volume based technique consists of:

- division of the domain into discrete control volumes using a general curvilinear grid,
- integration of the governing equations (differential) about each control volume,
- solution of the discretized equations.

FLUENT defines the discrete control volume using a non-staggered grid storage scheme as illustrated in fig. 6.1. In this scheme the same control volume is employed for integration of all the conservation equations and all variables are stored at the control volume cell centre.

The differential equations are integrated on the individual control volumes to construct the algebraic equations for discrete unknowns (velocities, pressure, scalars). These algebraic equations can be solved provided the unknowns are interpolated in a manner that relates their values at the control volume faces to the stored values at the control volume centres. The discretization procedures used by FLUENT to perform this interpolation are accomplished via either the power law or Quick interpolation schemes.

The continuity and momentum equations in three dimensions, provide four equations for solution of four unknowns: u_1 , u_2 , u_3 and p . The solution of these is performed by FLUENT through a sequential process, since a simultaneous solution is computational intensive. An algorithm, SIMPLE, is used to relate the velocity and pressure fields which satisfy the linearized momentum and continuity equations at a point.

To find a solution in which all the equations are satisfied at all points, an iterative solution procedure is required. The reason for this is that FLUENT does not solve the equations at all points simultaneously and because the equations are coupled and non linear.

Each iteration of FLUENT's solution procedure consists of the following steps:

- The u_1 , u_2 and u_3 momentum equations are solved in turn using the guessed pressure field, p^* .
 - The pressure correction equation (mass balance) is then solved to obtain the necessary corrections to the pressure field. Corresponding adjustments to the velocity components are also made.
 - For turbulent flows, the K and ϵ equations (or Reynolds stress transport equations) are solved using the updated velocity field to obtain the distribution of the effective viscosity and/or Reynolds stresses.
 - Any auxiliary equations (e.g., enthalpy, radiation) are solved using the previously updated values of other variables.
 - Fluid properties are updated.
-

These steps can be continued until the error in each conservation equation within each volume has decreased to a required value.

Consideration of a dispersed second phase

In addition to solve transport equations for one continuous phase, FLUENT simulates two phase flows involving a dispersed second phase. This second phase may consist of particles or droplets. FLUENT is able to compute the trajectories of the dispersed phase entities as well as heat and mass transfer to/from them.

6.3 SIMULATION CONDITIONS

Simulation of the gas jet flows in a two dimensional -2D- domain under different conditions was carried out using FLUENT V3.0.

The simulation was performed considering the following situations:

- actual experimental conditions in terms of experimental arrangement;
- modification of the gas jet nozzle length;
- introduction of a lens gas in various experimental arrangements.

The nomenclature of the different simulation experiments is presented in page 137.

6.3.1 Assumptions

The gas flow simulation was performed assuming a two dimensional (2D) model, which is an approach to the real three dimensional (3D) situation. This assumption was taken provided that FLUENT is limited to 25 000 cells. The grid used was 100x100 which also represents the maximum of the domain in the x and y directions. Therefore, only 2.5 cells were left to be used in the z direction, which if used would lead to a distortion in the model. An alternative could have been a reduction in the number of cells in the x, y and z directions of the domain to be modeled, which would be negatively reflected in the accuracy of the fluid flow profiles. In addition, the 2D assumption was taken, since no significant alterations were expected to result in the gas flow pattern contour relatively to the 3D model, although in the later condition lower gas flow rates were to be expected due the constraint imposed in the z direction.

The simulation was performed assuming a cold condition. This means that the gas properties were taken to be constant, with their values at the ambient temperature.

A grid with a refined mesh was constructed about the zone to be modelled (fig. 6.2). This domain comprised about 14 mm of the gas path in the nozzle and about 8 mm after gas exit (ahead of the nozzle tip).

A distortion in the gas (at its entry in the nozzle) was introduced, to simulate a turbulence at its entrance.

The k- ϵ turbulence model was used, since it was considered that as the gas flow under analysis was not a complex one and it did not present any severe inflexion in its flow in the whole domain. In addition, there was a limitation on the equipment available as well as on the computing times, which made this model more convenient, provided it did not adversely influence the final results.

The assumptions for each simulation condition are presented in appendix B.

The geometry of the "standard" nozzle in terms of rectangular cartesian coordinates and the cell types is represented in annex 6A. Other nozzle configurations, i.e., longer or shorter or yet with a "modified" tip morphology, were obtained from this basic one, being illustrated in the plot of annex 6A.

The gas variables selected and worked out to perform the simulation were:

• velocity in the x direction, u	yes
• velocity in the y direction, v	yes
• angular velocity, w	no
• pressure, p	yes
• turbulent kinetic energy, E	yes
• eddy dissipation, D	yes
• fluid properties	yes

6.3.2 Gas Jet Nozzle Set-up

The simulation of the gas jet flows was initially carried out assuming the actual conditions of the plasma control device. This device, shown in fig. 4.3, comprises a nozzle for the plasma control jet as well as a gas shielding arrangement (gas lens and shroud).

The design of a "standard" gas jet nozzle is shown in fig. 6.3a and that of a nozzle with a modified tip, due to the welding conditions, is illustrated in fig. 6.3b. The bevelled profile of the nozzle tip is variable according to its wear (fig. 4.4).

The nozzle set-up in the actual experimental conditions is illustrated in fig. 6.4. The set-up parameters and dimensions of the nozzle were the following:

- angle of the nozzle relatively to the beam axis: 45°
- distance between the nozzle tip and the beam axis: 2 mm
- nozzle bore diameter: 2 mm
- nozzle length between the gas lens exits and tip: 10 mm (actual experimental conditions) or 9, 7.5 and 11.5 mm (under simulation conditions)
- nozzle tip worn length: 2-3 mm. For simulation purposes it was assumed 2.5 mm
- distance between the nozzle tip and the copper surface: 3 mm

The "modified" nozzle conditions illustrated in fig. 6.4 were those that allowed coupling and stable welding operations to occur.

The geometrical outline of the actual nozzles, produced by FLUENT, is illustrated in fig. 6.5 a-b and annex 6A.

A variation from the set-up illustrated in fig. 6.4 for the "standard" nozzle condition, which had consisted in increasing and decreasing the nozzle length, is presented in fig. 6.5c to e. This situation was aimed at analysing the influence of the nozzle length and therefore set-up variation on the gas flow behavior.

6.3.3 Gas Lens Set-up

A gas lens, shown coaxial with the jet (fig. 4.3), increases the extent of gas coverage and prevents entrainment of air around the jet. Laminar flow in the lens is arranged by 6 equispaced 1 mm diameter holes.

The analysis of the gas lens influence on the gas jet flow patterns and on the interaction zone was made under two different conditions:

- actual experimental parameters in terms of the jet nozzle length and tip geometry (fig. 6.5 a-b);
- nozzle length longer and shorter than the one in the previous condition (fig. 6.5 c-d-e).

In the simulation of the gas lens no perturbation in the entry of the gas flow was considered since it leaves directly to the exterior. Therefore, it was assumed the gas entry at an angle of 45° , would allow it at its exit to run parallel to the jet nozzle.

6.3.4 Gas Jet Composition and Flow Rate

The analysis of the behaviour of nitrogen was the prime aim of this study, due to its good performances as the plasma control gas. Therefore, the gas flow simulation work was mainly focused on this gas. The gas flow rates used for simulation were 10 l/min.

6.3.5 Lens Gas Composition and Flow Rate

Nitrogen was the only gas used as lens gas in the experimental welding work (chapter IV) and considered for simulation purposes. A flow rate of 10 l/min was used, in the later.

6.3.6 Gas Velocity Distribution Profile

In order to analyse the gas velocity distribution along the direction of intersection of the laser beam with the material surface at a certain point, profiles were built representing the variation of the ratio between the local velocity and the inlet velocity (in the nozzle) as a function of the distance from the material surface. The positions considered are indicated in the cell type plot of annex 6A, by two vertical lines corresponding to different points of interaction beam/material. These two positions represent approximately the beam/material interaction points experimentally used (chapter IV), with the "standard" ($I=24$) and "modified" ($I=33$) nozzle types, since the gas jet nozzle was set up at 2mm from the laser beam axis. However,

this distance led to different beam/material intersection points due to the different geometries presented by the nozzle's tips.

6.4 RESULTS

6.4.1 Effect of the Nozzle Tip Geometry on the Gas Jet Flow Pattern

The gas flow pattern produced by a "standard" nozzle, whose design and set-up was illustrated in fig. 6.5a, is presented in figs 6.6a, 6.7a and 6.8a. In figs 6.6a and 6.8a this is shown through the gas velocity in a colour raster plot of its magnitude and in fig. 6.7a, the flow pattern is illustrated by the velocity vectors.

The "modified" nozzle shown in fig. 6.5b yields to a flow pattern as displayed in fig. 6.6b and 6.7b.

6.4.2 Effect of Increasing /Decreasing the Nozzle Length

This simulation condition, which consisted in increasing (fig. 6.5c) and decreasing (fig. 6.5d-e) the nozzle length relatively to the one shown in fig. 6.5a, has produced the gas flow patterns shown in fig. 6.8, as illustrated by the colour raster plot of velocity magnitude.

Fig. 6.8a concerns the longer nozzle, whose set-up places it closer to the copper surface. Whereas fig. 6.8b represents the gas flow pattern produced by a nozzle shorter than the "standard" nozzle shown in fig. 6.5a, fig. 6.8c shows the result of a simulation designed to find a gas flow behavior similar to that obtained with the "modified" nozzle (fig. 6.5c).

6.4.3 Effect of the Use of a Lens Gas

The simulation of the gas lens was carried out using the set-up defined in fig. 6.5a to e. The plots obtained in the different conditions of nozzle length and tip geometry are shown in figs 6.9a to e.

6.4.4 Particle/Droplet Trajectory

In order to clarify the visualisation of the gas flow patterns a method which consisted in following the trajectories of groups of particles was also used. These were assumed to be a second phase dispersed in the continuous phase. The results obtained in different conditions are shown in figs 6.10 to 6.13. The different colours refer to different particle sizes.

6.4.5 Gas Velocity Distribution Profile

The gas velocity distribution profiles obtained in both beam/material intersection positions for different simulation conditions are presented in figs. 6.14 to 6.18.

6.5 DISCUSSION

A turbulence was imposed to the gas flow at its entry in the jet nozzle to simulate the real experimental conditions, but this had no effect on the flow at its exit, since it soon became laminar flowing parallel to the nozzle walls. At its exit from the nozzle, the gas flow spreads out, colliding shortly afterwards with the copper surface. A recirculation zone is produced, as that illustrated for example in figs 6.6 and 6.7. This is a zone free from the main flow of the gas, where there is recirculation of the gas at low velocities (compared to those involved in the gas flow pattern). This zone by its characteristics can be designated by stagnation zone.

The assessment and discussion of the results obtained in the simulation analysis of the gas flows described above will be made in qualitative and comparative terms rather than in quantitative values, due to some of the assumptions made, which are likely to affect the real behaviour of the gas flows. From these, the assumptions of gas flow modelling in a 2D and cold conditions are considered the most important. Some attempts were made to simulate the presence of a laser source through an heated radiating surface located at the copper's surface. This approach besides being quite complex did not allow to provide data on the expected effects of a laser source on the gas flow behaviours. Thus, all the simulations were performed at a constant temperature and the results provided by the different conditions compared.

The results obtained in the simulation of gas jet flows from nozzles with different lengths and tip geometries showed very significant differences between the various conditions.

The comparison of the results provided by the simulation conditions corresponding to BICO 50 and BICO 60 showed significant differences in the gas flow patterns, easily visible in figs 6.6 and 6.7. If these patterns were also analysed in terms of approximate experimental set-ups, then the performances of BICO 50 at the position $I=24$ and BICO 60 at $I=33$ must be evaluated and compared. The later shows clearly that the gas velocity profile in position $I=33$ of BICO 60 (fig.6.15) is shifted to the right relatively to that of BICO 50 (fig. 6.14) at $I=24$. The main difference between both gas velocity profiles is the existence in condition BICO 60, close to the copper surface, of a range (width ≈ 0.5 mm) where the gas velocity is quite low. On the contrary, BICO 50 shows on that range very high gas velocity values. If BICO 50 is now analysed relatively to position $I=33$ (fig. 6.14), it is seen that the profile curve is shifted to the right relatively to $I=24$ and thus the zone next to the copper surface is not swept along as at $I=24$. This appears to mean that BICO 50 is able to show similar performances to BICO 60, if the set up of the nozzle, that is the relation between the beam/copper interaction point and the gas flow/copper intersection point is adequately chosen.

The later feature is particularly important since it appears to be the key point in the relationship between the plasma control gas and coupling behaviour. In this context, the differences detected in the gas flow velocity profiles between BICO 50 at $I=24$ and BICO 60 at $I=33$ could explain the differences observed in the coupling behaviour during the interaction of a laser beam with copper. On the other hand, an agreement between the simulation results of BICO 50 at positions $I=24$ and $I=33$ with the results obtained during the experimental welding programme (chapter IV), exists.

In chapter IV (pt. 4.3.2.1) it was reported that when a "standard" nozzle or a nozzle with a slightly worn tip was used, if the plasma control device was moved 0.5 mm forward in the welding direction, welds could be performed. Actually, this approach, i.e., reduction of the original 2 mm distance nozzle/beam axis to approximately 1.5 mm, corresponded to a variation in the gas flow pattern and behaviour relatively to the copper surface.

The analysis of figs 6.15 to 6.19 suggest that the gas velocity profiles from different nozzles show a common trend in positions $I=33$ and $I=24$, except for the condition SMALL 03 at position $I=24$. This common trend, specially close to the copper surface, seems to mean that within certain limits (nozzle length and tip geometry) the most important factor in the coupling process is the beam/copper interaction point relatively to the gas jet/copper intersection point. Although, a certain tolerance in the nozzle positioning appears to exist, as shown by the gas velocity profiles from different nozzles at $I=24$, the gas velocity magnitude plots should be analysed in terms of the global behaviour of the gas flow.

The effect of moving the nozzle tip towards the material surface (whose simulation was performed by using a longer nozzle), was seen to result in a more concentrated gas stream (compare fig. 6.8a to fig. 6.6a). On the contrary, the increased separation of the gas jet nozzle and the material surface (simulation carried out using shorter nozzles) leads to an enlargement of the gas flow profile (at the exit from the nozzle) since the free flow distance (before colliding with the copper surface) increases, and to a reduction in the gas velocity magnitude in the radial direction. Thus, the impingement of the gas flow with the copper surface occurs at a greater distance from the nozzle tip, with the gas having a lower velocity than in the condition defined by fig. 6.5a (compare fig. 6.6a to figs 6.8b-c). Nevertheless, it is seen that shorter nozzle lengths with the same set up lead to an increase in the gas velocity in the so called stagnation zone, which can be reduced and almost eliminated by the use of a gas lens.

The lens gas appears to have two main effects: it focuses the gas jet flow, reducing the spreading of the gas flow external contour and it slightly increases the gas flow velocities. Both effects can be observed in fig. 6.9 and figs 6.14 to 6.18. It should be stressed the particular effect on the downward component of the gas jet flow, which yields to a slight shift to the right of the profile curves of figs 6.14 to 6.17, thus increasing the range next to the copper surface of very low gas velocity, which appeared to be a critical factor in explaining different coupling behaviours in the laser welding of copper.

The condition SMALL 03 (fig. 6.9e) with gas lens appears to represent a quite interesting alternative to BICO 60, condition that has enabled the best results in terms of coupling and welding to be obtained during the welding of copper by a CO_2 laser. This nozzle gave a larger tolerance in terms of set up, being able (according to the results shown in fig. 6.18) to be used with performances comparable to those of BICO 60, set at a larger distance from the beam/copper interaction point. This would significantly reduce the chances of melting of the nozzle tip or its blocking with spatter, thus improving the reproducibility of the plasma control performance.

6.6 CONCLUSIONS

The main conclusions to be drawn from the simulation study of the gas jet flows are the following:

- Gas flow visualisation was possible through the use of a fluid flow modelling computer program, which is the FLUENT V3.0.
 - The assumptions considered allowed a reasonable analysis of the gas flow behaviour in qualitative and comparative terms.
 - Significant differences in the gas flow patterns and gas velocities were observed from nozzles with different tip geometries.
 - The nozzle length and its position relative to the copper surface define the gas jet/metal intersection point and the gas velocity at that point, which are the key factors to be related to the beam/metal interaction point.
 - Slight differences in the nozzle setting relatively to the beam/metal interaction point lead to important differences in the gas/metal intersection point.
 - The critical factor relatively to the plasma control nozzle in the laser welding, appears to be the relation between the beam/copper impingement point and the gas jet/copper intersection point. These points should never be coincident, since this would be expected to prevent the performance of welds in copper.
 - A gas flow pattern similar to that produced from a nozzle with a "modified" tip, was obtained from a "standard" nozzle by increasing the distance of its tip to the copper surface (simulation condition SMALL 03) or alternatively by reducing the distance between the beam/copper interaction point and the nozzle tip (condition BICO 50, position I=33).
 - The gas lens slightly focuses the gas jet flow, increasing its velocity but more importantly, it reduces significantly the downward component of the gas jet, thus creating close to the copper surface a small range where the gas velocity is very low.
 - The results from the two dimensional modelling allowed a qualitative prediction of the gas flow patterns and a comparative analysis in terms of the nozzle morphology variation.
-

Nomenclature used to designate the simulation experiments

BICO 50 - "standard" nozzle (10 mm); jet gas: nitrogen

BICO 60 - "modified" nozzle; jet gas: nitrogen

BICO 51 - "standard" nozzle (10 mm); jet gas: nitrogen; lens gas: nitrogen

BICO 61 - "modified" nozzle; jet gas: nitrogen; lens gas: nitrogen

LARGE 01 - "standard" nozzle (11.5 mm); jet gas: nitrogen

LARGE 02 - "standard" nozzle (11.5 mm); jet gas: nitrogen; lens gas: nitrogen

SMALL 01 - "standard" nozzle (9 mm); jet gas: nitrogen

SMALL 02 - "standard" nozzle (9 mm); jet gas: nitrogen; lens gas: nitrogen

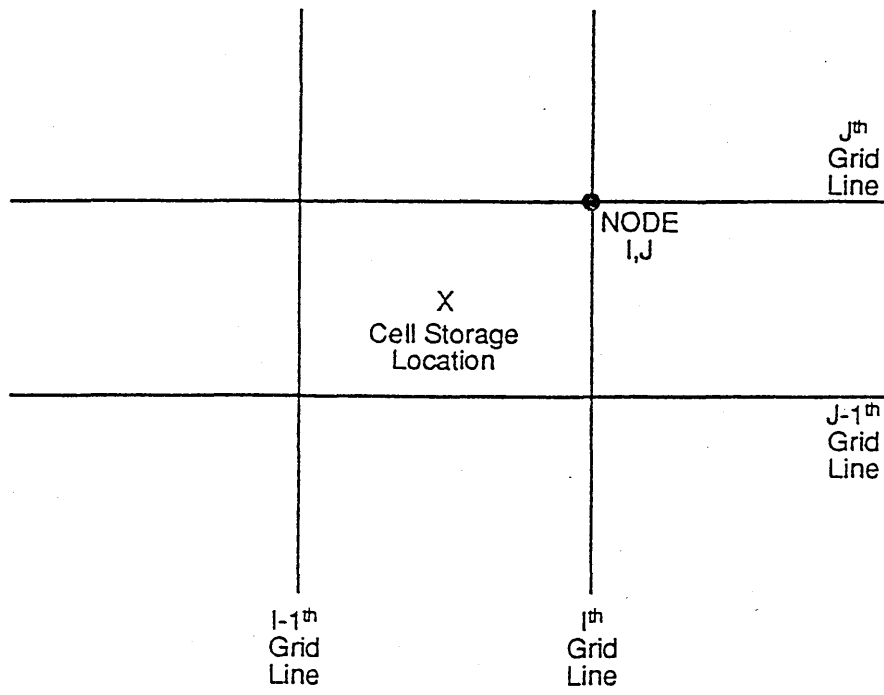
SMALL 03 - "standard" nozzle (7.5 mm); jet gas: nitrogen

SMALL 31 - "standard" nozzle (7.5 mm); jet gas: nitrogen; lens gas: nitrogen

CHAPTER VI**FIGURES**

- 6.1** - Non staggered control volume storage scheme
 - 6.2** - Finite difference grid for a "standard" and "modified" nozzle's geometry
 - 6.3a** - "Standard" gas jet nozzle configuration
 - 6.3b** - Illustration of a "modified" tip nozzle
 - 6.4** - Illustration of the experimental set-up of the "standard" and "modified" nozzles
 - 6.5a-b** - Geometrical outline of the nozzles (BICO 50 and BICO 60)
 - 6.5c-d** - Geometrical outline of the nozzles (LARGE 01 and SMALL 01)
 - 6.5e** - Geometrical outline of the nozzles (SMALL 03)
 - 6.6** - Colour raster plots of velocity magnitude for a "standard" and "modified" nozzle
 - 6.7** - Gas flow patterns illustrated by the velocity vectors for a "standard" and "modified" nozzle
 - 6.8a** - Colour raster plot of velocity magnitude from a "standard" nozzle with 11.5 mm length (LARGE 01)
 - 6.8b** - Colour raster plot of velocity magnitude from a "standard" nozzle with 9.0 mm length (SMALL 01)
 - 6.8c** - Colour raster plot of velocity magnitude from a "standard" nozzle with 7.5 mm length (SMALL 03)
 - 6.9a** - Colour raster plot of velocity magnitude obtained with gas lens from a "standard" nozzle, 10mm length (BICO 51)
 - 6.9b** - Colour raster plot of velocity magnitude obtained with gas lens from a "modified" nozzle (BICO 61)
 - 6.9c** - Colour raster plot of velocity magnitude obtained with gas lens from a "standard" nozzle, 11.5mm length (LARGE 02)
 - 6.9d** - Colour raster plot of velocity magnitude obtained with gas lens from a "standard" nozzle, 9mm length (SMALL 02)
 - 6.9e** - Colour raster plot of velocity magnitude obtained with gas lens from a "standard" nozzle, 7.5mm length (SMALL 31)
-

- 6.10a** - Particle/droplet trajectories in a "standard" nozzle, 10mm length (BICO 50)
 - 6.10b** - Particle/droplet trajectories in a "standard" nozzle, 10mm length, with gas lens (BICO 51)
 - 6.11a** - Particle/droplet trajectories in a "modified" nozzle (BICO 60)
 - 6.11b** - Particle/droplet trajectories in a "modified" nozzle with gas lens (BICO 61)
 - 6.12a** - Particle/droplet trajectories in a "standard" nozzle, 11.5mm length (LARGE 01)
 - 6.12b** - Particle/droplet trajectories in a "standard" nozzle, 11.5mm length, with gas lens (LARGE 02)
 - 6.13a** - Particle/droplet trajectories in a "standard" nozzle, 9mm length (SMALL 01)
 - 6.13b** - Particle/droplet trajectories in a "standard" nozzle, 9mm length, with gas lens (SMALL 02)
 - 6.14** - Particle/droplet trajectories in a "standard" nozzle, 7.5mm length, with gas lens (SMALL 31)
 - 6.15** - Gas velocity distribution profiles for a "standard" nozzle, 10mm length with and without gas lens (BICO 50 and BICO 51)
 - 6.16** - Gas velocity distribution profiles for a "modified" nozzle, with and without gas lens (BICO 60 and BICO 61)
 - 6.17** - Gas velocity distribution profiles for a "standard" nozzle, 11.5mm length with and without gas lens (LARGE 01 and LARGE 02)
 - 6.18** - Gas velocity distribution profiles for a "standard" nozzle, 9mm length with and without gas lens (SMALL 01 and SMALL 02)
 - 6.19** - Gas velocity distribution profiles for "standard" nozzles, 9 and 7.5mm length (SMALL 01 and SMALL 03)
-

**Fig. 6.1** - Non staggered control volume storage scheme

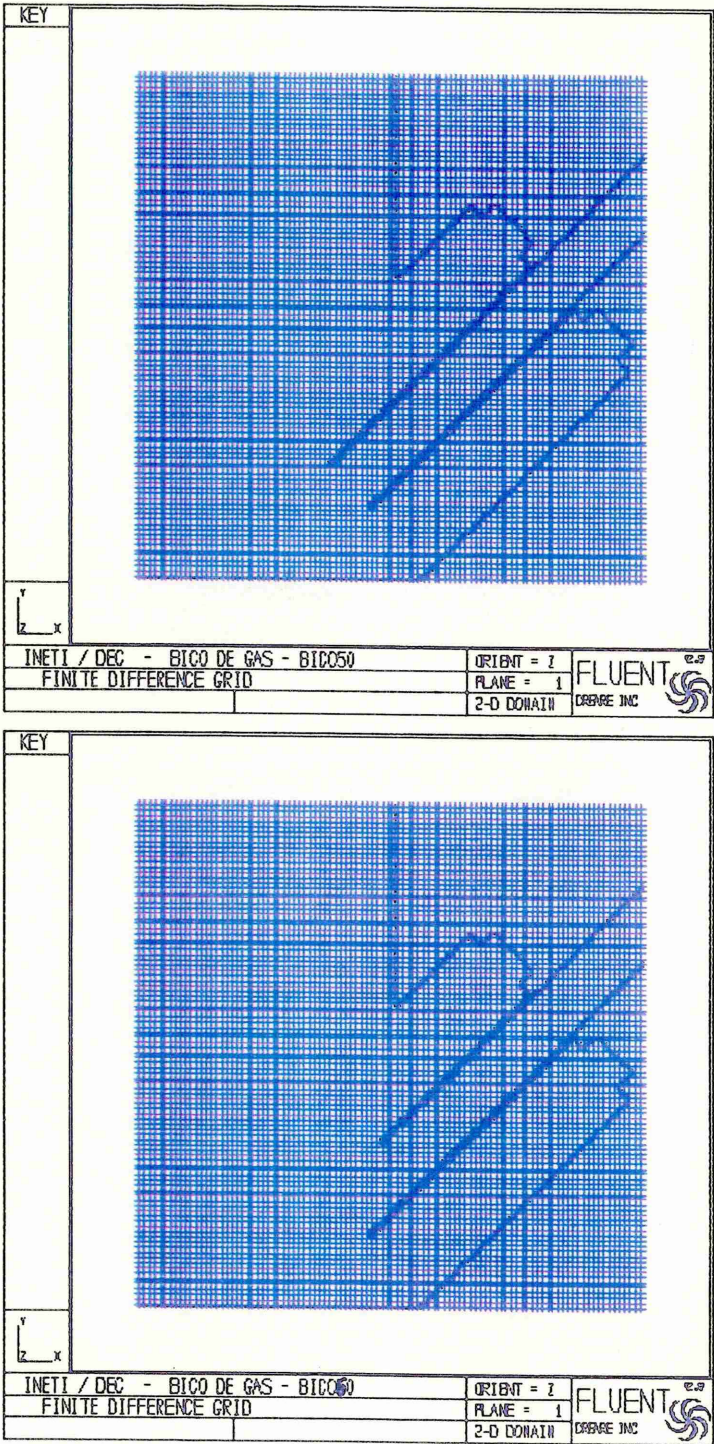


Fig. 6.2 - Finite difference grid for a "standard" and "modified" nozzle's geometry

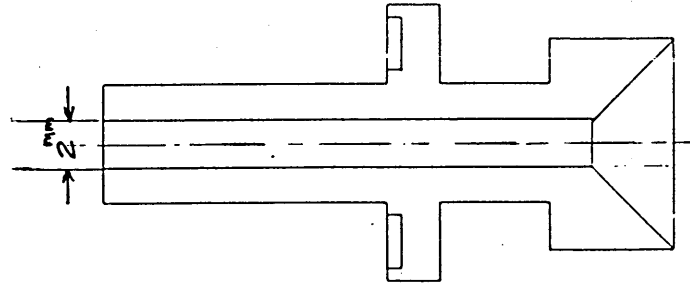


Fig. 6.3a - Gas jet nozzle and gas lens design

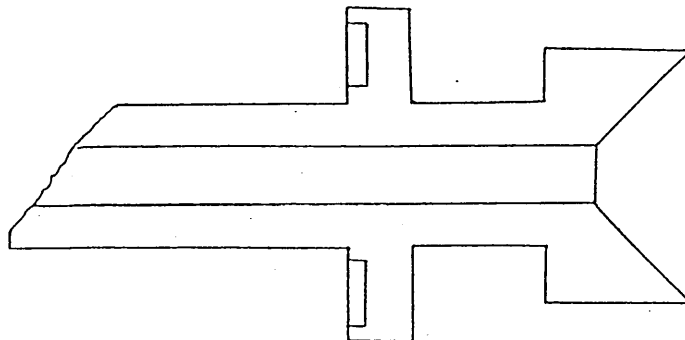


Fig. 6.3b - Illustration of a "modified" tip nozzle

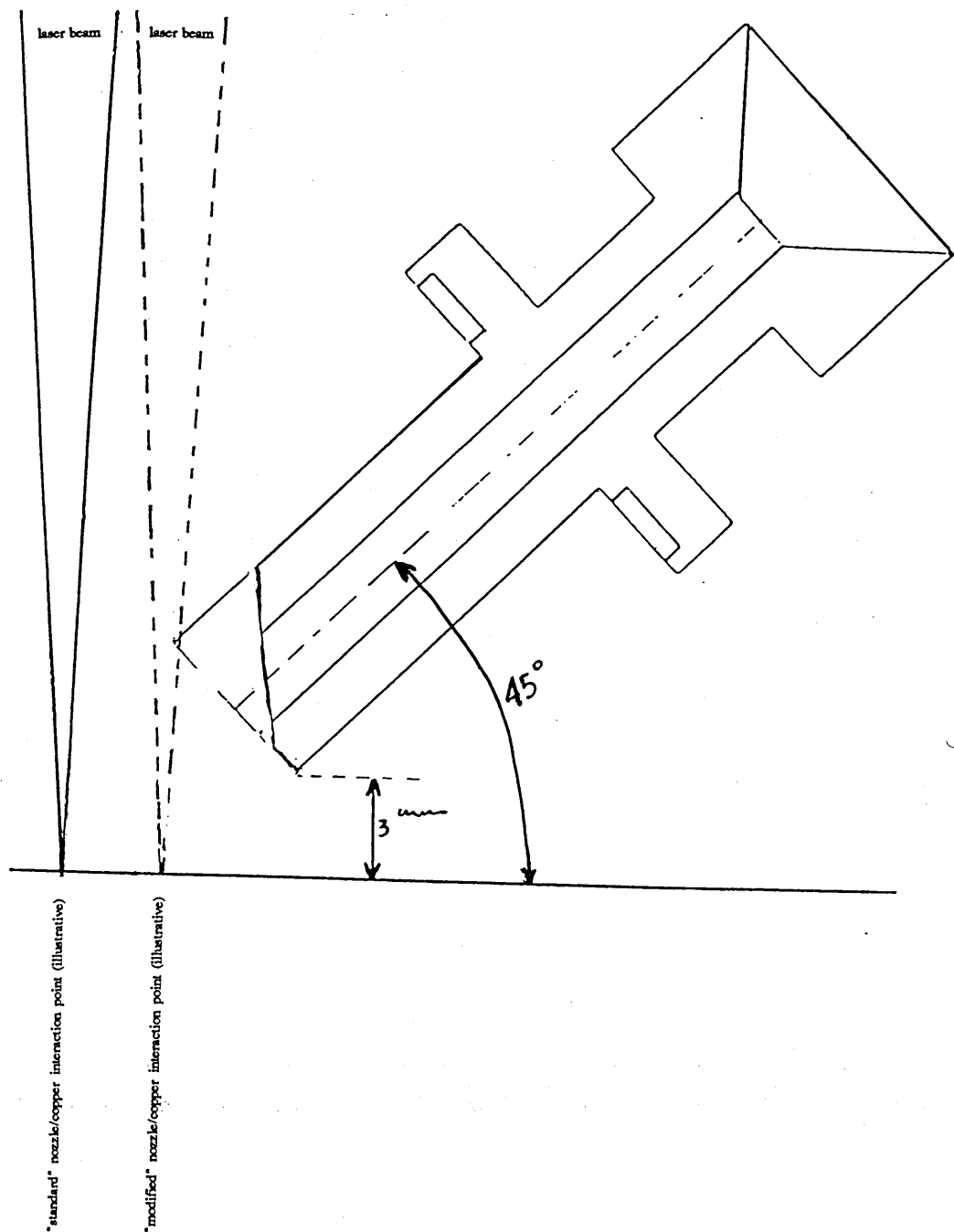


Fig. 6.4 - Illustration of the experimental set-up of the "modified" and "standard" nozzles

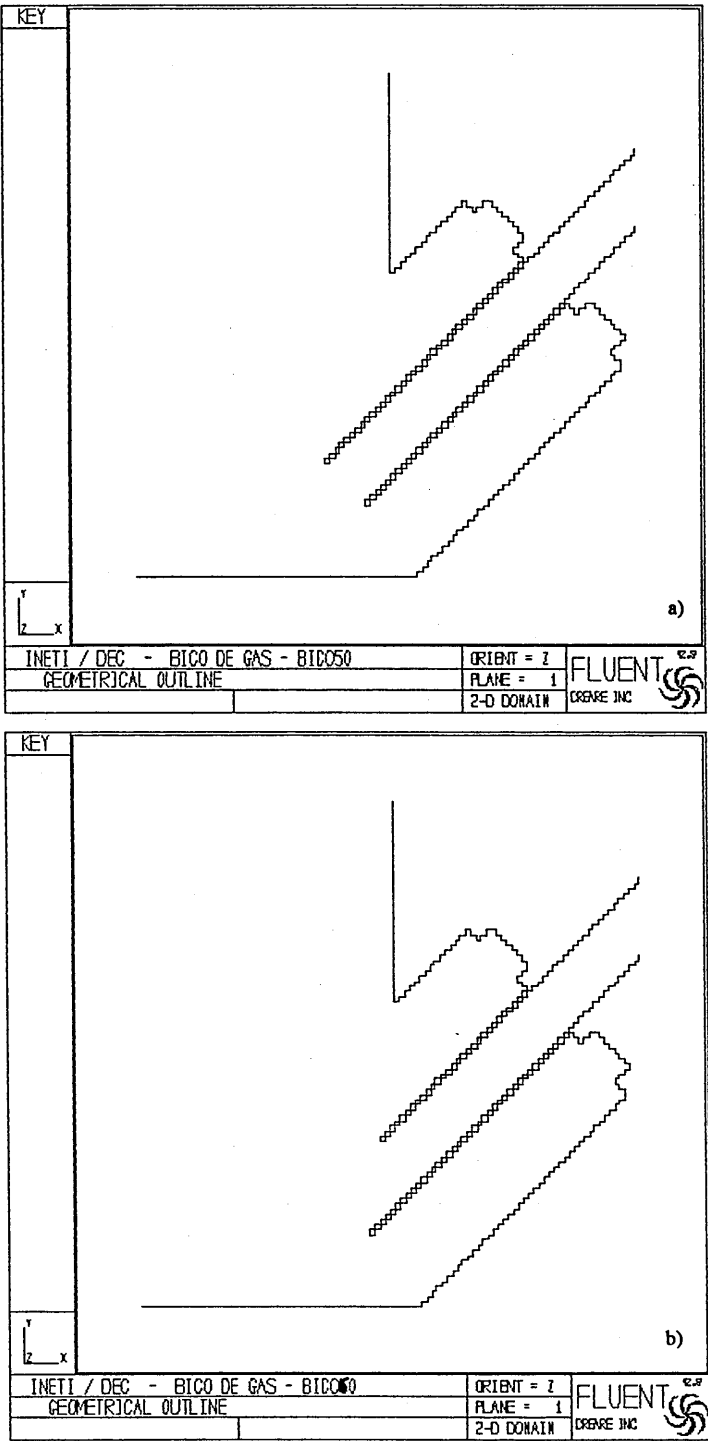


Fig. 6.5a-b - Geometrical outline of the nozzles

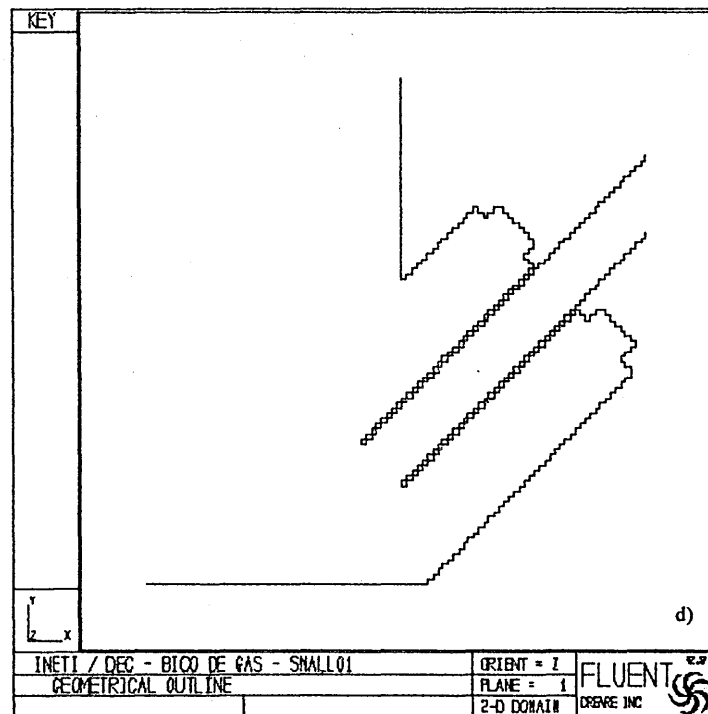


Fig. 6.5c-d - Geometrical outline of the nozzles (cont.)

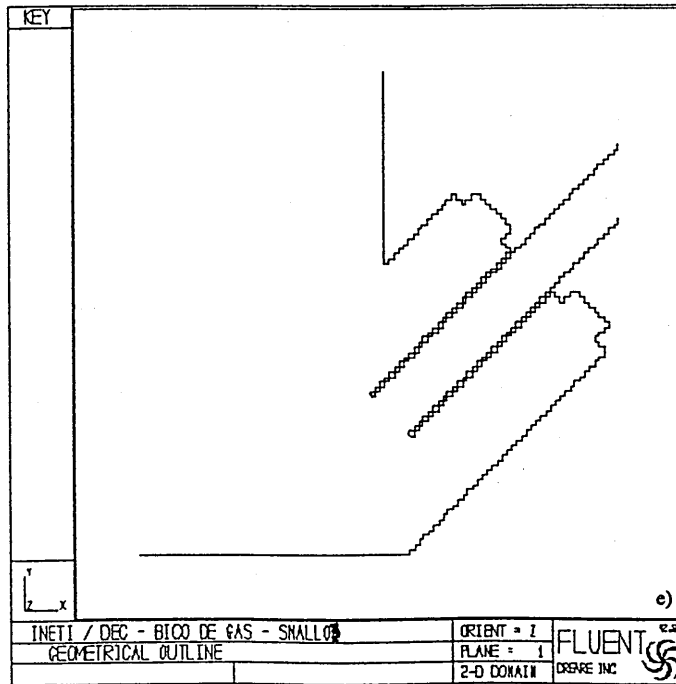


Fig. 6.5e - Geometrical outline of the nozzles (cont.)

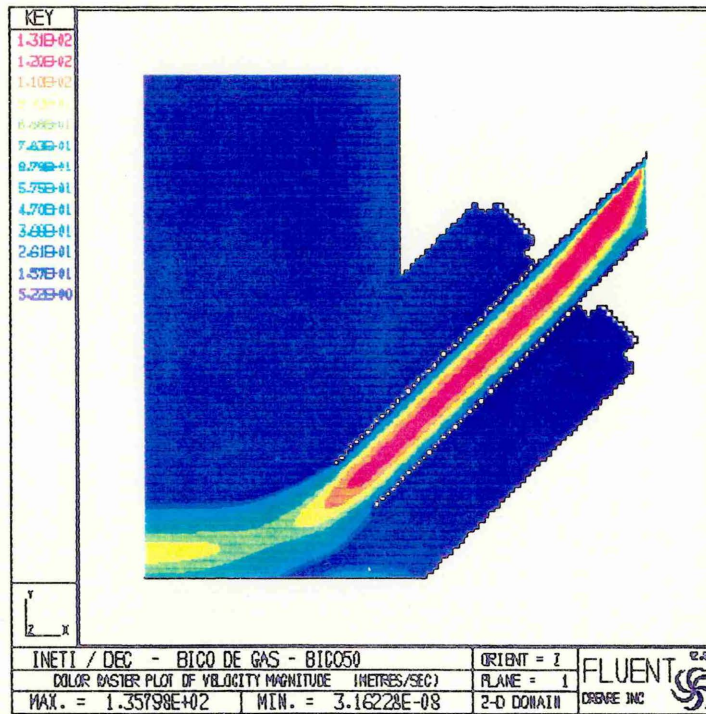
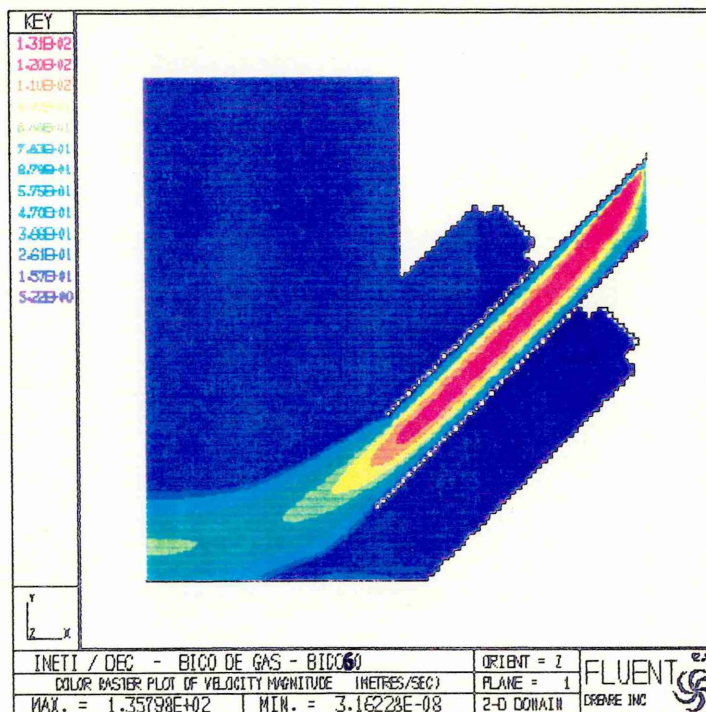


Fig. 6.6a-b - Colour raster plots of velocity magnitude for a "standard" and "modified" nozzles

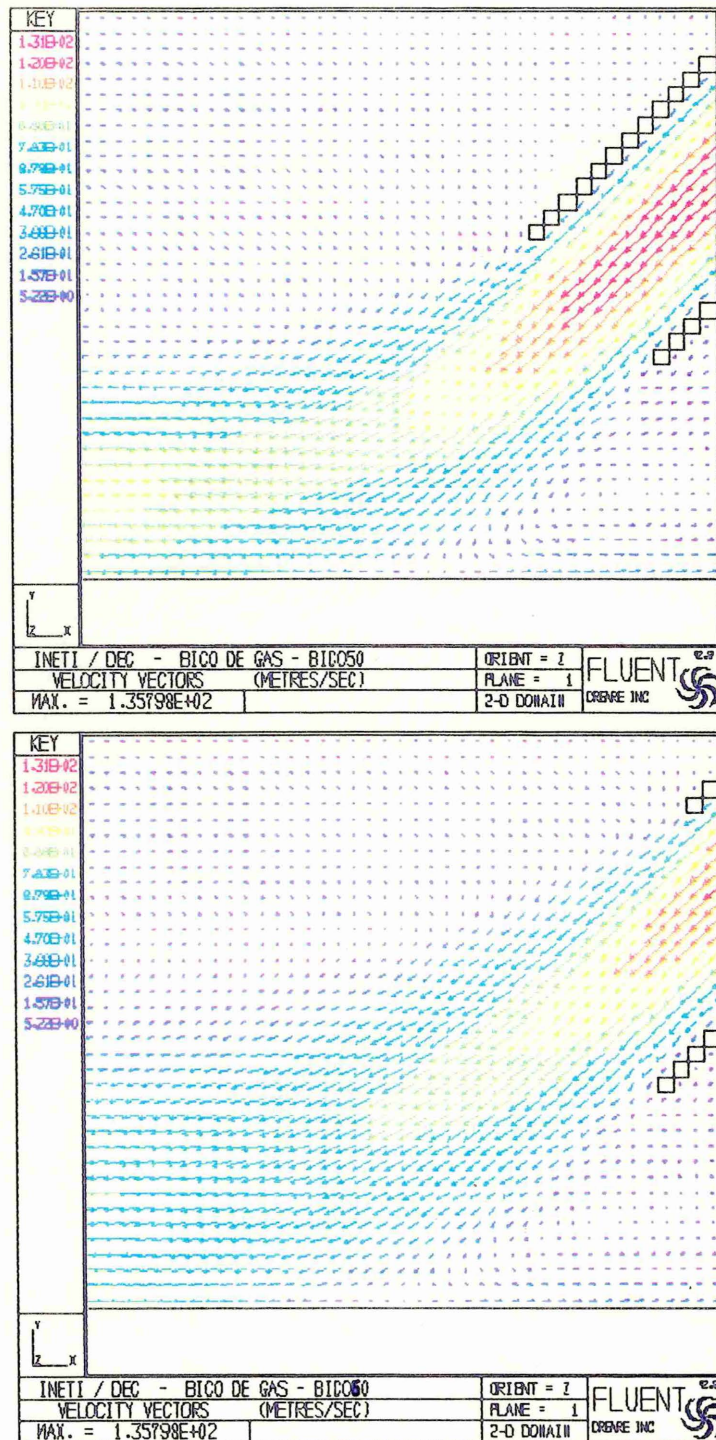


Fig. 6.7 - Gas flow patterns illustrated by the velocity vectors for a "standard" and "modified" nozzle

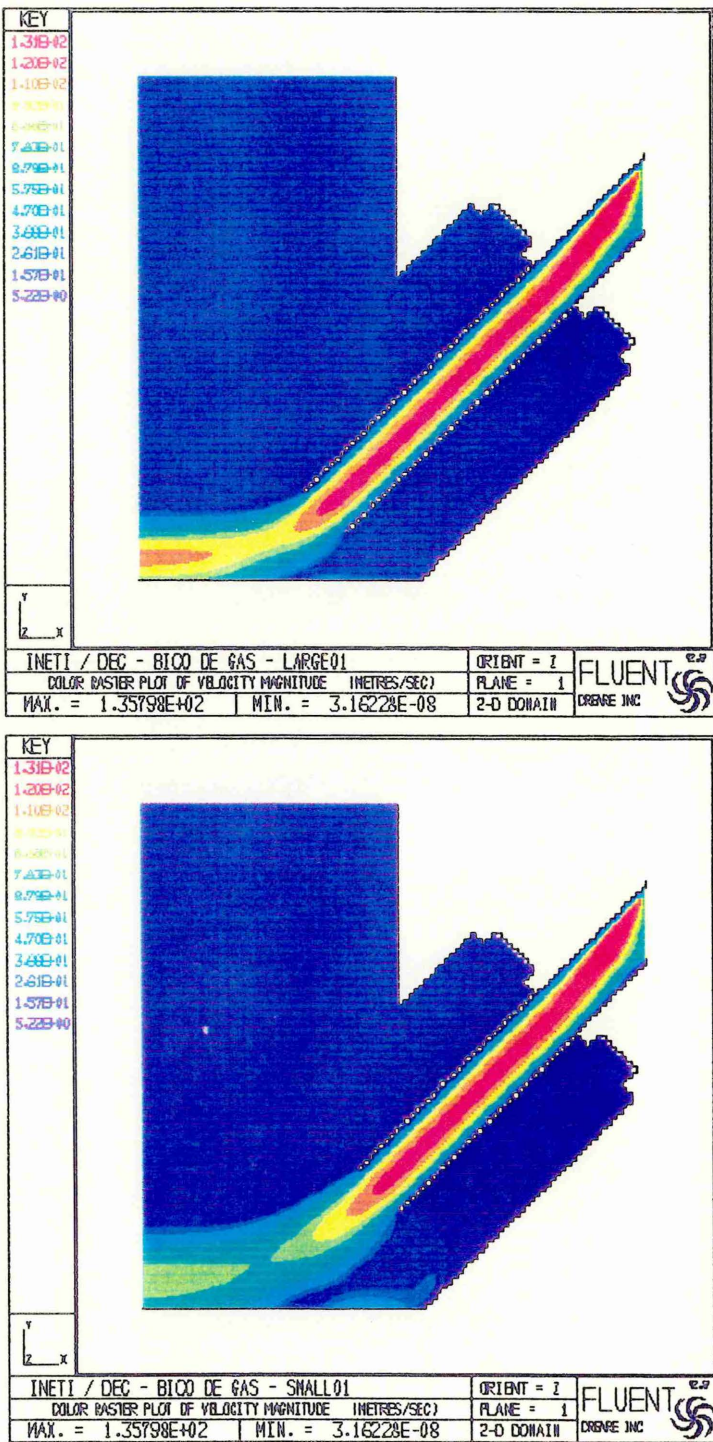


Fig. 6.8a-b - Colour raster plots of velocity magnitude from "standard" nozzles with 11.5 mm and 9 mm length

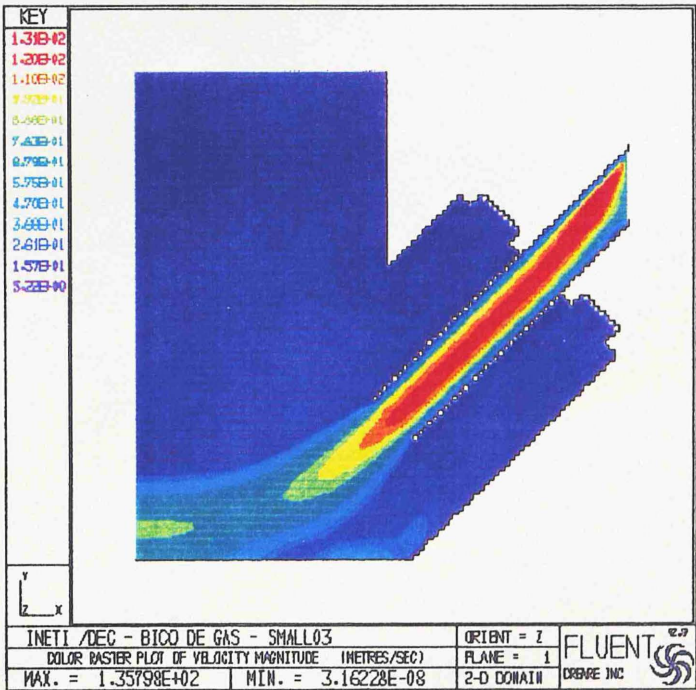


Fig. 6.8c - Colour raster plot of velocity magnitude from "standard" nozzle with 7.5 mm length

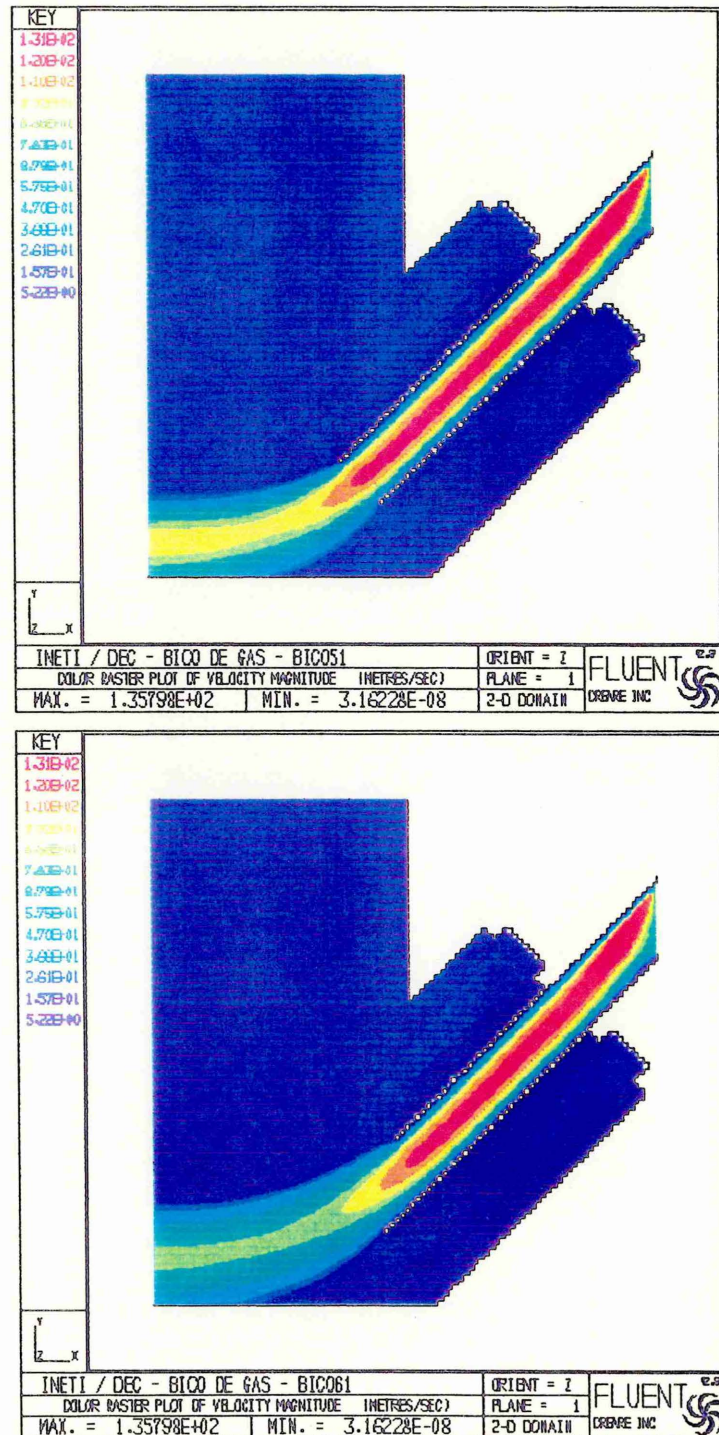


Fig. 6.9 a-b - Colour raster plots of velocity magnitude obtained with gas lens from "standard" and "modified" nozzles

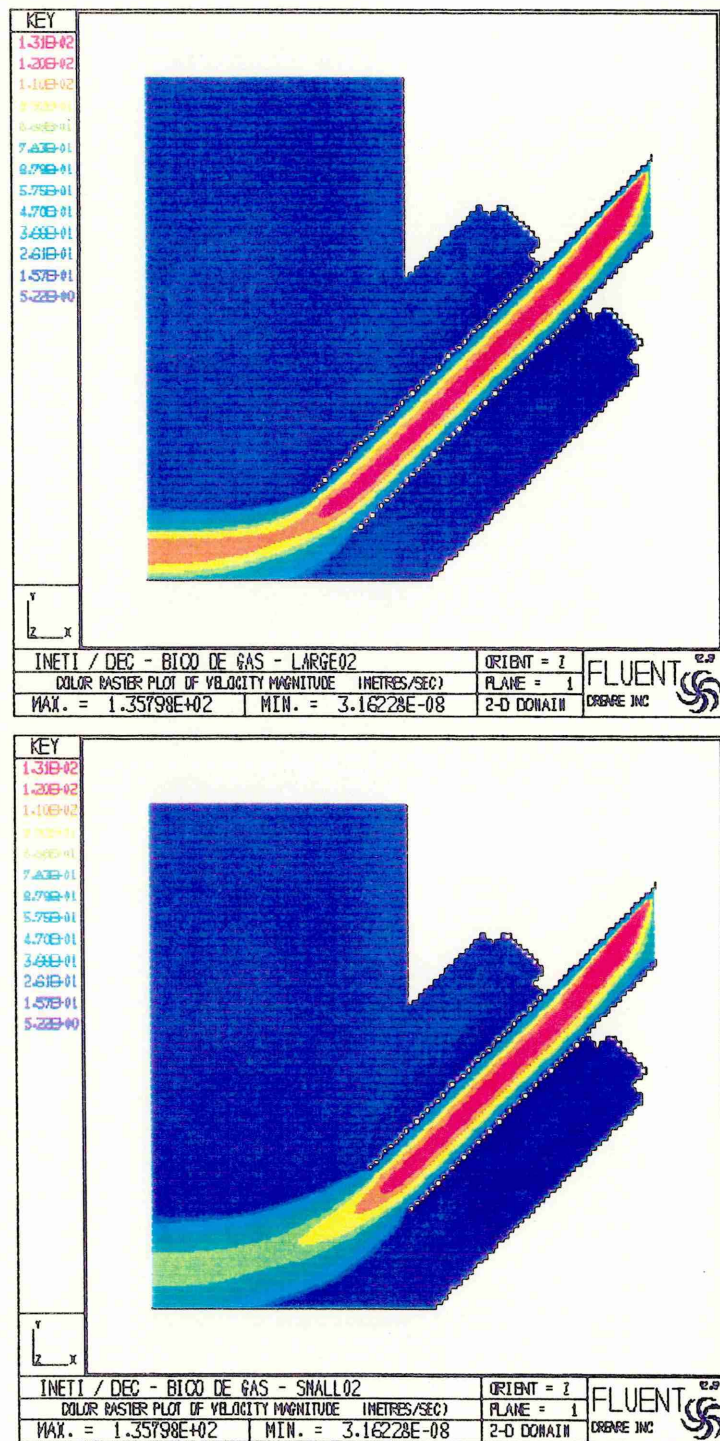


Fig. 6.9c-d - Colour raster plots of velocity magnitude obtained with gas lens from "standard" nozzles with 11.5 and 9mm length

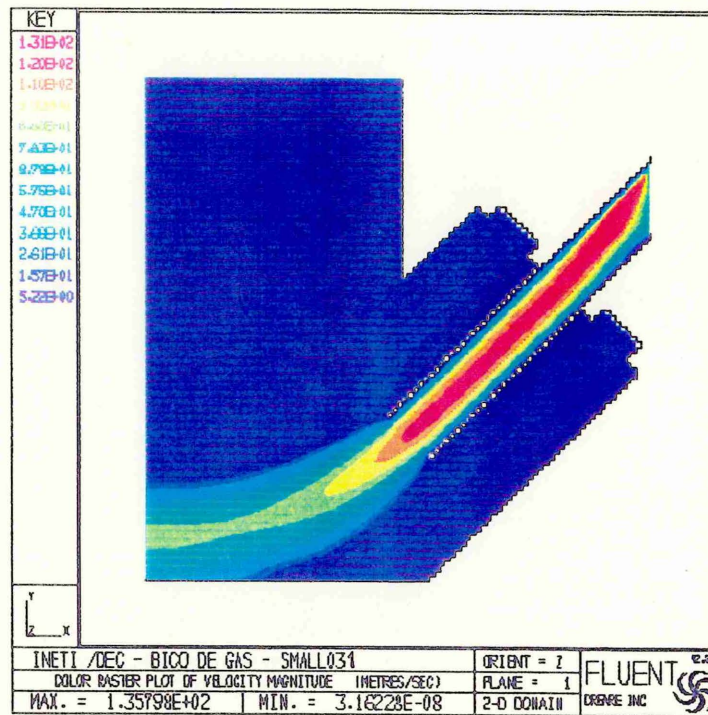


Fig. 6.9e - Colour raster plot of velocity magnitude obtained with gas lens from a "standard" nozzle with 7.5 length

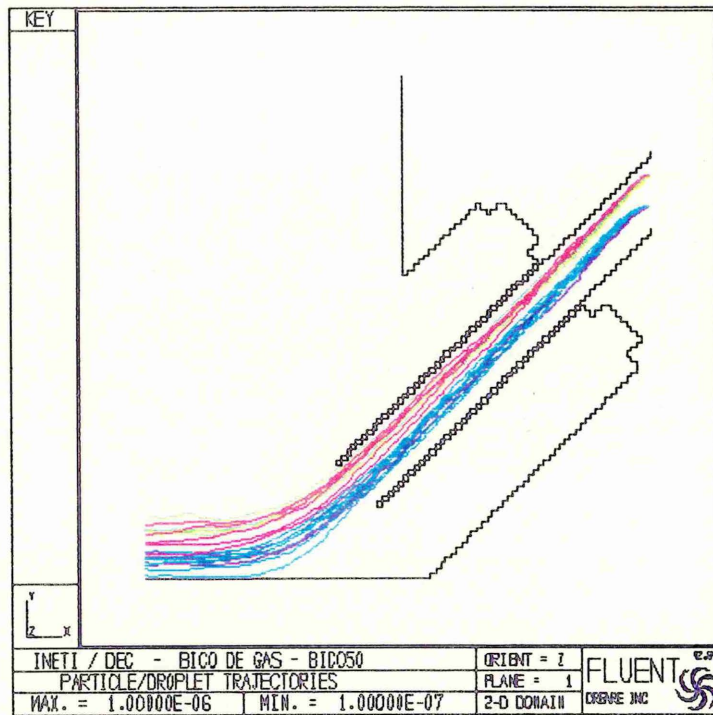


Fig. 6.10a - Particle/droplet trajectories in a "standard" nozzle, 10mm length

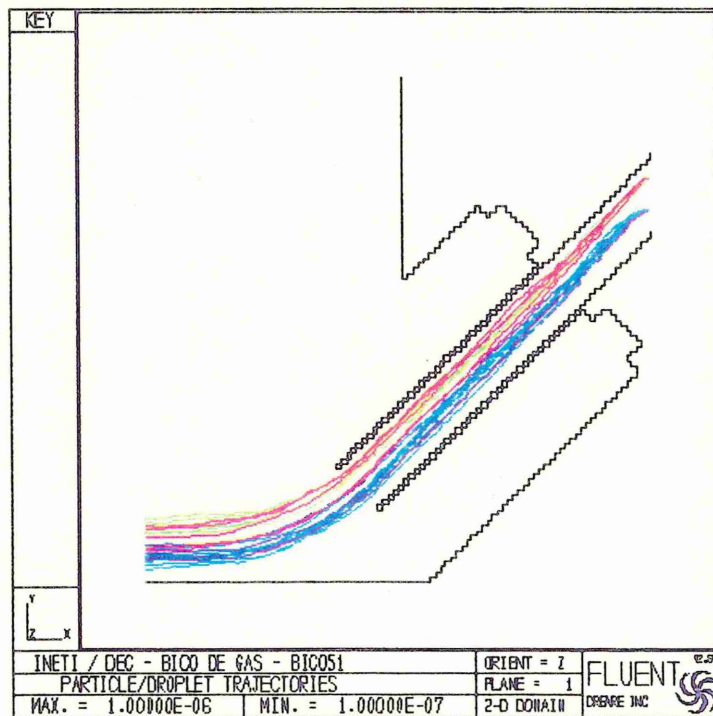


Fig. 6.10b - Particle/droplet trajectories in a "standard" nozzle, 10mm length, with gas lens

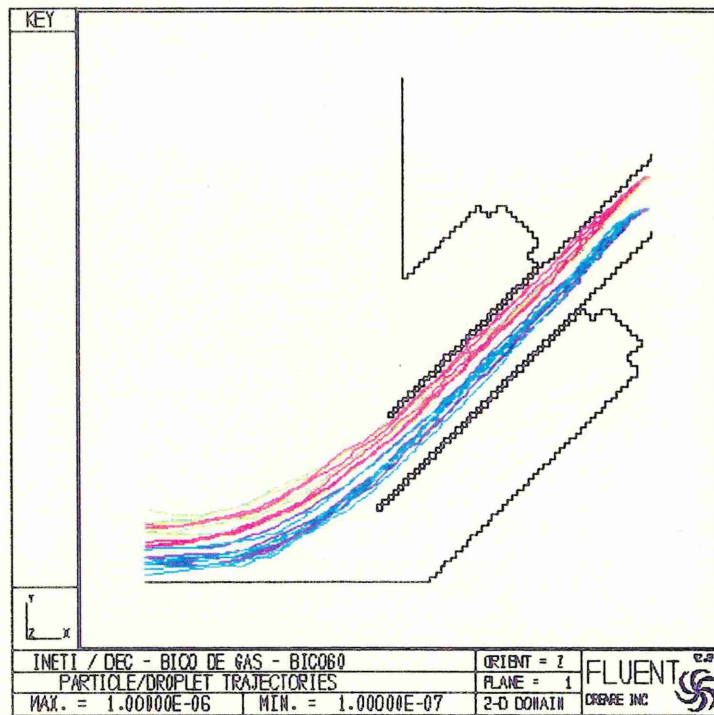


Fig. 6.11a - Particle/droplet trajectories in a "modified" nozzle

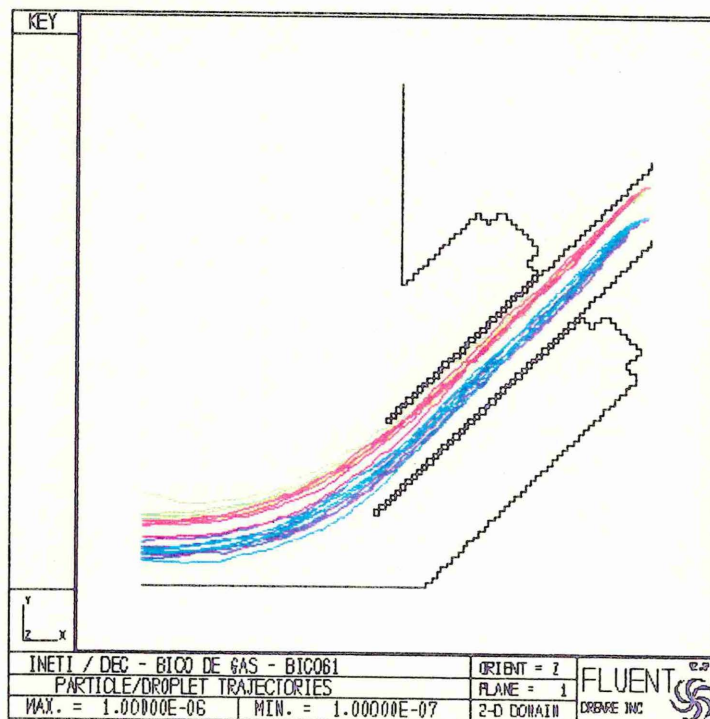


Fig. 6.11b - Particle/droplet trajectories in a "modified" nozzle with gas lens

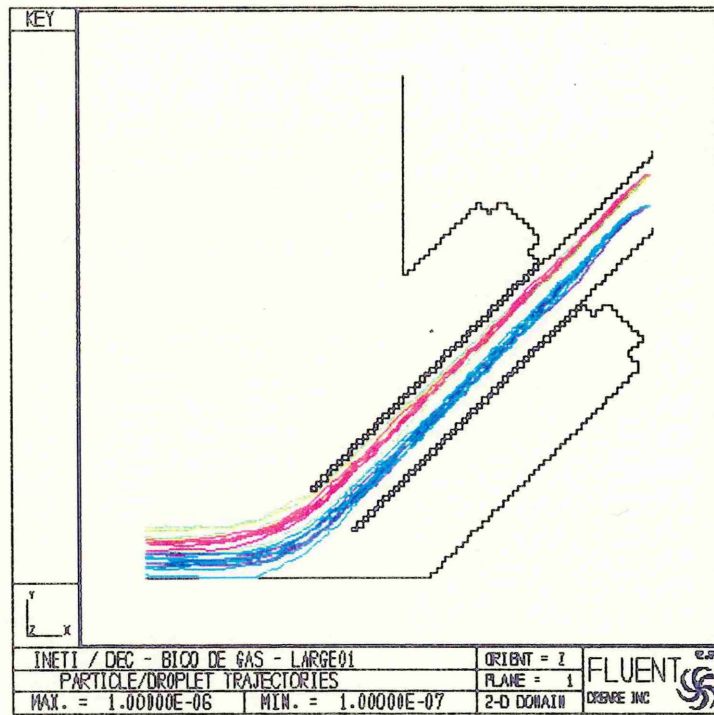


Fig. 6.12a - Particle/droplet trajectories in a "standard" nozzle, 11.5mm length

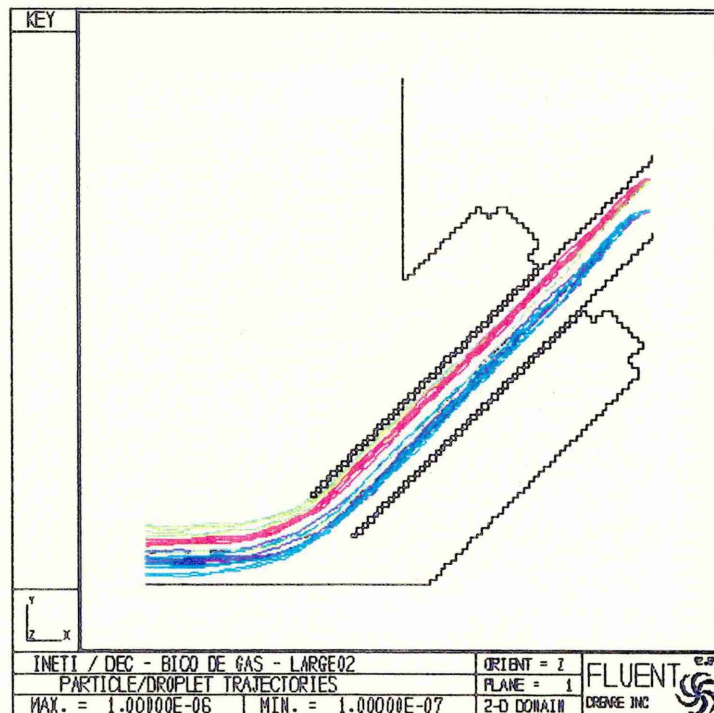


Fig. 6.12b - Particle/droplet trajectories in a "standard" nozzle, 11.5mm length, with gas lens

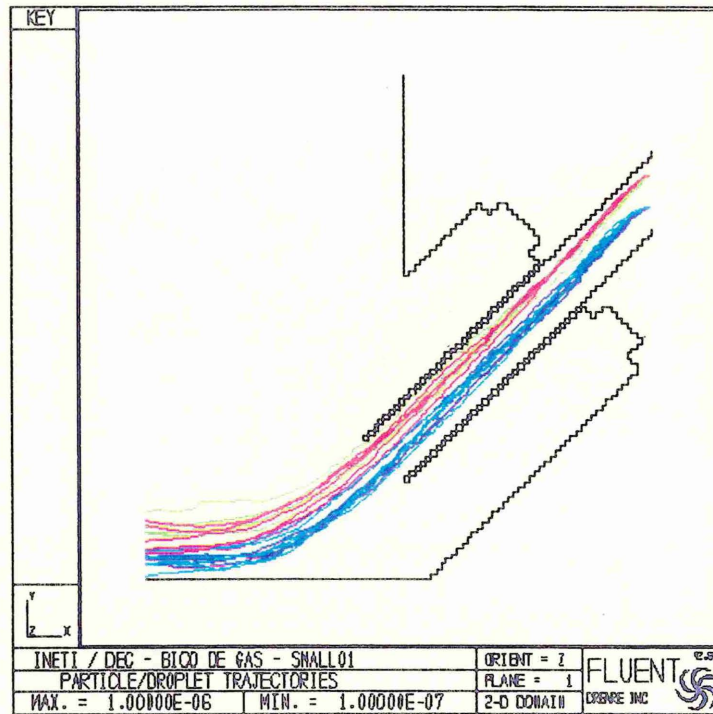


Fig. 6.13a - Particle/droplet trajectories in a "standard" nozzle, 9mm length

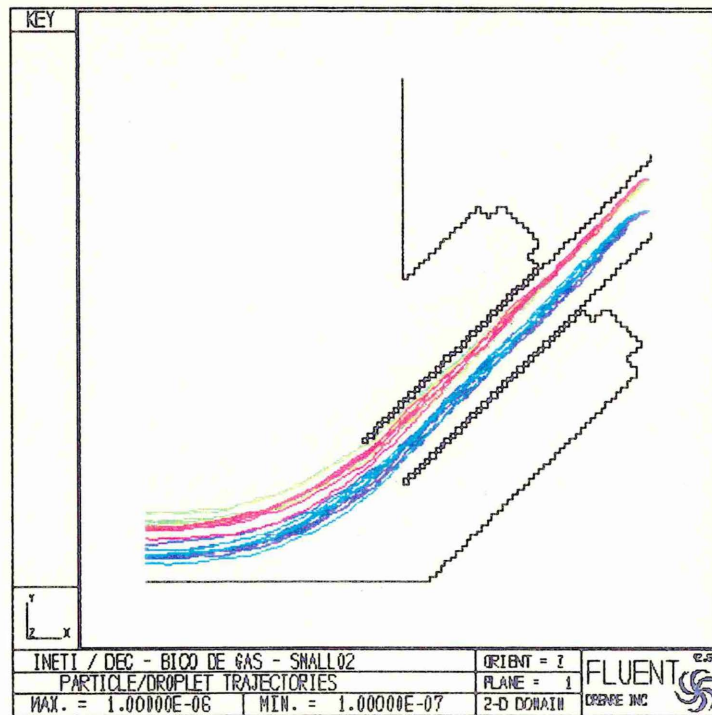


Fig. 6.13b - Particle/droplet trajectories in a "standard" nozzle, 9mm length, with gas lens

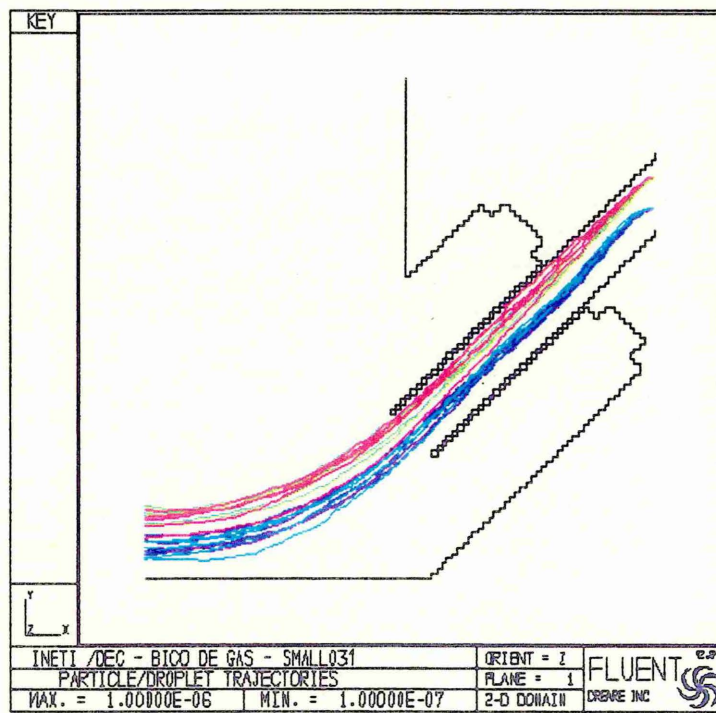
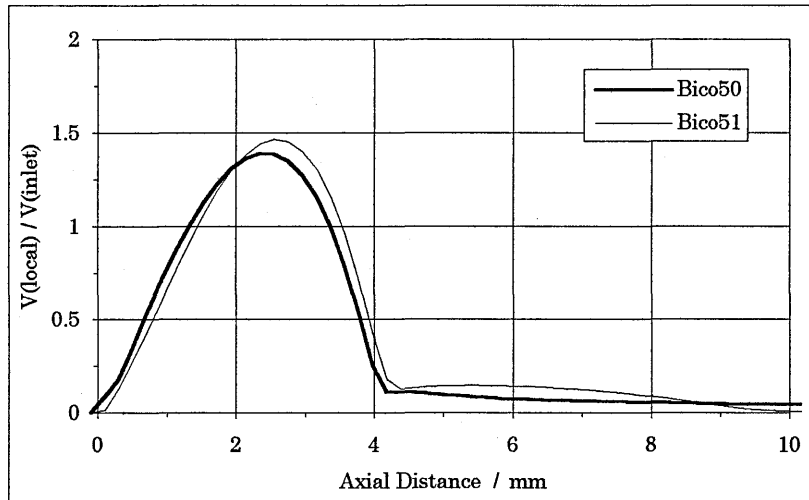


Fig. 6.14 - Particle/droplet trajectories in a "standard" nozzle, 7.5mm length, with gas lens

Position: I = 33



Position: I = 24

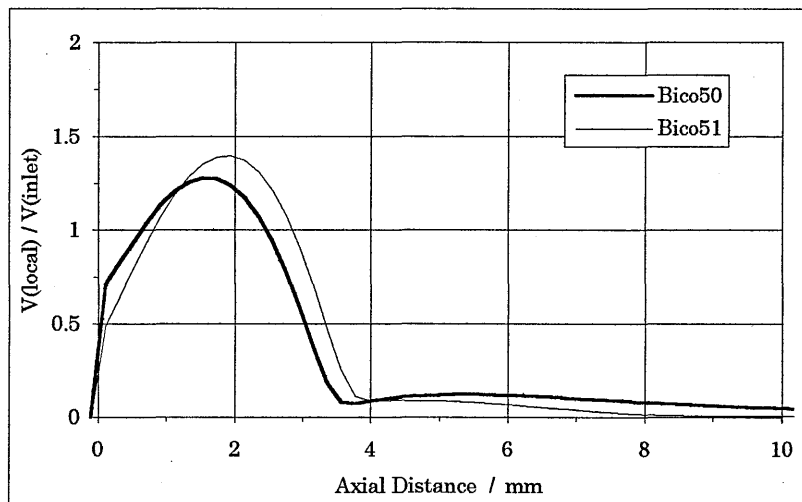
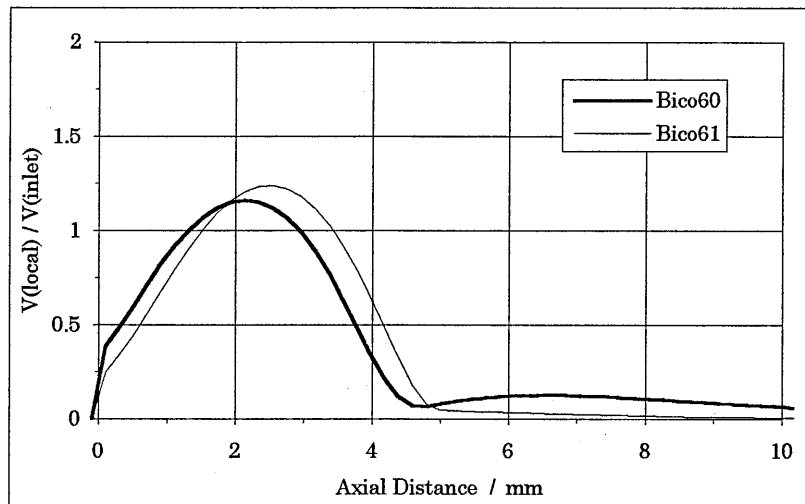


Fig. 6.15 - Gas velocity distribution profiles for a "standard" nozzle, 10mm length with and without gas lens

Position: I = 24



Position: I = 33

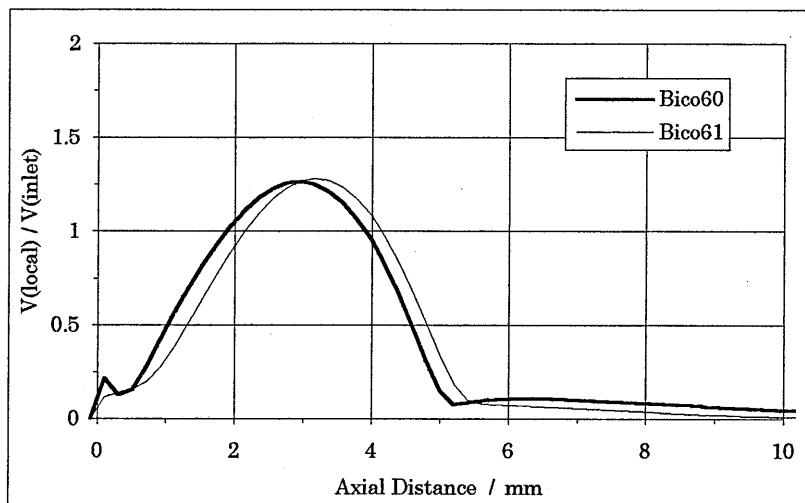
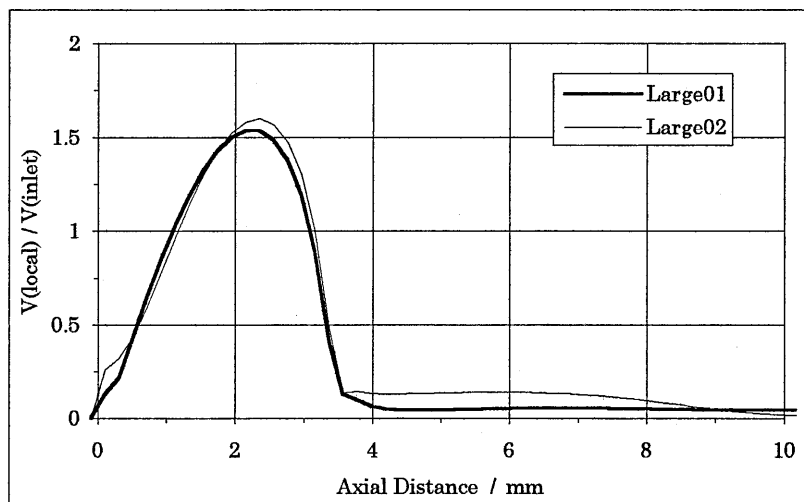


Fig. 6.16 - Gas velocity distribution profiles for a "modified" nozzle, with and without gas lens

Position: I = 33



Position: I = 24

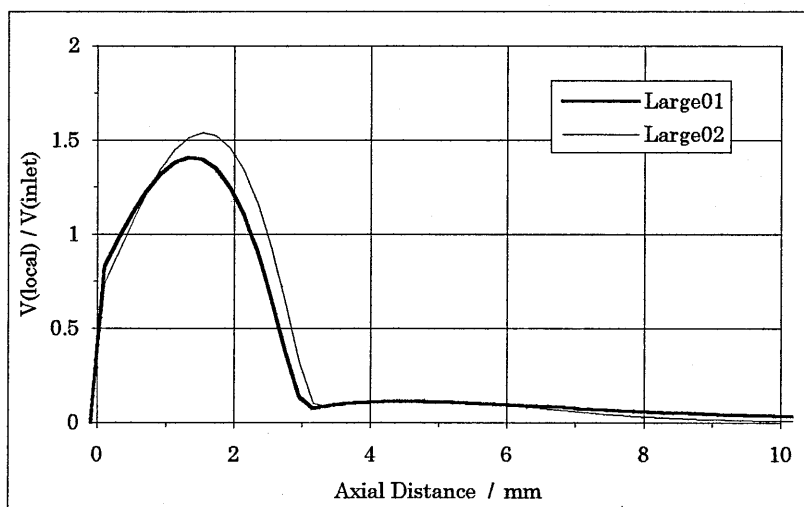
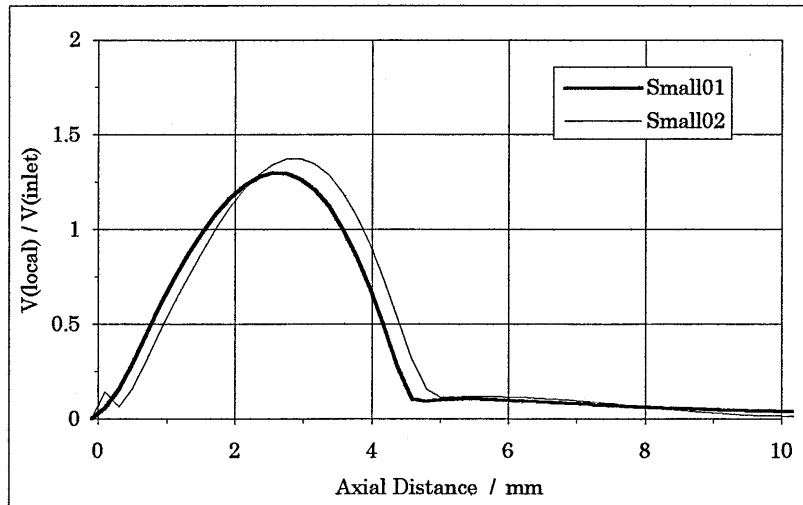


Fig. 6.17 - Gas velocity distribution profiles for a "standard" nozzle, 11.5mm length with and without gas lens

Position: I = 33



Position: I = 24

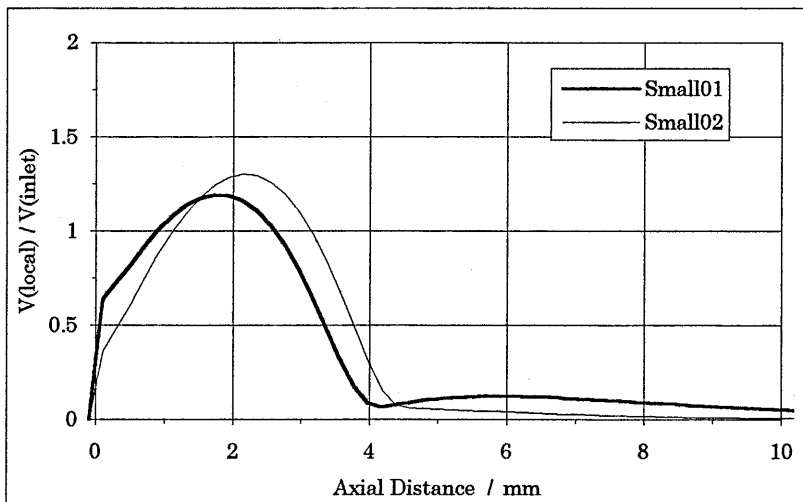
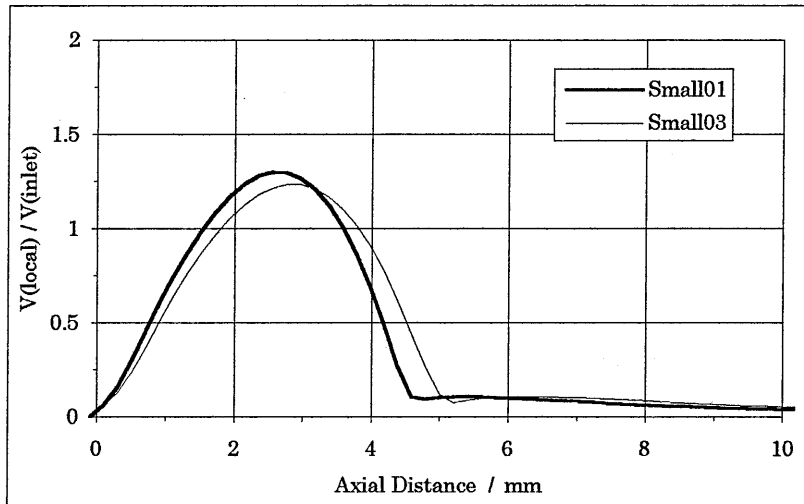


Fig. 6.18 - Gas velocity distribution profiles for a "standard" nozzle, 9mm length with and without gas lens

Position: I = 33



Position: I = 24

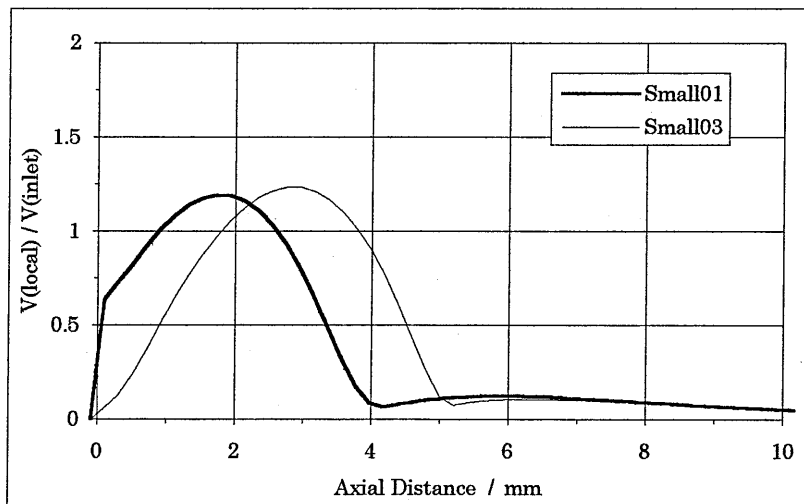


Fig. 6.19 - Gas velocity distribution profiles for "standard" nozzles, 9 and 7.5mm length, without gas lens

**ANNEX 6A - GEOMETRY AND CELL TYPES
OF A "STANDARD" NOZZLE**

- GEOMETRY -

RECTANGULAR CARTESIAN COORDINATES

NI = 100 NJ = 100 NK = 1

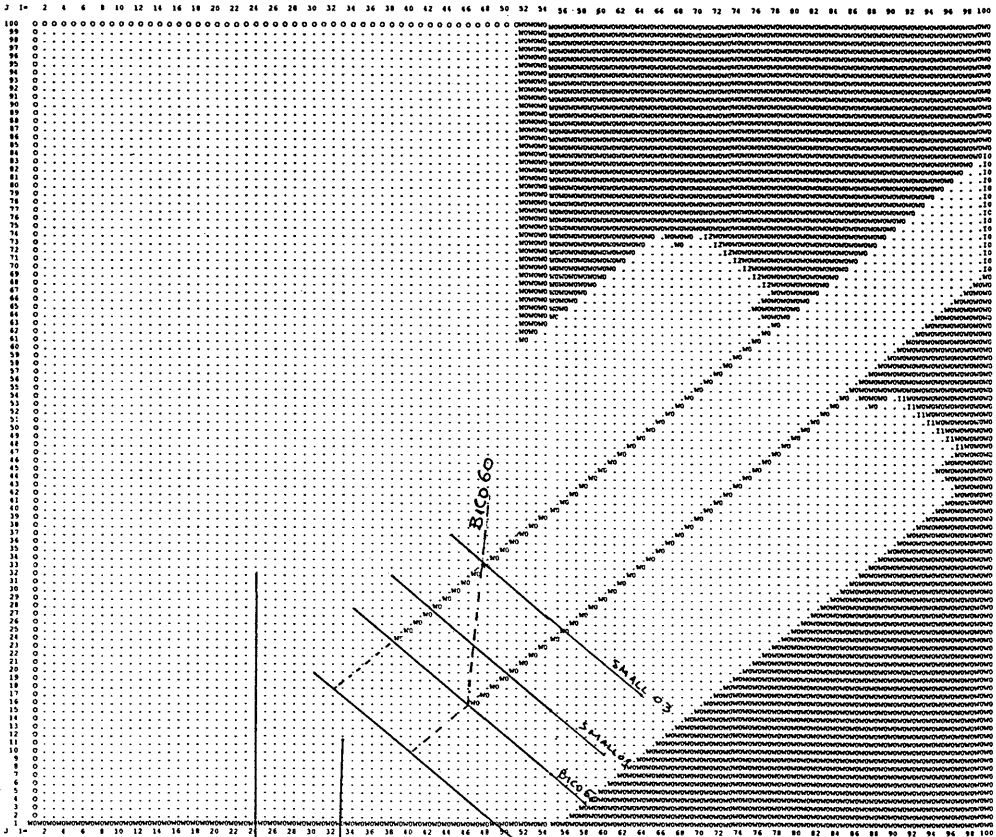
.....NODE CENTRES.....				POSITIVE FACES.....			CELL DIMENSIONS.....			No.
No.	X-GRID	Y-GRID	Z-GRID	X-GRID	Y-GRID	Z-GRID	X-GRID	Y-GRID	Z-GRID	
1	-1.0204E-04	-1.0204E-04	1.9799E+00	0.000E+00	0.000E+00	0.000E+00	2.041E-04	2.041E-04	1.000E+00	1
2	1.0204E-04	1.0204E-04	1.0000E+00	2.041E-04	2.041E-04	0.000E+00	2.041E-04	2.041E-04	0.000E+00	2
3	3.0612E-04	3.0612E-04	0.0000E+00	4.082E-04	4.082E-04	0.000E+00	2.041E-04	2.041E-04	0.000E+00	3
4	5.1020E-04	5.1020E-04	0.0000E+00	6.122E-04	6.122E-04	0.000E+00	2.041E-04	2.041E-04	0.000E+00	4
5	7.1429E-04	7.1429E-04	0.0000E+00	8.163E-04	8.163E-04	0.000E+00	2.041E-04	2.041E-04	0.000E+00	5
6	9.1837E-04	9.1837E-04	0.0000E+00	1.020E-03	1.020E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	6
7	1.1224E-03	1.1224E-03	0.0000E+00	1.224E-03	1.224E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	7
8	1.3265E-03	1.3265E-03	0.0000E+00	1.429E-03	1.429E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	8
9	1.5306E-03	1.5306E-03	0.0000E+00	1.633E-03	1.633E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	9
10	1.7347E-03	1.7347E-03	0.0000E+00	1.837E-03	1.837E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	10
11	1.9388E-03	1.9388E-03	0.0000E+00	2.041E-03	2.041E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	11
12	2.1429E-03	2.1429E-03	0.0000E+00	2.245E-03	2.245E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	12
13	2.3469E-03	2.3469E-03	0.0000E+00	2.449E-03	2.449E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	13
14	2.5510E-03	2.5510E-03	0.0000E+00	2.653E-03	2.653E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	14
15	2.7551E-03	2.7551E-03	0.0000E+00	2.857E-03	2.857E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	15
16	2.9592E-03	2.9592E-03	0.0000E+00	3.061E-03	3.061E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	16
17	3.1633E-03	3.1633E-03	0.0000E+00	3.265E-03	3.265E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	17
18	3.3673E-03	3.3673E-03	0.0000E+00	3.469E-03	3.469E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	18
19	3.5714E-03	3.5714E-03	0.0000E+00	3.673E-03	3.673E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	19
20	3.7755E-03	3.7755E-03	0.0000E+00	3.878E-03	3.878E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	20
21	3.9796E-03	3.9796E-03	0.0000E+00	4.082E-03	4.082E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	21
22	4.1837E-03	4.1837E-03	0.0000E+00	4.286E-03	4.286E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	22
23	4.3878E-03	4.3878E-03	0.0000E+00	4.490E-03	4.490E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	23
24	4.5918E-03	4.5918E-03	0.0000E+00	4.694E-03	4.694E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	24
25	4.7959E-03	4.7959E-03	0.0000E+00	4.898E-03	4.898E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	25
26	5.0000E-03	5.0000E-03	0.0000E+00	5.102E-03	5.102E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	26
27	5.2041E-03	5.2041E-03	0.0000E+00	5.306E-03	5.306E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	27
28	5.4082E-03	5.4082E-03	0.0000E+00	5.510E-03	5.510E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	28
29	5.6122E-03	5.6122E-03	0.0000E+00	5.714E-03	5.714E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	29
30	5.8163E-03	5.8163E-03	0.0000E+00	5.918E-03	5.918E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	30
31	6.0204E-03	6.0204E-03	0.0000E+00	6.122E-03	6.122E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	31
32	6.2245E-03	6.2245E-03	0.0000E+00	6.327E-03	6.327E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	32
33	6.4286E-03	6.4286E-03	0.0000E+00	6.531E-03	6.531E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	33
34	6.6327E-03	6.6327E-03	0.0000E+00	6.735E-03	6.735E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	34
35	6.8367E-03	6.8367E-03	0.0000E+00	6.939E-03	6.939E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	35
36	7.0408E-03	7.0408E-03	0.0000E+00	7.143E-03	7.143E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	36
37	7.2449E-03	7.2449E-03	0.0000E+00	7.347E-03	7.347E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	37
38	7.4490E-03	7.4490E-03	0.0000E+00	7.551E-03	7.551E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	38
39	7.6531E-03	7.6531E-03	0.0000E+00	7.755E-03	7.755E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	39
40	7.8571E-03	7.8571E-03	0.0000E+00	7.959E-03	7.959E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	40
41	8.0612E-03	8.0612E-03	0.0000E+00	8.163E-03	8.163E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	41
42	8.2653E-03	8.2653E-03	0.0000E+00	8.367E-03	8.367E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	42
43	8.4694E-03	8.4694E-03	0.0000E+00	8.571E-03	8.571E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	43
44	8.6735E-03	8.6735E-03	0.0000E+00	8.776E-03	8.776E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	44
45	8.8776E-03	8.8776E-03	0.0000E+00	8.980E-03	8.980E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	45
46	9.0816E-03	9.0816E-03	0.0000E+00	9.184E-03	9.184E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	46
47	9.2857E-03	9.2857E-03	0.0000E+00	9.388E-03	9.388E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	47
48	9.4898E-03	9.4898E-03	0.0000E+00	9.592E-03	9.592E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	48
49	9.6939E-03	9.6939E-03	0.0000E+00	9.796E-03	9.796E-03	0.000E+00	2.041E-04	2.041E-04	0.000E+00	49
50	9.8980E-03	9.8980E-03	0.0000E+00	1.000E-02	1.000E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	50
51	1.0102E-02	1.0102E-02	0.0000E+00	1.020E-02	1.020E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	51
52	1.0306E-02	1.0306E-02	0.0000E+00	1.041E-02	1.041E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	52
53	1.0510E-02	1.0510E-02	0.0000E+00	1.061E-02	1.061E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	53
54	1.0714E-02	1.0714E-02	0.0000E+00	1.082E-02	1.082E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	54
55	1.0918E-02	1.0918E-02	0.0000E+00	1.102E-02	1.102E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	55
56	1.1122E-02	1.1122E-02	0.0000E+00	1.122E-02	1.122E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	56
57	1.1327E-02	1.1327E-02	0.0000E+00	1.143E-02	1.143E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	57
58	1.1531E-02	1.1531E-02	0.0000E+00	1.163E-02	1.163E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	58
59	1.1735E-02	1.1735E-02	0.0000E+00	1.184E-02	1.184E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	59
60	1.1939E-02	1.1939E-02	0.0000E+00	1.204E-02	1.204E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	60
61	1.2143E-02	1.2143E-02	0.0000E+00	1.224E-02	1.224E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	61
62	1.2347E-02	1.2347E-02	0.0000E+00	1.245E-02	1.245E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	62
63	1.2551E-02	1.2551E-02	0.0000E+00	1.265E-02	1.265E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	63
64	1.2755E-02	1.2755E-02	0.0000E+00	1.286E-02	1.286E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	64
65	1.2959E-02	1.2959E-02	0.0000E+00	1.306E-02	1.306E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	65
66	1.3163E-02	1.3163E-02	0.0000E+00	1.327E-02	1.327E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	66
67	1.3367E-02	1.3367E-02	0.0000E+00	1.347E-02	1.347E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	67
68	1.3571E-02	1.3571E-02	0.0000E+00	1.367E-02	1.367E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	68
69	1.3776E-02	1.3776E-02	0.0000E+00	1.388E-02	1.388E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	69
70	1.3980E-02	1.3980E-02	0.0000E+00	1.408E-02	1.408E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	70
71	1.4184E-02	1.4184E-02	0.0000E+00	1.429E-02	1.429E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	71
72	1.4388E-02	1.4388E-02	0.0000E+00	1.449E-02	1.449E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	72
73	1.4592E-02	1.4592E-02	0.0000E+00	1.469E-02	1.469E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	73
74	1.4796E-02	1.4796E-02	0.0000E+00	1.490E-02	1.490E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	74
75	1.5000E-02	1.5000E-02	0.0000E+00	1.510E-02	1.510E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	75
76	1.5204E-02	1.5204E-02	0.0000E+00	1.531E-02	1.531E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	76
77	1.5408E-02	1.5408E-02	0.0000E+00	1.551E-02	1.551E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	77
78	1.5612E-02	1.5612E-02	0.0000E+00	1.571E-02	1.571E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	78
79	1.5816E-02	1.5816E-02	0.0000E+00	1.592E-02	1.592E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	79
80	1.6020E-02	1.6020E-02	0.0000E+00	1.612E-02	1.612E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	80
81	1.6224E-02	1.6224E-02	0.0000E+00	1.633E-02	1.633E-02	0.000E+00	2.041E-04	2.041E-04	0.000E+00	81
82										

CHAPTER VI

RESEARCH PROGRAMME
PLASMA CONTROL GAS FLOW SIMULATION

- CELL TYPES -

K = 1



I=24

I=33

CHAPTER VII

DISCUSSION

7.1 INTRODUCTION

The initial experimental programme showed that the key problem with the laser welding of copper was the coupling process, which appeared somehow related with the jet gas nature and flow dynamics over the interaction zone. However, this apparent relationship was not clear and therefore a further research programme was designed with the aim of obtaining a better understanding of the complex mechanisms involved.

The visualisation of the gas jet flow in non welding conditions appeared to be an obvious approach to the determination of the effects of assist gases over the interaction zone and the differences in their flow behaviour as a consequence of the nozzle tip geometry.

Despite the use of several flow visualisation techniques, the results obtained were rather inconclusive. In view of this and the vital need to assess the gas flow patterns in the welding zone a different approach was used. This consisted of gas flow simulation using the "Fluent" software. This approach provided the first evidence of the gas flow behaviour over the interaction zone in a cold condition, which enabled the apparent relationship between the gas jet flow and coupling behaviour detected during the experimental programme to be explained. This allowed a theoretical model to be designed to describe the mechanisms of coupling in the welding of copper with a high intensity CO₂ laser.

From the experimental programme the following features could be observed:

- the onset of welding occurred as soon as a plasma plume was seen over the interaction zone;
- the plasma appeared as a bright blue-white coloured plume and its formation occurred in a very short period after impingement of the beam on copper surface;
- if no plasma plume was observed, no weld was formed and no visible traces of the laser/copper interaction could be detected on the copper surface ;
- the different behaviour in terms of welding/no welding were observed under the same experimental conditions except for the gas jet nozzle;
- the jet and lens gases (assist gases for plasma control) appeared to influence the coupling and welding processes;
- the gas flow patterns over the interaction zone were significantly affected by the geometry of the gas nozzle tip;
- the location of the beam/copper interaction point relatively to the gas jet/copper intersection point, changes significantly according to the nozzle tip configuration (all the other conditions being the same);
- whereas in the case of a "modified" nozzle the beam/copper interaction point was clearly located in a zone with slight recirculation, when a "standard" nozzle was used this point appeared located near the gas jet/copper intersection point (same experimental set-up) (fig. 6.6).

These features allowed the following hypotheses to be formulated:

- the coupling process and welding onset are dependent on the plasma plume formation;
 - plasma plume formation is influenced by the assistance gas flow patterns and composition, i.e., helium, oxygen and argon can be shown to produce different effects;
 - plasma plume formation results from a mechanism other than keyholing, since when the plume is not formed no trace of melting/vaporisation is seen on the copper plate;
 - plasma plume formation must result from the excitation of "seed" particles originating on the copper surface;
 - the assist gas flow patterns affect the plasma plume formation by interfering with the "seed" particles;
 - copper surface condition is of fundamental importance since it must be able to provide the "seed" particles as soon as of its interaction with the laser beam occurs;
-

- the plasma plume must behave as a means of energy transfer, providing the energy needed to assist the opening of a keyhole, to the underlying copper.

7.2 MODEL FOR THE COUPLING PROCESS IN THE LASER WELDING OF COPPER

7.2.1 Outline of the Coupling Mechanism

In the interaction of a high power CO₂ laser beam with a copper target a microvolume of particles is removed and/or detached from the copper surface and this is confined to the region close to the copper surface and delimited by the focal spot dimensions (this will be named hereafter "focal volume"). These particles act as the "seeds" which trigger the plasma formation mechanism. These "seed" particles originate on surface irregularities, asperities and defects, which having different properties from those of the bulk copper are able to more efficiently absorb the laser energy or interact with the electric field of the radiation, being therefore removed by evaporation or emission (e.g. electrons from overheated defects). After evaporation/emission, these particles may be concentrated over the interaction zone on the focal volume for further interaction with the laser beam. The absorption of the laser radiation by these particles by an inverse bremsstrahlung mechanism causes their breakdown and the development of a plasma plume, which must be maintained close to the surface in order to act as a point source, thus enhancing the coupling of the laser beam by transferring to the copper beneath the energy required for a keyhole to open.

The gas jet flow pattern and dynamics play a significant role in the initiation and development of the plasma plume, which is fundamental for coupling to occur and therefore for welding to be produced. In the initiation process (i.e., removal of particles from the copper surface and its concentration over it in a zone delimited by the focal volume) the gas flow should not cause any disturbance over the interaction zone, which could lead to dispersal of the "seed" particles from the focal volume. This would prevent the attainment of the required density for their further interaction with the laser radiation and plasma development. On the other hand, once the plasma plume is formed the characteristics of the gas flow pattern is again essential to avoid the plasma propagation away from the copper surface causing decoupling of the beam from copper.

Once the keyhole is opened through the plate thickness the copper vapour filling it, tends to escape from it and it will sustain the plasma plume, maintaining henceforth the energy transfer vehicle to the underlying material.

The surface breakdown threshold intensity and the gas jet flow pattern over the interaction zone appear to be the key factors for the control of the coupling process and therefore of the welding of the copper with a high power CO₂ laser.

This is a simple outline of the mechanisms that it is suggested to take place in the interaction of high power CO₂ beams with copper. This picture presents important innovative aspects related to the laser beam/material interactions in the welding of high reflectivity and conductivity materials, as long as it assumes that for the CO₂ laser welding of copper the

coupling process and keyhole formation are dependent on the formation of a plasma plume by a mechanism that involves the formation of "seed" particles, by processes other than the copper's vaporisation.

The proposed mechanisms and processes have been analyzed in depth below and a theoretical model is presented to explain the phenomena occurring in the CO₂ laser beam/copper interaction.

7.2.2 Mechanism of Formation of the "Seed" Particles

7.2.2.1 Theoretical considerations

The role of metallic surfaces in the initiation of laser induced gas breakdown processes has long been recognised, since experimental results showed that if a metallic surface was used for pre ionisation, the gas breakdown thresholds were lower than those obtained for a cold gas.

Several mechanisms have been proposed to explain the experimentally observed low thresholds for gas breakdown near solid surfaces and these include: bulk vaporisation followed by equilibrium vapour heating [Smith, 1977], local target heating at surface defects, enhanced electric fields at surface protusions [Bloembergen, 1973], vaporisation of metallic and nonmetallic defects [Ursu et al., 1984b], thermionic emission of electrons from surface defects [Walters et al., 1978a; McKay et al., 1979], shock heating of the surrounding air by the vapour blow off, field emission from surface defects [Smith, 1977], and desorption of gases on the surface [Mahler et al., 1974]. It must be stressed that in the gas breakdown studies the target material was simply regarded as the emission source of electrons, which would initiate the gas breakdown process by absorption of laser photons by inverse bremsstrahlung absorption in the presence of neutral gas atoms and thus generating a plasma.

Laser induced plasmas produced on metallic surfaces and used to initiate a gas breakdown process, have been reported by several researchers [Smith, 1977; Ursu et al., 1984b; Mazumder et al., 1987]. These plasmas can present different characteristics according the conditions of their formation. However, it is clearly recognised that they are responsible for the "enhanced thermal coupling" observed in the interaction of high intensity beams with high reflectivity materials [McKay et al. 1979; Metz et al., 1975; Walters et al. 1978a; Marcus et al., 1976].

The diversity of mechanisms mentioned above for initiation of a plasma in the presence of a metallic surface during gas breakdown studies, show that the way laser radiation interacts with metallic surfaces is a complex and controversial subject.

The surface breakdown threshold intensity is always lower than that of the bulk material, even for an ideal surface. Therefore, a real surface's properties may have a vital influence on the coupling process, since its behaviour with respect to laser radiation is able to determine the mechanisms of light absorption into the material.

The influence of the surface condition on its absorption behaviour to the interaction with low intensity beams was discussed in chapter III. However, surface condition is also likely to affect the metal's absorptivity in the high intensity range.

The way in which surface impurities and defects influence absorptivity has been object of an extensive research but experimental studies have shown that this can be attributed to either a vaporisation of these imperfections at radiation intensities lower than the material's vaporisation and even sometimes melting intensities [Hopper et al., 1970; Sparks et al., 1973] or to a thermionic emission of electrons from overheated defects thermally isolated from the substrate material [Smith, 1978]. In the latter case, the overheated defects act as "hot" points on the surface which show high absorptivity due to the temperature dependence on the metal absorptivity. The impurity/defect vaporisation and/or the emission of electrons from them constitute the priming mechanism from which an absorbing plasma can be formed. Oxides were also reported to contribute to this mechanism by their vaporisation at temperatures lower than those of the bulk material [Ursu et al., 1984b].

The metal's reflectivity dependence on temperature was depicted in figs 3.3 and 3.4. This behaviour obtained with moderate intensity radiation ($I < 10^6 \text{ Wcm}^{-2}$) is, however, radically changed when a high intensity beam is used (fig. 7.1). Fig. 7.1 shows some discrepancy in the results given by different researchers. Whereas some researchers claim a decrease in the surface reflectivity at or even before the melting point of a metal surface is reached [Chan et al., 1977; Walters et al., 1978b] others [Park et al., 1979] suggest a deviation in the reflectivity does not occur until the surface temperature attains the metal's evaporation temperature.

From the reported observations of several researchers on the sudden drop in metal reflectivity under intense laser light, it is difficult to draw conclusions since no analysis of the associated target damage is generally presented.

The sudden rise in absorptivity for values close to unity at a critical intensity (I_c) is known as "anomalous" absorption by metals and is accompanied by a laser induced plasma generated in the evaporated target surface [Herziger, (1983); Allmen et al. (1978)]. However, according Prokhorov et al. [1973] that effect could be associated with a dielectric like behaviour of the molten material.

To obtain the vaporisation of a metal surface by laser irradiation, the surface temperature T_s , has to exceed its vaporisation temperature T_{vap} . The temporal development of T_s is described by the heat flow equation. For a continuous source, losses due to heat conduction, radiation and convection should be accounted for in this equation [Ready, 1971] in order to get a more accurate estimate of the temperature distribution. However, the mathematical treatment of the last two terms is quite complex and therefore only losses by conduction are considered.

Assuming a Gaussian beam intensity¹, the temperature at the surface at the centre of a laser irradiated spot can be estimated as [Ready, 1971]:

¹ - An idealised situation

$$T(o,o,t) = T_0 + \frac{A I r_F}{K\sqrt{\pi}} \tan^{-1} \left(\frac{4kt}{r_F^2} \right)^{1/2} \quad (7.1)$$

where, I is the laser intensity, A the absorptivity, r_F the focus radius, t the time, k the thermal diffusivity, K the thermal conductivity and T_0 the initial temperature.

The later expression takes no account of the latent heat of vaporisation which becomes a dominant factor since for vaporisation to occur the energy must be supplied rapidly enough that little is conducted out of the region in which it is concentrated.

Assuming as an approximation, the heat of fusion as an equivalent of temperature increment, $\Delta T = L_f / c_p$ [Rosen et al., 1982], then for $T > T_m$, eqn. 7.1 will be replaced by:

$$T(0,0,t) = T_0 - \frac{L_f}{c_p} + \frac{A I r_F}{K\sqrt{\pi}} \tan^{-1} \left(\frac{4kt}{r_F^2} \right)^{1/2} \quad (7.2)$$

where, L_f is the latent heat of fusion and c_p the heat capacity.

After the onset of vaporisation, and until the steady state vaporisation is attained, there is no exact solution for $T(o,o)$. Asymptotically:

$$T(x) = (T_0 - \frac{L_f}{c_p}) + (T_{ss} - T_0 + \frac{L_v}{c_p}) e^{-\frac{x}{x_0}} \quad (7.3)$$

where, L_v is the latent heat of vaporisation, T_{ss} is the steady surface temperature and $x_0 = K/\rho v c_p$, and,

$$v = \frac{A I}{\rho [L_v + L_f + c_p (T_{ss} - T_0)]} \quad (\text{surface retreating velocity}) \quad (7.4)$$

x is always measured from the instantaneous position of the surface of the plate.

7.2.3 Copper Behaviour in the Interaction with a Laser Beam

The enhancement of coupling in the interaction of a pulsed CO_2 beam with copper, was found at laser intensities sufficient to cause breakdown of the copper surface ($\sim 10^6 \text{ W/cm}^2$) [Marcus et al., 1975]. Coupling coefficients of 0.036 and 0.33 were reported for copper as determined at low intensities, and at intensities where breakdown occurred respectively. No

details on the pulse duration and laser induced surface damage were given, although the presence of a plasma was reported.

Data on breakdown of copper reflectivity under intense radiation from a Nd-YAG laser [Allmen et al., 1978], shows that enhanced absorption started at a characteristic temperature, independent of intensity, which in the case of copper was about 3100K ($\sim 2830^\circ\text{C}$). Therefore, it was assumed that the drop in reflectivity was coincident with the formation of a plasma wave initiated in the metal vapour for intensities of the order of 10^7 to $\sim 6 \times 10^8 \text{ W/cm}^2$. Zavecz et al. [1975] reported on the reflectivity behaviour of oxide free copper samples exposed to a high intensity Nd-YAG laser and describes a characteristics feature: for an intensity of $3 \times 10^8 \text{ W/cm}^2$, a reflectivity value of ~ 0.64 was found, for which no noticeable surface damage was detected by SEM analysis.

Specular and total reflectance measurements carried out on copper samples in vacuum, during irradiation with a Q-switched ruby laser for 30ns with intensities variable between $10^7 - 10^9 \text{ W/cm}^2$ [Park et al., 1979], have shown that at an intensity of $5 \times 10^8 \text{ W/cm}^2$ (fig. 7.2), the specular reflectance undergoes a sharp drop, and a permanent damage at the interaction point was observed. Heat conduction calculations showed that the maximum temperature attained by the copper surface was in excess of its boiling point.

Determination of ignition thresholds of laser supported detonation (LSD) waves on a copper target has been reported by Mahler et al. [1974]. The ignition of the LSD wave was detected by the rapid loss of reflected power and was observed to occur within $0.5\mu\text{s}$ for a beam with an energy density of approximately 191 J cm^{-2} and peak intensity at the first laser spike of $2.75 \times 10^7 \text{ Wcm}^{-2}$.

Reflectivity measurements carried out by Schellhorn et al. [1986] not for copper but for aluminium found that $2-4\mu\text{s}$ after laser irradiation on an aluminium sample an important drop in the reflected signal occurred. No interpretation is given for this very short period, although it was suggested that a mechanism other than aluminium vaporisation and keyhole formation may explain it.

A rough estimate of the time needed to attain the vaporisation temperature on a copper surface, when a beam of 7kW was focused in a 0.5 mm diameter focal spot ($I \approx 3.6 \text{ MW/cm}^2$), can be obtained through eqns 7.1 and 7.2 and using the physical properties of copper given in table 7.1. Values of approximately $12\mu\text{s}$ (eqn 7.1) and $17\mu\text{s}$ (eqn 7.2) were obtained assuming $A = 0.012^3$. If, however, a higher value of A is assumed (as it is expected to be the case with a real surface), example $A = 0.05$, then t will become $0.7\mu\text{s}$ (eqn 7.1) or $0.9\mu\text{s}$ (eqn 7.2).

³ - This value was derived from the reflectivity ($A=1-R$) calculated from the Fresnel equations for a normal incidence at room temperature in a smooth copper surface. For a $10.6 \mu\text{m}$ wavelength radiation, n and k are respectively 12.80 and 64.0 [Prokhorov, 1990].

Table 7.1 - Physical properties of copper

Atomic weight	63.54
Melting point [°C]	1083
Boiling point at 1 atm. [°C]	2590
Specific heat (solid) [J/g°C]	0.385
Specific heat (liquid) [J/g°C]	0.473
Average value for specific heat [J/g°C]	0.429
Density (solid) [g/cm ³]	8.89
Density (liquid) [g/cm ³]	8.53
Heat of fusion [J/g]	205
Heat of vaporisation [J/g]	5240
Thermal conductivity (solid) [J/cm s °C]	3.93
Thermal conductivity (liquid) [J/cm s °C]	3.35
Average value for thermal conductivity [J/cm s °C]	3.64

(FROM: "COPPER AND ITS ALLOYS", 1982, E.G. WEST)

7.2.4 Copper Behaviour in the Interaction with a High Intensity CO₂ Laser Beam

Assuming that the interaction of a continuous wave high intensity CO₂ beam with copper, as described in the present work, could be explained by the classical approach involving the heating and the vaporisation of a thin superficial layer of copper, then the formation of a small amount of vaporised copper should occur in a fraction of time lower than approximately 17μs, dependent on the copper superficial condition.

In the actual conditions, the beam has an annular profile and therefore the area of interaction will be larger than the 0.196 mm² determined (focal spot ≈ 0.5mm), assuming for simplicity a gaussian beam profile. Consequently the energy density will be lower than 3.6 MW/cm². Thus, the time needed to reach the boiling temperature of copper will be correspondingly higher than that calculated in pt. 7.2.3. For example, assuming an increase in the focal spot to 1mm, then the time needed to reach copper's boiling temperature is increased to about 0.2 or 0.3 ms as obtained from eqns 7.1 and 7.2 for A=0.012.

Notwithstanding these theoretical results, which under the conditions used predict the boiling of copper with some delay after the laser beam impingement, it was found experimentally in the present work that the coupling of the laser radiation into copper was not always achieved, even under similar welding conditions except for the plasma control gas flow (chapter IV). This suggests that the achievement of coupling and the keyhole formation does not only depend on the absorption of the laser radiation by copper, which otherwise would always yield to copper vaporisation with the formation of a small superficial melted spot.

Thus, the production of some metal/particles vapour (the source for plasma development) in the interaction zone it is not likely to be due to copper vaporisation by direct absorption of radiation.

Further experimental evidence that the surface vaporisation did not occur as a result of the laser/copper interaction was given by the lack of any trace of shape modification (which could be for example a tiny pool, if at least melting had taken place) on the copper surface, whenever coupling was not achieved in consequence of the use of a "standard" gas jet nozzle, as described in chapter IV. Moreover, this same behaviour was also observed with a more powerful beam of 10 kW. This appears to mean that, although the surface vaporisation of copper was theoretically predicted to occur in very short periods of time, actually it did not occur unless non-conventional phenomena were considered.

Results from Dell' Erba [1985] show that 3mm thickness copper was welded with a 2 kW continuous wave CO₂ power beam, with oxygen assistance. Focal spots of 500 μ m were reported at which corresponded an intensity of approximately 1MW/cm².

Some experiments were also performed on Cu-OFHC 3mm thickness, with a 2 kW continuous wave CO₂ laser beam, TEM₂₀, using as assist gases Ar, He and compressed air, delivered to the welding zone through a small hole perforated mesh box (gas spreader). The beam intensity was approximately 1.6 MW/cm². The copper surfaces were uncoated and roughened. No coupling was obtained, even after periods of interaction (in the same spot) of the order of some seconds. The radiation was mainly reflected instead of being absorbed.

There is a fundamental discrepancy between the later results⁴, i.e., the results reported by Dell'Erba et al. [e.g., 1985, 1986] and the results achieved in the present research work, as described in chapter IV.

The first consideration to be made is that the coupling and welding achievement does not seem to depend on the beam power available and more specifically on the beam intensity. Experiments carried out at different power intensities produced quite different results. Whereas at 1 MW/cm² coupling and full penetration welds were reported, at 1.6 MW/cm² no coupling was achieved. The latter behaviour was also observed with higher intensity laser beams. Therefore, it can be assumed that the apparent successful results of Dell'Erba et al. [1985-86] in welding uncoated copper with a CO₂ laser could be attributed to the effects of the use of an oxygen gas jet. As a matter of fact, this was the explanation given by Dell'Erba [1985], who supported this hypothesis by reference to the theory developed by Ursu et al. [1983 - 84a].

The role of oxygen was claimed to promote the rapid formation of a superficial layer of copper oxide, whose properties (table 7.2) would then determine the efficiency of the interaction. This layer was reported to present absorptivity values as high as 50% [Ursu et al., 1984b].

⁴ - There must be some caution when comparing results obtained in different conditions and with different equipments and in the present case it must be kept in mind that a comparison is being made with data reported in literature.

Ursu et al. [1984b] also reported in work on air breakdown studies in the presence of a copper plate, that the role of the copper oxides could be ascribed to their poor thermal contact with the metallic substrate which combined with interference phenomena would lead to a decrease in the vaporisation threshold and consequently in the air breakdown threshold for plasma formation in the presence of the copper target. No values for the vaporisation or air breakdown thresholds were given.

The role of oxides in the improvement of coupling of the laser radiation into metals, has been reported by several researchers, for the laser heating [Duley et al. ,1979] and welding [Jorgensen, 1980; Ohmine, 1988]. The interpretations given for the oxide effects relied on the better optical properties provided by a layer of oxide relatively to the uncoated metal. Although, this effect could be considered acceptable to explain the radiation absorption and coupling phenomena in the low intensity beam range, it appears rather controversial to describe these same phenomena in the high intensity range. The reasons for this will be discussed later but the results from Dell'Erba's work [1986b], which showed that the use of a pre laser oxidised copper target in the presence of assist inert gases did not yield to the coupling of the laser radiation into copper, should be recalled. Consequently, it is concluded that the presence of an oxide formed as the result of the use of a CO₂ laser beam and a jet of oxygen, seems not to be able to act as the priming agent of the coupling process.

The heat of formation of the oxides of copper is low (-166.7 and -155.2 kJmol⁻¹ for the Cu₂O and CuO, respectively), thus no significant increase in the heat input to laser welding is expected to result from the use of an O₂ gas jet.

The oxidation of copper under laser conditions was described by Ursu et al. [1983-84a] to occur at rates two order of magnitude higher than in non laser conditions. However, the analysis of their published results leads to the conclusion that the copper oxidation was obtained at low beam intensities ($\approx 10^2$ W/cm²) and for time intervals in the range of minutes to hours. These irradiation conditions seem not to comply with the actual welding conditions presented in the Dell'Erba work (beam intensity $\approx 10^6$ W/cm²).

This important difference in terms of the beam intensities used, to induce copper oxidation is thought to have consequences in the kinetics of the laser induced process of oxidation, even under non isothermal conditions.

Table 7.2 - Physical properties of copper oxides

	Melting temp. (°C)	Boiling temp. (°C)	Density (g cm ⁻³)
Cu	1084.5	2580	8.933
CuO	1326	---	6.40
Cu ₂ O	1235	2073 ^{dec}	6.0

(FROM: Chemistry, Physical Science, Physics, R. D. Harrison, 4th edn, 1977)

The copper oxidation process induced by the presence of oxygen, which occurs simultaneously with the welding process appears rather to result from the increase in the copper surface temperature, due to the absorption of laser radiation by its imperfections, defects, etc., than as the prime cause for the increase in the copper's absorptivity. This means that the oxidation process seems more likely to be driven by the interaction of the laser beam/copper (defective points) than to drive it. Once the copper oxides are formed on the copper surface they will also contribute to the coupling process. On one hand, the copper oxides present a lower vaporisation threshold (table 7.2), and on the other hand, due to the kinetics of their formation, they are likely to be produced in layers not in good thermal contact with the copper substrate. It could be expected that a rapid overheating of the oxides would result, and consequently their evaporation at temperatures much lower than the vaporisation temperature of copper. These vaporised particles would increase the density of particles removed in the onset of the beam/copper interaction, thus enhancing the formation of a plasma plume.

It is thought that at the onset of beam/copper interaction the main role of copper oxides would be the increase in the number density of "seed" particles. Copper oxides appear then as a secondary source in addition to the primary one constituted by the surface defects. Thus, an enhancement in the plasma plume formation and coupling process result.

This explains why the interaction of the CO₂ laser beam with a laser pre-oxidised copper sample did not give an acceptable result as reported in Dell' Erba [1986] work. An uniform oxide layer is not able to respond efficiently to the interaction with the laser beam, i.e., it does not absorb significantly the laser radiation to attain its vaporisation, (which appears to be the only way it could contribute for the plasma plume formation). This means that either its optical characteristics are not sufficient to ensure the required absorptivity or the conductivity of the absorbed energy to the underlying copper does not allow the achievement of sufficiently high temperatures. As, according to Ursu et al. [1986] the thermal contact of copper oxides with the substrate is poor, then the former assumption seems to be valid. In addition, an oxide layer is not expected to present particular features as those found in a real uncoated surface, which could imply that its vaporisation is required to ignite a plasma plume.

The hypothesis of oxygen mixing with the gas jet due to the particular geometry of the nozzle tip used in this research programme was put forward in chapter IV, as a way of explaining the enhanced coupling of the laser radiation into copper. However, this hypothesis was dismissed since the use of a lens gas (which promotes a better protection of the interaction zone against the ambient atmosphere) did not appear to interfere in the coupling process.

The mechanical preparation of the copper surfaces prior to welding (as carried out in this research programme) besides destroying superficial oxides on copper, produced an amorphous and distorted superficial layer. The distortion effect can be significant in a ductile metal such as copper. This distorted, strained layer is thought to have a fundamental influence on the interaction of copper with a high power CO₂ beam, since its properties, which are essentially different from those of the bulk copper and even from those of a copper smooth strain free surface, will determine the laser induced surface breakdown threshold.

It should be stressed that a copper surface in its "as received" condition can present an appearance as shown in fig. 7.3. The surface shows a superficial layer of oxides (resulting

from atmospheric oxidation), roughness and several defects (e.g., scratches). This figure illustrates what is to be expected from a real surface. The morphology and condition of such a surface is far from that of a "perfect" surface. Therefore, the behaviour of a real surface is expected to be different from that which can be predicted using the constants and properties obtained on an almost "ideal" sample in vacuum or controlled atmosphere.

It is clear from the above discussion that the material's surface has a fundamental influence on the coupling process. Despite that, whereas at low beam intensities the efficiency of coupling only depended on the material surface condition, at high beam intensities, although other mechanisms may be operative, the surface condition still appears to exert a primary role in the coupling process at least at the onset of laser/material interaction.

7.2.4.1 Coupling mechanism

■ *Onset of interaction*

For copper, it was seen that even with quite high beam intensities, coupling was not achieved if the mechanism for the onset of coupling did not become operative. This mechanism is thought to be related to the plasma, whose formation depends on the existence of vaporised material in the interaction zone. The vaporised material could be produced by the vaporisation of the metal or/and surrounding atmosphere. However, as the ionisation potentials for gases are more than two times higher than those for metals (table 3.2), it is expected that the vaporised material results from the vaporisation of the metals. The vaporisation of metals is not easily attained in the case of high reflectivity and conductivity metals (e.g., copper, aluminium, etc.). Therefore, one of the ways of overcoming this problem is by means of decreasing the effect of the surface barrier at least at the onset of the coupling process. This seemed to be the objective of the use of an oxygen jet in the laser welding of copper.

The objective of mechanically roughening the copper surfaces was also to improve the initial absorptivity of copper to the laser radiation. However, it was shown in chapter IV that by itself its influence on coupling was negligible.

It was also shown in chapter IV that when coupling and welding occurred a plasma was seen over the welding zone. Therefore, the formation and maintenance of this plasma seems to be the key factor in the mechanism of coupling.

This plasma always appeared to be associated with coupling and welding and therefore to conditions where a keyhole was formed. The formation of a keyhole and thus of a metal vapour source, is a consequence of the coupling of the CO₂ beam into copper. Consequently, the main question concerns the mechanism of coupling. If a sufficiently high laser beam intensity is not able to produce the vaporisation of copper even in a roughened sample, then the keyhole formation must result from a different coupling mechanism.

The presence of plasma in successful welds, at the beginning of welding as well as during the whole operation can have two different interpretations: on one hand, it is an indication of the formation and maintenance of a keyhole and on the other hand it shows that an "enhanced coupling" took place in the laser/copper interaction.

In the later, plasma is "seen" to behave as a complementary energy transfer source to that represented by the direct infrared radiation on the copper surface.

The formation of some plasma above the copper surface to allow the onset of coupling, is a question which should be analyzed in more depth.

It was shown earlier that the laser beam intensities used in this work were not able to produce the bulk vaporisation of the copper surface needed to ignite the plasma formation. On the other hand, as seen in table 3.6 and discussed above, the breakdown of gases in the presence of a metallic surface is always initiated by the vaporisation or electron emission from the metallic surface.

Therefore, it seems that the problem of plasma initiation could be restricted to the copper surface, which would provide the material required for plasma ignition.

Figs 4.1 and 7.3 show the mechanically prepared surface and the surface in its "as received" condition. Both show surfaces containing several defects, imperfections and roughness. In addition, the mechanically prepared surface is likely to contain loose particles resultant from the brushing operation and not removed by the cleaning with "Genklene". In the "as received" sample surface the presence of many sharp points were noticed in the oxidized surface background.

All the features described above are likely to respond significantly to the interaction with a CO₂ laser beam mainly because their absorption properties are higher than those of a smooth surface and for many of them the thermal contact with the substrate is weak or even non existent.

The response of copper surface features to the interaction with a high intensity CO₂ laser beam can present different forms but the final result will always be a volume of particles, either neutral, electrons or ions confined to the focal volume.

Laser induced particle emission from the metal surface has been reported by several researchers [e.g., Duley, 1968-69; Honig, 1963; Cobb et al., 1965; Ready, 1963]. Ionic emission is expected not to depend on the heating of the bulk copper but instead to proceed from highly localized surface sites [Duley, 1968-69]. The likelihood of the thermionic emission from the copper irradiated surface appeared quite difficult since neither the density of the emission points (i.e., defects, sharp points, etc) nor the distribution of temperature on those points is known.

In the case under discussion it is thought that an important laser induced emission should occur at temperatures lower than the melting temperature of copper, since when no coupling was achieved no apparent modification was seen on the copper surface. Although, the lack of coupling could also be interpreted as due to an insufficient density of particles emitted/vaporised, there is experimental evidence to support the former idea. Under the same experimental conditions, i.e., copper surface preparation, experimental set-up and parameters, the achievement of coupling only depended on the nozzle tip geometry of the plasma control gas and therefore of the gas flow pattern.

The material emitted by the copper surface is likely to consist of different species, i.e., neutral atoms of copper and impurities (by vaporisation) and ionic particles (i.e., electrons and ions) essentially due to a thermionic phenomenon. The quantity of displaced material will depend strongly on the copper surface condition and actual focal spot size, and therefore quantitative predictions are quite difficult to make.

The formation of a volume of displaced particles above the copper surface represents the critical point of the interaction, which determines the occurrence of coupling. For coupling to occur it is necessary that the volume of removed particles will develop into a plasma plume, which will act as a complementary energy source, thus enabling the vaporisation of bulk copper and keyhole formation. The condition for this plasma plume to behave like a point source is to maintain it close to the copper surface. In addition, the development of a plasma plume with the required properties will depend strongly on the particle vapour density.

The density of the displaced material will vary with the time of interaction, so a maximum is attained shortly after the laser copper interaction, decreasing afterwards due to the erosion of surface peaks and to a gradually "polishing" and "cleaning" of the surface, detectable by an increase in the effective reflectivity of the surface [Ursu et al., 1986].

It is precisely in the period where a critical particle density is attained, that the gas flow patterns appear the most significant influence in the coupling process.

The gas flow pattern should allow a volume of displaced material to develop in a plasma plume with the required characteristics to comply with its role, i.e., "enhanced coupling". This means that the material removed from the copper surface should be able to remain sufficiently close in the focal area to attain adequate density (in a very short period after laser interaction with the copper target) for the laser beam to interact with it rather than with the copper surface. This condition was achieved with a "modified" nozzle at beam/copper interaction point ($I=33$) (fig. 6.15) but not with a "standard" nozzle in the setting conditions used in the experimental work ($I=24$) (fig. 6.14), where the gas flow swept away the plasma forming particles at the beam/copper interaction point.

In the later condition the gas flow pattern causes the dispersal (i.e., blows away) of the displaced material (this was also the case in the experiments described above where a gas spreader was used to assist the welding process) as soon as this is emitted from the copper surface, then the attainment of a critical density will be prevented. Even if some plasma is formed (as it could be the case where the gas jet nozzle tip only presents slight wear) its density will be low and it will be not able to function as the required energy transfer source to allow bulk copper vaporisation temperature to be attained and the keyhole to be opened. Finally, the embryo plasma will be extinguished since no vaporisation will exist to maintain it. A larger period of interaction will not solve the problem since the reflectivity of the copper surface will increase with time, as discussed above.

In the case of limited dispersal of the displaced material, a portion of the incident radiation energy is absorbed in the vapour, by several processes particularly by interaction with the charged particles. This causes rapid ionisation of the vapour which thus forms a plasma. Further absorption of the energy by the plasma plume rapidly increases its temperature, wherein it begins to undergo a rapid expansion or to propagate from the surface. Once again

the gas flow pattern has a decisive role, since to accomplish the condition needed for "enhanced coupling" to occur, the gas flow pattern should be able to maintain the plasma close to the copper surface, preventing its axial expansion or propagation. Plasma expansion as a consequence of the increase in its temperature will be mainly radial, which will affect the weld bead morphology (see for example figs 4.14 and 4.15) and could decrease the efficiency of the transfer of energy to the copper target (due to the losses in the energy transfer to target regions outside of the focal spot). The radial expansion of the plasma plume will lead to a reduction in its density.

In addition, the gas flow must be able to control the composition of the plasma plume and therefore its characteristics to guarantee its performance as an energy transfer source.

The role of the gas jet flow at the onset and during the welding process will vary according to the particular characteristics of each of these phases.

■ *Maintenance of the process*

When the vaporisation of copper is attained and a keyhole is formed through the plate thickness, the metal vapour coming from the evaporation of the walls of the keyhole will flow upwards in the direction of the keyhole mouth and it will emerge from it as a jet of copper vapour plasma, which will sustain the plasma plume. This copper vapour plasma jet will collide with the downward component of the jet plasma control gas and from the collision of the two jets turbulent mixing is likely to be produced. This phenomena leads to a reduction in the electron density of the vapour plasma since the gas atoms will diffuse in it, diluting it. As a consequence, the plasma vapour could be extinguished if its dilution reduces beyond the minimal electron density required to sustain it. On the other hand, as soon as the metal vapour plasma emerges from the keyhole, it expands under the atmospheric pressure and cools [Ducharme et al., 1992]. In addition its mixing with the cold jet gas also contributes to a further drop in its temperature.

The temperature, number density, location and extension of the plasma plume are the fundamental factors which influence a stable and consistent weld process. They will determine the amount of the laser energy absorbed in the plasma and the energy delivered to the underlying copper.

The gas jet composition, flow rate and set-up appear to control the above factors, assuming all the other parameters are fixed.

Taking into consideration the observations and results from the experimental work carried out and described in chapters IV and VI, it is thought that the plasma plume should be defined in two regions: a core closer to the copper surface (keyhole mouth) which is surrounded by a less dense region, where diffusion processes with the gas atoms, become important. The visualisation of the gas flow patterns in different conditions (chapter VI) and the actual coupling and welding results related to the different conditions allow the assumption that the stability of the welding process is dependent on the plasma core characteristics and stability.

The influence of the gas jet flow rate on the coupling and welding behaviours were described in chapter IV (pt. 4.3.2.4), where it was reported that for very low (2-4 l/min) and very high

(15 l/min) N_2 flow rates, highly unstable processes were observed. In the low gas flow rate range, too much plasma was seen above the copper plate, resulting in wide, non penetrating welds, whereas for a high jet flow rate, the plasma seemed to have almost disappeared and only a faded plume was observed above the copper target. Welds with intermittent penetration then resulted. In the former case, it is thought that the plasma had become too hot (dense) due to an insufficient gas flow to lower its temperature resulting in a severe attenuation of the laser power beam reaching the copper and therefore limiting penetration. Conversely, a high gas flow rate will cause a higher turbulence in its collision with the plasma plume, which is likely to affect the plasma core stability (i.e., by cooling it). In addition, the high jet gas flow rates will blow away the plasma plume, thus reducing its density to levels, at which it becomes difficult to sustain a plasma with the required characteristics for energy absorption and transfer.

Besides the influence from the plasma control gas flow rate, welding parameters are also likely to affect plasma performance in the coupling and welding behaviour.

A relationship between the plasma density, the plasma-copper energy transfer rate and the satisfactory copper evaporation rate exists. The balance between these factors will maintain the coupling and satisfactory welding conditions. This means that the range of parameter variation is restricted by the achievement of an equilibrium among the three factors. The welding speed is one of the parameters likely to affect this balance. Although, it appeared that at the lower welding rates the maintenance of such an equilibrium is more critical, since the plasma absorption coefficient is a linear function of the metal vapour density [Herziger, 1986], it was experimentally verified that for welding speeds above 30 l/min, albeit in some cases welds had been produced in reasonable conditions, in others, unexpected weld breakdowns were verified. It is thought that these results were due to the effects of the gas jet flow patterns rather than to the welding rate since the gas jet nozzle tip condition was the only variable factor, not controlled.

The gas jet composition is also likely to affect coupling and welding behaviour. In the preliminary welding tests performed in the context of this research work, which are described in pt. 4.2 (chapter IV), the use of helium did not allow welds to be produced even when some coupling was achieved. In the light of the theoretical model presented here this can be interpreted as being due to the quite high mobility and diffusivity of the helium atoms in the hot vapour material, which would rapidly cause the dissipation of the vapour species thus preventing its ignition in a plasma, which then leads to the breakdown of the welding process. In addition, helium has a very high ionisation potential (table 3.2) and therefore there is no risk of its atoms being ionised and contributing to the plasma plume formation. It must be stressed that these are precisely the reasons why helium is normally considered the best gas to control the plasma plume in the welding of materials with high power CO_2 lasers.

A similar behaviour was reported by Ohmine et al. [1988] relatively to the CO_2 laser welding of aluminium. According to this researcher no weld was formed when helium was used as assist gas supplied from a coaxial nozzle to the interaction zone.

Nitrogen and argon have both shown good performance in the CO_2 laser welding of copper. However, under similar experimental conditions they showed different behaviour with respect to the plasma plume quantity and brightness. This is thought to be due to their capacity to remove heat from the hot vapour as it mixes with it.

The thermal conductivity and specific heat capacity of nitrogen are higher than those of argon; thus, nitrogen tends to maintain a lower vapour plasma temperature and hence lower nitrogen flow rates are needed to control the plasma plume condition for absorption and transfer of laser energy. On the other hand, nitrogen and argon have sufficiently high ionisation potentials and therefore it is expected that they will remain essentially neutral at the temperatures involved.

In the Ohmine et al.[1988] work, the above gases have shown good performance for welding aluminium. The performance was explained by the researchers as being due to the thermochemical effect produced on aluminium by these gases, which would explain the easier coupling and stable welding operation.

For reasons already discussed in pt. 7.2.4 this interpretation is not able to explain all the phenomena observed. The lower ionisation potential of oxygen relatively to the other gases (e.g., argon, nitrogen and helium) makes it more likely to become ionised in the interaction of the laser beam with the vapour atmosphere, thus contributing to the plasma plume formation.

The suggested participation of oxygen in the plasma formation through its partial ionisation does not seem to occur since if it does, then the number density of the plasma plume would be increased randomly (due to the mixing of the oxygen molecules and atoms in the vapour plasma) and then the plasma could develop in such a way that instead of acting as an energy transfer source it would attenuate energy transmission.

Although, no details are known from the Dell' Erba et al. work concerning the assist gas set-up, it did not appear to completely blow away the plasma plume vapour (the existence and need for a plasma plume is stressed in Dell' Erba work [1985-86]), which would otherwise cause the breakdown the welding process.

The oxygen flowing over the welding zone is rather "seen" to control the plasma plume density by electron attachment than to promote it by ionisation. The electron attachment process occurs at energies (approx. 4,5 eV) much lower than those required for oxygen to ionise, and which are of the order of magnitude of those existing under plasma conditions.

7.3 FINAL REMARKS

The coupling of CO₂ laser radiation to copper and in general high reflectivity and conductivity materials, depends on the formation of an intermediate energy transfer source, whose role is to enhance the transmission of the laser radiation and its absorption by the material. The intermediate source is provided by a plasma plume, whose origin depends primarily on the copper surface condition and on the assist gas flow patterns.

A summary of the mechanisms involved in the coupling process in the CO₂ laser welding of copper are:

■ Onset of the coupling process

- formation of "seed" particles

factors:

- surface condition
- beam intensity

- formation of plasma plume

factors:

- "seed" particles density
- gas jet flow pattern
- beam intensity

- opening of the keyhole

factors:

- plasma plume characteristics
- beam intensity

■ Welding process

- plasma plume maintenance

factors:

- plasma plume density
- vaporisation rate
- plasma plume-copper energy transfer rate
- gas jet composition and flow pattern
- welding parameters

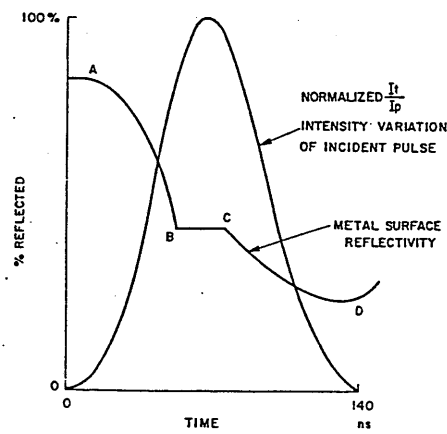
The copper surface condition is a fundamental factor specially at the onset of the laser/copper interaction. It must be able to provide the "seed" species from which a plasma would develop.

The assist gas flow pattern is the other vital factor, which must be able to control the plasma plume formation and its maintenance.

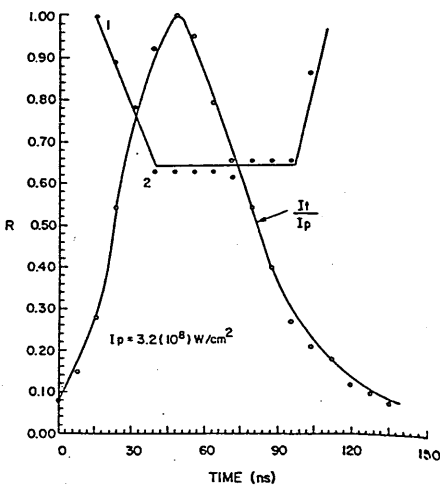
The theory developed above can be used to predict the "ideal" parameters for satisfactory high power CO₂ laser welding of copper. In particular the assist gas set up appears to be a key parameter.

The critical nature of the plasma control jet flow pattern is indicated by this work and computer simulation appears to be a possible technique for optimising the design of nozzles. This technique permitted the simulation of the "ideal" parameters in terms of a "standard" nozzle geometry, dimensions and set-up (figs 6.8c and 6.10e), which would produce a gas flow pattern similar to that which allowed coupling and welding to occur in good conditions (this nozzle is illustrated in figs 6.6 and 6.9b).

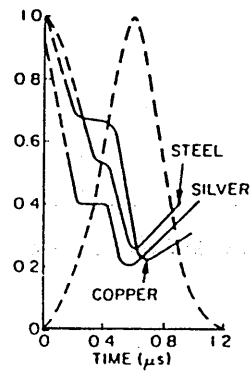
Although copper and high reflectivity materials are particularly vulnerable to control of plasma effects, it is likely that the same analysis could apply to other materials and could contribute to improved efficiency in laser welding and cutting.



Generalized reflectivity behaviour for a metal surface subjected to high intensity radiation.
 I_t = instantaneous intensity; I_p = peak intensity



Reflectivity behaviour of an oxide free copper surface below vaporisation threshold.
Calculated surface temperature (1) 320° K; (2) 1573 ° K
Reflectance measurements from Zavecz et al. [1975]



Reflectance measurements from Bronch-Bruevich et al. [1968]

Fig. 7.1 - Metal reflectance behaviour during an intense laser pulse

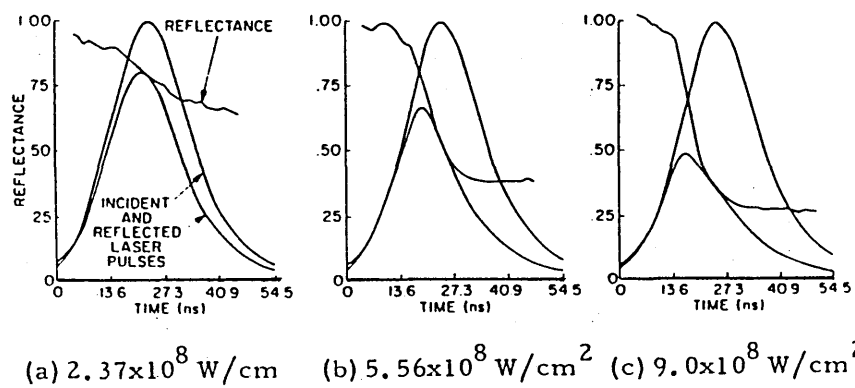


Fig. 7.2a - Specular reflectance of copper

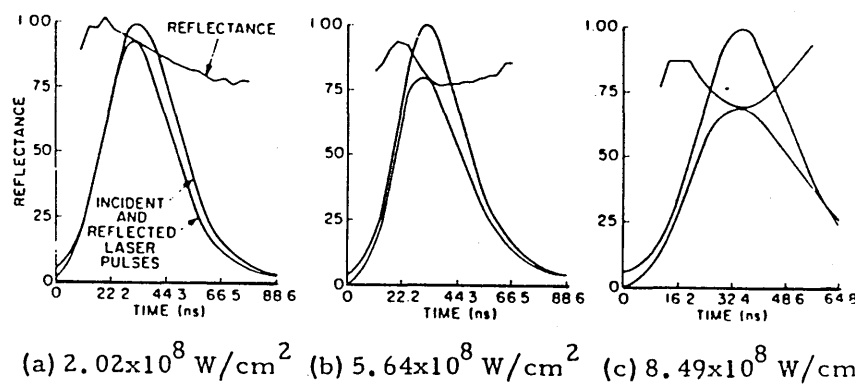


Fig. 7.2b - Total reflectance of copper

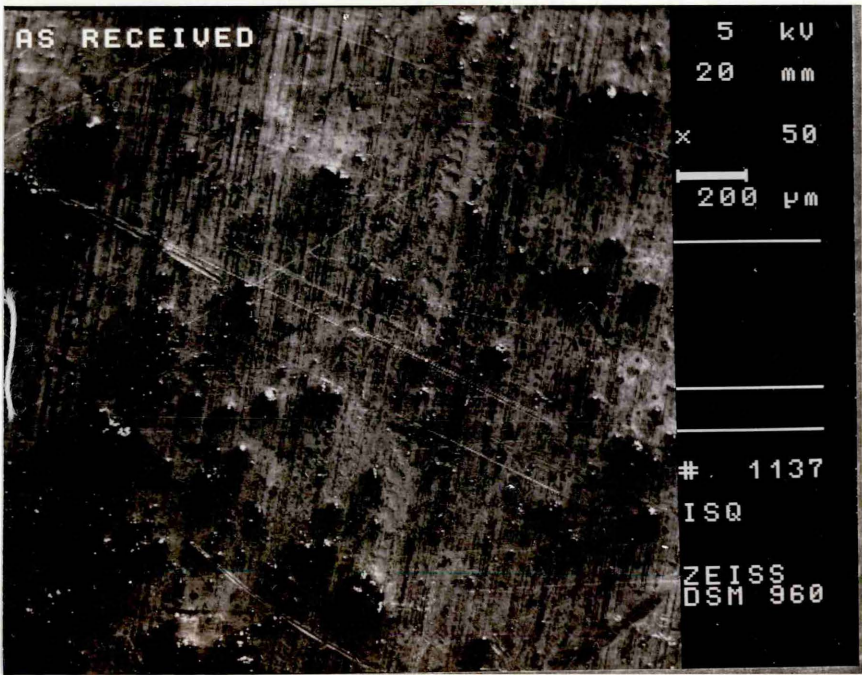


Fig. 7.3 - Surface of the copper used in the experiments, in its "as received" condition

CHAPTER VIII

CONCLUSIONS

- The welding of copper with a CO₂ laser, using nitrogen as plasma control gas is possible.
 - The plasma control gas has a prime role in the initiation and development of the laser welding process. The use of a plasma control gas is required due to the high beam intensities involved in the welding of copper but besides its role in the plasma control it has also been shown to control the mechanisms of coupling.
 - The onset of the coupling of the laser radiation into copper occurs when a plasma plume, formed as a result of the "seed" particles removed or vaporized from the copper surface, begins to act as an energy transfer vehicle, thus allowing a better transfer of the beam energy to copper.
 - The copper surface condition is a critical factor in the coupling process, since it must be able to provide the required "seed" particle density for ignition of a plasma plume. Therefore, it will determine the surface breakdown threshold intensity and consequently the intensity to trigger the coupling process.
 - The plasma plume acts as a complementary heat source (i.e., point source), allowing the vaporisation of the copper plate and therefore the opening of a keyhole.
 - The plasma plume formation and maintenance are the fundamental "key" factors for the coupling and welding of copper with a CO₂ laser. Both "key" factors are influenced by the plasma control gas flow patterns.
 - Once a plasma plume has been formed and the welding process initiated by the copper evaporation and opening of a keyhole, the plasma plume is maintained by the vaporized material ejected from the keyhole. The collision between the jet of vaporised material coming
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from the keyhole mouth and the gas jet must allow the required species density to maintain the plasma plume.

- The plasma plume appears to comprise two zones: a central core, which is surrounded by a less denser zone. The stability of the plasma core region appears to control the stability of the welding process. When the stability of the plasma core is directly or indirectly affected by the gas flow pattern, then the stability of the process becomes compromised, with the coupling and welding process showing an unstable behaviour, which can lead to the process breakdown.
 - The plasma plume performance appears to be controlled by a relationship depending on the plasma plume density, the plasma plume-copper energy transfer rate and the copper evaporation rate. Any interference in the equilibrium established between these factors is likely to affect the maintenance of the plasma plume and therefore disturb the coupling and welding process behaviours.
 - The simulation of the gas flow patterns, performed using a fluid flow modelling computer programme - FLUENT V3.0, identified the factors to which could be ascribed the influence of the plasma control gas on the coupling behaviour.
 - When the plasma control gas jet/copper intersection point coincides with the beam/copper interaction point no plasma plume is formed since the "seed" particles are "blown" away.
 - When the setting of the gas jet nozzle produces a flow pattern, whose intersection with the copper surface occurs ahead of the beam/copper interaction point, thus allowing the existence of a nearly stagnant zone, a plasma plume is able to be formed. For the plasma plume to act as a complementary source it should remain close to the copper surface, and not be allowed to travel into the beam direction. The gas flow pattern must also be able to prevent the departure of the plasma plume from the copper surface region which could lead to the decoupling of the beam from the copper.
 - The gas lens plays a fundamental role in the coupling mechanism by reducing the downward component of the gas flow, thus improving the conditions for a plasma plume formation.
 - The theoretical model developed and the gas flow simulation allow the prediction of an "ideal" nozzle design and configuration to produce satisfactory copper welds with a CO₂ laser.
 - Further support for the theoretical model developed to explain the coupling mechanisms in the laser welding of copper, is given by the practical experience. Copper plated mirrors and lens are used in laser equipment, on the basis that pure copper is almost 100% reflective and a very good thermal conductor, thus quickly dissipating heat. However, it is known that any defect, scratch, imperfection, etc., will make copper absorb energy, thus destroying the device.
 - Nitrogen was shown to be a suitable gas to assist the laser welding of copper, being able to produce welds with an acceptable quality. This is important, since nitrogen is a relatively low cost gas, and this could influence the viability of the process.
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- The main innovative aspects presented by this work rely on the establishment of the coupling mechanisms assuming a non-conventional model, on the use of a fluid flow simulation approach to support the theoretical model developed and on establishing nitrogen as an effective plasma control gas for the laser welding of copper.
 - The fluid flow simulation programme offer a new possibility for further investigation of the role of assist gases on the laser welding of materials.
 - This work represents the first contribution in the direction of the understanding of the complex phenomena that take place during the CO₂ welding of high reflectivity and conductivity materials. An obvious continuation of this work will be the investigation of the coupling mechanisms on the CO₂ laser welding of aluminium, in order to establish the theoretical model developed as the coupling model in the interaction of high power laser beams with high reflectivity metals. In addition, the coupling mechanisms of other metals will also need to be searched in order to determine the extent of application of the conventionally accepted coupling models.
 - The development of a mathematical model to describe the CO₂ laser welding of copper would represent a step forward in the direction of process control.
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■ PART I

○ Electromagnetic waves

The electromagnetic radiation consists of time varying electric and magnetic field components of a wave which propagates through a medium at a characteristic velocity.

The radiation produced by a laser can be described with a sufficient approximation as an electromagnetic plane wave [Allmen, 1987], i.e., waves in which the electric and magnetic field intensities, at any instant of time, vary only in the direction of its propagation. The basic features of an electromagnetic plane wave are shown in fig. A3.1.

The fundamental equations which describe the electromagnetic behaviour in any media are known as Maxwell's equations. Maxwell's equations for the electromagnetic field in a nonmagnetic isotropic dielectric medium with free charge density ρ and a free current density $\mathbf{J}$ are [Christman (1988); Thomas and Meadows (1985)]:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} - \frac{\nabla \cdot \mathbf{P}}{\epsilon_0}, \quad (1)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (2)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (3)$$

$$\nabla \times \mathbf{B} = \mu \mathbf{J} + \mu \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu \frac{\partial \mathbf{P}}{\partial t} \quad (4)$$

or¹

$$\nabla \times \left(\frac{\mathbf{B}}{\mu} \right) = \mathbf{J} + \frac{\partial}{\partial t} (\epsilon \mathbf{E}) \quad (4A)$$

where μ and ϵ are the permeability and permittivity of the medium, ϵ_0 is the free space permittivity, $-\nabla \cdot \mathbf{P}$ and $\partial \mathbf{P} / \partial t$ represent the charge and current density respectively, associated with the time varying polarization. The term $\epsilon_0 \partial \mathbf{E} / \partial t$ is called the "displacement" current, and describes light travelling through insulators (lossless propagation).

¹In the case of a homogeneous isotropic medium, $\mathbf{P}$ is related to $\mathbf{E}$ by $\mathbf{P} = \epsilon_0 \chi \mathbf{E}$, where χ is a constant.

Considering now the propagation of an electromagnetic wave in an infinite homogeneous and isotropic conductor, whose conductivity obeys to Ohm's law, i.e., $\mathbf{J} = \sigma \mathbf{E}$, and assuming that the net charge density at any point of the conductor is zero (due to equal amounts of negatively charged electrons and positively charged ions), then Maxwell's equations can be written [Thomas and Meadows (1985)]:

$$\nabla \cdot \mathbf{E} = 0, \quad (5)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (6)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (7)$$

$$\nabla \times \left(\frac{\mathbf{B}}{\mu} \right) = \sigma \mathbf{E} + \frac{\partial}{\partial t} (\epsilon \mathbf{E}) \quad (8)$$

These equations can be solved to obtain general expressions for $\mathbf{E}$ and $\mathbf{B}$ as a function of time and space coordinates. These equations are coupled in the sense that the electric and magnetic fields are interdependent. The manipulation of the equations (7) and (8) for the plane wave shown in fig. A3.1, $E_y = E_z = 0$, leads to the following equation for E_x [Thomas and Meadows (1985)]:

$$\frac{\partial^2 E_x}{\partial z^2} = \mu \sigma \frac{\partial E_x}{\partial t} + \mu \epsilon \frac{\partial^2 E_x}{\partial t^2} \quad (9)$$

with a similar equation for B_y .

Assuming that the propagating wave is a sinusoidal one a possible solution of eqn (9) is given by

$$E_x = E_{x0} \exp \{i(Kz - \omega t)\}, \quad \omega = 2 \pi \nu \quad (10)$$

where, E_x is the amplitude of the electric field intensity, ω is the angular frequency and K the propagation constant also known as the wave number.

From equation (10), it can be seen that

$$\frac{\partial}{\partial z} \equiv iK, \quad \frac{\partial}{\partial t} \equiv -i\omega, \quad (11)$$

which by substitution in eqn (9) leads to the following relation

$$K^2 = \omega^2 \mu \epsilon + i \omega \mu \sigma \quad (12)$$

$$K^2 = \omega^2 \mu \left(\epsilon + i \frac{\sigma}{\omega} \right) \quad (12A)$$

Eqn (13) is known as the **dispersion equation**. This equation gives a relationship between the angular frequency ω and the wave number K ($K=2\pi/\lambda$, and is related to the phase velocity by $v_p = \omega/K$). Thus, unless ω and K are linearly related, the various frequencies propagate with different velocities and at the boundary of two media are refracted at different angles.

$$K = \omega (\mu \epsilon)^{\frac{1}{2}} \quad (13)$$

For a non conducting medium, i.e., $\sigma=0$, the relationship between K and ω is simply
Thus, whenever $\sigma \neq 0$, the propagation constant is a complex number, i.e., $K = K_1 + i K_2$.

The amplitude of a wave with a complex propagation constant decreases exponentially with distance into the solid. Looking at the spatially varying part of the exponent of eqn (10)

$$\exp(iKz) = \exp\{i(K_1 + iK_2)z\} = \exp(iK_1z) \exp(-K_2z) \quad (14)$$

which substituting into eqn (10) yields to

$$E_x = E_{x0} \exp(-K_2z) \exp\{i(K_1z - \omega t)\} \quad (15)$$

This eqn means that over a distance equal to $1/K_2$ the wave amplitude decreases by the factor $1/e$ (≈ 0.37). Thus, it may be concluded that the imaginary part of the propagation constant leads to absorption of the electromagnetic wave as it propagates through a material.

■ **PART II**

- Optical properties (macroscopic approach)

If the expression

$$c = \frac{1}{(\mu_o \epsilon_o)^{\frac{1}{2}}} \quad (16)$$

is used in eqn (13), then the propagation constant becomes²

$$K = \frac{\omega}{c} \left(\frac{\epsilon}{\epsilon_o} \right)^{\frac{1}{2}} \quad (17)$$

This relationship can be written in the form

$$K = \frac{\omega}{c} (n + i\kappa) \quad (18)$$

where n and κ are the real and imaginary parts, respectively, of the **relative permittivity** ϵ_r . n is called the **index of refraction**, κ the **extinction coefficient** and the term $(n + i\kappa)$ is known as the **complex index of refraction**, N , where the real part, n , represents the ratio of wave phase velocity in vacuum to that in the material, and the imaginary part, κ , the damping of the light wave.

Thus, being $\epsilon_r = \epsilon_1 + i\epsilon_2$, and also

$$\epsilon_r = (n + i\kappa)^2 = n^2 - \kappa^2 + 2in\kappa \quad (19)$$

Then the real and imaginary parts of the relative permittivity, ϵ_1 and ϵ_2 respectively, become

$$\epsilon_1 = n^2 - \kappa^2, \quad \epsilon_2 = 2n\kappa, \quad (20)$$

These equations yield to

²Since $\mu \approx \mu_o$ at optical frequencies.

The ratio ϵ/ϵ_o is called the relative permittivity or dielectric constant of the medium.

$$n^2 = \frac{1}{2} [(\epsilon_1^2 + \epsilon_2^2)^{\frac{1}{2}} + \epsilon_1] \quad (21)$$

$$\kappa^2 = \frac{1}{2} [(\epsilon_1^2 + \epsilon_2^2)^{\frac{1}{2}} - \epsilon_1] \quad (21A)$$

The dielectric function fully describes the response of a material to weak electromagnetic radiation. It depends on the light frequency in a manner dependent on the microscopic structure of the material [Allmen, 1987].

The **absorption coefficient** and **reflectivity** are the other optical properties used to describe the optical behaviour of materials.

The **absorption coefficient**, α of a material gives the power density attenuation per unit length (fig. A3.2), and therefore it will be proportional to the attenuation coefficient of E_x^2 [Saifi, 1972]. Knowing that the beam intensity equals the square of the electric field, i.e., $I = E_x^2$ then from eqns (15) and (18),

$$\alpha = 2K_2 = 2 \frac{\omega}{c} \kappa, \quad \alpha = 4 \frac{\pi}{\lambda} \kappa \quad (22)$$

Its reciprocal, called the **skin depth**, δ , is a measure of the distance a wave penetrates in a material, within which the intensity drops down to $1/e$ of its initial value [Saifi, 1972], and is given by

$$\delta = \frac{1}{\alpha} = \frac{\lambda}{4\pi\kappa} \quad (23)$$

For a beam normally incident on a material surface, the incident wave travels with a propagation constant $K_1 = \omega/c$ along the normal to the surface, the transmitted wave travels in the same direction, but, because it is in the material, its propagation constant is $K_2 = N K_1 = (n + i\kappa) K_1$. The reflected wave travels in the opposite direction with a propagation constant $-K_1$.

The continuity of the electric field at the material surface leads to

$$E_{inc} + E_{refl} = E_{trans} \quad (24)$$

while the continuity of the magnetic field leads to³

$$\frac{K_1}{\omega} E_{inc} - \frac{K_1}{\omega} E_{refl} = \frac{K_2}{\omega} E_{trans} \quad (25)$$

Elimination of E_{trans} from eqn (25) through eqn (24) yields to

$$\frac{E_{refl}}{E_{inc}} = -\frac{K_2 - K_1}{K_2 + K_1} = -\frac{n + i\kappa - 1}{n + i\kappa + 1} \quad (26)$$

The reflectivity is the ratio of the reflected intensity to the incident intensity, and thus is given by [Christman, 1988]

$$R(\omega) = \frac{I_{refl}}{I_{inc}} = \frac{|E_{refl}|^2}{|E_{inc}|^2} = \frac{|N-1|^2}{|N+1|^2} \quad (27)$$

which is known as the Fresnel expression.

The development of the modulus of R yields to

$$R(\omega) = \frac{(n+i\kappa-1)(n-i\kappa-1)}{(n+i\kappa+1)(n-i\kappa+1)} = \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2} \quad (28)$$

which is known as the Beer's equation.

³From eqns (11) and using the expression

$$\frac{\partial E_x}{\partial z} = -\frac{\partial B_y}{\partial t}$$


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I  FFFFF L   U   U   EEEEE N   N   TTTT
I  F      L   U   U   E   NN  N   T
I  FFFF  L   U   U   EEEE  NN  N   T
I  F      L   U   U   E   N   NN  T
I  F      LLLL  UUU  EEEEE N   N   T          F L U I D   F L O W   M O D E L L I N G
I-----I
I  OUTPUT PRODUCED BY RELEASE 2.99          INET1 /DEC -
I-----I

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- UNITS SYSTEM -

INDEX	PROPERTY	UNITS	S.I. CONVERSION FACTOR
1		DIMENSIONLESS	1.000E+00
2	MASS	KILOGRAMS	1.000E+00
3	LENGTH	METRES	1.000E+00
4	TIME	SECONDS	1.000E+00
5	VELOCITY	METRES/SEC	1.000E+00
6	FORCE	NEWTONS	1.000E+00
7	ACCELERATION	METRES/SEC/SEC	1.000E+00
8	ENERGY	JOULES	1.000E+00
9	POWER	WATTS	1.000E+00
10	MASS FLOW RATE	KILOGRAMS/SEC	1.000E+00
11	TEMPERATURE	KELVIN	1.000E+00
12	ENTHALPY	JOULES/KILOGRAM	1.000E+00
13	PRESSURE	PASCALS	1.000E+00
14	DENSITY	KILOGRAMS/CU.M	1.000E+00
15	VISCOSITY	KG/M-SEC.	1.000E+00
16	K.E.OF TURBULENCE	M.SQ/SEC/SEC	1.000E+00
17	K.E.DISS.RATE	M.SQ/SEC/SEC/SEC	1.000E+00
18	SPEC. HT. CAP.	JOULES/KG-K	1.000E+00
19	THERMAL COND.	WATTS/M-K	1.000E+00
20	DIFFUSIVITY	M.SQ/SEC.	1.000E+00
21	ACTIVATION ENERGY	JOULES/KGMOL	1.000E+00
22	ANGLE	RADIANS	1.000E+00
23	HEAT FLUX	WATTS/M.SQ.	1.000E+00
24	PARTICLE DIAM.	METRES	1.000E+00
25	MOMENTUM TR RATE	KG.M/SEC/SEC	1.000E+00
26	HEAT TRANSF COEF	WATTS/M.SQ-K	1.000E+00
27	PERMEABILITY	M.SQ.	1.000E+00
28	(INTERNAL MISC.)	UNDEFINED	1.000E+00
29	VOL. FLOWRATE	CU.M/SEC.	1.000E+00
30	AREA	M.SQ.	1.000E+00
31	ARRHENIUS FACTOR	CU.M./KGO.-SEC.	1.000E+00
32	INERTIAL FACTOR	PER METRE	1.000E+00
33	VOL. HEAT RATE	WATTS/CU.M.	1.000E+00
34	ABSORB./SCATTER.	PER METER	1.000E+00
35	ANGULAR VELOCITY	PER SECOND	1.000E+00
36	SPARE	UNDEFINED	1.000E+00

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I  FFFFF L      U  U  EEEEE N  N  TTTT
I  F      L      U  U  E     NN N  T
I  FFFF  L      U  U  EEEE  N N N  T
I  F      L      U  U  E     N NN  T
I  F      LLLLL UU  EEEEE N  N  T          FLUID FLOW MODELLING
I-----I
I  OUTPUT PRODUCED BY RELEASE 2.99      INET1 / DEC - GAS NOZZLE - BICO50
I-----I

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- SOLUTION CONTROL PARAMETERS -

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PARAMETER .....VALUES.....
          (P)  (U)  (V)  (W)  (E)  (D)  (H)  (T)  (F)  (O)  (C)  (VS)  (PT)
SOLVED    Y      Y      Y      N      Y      Y      N      N      N      N      N      Y
NO. SWEEPS 5      1      1      1      1      1      1      1      1      1      1
UNDERRELAX 1 5.0E-01 2.0E-01 2.0E-01 2.0E-01 2.0E-01 2.0E-01 2.0E-01 3.0E-01 2.0E-01 2.0E-01 2.0E-01 3.0E-01
UNDERRELAX 2 5.0E-02 2.0E-02 2.0E-02 2.0E-02 2.0E-02 2.0E-02 2.0E-02 3.0E-02 2.0E-02 2.0E-02 2.0E-02 3.0E-02
PR/SC NO.          1.0E+00 1.3E+00 7.0E-01          7.0E-01 7.0E-01 7.0E-01
RESIDUALS  4.2E-04 8.2E-05 8.8E-05 0.0E+00 2.5E-04 7.9E-05 0.0E+00          0.0E+00 0.0E+00 0.0E+00

```

- BOUNDARIES -

```

BNDRY .....BOUNDARY CONDITIONS.....
ZONE (U) (V) (W) (E) (D) (T) (F) (O) (C) (2)
W0 0.0000E+00W 0.0000E+00W 0.0000E+00W 0.0000E+00S 0.0000E+00S 2.7300E+02W 0.0000E+00C 0.0000E+00C 0.0000E+00C R
O 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E
I0 -7.0000E+01L 0.0000E+00L 0.0000E+00L 7.3500E+01L 9.6639E+05L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E
I1 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E
I2 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E

```

- CONSTANTS -

```

CYCLIC CELLS PRESCRIBED PRESSURE DROP = 0.000E+00
DIFFERENCING SCHEME - POWER LAW
REFERENCE PRESSURE AT I= 2 J= 2 K= 1 (ACTUAL PRESSURE = 1.013E-05)
GAS DENSITY AT STP = 1.165E+00 USE GAS LAW - Y PRESSURE CORRECTED - N
SECOND RELAXATION FACTORS ON AFTER 32000 ITERATIONS.
PATCH OPTION -N
CONVERG/DIVERG CHK -Y
NORMALIZE RESIDS. -Y
CONTINUITY CHECK -Y
RESET OPTION -Y
SWEEP DIRECTION -2
REYNOLDS STRESS MODEL-N
NON-NEWTONIAN FLOW -N
POROSITY MODEL -N
ALLOW LINK SETTING -N
SET INLET TURBULENCE -N
MONITOR OPTION -N
LINK OPTION -N
PARTICLE TRACKING 0 TRACKS EVERY 0 ITNS.
GRAVITATIONAL ACCELERATIONS- X = 0.000E+00 Y = 0.000E+00 Z = 0.000E-00
APARAM = 1.000E+01
CONRES = 1.000E+03
CONCHN = 1.000E+03
ITMAX = 9

```

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TURBULENCE MODEL - CD C1 C2 CMU RSMCD
                    5.5E-01 1.4E+00 1.9E+00 9.0E-02 1.0E+00

```

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WALL TURBULENCE MODEL. WALL ZONE CAPP ELOG
                        W0 4.187E-01 9.793E+00

```

```

NON-NEWTONIAN FLOW - N K
                    1.0E+00 1.0E+00

```

- TEMPERATURE DEPENDENT PROPERTIES -

```

PROPERTY COEFFS 0 1 2 3 4
-----
DYNAMIC VISCOSITY 1 1.6800E-05
LIQ. DENSITY INERTS 1 1.2930E+00
LIQ. DENSITY SPECIES F 1 1.2930E+00
LIQ. DENSITY SPECIES O 1 1.2930E+00
LIQ. DENSITY SPECIES C 1 1.2930E+00
SPECIFIC HEAT (GAS) 1 1.0360E+03
THERMAL COND. (GAS) 1 2.4100E-02
SPECIFIC HEAT (PART.) 1 1.0000E+03
THERMAL COND. (PART.) 1 7.8000E-02
BINARY DIFFUSIVITY 1 3.0000E-05
VAP. PRESS. (PHASE 2) 1 2.5331E+03

```

- SECOND PHASE PARTICLE/DROPLET TRACKING -

MAX. NO. OF STEPS = 5000
 STEP LENGTH FACT. = 2.000E+01
 PARTICLE DENSITY = 1.000E+03
 BOILING POINT = 3.730E+02
 LATENT HEAT OF VAPORIZATION = 1.000E+03
 COEFFICIENT OF RESTITUTION = 1.000E+00
 VAPORIZATION TEMPERATURE = 3.730E+02
 SWELLING COEFFICIENT = 2.000E+00
 FRACTION VOLATILE COMPONENT = 1.000E+00
 FRACTION NON-VOLATILE COMPONENT = 0.000E+00
 STOICHIOMETRIC RATIO FOR SURFACE REACTION = 1.333E+00
 HEAT OF REACTION FOR SURFACE REACTION = 2.000E+07

PARTICLE LAWS ACTIVATED FOR USER-DEFINED HISTORY -

INERT VAPORIZE BOILING DEVOLAT BURNOUT INERT
 Y N N N N Y

INJECTINITIAL VALUES.....
 NO TYP (X) (Y) (Z) (U) (V) (W) (T) (DIAM) (MFLOW)
 1 PA 2.0E-02 1.5E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-07 1.0E-09
 2 PA 2.0E-02 1.5E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-06 1.0E-09
 3 PA 2.0E-02 1.6E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-07 1.0E-09
 4 PA 2.0E-02 1.6E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-06 1.0E-09

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I  F     L   U   U E     NN  N T              I
I  FFFF  L   U   U EEEE  NN  N T              I
I  F     L   U   U E     N  NN T              I
I  F     LLLL  UUU  EEEE  N   N T              I
I                                     FLUID FLOW MODELLING
I-----I
I  OUTPUT PRODUCED BY RELEASE 2.99      INET1 / DEC - GAS NOZZLE - BICO51
I-----I

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- SOLUTION CONTROL PARAMETERS -

PARAMETER	(P)	(U)	(V)	(W)	(E)	(D)	(H)	(T)	(F)	(O)	(C)	(VS)	(PT)
SOLVED	Y	Y	Y	N	Y	Y	N		N	N	N	Y	
NO. SWEEPS	5	1	1	1	1	1	1		1	1	1		
UNDERRELAX 1	5.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	3.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	3.0E-01
UNDERRELAX 2	5.0E-02	2.0E-02	2.0E-02	2.0E-02	2.0E-02	2.0E-02	2.0E-02	3.0E-02	2.0E-02	2.0E-02	2.0E-02	2.0E-02	3.0E-02
PR/SC NO.					1.0E+00	1.3E+00	7.0E-01		7.0E-01	7.0E-01	7.0E-01		
RESIDUALS	4.2E-04	8.2E-05	8.8E-05	0.0E+00	2.5E-04	7.9E-05	0.0E+00		0.0E+00	0.0E+00	0.0E+00		

- BOUNDARIES -

BNDRY	(U)	(V)	(W)	(E)	(D)	(T)	(F)	(O)	(C)	(2)
W0	0.0000E+00W	0.0000E+00W	0.0000E+00W	0.0000E+00S	0.0000E+00S	2.7300E+02W	0.0000E+00C	0.0000E+00C	0.0000E+00C	R
O	0.0000E+00L	0.0000E+00L	0.0000E+00L	0.0000E+00L	0.0000E+00L	2.7300E+02L	0.0000E+00L	0.0000E+00L	0.0000E+00L	E
I0	-7.0000E+01L	0.0000E+00L	0.0000E+00L	7.3500E+01L	9.6639E+05L	2.7300E+02L	0.0000E+00L	0.0000E+00L	0.0000E+00L	E
I1	-1.0000E+01L	-1.0000E+01L	0.0000E+00L	3.0000E+00L	6.0677E+04L	2.7300E+02L	0.0000E+00L	0.0000E+00L	0.0000E+00L	E
I2	-1.0000E+01L	-1.0000E+01L	0.0000E+00L	3.0000E+00L	6.0677E+04L	2.7300E+02L	0.0000E+00L	0.0000E+00L	0.0000E+00L	E

- CONSTANTS -

CYCLIC CELLS PRESCRIBED PRESSURE DROP = 0.000E+00
 DIFFERENCING SCHEME - POWER LAW
 REFERENCE PRESSURE AT I= 2 J= 2 K= 1 (ACTUAL PRESSURE = 1.013E+C5)
 GAS DENSITY AT STP = 1.165E+00 USE GAS LAW - Y PRESSURE CORRECTED - N
 SECOND RELAXATION FACTORS ON AFTER 32000 ITERATIONS.
 PATCH OPTION -N
 CONVERG/DIVERG CHK -Y
 NORMALIZE RESIDS. -Y
 CONTINUITY CHECK -Y
 RESET OPTION -Y
 SWEEP DIRECTION -2
 REYNOLDS STRESS MODEL-N
 NON-NEWTONIAN FLOW -N
 POROSITY MODEL -N
 ALLOW LINK SETTING -N
 SET INLET TURBULENCE -N
 MONITOR OPTION -N
 LINK OPTION -N
 PARTICLE TRACKING 0 TRACKS EVERY 0 ITNS.
 GRAVITATIONAL ACCELERATIONS- X = 0.000E+00 Y = 0.000E+00 Z = 0.000E+00
 APARAM = 1.000E+01
 CONRES = 1.000E+03
 CONCHN = 1.000E+03
 ITMAX = 9

TURBULENCE MODEL - CD C1 C2 CMU RSMCD
 5.5E-01 1.4E+00 1.9E+00 9.0E-02 1.0E+00

WALL TURBULENCE MODEL. WALL ZONE CAPPA ELOG
 W0 4.187E-01 9.793E+00

NON-NEWTONIAN FLOW - N K
 1.0E+00 1.0E+00

- TEMPERATURE DEPENDENT PROPERTIES -

PROPERTY	COEFS	0	1	2	3	4
DYNAMIC VISCOSITY	1	1.6800E-05				
LIQ.DENSITY INERTS	1	1.2930E+00				
LIQ.DENSITY SPECIES F	1	1.2930E+00				
LIQ.DENSITY SPECIES O	1	1.2930E+00				
LIQ.DENSITY SPECIES C	1	1.2930E+00				
SPECIFIC HEAT (GAS)	1	1.0360E+03				
THERMAL COND. (GAS)	1	2.4100E-02				
SPECIFIC HEAT (PART.)	1	1.0000E+03				
THERMAL COND. (PART.)	1	7.8000E-02				
BINARY DIFFUSIVITY	1	3.0000E-05				
VAP. PRESS. (PHASE 2)	1	2.5331E+03				

- SECOND PHASE PARTICLE/DROPLET TRACKING -

MAX. NO. OF STEPS = 5000
 STEP LENGTH FACT. = 2.000E+01
 PARTICLE DENSITY = 1.000E+03
 BOILING POINT = 3.730E+02
 LATENT HEAT OF VAPORIZATION = 1.000E+03
 COEFFICIENT OF RESTITUTION = 1.000E+00
 VAPORIZATION TEMPERATURE = 3.730E+02
 SWELLING COEFFICIENT = 2.000E+00
 FRACTION VOLATILE COMPONENT = 1.000E+00
 FRACTION NON-VOLATILE COMPONENT = 0.000E+00
 STOICHIOMETRIC RATIO FOR SURFACE REACTION = 1.333E+00
 HEAT OF REACTION FOR SURFACE REACTION = 2.000E+07

PARTICLE LAWS ACTIVATED FOR USER-DEFINED HISTORY -
 INERT VAPORIZE BOILING DEVOLAT BURNOUT INERT
 Y N N N N Y

INJECTINITIAL VALUES.....
 NO TYP (X) (Y) (Z) (U) (V) (W) (T) (DIAM) (MFLOW)
 1 PA 2.0E-02 1.5E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-07 1.0E-09
 2 PA 2.0E-02 1.5E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-06 1.0E-09
 3 PA 2.0E-02 1.6E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-07 1.0E-09
 4 PA 2.0E-02 1.6E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-06 1.0E-09
 5 PA 2.0E-02 1.5E-02 0.0E+00-6.0E+01 1.1E-01 0.0E+00 2.7E+02 1.0E-07 1.0E-10
 6 PA 2.0E-02 1.5E-02 0.0E+00-5.0E+01-1.1E-01 0.0E+00 2.7E+02 1.0E-07 1.0E-10
 7 PA 2.0E-02 1.6E-02 0.0E+00-4.0E+01-3.3E-01 0.0E+00 2.7E+02 1.0E-07 1.0E-10
 8 PA 2.0E-02 1.6E-02 0.0E+00-3.0E+01-5.6E-01 0.0E+00 2.7E+02 1.0E-07 1.0E-10
 9 PA 2.0E-02 1.6E-02 0.0E+00-2.0E+01-7.8E-01 0.0E+00 2.7E+02 1.0E-07 1.0E-10
 10 PA 2.0E-02 1.6E-02 0.0E+00-1.0E+01-1.0E+00 0.0E+00 2.7E+02 1.0E-07 1.0E-10

FLOW FIELD AFTER 0 ITERATIONS--

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*-----*
I  LICENSED BY AND THE PROPERTY OF CREARE INC.      P.O. BOX 71, HANOVER, NEW HAMPSHIRE 03755.  (603) 643-3800 I
I-----I
I  FFFFF L      U  U  EEEEE N  N  TTTT
I  F      L      U  U  E     NN N  T
I  FFFF  L      U  U  EEEE  NN N  T
I  F      L      U  U  E     N  NN  T
I  F      LLLLL UUU  EEEEE N  N  T          F L U I D   F L O W   M O D E L L I N G
I-----I
I  OUTPUT PRODUCED BY RELEASE 2.99      INET1 / DEC - GAS NOZZLE - BICO60
I-----I

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- SOLUTION CONTROL PARAMETERS -

PARAMETER	VALUES												
	(P)	(U)	(V)	(W)	(E)	(D)	(H)	(T)	(F)	(O)	(C)	(VS)	(PT)
SOLVED	Y	Y	Y	N	Y	Y	N		N	N	N	Y	
NO. SWEEPS	5	1	1	1	1	1	1		1	1	1		
UNDERRELAX 1	5.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	3.0E-01	2.0E-01	2.0E-01	2.0E-01	2.0E-01	3.0E-01
UNDERRELAX 2	5.0E-02	2.0E-02	2.0E-02	2.0E-02	2.0E-02	2.0E-02	2.0E-02	3.0E-02	2.0E-02	2.0E-02	2.0E-02	2.0E-02	3.0E-02
PR/SC NO.					1.0E+00	1.3E+00	7.0E-01		7.0E-01	7.0E-01	7.0E-01		
RESIDUALS	7.6E-03	1.1E-03	1.5E-03	0.0E+00	1.8E-03	1.5E-03	0.0E+00		0.0E+00	0.0E+00	0.0E+00		

- BOUNDARIES -

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BNDRY .....BOUNDARY CONDITIONS.....
ZONE (U) (V) (W) (E) (D) (T) (F) (O) (C) (2)
W0 0.0000E+00W 0.0000E+00W 0.0000E+00W 0.0000E+00S 0.0000E+00S 2.7300E+02W 0.0000E+00C 0.0000E+00C 0.0000E+00C R
O 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E
I0 -7.0000E+01L 0.0000E+00L 0.0000E+00L 7.3500E+01L 9.6639E+05L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E
I1 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E
I2 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E

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- CONSTANTS -

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CYCLIC CELLS PRESCRIBED PRESSURE DROP = 0.000E+00
DIFFERENCING SCHEME - POWER LAW
REFERENCE PRESSURE AT I= 2 J= 2 K= 1 (ACTUAL PRESSURE = 1.013E+05)
GAS DENSITY AT STP = 1.165E+00 USE GAS LAW - Y PRESSURE CORRECTED - N
SECOND RELAXATION FACTORS ON AFTER 32000 ITERATIONS.
PATCH OPTION -N
CONVERG/DIVERG CHK -Y
NORMALIZE RESIDS. -Y
CONTINUITY CHECK -Y
RESET OPTION -Y
SWEEP DIRECTION -2
REYNOLDS STRESS MODEL-N
NON-NEWTONIAN FLOW -N
POROSITY MODEL -N
ALLOW LINK SETTING -N
SET INLET TURBULENCE -N
MONITOR OPTION -N
LINK OPTION -N
PARTICLE TRACKING 0 TRACKS EVERY 0 ITNS.
GRAVITATIONAL ACCELERATIONS- X = 0.000E+00 Y = 0.000E+00 Z = 0.000E+00
APARAM = 1.000E+01
CONRES = 1.000E+03
CONCHN = 1.000E+03
ITMAX = 9

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TURBULENCE MODEL - CD C1 C2 CMU RSMCD
5.5E-01 1.4E+00 1.9E+00 9.0E-02 1.0E+00

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WALL TURBULENCE MODEL. WALL ZONE CAPPA ELOG
W0 4.187E-01 9.793E+00

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NON-NEWTONIAN FLOW - N K
1.0E+00 1.0E+00

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- TEMPERATURE DEPENDENT PROPERTIES -

PROPERTY	COEFFS	0	1	2	3	4
DYNAMIC VISCOSITY	1	1.6800E-05				
LIQ.DENSITY INERTS	1	1.2930E+00				
LIQ.DENSITY SPECIES F	1	1.2930E+00				
LIQ.DENSITY SPECIES O	1	1.2930E+00				
LIQ.DENSITY SPECIES C	1	1.2930E+00				
SPECIFIC HEAT (GAS)	1	1.0360E+03				
THERMAL COND. (GAS)	1	2.4100E-02				
SPECIFIC HEAT (PART.)	1	1.0000E+03				
THERMAL COND. (PART.)	1	7.8000E-02				
BINARY DIFFUSIVITY	1	3.0000E-05				
VAP. PRESS. (PHASE 2)	1	2.5331E+03				

- SECOND PHASE PARTICLE/DROPLET TRACKING -

MAX. NO. OF STEPS = 5000
STEP LENGTH FACT. = 2.000E+01
PARTICLE DENSITY = 1.000E+03
BOILING POINT = 3.730E+02
LATENT HEAT OF VAPORIZATION = 1.000E+03
COEFFICIENT OF RESTITUTION = 1.000E+00
VAPORIZATION TEMPERATURE = 3.730E+02
SWELLING COEFFICIENT = 2.000E+00
FRACTION VOLATILE COMPONENT = 1.000E+00
FRACTION NON-VOLATILE COMPONENT = 0.000E+00
STOICHIOMETRIC RATIO FOR SURFACE REACTION = 1.333E+00
HEAT OF REACTION FOR SURFACE REACTION = 2.000E+07

PARTICLE LAWS ACTIVATED FOR USER-DEFINED HISTORY -
INERT VAPORIZE BOILING DEVOLAT BURNOUT INERT
Y N N N N Y

INJECTINITIAL VALUES.....
NO TYP (X) (Y) (Z) (U) (V) (W) (T) (DIAM) (MFLOW)
1 PA 2.0E-02 1.5E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-07 1.0E-09
2 PA 2.0E-02 1.5E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-06 1.0E-09
3 PA 2.0E-02 1.6E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-07 1.0E-09
4 PA 2.0E-02 1.6E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-06 1.0E-09

FLOW FIELD AFTER 0 ITERATIONS--

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*-----*
I  LICENSED BY AND THE PROPERTY OF CREARE INC.      P.O. BOX 71, HANOVER, NEW HAMPSHIRE 03755.  (603) 643-3800 I
I-----I
I  FFFFF L      U  U  EEEEE N  N  TTTT
I  F      L      U  U  E     NN N  T
I  FFFF  L      U  U  EEEE  NN N  T
I  F      L      U  U  E     N NN  T
I  F      LLLL  UU  U  EEEE  N  N  T          F L U I D   F L O W   M O D E L L I N G
I-----I
I  OUTPUT PRODUCED BY RELEASE 2.99          INETI / DEC - GAS NOZZLE - BICO61
I-----I

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- SOLUTION CONTROL PARAMETERS -

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PARAMETER .....VALUES.....
(P)      (U)      (V)      (W)      (E)      (D)      (H)      (T)      (F)      (O)      (C)      (VS)      (PT)
NO. SWEEPS 5      1      1      1      1      1      1      1      1      1      1      1      1
UNDERRELAX 1 5.0E-01 2.0E-01 2.0E-01 2.0E-01 2.0E-01 2.0E-01 2.0E-01 3.0E-01 2.0E-01 2.0E-01 2.0E-01 3.0E-01
UNDERRELAX 2 5.0E-02 2.0E-02 2.0E-02 2.0E-02 2.0E-02 2.0E-02 2.0E-02 3.0E-02 2.0E-02 2.0E-02 2.0E-02 3.0E-02
PR/SC NO.      1.0E+00 1.3E+00 7.0E-01
RESIDUALS      7.6E-03 1.1E-03 1.5E-03 0.0E+00 1.8E-03 1.5E-03 0.0E+00      0.0E+00 0.0E+00 0.0E+00

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- BOUNDARIES -

```

BNDRY .....BOUNDARY CONDITIONS.....
ZONE (U) (V) (W) (E) (D) (T) (F) (O) (C) (2)
W0 0.0000E+00W 0.0000E+00W 0.0000E+00W 0.0000E+00S 0.0000E+00S 2.7300E+02W 0.0000E+00C 0.0000E+00C 0.0000E+00C R
O 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 0.0000E+00L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E
I0 -7.0000E+01L 0.0000E+00L 0.0000E+00L 7.3500E+01L 9.6639E+05L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E
I1 -1.0000E+01L -1.0000E+01L 0.0000E+00L 3.0000E+00L 6.0677E+04L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E
I2 -1.0000E+01L -1.0000E+01L 0.0000E+00L 3.0000E+00L 6.0677E+04L 2.7300E+02L 0.0000E+00L 0.0000E+00L 0.0000E+00L E

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- CONSTANTS -

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CYCLIC CELLS PRESCRIBED PRESSURE DROP = 0.000E+00
DIFFERENCING SCHEME - POWER LAW
REFERENCE PRESSURE AT I= 2 J= 2 K= 1 (ACTUAL PRESSURE = 1.013E+05)
GAS DENSITY AT STP = 1.165E+00 USE GAS LAW - Y PRESSURE CORRECTED - N
SECOND RELAXATION FACTORS ON AFTER 32000 ITERATIONS.
PATCH OPTION -N
CONVERG/DIVERG CHK -Y
NORMALIZE RESIDS. -Y
CONTINUITY CHECK -Y
RESET OPTION -Y
SWEEP DIRECTION -2
REYNOLDS STRESS MODEL-N
NON-NEWTONIAN FLOW -N
POROSITY MODEL -N
ALLOW LINK SETTING -N
SET INLET TURBULENCE -N
MONITOR OPTION -N
LINK OPTION -N
PARTICLE TRACKING 0 TRACKS EVERY 0 ITNS.
GRAVITATIONAL ACCELERATIONS- X = 0.000E+00 Y = 0.000E+00 Z = 0.000E+00
APARAM = 1.000E+01
CONRES = 1.000E+03
CONCHN = 1.000E+03
ITMAX = 9

```

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TURBULENCE MODEL -      CD      C1      C2      CMU      RSMCD
                        5.5E-01 1.4E+00 1.9E+00 9.0E-02 1.0E+00

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WALL TURBULENCE MODEL. WALL ZONE  CAPP      ELOG
                        W0      4.187E-01 9.793E+00

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NON-NEWTONIAN FLOW -      N      K
                        1.0E+00 1.0E+00

```

- TEMPERATURE DEPENDENT PROPERTIES -

```

PROPERTY      COEFFS      0      1      2      3      4
-----
DYNAMIC VISCOSITY 1      1.6800E-05
LIQ.DENSITY INERTS 1      1.2930E+00
LIQ.DENSITY SPECIES F 1      1.2930E+00
LIQ.DENSITY SPECIES O 1      1.2930E+00
LIQ.DENSITY SPECIES C 1      1.2930E+00
SPECIFIC HEAT (GAS) 1      1.0360E+03
THERMAL COND. (GAS) 1      2.4100E-02
SPECIFIC HEAT (PART.) 1      1.0000E+03
THERMAL COND. (PART.) 1      7.8000E-02
BINARY DIFFUSIVITY 1      3.0000E-05
VAP. PRESS. (PHASE 2) 1      2.5331E+03

```

- SECOND PHASE PARTICLE/DROPLET TRACKING -

MAX. NO. OF STEPS = 5000
 STEP LENGTH FACT. = 2.000E+01
 PARTICLE DENSITY = 1.000E+03
 BOILING POINT = 3.730E+02
 LATENT HEAT OF VAPORIZATION = 1.000E+03
 COEFFICIENT OF RESTITUTION = 1.000E+00
 VAPORIZATION TEMPERATURE = 3.730E+02
 SWELLING COEFFICIENT = 2.000E+00
 FRACTION VOLATILE COMPONENT = 1.000E+00
 FRACTION NON-VOLATILE COMPONENT = 0.000E+00
 STOICHIOMETRIC RATIO FOR SURFACE REACTION = 1.333E+00
 HEAT OF REACTION FOR SURFACE REACTION = 2.000E+07

PARTICLE LAWS ACTIVATED FOR USER-DEFINED HISTORY -
 INERT VAPORIZE BOILING DEVOLAT BURNOUT INERT
 Y N N N N Y

INJECTINITIAL VALUES.....
 NO TYP (X) (Y) (Z) (U) (V) (W) (T) (DIAM) (MFLOW)
 1 PA 2.0E-02 1.5E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-07 1.0E-09
 2 PA 2.0E-02 1.5E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-06 1.0E-09
 3 PA 2.0E-02 1.6E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-07 1.0E-09
 4 PA 2.0E-02 1.6E-02 0.0E+00-7.0E+01-5.0E+00 0.0E+00 2.7E+02 1.0E-06 1.0E-09

FLOW FIELD AFTER 0 ITERATIONS--
