IMPROVEMENTS TO THE ARC-SPRAYING PROCESS

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Doctor of Philosophy

ASTON UNIVERSITY

October 1988

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for the degree of Doctor of Philosophy

1988

SUMMARY

After a brief review of the various forms of thermal spraying equipment and processes, descriptions of the basic principles involved and the general functions for which thermally sprayed coatings are used are given. The background of the collaborating company, Metallisation, is described and their position in the overall market discussed, providing a backdrop against which the appropriateness of various project options might be judged.
Current arc-spraying equipment is then examined, firstly in terms of the workings of their constituent parts and subsequently by examining the effects of changes in design and in operating parameters both upon equipment operation and the coatings produced. Published literature relating to these matters is reviewed. Literature relating to the production, comminution and propulsion of the particles which form the spray is discussed as are the mechanisms involved at impact with the substrate. Literature on the use of rockets for thermal spraying and induction heating as a process for feedstock melting are also reviewed.
Three distinct options for further study are derived and preliminary tests and costings made to allow one option alone, the use of rocket acceleration, to go forward to the experimental phase.
A suitable rocket burner was developed, tested and incorporated into an arc-spray system so that the sprayability of the whole could be assessed. Coatings were made using various parameters and these are compared with coatings produced by a standard system. Coatings were examined for macro and micro hardness, cohesive strength, porosity and by microstructural examination.
The results indicate a high degree of similarity between the coatings produced by the standard system and the high velocity system. This was surprising in view of the very different atomising media and velocities. Possible causes for this similarity and the general behaviour of this new system and the standard system are discussed before the study reaches its conclusions in not proving the hypothesis that an increase in particle velocity would improve the mechanical properties of arc-sprayed steel coatings.

KEY WORDS: Sprayed metal coatings, Electric arc spraying, High velocity flame spraying, Sprayed coating properties.

Acknowledgements

I would like to express my gratitude to the tutors and staff of the IHD scheme who were always most helpful and in particular David van Rest. I would also like to thank Dr. Alan Bowden, my first supervisor, for getting me started, and L.W.Crane, my present supervisor, for getting me finished and the industrial supervisor, D.H. James for always being available to talk over some point or other.

I thank my wife and family for their unselfishness and patience over many evenings and weekends lost to a wordprocessor.

Finally I would like to thank Dr. R.C. Cobb of Nottingham University for his collaboration in testing the thermal input to the substrate from the H.S.G. burner and I confirm that this was the only area in which collaboration took place.

......................T.P. Lester.

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Introduction

1.1 The thermal spraying process.

Thermal spraying is a process whereby heated particles of the desired material are projected at a prepared surface in such a way that they adhere and form a coating. Since the individual particles are small they have a small heat capacity so that heat input to the substrate can be kept low. Thus distortion and damage to the component being sprayed are avoided. Heat affected zones and dilution are also absent, since there is no fusion of the substrate material involved. The temperature of the substrate can almost always be kept below 200 degrees C and in many cases below 50 C. There are many ways of producing and projecting the heated particles. These may be categorised by the type of energy used to melt the material and the form of the feedstock as shown in table 1. Not shown in the table is the molten metal process in which low melting point alloys are held as liquid within the pistol and sprayed using a compressed air jet for atomisation. This system has not been included because it has very limited specialised applications.

Table 2 shows the capabilities of the various processes and in table 3 these process are ranked according to the quality of coating they can produce and by cost.

Table 1. Characteristics of the thermal spraying processes

	Oxy-fuel gas flame	Electric arc	Arc plasma	Detonation
Fuel	O_2 + Propane or Acetylene	Electricity	Electricity + Inert Gas	Oxygen + Acetylene
Flame temperature °C	2600 – 3100	4000 – 6000	to 20 000	3100
Feedstock	Powder Wire Rod Cord	Wire	Powder	Powder
Atomising	Compressed air	Compressed air	Pre-atomised	Pre-atomised
Particle velocity m/sec	90 – 100	150 – 300	to 600	to 760

Table 2. Thermal spraying process capabilities

	Oxy-fuel gas flame	Electric arc	Arc plasma	Detonation
Consumable materials	Metal Ceramics Selected cermets Composites	Metal Metallic-composites	Metal Ceramics Cermets Composites	Mainly oxide and carbide ceramics and cermets
Porosity %	5 – 15	3 - 10	0.5 - 10	0.25 – 5
Oxide level	Usually high	Medium to low	Medium to low	Very low
Deposition rate, kg/hr	1 – 10	1 – 50	0.5 – 10	1 - 3
Thickness mm	0.1 – 15	0.1 - 50+	0.05 – 1	0.05 – .3

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Figures 1 to 6 show sections through each of the forms of equipment used.

In the powder flame process powder is fed into an oxy-acetylene flame and the particles are melted and projected at relatvely low speed towards the substrate. Because of the diffuse nature of the flame, heating of the substrate can be a serious problem and the low velocities used tend to produce rather porous coatings. However it is by far the cheapest system and can deposit a wide range of materials.

The wire flame process uses a similar flame which is surrounded by a high velocity air stream which is used to atomise molten material from the wire tip. The air stream forces the flame onto the wire surface and also dilutes the flame further downstream, greatly reducing substrate heating. This, and the fact that no unmelted material can be incorporated into the deposit, make the process much less technique dependent.

In arc-spraying, wires are melted by an electric arc which is struck between them. By changing the speed of the wires, the deposit rate can be adjusted over a very wide range, with no theoretical top limit to the rate of deposition. Since no flame is used it gives the lowest substrate heating and also has the lowest running costs. However materials are restricted to conductors available as wires.

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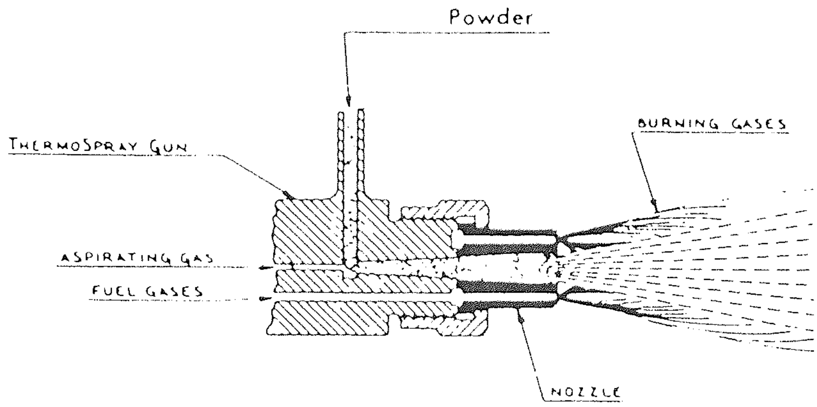

Figure 1. Powder Flame Spraying.

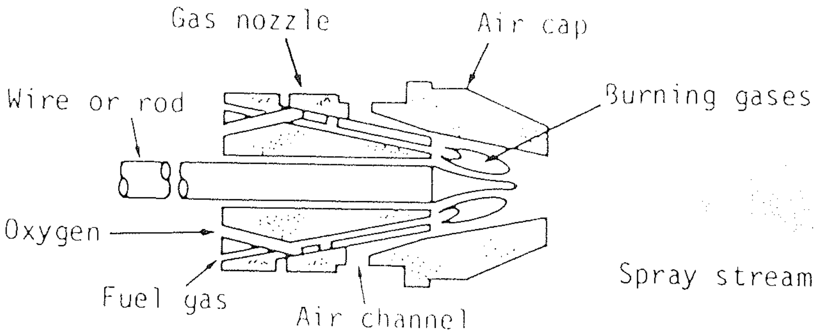

Figure 2. Wire Flame Spraying.

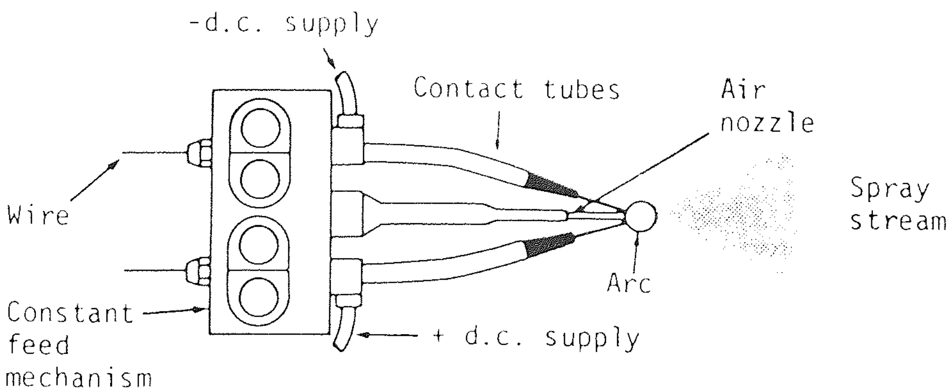

Figure 3. Twin wire Arc Spraying.

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The arc plasma process involves an arc struck between a cathode and a tubular copper anode. As a swirling stream of inert gas is forced through the anode it constricts the arc and causes temperatures of up to 20,000K to be reached. Particle velocities are high and coatings are among the best available. Also any material that does not decompose or sublime before melting may be sprayed. However the capital and running costs are relatively high since the energy efficiency may be only one tenth as high as for arc-spraying.

The detonation gun, used only by Union Carbide who hold the patents, may be thought of as an oxy- actylene shotgun, firing powder material at the substrate at extremely high velocity. A system of inlet, exhaust and purge valves similar to those found in vehicle engines allow the process to be repeated many times a second. The coatings produced are of the highest quality but are very expensive.

High velocity combustion spraying (HVCS) is a recent introduction which uses a propane oxygen rocket to melt and accelerate powder particles to very high speeds. The best HVCS coatings are comparable with the detonation system but ceramics cannot usually be sprayed due to their poor thermal conductivity and short dwell times in the flame which do not allow proper softening of the particle. The capital cost of HVCS is commonly around half that of plasma but the running costs are high and applications are restricted.

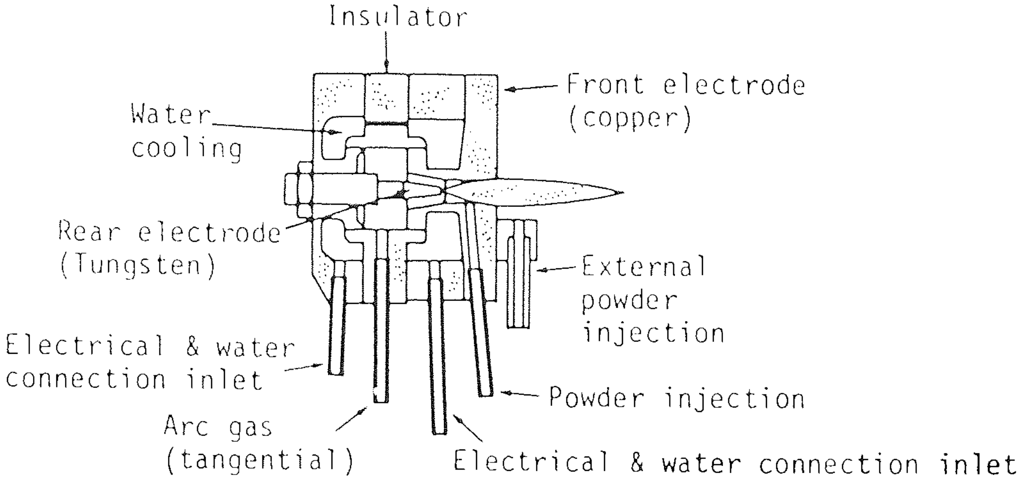

Figure 4. Arc Plasma Spraying.

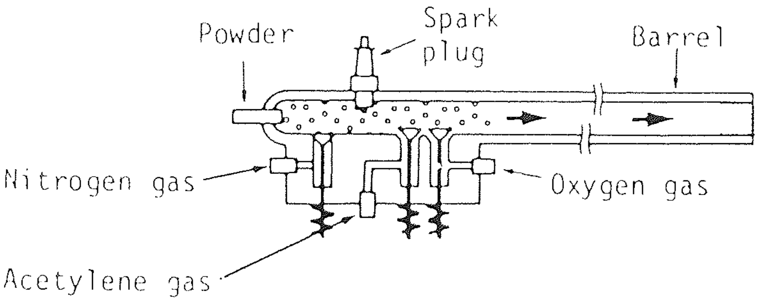

Figure 5. Detonation Gun Spraying.

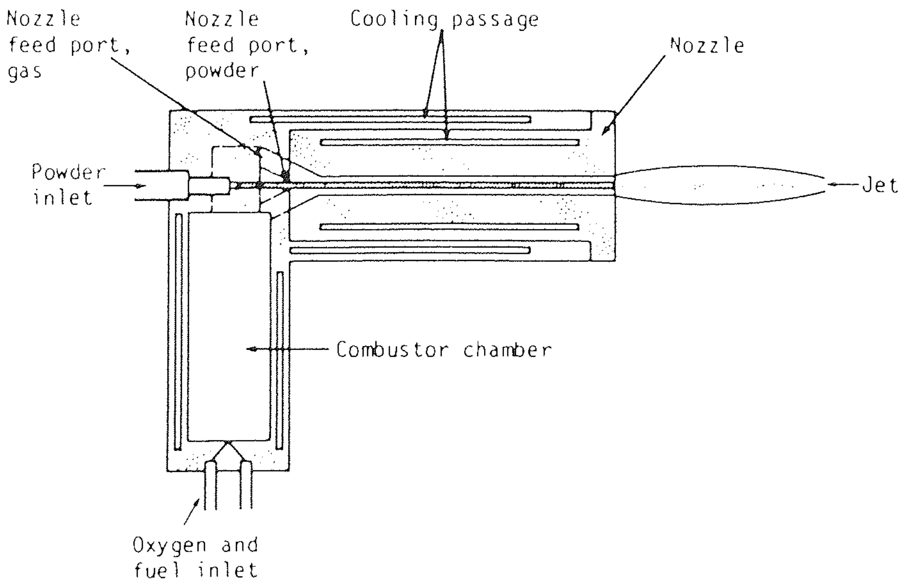

Figure 6. High Velocity Combustion Spraying. (H.V.C.S.)

Introduction

The function of any thermally sprayed coating is to enhance the surface properties of the component to which it is applied. Applications are extremely varied and include corrosion protection, wear and abrasion resistance, the provision of bearing surfaces and many more using a wide variety of coating materials.

For each different situation the set of properties required from the coating will be different, even when the same material has been selected. For instance in one situation where stainless steel is chosen as the coating material corrosion resistance may be most important, whilst in another, wear resistance is the deciding factor.
Other coating properties which may be exploited are listed below:

Electrical conductivity / insulation
Hardness
Surface finish
High / low friction coefficient
Thermal conductivity / insulation
The ability to create moulds.

In any particular situation the coating must provide the required set of surface properties. However, density adhesion and cohesion are essential to the functioning of almost all coatings and are the basic properties most often used to define "quality".

1.2. Company background.

Metallisation was founded in 1922 on the same site as it presently occupies in Dudley. In the beginning, the company offered a metal spraying service using German manufactured flame spraying pistols. By 1930 pistols of the original design were being made in Britain under licence and in 1938 the company had sufficient expertise to be able to build and sell a new pistol, known as the Mk.16, which was the first all British wire fed flame spray pistol.

For the most part, advances in the design of Metallisation's equipment have been as a result of manufacturing other companies' designs under licence, or importing new forms of pistol, until the company's new experience allowed it to manufacture its own equipment.

With a few notable exceptions, such as the Mk.40 nozzle system of 1962 and the constant geometry ceramic nozzle systems for arc pistols which continue to be developed, the company has successfully followed the technology rather than discovered it. Research within the company has concentrated on developing applications for existing equipment.

This approach, coupled with a policy decision to abandon all forms of powder spraying, has restricted the number of forms of equipment produced. This in turn prevents Metallisation from competing in certain areas of the thermal spraying market.

The company currently employs 39 people and has a turnover of around 2.5 million pounds. It is also part of a much larger group but is operated entirely separately with no sharing of resources from other arms of the group.

1.3. Companies in competition with Metallisation.

The following companies are in direct competition with Metallisation.

1/. Metco. This is the worlds largest thermal spraying company. They are a subsidiary of Perkin Elmer and have a turnover of many hundred million dollars. They are based in New York but also have design and manufacturing facilities in West Germany. Their principle interest has always been in plasma and the flame spray systems but recently more attention has been focussed on arc-spraying. They are reputed to spend an amount equal to Metallisations turnover on R&D alone.

2/. O.S.U. This West German company were first in the field with arc-spraying and at one time Metallisation were their agents in the U.K. However, although they are very strong in Germany and some parts of Scandinavia and eastern Europe they are not perceived as being a serious threat to

Metallisation's home market unless they decide to buy their way in through extremely low prices. O.S.U. have recently split into two factions and this must weaken their position.

3/. Metallizing company of Europe. Once again a West German company servicing Germany and east and central Europe. This was at one time connected to an American company of a similar name which was bought by Miller Thermal technologies, the welding equipment manufacturer who also purchased Plasmadyne, an American plasma manufacturer, to form the largest group involved in thermal spraying. However Miller did not purchase the European concern and it is now a small company which does not do much business outside its immediate market.

4/. Tafa. This U.S. company was formerly Metallisation's agent in the U.S.A. and Metallisation owned 49% of the company. After buying back that share Tafa now manufacture an arc-spraying pistol very similar to the last model which Metallisation supplied. Operating through distributors in Europe and the U.K. they are beginning to sell equipment into Metallisation's home market. After Metco, Tafa are seen as being the largest threat.

1.4. Background to problem and objectives of the project.

The various methods of producing thermal sprayed coatings are listed below in order of coating quality (as defined earlier) and cost. Metallisation produces equipment in categories (e) and (f) only, i.e. wire fed processes, whereas its largest competitor produces equipment in all categories except (a) and (b). Metallisation must compete not only against other manufacturers products in its own categories but also against equipment in other categories.

Table 3. Coating processes ranked by cost.

(a)	Detonation Gun
(b)	High velocity combustion spray
(c)	High energy plasma
(d)	Low energy plasma
(e)	Two wire Arc-spraying
(f)	Wire fed flame
(g)	Powder fed flame

The aims of the project were to understand the benefits and limitations of the various spraying technologies and to find improvements to Metallisations arc-spraying system which were compatible with the company's background and strengths and which would allow it to compete more strongly in the thermal spraying market.

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The first step towards this goal was to assess the current information on arc-spraying and other allied technologies.

Literature Review

2.1 Commercially available arc spraying systems.

All general purpose arc spraying systems at present on the market comprise three basic units.

i. A wire feeding system.

ii. A power and air supply system.

iii. An arrangement for bringing the above together, so as to melt, atomize and project the metal feedstock.

Taking each of these in turn, comparisons can be made between the different systems that are commercially available.

2.1.1. Wire drives.

These are split into two main types; those which pull the wire from the supply reels by means of a drive system contained within the pistol, and those which push wire from a point near to the supply reel, up conduits, to the pistol.

Pulling systems are more reliable since the wire is less likely to buckle in feeding. Also such systems do not suffer from irregular feed rate, as caused by elasticity in the conduits of pusher systems. On the other hand the pistol of a pusher system weighs less since it contains no drive system, therefore operator fatigue may be reduced. In general, because a large proportion of arc spraying work is machine operated, and reliability of operation becomes the main concern, the pulling system is many times more popular than the pushing type. Recently a system has been marketed which combines a powerful pushing system with a relatively light pulling pistol in a push/pull unit. Theoretically this provides the optimum in wire transport but with penalties in terms of complexity. At this stage industry has not had sufficient time to assess the system.

2.1.2. Power Supplies.

All commercial spraying systems use DC power supplies with an open circuit maximum voltage of around 40-50 volts and the capacity for continuous operation at currents between 100 to 1000 amps, depending upon the model chosen.

In the early days rotary converters were used by the German OSU Company, but now three-phase transformers and silicon diode rectifiers are universal. The dynamic characteristics of power supplies have a profound effect upon the stability of the arc spraying process, as will be shown later. Power supplies are all chosen to have a flat static characteristic. Nowadays many power supplies allow infinite adjustment of the spraying voltage to allow the optimum conditions to be set while spraying. (1,2)

All commercial systems use compressed air as the atomizing medium, although other media have been used for research and special applications. (3,4)

The air pressure may be changed by the operator to achieve particular results, but it is almost always set once, at the beginning of a job, then left constant.

2.1.3. Spraying Head.

The device or area in which the power, wire and air are brought together is known as the spraying head. Many arrangements are possible as shown by Kretschmar.(5) It is possible to have systems which use one, two,three or even more consumable wires, but the two wire system is relatively simple and provides a very high energy efficiency of melting, ie. 58% according to Kretschmar. It is currently the only commercially available system.

Atomization and projection of particles is achieved by using high velocity jets of compressed air to sweep the molten metal from the wire tips in the arc zone. (see fig.3)

Currently two types of head are available. These are so-called 'open' and 'closed' systems. (Closed is certainly a misnomer, but will be used here as it has a particular meaning within the industry.) In the open system a single jet, or pair of jets, impinges upon the wires from the rear and causes atomization and projection of metal droplets stripped from the wire tips. However, the most forward points of the wire tips are in the lee of the wire and are less well atomized. This leads to the production of larger particles, which may splash upon impact with the substrate and cause unevenness in the deposit. This is particularly important for anti-corrosive coatings which may be the basis for decorative paintwork etc..

In the closed system, a secondary, usually annular, stream of air is directed at the outside front tips of the wires. This stream of air atomizes the metal previously shielded from the air stream, and thus the coating texture is made finer.(6,7,8). The spraying head is the heart of the metal spraying system. It is the spraying head which largely characterises the coatings produced.

There are four groups of factors influencing the way in which the head behaves.

i. Electrical phenomena, eg; power supply characteristics.

ii. Changes in imputs to the spray head, ie; changes in spraying parameters for a fixed form of head.

iii. Changes in the form of the spray head itself.

iv. Particle atomization and heat and mass transfer phenomena.

Each of these areas will be examined to review current thinking.

2.2. Description of each system and a review of work concerning each area.

2.2.1 Electrical Factors.

2.2.1.1 Power supplies for arc spraying.

As has been stated above, the static characteristics for metal spraying supplies commonly have a slope of around two volts per hundred amperes. In other words they are "constant voltage" systems. Indeed on occasions, lead-acid accumulators have been used successfully as a power supply. (9) Series inductance is almost always added in varying degrees to limit the rate of rise of current under short circuit. The dynamic characteristics produced are of crucial importance to the stability of the arc, and for optimum results should be different for different spraying materials and wire sizes. For instance, for 3.2mm dia. zinc. the system may operate well with the choke bridged out. However, it is impossible to spray 1.6mm dia. steels with such a system, because the arc becomes very unstable.

To some extent the amount of inductance required is also related to the spraying rate, in that greater inductance is required at lower throughputs. In an experiment, Blewitt (10) found that by a combination of atomizing air changes and the addition of extra inductance, the minimum stable spraying current, for 1.6 mm 70/30 brass, could be reduced from 150 to 40 amps, with the change in inductance alone accounting for 50 amperes change. On the other hand, Morantz claims(11) "... that the presence of even a small amount of DC inductance in the output circuit is detremental to maintaining a high degree of arc stability, due to the fact that it inhibits the ability of the power supply to rapidly respond to the transient arc conditions." Morantz also advocates the use of 'constant current' rather than 'constant voltage' especially for spraying low melting point materials at low rates, since the large changes in voltage which are possible with such a system, enable it to cope with the ever changing length of arc. In this case the maximum current in the arc is limited by the static characteristic of the supply. In the case of Blewitt's experiment the rate of rise of current was limited by the series inductance, but the peak current was as much as six times the nominal value in some circumstances.

The requirement is for a power supply which is able to respond rapidly to the transient current demands of the particular spraying situation, and yet will not produce current peaks which are so violent as to explosively remove the wire ends, and force an open circuit. The system must supply sufficient voltage for re-striking the arc without allowing very large current surges on short circuit.

Wagner and Kminok (12) have designed and built a power supply using thyristor voltage control, whose static and dynamic characteristics are set using a 'black box' regulator. This appears to be similar to a power supply produced by J.C.Needham (13) for the Welding Institute, which used many transistors to control the output voltage and could be programmed to any static characteristic, or to give pulsed or otherwise modulated output. However, this was applied to MIG and TIG welding rather than to arc spraying. The virtue of such a system is said to lie in its versatility rather than its effectiveness in any one situation (81).

2.2.2. The effect of spraying head geometry upon spraying stability and the quality of coatings.

The stability of spraying depends upon achieving the following aims:

i. To correctly align and bring together the two wires.

ii. To ensure that the current passes into the wire readily.

iii. To ensure that metal is properly removed from the wire ends by an aligned stream of air at the correct velocity and flow rate.

The effect of changes made to the geometry of the spraying head may be measured against how they affect the system's reliability in achieving these objectives. Further, there are changes that can be made which mainly affect the properties of the coatings rather than the stability of the arc. Head geometry differences may be divided as follows:

i. Changes in included angle between the wires.

ii. Disposition and power of air stream.

2.2.2.1 Included angle between wires.

Two included angles are common, 30 degrees and 50 degrees. Smaller included angles, between 25 and 35 degrees. tend to be more electrically stable in that the short circuit with which the arc is initiated is 'softer', because there is a lower contact pressure between the wires. On the other hand there is more 'stick out', (the distance between end of contact tube and arc point), and this can lead to problems of alignment. Increasing stick out also leads to increased resistance heating of the wire end, which can cause collapse of the wire tips and hence a loss of arc. Problems of misalignment have been greatly reduced by recent 'constant geometry' designs of head.

The smaller included angle is found to be more energy efficient and to produce finer particles, which is important where a fine textured surface is required. The implications of spraying with finer particles will be discussed in 2.3 .

The larger included angle can cause stability problems due to a higher rate of bringing the wire ends together and the faster response time required from the power supply. This is especially so when spraying high conductivity materials. However, because of the greater angle through which the wire is turned (usually in bent contact tubes), the contact pressure between wire and contact tube is improved and poor current transfer problems are rare with this system.

Whilst reasonable wire alignment must be maintained to prevent loss of arc, this is not to say that the wires must be at all times perfectly aligned, with the centre line of each wire parallel and in the same plane. In fact a small amount of misalignment is beneficial (say 1/4 x dia.), as this reduces the contact pressure and is said to increase energy efficiency (14). In addition less pressure is exerted upon the components of the spray head.

The above suggests that included angle size, providing it is between 30 and 50 deg. is relatively unimportant. In recent work Blewitt has found that quite small changes in included angle can have significant effects upon the stability of an 1/8" Zn spraying system (14).

2.2.2.2. Disposition and power of air stream.

The air stream is of great importance to the stability of the arc. It not only atomises the molten metal into projectable particles, but also clears molten metal away from the electrode faces. This prevents prolonged short circuits which tend to 'explode' the wire tips, causing splatter and inhomogeneous coatings. Such short circuits also cause very large current surges, which can blow fuses in the power supply.

On the other hand, excessive air supply to the arc zone can also cause instability. Blewitt attributes this to excessive chilling of the wire tips (10), so that at any time the arc is lost, the cold wire tips make re-ignition impossible and the arc must be struck again.

Thus the air stream must perform the dual functions of atomizing the spray stream and clearing molten metal from the arc zone. Much of the work involved in developing closed head systems related to achieving the correct levels of air flow, correctly positioned to achieve each function. Given a limited amount of air which could be supplied, it was necessary to achieve a proper balance between the two functions.

As regards the effect of head geometry upon coating properties, much work was done in development facilities and is not well documented. However changes in head geometry are known to have effects upon the particles produced in a similar way to changes in spraying parameters. For instance, a change in the included angle would be expected to cause a change in particle size distribution, smaller angles giving finer particles. Similarly, closed systems give a more even size distribution and are capable of producing much finer mean particle sizes. In view of the limited amount of information on this topic, discussion on the effects of changes in particle size etc. will be included in section 2.2.3.

2.2.3. The effects of changing spray parameters.

2.2.3.1. Voltage.

Vakhalin, Kudinov and Belashcenko (49) suggest that the useful energy in the arc is produced in the near electrode areas and that, due to the gas stream, heat produced in the arc column is largely lost. Since the minimum stable voltage is that which can sustain the near electrode drops, excessive voltage only serves to increase the length of the arc column and is wasteful of energy. At a constant electrode feed rate, as the voltage is increased, so the specific heat input into the wires is raised. This effect is shown by the change in shape of the wire tips, which become less extended, and in the production of larger hotter particles. Also more noise is produced and it is common practise to adjust the spraying voltage by adjusting to the minimum stable noise level. However, increasing the voltage slightly can make the arc more stable, and better able to cope with disturbing influences such as excessive wire tip movement.

As the voltage is reduced the effect of the faster melting of the cathode becomes less noticeable until at the minimum voltage the effect is only noticeable as a different shape of the cathode tip. If the voltage is reduced still further then the arc may become unstable, as any disturbance may be sufficient to pull the voltage at the arc below that required to maintain the near electrode drops and the arc is temporarily extinguished.

Increasing voltage also causes increasing losses of some alloying elements, but reduces the loss of others due to increasing the average particle size.(50,64)

2.2.3.2. Atomising air pressure

In addition to the effects upon stability dealt with above (2.2.2), increased air pressure leads to finer particles and vice versa. The effect of decreasing the particle size is to increase oxidation and the loss of some alloying elements. Also increasing amounts of dust will be produced which, if incorporated into the coating, will create weaknesses. However, coatings produced from finer particles do appear less porous and are usually harder.(64)

2.2.3.3. Spray rate.

In further analysing the work of Cifuentes (65), James (66) has shown that the number of particles produced in unit volume of spray remains approximately constant so that the average particle size increases with increasing spray rate. One would expect the effects produced to be similar to those of reduced air pressure. Of more importance is the rate of arrival of molten metal, per unit area of substrate, in a given time. This directly affects the surface temperature, the particle quench rate and the time for which the particle is exposed on the surface before being covered by a new particle. All these factors have an important influence upon the degree of oxidation of the coating.

In addition there are limits to the spray rate that a given wire and spray head can produce. There is a lower limit at which the arc becomes intermittent causing a pulsing spray. This is commonly at around 90 amperes although modification of the power supply can reduce this to 50 amps for certain materials.(10) There is also an upper limit when the size of wire is no longer capable of carrying the current from the pick up point at the contact tube, to the arc point and melts prematurely.

2.3 Atomisation and propulsion of particles.

2.3.1 Models of metal atomisation.

Much has been written on theories of atomisation of fluids, mostly from the point of view of atomisation of fuels and other liquid sprays, driven by research into gas turbine fuel burning and spray drying.(20 -23 and 41) There has also been a considerable amount of work on the subject of metal powder production.(28,46,58 and 67)

Bradley (21) has developed a predictive model based upon the fastest growing wavelength of a disturbance on a molten surface and hence the size of filaments created by the breaking off of such wave crests. Bradley states that drop size is linearly dependent upon the surface tension of the molten metal and dependent otherwise upon the Mach number of the flow. He assumes that once having broken into particles from the wave crest filament, the droplets are not further atomized by the gas stream and cites Harper et al (22) and Simpkins and Bales (23) in support of this theory.

Bradley's work suggests a transverse crest and hence a transverse filament. In arc-spraying, filaments are drawn axially forward from the tips of the wires and it has also been shown that further comminution does take place after the break up of these filaments.

High speed film has been used to show the production of filaments at the wire ends in much more detail than can be observed with the eye in real time (15). From these and other sources, a mechanism for the break up of spray droplets has been derived. After a filament is formed aerodynamic forces act upon perturbations in the column to exaggerate any swelling or necking of the filament. In this way it is broken into droplets which can undergo further comminution as shown by Cifuentes (65), who has found the following relationship between particle size and range.

$$V=(1/d)^n$$

Where: V = particle volume, d = spray range, n = 1.8 approx and is dependent upon pistol type and parameters. A similar process of filament production is shown for gas wire spraying by Matting and Becker (25).

The atomisation of a particle is said to depend upon the Reynolds and Weber numbers of that particle in the flow field.

$$Re = \frac{\rho g\ Vr\ Dg}{\mu g} \qquad We = \frac{\rho p\ Dp\ Vr}{\sigma r}$$

where; ρ = density
D = diameter
μ = viscosity
σ = interfacial tension
V = velocity

suffices; p = particle
g = gas
r = relative

Having accepted that a filament drawing regime accounts for production of droplets, there are two modes of breakup which may be at work further downstream.

1/. Further filament drawing.

2/. Formation and bursting of bags.

In the first case, filaments are drawn out from the periphery of the larger particle. These filaments subsequently break up and the size of the filament, and hence of the secondary particles it produces, is dependent upon the relative velocity between particle and fluid. This is of course continually changing as the particle is accelerated. This mechanism of break up is supposed to be prevalent at higher relative velocities.

In the second situation a particle is blown into a bag shape by the pressure differential between its upstream and downstream faces. When the skin of the bag becomes too weak it bursts. The bag itself forms fine particles and the rim tends to form coarser particles. This mechanism is more commonly found at lower relative velocities.

In any atomisation situation there will be a critical Weber number below which a particle will be stable. It will also require a finite time for any break up to occur. Gordon offers the following expressions for critical diameter D and the time for breakup t:

$$D = \frac{16\,\sigma}{\rho g\ Vr^2} \qquad t = \frac{2\,D\,\rho p^{\frac{1}{2}}}{(\rho g\ Vr^2 - 16/Dp)^{\frac{1}{2}}} + \frac{32\,\mu p}{\rho g\ Vr^2 - 16\,\sigma/D}$$

but only claims agreement with experimental evidence to within a factor of two.

The following expressions are given by Nichiporenko and Naida for comminution of molten copper droplets (28). Where W' is the critical velocity for commencement of comminution and W'' is the critical velocity for instantaneous and explosive comminution.

$$W' = \sqrt{\frac{10 \times \sigma p}{Dp \times \rho g}} \qquad W'' = \sqrt{\frac{14 \times \sigma p}{Dp \times \rho g}}$$

According to Fedorchenko and Nichiporenko (46)the effect of addition of elements having refractory oxides, such as aluminium, is to raise the viscosity of the melt by several orders. The effect would be to raise the critical comminution velocity and thus to produce a higher proportion of large particles. This theme may explain the behaviour of arc-sprayed copper and nickel alloys containing aluminium which tend to spray more coarsely than the pure metals (47).

In general, correlations have been produced which use the parameters of a particular piece of equipment as independent variables such as nozzle diameter or supply pressure and such results cannot be transferred easily to the arc-spraying situation.

2.3.2 Modelling of particle projection.

Once a particle has been produced it begins to be accelerated and cooled by the airstream. Clearly there are parallels between this process and the projection of particles in plasma spraying, since both involve the transfer of heat and momentum between particles and fast moving gas streams. A great deal of theoretical and experimental work has been carried out in this area and in all cases the equations of motion of the particle are of the following form:

$$\frac{dVp}{dt} = \frac{3}{4}\, CD\, (Vp - Vg)(Vpg)\, \frac{\rho g}{\rho p\; Dp}$$

Stokes Law gives a value of CD = 24/Re but this is only applicable for very low values of Reynolds number and corrections must usually be made, the simplest of which is the Oseen correction.

$$CD = \frac{24}{Re}(1 + 0.187\ Re) \qquad \text{for} \quad 0.15 < Re < 2$$

Scott and Cannell (29) use a correction derived from Lapple's work (68).

$$CD = 23.707\ (1 + 0.165\,Re^{\frac{2}{3}} - 0.05\,Re^{-0.1}) \qquad 0.15 < Re < 500$$

Wallis suggests a simpler correction (36)

$$CD = \frac{24}{Re}(1 + 0.15\,Re^{.687}) \qquad Re < 700$$

A further list of relationships between CD and the Reynolds number can be found in work by Boothroyd (37). In Plasma spraying the Reynolds number is low due to the high viscosity of the very hot gases. For the anode bore, Houben (39) gives Re = 281, almost an order of magnitude smaller than that associated with the onset of turbulent flow. Similarly the particle Reynolds number will be low, being around 1. Guo Chang Jiang (38) gives Re = 0.5819 for a 15 micron particle and Houben (39) gives values from 0.63 to 5.67 for particles of sizes from 10 to 90 microns. However in arc-spraying the particle Reynolds number is around 1000 and Re for the nozzle exit is about 90,000 so that flow is very turbulent.

Equations of a similar form are proposed for heat transfer to and from the particle, thus:

$$\frac{dTp}{Tp} = \frac{6}{Prg} \; Nu \; \frac{Cpg}{Cpp} \; \frac{((Tg/Tp) - 1) \; dx/Dp}{\rho p \; Dp \; Vp/Vg} \qquad \text{(Hoglund (60))}$$

$$\frac{dTp}{dx} = \frac{12kg}{Dp^2 \; \rho p} \; \frac{(Tg - Tp)}{Vp} \qquad \text{(Wallis (36))}$$

where: Nu = h Dp/kg the Nusselt number

h = heat transfer coefficient

Pr = U Cpg/kg the Prandtl number

kg = gas conductivity

The Wallis equation assumes that Nu = 2, which is the case for a stationary sphere in an infinite medium. In fact there are many correlations for Nu, just as there are for Cd. The most popular appears to be that supplied by Ranz and Marshall (41).

$$Nu = 2.0 + 0.6(Pr)^{\frac{1}{3}}(Re)^{\frac{1}{2}}$$

This equation is used by Scott and Cannell (29), Vardelle, Vardelle and Fauchais (30) and is noted by Houben (35), but not used for ease of calculation, as it was shown that with the low values of Re and Pr arising from the plasma system the difference between the two expressions was only about 15%.

2.3.3 Measurement of particle properties.

Vardelle, Vardelle and Fauchais (30) have used Laser Doppler Velocimetry (L.D.V.) to measure the velocity of particles in a plasma stream and also used radiation pyrometry to measure their temperature. In this way they have been able to assess the effectiveness of powder injection into the plasma stream. More recently using L.D.V. combined with a great deal of computing power, Meyr (69) has been able to show the particle temperature, particle velocity and and particle flux distribution in real time for a plasma system. The use of L.D.V. on the arc-spraying system is much more difficult due to the high degree of turbulence present, nevertheless it is possible, as demonstrated by Busse (70).

2.4. Particle / Substrate interactions

Upon impact with the substrate, the particle will, in general, spread over the surface and freeze rapidly. However the actual shape of the final lammella depends upon a balance between several factors, notably, the size of the particle, the degree of melting, the surface tension, the impact velocity, the temperature and conductivity of the substrate and the surface roughness of the substrate. These factors will determine the rate of spread and the cooling rate of the droplet. The situation is further complicated by the action of shock waves within the molten droplet, which can make the particle splash into many small particles, each of which has a small heat content and a velocity which was largely parallel to the substrate surface. Therefore, one would expect these splashy droplets not to be as adherent as the main parent droplet.

In plasma sprayed deposits, Houben (71) has found that large hot particles tend to produce splashy floret type lammellae, whereas smaller cooler particles produce lammellae which are like a pancake. He states that the splashy lammellae often have voids at the outer edges which are partially filled by subsequent particles. However the cohesive strength in the region of the old void is low and the stress concentration factor is high. Houben cites this as the principal reason for the brittle nature of even the most dense coatings.

However, in plasma spraying, it is possible to choose the size of the spray particles, but in arc-spraying, a wide spread of particle sizes is always produced.

Another critical factor concerning the adhesive strength of the deposit, is the degree of interdiffusion which may take place at the particle/ substrate interface. Many studies of arc-sprayed bonding coatings have shown that those materials which will adhere well to a clean smooth metallic surface all exhibit some degree of diffusion across this interface. This has been shown to occur for nickel,manganese,aluminium alloys, aluminium bronze and also for plasma sprayed molybdenum. However pure nickel and pure copper do not exhibit these effects. This may be explained as follows. According to Jinlin Wen and Zhongli Zhang (72), during flight the aluminium content oxidises giving out a great deal of heat and preventing oxidation of the other components. Upon impact, the hot aluminium remaining is sufficient to reduce surface oxides so as to provide a very active surface across which diffusion of the copper or nickel is possible. Figure 7 shows a plot of copper concentration across the interface of an aluminium bronze coating on a mild steel substrate.

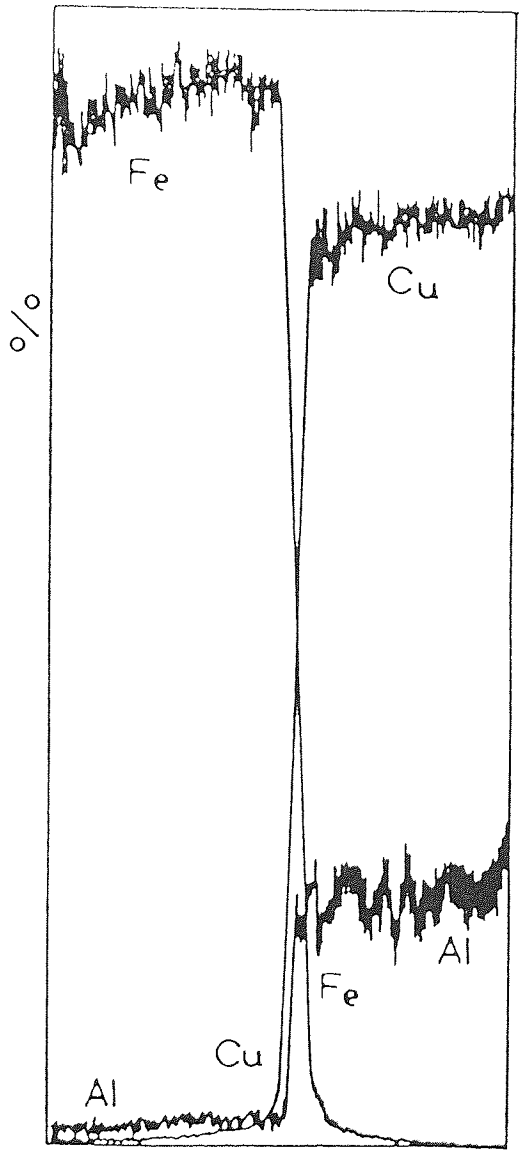

Figure 7. Concentration of elements across an aluminium bronze coating interface with a steel substrate.

At the coating / substrate interface the above phenomena will determine the adhesive strength of the coating. Similar effects will determine the cohesive strength and the porosity of the coating as it is built up.

According to McPherson (45), if the liquid does not wet the substrate the size of pore into which the particle will flow and penetrate is given by:

$$D = (4T\cos\theta)/p$$

Where: D = pore diameter.

T = surface tension.

θ = contact angle.

p = effective pressure.

If the liquid does wet the surface, the liquid will penetrate the pores without external pressure, and remain. The degree of wetting is increased by surface roughness thus:

$$\cos\theta = r(T_{1-3} - T_{2-3}) / (T_{1-2})$$

Where: T_{1-3} = solid-gas interfacial tension

T_{2-3} = solid-liquid interfacial tension

T_{1-2} = gas-liquid interfacial tension

r = roughness factor

Thus, different material combinations will give different degrees of porosity depending upon the wetability at the various interfaces, as well as the effective pressure applied.

McPherson assumes an effective pressure of $\rho_p v_p^2$, where v is the particle velocity, and it can be shown that this implies a constant ratio of particle diameter to lammellar thickness. This suggests a positive parabolic relationship between particle velocity and coating density. This is not shown, but certainly, the densest coatings are produced by equipment giving the highest particle velocities, such as the detonation gun, Jet-Kote and high energy plasma spraying.

2.5. Gas Burner Descriptions

Burners have various features by which they may be classified as follows:

Fuel type: solid liquid or gaseous.

Form of oxidant : solid, liquid or gas and the concentration of the active material, commonly oxygen.

Point of mixing of fuel and oxidising medium : whether pre-mixed or diffusion flames.

Method of flame stabilisation : gas turbulence and hot surfaces for re-ignition are common.

These features may be in any combination, for instance a gas turbine burner will burn liquid fuel, in a gaseous diluted oxidant, without pre-mixing, and stabilised by gas turbulence. A tunnel burner may burn pre-mixed gaseous fuel and oxidant and the flame will be stabilised by contact with the hot inner surface of the burner liner.

The stability of the flame is critical. In its simplest form if the gas velocity greatly exceeds the flame velocity then the flame will tend to lift off the burner and be extinguished. If the reverse is true then the flame will burn back into the burner and may cause damage. As an example the maximum flame velocity of a laminar propane/ air flame at S.T.P. is 0.472 metres per second (73). However the flame velocity is strongly affected by the initial gas temperature, for instance the burning velocity of a methane/ air flame was given empirically by:

$$S = 0.1 + 3.42e{-6} \times T^{2} \quad (73)$$

The effect of stabilisation is to allow greater gas speed, and hence throughput, by increasing the effective flame speed.

When turbulence is used for stabilisation, the effect is to mix cold unlit, gas more thoroughly with hot burning gas and hence to increase the number of sites of flame initiation. Thus the time taken for the flame front to travel through the gas is reduced.

Turbulence, when used for flame stabilisation, should consist of re-circulating flow rather than small scale turbulence. This may be achieved in three ways. Firstly, if the flow encounters a sudden expansion, then vortices will be created bringing burning gas into contact with the issuing unburnt mixture. Secondly, a bluff body may be placed in the flow which will create re-circulating flow by shedding vortices from several points. It has been suggested that a bluff body might be expected to stabilise a stoichiometric flame at up to a mixture Mach number of 0.1. (74)

Thirdly a high degree of swirl may be introduced. The degree of swirl is indicated by the swirl number, which is the ratio of axial to tangential velocity of the flow. The effect of a swirl number in excess of around 0.65, is to create reduced pressure at the centre line of the burner. The swirl will be strongest, and the pressure lowest, at the rear of the burner and hence a reverse flow may be created along the centre line, once again mixing burning and unburnt gases.

In a tunnnel burner, in addition to gas turbulence, the walls of the burner are lined with refractory material which, when heated, provides many more sites for flame initiation. An interesting variation of the tunnel burner is the porous wall burner. In this case the refractory walls are porous and the combustible mixture is fed into the burner through the walls. In this case combustion occurs usually just below the surface of the refractory so that the gases are in intimate contact with the hot surface.

The flame temperature may be calculated if the composition of the combustible mixture is known. The difference between the total enthalpy at S.T.P. of the products of combustion and that of the initial mixture is equal to the energy released during the process. However, dissociation complicates the matter, since the composition of the products cannot be accurately known without first knowing the flame temperature. This problem is solved iteratively by first assuming a flame temperature, then finding the resulting product composition and re-evaluating the heat released to arrive at a revised flame temperature. The process is repeated until the required accuracy is achieved.

Several authors have presented computer solutions to such problems for a variety of gas/ air and gas/ oxygen mixtures (75-77).

The majority of commercially available burners are intended to operate at low pressures for heating of furnaces and boilers etc. Many examples of various designs are known and fig 8 shows a design of gas/air turbulence stabilised burner while fig 9 shows a typical tunnel burner.

However some burners are intended to operate at several bars pressure in order to develop high exit velocities. These may be classed as forms of rockets. Browning engineering (78) produce burners in which commpressed air and kerosene are burnt at a pressure of around 4 bar. The resulting efflux gases have a very high velocity. When suitable granulated material is added, they may be used for cutting rock, grit blasting and indeed for metal spraying. A propane /oxygen derivative known as "Jet-Kote" has found wide usage in the spraying of tungsten carbide coatings. Klaruw (79) use a similar system for slitting tarmacadam road surfaces and for stripping unwanted road paint, except that this system is partially stabilised by hot internal surfaces.

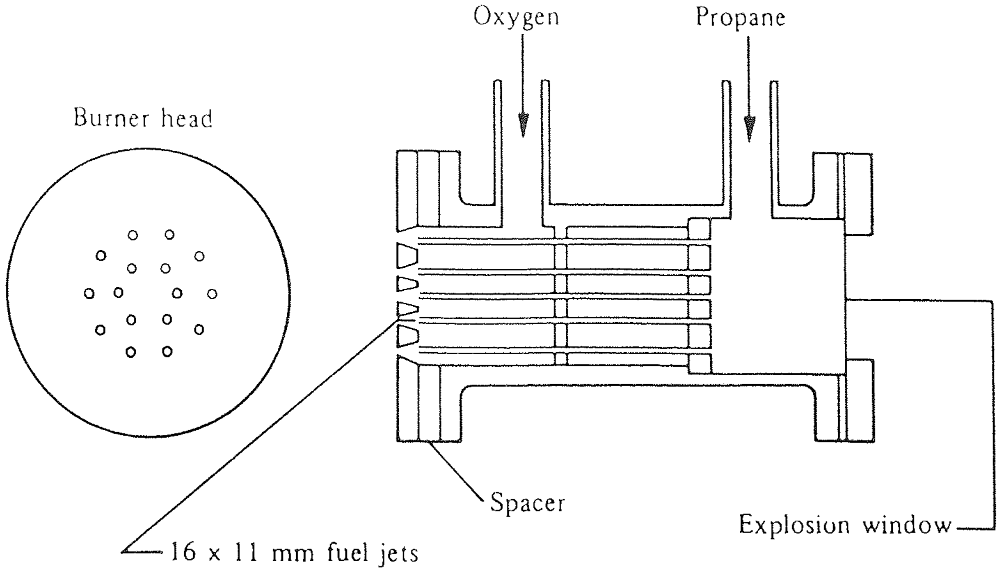

Figure 8. Gas/ oxygen turbulence stabilized burner.

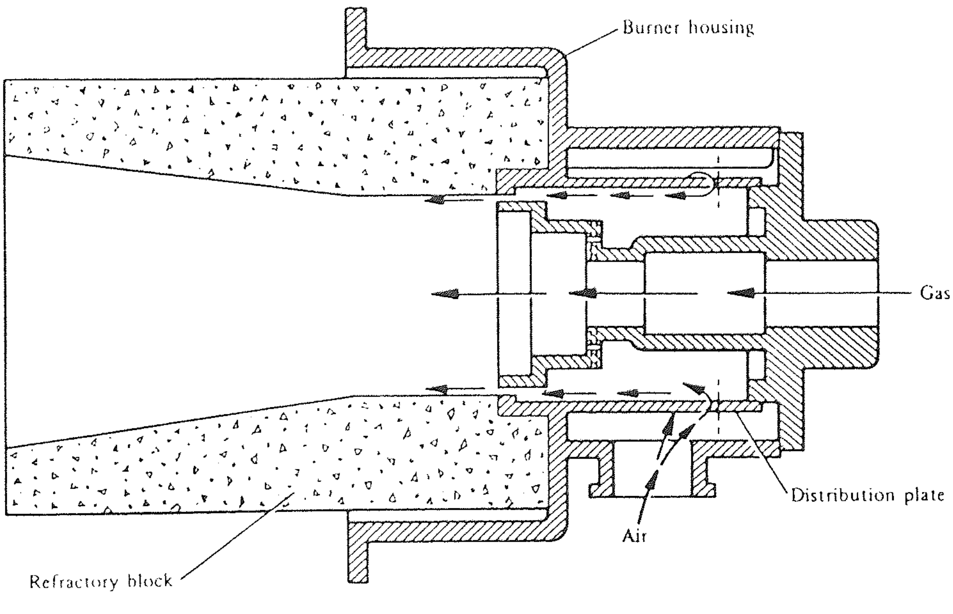

Figure 9. Typical tunnel burner.

When pure oxygen is used, higher flame temperatures are achieved and the flame speed of the mixture is also higher, leading to fewer problems in stabilisation. Fig 6 shows a cross section of a "Jet-Kote" burner.

The "Jet- Kote" burner is water cooled and this allows high internal temperatures to be reached using simple metals for the construction. Also the burner requires no thick insulating layer to reduce the outer surface temperature to a safe level. However, the water cooling system is an added complexity and expense.

The maximum theoretically achievable exit velocity of a nozzle when it is expanding into a vacuum, is a function of the gas composition and the stagnation temperature T_o only, since it is directly related to the ratio of the specific heats of the gas and the stagnation sonic velocity as shown below (80).

$$V_{max} = a_o(2/(g-1))^{0.5}$$

And $$a_o = (gRT_o)^{0.5}$$

Thus for a particular system, the exit velocity will rise with the square root of the absolute stagnation temperature which may generally be taken as the temperature within the burner at the point of entry into the nozzle.

2.6. Induction heating.

In this process, eddy currents are induced in the surface of the piece to be heated, by the coupling of a fluctuating magnetic coil which is placed around, or adjacent to, the workpiece. These currents heat the surface through resistive heating as shown in figure 10.

Typically, the energising coil is made of tubular copper through which cooling water is passed to remove the waste heat produced by losses in the coil itself. Alternating electrical energy is passed through the copper tube at frequencies which range from 50 Hz to around 5 MHz, depending on the application. The efficiency of the process depends upon the properties of the material being heated, the geometry of the workpiece and coil, and the frequency of the electricity being supplied to the coil.

Taking the properties of the material first, the efficiency of heating is dependent upon the conductivity and magnetic permeability. These properties vary with temperature and in ferro-magnetic materials the relative permeability is reduced to 1 as the Curie point is reached and the magnetic properties are lost. The efficiency of energy transfer to the workpiece decreases with increasing conductivity and with decreasing permeability.

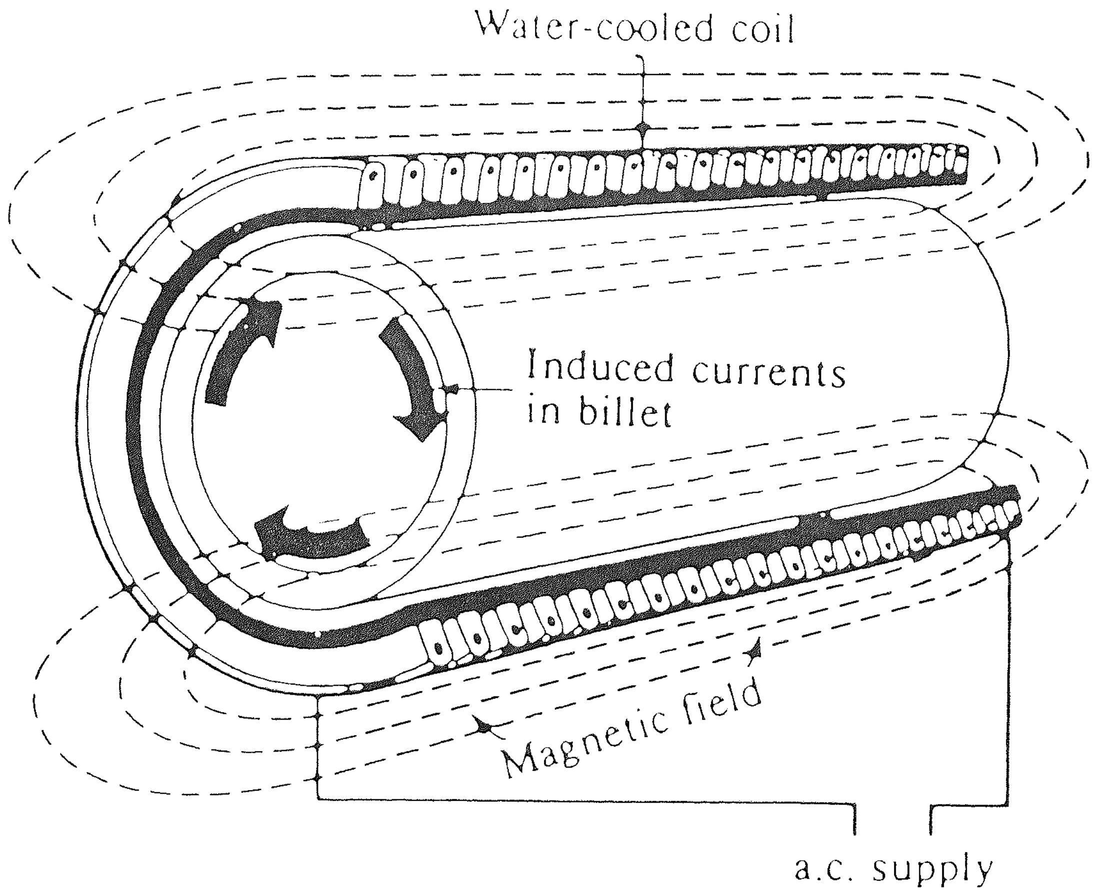

Figure 10. Principles of induction heating.

Good magnetic coupling is required for high energy efficiencies and this requires that air gaps between the workpiece and the coil be small. The actual size of the gap depends largely upon the scale of the piece being heated and the frequeny being used. For large pieces and low frequencies, a relatively large gap of tens of millimetres would be permissible, but for small pieces such as 3mm wire and high frequencies of say 450 kHz the air gap must be as small as possible.

The calculation of heating efficiency is a complex affair requiring the use of Bessel functions but fortunately graphs which simplify the mathematics considerably have been produced (82), as shown in figure 11.

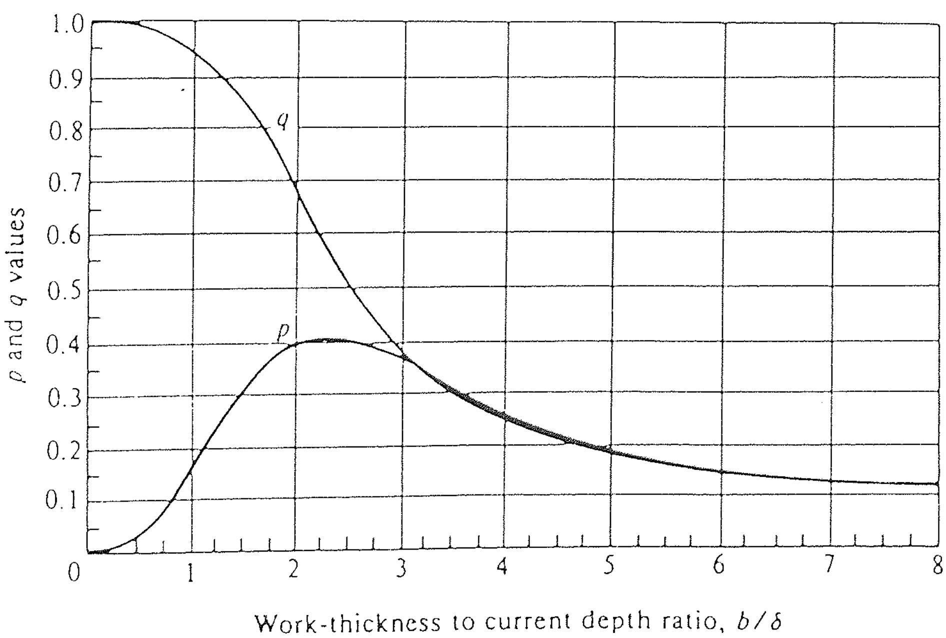

Figure 11. p and q functions for a solid slab. When $b/\delta > 8$, $p = q = 1/(b/\delta)$.

The calculation method is best shown by an example.

List of Variables

Pw   Power into workpiece

F   Frequency of generator

Dw   Wire diameter

Dc   Coil inner diameter

Lc   Length of coil

dw   Depth of penetration in work

dc   depth of penetration in coil

rw   Resistivity of workpiece

rc   Resistivity of coil

Rw   Resistance in workpiece

Rc   Resistance in coil

Xg   Reactance in air gap

Xw   Reactance in workpiece

Xc   Reactance in coil

Z   Total impedance of coil, work and airgap

Nc   Number of turns in coil

Aw   Cross sectional area of workpiece

Ac   Cross sectional area within coil

Ag   Cross sectional area of airgap i.e. Ac - Aw

MUo   Magnetic permeability of free space (4π e-7)

MUr   Relative magnetic permeability

p & q   Factors related to Dw/dw (see fig 11)

kr   Coil correction factor, assumed to be 1.5

If non magnetic materials are selected, the relative permeability MUr of both coil and workpiece is 1.

Assuming a wire diameter of 3.2 mm and a clearance between the coil and work of 1 mm and a coil length of 10 mm

$dc = (2rw/(MUr \times MUo \times 2\pi F))^{0.5}$

$Rc = K(kr \pi Dc\ dc)/2 \quad = 1.25e-6$

$Rw = K(MUr\ p\ Aw) \quad = 2.90e-6$

$Xc = Rc \quad = 1.25e-6$

$K = (2\pi\ F\ MUo\ Nc^2 / Lc) = 35 \times Nc^2$

$Z = ((Rc+RW)^2 + (Xg+Xw+Xc)^2)^{0.5}$

Coil efficiency $Ec = Rw \times 100 / (Rw+Rc)$

$= 70\%$

Coil power factor $pF = (Rw+Rc) / Z$

$= 0.22$

Coil volt amperes $= Pw / (Ec \times Pf)$

$= 32.5e3$

Power at terminals $= Pw / Ec$

$= 6.85e3$

$Z / Nc^2 = 355((Rc + Rw)^2 + (Xg + Xw + Xc)^2)^{0.5}$

$= AA$

Coil volts per turn $= Ec/Nc = (VA \times AA)^{0.5}$

$=13.7$

Ampere turns $= IcNc = (VA / AA)^{0.5}$

$=2370$

Assuming a voltage of 240 volts then

$$N_c = \text{volts} / \text{volts per turn} = 240 / 13.7 = 17$$

$$\text{Coil current} = \text{Ampere turns} / N_c = 2370 / 17 = 140 \text{ amperes}$$

The length of the coil Lc has no bearing upon the theoretical efficiency of the system but it does affect coil ampere turns and volts per turn. IcNc is proprtional to the square root of Lc and Ec/Nc to one over the square root of Lc. Thus, if the coil length increases then the ampere turns also rise, but if the number of turns also increases then the actual current may remain the same or even decrease. If, in the above example, the coil length is doubled with twice as many turns then the current is reduced to 99 amperes and the voltage required becomes 330 vots. The length of the coil also determines the power density, which if too high will not allow time for proper heat transfer into the middle of the material.

The graphs of energy input vs wire diameter for various metal conductivities, in figure 12, show the problems arising from trying to heat small diameter wires such as 3.2 mm which is the spraying industry standard. The problem is worse for materials with a low resistivity such as aluminium.

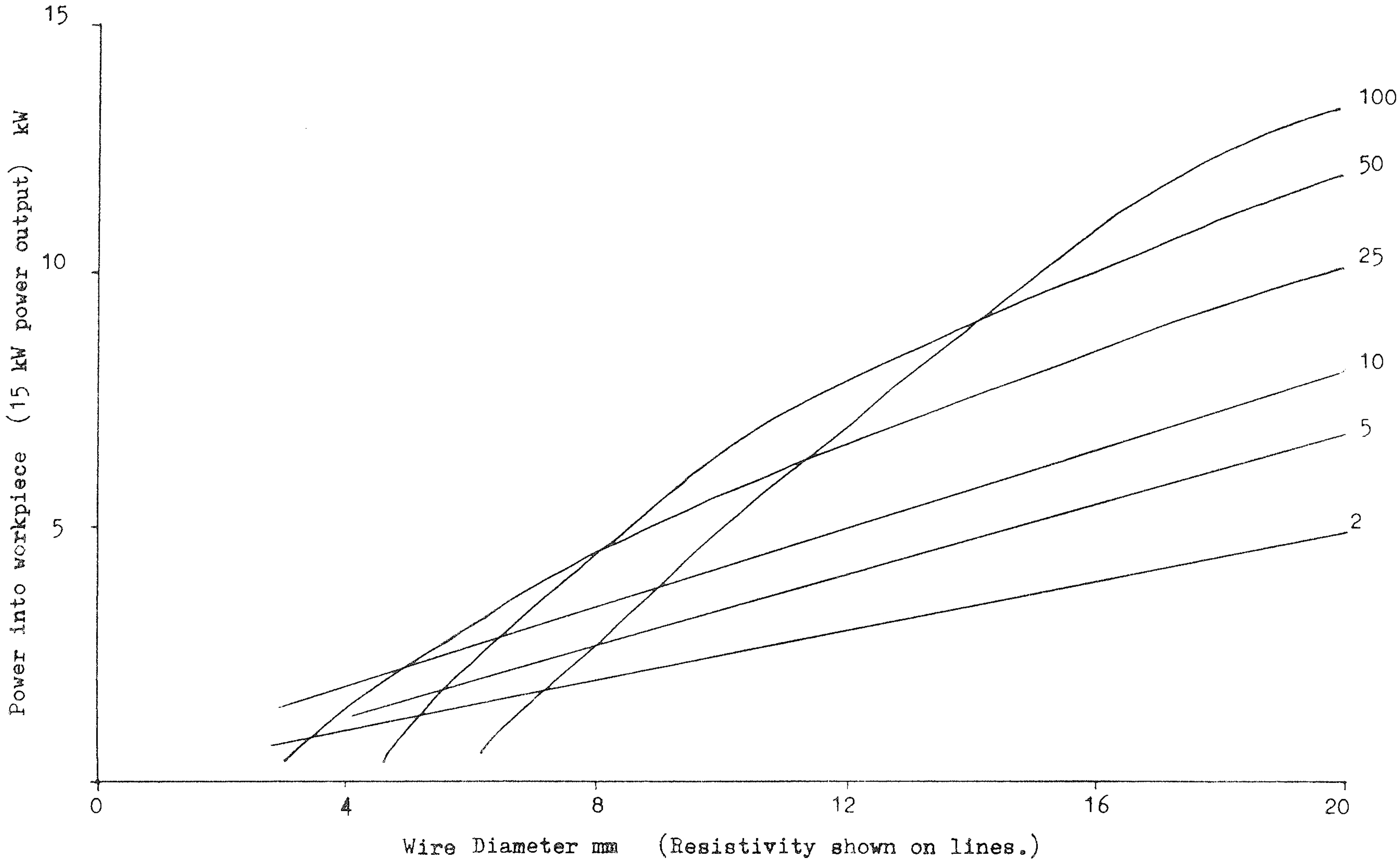

Figure 12. Heating efficiency Vs wire diameter and resistivity.

Options for Improvement

3.1. Introduction.

There are three possible areas for equipment improvement, each of which is aimed at increasing the market for wire fed spraying equipment. These possibilities are as follows.

1/. Improvement of coating quality.

2/. Improvement of process acceptability.

3/. Improvement of process and coating reliability.

3.2. The improvement of coating quality.

There is a considerable difference in both capital and running cost between arc spraying and low energy plasma. Those who require a thermally sprayed coating and yet are marginally unable to accept arc-sprayed coating quality, will be forced to use the more expensive Plasma system (up to ten times the cost), or use some other technology to overcome the problem.

Thus, if the quality of arc-sprayed coatings could be improved, without incurring the cost associated with the plasma system, a new market could be found in between arc-spraying and plasma. This market might use a wire fed process, based on arc-spraying, and would be particularly accessible to Metallisation. Not only would the arc-spray market, in which the company is very active, grow at the expense of the plasma market, in which Metallisation does not compete, but new applications would be found for the new system and the wider thermal spraying market would be enlarged.

In general the properties which should be improved are as follows:

(i) Adhesion
(ii) Porosity
(iii) Oxidation
(iv) Composition
(v) Residual stress

Taking each property in turn the factors affecting that property and its interconnections with other properties are detailed below.

3.2.1. Adhesion.

This is affected by the impact stress, temperature and surface condition of the particle as it impinges upon the substrate. Provided that the particle is hot enough to deform plastically upon impact and assuming that no chemical or metallurgical reactions take place between the particle and the substrate, then the level of adhesion achieved by each particle will depend upon the ability of that particle to disrupt any oxide films both around itself and on the substrate and to fill small crevices in the substrate surface. This depends upon the impact stress and hence upon the particle velocity. The surface conditions of the substrate and particle are critical, since contaminants prevent the particle achieving intimate contact with the substrate and forming a close mechanical bond.

3.2.2. Porosity.

The level of porosity depends upon the ability of a particle to fill small pores in the substrate or coating surface. This depends upon the viscosity and hence temperature of the particle, the impact stress and the interfacial tension between the particle and substrate surfaces. Porosity may consist of isolated pores as well as interconnected voids and fissures. In most cases the connected variety causes concern since connected pores may form a route from the coating surface to the substrate. Aggressive chemicals may then permeate and corrode the interface, causing the coating to spall. In addition, although cracks may initiate at any pore causing weaknesses within the coating, they may propagate more easily through interconnected pores.

3.2.3. Oxidation.

In some cases, especially where wear resistance is required, it is beneficial to produce a highly oxidised coating. Howeever, in general, excessive oxidation leads to low cohesive and adhesive strength. This is presumably due to brittle oxide paths along which cracks may more easily propogate. Excessive oxides also reduce electrical conductivity and corrosion resistance. Oxidation can only be prevented completely by spraying in inert atmospheres and is extremely expensive to eliminate. However, by controlling the spraying parameters, it is possible to influence the level of oxidation. Oxidation increases most noticeably with reduction in particle size. However, if the spraying cycle is such that the surface of the coating remains at a high temperature, then much of the oxidation can occur at this surface after the impact of the particles.

3.2.4. Composition.

For the properties of coatings to be predicted, the coating should maintain a similar composition to that of the wire, or at least differ from it in a predictable way. In the arc spraying system, loss of alloying elements occurs in two regions, the arc region and the flight region. Different elements are prone to loss in each. Those that are removed in the arc are lost more with increasing arc energy i.e. voltage, whereas those that are lost in flight are lost more with decrease in particle size. Furthermore, due to the inhomogenious nature of heating within the arc, some particles will be greatly superheated and such particles will tend to lose more alloying elements than those from other areas of the arc.

3.2.5. Residual stress.

The residual stress exhibited by a coating is a composite of the stress within particles, the cohesive strength of the coating and the adhesive strength of the coating. It is a complex phenomenon involving not only the thermal history of the coating and substrate, but also any chemical reactions or metallurgical phase changes that may have taken place. Residual stress is seen to be detrimental when it overcomes the adhesive strength of the coating causing it to crack and spall. However recent work by Cobb (88) suggests that close control of the spraying cycle and spraying parameters will allow a measure of control over this effect.

3.2.6. Summary.

Clearly it is not possible to satisfy all requirements and any device design must therefore be a compromise. However, in order to compete with the plasma system, it is particularly important to improve the adhesion, strength and density of the coating. To improve these properties, the impact stress of the particles must be increased. This requires an increase in particle velocity and hence in gas velocity. For the gas velocity to be significantly increased, the gas temperature must also be increased. Fortunately, raising the gas temperature raises the sonic velocity of the gas and simplifies the design of the required nozzle system. According to Nichiporenko (28), the critical Weber number for comminution is a function of gas density and raising the temperature will reduce the density and lower the Weber number. This will reduce the tendency towards excessive atomisation leading to losses of alloying elements and oxidation.

3.3. The improvement of process acceptability.

Due to the noise, dirt and radiation produced by spraying systems there is considerable customer resistance to the equipment on safety and environmental grounds. In addition to the capital cost of the spraying equipment, the first time buyer may also need to purchase an extraction booth, an accoustically attenuating room and perhaps other equipment to protect the rest of the factory and personnel. In many cases the cost of the protective equipment can be much greater than that of the spraying device. Therefore it would be of considerable advantage to be able to offer safer, less polluting equipment.

All thermal spraying processes produce environmental pollutants of the following forms:

1/. Dust and fume.

2/. Radiation.

3/. Noise.

In addition, the spraying system may present other health hazards such as the use of explosive gases.

Options for Improvement

Taking each pollutant in turn, the way each is produced and dealt with is detailed below.

3.3.1. Dust and fume.

Presuming the target substrate is large enough for overspray to be neglected, the production of dust implies a failure of some of the particles to adhere. This may be due to two factors, firstly the premature solidification of the particle and secondly the total oxidation of some materials in flight to produce a fine oxide dust. Since the time taken to solidify or to completely oxidise is inversely related to the particle size, it follows that excessively fine atomisation is the most likely cause of dust production. The production of fume is similar except that in this case the particles, some of which are condensed metal vapour, are so fine as not to reach the substrate at all, and disperse in the turbulent air surrounding the spray-stream.

Even under ideal conditions an atomising process will produce a wide distribution of particle sizes but this can be influenced by careful choice of spraying parameters, especially atomising air pressure.

In the arc-spraying process certain regions of the arc produce very fine particles and fume even at greatly reduced atomising air pressure. Therefore arc-spraying systems tend to produce greater quantities of fume than say a wire flame spray pistol. Where toxic fumes such as those of aluminium bronze are evolved, this is of particular concern.

At present the dust and fume are commonly dealt with by water-wash extraction booths which withdraw and filter large quantities of air before discharging to atmosphere. Where this is impracticable the operator can be provided with a filtered air supply via a special metal spraying helmet.

3.3.2. Radiation.

Infra-red, visible and ultra violet radiation may be produced by thermal spraying processes. The first two forms are emitted by thermal radiation from the material being sprayed. The only form of protection that is usually necessary is the wearing of darkened glasses. These forms of radiation are usually not so intense as to be a hazard to personnel not directly using the equipment.

However both plasma and arc-spraying systems produce ultra-violet radiation, and full face darkened visors must be worn by operators. Unless other personnel are shielded from the radiation they too must wear darkened glasses.

Since ultra-violet radiation is an inevitable product of arc processes only by using some other melting process can it be entirely eliminated.

3.3.3 Noise.

Since all thermal spraying processes use a fast moving jet of gases to propel the particles, a certain amount of noise is inevitable. However the noise produced by the air jet itself is of the order of 90-95 dB whereas a working arc-spray system has a noise level of about 110-115 dB. The noise level is affected strongly by the material being sprayed and by spraying settings especially arc voltage.

At present either the operator and those nearby must wear ear protection, or the entire spray system must be enclosed within a sound attenuating enclosure. Clearly a quieter melting process would reduce the need for protective equipment.

3.3.4. Summary.

In order to reduce the overall level of pollution a design should incorporate the following features.

1/. Minimum quantity of atomising gas.

2/. A nozzle designed to reduce noise.

3/. A quieter heating process.

4/. An ultra-violet free, heating process.

3.4. The improvement of coating and process reliability.

There is much concern as to the reliability of thermal sprayed coatings. For instance an end user may require a minimum level of adhesion. Whilst this may be within the capabilities of the spraying system, many contractors would feel unable to offer such a guarantee. Often the problem of inconsistent coating properties can be traced to the operator, bearing in mind that thermal spraying is often a dirty, noisy and low-paid job. However even the most highly skilled operator is incapable of absolute consistency, especially where repetitive and yet precise work is involved. It would therefore be beneficial to automate the spraying process as much as possible.

Furthermore, thermal spraying equipment is now very often fitted to automatic plant and the need arises to be able to interface easily with various other pieces of machinery and control systems. A degree of programmability within the spraying system would offer great flexibility in this respect.

3.4.1. Sources and Control of Inconsistency.

The major source of inconsistent coatings is human error. Apart from incompetence and inexperience it is often impossible to control exactly the manner in which the coating is produced i.e. the range, traverse rate and spray rate which would ideally suit the job in hand.

Furthermore research is now showing that it may be possible to control such factors as residual stress and composition by the way in which the coating is sprayed. Similarly hardness, porosity and electrical conductivity are all known to be affected by both the spraying parameters and the method adopted by the operator.

For this inconsistency to be removed it is essential that as much as possible of the spraying process is automated, thus removing human error.

3.4.2. Summary.

For operator based inconsistency to be eliminated the following features of the spraying system should be automated

1/. Parameter setting, especially spray rate, voltage and air pressure.

2/. Parameter holding, especially spray rate, and voltage.

3/. The spraying cycle, i.e. the range, rate, traverse rate etc.

4/. Monitoring of parameters for unforeseen change e.g. loss of air pressure.

3.5. Preliminary Trials

3.5.1. Particle Atomisation and Projection

The differential equations for heat and mass transfer were applied to the arc-spraying situation and solved by computer, using a fourth order Runge Kutta technique, in several programs, as shown in appendix 1. The results were as in figures 13 and 14. The following assumptions were made.

1/. A velocity distribution as suggested by Forstall and Shapiro (44).

2/. No correction of Nusselt No i.e. Nu = 2

3/. No account was taken of phase changes.

4/. Chemical reactions were ignored.

5/. Radiation losses were ignored.

6/. Heat transfer within the droplet is much faster than from the particle to the air and the particle is at one temperature throughout.

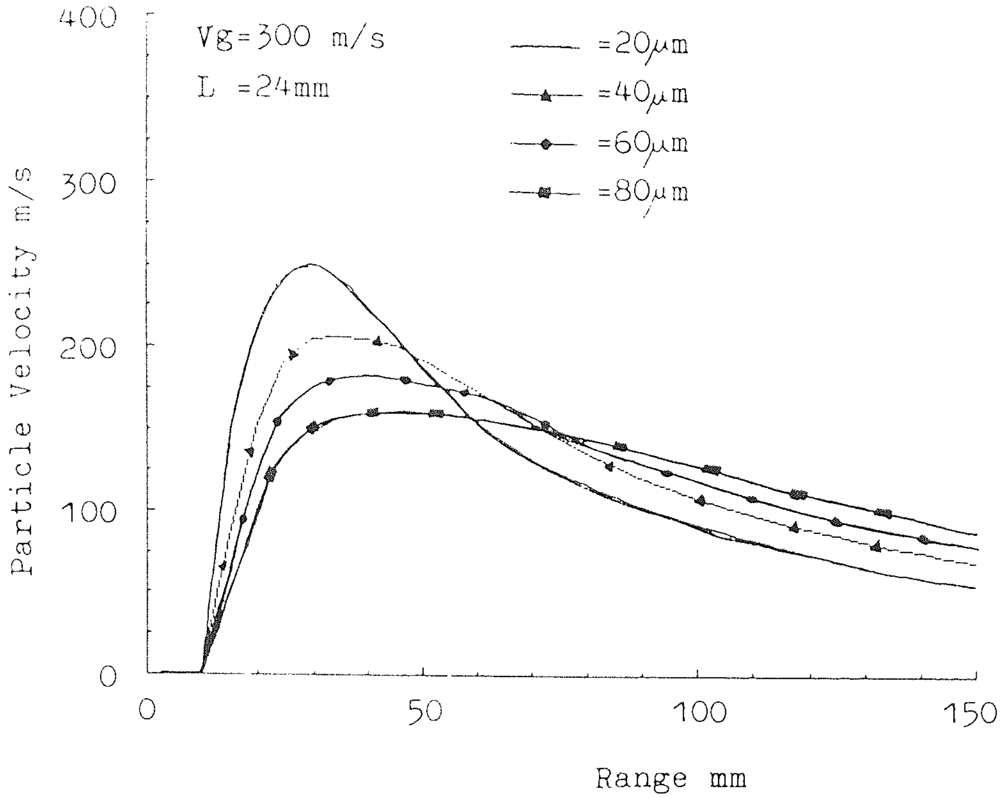

Figure 13. Theoretical particle velocity vs range

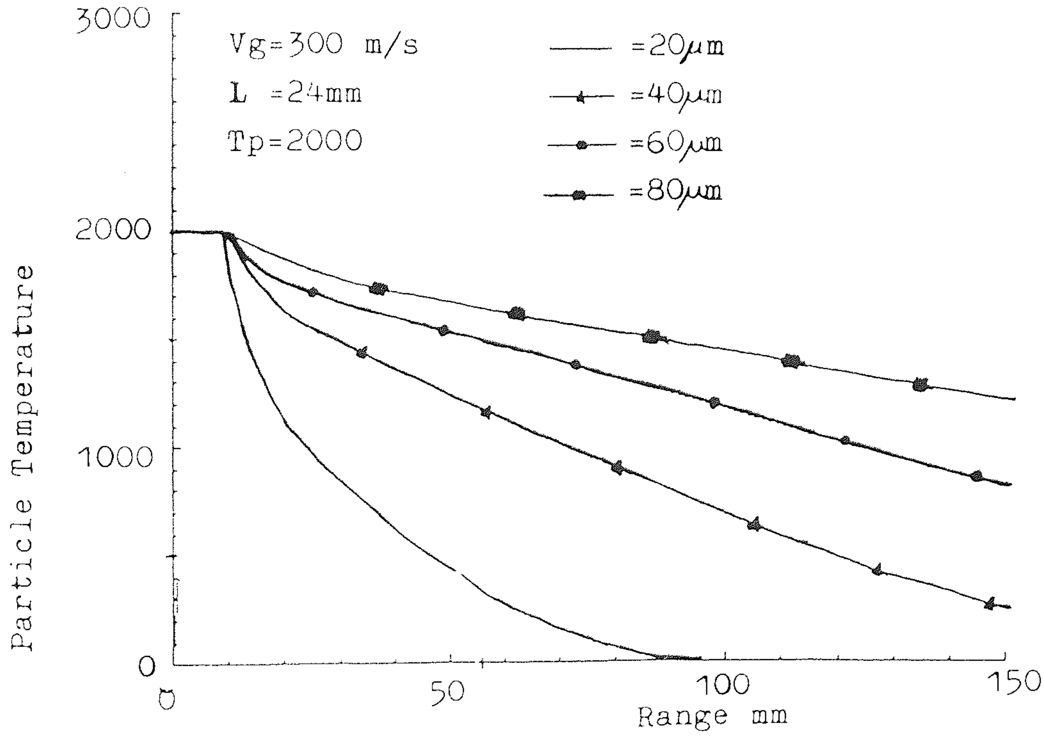

Figure 14. Theoretical particle temperature vs range

Options for Improvement

The following parameters were set in each case:

Initial gas speed	Vg
Potential core length	L
Initial metal temp.	Tp

If the temperature of the gas is raised, as is the case with the H.S.G. burner, then the properties of the gas will change. This was catered for in the computer model by taking a temperature/ range correlation from Forstall and Shapiro, combined with temperature correlations for viscosity, density and conductivity obtained from tables (84). In this way the required properties were re-calculated at each value of range. The properties of the particles were assumed to be constant with temperature. Figure 15 shows a comparison of the gas velocity correlation used with the measured centre-line distribution of a standard Metallisation CG20 spray head.

The temperature graphs for a standard arc spray system as shown in figure 14, show that below a certain size a particle would be unlikely to retain sufficient temperature or momentum to play a useful part in the production of a high quality coating.

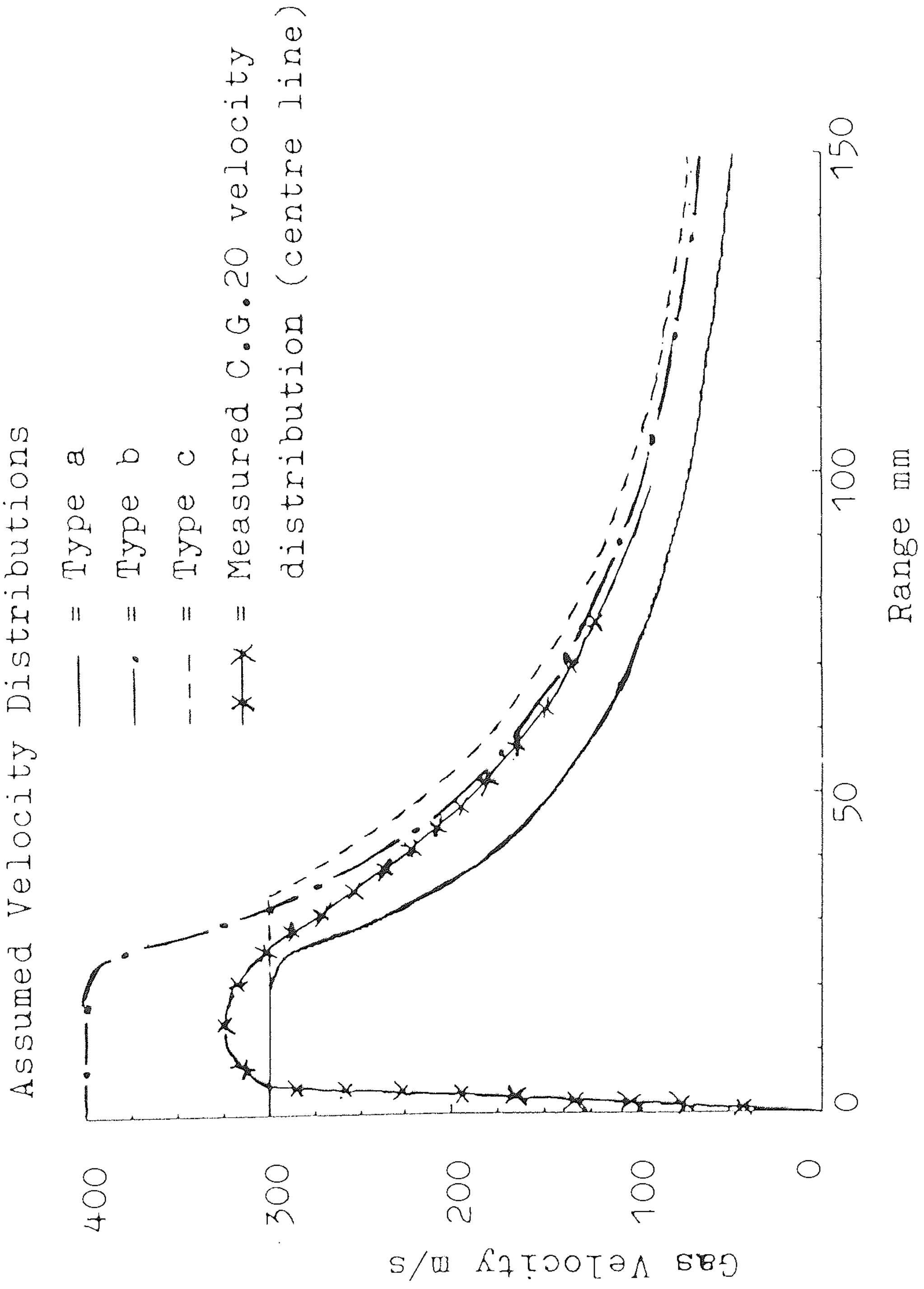

Figure 15. Comparison of theoretical and measured gas velocities vs range.

Options for Improvement

If a phase change is included, the effect of particle size upon temperature will be increased, although all particles would maintain a higher temperature. Even though a phase change has not been included, the distance at which a particle solidifies may be found if the following assumptions are accepted, in addition to those stated above.

Firstly, one must assume that solidification occurs with the whole particle at the melting point, which is not unreasonable for a pure metal. Secondly, it is assumed that the rate of heat loss remains constant regardless of phase changes and the maintenance of temperature during solidification is ignored. Although not strictly correct, they are sufficient to provide an indication of the trends.

If Q' = heat lost from particle

Q'' = heat released by solidification

C_p = specific heat of particle

$\Delta\theta$ = particle temperature drop

L = specific latent heat of fusion of particle

M_{tot} = total mass of particle

M_{sol} = mass of solid in particle

Then $M_{tot} = Q'/C_p\Delta\theta$ and $M_{sol} = Q''/L$

Thus $M_{sol}/M_{tot} = Q''\Delta\theta C_p/Q'L$

From assumptions made above $Q' = Q''$

and thus $M_{sol}/M_{tot} = \Delta\theta C_p/L$

Options for Improvement

By this analysis a 20 micron particle would be completely solid at 50 mm range where a 40 micron particle would be 25% solid. A 60 micron particle would not begin to freeze until a range of 55 mm and a 80 micron droplet would remain fully liquid until about 90 mm from the wire tips.

Calculations were also performed to show the effect of changing the gas velocity distribution. If the initial gas velocity is raised from 300 m/s to 400 m/s, the velocity of an 80 micron particle, at a range of 150 mm, rises from 80 m/s to 112 m/s and to 204 m/s for an initial gas velocity of 1000 m/s. If the length of the potential core of the jet is increased by one third, as occurs with correspondingly increasing jet diameter, this figure becomes 120 m/s for a gas velocity of 300 m/s. In a similar way, the onset of freezing also occurs at greater range with higher particle velocities.

Theoretical studies of atomisation and projection are severely limited by their simplifying assumptions. For instance surface chemical reactions such as oxidation could have a dramatic effect upon atomisation as follows:

1/. A surface oxide layer will have a different surface tension to the molten metal so that critical comminution velocities will be changed.

2/. A surface oxide film may reduce the rate of heat transfer between particle and gas, tending to maintain the particle temperature.

3/. The oxidation of the particle surface will generally be exothermic, once again raising the temperature of the particle.

It has been shown that the deposition efficiency of arc-sprayed steels is over 70% at a range of over two metres. This discrepancy can only be reconciled by effects such as exothermic oxidation maintaining the particle temperature. The relative velocity between particle and gas falls to below 50 m/s at a range of around 30 mm and it would be expected that comminution would have ceased at this point. However, this and other work show that it continues up to at least 150 mm, although at a reducing rate.

3.5.2. Hot gas atomisation trials.

As a crude test of the effectiveness of increasing the atomising gas velocity and temperature, the efflux gases from a "Jet Kote" hypersonic flame spray pistol were used to accelerate spray particles produced by an open arc spray pistol. Due to the shape of the hot gas stream this could not be used to atomise the material and was used to accelerate the already produced particles. The pistols were mounted on a small lathe so that the position of the flame, relative to the arc point could be moved in all three orthogonal planes . In this arrangement the hot gas stream had to be used at an angle to the main airstream as shown in the schematic drawing in figure 16. Several sample coatings were produced for metallographic examination using various conditions as shown below.

The standard settings for each parameter were as follows:

R1	Range from arc to substrate	150mm
R2	Range Jet-Kote to arc centre-line	8mm
R3	Range Jet-Kote centre-line to arc point	8mm
I	Arc pistol current	300
V	Arc pistol voltage	28
P	Arc pistol nozzle pressure	0.36 MPag

The Jet-Kote parameters remained constant as follows:

Fuel gas	Oxygen	Nitrogen	Hydrogen
0.40 MPag	0.54 MPag	0.14 MPag	0.14 MPag

Sample plates B1-4 were made with parameters as follows:

B1 R3 8mm increasing to 17mm in 3mm steps.

B2 I 300 decreasing to 200A in 50A steps.

B3 R2 8mm increasing to 23mm in 5mm steps.

B4 P 0.36MPag increasing to 0.56 MPag in 0.1 MPa steps.

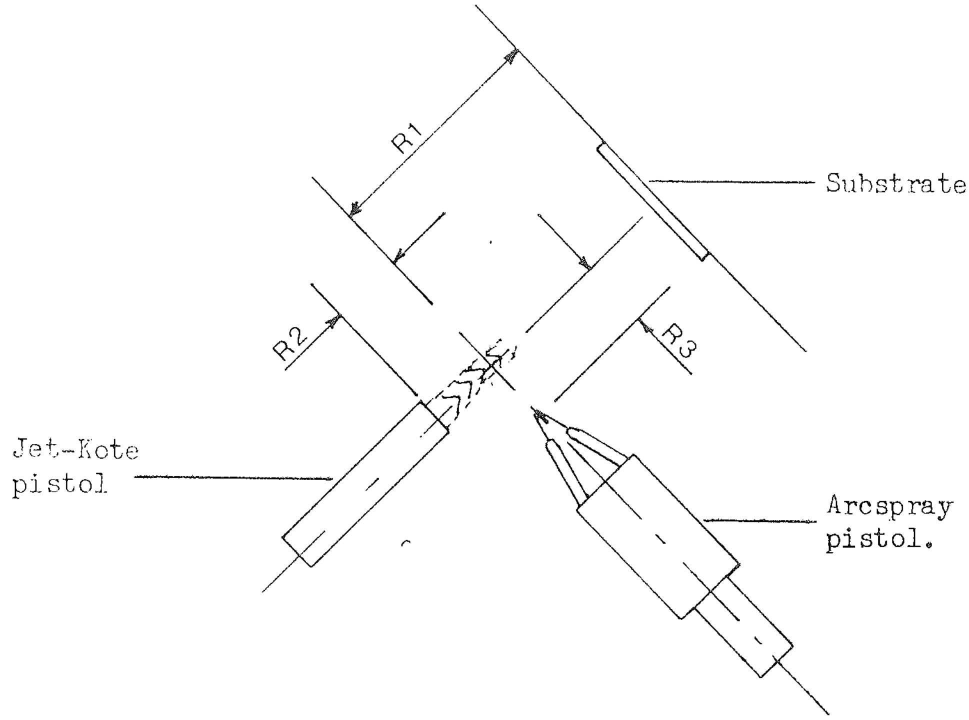

Figure 16. Layout of Jet-Kote / Arc-spray trials

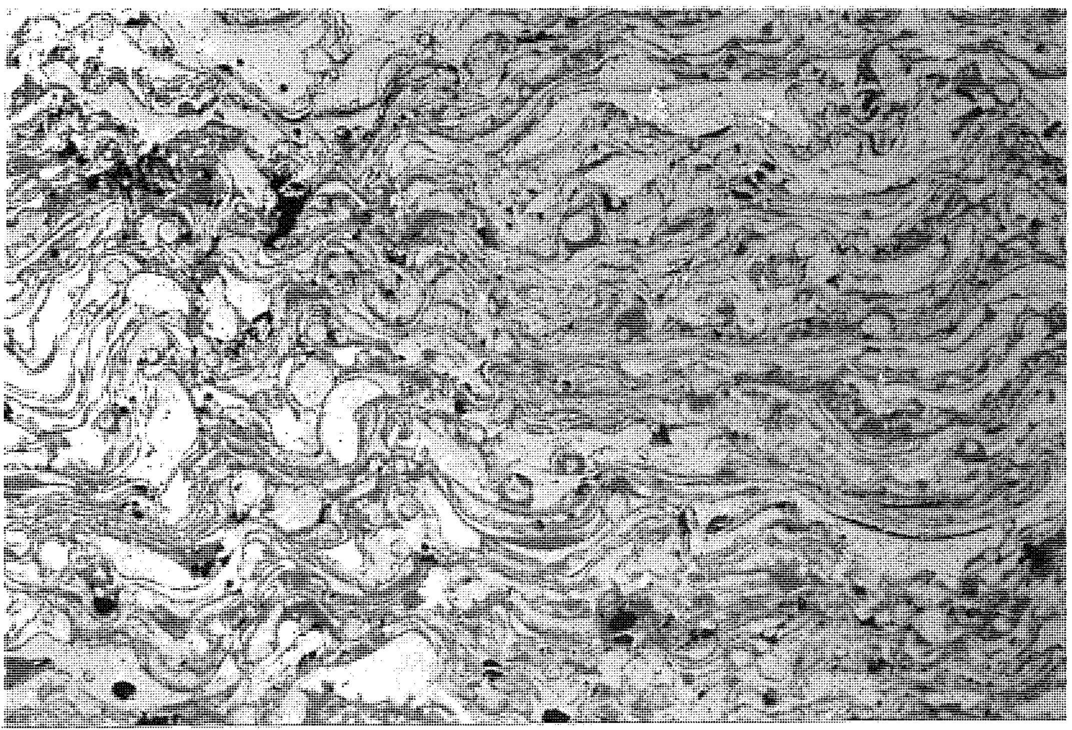

Figure 17. Typical microstructure of coating produced by combined Jet-Kote / Arc-spray.

Various samples to show the effect of changing parameters I, P, R2 and R3 were produced but the only truly distinguishing feature of the coatings was the high level of oxidation. This may be attributed to the increased temperature of both the coating and the particles in flight. Also the particles were pre-atomised by the arc-spray pistol nozzle and may well have been excessively fine. Furthermore the flame was produced from propane and pure oxygen and was considerably hotter than the intended propane/ air flame. In view of the differences between this system and the envisaged design, direct parallels could not be drawn. As an example figure 17 shows a coating produced in this way.

3.5.3. Induction melting trials.

A set of calculations were performed to assess the feasibility of induction heating as a method of melting wire as shown below. Thus the optimum supply frequency and power requirement may be derived. These calculations expose the relative difficulty of melting aluminium which has a high electrical conductivity as well as a high specific heat content at the melting point. It is also shown that for a geometry suited to the melting of wire, frequencies of the order of 450 kHz are necessary to achieve a reasonable efficiency with steels.

To test the feasibility in a more practical sense, Radyne, a large manufacturer of induction heating generators, agreed to make and test a suitable coil to find the maximum rate at which various wires could be melted. At first, this was attempted using a 20 kW generator at a frequency of 35 kHz. Although it was known that this was really too low a frequency, it was the only unit available at the time. However at lower frequencies levitation of the molten material can occur more readily and the aluminium rose back into the coil causing short circuits. Steel showed a similar tendency but melted much more slowly. The levitation effect prevented any judgement of the melting rate of aluminium in this case. When a 5MHz generator was used steel appeared to melt quite rapidly.

Having become convinced that a higher frequency was required, Radyne agreed to perform a set of tests using a frequency of 450 kHz. Melting trials were performed on 3.2mm 420S45 steel, aluminium, phosphor bronze and molybdenum, giving the following results using 3.5 kW. For comparison the normal spray rate for flame spraying is also shown in Figure 4.

Table 4. Induction heating melting rates.

Material	Melting rate	Flame spray rate
Aluminium	7.6 mm/s	40.6 mm/s
Bronze	5.1 mm/s	20.0 mm/s
420S45 steel	5.4 mm/s	16.7 mm/s
Molybdenum	1.7 mm/s	14 mm/s

Options for Improvement

A representative of Radyne felt that with proper design of the coil an improvement of 50% was possible, but melting speeds would still be low compared with flame spraying and very low compared with arc-spraying. However there is also no real restriction, other than cost, upon the power that could be applied.

Device Designs and Selection

4.1 High Temperature, High Velocity Atomisation.

4.1.1 Envisaged design.

In following this line of investigation the following device design was envisaged.

A pistol essentially similar to an arc-spray pistol but having a nozzle system capable of supplying a stream of gas at a temperature of approximately 1200 Kelvin and a velocity of approximately 600 m/second.
To achieve these gas properties, a fuel/air mixture would be burnt in a combustion chamber at a pressure of about 0.4 MPa. The efflux would then pass to a nozzle for expansion and acceleration. Upon leaving the nozzle, the hot gases would impinge upon the molten metal produced by the arc and would atomize it and project the particles at a much greater velocity than is the case when compressed air alone is used.

4.1.2 Possible applications.

Such a device would have specialised applications, in that it would offer some of the benefits of plasma spraying except that only conductors could be sprayed. One use would be for cladding mild steel vessels against corrosive attack in the chemical industry. If such a system could be made to work then the potential market is very large indeed. Similarly, the application of anti-fouling coatings to the hulls of ships is a large market which would be available if sufficiently impervious coatings could be produced.

4.1.3 Advantages.

1/. The system might produce coatings which were denser, stronger and with a greater adhesive strength than arc-sprayed coatings.

2/. If suitable shrouding can be arranged and the gases can be made to be reducing then it may be possible to reduce the loss of alloying elements from particles and reduce oxide levels in the coating.

4.1.4 Disadvantages.

1/. More heat would be produced in the substrate making the system inapplicable for spraying onto delicate substrates as in mould manufacture or screening.

2/. If, as is likely, the gases cannot be made reducing, then increased alloying element loss and oxidation may result.

4.1.5 Cost.

The capital and operating costs will both be raised as follows:

1/. Production cost raised by between £1000 and £1500

2/. Operating costs raised by around £5.00/hr.

4.1.5 Summary.

The above device has a potential market which is limited in scope but nevertheless very large if there is a sufficient increase in the coating quality. If however the coating quality falls short of that required for corrosion protection, then the market is severely reduced and the device is unlikely to remain a viable proposition.
Unfortunately at this stage, the properties of the coating cannot be predicted.

This system would not replace either flame or arc-spraying but would complement arc-spraying and extend its range of application.

4.2 Melting by Induction Heating.

4.2.1 Envisaged design.

The following is a brief description of the proposed design. The complete system would comprise:

1/. A pistol similar in size and shape to a flame spray pistol, consisting of a single wire drive and a melting and atomizing head. This head would contain the induction heating coil through which the wire would be fed. As the wire melted a small amount of air would transport the molten material out of the coil and into a stronger atomising gas stream. This would then atomise and project the particles. A "matching capacitor" would be fitted to the pistol allowing flexible leads to be used to carry power to the induction coil.

2/. A generator providing about 5kw at the terminals. This would be in a box approximately 500mm x 500mm x 250mm.

3/. A cooling sytem comprising a water tank, pump and heat exchanger. This would be very similar to a car radiator in size.

4.2.2 Possible applications.

Such a device would fulfil many of the functions of arc-spraying except where high throughput is required especially where high conductivity materials such as aluminium or copper are to be used. Due to the low throughput it would not be competitive in anti-corrosive work. The most likely applications are in higher quality engineering coating and in light work such as screening or mould making.

4.2.3 Advantages.

1/. The melting process would be smoother and less violent. The spraystream should therefore be more amenable to collimation and hence to acceleration within a nozzle. This may allow a greater efficiency of acceleration of the particles, giving rise to increased particle velocities and fewer particles which had not been properly accelerated. This would in turn lead to higher quality coatings.

2/. Particles would be less superheated than with arc-spraying so that fume, oxidation and loss of alloying elements would be reduced.

3/. It would be possible to spray using inert gases or perhaps a high velocity stream as in 4.1 above.

4/. The drive would be simplified since only one wire is used.

5/. No ultra-violet radiation is produced by induction heating.

6/. The heating process is virtually silent.

7/. A single phase ac supply might be used.

4.2.4 Disadvantages.

1/. The need for a water cooling system which might impair mobility.

2/. The process is not well suited to the spraying of high conductivity materials and spraying rates would be low. However steels would be sprayed at a rate similar to that of a flame wire pistol.

3/. The pistol may be slightly bulkier than a flame wire pistol due to the need to mount the matching capacitor near to the head.

4/. Some effects peculiar to arc-spraying may be lost e.g. the high bond strength of nickel/aluminium.

4.2.5 Cost.

1/. The capital cost of the system would be about £1500 if made in house or £3750 if bought in from a recognised manufacturer. A heat exchanging system might add around £500.

2/. Running costs would be very similar to arc-spraying but it must be remembered that the throughput is much reduced.

4.2.6 Summary.

The envisaged system would fill a market falling between the portability of flame spraying and the throughput of arc-spraying but possibly allowing for a better coating than either. It offers considerable advantages in ease of use and the reduction in noise, dust and fume and radiation. It would produce a more controllable spraystream and allow combination with inert or reactive atmospheres. Unfortunately it suffers from a lack of throughput, especially with high conductivity materials. It would also carry a slightly higher capital cost than an arc-spraying unit. This would not replace either arc or flame spraying since both possess attributes such as throughput and ceramic spraying, which would not be possible with induction spraying.

4.3 Close Automatic Control of the spraying system.

4.3.1 Envisaged design.

The control system would comprise:

1/. A microprocessor system receiving and transmitting information and control signals from and to the rest of the system. This would take in information as to the levels of parameters and the instructions of the operator and output signals to control the parameters.

2/. A sensing sytem translating information such as wire speed, voltage etc. into a form which is meaningful to the microprocessor.

3/. The means to control the given parameter, e.g an electronically driven voltage control.

The system would operate either as a static means of ensuring that the correct parameters are set, or as a dynamic system responding to changing requirements. In particular the arc voltage might be controlled such that in the event of an arc instability being imminent, say due to wire movement etc., the voltage would be temporarily raised to compensate for the increased arc length thus averting the instability and allowing the absolute minimum of voltage to be used.

4.3.2 Possible applications.

Such a control sytem would allow arc-spraying to be used where inconsistncy of coating properties caused by human error prevented its use, or where programmability would allow the coating properties to be closely controlled. This would be of most importance in industries where the cost of coating failure is high e.g. shipping, process plant and military applications.

4.3.3 Advantages.

1/. Faults arising from operator error would be largely eliminated.

2/. Programmed sequences, such as might be used to control residual stress, may easily be implemented.

3/. Where faults occur in the system such as falling supply voltage, low air pressure, running out of wire etc., warning messages could be output to either the operator or a larger control system.

4/. If dynamic voltage and spray rate control is implemented the operator need only load the wire and switch on. The system would spray at a pre-determined rate and at the minimum stable voltage.

5/. Interfacing the spraying system to other devices is made very simple.

6/. In some instances a less experienced operator could be used thus reducing labour costs.

4.3.4 Disadvantages.

1/. Reliance upon automatic systems may encourage users to reduce the quality of operator to an unacceptable level.

4.3.5 Cost.

The cost of the sytem depends largely upon the level and scope of control required. In view of the savings involved in removing the present manual controls, a system capable of controlling the voltage and monitoring and displaying the voltage, spray rate and atomising air pressure would have a production cost of around £200, ignoring tooling and development costs. To add control of the air pressure would cost about £150 and a similar amount would be required for current control.

4.3.6 Summary.

A microprocessor based system would offer the possibility of removing almost all operator error. It would also simplify interfacing to, and control of, other devices. In addition sequences may be programmed which would allow control of coating properties such as surface finish or residual stress.

However in many cases, such a system would not offer technical advantages over correct selection and training of the operator. Since many users prefer to forego this selection and training in order to save money, they may be unwilling to pay more for a system which is not absolutely essential. On the other hand, the incorporation of micro electronics is seen by some potential customers as a sign that the equipment is tecnologically up to date.

4.4. The selection of a device for development.

Each of the three options was assessed using the following criteria.

1/. The likelihood of a successful technical outcome within the project time.

2/. The technical and commercial benefits of the device.

3/. The resources of the company in terms of technical support, production capabilities and the ability to market the product effectively.

4.4.1. The high velocity burner.

This was assessed as being difficult to achieve, particularly in view of the low cost that was required of the final product. On the other hand a parallel technology had been successfully used in powder spraying in the "Jet-Kote" system. Nevertheless there were several fundamental differences between the envisaged design and "Jet-Kote", so that technical success was by no means certain. Furthermore partial success would be of no value, only if the coatings were a significant improvement over arc- sprayed deposits would the device be useful. However if successful, the system might offer coatings that were hitherto unavailable. It would not require many applications for these new coatings to make the system viable. In addition, the product would be patentable so that the fruits of the development work could be protected. Since the product was in some ways a marriage of two technologies with which the company was familiar i.e. flame and arc-spraying, no problems were envisaged in the support and marketing of the device. However, as with any new product in this area, there would be a period in which information must be found about the suitability of the process for any particular application and this means that initial sales might be slow until such an application base was established. In summary, this device was thought to be a high risk project with possibly high benefits.

4.4.2. Induction melting system.

This was also thought to have problems in reaching a successful technical outcome and had the added disadvantage of being a technology with which the company was unfamiliar. However, some of the envisaged benefits such as low noise levels and lack of ultra-violet radiation, made the system very attractive to the sales department at Metallisation who were continually faced by customer resistance to the environmental problems of arc-spraying. On the other hand, the low throughput rates would have made the coatings commercially uncompetitive.

4.4.3. Automatic control of Arc-spraying.

Such a system could have been implemented in several stages, ranging from simple monitoring of the parameters through to complete automatic control of the dynamic processes. Thus in this way, even if, for instance, real time voltage control was not achieved within the project, the company would still have tangible benefits in improved and up to date controls. At this time the company has virtually no experience of micro-electronics and this might be seen as a negative aspect of this option. On the other hand some would see increased awareness in this field as essential and the choice of this option as a productive inducement to become involved. However, the system does not offer much that could not be achieved by careful use of a manually controlled system and opinions differred within the company as to the marketability of such a system.

4.4.4. Other options.

It should be noted that there were other possibilities for investigation such as inert gas arc-spraying, low pressure arc-spraying, single wire arc-spraying and plasma devices which had been ruled out at that time either because other workers were already involved on Metallisation's behalf, or because the project would be too costly to execute.

4.5. The final selection.

A supervisors meeting was held in October 1984 and these matters were resolved after much discussion. The technical novelty and the possibilities of higher quality coatings made the high velocity burner system very attractive to the technical management at Metallisation and this option was selected.

Having chosen this system, the requirements of the design and the constraints upon it are discussed below.

4.6. Design requirements.

The fundamental purpose of the burner is to provide a high energy gas stream with a geometry suitable for using with the arc-spray system. This would accelerate the spray particles to higher velocities, giving a greater impact stress and lowered porosity. It follows that the gas stream must not only have a high velocity, but also have a geometry which fulfils the requirements of particle atomisation and arc stability.

The burner was originally intended to operate with the same mass flow rate of compressed air as a standard pistol, except that the gases would be at a higher temperature and possess a much greater velocity. As a first step it was envisaged that the maximum gas temperature would be around

1200K, giving a possible velocity of around 1400 m/sec. The temperature was to be kept this low to ease any problems of constructional material survival, although it was appreciated that the higher the temperature the higher the gas velocity and the possible particle velocities. For instance a gas temperature of 1800K would theoretically allow a maximum gas velocity of around 1700 m/sec. The standard system has a gas temperature of around 300K giving a maximum possible velocity of 700 m/sec although in practice only 450 m/sec is achieved. At the same proportion, 900 m/s would be achieved at a temperature of 1200K.

It was intended that the operating volume of the jets should be similar to that of a standard system, except that the gases contained within that envelope would be hotter and travelling at much higher velocities. An examination of total pressure across the nozzle of a standard head show that the pressure is at its maximum at a distance of 2 or 3 millimetres above and below the pistol centre line and that an area of reduced pressure exists on the centre line. The purpose of this depressed area is to control the energy used to sweep molten metal away from the rear of the arc zone. If insufficient energy is devoted to this task then the arc becomes unstable and large globules are produced rather than the normal smooth and continuous atomization process giving smaller droplets. If this area is swept too well the arc can become extinguished by the force of the blast, once again leading to instability. For this reason, the nozzles for the high temperature system were designed to produce a similar jet pressure profile.

4.7. Design constraints.

The constraints upon the design were as follows:

Firstly the device had to fit its intended cost/performance niche. In other words there would be no point in producing something at higher cost than a plasma system, which gave inferior performance. It was felt that if the manufacturing costs of the system rose by no more than £1000.00 and the running costs were held to around £10.00 /hr plus labour and material, then the system would be very competitive, assuming adequate coating quality as discusssed in section 4.1 above.

Secondly, if costs were to be kept down, it must be compatible with existing arc-spraying equipment. In particular this imposes a restriction upon the external diameter of the burner and upon the dimensions of the nozzle as shown in fig 18, in other words the diameter must be less than 50mm and the nozzle should be small enough to be positioned at around 12mm behind the arc point. Furthermore, the complete device should be able to spray the standard range of materials, preferably using standard sizes of wire.

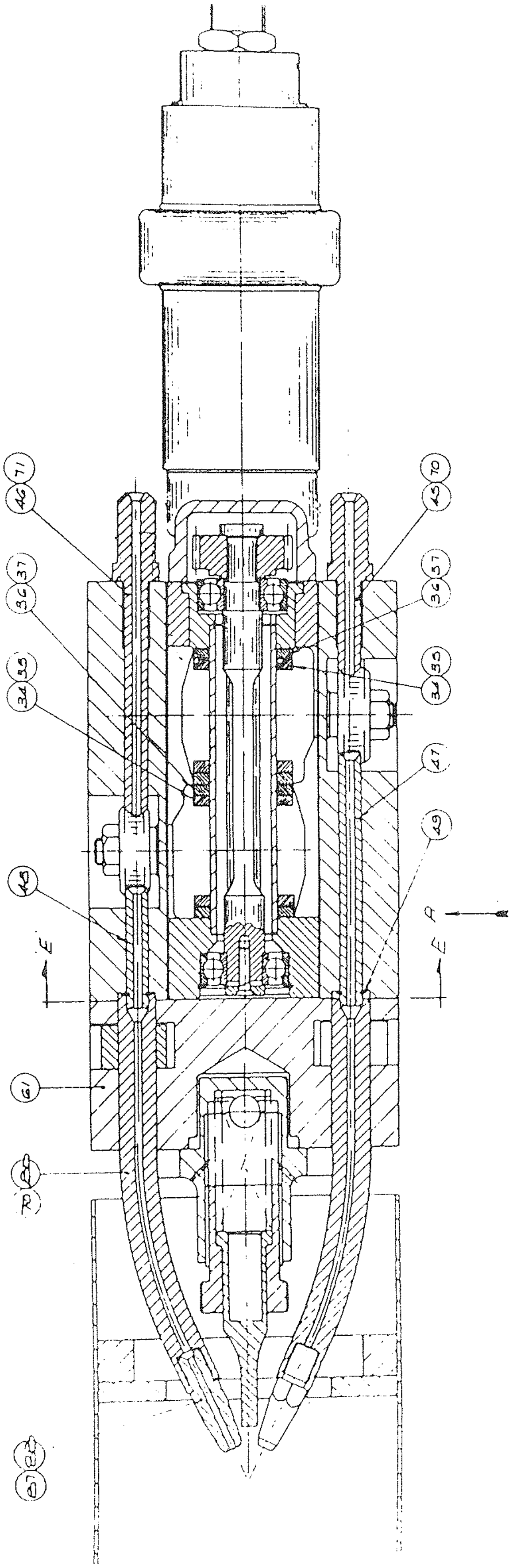

Figure 18. Horizontal section through Arc-spray 400 pistol.

Note. Pitch of contact tubes 79 & 80 is 2.5 inches.

Thirdly, the device might be potentially very dangerous in that mixed fuel gas and air are used and very hot gas streams and surfaces exist. Therefore it would be important to produce a device which was safe to use and complied with health and safety regulations.

Fourthly, due to increased pressure of work on a reduced technical staff, the company would be able to devote very little in the way of support effort to the development of the device, apart from the purchase of essential items that could not be self produced. Apart from occasional discussions, the student would be the only person working on the project. Similarly, the project did not have any budget allocated to it other than the required payments to the University and the student.

Experimental and Development Techniques

5.1. High velocity burner development.

The following section outlines the development of the high speed propane/ air burner. The principle stages in which this took place are summarised in the table below. The reasoning behind each stage and the outcome of a change are explained in more detail in the text. During the development phase, the criteria by which the burner was judged were the mass flow rate, flame stability and the durability and safety of the unit. Details of the design calculations for many aspects of the burner are contained in the text.

1/. A Ram-Jet device with a single jet and steel nozzle, using secondary air.

2/. Modifications to the pre-mixing area and gas injector.

3/. Enlargement of the burner, both in length and diameter.

4/. Abandonment of the Ram-Jet system in favour of a hot walled rocket.

5/. Testing of the burner stability with various positions of the tube bundle.

6/. Testing of the burner using mullite, porcelain and fused silica tube bundles.

7/. Making the device usable for arc-spraying.

8/. Testing of the burner stability using short, medium and long nozzle assemblies.

5.1.1. The Ram-Jet design.

In principle a ram jet is a very simple device in which fuel is injected into an airstream and ignited. The resultant hot gases expand through the nozzle to produce thrust. The energy of combustion of the fuel is transferred into increased kinetic energy of the airstream. In more normal circumstances, flames within larger ram-jets may be stabilised up to a Mach number of around 0.1. Thus a device was designed to operate with a combustion chamber Mach No. of 0.08 approximately, and at a pressure of 0.4MPa gauge, as shown in figure 19. A single jet, steel nozzle was chosen for simplicity and ease of manufacture although, even at this stage, a two-jet ceramic nozzle was envisaged to provide the correct gas stream geometry for the final device. A stream of secondary air was used to cool the burner walls and allow adjustment of the exhaust gas temperature by dilution. The path of the secondary air was chosen to provide a relatively cool boundary layer on the walls of the nozzle.

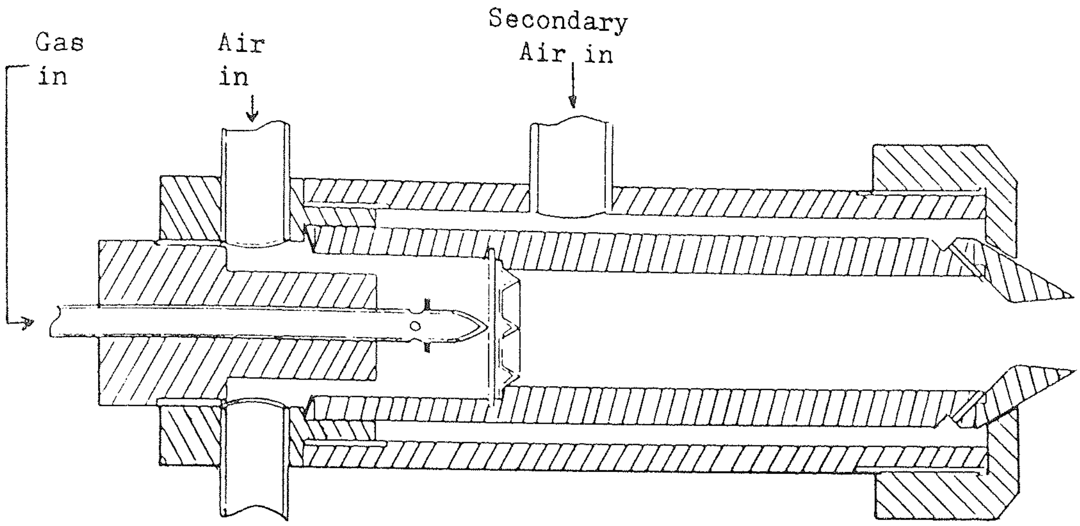

Figure 19. First ram - jet design.

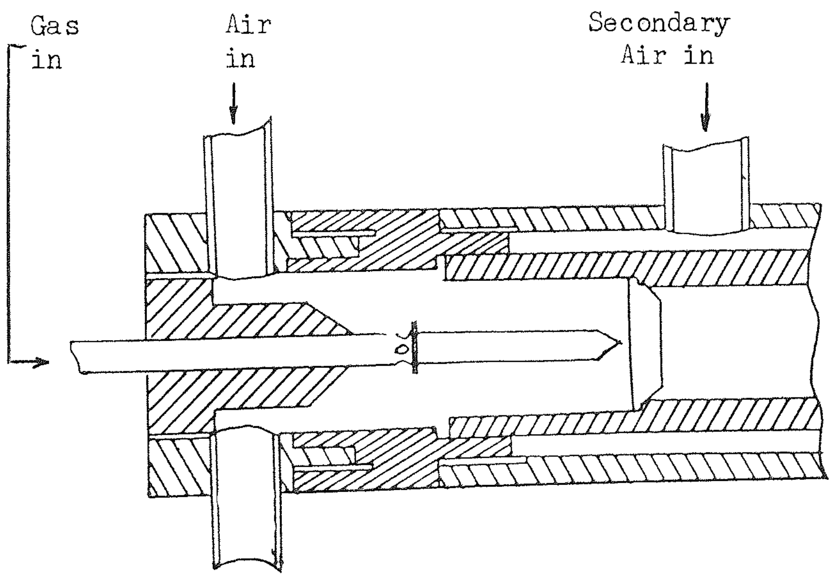

Figure 20. Improved ram - jet design.

5.1.2. Modifications to the ram-jet.

Upon testing the burner shown in figure 19, it was found that stable flames could only be maintained at less than 25% of the design air flow rate, with a chamber pressure of less than 0.1MPa . It appeared that combustion was taking place at the exit from the nozzle rather than at the gutter stabiliser as was intended. This was attributed to poor mixing of the gases in the chamber and the gas injector was modified to allow easier contact between the incoming gas and air streams. The effect was to increase the general stability of the flame up to its previous flow limits and to marginally improve the maximum flow. To further increase the quality of gas mixing, the chamber was extended to three times its original length, but the effect upon the maximum throughput was very slight. To ensure adequate mixing, the gases were pre-mixed before inlet to the burner, but without a significant improvement. See figure 20.

It was thought that the instability may be a transitional phenomenon. Until the nozzle becomes choked, the pressure in the combustion chamber will be low, with a correspondingly high gas velocity. If back pressure were applied to the combustion chamber, by means of a throttling valve, the internal velocities during the unstable phase would be reduced thus improving stability. When the design conditions were reached, the device might once more be stable and the throttling chamber could be removed. For this reason a throttling chamber was designed and built.

5.1.3. Enlargement of the burner.

It became apparent that the original premise that flame stability could be achieved at a Mach No. of 0.1 was not appropriate, so an enlarged burner, intended to reduce the gas velocity by a factor of four, was designed. However for reasons explained below, the enlarged ram-jet was never built.

5.1.4. The hot-wall rocket (H.S.G. burner).

From a very early stage, advice had been sought from sources outside the University, such as various burner manufacturers, British gas and Calor gas development, as to whether suitable proprietry burners might be available, as well as looking for suggestions as to suitable design types.

Unfortunately the device requirements appeared to be well beyond the scope of normal burner performance. However during the period in between designing and manufacturing the enlarged burner, a colleague suggested contacting a burner hobbyist, David Read, who builds rockets, ram-jets and pulse-jets in his spare time. He was of the opinion that the required result could not be achieved using the ram-jet concept, and laid out some general principles for building a hot-walled rocket. Armed with this information a rocket was designed and built as shown in figure 21.

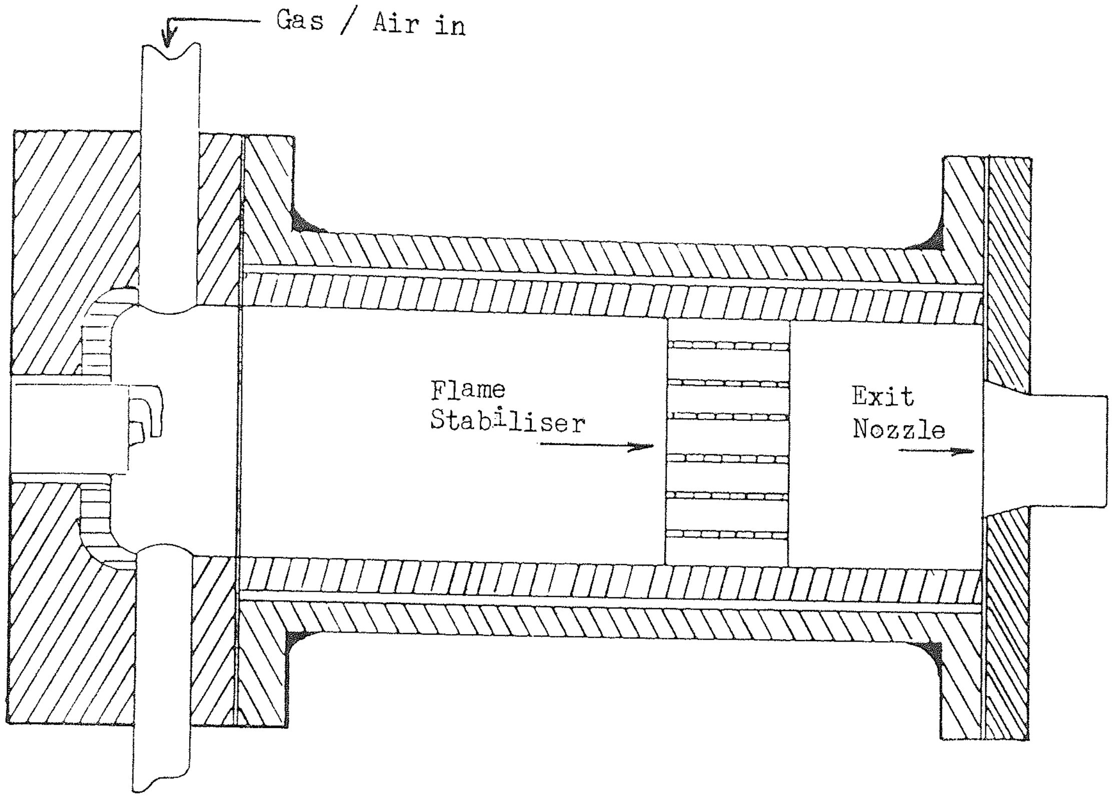

Figure 21. First hot wall rocket including nozzle.

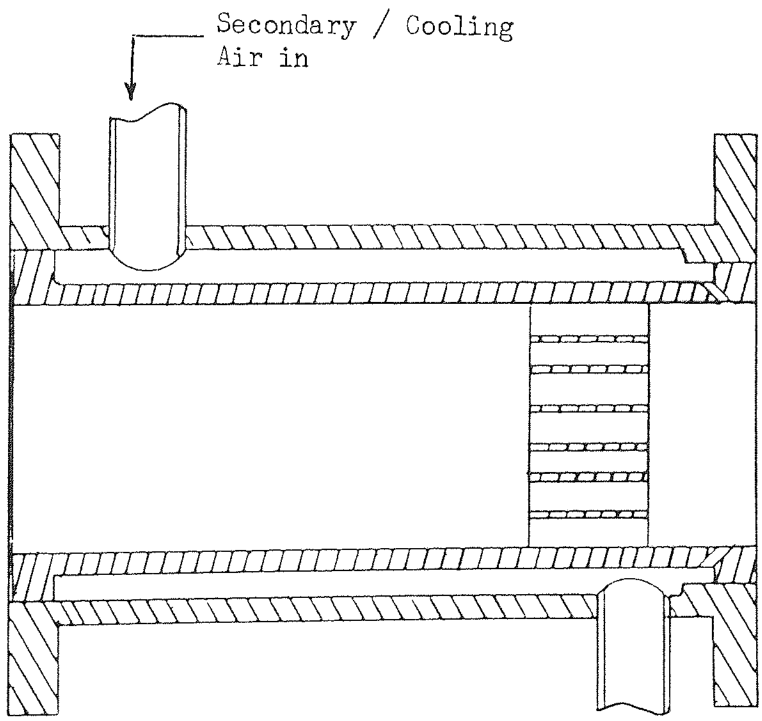

Figure 22. Modified hot wall rocket combustion chamber.

This first device used a liner and tube bundle made from mullite tubes bonded together with high temperature cement. To provide extra turbulence and mixing of the burning gases the injector ports were arranged at a slight angle to the radial direction. This imparted a tangential velocity component to the gas giving a swirl number of 0.4 approximately. It was also important that the pre-mixed gases should not ignite back down the supply lines and so the injectors contained a restricted section. At this point, the gas velocity was many times higher than the flame speed, so preventing burn back. The calculations upon which the injector sizes and angles were based are shown below.

It can be shown that for orifices opening into relativley large spaces the pressure drop incurred = $\rho \times v_1/2$ where v_1 is the velocity and ρ is the density of the gas at the exit plane.

Now mass flow $m = \rho A_1 v_1$ Taking a mass flow of 4.2e-3 kg/s and an outlet diameter of 9 mm giving A_1 = 6.36e-5.

Density $\rho = P/(R \times T)$ Taking an operating pressure of 5 bar abs and an inlet temperature of 300K

$$\rho = 5e5/(287 \times 300) = 5.8 \text{ kgm}^{-3}$$

$$v_1 = 4.2e{-3}/(5.8 \times 6.36e{-5}) = 11.4 \text{ m/s}$$

and $$dP = 5.8 \times 11.4^2/2 = 375 \text{ Nm}^2$$

Repeating the exercise for the restrictor opening into the injector.

$$dP = \rho(v_1 - v_2)^2/2$$

If the pressure drop is to be no more than 0.3e5 Nm^{-2} and the gas temperature and density are constant, then:

$$0.3e5 = 5.8(v_1 - 11.4)^2/2$$

Rearranging and calulating

$$v_1 = 113 m/s$$

Now $\quad v_1/v_2 = A_2/A_1 = (d_2/d_1)^2 = 11.4/113$

Thus $\quad d_1 = (11.4/113)^{0.5} \times 9 = 2.85$ mm.

Having established the larger injector size and the size of the restriction to calculate the swirl number and hence the injection angle:

The axial velocity $v_a = m/(\rho \times A)$ where A is the cross sectional area of the main burner chamber which has a diameter of 32 mm. This results in an axial velocity v_a of approximately 1m/s.

The tangential component v_t of the injection velocity is that velocity multiplied by the sin of the injection angle θ:

$$v_t = v \times \sin\theta$$

For a swirl number of 0.4

$$v_t = 0.4 \times v_a = 0.4$$

Thus $\quad v_t/v = \sin\theta = 0.4/11.4 = 0.035$

and $\quad \theta = 2.0$ degrees

Summarising, each injector has a diameter of 9mm with a restriction of 3mm, drilled at an angle of two degrees to the radial to acheive a swirl number of 0.4.

This device was immediately stable in operation at flows from 15 to 50% of the design flow and over a range of air fuel ratios. Ignition from the built-in spark plug was simple and undramatic, without explosive burn-back. Provided the air fuel ratio was maintained within limits, it was easy to raise the flow to the maximum stated above. Indeed the limit to flow was not the flame stability, but the amount of gas that the supply lines and flashback arrestors could pass. When the supplies were improved, the maximum flow level rose to approximately 80% of design levels and was limited only by the onset of sudden short pulses of loss of flame. The situation was improved if the A.F.R. was slightly rich, around 23:1 rather than 25:1 by volume. Since the original design flows were only nominal, it was decided that this flow rate would be accepted as sufficient. Since strong shock patterns could clearly be seen in the flame, the flow was certainly supersonic and the velocity was estimated at between 800 and 1000 m/s. With such an advance using the hot-wall rocket, the enlarged ram-jet design was dropped.

5.1.5. Testing for flame stability.

After several test runs, it was noticed that the shock waves had disappeared and the flow was no longer supersonic. Upon dismantling the burner it was found that the tube bundle had cracked away from the liner wall and had moved forwards to within 12mm of the nozzle assembly. This was causing undue turbulence at the inlet to the nozzle. However, when the bundle was returned to its original position the flame was unstable. To check the effect of bundle position upon stability and the achievement of supersonic flow, several bundles were made and tested at different positions. A position 15mm from the nozzle assembly flange was finally selected. The stability of the flame was also found to be dependent upon the swirl generated at the rear of the chamber, as the flame became difficult to stabilise when one of the flashback arrestors failed, cutting flow to one of the four inlet ports.

5.1.6. Testing various materials for tube bundles.

Because of long delivery times for mullite tube, the tube bundles were made of porcelain, cut from thermocouple sheaths. These were adequate for testing the burner geometry but softened, and in some cases melted, in use. Similar results occurred when fused silica tubes were used. Since mullite tubes had not melted, this establishes the internal temperature to be between 1700C and 1850C at the centre-line, falling to below 1700C at the liner wall where no tubes had melted. The temperature within the flame, at a distance of approximately 10mm from the nozzle front, was measured as 1450C using a Platinum/Platinum,Rhodium thermocouple.(This reading will be low since no compensation has been made for radiation losses).

5.1.7. Making the device usable for arc-spraying.

Having established that a burner could be made which would produce the required flows and be compatible with the general geometry of a conventional arc-spray pistol, two problems remained. Firstly, the temperature of the outer shell of the burner had to be reduced from around 650C to around 300C for both safety and structural reasons. Secondly, a nozzle assembly had to be produced which would comply with this first requirement and yet be small enough for the jet to closely approach the arc point of the pistol and make maximum use of the high velocities available.

Appendix 2 shows a theoretical appraisal of the likely heat transfer through the walls of the burner both by conduction and radiation, taking radiation and convection at the outer surface into account.

To reduce the rate of heat transfer to the outer shell, a ceramic liner with an air gap between the liner and the shell was made. Silicon nitride was chosen as the material, since it could be accurately machined to complex shapes, allowing the tube bundle and liner to be machined in one piece. In addition, radial drillings were made forward of the tube bundle so that pressure would be equalised between the air gap and the combustion chamber, and secondary air could be added to cool the flame if required.(see figure 22)

With the earlier design of rocket, in which the liner was cemented into the steel shell, it was a simple matter to evaluate the thermal resistance of each of the layers of material and hence to calculate the surface temperature after estimating the outer surface heat transfer coefficient. However, when the air gap was used the calculation involved radiation as the major mode of heat transfer across the air gap.

Since without knowing the temperatures of both surfaces one cannot determine the amount of heat radiated from one to the other, it was necessary to iteratively calculate the temperature of the silicon nitride liner outer and inner surfaces until a sensible value for the inner surface temperature was reached. This was actually done using a computer, but an example calculation is shown below.

T_1 = Inner wall temperature.

T_2 = Liner outer surface temperature.

T_3 = Shell inner surface temperature.

T_4 = Shell outer surface temperature.

T_5 = Surrounding air temperature.

R_1 = Resistance of Liner.

R_2 = Resistance of Air gap.

R_3 = Resistance of Steel shell.

R_4 = Resistance of outer surface.

Assuming a convective heat transfer coefficient of 15 W/mK at the shell surface and thermal conductivities of the steel and the silicon nitride to be 50 W/mK and 8 W/mK respectively then:

Let the surface temperature be 600K.

Radiative heat loss from surface:

$$Q = f_{4-5}\ F_{4-5}\ A_4\ s(T_4^4 - T_5^4)$$

f_{1-2} is assumed equal to e = 0.7 for steel.

F_{1-2} is assumed equal to 1 and T_5 = 300K

$$A_1 = \pi dl = \pi/200\ m^2$$

$$Q = 0.7 \times \pi(600^4 - 300^4) \times 5.67e{-9}\ /200 = 7.57W$$

Convective heat loss from surface:

$$Q = h(T_4 - T_5) \times A_4$$

$$= 15(600-300) \times \pi/200 = 71W$$

Thus total loss from surface = 78.5 W

Taking the shell as being thin walled so that the mean area is approximately equal to the surface area:

$$Q = k(T_3 - T_4) \times A$$

$$T_3 = Q \times k/A + T_4 = 699K$$

If Q = 78.5 and T_3 = 700K then to find the temperature of the radiating surface:

$$Q = f_{2-3}\ F_{2-3}\ A_2\ s(T_2^4 - T_3^4)$$

$$f_{2-3}\ 1/(1/e_2 + (A_2/A_3)x(1/e_3 - 1))$$

$$F_{2-3} = 1$$

$$A_2 = \pi \times 38e{-3} \times 100e{-3} = 12e{-3}\ m^2$$

e for steel = 0.7 and for silicon nitride = 0.4

Then $f_{2-3} = 0.364$

Re-arranging and calculating:

$$T_2 = 1374\ K$$

To calculate the inner surface temperature:

$$Q = k_1(T_1 - T_2)A_1$$

Re-arranging and calculating:

$$T_1 = 1480\ K$$

This is an acceptable value for the flame temperature.

This design also allowed cooling air to be passed over the liner surface and out through pipe connections in the steel shell. This liner was tested and found to be satisfactory in every respect but one. The flame was stable at flows up to around 90% of design levels, secondary air could be added so that the flame temperature could be adjusted and the rate of rise of temperature of the outer steel shell was much reduced. However after dismantling the burner to perform a routine check upon the state of the tube bundle, it was found that the liner had cracked along its length.

Figure 23. Cracked ceramic liner trapped
in outer shell.

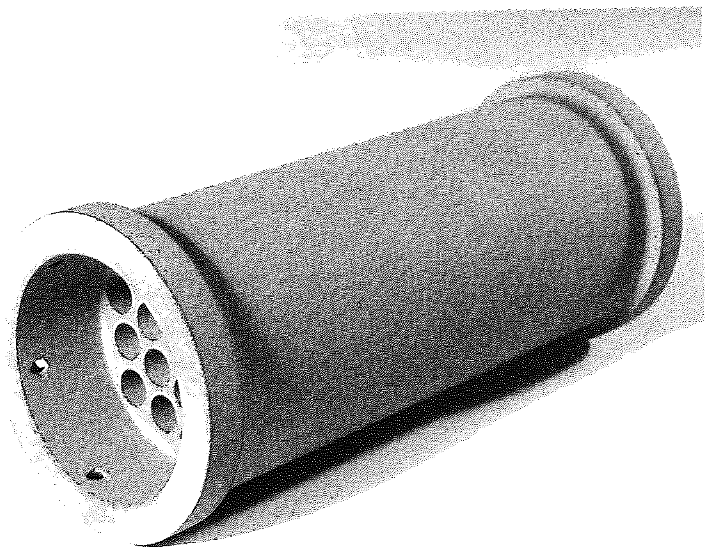

Figure 24. Original ceramic liner.

Experimental and Development Techniques

There are two possible modes of failure of the liner, either by thermal effects such as shock and heat cracking, or by mechanical failure caused by extreme pressure fluctuations or by differential thermal expansion of the liner and the outer shell. Early systems using a mullite liner suffered from the first form of failure and were also ineffective in preventing overheating of the outer shell. This was lessened by using a silicon nitride liner with a pressurised air gap between the liner and the steel shell.

The first such liner with an integral "stabiliser" was made to the same length as the steel shell. Taking into account the thickness of the gaskets at either end, this should have allowed for any mis-match in thermal expansion. However at the first trial the liner cracked longitudinally and, since the shell had not overheated, and considering the relative thermal cycles of the liner and the shell, the crack had probably ocurred as the burner was cooling.

Increasing both axial and radial clearances appeared to solve the problem, in that the liner was unaffected by thermal shock and the shell could be maintained at a reasonable temperature for sufficient time to produce sample coatings. This system worked well for perhaps an hour of intermittent operation but then failed by the liner cracking longitudinally. The liner was replaced and the new liner operated successfully for a time but again failed by cracking. This time it was clear that the rear of the liner had become trapped awkwardly by the outer shell. A small piece of debris was lodged between the liner and the shell and upon contraction this had induced a high point loading on the ceramic liner (See figure 23). For comparison an original liner is shown in figure 24. Since the rear of the liner was partially sealed by a ceramic fibre washer it may have been that the prevention of flow did not allow debris to be cleared from the mating faces. The debris was oxide scale from the steel shell. Improvements in the geometry of these mating faces may improve matters in that debris could be excluded or prevented from accumulating in this area thus affording less opportunity for stress concentrations. A change of shell material or a surface treatment such as aluminising may reduce the production of oxide. Nevertheless, the device as presently constituted appears to be adequate for test purposes although further work is required to give an acceptable lifespan.

5.1.8. Testing using short, medium and long nozzle assemblies.

To keep the front of the nozzle assembly at a reasonable temperature, a certain thickness of insulation material is required. However if the nozzle is to be placed as close as possible to the arc point then the whole assembly must be as small as possible. An intermediate assembly was made to check that the flame would remain stable with the diameter of the burner, tapering down as the nozzle was placed further away from the tube bundle. Flame sprayed Zirconia

3mm thick was used as the insulation and was very satisfactory, if awkward to apply and shape. A long nozzle assembly (figure 25) was then made which extended the previous assembly to a length suitable for arc-spraying. The steel wall and liner thicknesses were reduced to 3 & 2mm respectively, and the nozzle was fitted directly into the steel shell rather than being bedded in high-temperature cement.

Both the intermediate and long assemblies gave stable supersonic flames but with the long nozzle the shell temperature reached 900C at the very tip and about 400C at the base. It appeared that the wall thickness was insufficient to conduct the heat from the tip into the body of the nozzle assembly. The latest design as shown in figure 26 features both radial clearance and a buffer layer of ceramic fibre blanket around the nozzle. Furthermore the nozzle alone is elongated so that the carrier has a larger diameter and is more easily insulated.

The present design of burner provides a gas stream which is both hotter and faster than the original specification. The temperature and velocity of the gas-stream are adjustable and the flame is stable over a wide range of settings. However in terms of its survival and compatibility with arc-spraying systems there is still some work to be done.

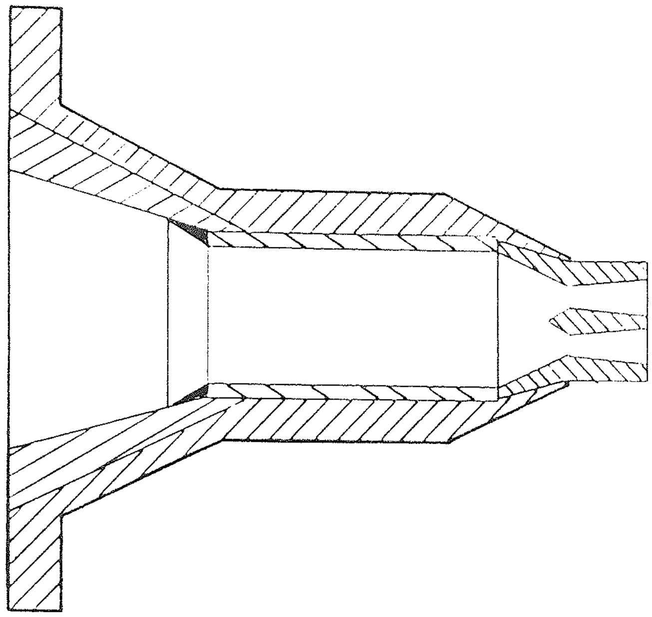

Figure 25. Long nozzle assembly.

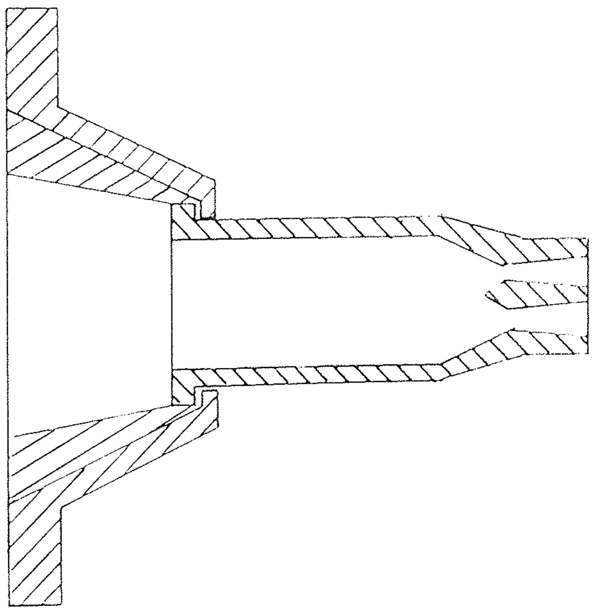

Figure 26. Final long nozzle assembly.

5.2. Burner Performance Measurement

The performance of the burner may be classified under headings of jet characteristics, reliability and the way in which it fits in with the operation of the arc pistol.

5.2.1. Jet Characteristics.

These may be defined as the velocity, temperature, composition and geometry of the jet.

5.2.1.1. Velocity.

The velocity at exit from the burner can be inferred from the geometry of the nozzle and the input pressures and flows of fuel gas and air if the following assumptions are made.

i. The nozzle has a fixed and known coefficient of discharge.

ii. All chemical processes are complete before entry into the nozzle.

iii. The composition of the exhaust gas is known.

iv. The mass flow rate into the system is known.

v. The process is assumed to be isentropic.

vi. The temperature of the exhaust gas at entry to the nozzle is known.

In other words jet velocity can be inferred from measurements of pressure and flow in the cold inlet flows upstream of the burner.

In practice, all of the assumptions are flawed to some extent. However, as long as the calculated values are to be used for comparisons of similar systems, the relative error will probably be acceptable. For instance, a change in polytropic index of the gases from 1.4 to 1.3, a very large change, results in only a 10% change in exit velocity.

The gas velocity may be measured at any point downstream of the nozzle exit using total pressure and total temperature probes. Inherent inaccuracies in such measurements, due to yaw & pitch of pressure probes, and radiation & conduction losses in thermocouples, as described in more detail by Gorlin and Slezinger (84) must be born in mind.

5.2.1.2. Composition of the exhaust gases.

If complete combustion, taking dissociation into account, is assumed, then the exhaust gas composition will be known if the air fuel ratio is known. If combustion is incomplete, then various amounts of carbon monoxide and free oxygen will be present. It is extremely unlikely that hydrocarbons will still be present. Density and viscosity are not very sensitive to gas composition since the properties for each species are very similar and close to those of dry air. Furthermore, the properties of the exhaust gases are dominated by the high nitrogen concentration. A simple assumption used in this work is that, as the mixture is weakened, at the air/fuel ratio (A.F.R.) at which the flame becomes invisible, the combustion is complete. This has been the setting at which most spraying has been carried out.

5.2.1.3. Jet geometry.

The velocity and temperature distribution within the jets outside the nozzle may be modelled using correlations produced by Forstall & Shapiro (44), which are shown to be accurate when applied to the cold jets of normal arc-spraying equipment. A distribution of this sort was used in the computer program upon the results of which, the physical device requirements were based. The velocity and temperature were measured at several points within the flame to find whether the assumed model was appropriate. The total pressure was measured with a fused silica probe and the temperature by means of a Pt/Pt,Rh thermocouple positioned within a fused silica shroud to reduce losses due to radiation.

5.2.2. Reliability.

The reliability of the device may be expressed in two ways.

Firstly, whether the same output in terms of the jet is produced each time it is used, and secondly, whether the device survives for a reasonable length of time. Both are discussed below.

5.2.2.1. Output consistency.

The burner output has proved to be generally consistent, except when the gas supply is low in pressure or when one of the flashback arrestors has failed. The repeatability is shown by the fact that similar input pressures produce similar flow rates as measured by the flowmeters.

5.2.2.2. Device survival.

The surface temperature within the burner must be maintained at around 1800 degrees Celsius whist keeping an outer wall temperature of around 300 degrees or less. The problem is compounded by the restricted space available between the contact tubes of the pistol. The outer wall temperature was measured using a Minolta Total radiation pyrometer. A surface temperature of 600 C was chosen as a maximum safe level and the time taken to reach this temperature was used as a measure of the insulating qualities of the burner wall.

Where components have failed during service, an estimation has been made of the operating time and the mode of failure.

5.3. Coating Production Techniques.

Coatings have been produced on three forms of substrate and using various spraying parameters, depending upon the purpose of the tests for which the sample was produced. Unless otherwise stated the coating material was Metallisation 60E 420S45 steel.

5.3.1. Samples showing effect of varying flame parameters.

Spraying was carried out at a fixed range of 165 mm and at various flame settings as shown in table 5 below.

Table 5 H.S.G. Burner Parameters

Run No.	Air Pressure p.s.i.g	Air Flow l/min	Gas Pressure p.s.i.g.	Gas Flow l/min	Air/ Fuel Ratio	By-pass Air
1	70	583	65	20	29	High
2	62	583	65	13	44	High
3	60	547	65	2	27	Low
4	56	559	60	13	43	Low
5	35	335	40	13	25	High
6	29	314	31	8	39	High
7	32	324	35	13	24	Low
8	28	310	30	7	44	Low

Samples were produced according to a three variable two level factorial plan, the variables being mass flow , volumetric air/fuel ratio and high or low by-pass air. These test pieces were produced using 2.3mm diameter 420 S45 steel wire and sprayed on to 150 mm diameter cast steel pipe at a range of 165 mm. Successive samples were sprayed on top of each other with a thin layer of flame sprayed bronze in between to delineate sample boundaries. These samples were primarily for sectioning and metallographic examination.

5.4.2. Samples showing the effect of spray range.

Subsequently, samples were produced for bend tests and for porosimetry and all coatings were produced using a flame setting as for run number 2 above, with range being the altered variable. Samples were produced on 1" x .125" x 3" steel strip for bend tests and on 15 mm o.d. copper tube for tensile testing and intrusion porosimetry.

The samples for the bend tests were produced according to the following plan in table 6.

Table 6 Bend test coatimg parameters.

Sample No.	Range(mm)	Current	Voltage
1	25	250	26
2	50	"	"
3	37	"	"
4	62	"	"
5	75	"	"
6	100	"	"
7	62	"	"
8	87	"	"
9	112	"	"
10	137	"	"

A single shot, traversing rig was used and the samples were cooled by a jet of carbon dioxide vapour using a 4 second spray/ 6 second cool cycle. Samples 7 - 10 inc, were sprayed in several passes, indexing the pistol in between passes to try and achieve an even thickness over the testpiece.

The samples for porosimetry and tensile tests were sprayed onto 15 mm copper pipe in a single pass so that coatings of the highest possible integrity of both H.S.G. and standard arc-spraying could be tested. Coatings of approxiately 3 mm thickness were deposited at a current of 100 Amperes and a throughput of around 4.5 kg/hr. H.S.G. coatings were produced at ranges of 75mm and 125mm and standard arc-spray coatings were produced at 75mm range only. Each sample was triplicated. The coatings were cooled with a jet of compressed air impinging on the workpiece on the same line but at right angles to the spray-stream.

Samples produced with the H.S.G. burner at 75mm and 125mm range were labelled HGA and HGB resectively and those produced by the standard system were labelled ST. In addition each sample was labelled with the run number i.e. ST2 or HGA3 etc.

5.4. Coating Testing Techniques.

A series of tests were carried out to determine the various properties of the spraying system and the coatings it produced.

1/. Sprayabilty trials to find the limits of operation.

2/. Macro and micro hardness of H.S.G. 60E coatings, variability with range and flame parameters.

3/. Comparative cohesive strength measurements by three-point bend test and some S.E.M. examination of fracture faces.

4/. High speed cine-filming of H.S.G. spray to determine particle speed.

5/. Porosity determination by visual examination/ immersion in toluene.

6/. Oxidation levels by visual examination.

7/. A brief investigation of H.S.G. spraying of alternative materials such as aluminium and nickel alloys.

8/. Tests to determine heat transfer to the substrate.

5.4.1. Spraying trials.

Prior to the production of the testpieces, various spraying parameters were tried to find the range of stability of the system and to examine the general appearance of the spraystream. The voltage, current and the gas flowrate and air/fuel ratio were varied.

5.4.2. Macro and micro hardness testing.

Macro hardness tests were performed using a Vickers testing machine at a 30kgf load on ground surfaces normal to the substrate. Micro hardnesses were measured on transverse sections of coating, using a Vickers photoplan microscope fitted with a pneumatic indenter . A test load of 20 grams was employed.

5.4.3. Cohesive strength testing by three point bend test.

During some preliminary trials it was found that the number of cracks depended greatly upon the thickness of the coating. In thin coatings several parallel cracks occurred but thicker coatings produced a single crack followed by peeling along the interface. This demonstrates that the nature of the failure indicates the relative strengths of the coating in cohesion and adhesion. A single crack indicates that the cohesive strength within the coating is large compared with its adhesive strength onto the substrate. The change in behaviour with thickness arises because the adhesive strength is fixed by spraying conditions, but the cohesive strength rises with thickness. For standard arc-sprayed 60E, the transition from multiple to single crack occurs at around .020" and this was chosen as the test thickness. Coating thickness varied from .017" to .025" in the worst case. Testing was carried out in an Instron machine using a crosshead speed of .05 cm/min. The test rig employed 1" rollers spaced at 50mm.

5.4.4. Direct tensile tests.

In view of the limited information which the bend tests produced, direct tensile tests were carried out to determine U.T.S. and Youngs modulus of whole coating samples. Firstly the coating to be tested was sprayed onto a 150mm long, 15mm od Copper pipe to a thickness of 3.5mm. and ground to 20.5mm finished diameter. A ring approximately 8mm long was removed for porosity testing and the remainder was slit into four sections using an abrasive cut off wheel fitted to a tool grinder. Each section was fitted with shaped aluminium adaptor pieces as shown in figure 27 overleaf, so that flat wedge grips could be used without distorting the testpiece. A foil strain gauge, with properties shown in table 7 overleaf, was glued to the central region of the piece.

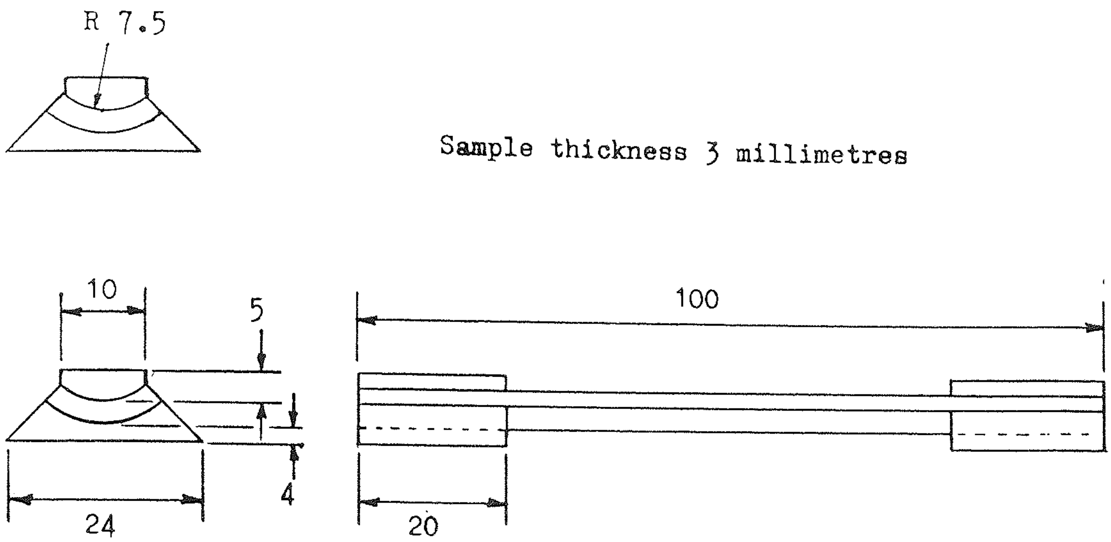

Figure 27. Direct tensile test piece.

Table 7. Strain Gauge Properties.

TYPE.	FLA - 6 - 11
GAUGE LENGTH	6 mm
RESISTANCE	120 0.03
GAUGE FACTOR	2.12
MANUFACTURER	TOKYO SOKKI KENKYUJO
LOT No.	152711

These adaptors were also designed so that the centroid of the test section was on the centre-line of the wedge grips. An Instron 1197 50 ton test machine was used, set to a maximum load of one Tonne and a crosshead speed of 0.2 mm/min. A Tinsley 5792 strain gauge amplifier was used in combination with the load cell output from the test machine to drive an X-Y plotter and produce load / strain curves. After tensile testing some of the fracture faces were examined using a scanning electron microscope.

5.4.5. High speed filming of H.S.G. spray.

This was carried out using a Fastax camera with a peak frame speed of 8000/sec. Three films were produced at varying spraying parameters. Particle velocities were found by measuring streak lengths on single frames. The film also allowed closer examination of the general appearance of the spray stream.

5.4.6. Porosity determination by visual examination

The coatings produced by H.S.G. are finer than standard arc-spray and thus determination of porosity by direct observation and estimation was considered impractical. A system exists which views a polished sample through a video camera and divides the image into 64 grey levels. By manipulation in a micro-computer one can find the percentage of the image which is darker than a pre-set level. Since porosity appears black it is possible to find the area percentage of porosity. The principle difficulty is in preparing samples without smear, which reduces porosity, or pick-out where porosity is over estimated.

5.4.7. Porosity determination by toluene immersion tests.

The samples produced for the bend tests were awkward for hydrostatic porosity testing. In order to raise the sample weight several layers were processed together but this created areas which trapped air and prevented a true weight under liquid being found. The rings from the tensile test pieces were much easier to use. These were boiled in Toluene for one hour then left overnight for absorption to be complete. Each sample was then weighed under toluene without being exposed to the atmosphere. The samples were then dried in an oven at 105 C for a further hour and allowed to cool before re-weighing. Valve grease, as used on laboratory glassware, was smeared lightly over the entire sample surface and the excess was removed with a clean tissue. Thus waterproofed, the samples were weighed first in air and then in water before finally cleaning away the grease with acetone. The apparent density of the deposit with and without open pores may be determined in the following way.

$$\text{Density inc. open pores} = \frac{Dew \times Ma}{Ma - Ww}$$

$$\text{Density not inc. open pores} = \frac{Det \times Ma}{Ma - Wt}$$

Where Ma = Sample weight in air

Ww = Sample weight in water

Wt = Sample weight in toluene

Dew = Density of water

Det = Density of toluene

To find whether the toluene had penetrated the full depth of the coating the ring samples were ground from 20.5 mm to 18.5mm and to 17mm and the test repeated at each stage.

5.4.8. Porosity determination by mercury intrusion porosimetry.

A further technique known as Mercury Intrusion Porosimetry was also employed, as this can give not only the total connected porosity but also the size of the pores subject to the following assumptions.

1/. The pores are cylindrical.

2/. The material under test is not wetted by, nor reacts with, mercury.

3/. The pores are independent and non interactive.

When applied to sprayed metal coatings assumptions 1 and 3 are almost certainly invalid but this will only affect the absolute values measured still allowing the technique to be used to compare porosity levels. For 60E assumption 2 seems to hold but would not for many other metals.

5.4.9. Oxide levels by visual examination

A qualitative view of the oxide present was obtained by examination of metallographic samples and a more quantitative assessment was attempted using the computer vision system mentioned in 5.4.6. above.

5.4.10. H.S.G. Spraying of alternative materials

Aluminium was sprayed and produced a very fine textured coating. The level of glare was much reduced especially at low throughput rates. 80/20 Nichrome was sprayed satisfactorily.

5.4.11. Thermal input and residual stress.

In conjunction with Dr. R.C. Cobb at Nottingham University, heat input to a substrate was measured. Trials were carried out with the flame alone and whilst spraying, to find the effect of the flame. The temperature of the substrate was measured using a "K" type thermocouple brazed onto the rear of a 75mm x 50mm x 1.6mm mild steel plate. As the pistol was traversed across the face of the plate the temperature was recorded by a B.B.C. micro-computer, sampling seven thousand times per minute. Traces were produced with various traverse rates and ranges. A similar series of tests were performed with the thermocouple attached to the front surface of the plate.

Results

6.1. Modelling of standard and H.S.G. gas and particle speeds.

6.1.1. Gas velocity measurements.

A three dimensional map of the total pressure of the gas stream of both a standard closed nozzle system and the H.S.G. system was produced by traversing a probe across the face of the nozzle and using suitable transducers to provide a series of two dimensional pressure/ position plots on an X-Y plotter. If certain assumptions are made the gas velocity may be calculated. Figure 28 shows the variation of velocity with range and with distance from the axis of the nozzle measured from the standard system. Figure 29 shows the results for systems similar to the H.S.G. nozzle and also what would be expected of the H.S.G. nozzle itself using cold air.

6.1.2. Theoretical H.S.G. gas temperatures and velocities

Given certain assumptions it is possible to estimate the combustion chamber temperature and pressure and thence the efflux temperature and velocity from the inlet mass flow and air/ fuel ratio.

Results

Since the nozzle is exhausting into atmosphere which is at a pressure of 1 bar absolute, and assuming the fluid to be air so that R is 287 and g, the ratio of specific heats is 1.4, then the critical pressure ratio for choked flow is 0.528. Thus to acheive supersonic flow, the chamber must be at a pressure of at least 1.89 bar absolute. Comparing the conditions witin the chamber and at the exit plane we have.

In the chamber: $T_1 = To_1$

$V_1 = 0$

$P_1 = Po_1$

And at the exit plane: $P_2 = 1bar$

If we assume $To_1 = 1800K$ from calculation of flame temperature

and also that $Po = 2bar$ abs then

$$T_1/T_2 = (P_1/p_2)^{(g-1/g)}$$

$$1800/T_2 = 2^{(g-1/g)}$$

$$T_2 = 1476K$$

Now $V_2 = 44.72((Cp(T_1 - T_2))^{0.5}$

$$V_2 = 806 \ ms^{-1}$$

Also $ro_2 = P_2/(RT_2)$

$$ro_e = 0.236 \text{ kgm}^{-3}$$

Mass flow m = ro x A x V

$$m = 0.236 \times 14E{-6} \times 806$$

$$m = 2.66E{-3} \text{ kg/s}$$

For a given pressure the mass flow and exit velocity are related to chamber temperature as shown in figure 30. For a given temperature the exit velocity depends upon chamber pressure as shown in figure 31, and the mass flow is related to chamber pressure as shown in figure 32. It can be seen from the change in slope that the nozzle becomes choked at a flow of around 1.5 g/s.

6.1.3. Theoretical particle velocities.

Prior to the construction of the H.S.G. system a computer model of the flight of particles was set up on a Hewlett Packard 9845A microcomputer. This was used to evaluate the likely particle size/ velocity/ range relationships to compare particle acceleration by hot exhaust gases and by cold compressed air. In the first instance it was assumed that the particle size was a constant with range. After spraying, the relationship between particle size and range could be determined and this was fed back into the system.

Results

Figure 13 (p82) shows velocities for the standard system with fixed particle sizes, and figure 33 shows the theoretical particle velocity for the same spray head using a correlation produced by Cifuentes (24) to represent the size/ range relationship for standard arc-spraying. Figure 34 shows the velocity relationships for particle sizes of 20,40 & 80 x 10^{-6}m particles and for the H.S.G. size/range correlation using two arbitrary ratios of splat thickness to particle diameter. Figure 35 compares the two particle size correlations. Cifuentes suggests:

$$V = 1/d^n$$

Where V is the particle volume, d is the range and the index n is 1.8 and depends upon other spraying parameters.

The correlation for the hot gas system was :

$$D = f \times 13 \times EXP(-7.4555e-3 \times d)$$

Where D is the particle diameter and f is the ratio of splat thickness to particle diameter which is arbitrary and was chosen to be 10. This ratio was also assumed to be constant. For ease of comparison the Cifuentes correlation was converted to give a diameter rather than a volume.

6.2. Spraying trials.

Previous work has shown that any particular nozzle will perform best with a certain wire size. It was found that, using the original nozzle, 11 gauge Brown and Sharpe (.092") and 2mm (.078") could be accommodated. With 11 gauge wire the system would spray using cold compressed air as well as at all settings of the flame, but with 2mm wire only the most energetic flames produced an acceptable spray. At a later date it became difficult to spray with 2mm wire at all. However, when the system is well set up, the lower limits to operation are as follows:

Voltage: >23v at 250 amperes Current: >60 amps

This voltage level is around 4 volts less than can be tolerated normally and the minimum current was 20 amperes less than the normal lower limit.

When the more energetic flames are employed, the spraystream becomes considerably more concentrated than for a normal system using cold compressed air. At a range of 180 mm a standard spray head produces a spray-cone of about 180 mm whereas the H.S.G. head produced a cone less than 30 mm in diameter. This has considerable implications for the heat input per unit area of surface and the length of time for which a particle remains exposed on the surface prior to being covered by the next layer.

6.3. High speed filming of H.S.G. spray.

Three films were produced at varying spraying parameters. The film was analysed for particle velocity and general appearance of the spray stream. By measuring streak lengths it was found that particles with velocities as high as 600 m/s existed, as did particles travelling at a few tens of metres per second. In other words the spray-stream is a mixture of high and low velocity particles. The high speed film also shows some particles bursting into many smaller particles and that other particles are subject to sudden zig-zag motions. The whole spray-stream appeared to have an anti-clockwise spiral motion (viewed from the rear).

The films also show that the arc was occasionally extinguished for short periods (0.5 ms max) although these were not noticed during spraying and appeared to have no detrimental effect.

6.4. Coating mechanical properties.

6.4.1. Macro and micro hardness.

The macro-hardnessses of samples produced at varying spraying range were measured and are as shown in the table 8 below.

Table 8. Macro-hardness vs spray range.

Sample no	Hardness Hv30kg	Spread	Range.
01	344Hv	(275-429)	25mm
02	433Hv	(too few)	50mm
03	sample too cracked		37mm
04	378Hv	(360-392)	63mm
05a	397Hv	(499-334)	75mm

The macro-hardness of samples produced using varying flame parameters were also measured and are represented below in table 9. A constant range of 165mm was used throughout.

Results

Table 9. Macro-hardness vs Flame parameters.

Sample no	Hardness Hv30kg	Spread	A.F.R.	Flow l/min
1	316Hv	(290-333)	29:1	583
2	337Hv	(315-364)	44:1	583
3	373Hv	(346-387)	27:1	547
4	265Hv	(232-281)	43:1	559
5	275Hv	(232-303)	25:1	335
6	281Hv	(237-329)	39:1	314
7	320Hv	(295-356)	24:1	324
8	302Hv	(285-331)	44:1	310

The micro-hardnessses of samples produced at varying spraying range were measured and are as shown in the table 10 below. Sample numbers refer to table 6 on page 137.

Table 10. Micro-hardness vs spray range.

Sample no	Hardness Hv20g spread	Range mm.
std 60	426-1077	150
07	494-772	63
08	494-802	87
09	599-1030	112
10	772-905	137

As can be seen from the above results neither macro-hardness or micro-hardness seem to be affected significantly by range except that it my be lowered at very short range. As the micro-hardnesses are of the same order as those observed for conventional arc spraying the flame is clearly not affecting the particle quench rate or re-tempering the particles.

6.4.2. Cohesive strength testing by three point bend test.

During some preliminary trials, as discussed on page 140, it was found that the number of cracks occurring during the bend test depended greatly upon the thickness of the coating as well as the cohesive strength. Thin coatings cracked as several parallel cracks but thicker coatings produce a single crack followed by peeling along the interface. For standard arc-sprayed 60E the transition from multiple to single crack occurs at around .020" and this was chosen as the test thickness.

In all cases the H.S.G. coatings failed by a single crack followed by peeling along the sustrate interface. However the H.S.G. system produces a very narrow spray pattern and considerable difficulty arose in maintaining an even thickness across the sample. Coating thickness varied from .017" to .025" in the worst case. The failures were by single crack except where the coating thinned at the edges and the crack bifurcated. In some cases small pieces remained attached between the forks of such cracks.

6.4.3. Direct tensile testing of coating material.

The following figures are an average of at least seven tests.

Table 11. U.T.S. and Modulus of H.S.G. and Standard coatings.

Sample	Range mm	Modulus GPa	U.T.S. MPa	Max Strain $\times 10^{-6}$
H.S.G.	75	124	186	1800
H.S.G.	125	146	241	2054
Standard	75	135	308	2692

Selected test pieces were examined under the scanning electron microscope and the fracture faces are shown in figures 36 – 43. Figure 44 shows a typical load strain curve from this process.

6.5. Porosity determination.

6.5.1. Visual examination

The coatings produced by H.S.G. are finer in microstructure than those produced by standard arc-spray and thus determination of porosity by direct observation and estimation was considered impractical. A system known as

Results

Micro-eye from Digithurst views a polished sample through a video camera and divides the image into 64 grey levels. By manipulation in a micro-computer one can find the percentage of the image which is darker than a pre-set level. Since porosity appears black it is possible to find the area percentage of porosity.

At a spray range of 4" H.S.G. 60E has an optical porosity of 1.1% compared with 3.1% for std C.G. 60E at 6" range.

6.5.2. Immersion in Toluene.

When rings of the sprayed material were tested by the toluene immersion method estimates of closed and interconnected porosity were produced as shown in table 12. The H.S.G. samples show no significant improvement over standard spray performed in a single pass. When the toluene immersion test is repeated with different coating thicknesses, the volume of pores remains fairly constant, so that the percentage porosity appears to follow an inverse relation with thickness.

Table 12 Porosity as measured by Toluene immersion.

Sample type	Range	Surf. area	Volume	Pore vol.	Porosity
	mm	sq. mm	cu. mm	cu. mm	% (vol)
H.S.G.	75	1490	1590	27	1.7
H.S.G.	75	1241	910	29	3.2
H.S.G.	75	1075	365	16	4.4
H.S.G.	125	1517	1625	26	1.6
H.S.G.	125	1241	910	29	3.2
H.S.G.	125	1075	365	23	6.3
STD	75	1509	1615	42	2.6
STD	75	1340	1000	29	2.9
STD	75	1150	400	28	7.0

6.5.3. Mercury intrusion porosimetry.

Mercury intrusion porosimetry on selected samples show that a similar volume is penetrated, regardless of pressure, up to a maximum of 300 MPa as shown in figure 73.

6.6. Oxidation levels.

6.6.1. By visual examination

It is more difficult to estimate the volume of oxide present by an optical technique because there is less contrast in grey level. However for the 4" range sample it has been visually estimated at 30-40 % by volume which corresponds to a level of about 18% by weight.

6.7. H.S.G. Spraying of alternative materials

As discussed on page 146, aluminium was sprayed briefly and produced a very fine textured coating. The appearance of the spray-stream was different in that the level of glare was much reduced especially at low throughput rates. This was attributed to a lower oxygen concentration in the burning gases allowing less oxidation of the particles in flight. 80/20 Nichrome was also sprayed and gave an optical porosity of 3.1%. The microstructure of this coating is shown in figures 45 and 46.

6.8. Heat input to substrate.

The heat input to a substrate was measured in collaboration with Nottingham University . Trials were carried out with the flame alone and also whilst spraying to find the significance of the flame. The graphs in figures 74 - 77 show that the effect of the flame is far less than that of the spray particles.

Please note that the pair of graphs produced with the thermocouple on the rear face, were sprayed at different deposition rates and traverse speeds to those where the thermocouple is on the front face. Thus no comparisons should be made between the two pairs of results.

6.9. Coating appearance.

Micro-sections were made of each coating and are presented in figures 47 to 68 and figure 69 - 72 show both H.S.G coating and those produced by standard arcspraying to show the effect of polishing technique. Figures 70,71 and 72 were sprayed by hand and show a much more inhomogenious structure.

Figure 78 shows the H.S.G. system in operation spraying 2.3 mm 420S45 steel.

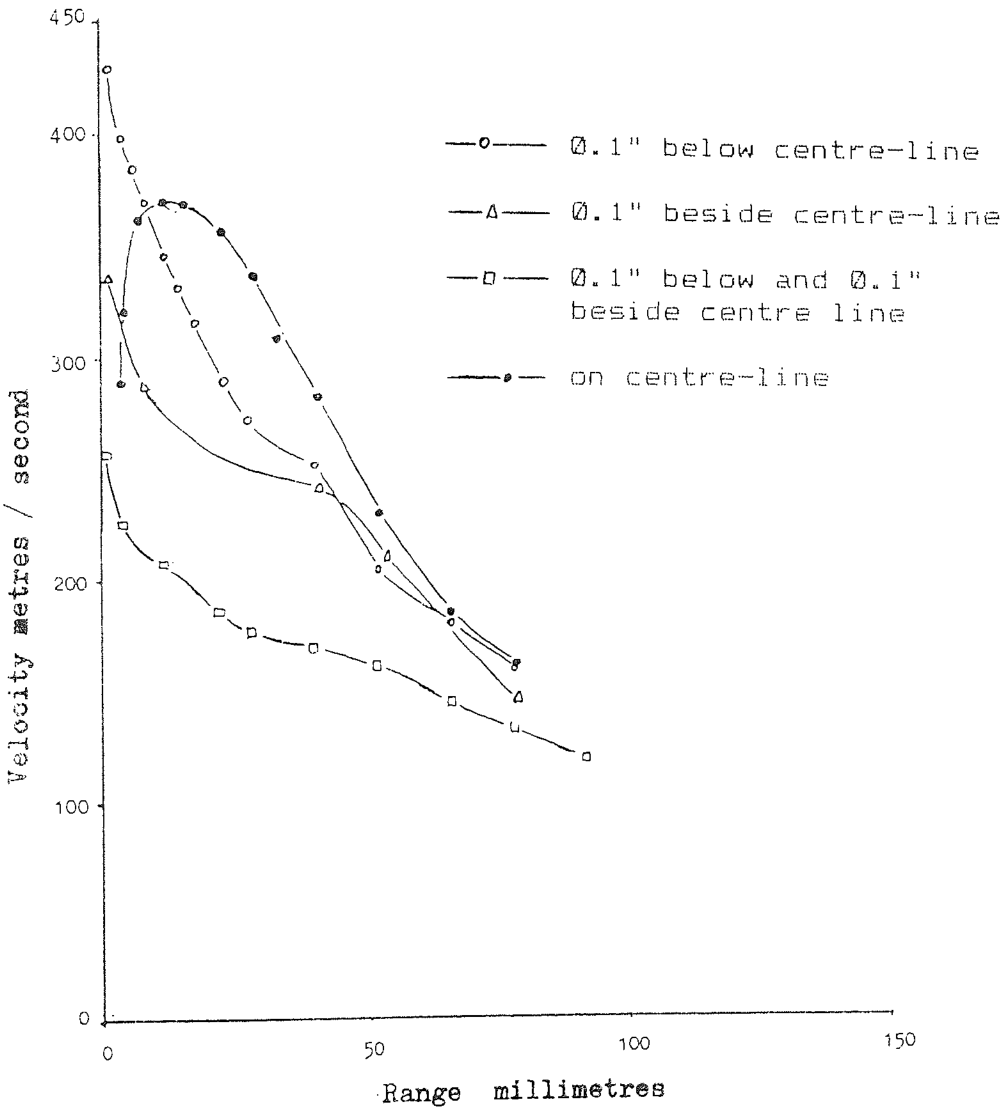

Figure 28. Variation of air velocity with range and distance from centre line.

‡ In the above calculations the static temperature and pressure were assumed to be constant at ambient values. This involves a possible error of up to 10% in the values of velocity obtained.

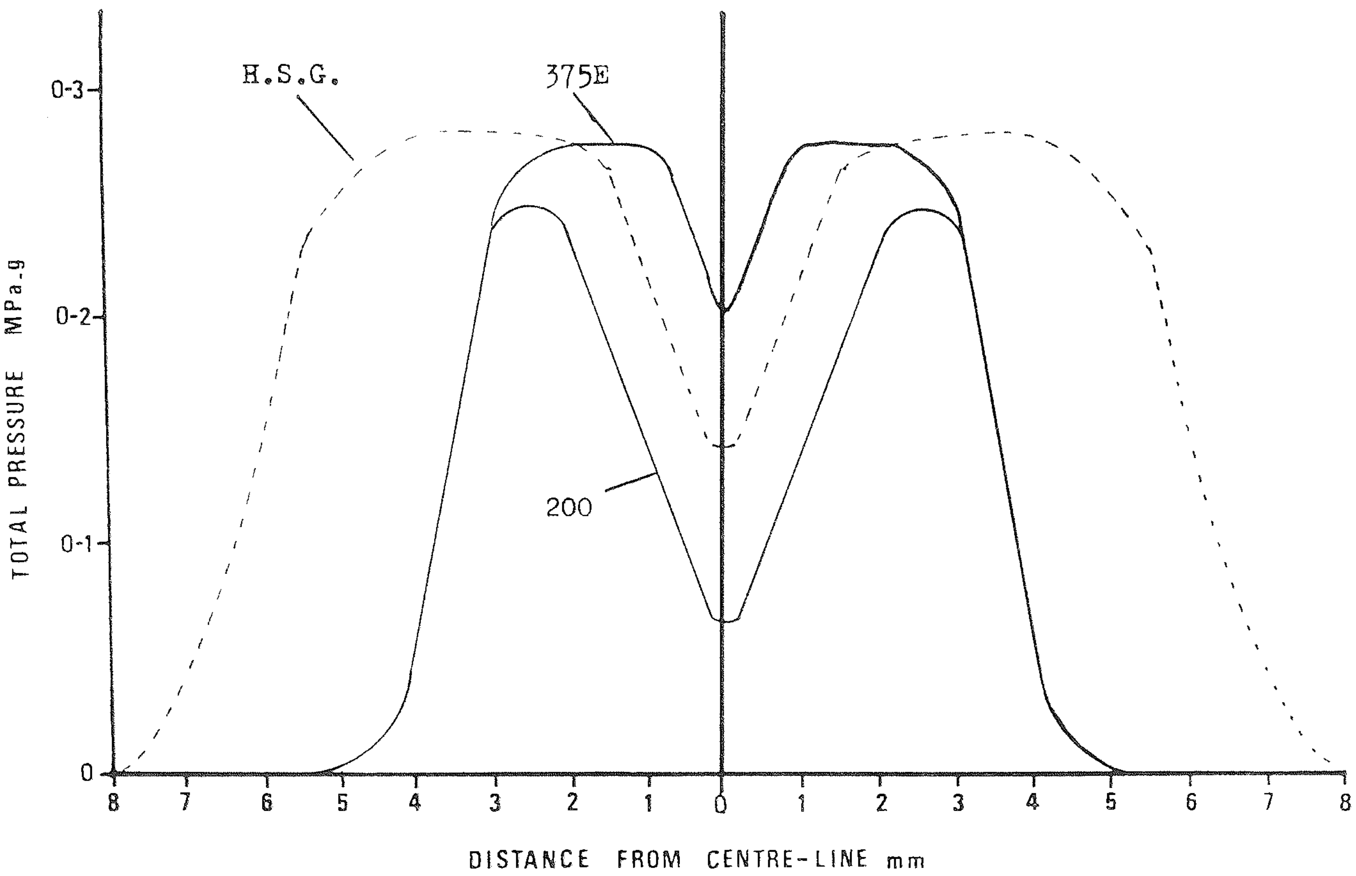

Figure 29. Total pressure plots through centre lines of Arospray 375E, 200 and H.S.G. nozzles.

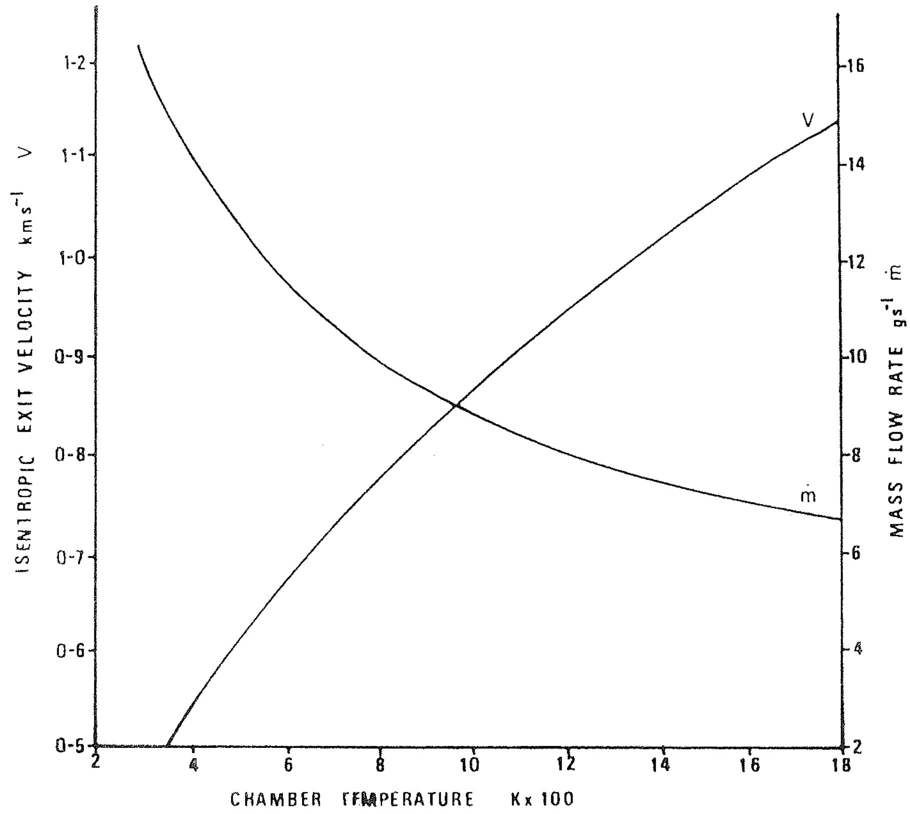

Figure 30. Mass flow and exit velocity Vs chamber temperature. (Chamber pressure = 0.4MPa)

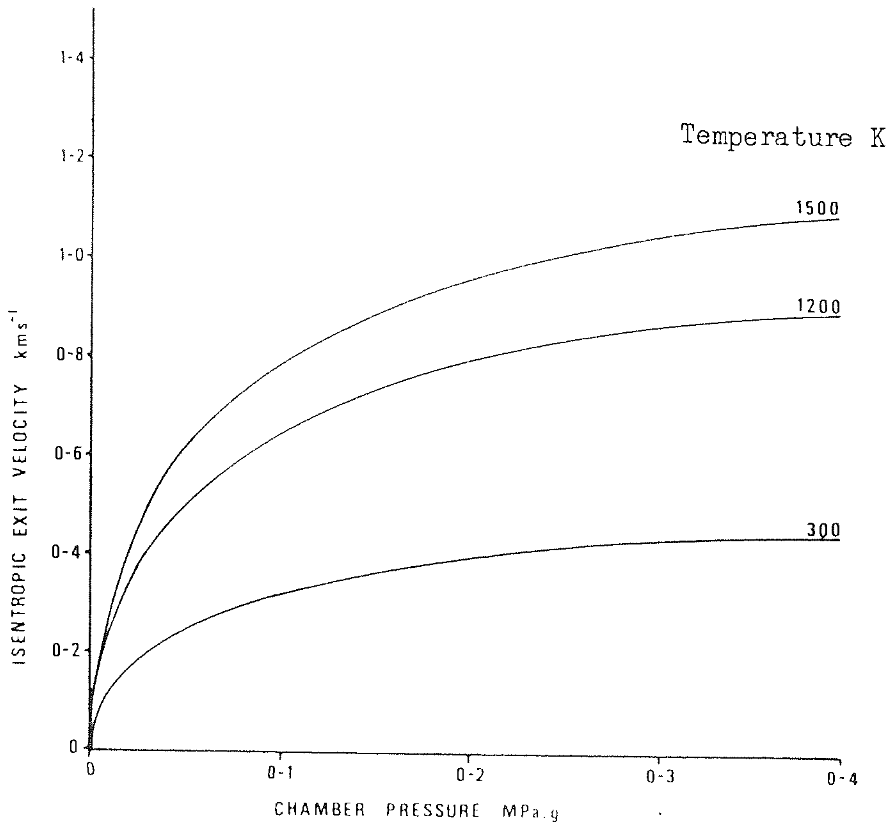

Figure 31. Exit velocity vs chamber pressure.

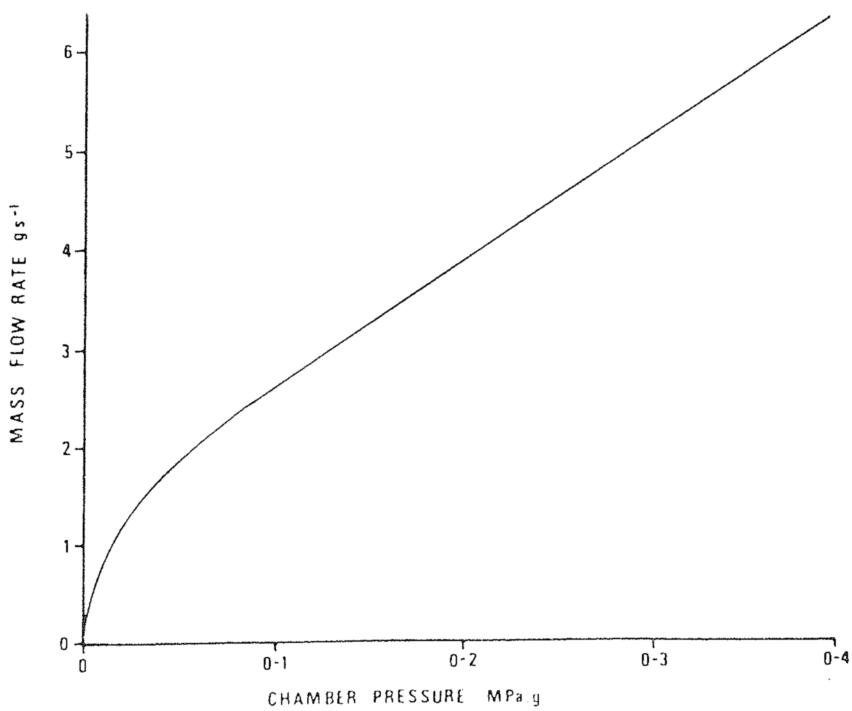

Figure 32. Mass flow vs chamber pressure.

(Chamber temperature = 1800K)

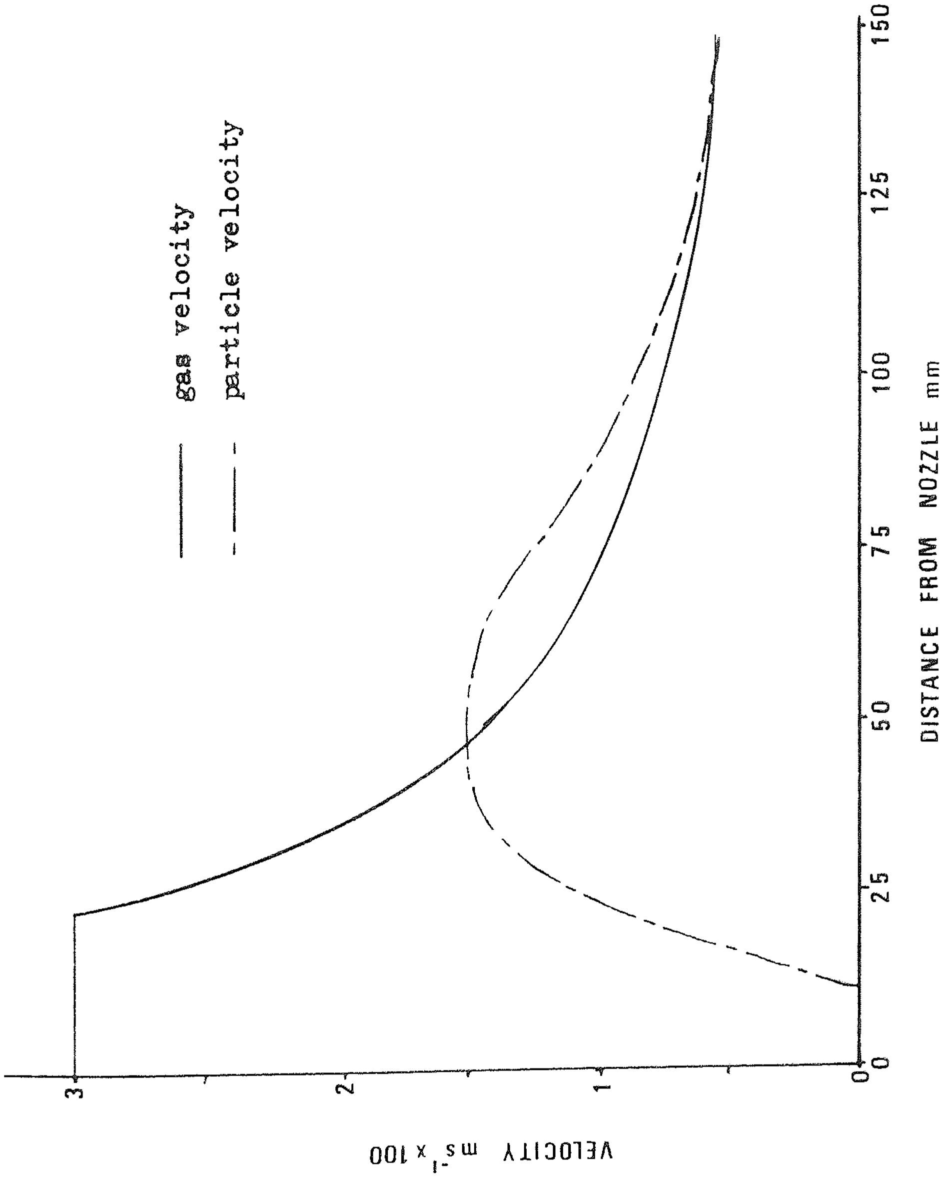

Figure 33. Particle velocity vs range for standard spray head using Cifuentes comminution correlation.

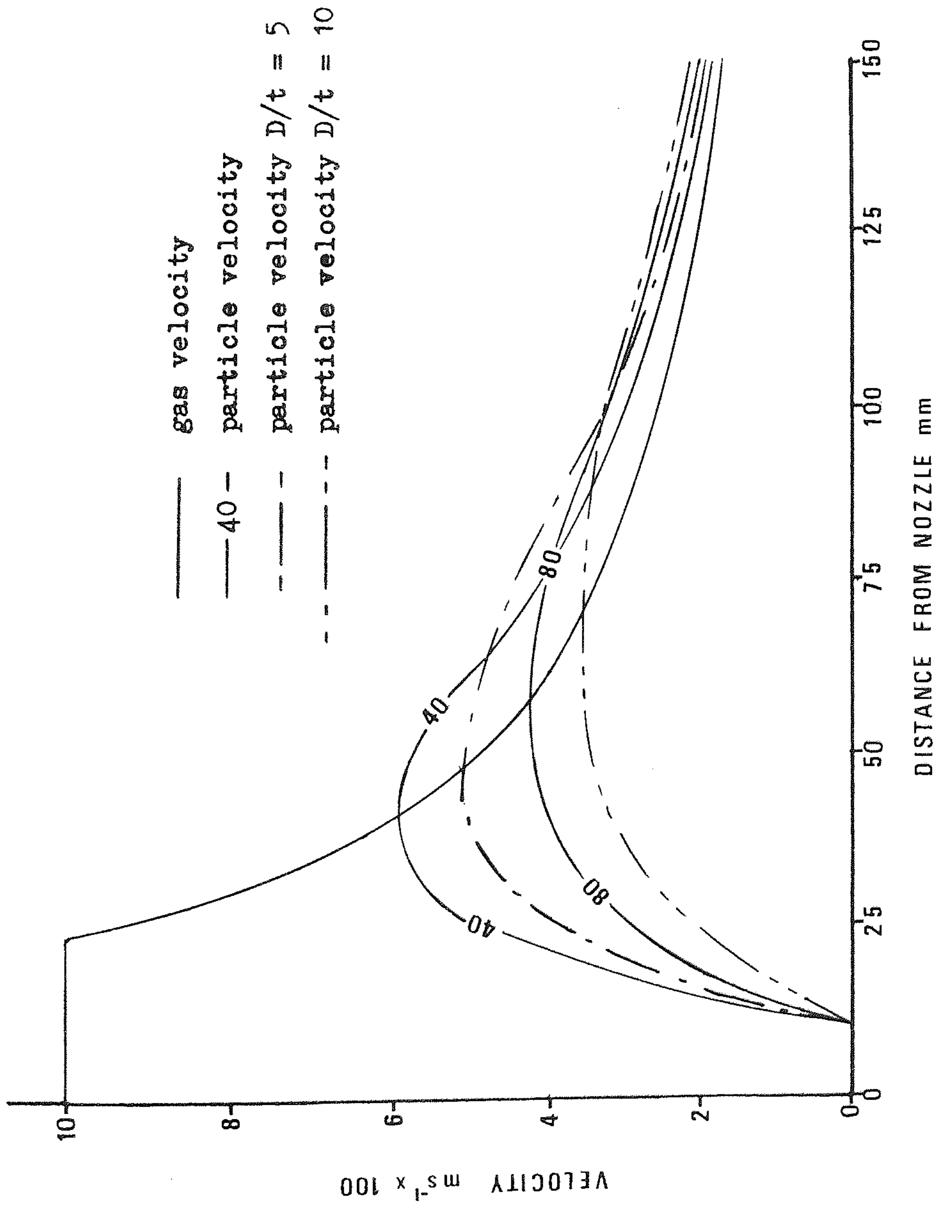

Figure 34. Particle velocity vs range for H.S.G. nozzle with and without comminution correlation. Sizes and particle diameter/splat thickness ratio as marked.

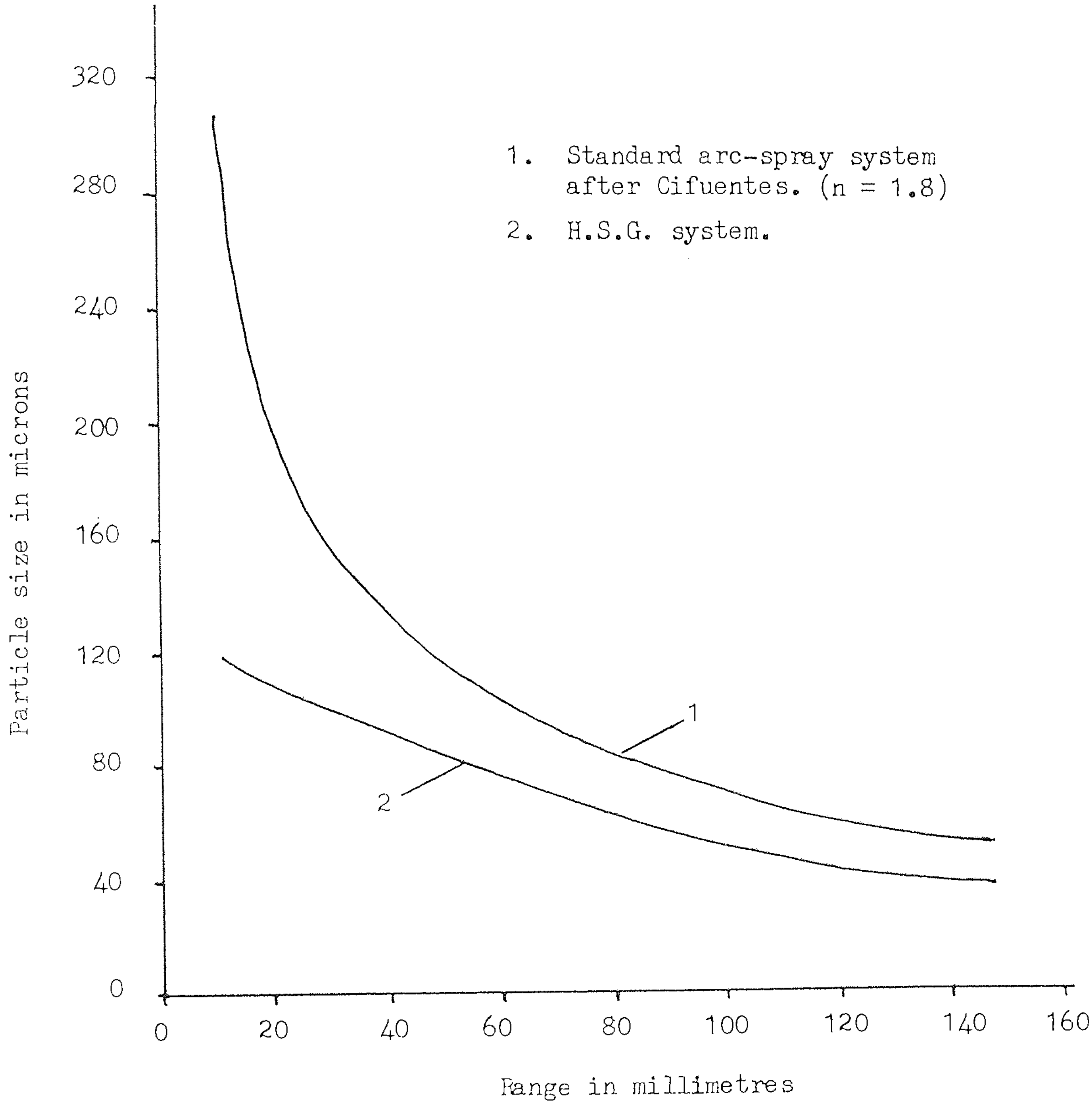

Figure 35. Comparison of comminution correlations.

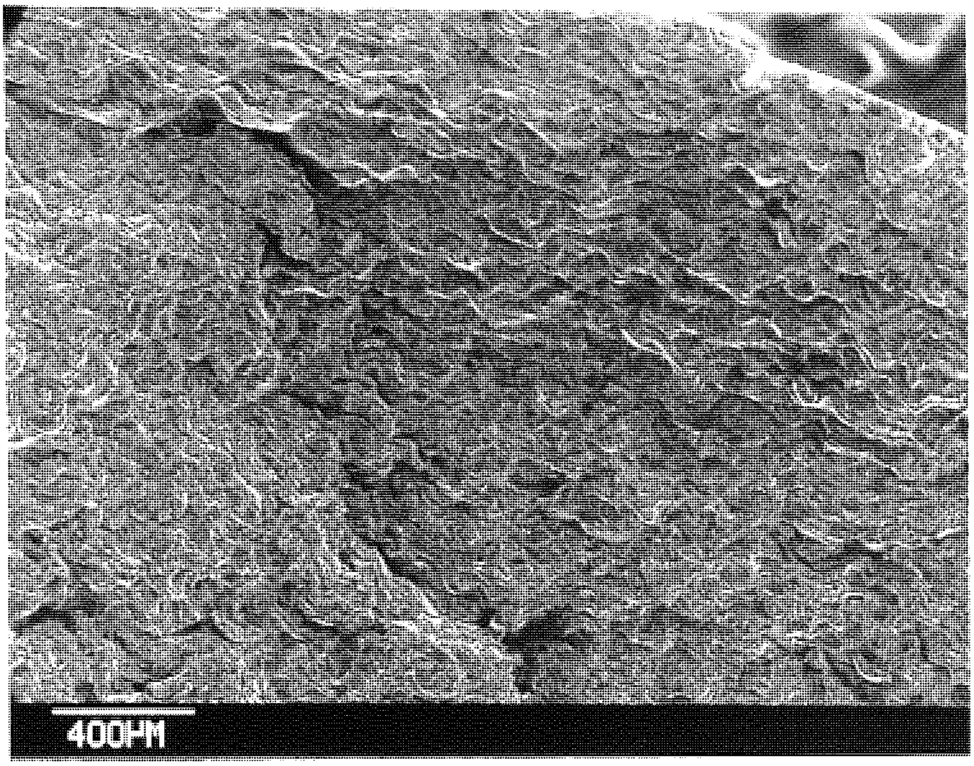

Figure 36. ST1 Fracture face at low magnification.

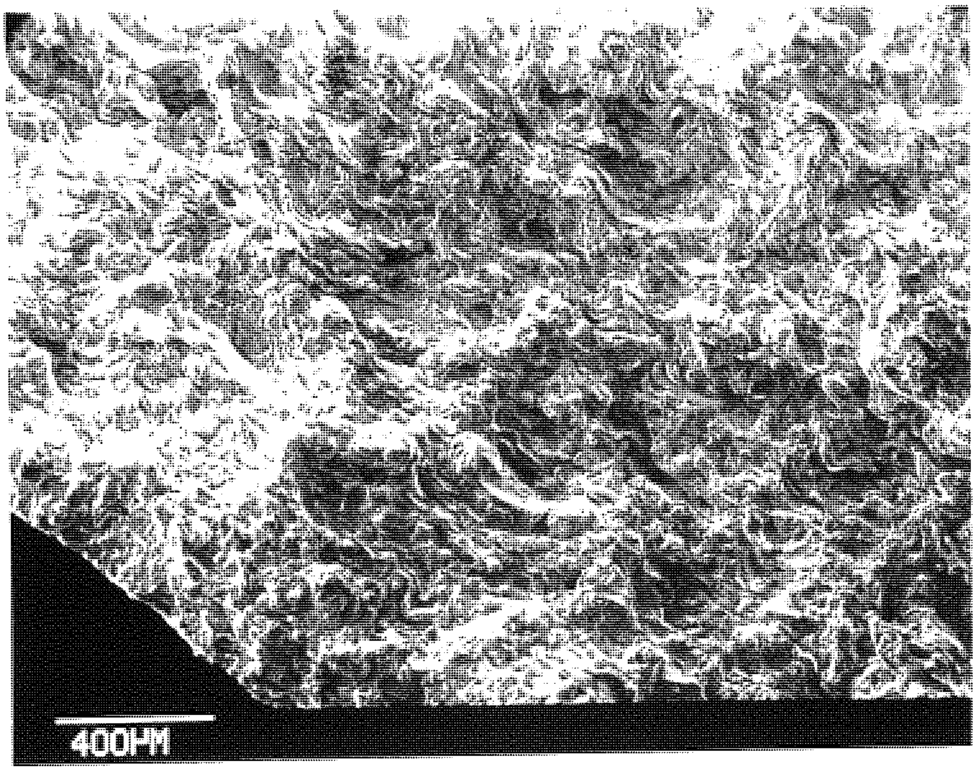

Figure 37. HGB1 Fracture face at low magnification.

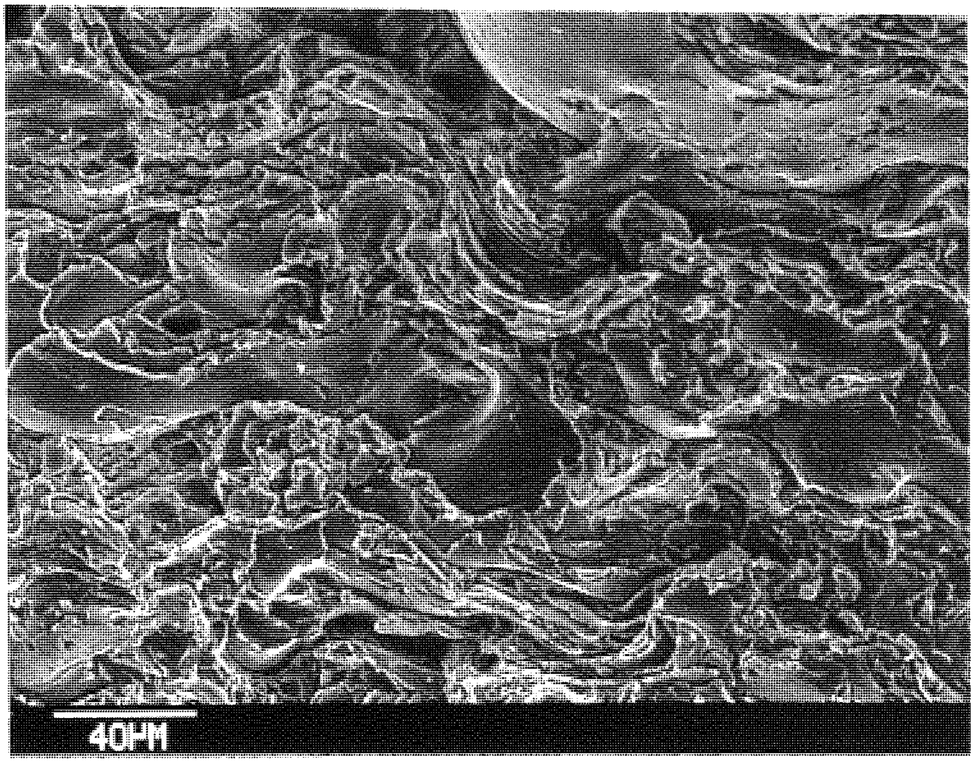

Figure 38. ST1 Fracture showing cleavage, pullout and depression left by removal of spherical particle.

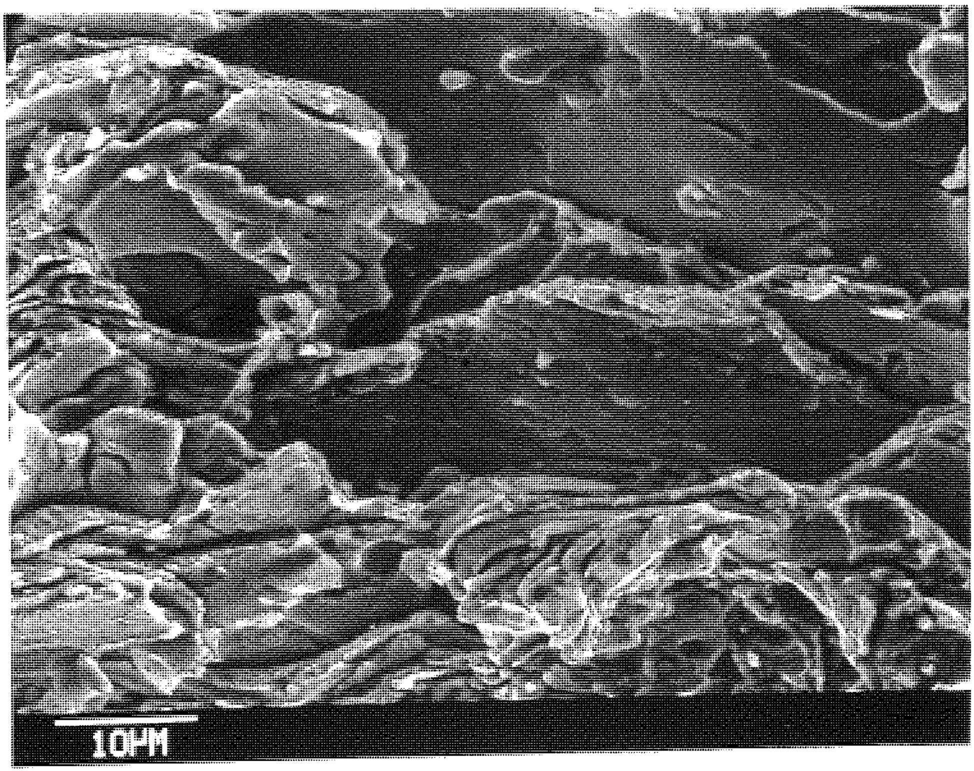

Figure 39. Higher magnification of figure 38.

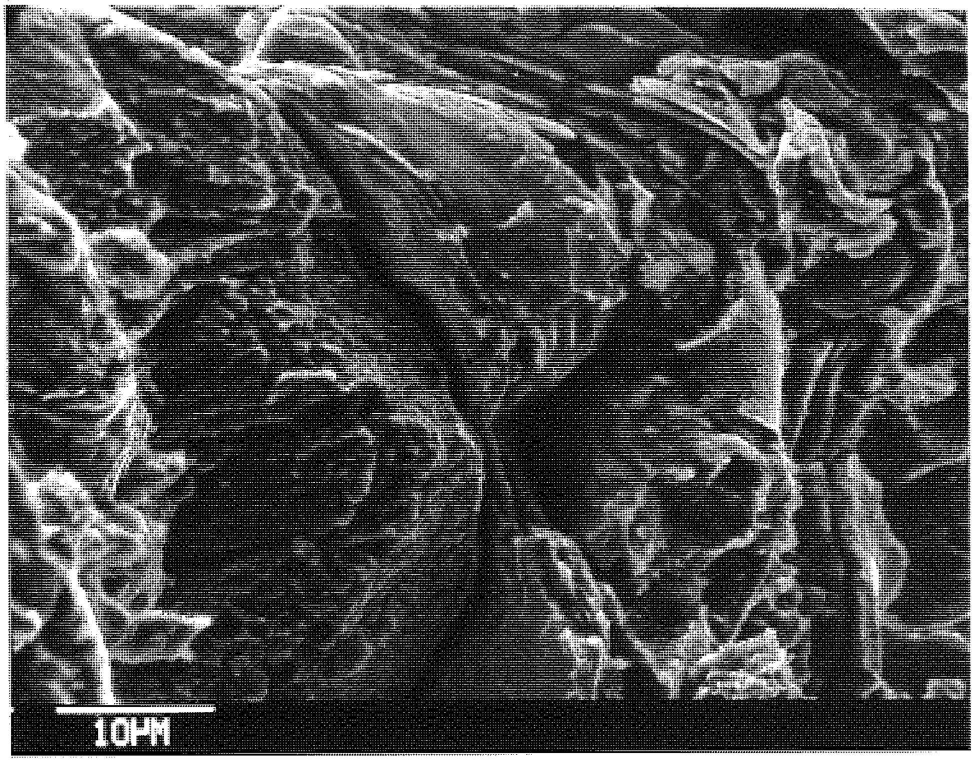

Figure 40. HGB1 Fracture showing brittle fracture of lammellae and fissure opened up between particles.

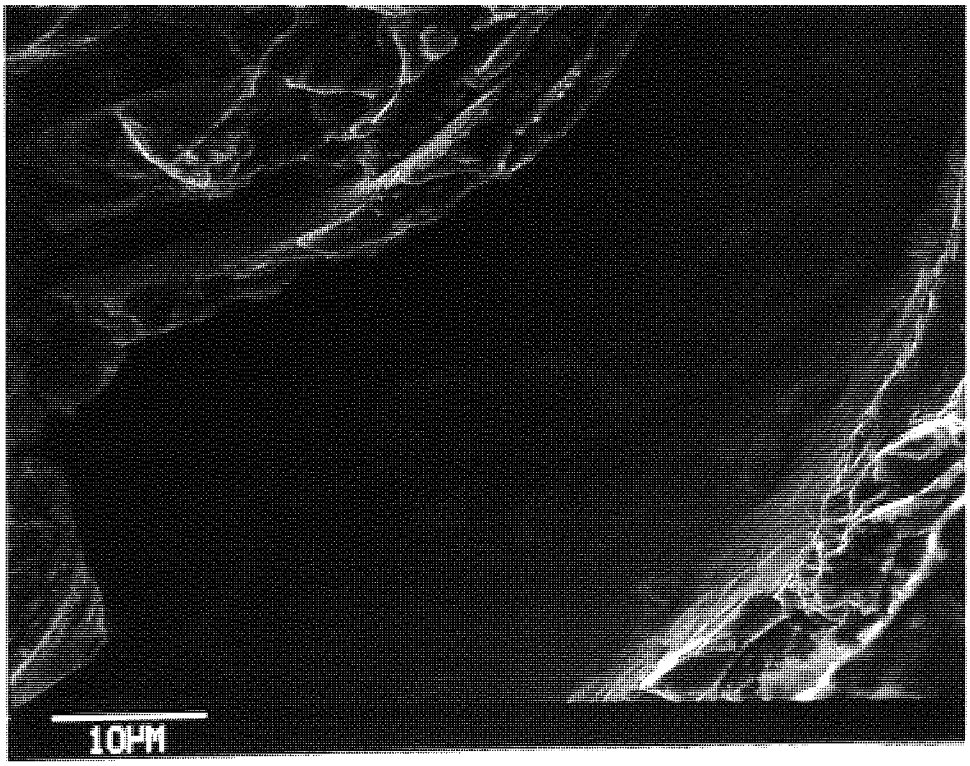

Figure 41. HGB1 Fracture showing particle pullout.

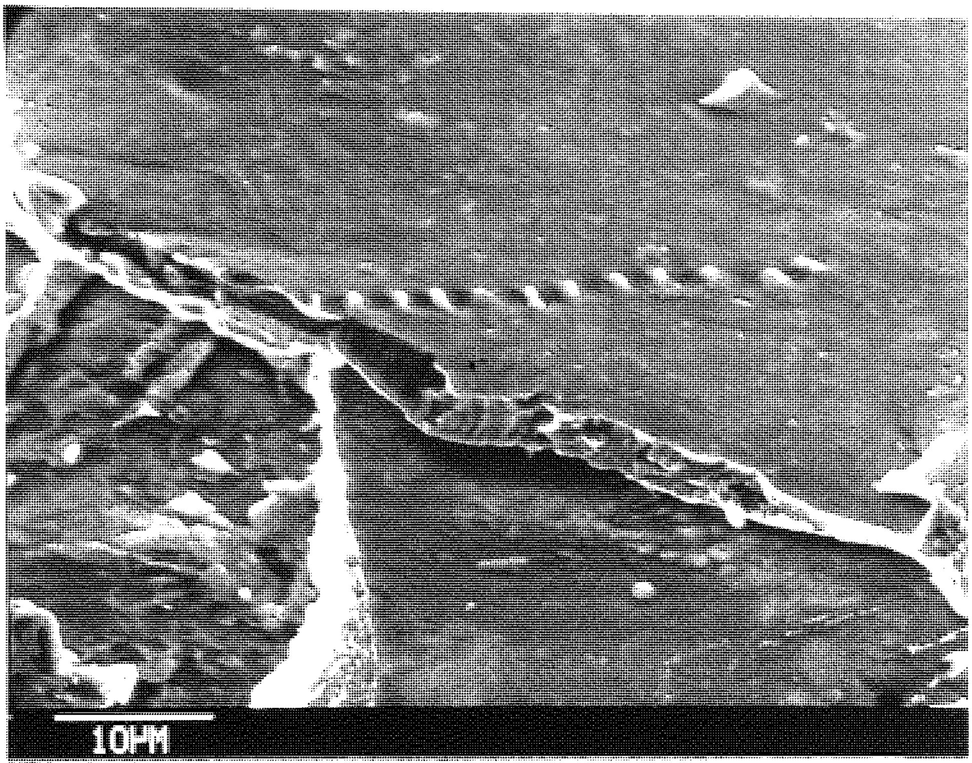

Figure 42. HGB1 Particle fracture showing strain pattern on lammella surface.

Figure 43. Higher magnification of figure 42.

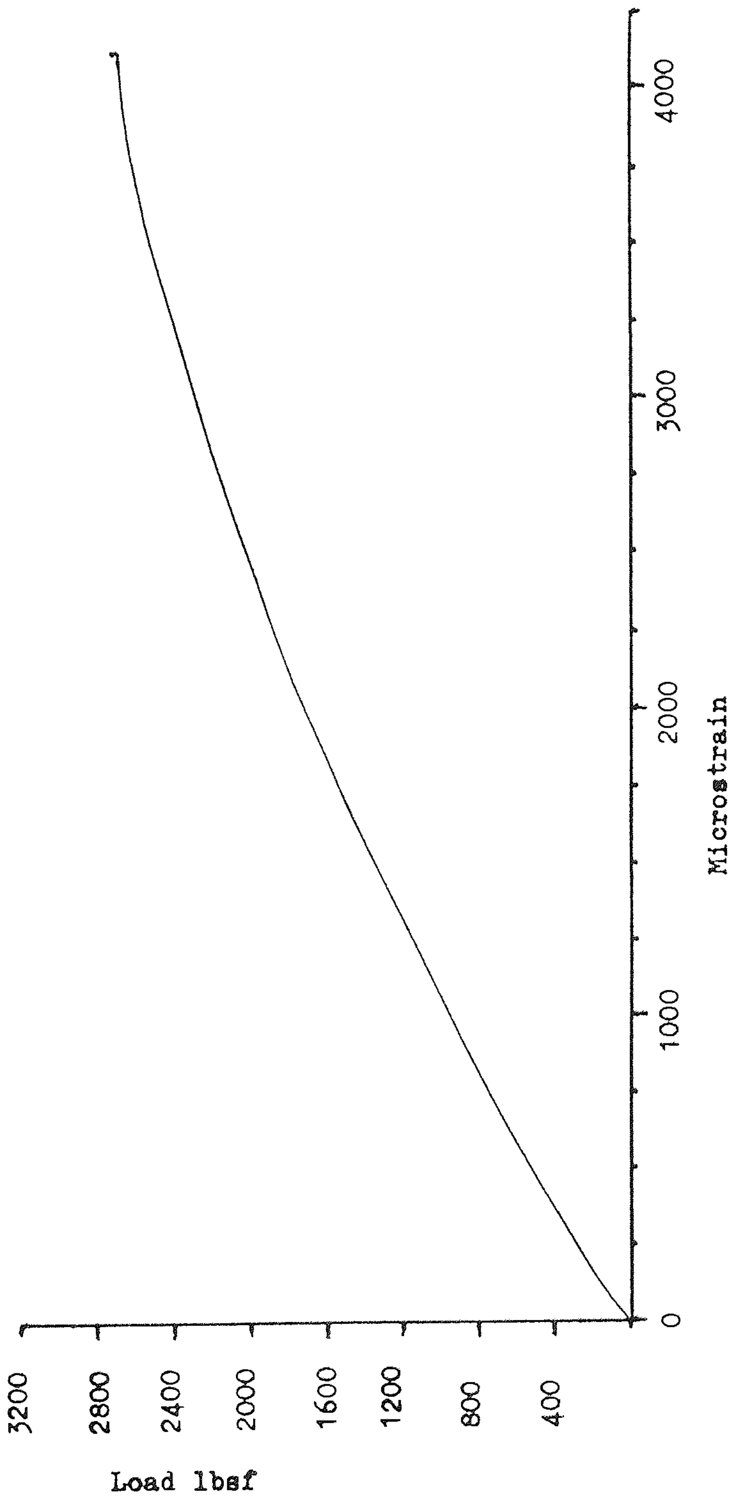

Figure 44. Typical tensile test load / strain curve.

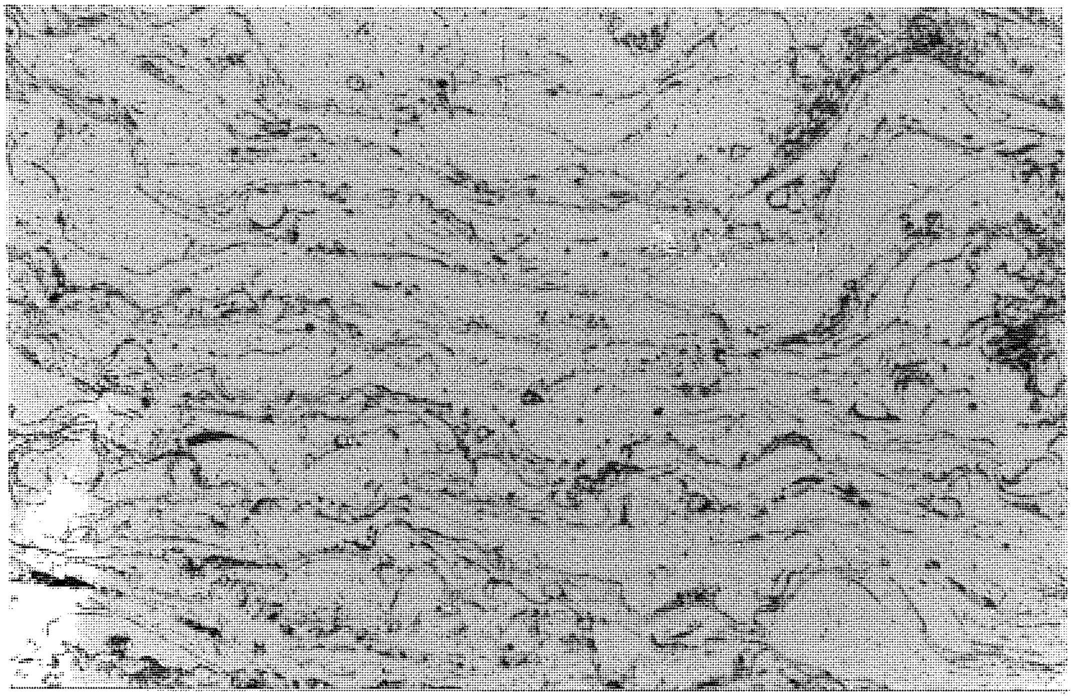

Figure 45. H.S.G. 80/20 nickel/chromium X 220

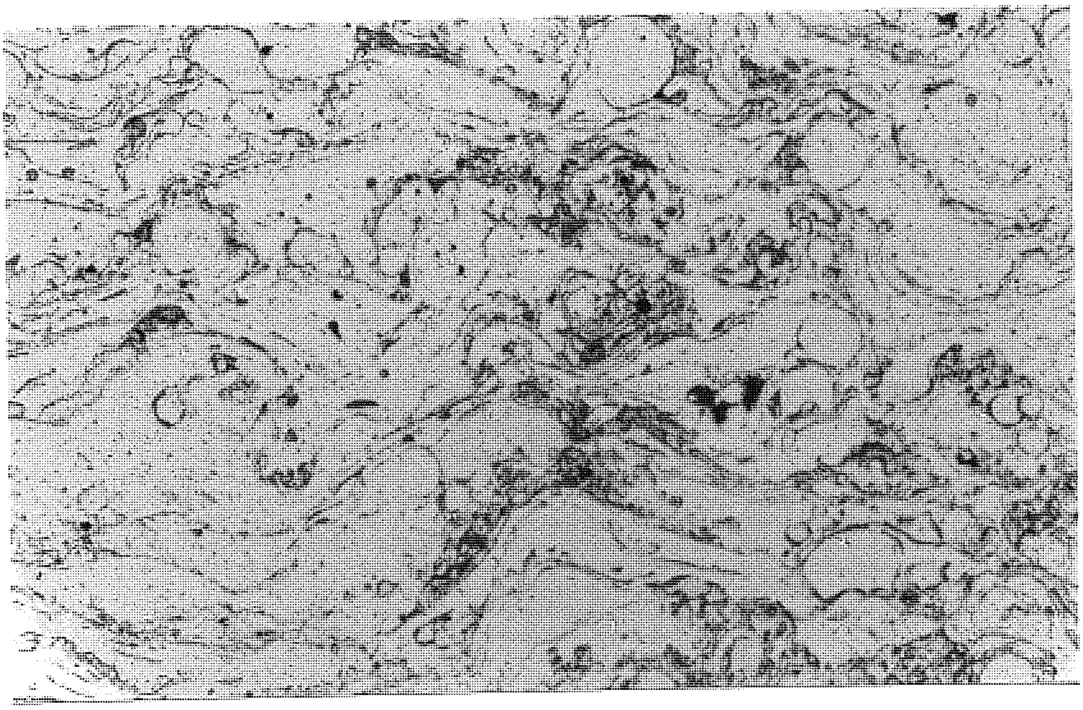

Figure 46. H.S.G. 80/20 nickel/chromium showing dust inclusions and spherical particles X 220.

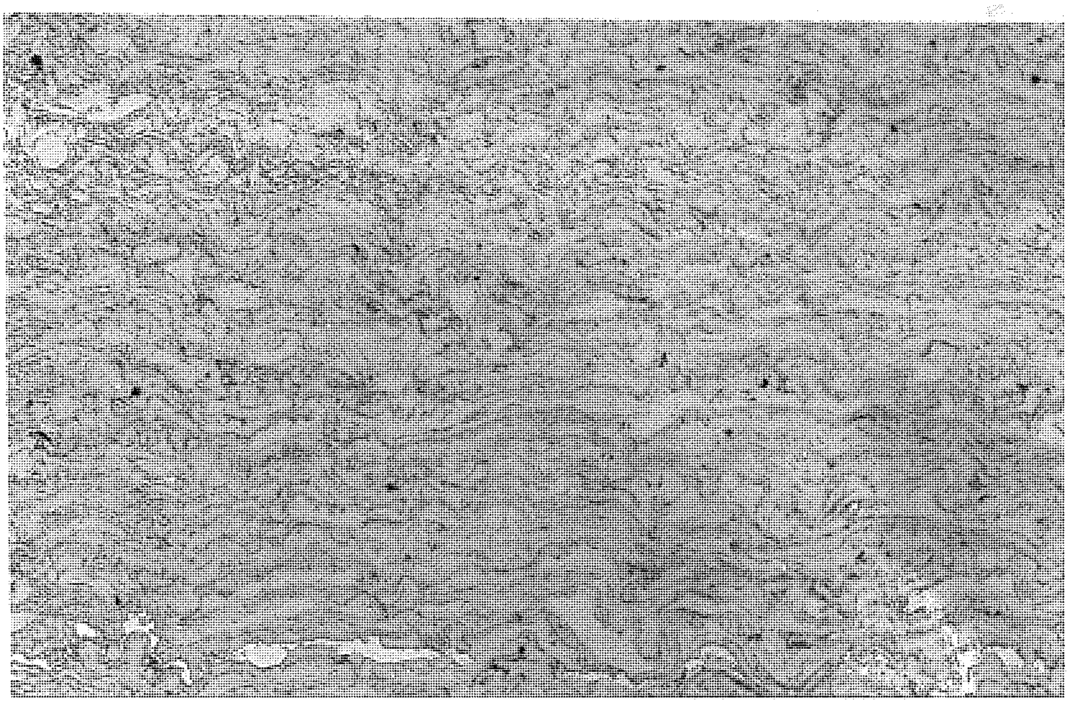

Figure 47. H.S.G. 420S45 steel sprayed with parameters as in run 1 table 5 p135. X 90

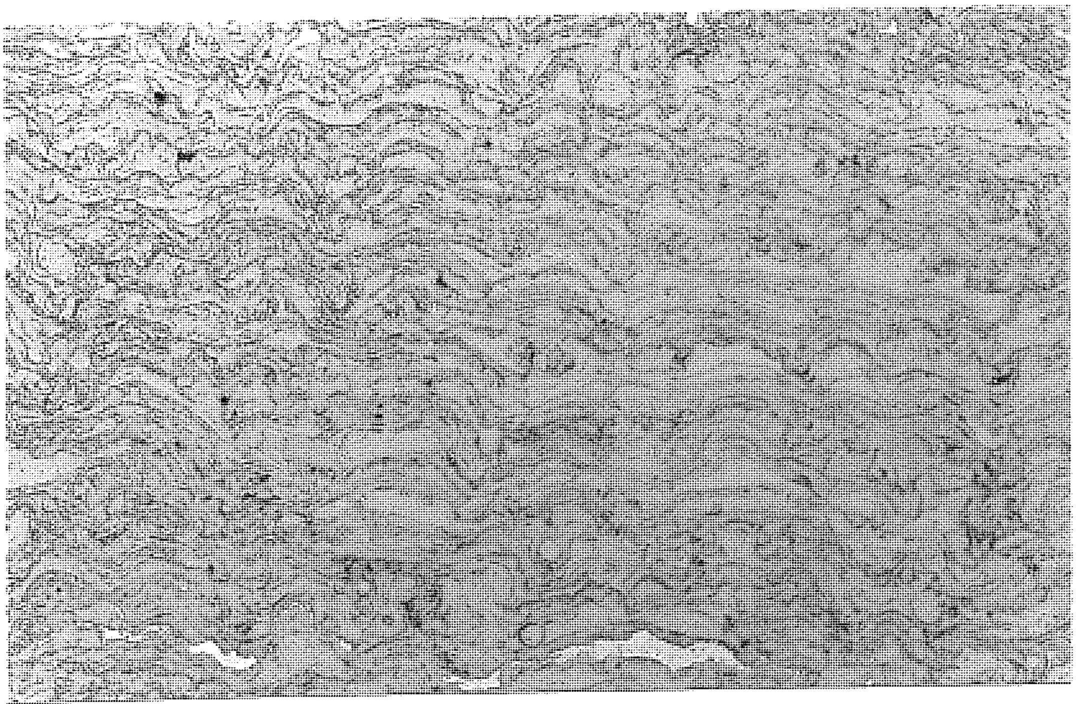

Figure 48. H.S.G. 420S45 steel sprayed with parameters as in run 2 table 5 p135. X 90

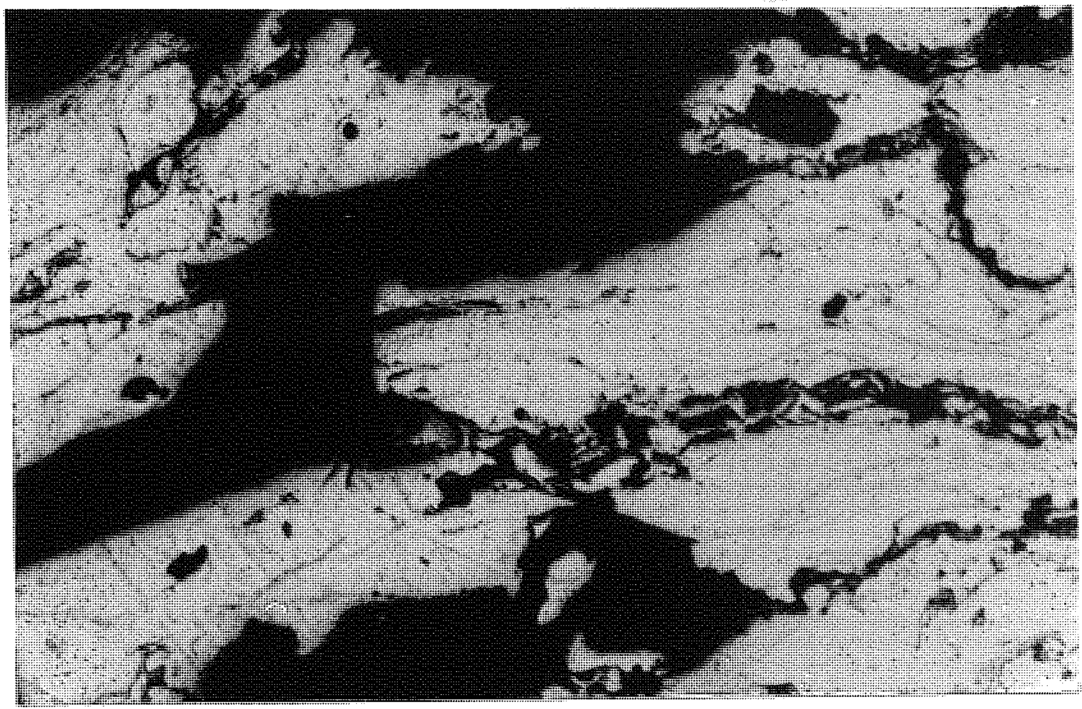

Figure 49. H.S.G. Sample 01 showing gross split due to very short spray range X 180

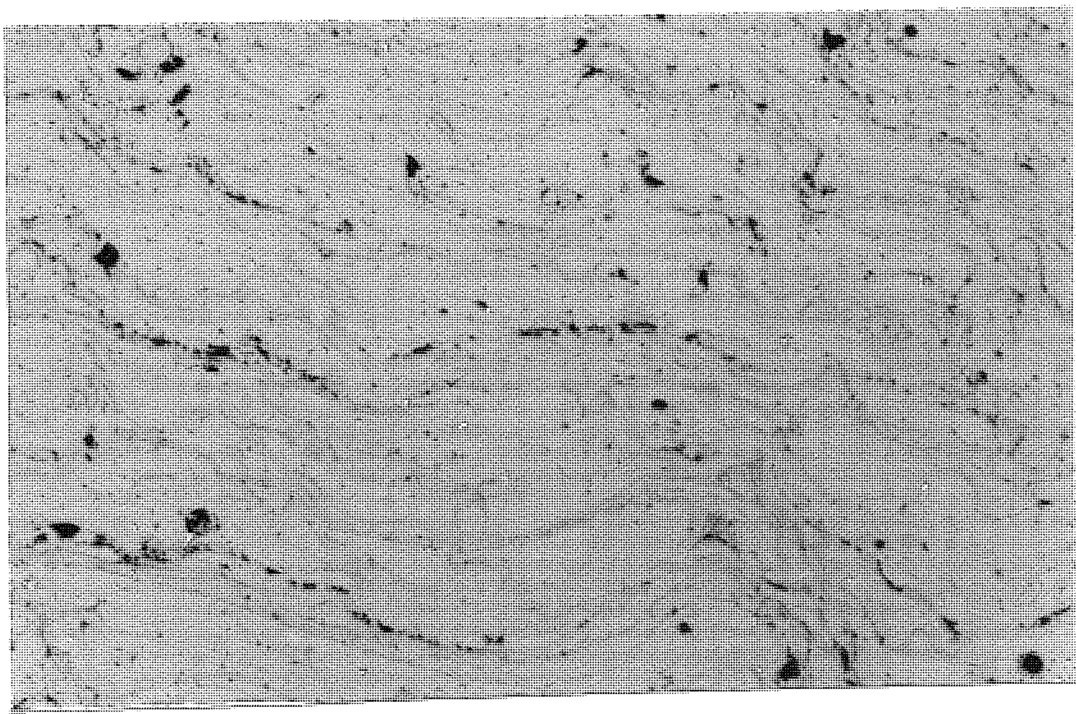

Figure 50. H.S.G. Sample 01 away from split region showing low oxide between particles. X 180

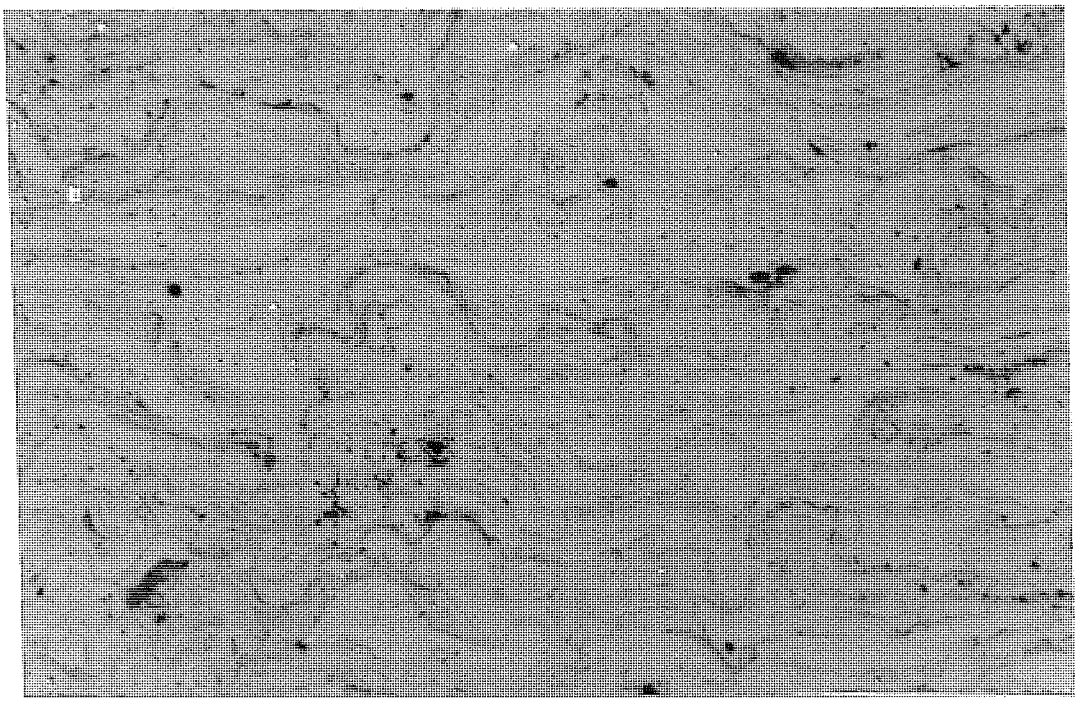

Figure 51. H.S.G. Sample 02 General view X 180

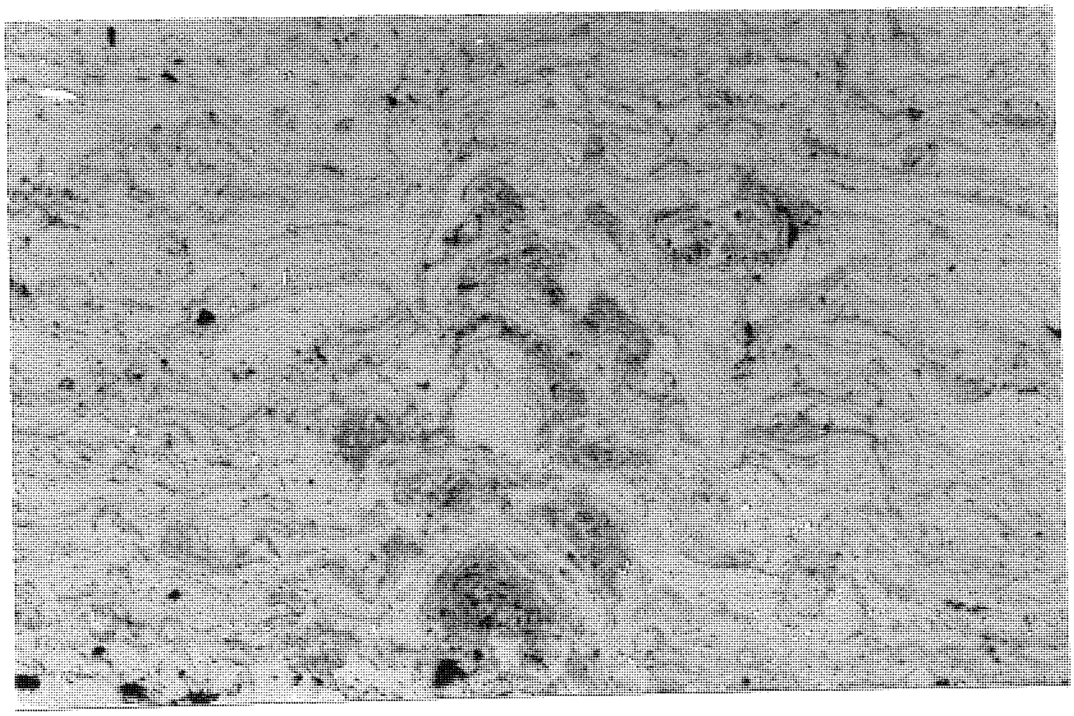

Figure 52. H.S.G. Sample 02 Showing oxide feature X 180

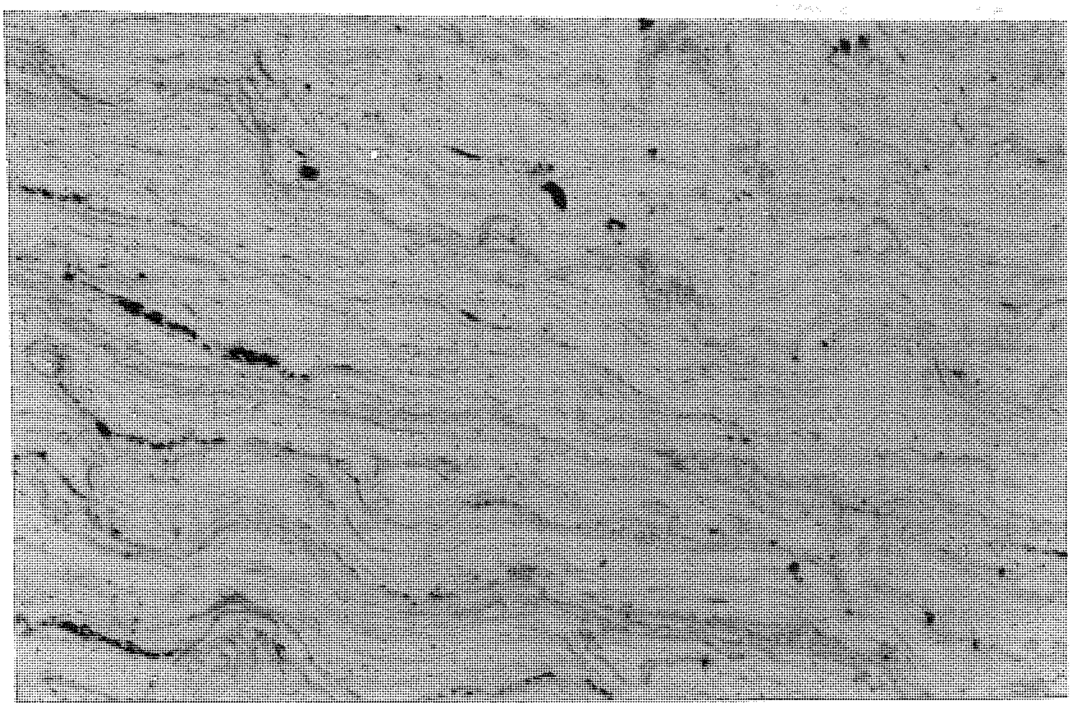

Figure 53. H.S.G. Sample 03 General view X 180

Figure 54. H.S.G. Sample 04 Showing good dense area X 180

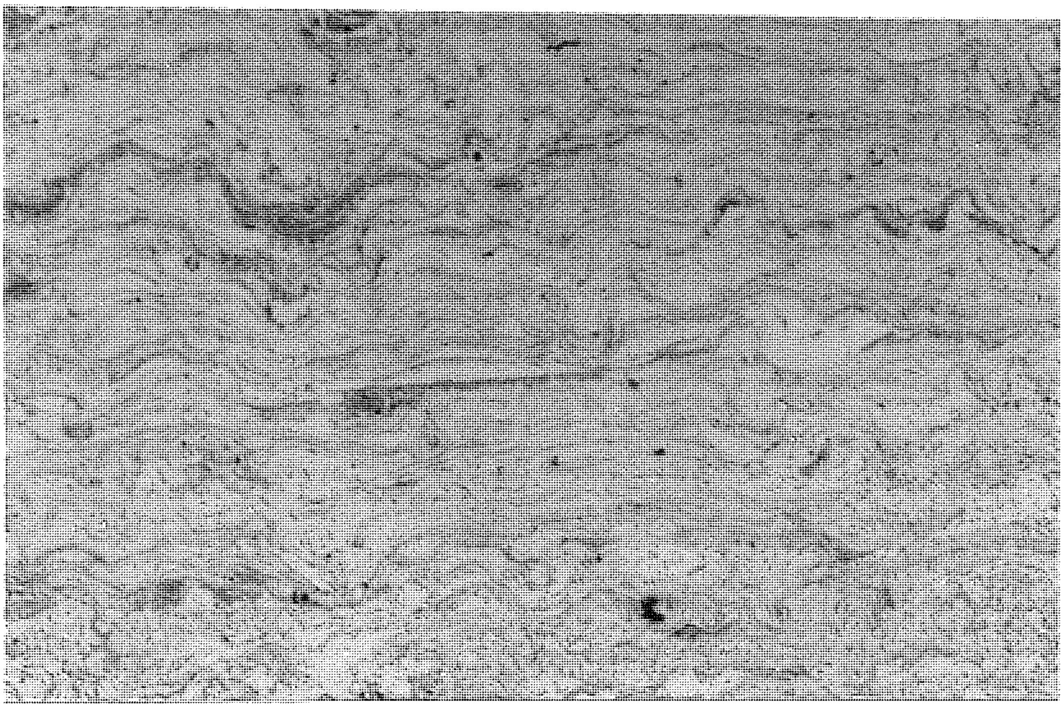

Figure 55. H.S.G. Sample 05A General view X 180

Figure 56. H.S.G. Sample 06A Polarized to show harder oxide bands in relief X 180.

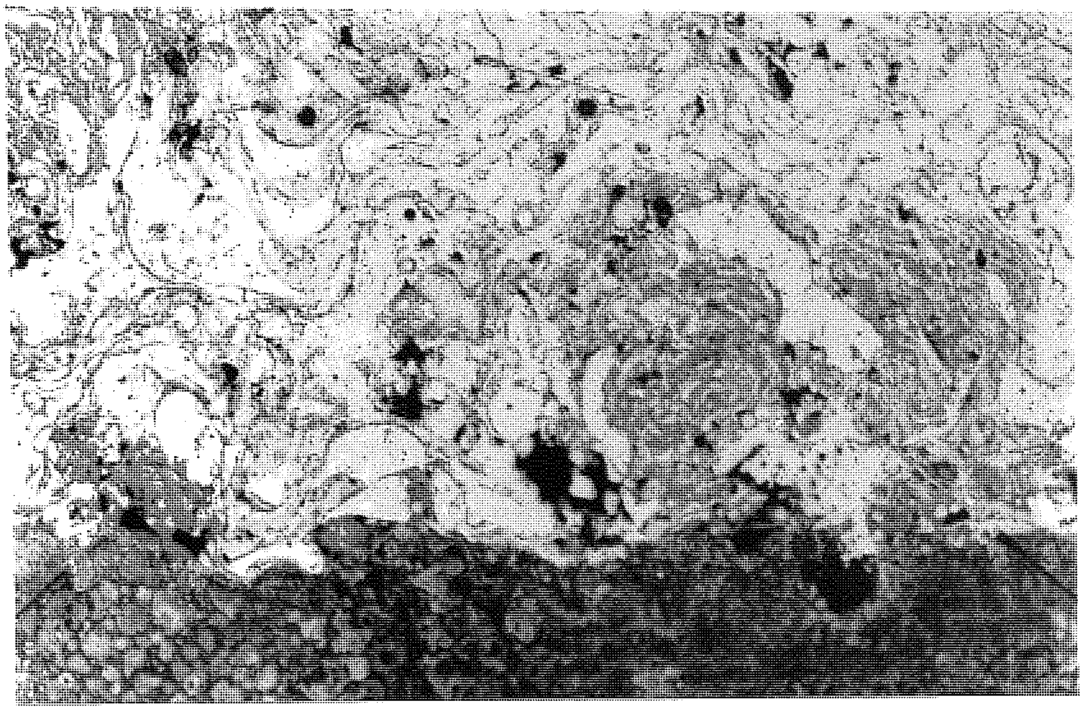

Figure 57. Std. Arcspray Sample ST1 showing dusty interface. X 220

Figure 58. Std. Arcspray Sample ST1 showing greater density in middle of coating X 220.

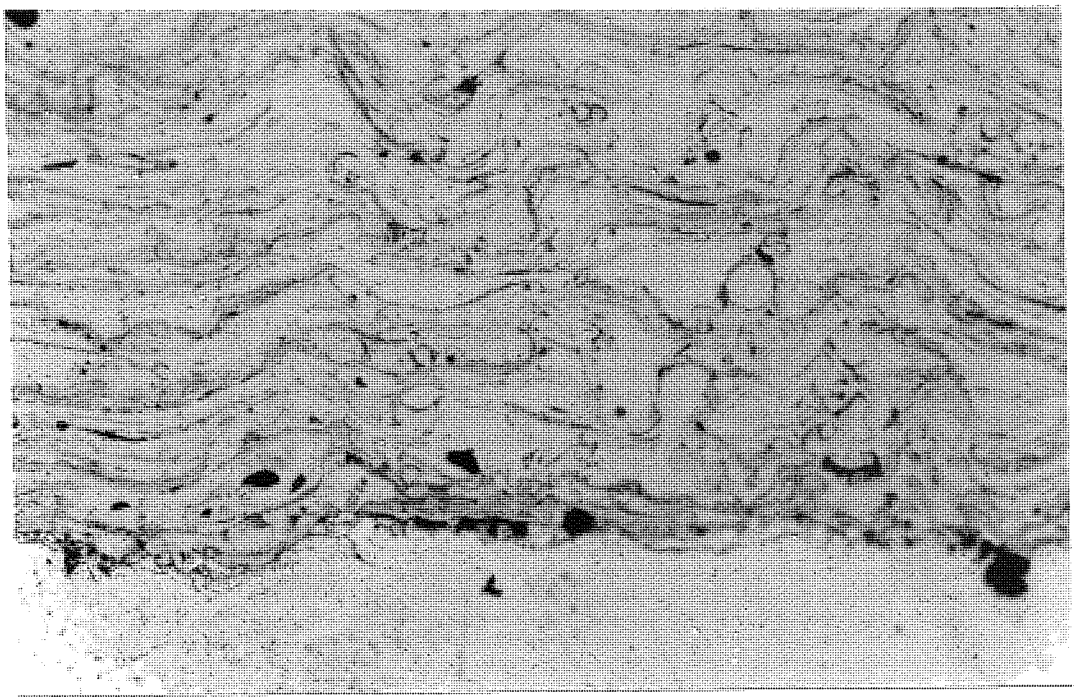

Figure 59. Std. Arcspray Sample ST3 showing good interface. X 220

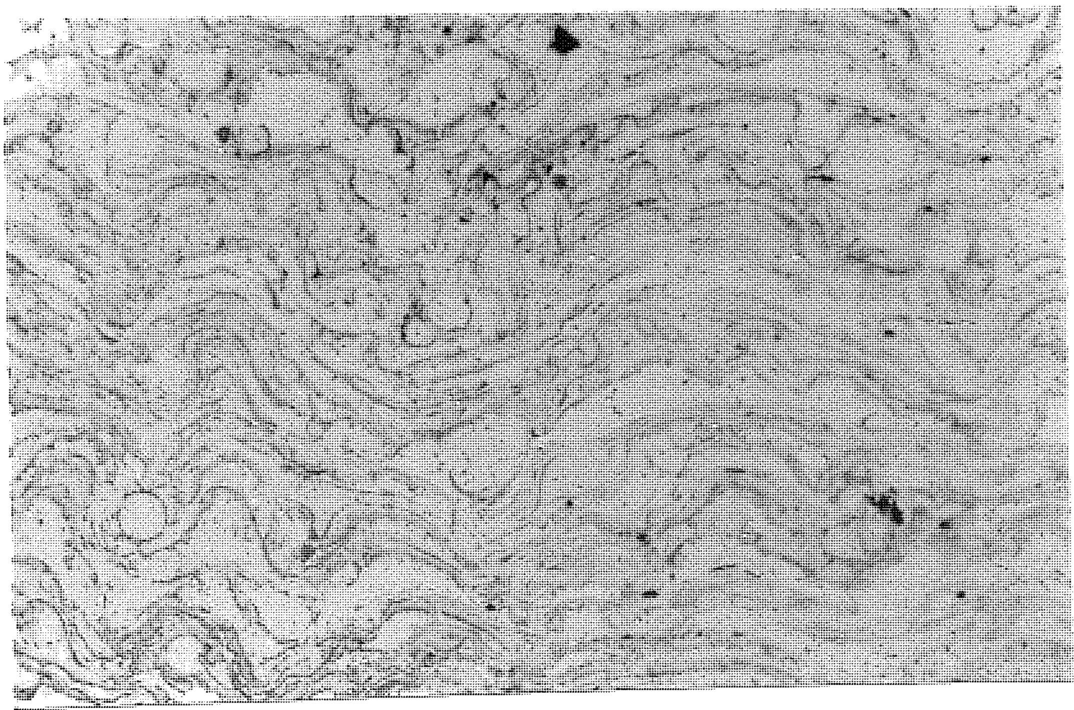

Figure 60. Std. Arcspray Sample ST3 showing middle of coating X 220.

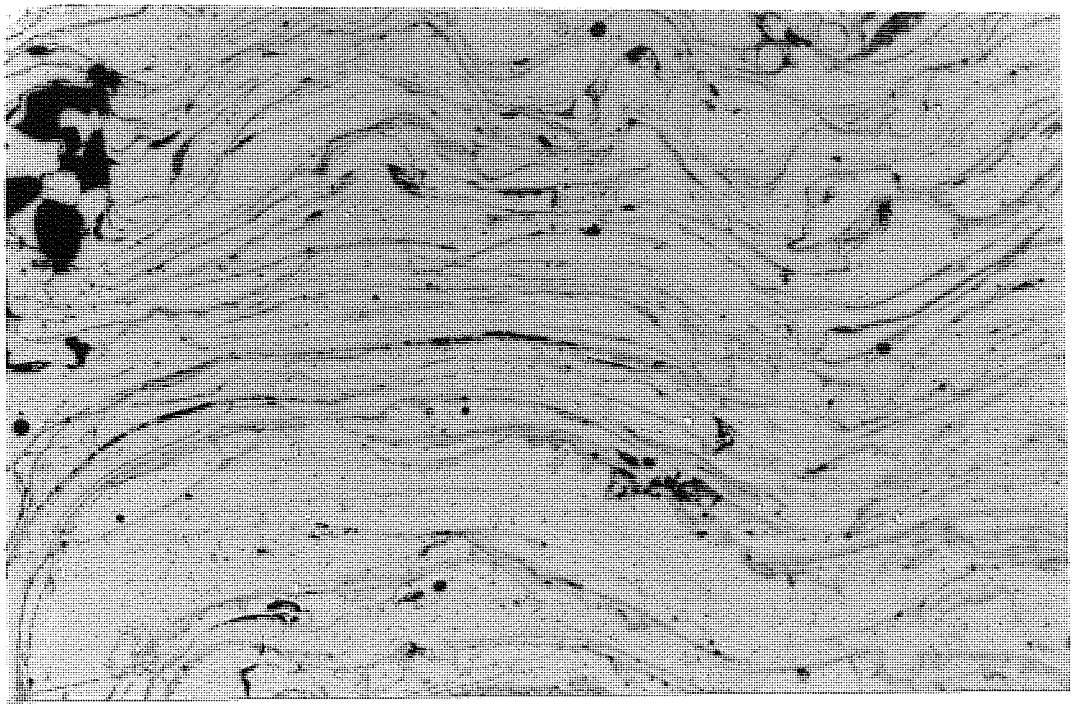

Figure 61. H.S.G. Sample HGA1 showing inner layers X 220

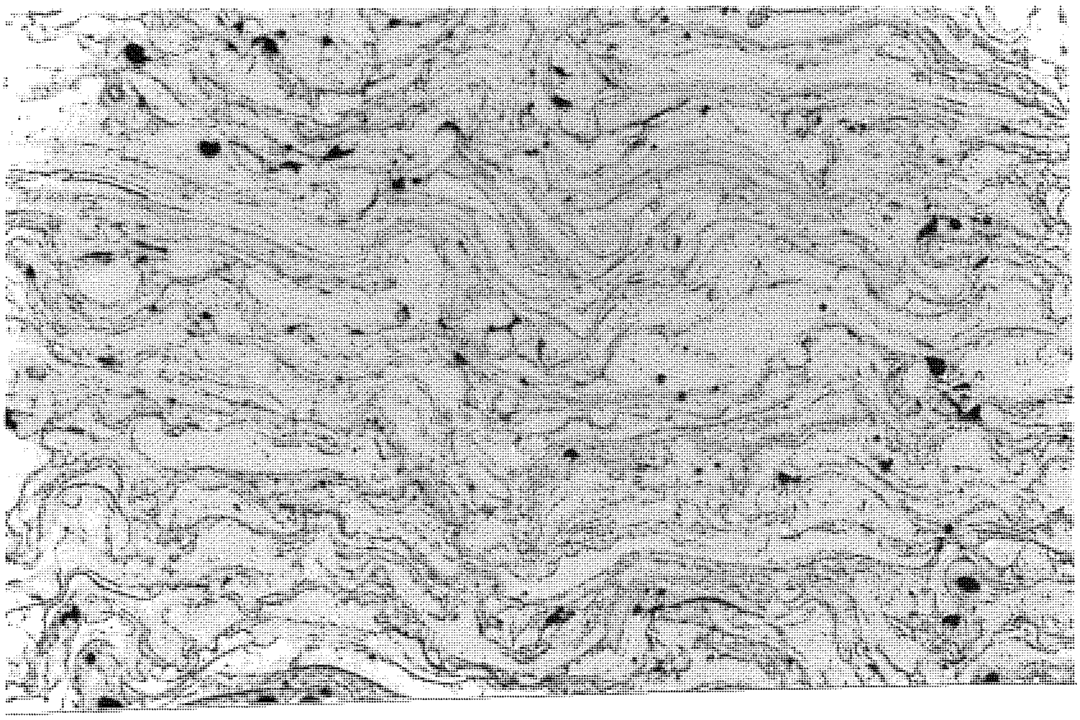

Figure 62. H.S.G. Sample HGA1 showing outer layers X 220

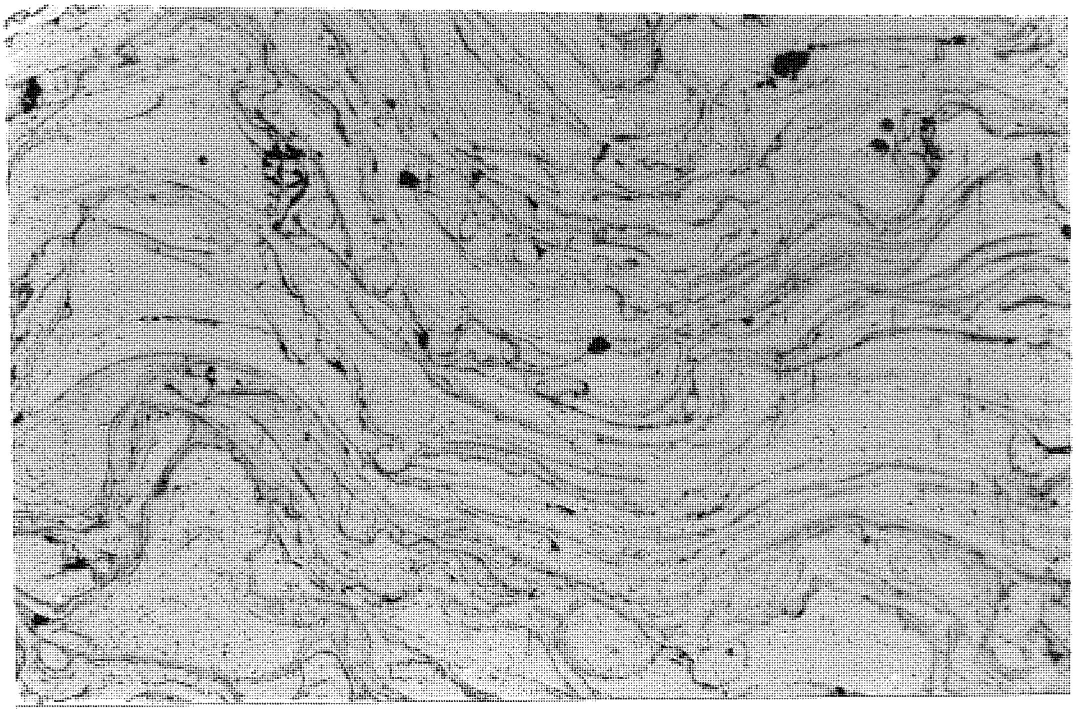

Figure 63. H.S.G. Sample HGA2 showing inner layers X 220

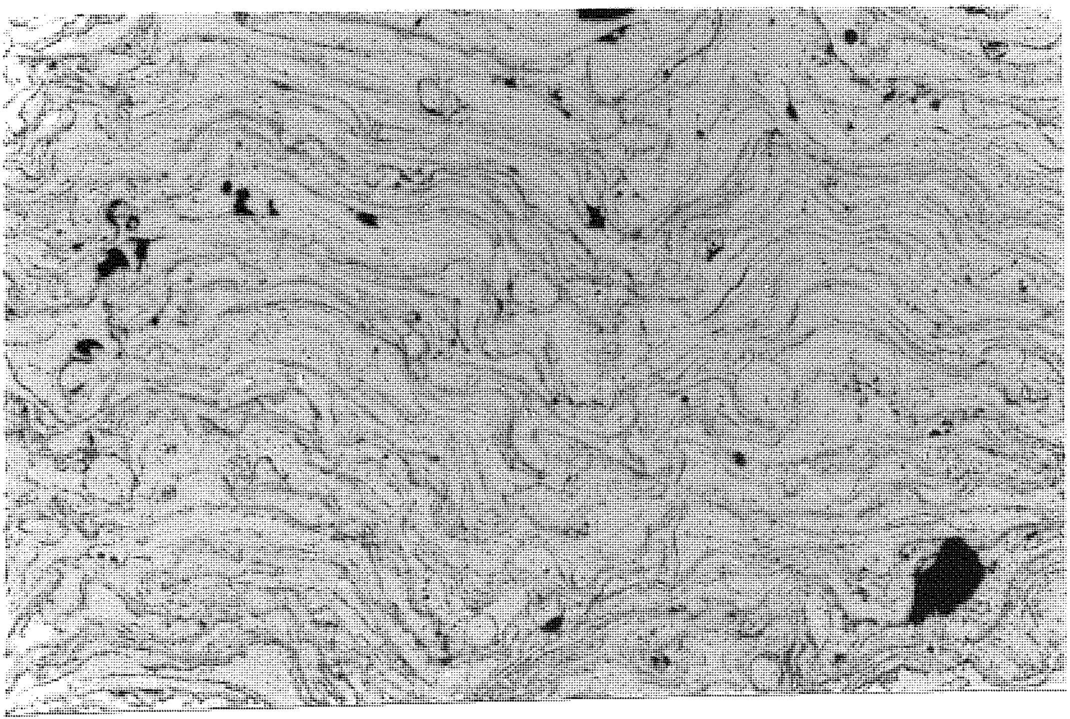

Figure 64. H.S.G. Sample HGA2 showing outer layers X 220

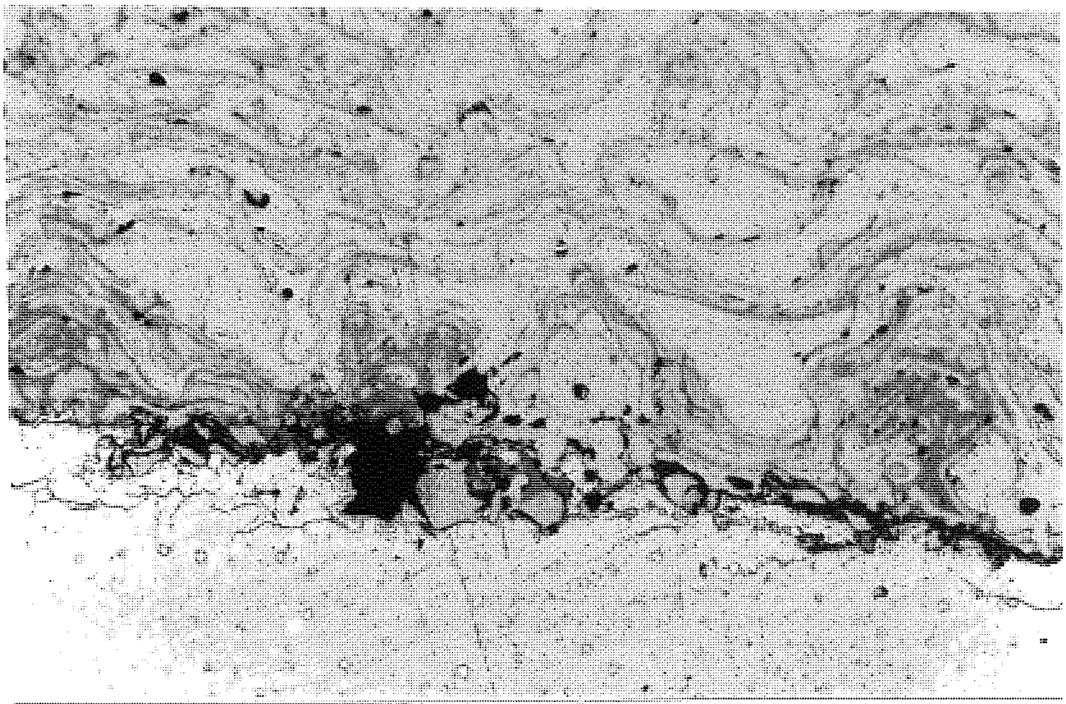

Figure 65. H.S.G. Sample HGB3 showing dusty interface X 220

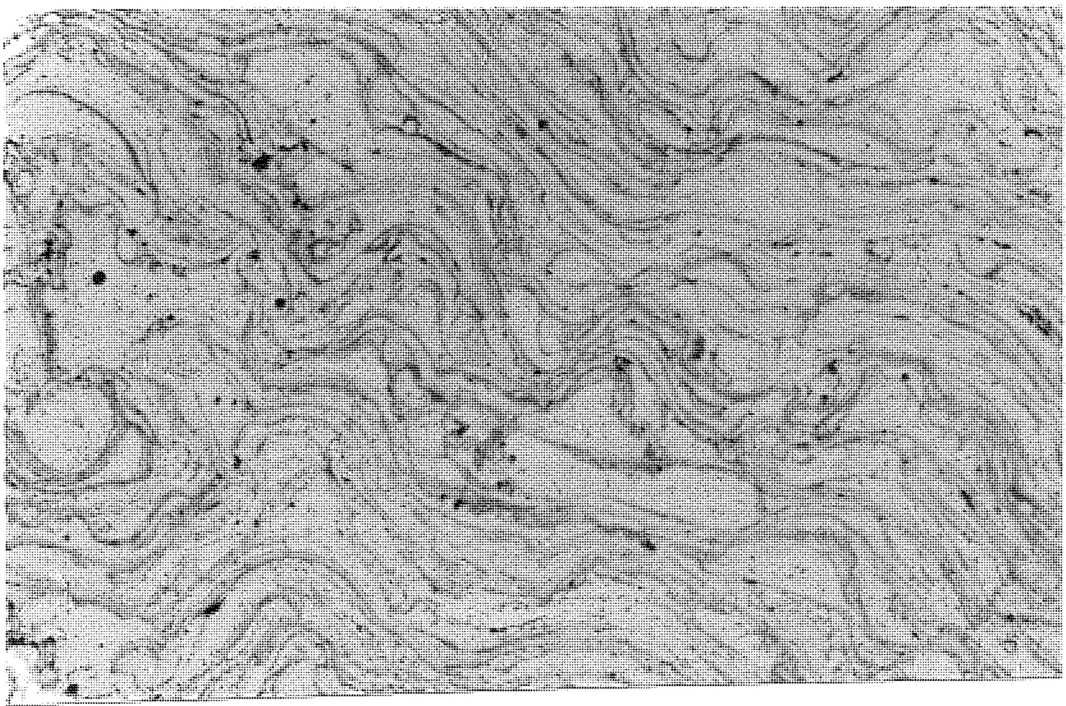

Figure 66. H.S.G. Sample HGB3 showing greater density in middle of coating X 220

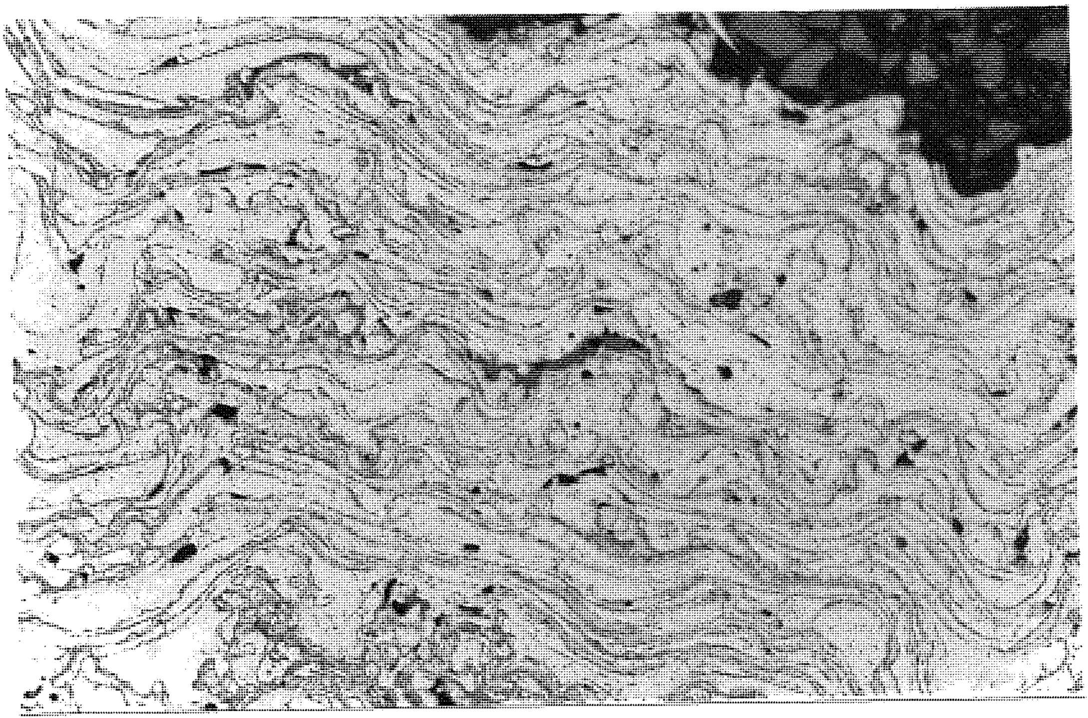

Figure 67. H.S.G. Sample HGB3 showing more dust in outer layers X 220

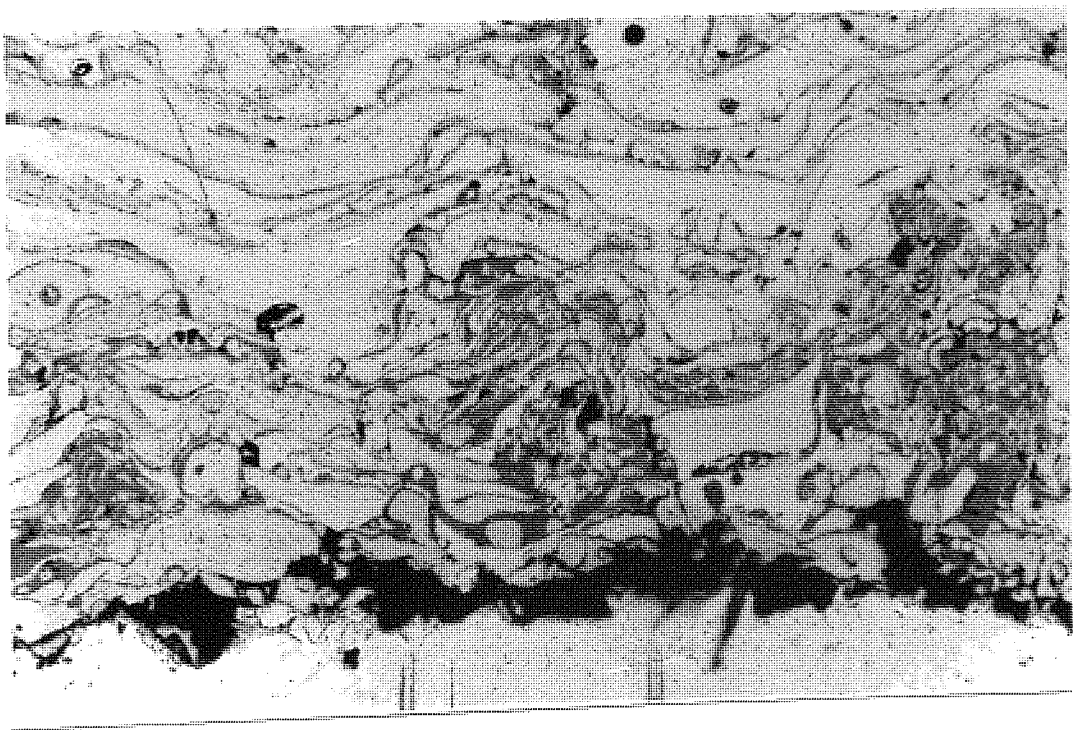

Figure 68. H.S.G. Sample HGA1 showing dusty interface. X 220

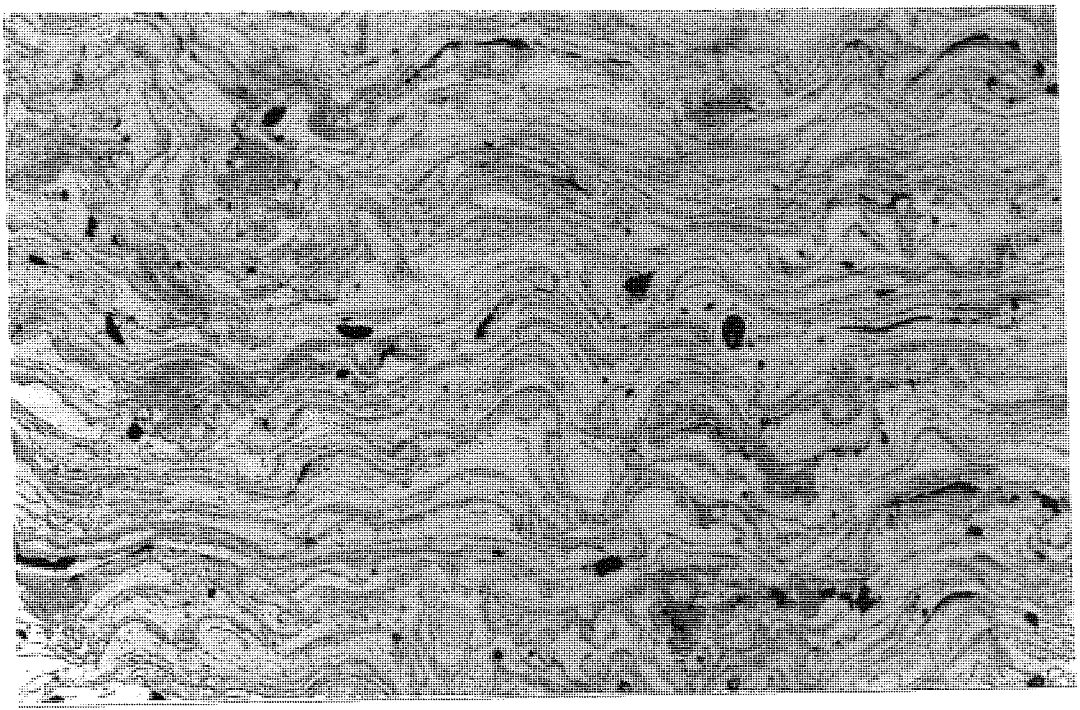

Figure 69. H.S.G. Sample 06A Vibratory polished X 220

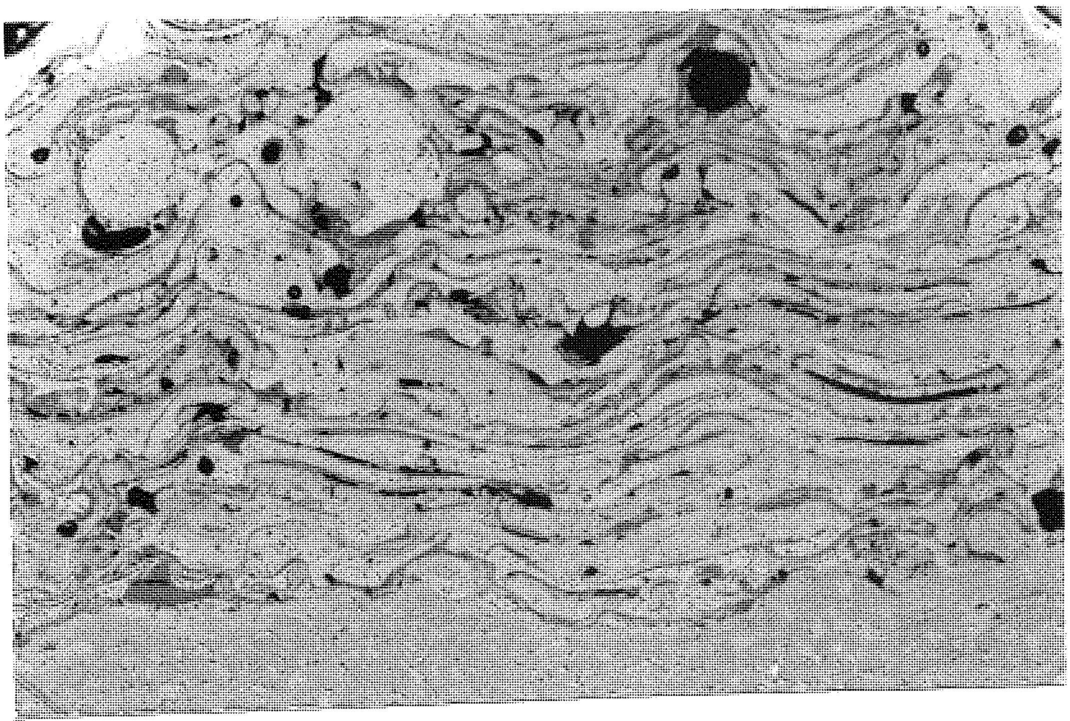

Figure 70. Std. Arcspray 60E Vibratory polished X 220

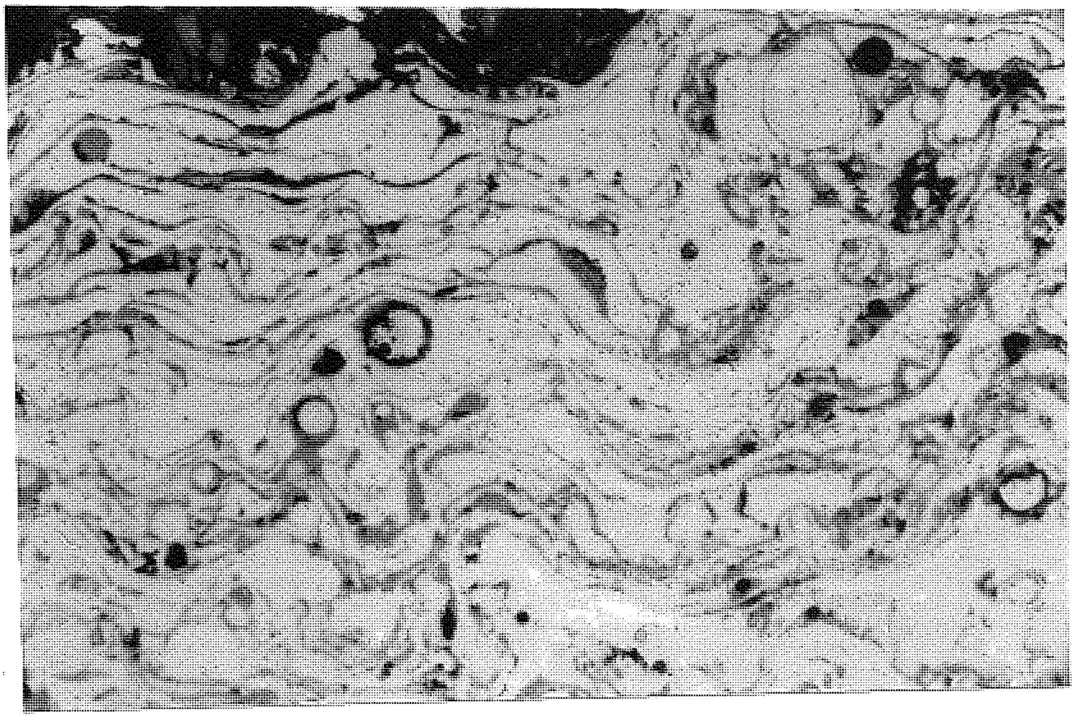

Figure 71. Std. Arcspray 60E Sprayed by hand and hand polished X 220

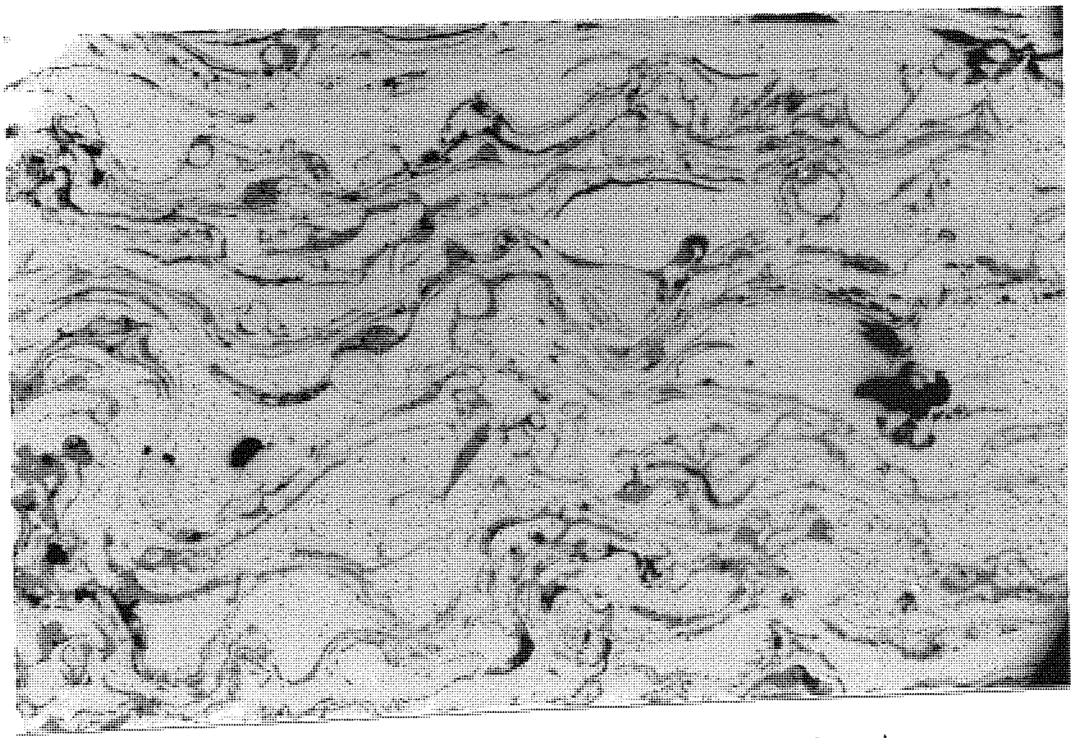

Figure 72. Std. Arcspray 60E Sprayed by hand and hand polished X 220

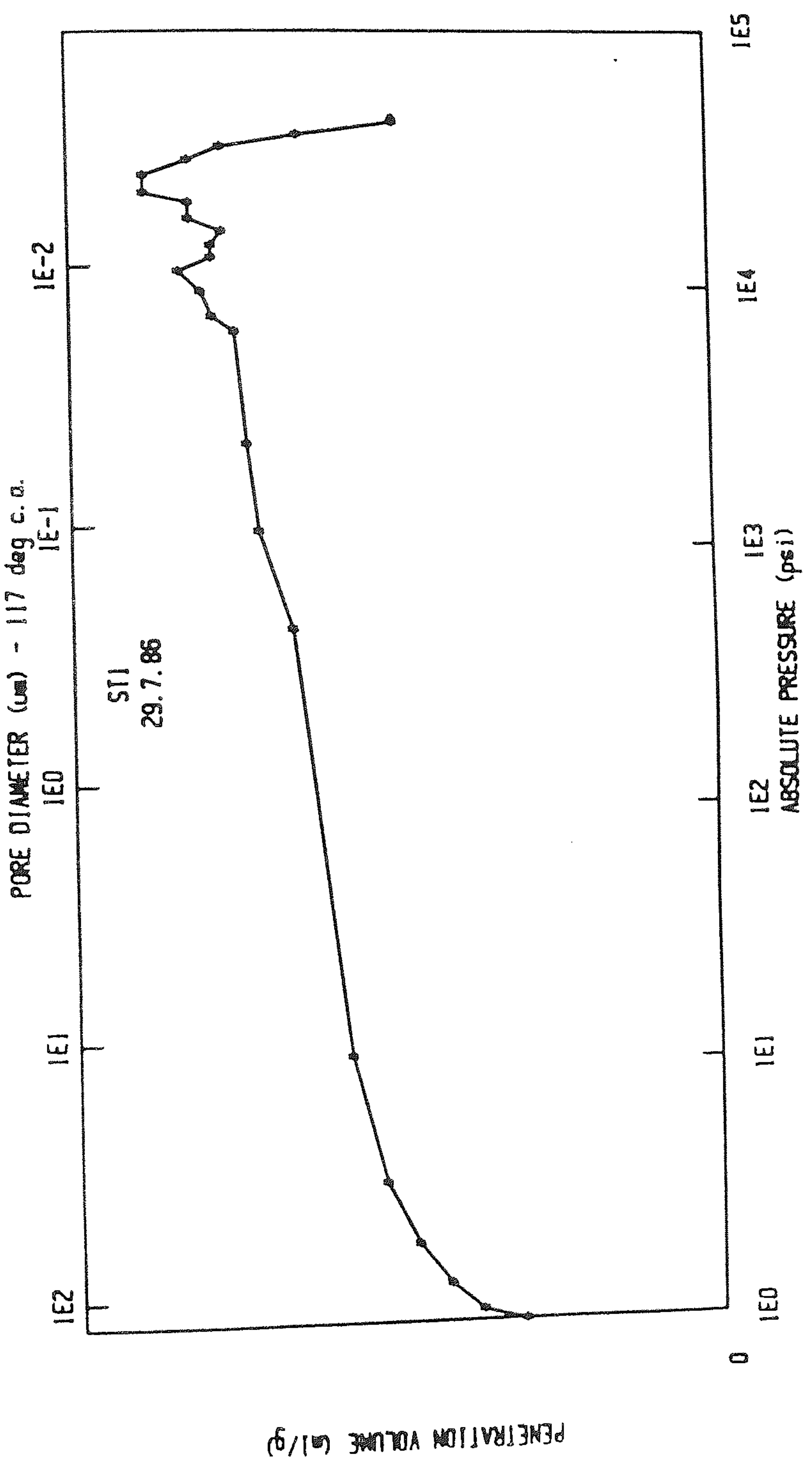

Figure 73. Mercury intrusion porosimetry plot.

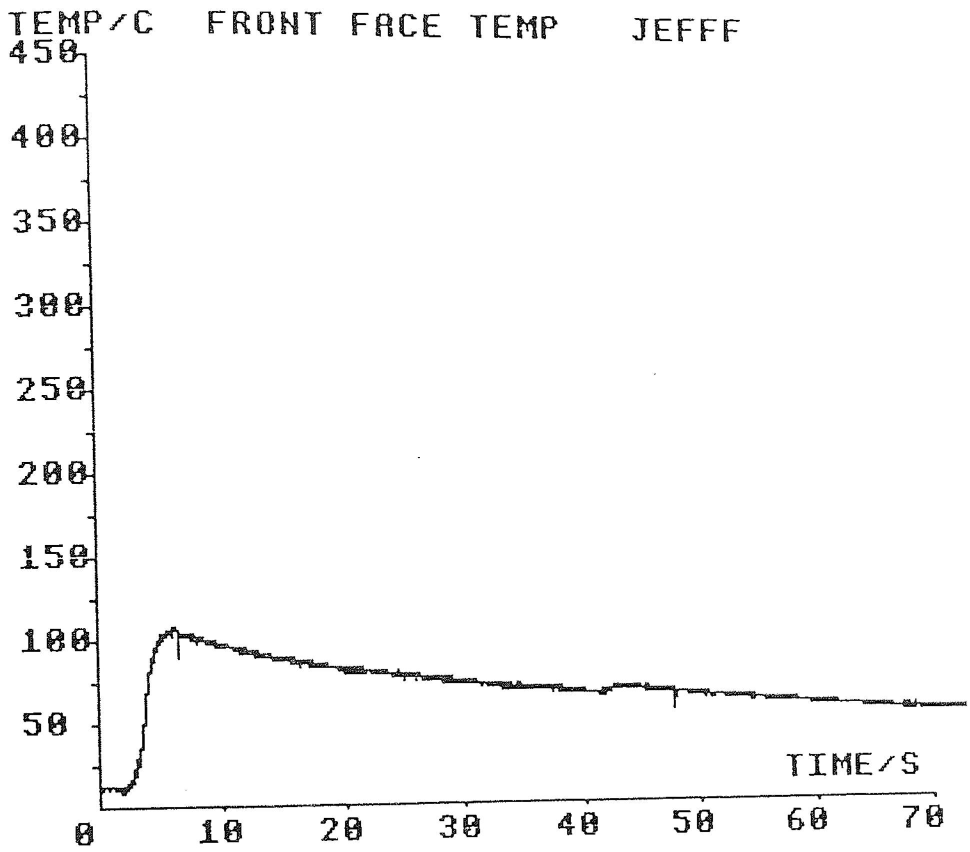

Figure 74. Sustrate face temperature, flame only.

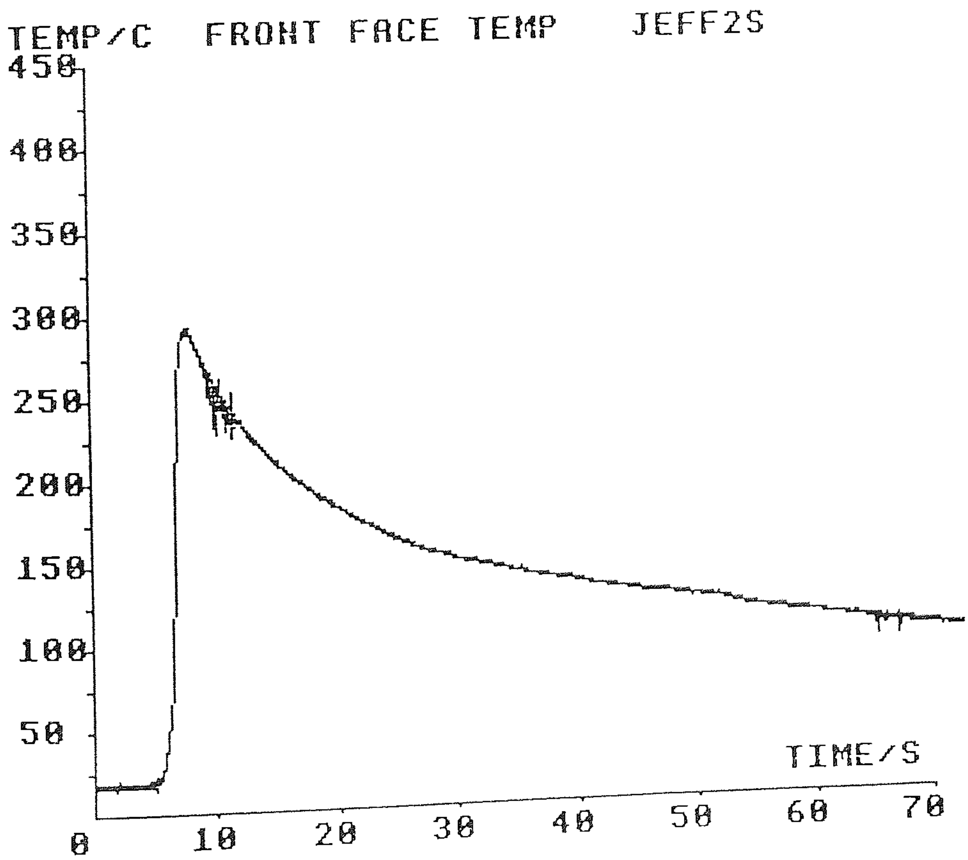

Figure 75. Substrate face temperature, flame & spray.

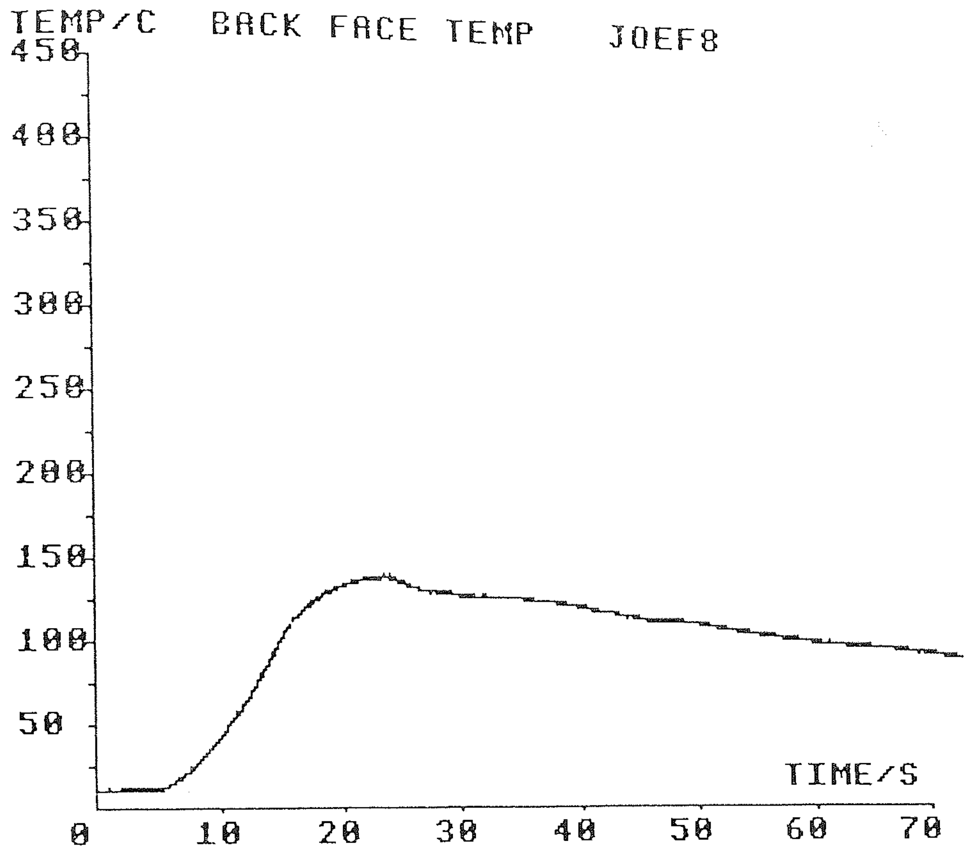

Figure 76. Substrate rear face temperature, flame only.

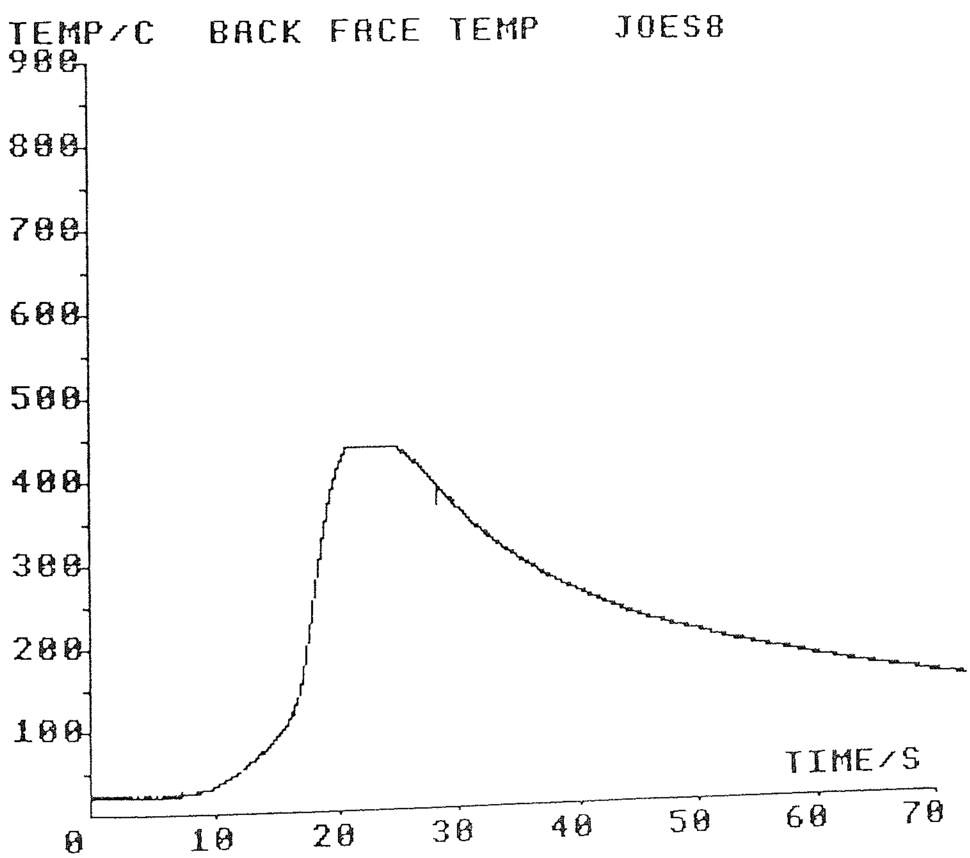

Figure 77. Substrate rear face temperature, flame & spray.

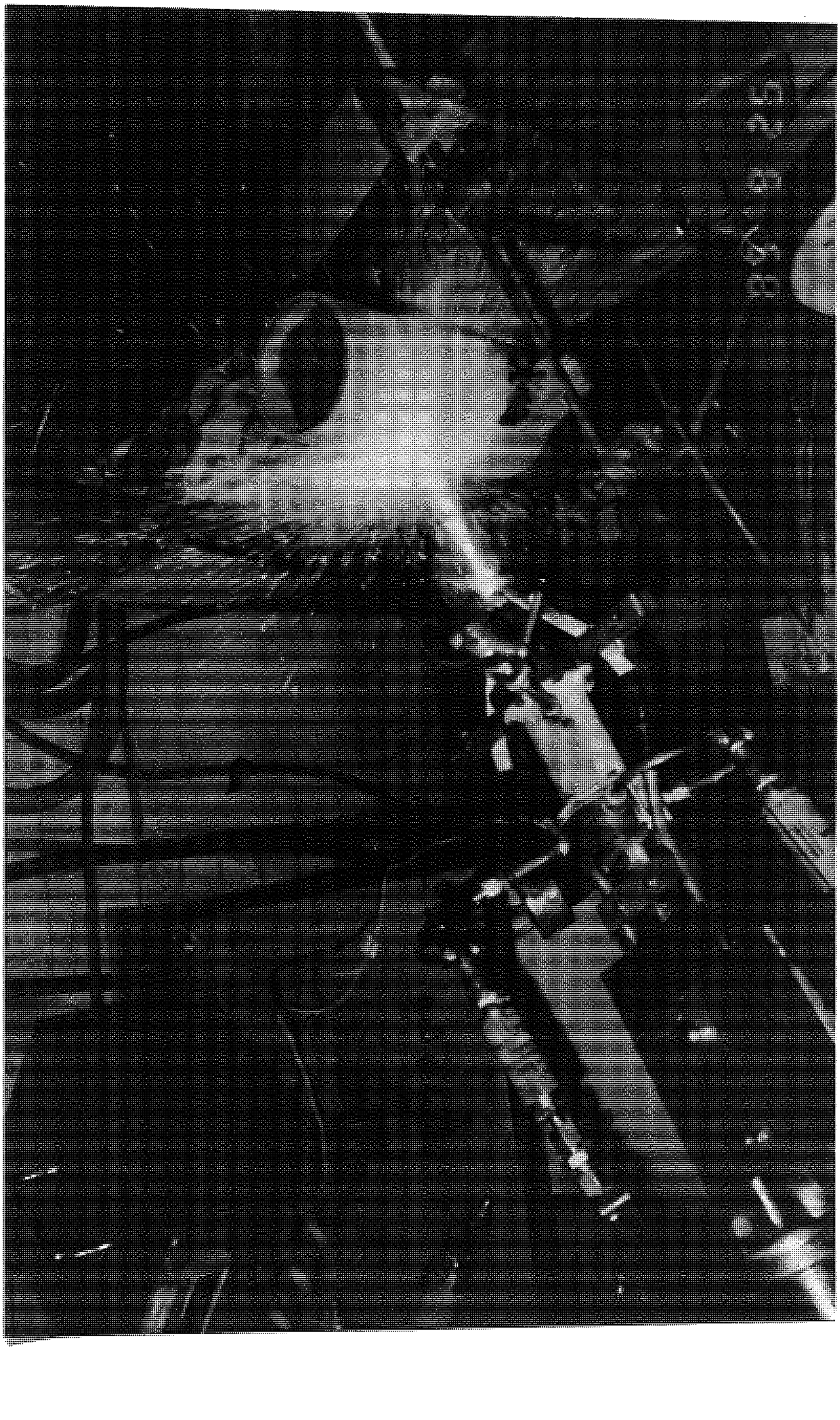

Figure 78. H.S.G. system spraying 2.3 mm steel.

Discussion

7.1. System Performance Vs Original Specification.

7.1.1 Burner performance

The original specification called for a device that used a similar volume of compressed air to a standard system and, by burning a fuel gas, accelerated these gases to a far greater velocity. At first, a gas velocity of up to 900 m/s with a temperature of 1200K was envisaged. In fact the burner can produce gas streams with temperatures from 1200K to about 1900K and velocities from 600 to 1100 m/s. Within these limits the flame is smooth and stable and the presence of several shock waves indicates that flow is certainly supersonic. If the measured velocities are compared with those predicted by theory, it can be seen that there is reasonable agreement.

The burner is very easy to ignite and to bring to full throughput, although a few seconds must be allowed for this process as the tube bundle stabiliser must be hot before the highest flows are stable. Were the device to go into production, an electrically operated valve would probably be employed for the lighting phase.

7.1.2 Stability of Arc-spraying.

In order to achieve stability at the arc, a balance must be struck between providing sufficient flow of gas to remove the molten metal, and not having so much as to "blow out" the arc. If molten metal remains at the rear of the arc it effectively shorts out the arc column and extinguishes the arc. After a short time, sufficient energy is built up to explosively remove the material and the arc is re-struck across the resulting gap, until metal builds up once more. The result is a noisy and splashy spray with a poorly directed spray-stream. At the other extreme, too much air will blow the arc away from the wire tips and the arc must re-strike onto relatively cold wire tips drawing very high currents for short periods. The effect is recognised by a repeated staccato cracking sound at a frequency ranging from a few Hertz to a hundred or so.

The total pressure plots of figure 29 (page163) show the flow pattern produced by a standard form of nozzle developed empirically. Such nozzles commonly provide two jets which coalesce at the arc-zone to form two high velocity regions designed to atomise and project spray material, and a central region of lower velocity aimed at stabilising the arc. The size and velocity of this region depends upon the size and pitch of the nozzle holes and the angle between them. In general any particular pistol will have been designed to spray one size range of wire only and the nozzle pressure distribution will reflect this in the size of the reduced pressure region. For ease of wire feed and reduced wear upon pistol parts, the industry standard wire sizes are 1.6 and 2 mm. If the best atomisation is to be achieved, the pressure distribution should be symmetrically positioned about the spray wires.

When these principles were applied to the production of the high speed gas (H.S.G.) nozzle, certain restrictions arose due to manufacturing problems. Since thin walls are difficult to achieve in the machining of powder compacts of silicon nitride, the nozzle has a wider than normal hole pitch. This creates difficulties in spraying small diameter wires (=< 2mm) with anything but the most energetic flames, indicating that there is insufficient flow to clear the rear of the arc. Moving the tips of both wires closer to the high velocity stream of one of the jets confirmed this view. This caused a marked improvement in stability, perhaps at the cost of quality of atomisation and particle acceleration. Since samples for tensile and porosity testing were produced using 2mm wire, it may be that coating quality was not as it might have been for these samples.

When operating at its best, the low voltages and currents at which spraying was possible demonstrated the generally beneficial effect of the hot gas stream upon arc stability. High speed film of the arc (15) and oscillographs of the arc voltage (11,12) suggest that the arc is not a continuous phenomenon, but is extinguished and re-struck frequently. Therefore the voltage required across the arc is more dependent on the energy needed to strike and re-strike the arc than the energy involved in melting metal when an arc exists. One can imagine that pre-heating of the wire tips and increased ionisation due to the presence of the flame, may reduce both the energy required to initiate and maintain an arc, and to melt wire. Heating of the wire tips also occurs through resistance effects because the wire must carry current for the distance between the contact tip and the arc. However, this effect is different to the flame heating of the wire tips, since gas heating ocurrs all the time but resistance heating occurs only when current is flowing, so that on breakdown of the arc the wire tips cool.

7.1.3. Particle behaviour.

Steffens (15) has used silhouetted high speed filming to show the initial stages of atomisation near to the wire tips. However, when high speed filming is performed further along the stream, the particle numbers increase to such an extent that individual particles cannot be tracked easily. Nevertheless it has been possible, using a speed of 8000 frames / second, to show particle tracks in the H.S.G. spraystream which infer a particle velocity of 600 m/s., which was the predicted velocity for a 40e-6 m particle travelling on the centre-line. However, the high speed film also shows that a large number of particles attain less than 50 m/s. Since the slow moving particles are less likely to be atomised into small particles, they will account for a higher percentage of the mass of the coating. Considering the strength of the coating, the effect of say ten percent of the inter-particle interfaces being weakened would be considerable.

The high speed film also showed that the particles were greatly affected by turbulence. The bulk of the spray-stream would follow an undulating path at short range as it was moved towards one or other of the main jets and was pushed back again by the higher pressure. Even at greater range, when the jets have coalesced fully, the particles do not travel along smooth arcs but zig-zag. The transverse velocity of such movements appeared to be as high as 100 m/s, although this cannot be found from a two-dimensional photograph without knowing the true direction of movement.

During the production of the first samples, a feature of the H.S.G. system spraying 2.3mm wire was the concentrated nature of the spray stream. The cone diameter was about one fifth of that reported by Johnston (64) at 195mm range i.e. 35mm compared with 180mm. However, the effect was not as marked when 2mm wire was used and a cone diameter of around 100mm was estimated. The concentration of the spraystream may be attributed to the change in balance between the accelerating forces applied by the gases and the electro-magnetic forces of the arc which tend to throw particles out at right angles. This implies that particle acceleration was more effective with 2.3mm wire.

On the whole, if the average impact stress of the coating particles has been raised then this should be beneficial. For this to occur more effectively as many as possible of the particles must be properly accelerated and this is a matter of refinement of the nozzle geometry.

7.2. System reliability

7.2.1. Operating consistency.

In terms of consistent operation the burner has been very good, giving a similar output stream for similar input pressures and flows at each run. Unfortunately the same cannot be said of the spray produced. When the system operates well, the spray is continuous and stable, but at other times instability and a mis-directed spray-stream have been produced. In addition to the limitations of the nozzle geometry with respect to atomisation of small wires, the distance between the contact tubes and the arc or "throw" was unusually long. The "set" present in coiled wires causes the wire tips to wander and become temporarily misaligned and the effect is exaggerated by the longer "throw". Tip misalignment is also less problematic when larger diameter wire is used.

7.2.2. System parts life.

For structural reasons the outer steel shell of the burner had to be kept to a temperature of less than 500C during extended operation. To remain within the cost constraints, it had been decided that water cooling should be excluded. Furthermore, the pistol geometry required a burner outer diameter of 50mm or less. The internal diameter of the combustion chamber is dictated by gas flow and flame stability considerations. This leaves a limited thickness in which to achieve the desired level of insulation. Since the nozzle and tube bundle stabiliser required a precise geometry, a refractory insulating material, stable at high temperatures without crumbling or flaking, and yet capable of precise forming at reasonable cost was required. Reaction bonded Silicon Nitride was selected. Although this material begins to decompose to its constituent elements at around 2000 K, the resulting silcon oxidises immediately to form an insulating skin of silica.

Earlier trials with mullite liners, cemented directly into the shell, had shown insufficient insulation so that an insulating layer had to be interposed. The cylindrical air space of the last design allowed cooling air to flow between the liner and the shell and also allowed the issuing gas stream to be further diluted with air if required. This extended the usable spraying time to seven minutes but this was clearly not adequate. The problem of insulation of the

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nozzle carrier was more acute since the outside diameter tapered to allow the contact tubes to approach the nozzle. A three millimetre layer of flame sprayed Zirconia allowed three minute spray before overheating. Finally, a copper coil was fitted around the nozzle carrier and cooled by tap water on a total loss basis, at a rate of approximately one litre per minute. This was sufficient to bring the equilibrium surface temperature of this part to 50 C. Clearly water cooling could reduce the main shell surface temperature by a similar amount.

The outer surface of the shell was grit-blasted and sprayed with 100 microns of aluminium and the regions likely to be touched by the contact tubes were sprayed with alumina to a thickness of approximately 150e-6 m. The shell was thus protected from high temperature oxidation and electrically insulated. The aluminium served an additional purpose, indicating that, when it formed globules on the burner surface, the temperature was excessive.
An alternative design of nozzle carrier used a longer nozzle so that the diameter of the steel nozzle carrier was not reduced as much. However, on the two occasions that such nozzles were tried, both failed by cracking, even though the stress was many times below the quoted yield strength of the material. It may be that on the second occasion the crack was initiated by thermal shock caused by contact with a cold copper contact tube and therefore it may be possible to use this design if such shocks can be avoided.

7.3. Coating properties

7.3.1. Coating structure.

In general, the structure of the steel coatings produced by H.S.G. were similar to conventional arc-sprayed coatings. They consisted of metallic lammellae surrounded by oxide layers of varying thicknesses, with pores and fissures. The pores and fissures are almost entirely associated with the oxide layers, indicating weakness usually at the oxide metal interfaces. At this point it is worth considering the difficulties in obtaining quantitative information on porosity from microstructural examination. The degree of porosity observed often depends much more upon the polishing technique than upon the porosity present. Having polished and measured the porosity by computer controlled image analysis on the same sample several times with results varying from 1 to 4 per cent it must be concluded that at best, the technique is unreliable. When compared with everyday arc-sprayed samples, the H.S.G. coatings do appear to be less porous. However there is also a considerable difference between standard coatings sprayed by machine and those produced by hand as shown by comparing figures 60 (p181) and 71 (p187).

The H.S.G. coatings produced at the higher gas flow rates are slightly finer in structure than standard. Taking into account the reduced mass flow of gas used, the hot system is clearly able to atomise the molten metal more efficiently.

7.3.2. Coating oxidation.

The fine deposit also appears to be more oxidised than normal and this would be expected, as previous work has shown an inverse relationship between particle size and oxidation. The degree of oxidation is influenced by several factors.

1/. Atomising environment.

2/. Particle size and temperature.

3/. Substrate temperature.

4/. Duration of exposure on substrate surface.

The kinetics of particle oxidation in flight are complex and depend upon reaction rates, oxygen concentration, gas boundary layer thickness and the melting point and volatility of oxides etc. Nevertheless, a judgement may be made as to whether conditions within the H.S.G. spraystream are more conducive to oxidation than normal.
Firstly, the temperature of the gas stream is much higher and the air/fuel ratio is high so that there will be an excess of available oxygen in a more reactive state. Furthermore the particles are finely atomised exposing an increased surface area in relation to their volume. On the other hand, due to higher velocities, the dwell in the

spraystream is shorter. Also, although the relative velocity is higher the Reynolds number for a given particle size is actually less in the hot system so that boundary layers on particles may be thicker reducing the availability of oxygen. Johnston (64) states that the time for which a particle remains exposed on the substrate surface is critical. This is clearly important since between spray passes where exposure times are long, very thick oxide bands can be produced. It may be thought that the importance of substrate surface oxidation is a result of the increased surface area available. However when the particle diameter is six times the splat thickness, it can be shown that the exposed surface areas are approximately equal. Since this is the correct order for such a ratio, higher levels of oxidation on the surface must be a result of an increased exposure time. Johnston (64) suggests that the exposure time for a standard system ranges from 0.16 seconds to 0.011 seconds depending upon throughput rate. Under similar circumstances the figures for the H.S.G. would be 0.027 to 0.002, approximately one sixth of the normal times. On the other hand the presence of the flame maintains the substrate at a marginally higher temperature.

The net effect of all these factors appears to be a small increase in the level of oxidation.

7.3.3. The effect of spraying technique.

The presence of surface oxidation is most obvious in multi-pass coatings. In figure 50 (p176) thick bands of oxide about fifteen particles apart are clear to see and these are formed on the surface, in between passes. These layers create weaknesses along which cracks may propogate easily, causing de-lamination of the coating. The presence of such weaknesses is often demonstrated during machining. If the tool is not very sharp and thick oxide layers exist, then the tool load can be sufficient to cause de-lamination and loss of large areas of coating. Spraying the coating in a single pass prevents such oxide bands but may not be wholly advantageous for the following reasons.

The spraystream is made up of particles with a wide distribution of temperatures and velocities. The highest velocity particles wil be found at the centre of the stream, whilst at the periphery particles become entrained in slower moving flows and are reduced to very low speeds. Also dust produced by particles which have not adhered is able to settle in the re-circulating air stream at the edge of the impact area. When thin deposit passes are used, this dust is evenly incorporated throughout the coating thickness, but with single pass coatings, all the dust and debris become incorporated at the coating/ substrate interface and a dust layer is left on the coating surface. Figures 65 (p184) to 67 (p185) show a dusty interface followed by a clean central region followed by further dust inclusions. Unless the dust is prevented from settling at the interface, the result is a cleaner coating but with relatively reduced adhesion. However, in terms of porosity and tensile strength, the properties of such coatings should be better than normal. For plasma spraying, Houben (71) and Fauchais et al (42) both suggest the use of a gas barrier to cool the substrate surface and to remove any slow moving particles travelling in the periphery of the spraystream so that only energetic particles are used to make the coating. This has not been used to any extent with arc spraying but Blewitt (9) has found that at extreme spray ranges, of greater than one metre, quite clean coatings are produced as the dust particles lack the momentum to reach the substrate at all. An interesting feature of the microstructure of the H.S.G. coatings sprayed in single passes, is the graduation in particle size that can be seen through the coating thickness. Figures 61 and 62 (p182) are sections at the same magnification taken through the same coating sample. The former shows the coating relatively close to the substrate whilst the latter is of the outermost layers and is finer in texture. This same pattern is repeated for a completely different sample piece sprayed with similar parameters as shown in figures 63 and 64 (p183). Presumably the earlier section is composed of particles from a coarser region of the spraystream. All the porosity test pieces were sprayed with the traverse in one direction only, travelling from right to left, and therefore the left side of the spraystream produced the earlier layers. This effect demonstrates the possible errors involved in thinking of the spraystream as a uniform system and of using average values as indicative of its properties.

7.3.4. Coating porosity

Johnston (64) has also shown that in normal arc-spraying the porosity of the coating decreases with increasing range from 11.73% at 40mm to 5.27% at 195mm. Interpolating would give a porosity of 8.9% at 127 mm. Toluene immersion porosity measurement on an H.S.G. coating at this range gave a value of 1.47% compared with a similarly tested standard coating which gave similar values. These were remarkably low values and to find the effect of coating thickness upon apparent porosity the samples were ground in two stages of 1mm on radius and re-tested. Plotting pore volume against surface area shows that this is almost a constant implying a limit to the depth of penetration. Thus, for toluene immersion tests to be valid, a pore volume and surface area should be quoted and the sample thickness should be sufficient to prevent passage of the liquid right through the coating. If percentage porosity is plotted against coating thickness and this graph is extrapolated to zero thickness this implies a maximum possible porosity of approximately 8%, which is similar to the published values. Within the scatter there does not appear to be a significant difference between the

H.S.G. and standard coatings.

The samples in this series of tests were all sprayed in single passes to a thickness of 3mm. whereas Johnston used a multi-pass technique.

7.3.5. Coating hardness.

As has been stated the structure of a sprayed coating is inhomogeneous, consisting of metallic and oxide lammellae and pores and fissures. The thickness of the lammellae varies from about 2 to 20 microns and is therefore small compared to the size of a hardness indent. Thus the macro-hardness is greatly influenced by the underlying structures. Therefore, if an indent is made over a pore, a low value will result, whereas if a dense oxidised area underlies the indent, an unusually high hardness will be recorded. The effect is to give a wide scatter of readings and it is a matter of judgment whether to discard readings that are considered abnormal. Ford motor company specification (83) for instance calls for the two lowest values out of five to be ignored in the estimation of macro-hardness of sprayed molybdenum coatings on piston rings.

Johnston (64) uses an average of six values when testing similar sprayed steels and this is the approach adopted here. The macro-hardness of H.S.G. 60E is slightly higher than normal, but does not appear to depend greatly upon range except that, in agreement with other work, it is slightly reduced at very close range. It is accepted that fine, oxidised coatings exhibit higher hardness so that somewhat higher than normal values may be expected due to increased oxide content and reduced porosity.

The micro-hardness is similarly affected by underlying particles and voids and thus scatter is large. However micro-hardnesses of the H.S.G. particles do not appear to be significantly different to those of standard arc-spray. The principle mechanisms of hardening i.e. the formation of martensite and a fine grain structure depend upon the cooling rate of the particle which is unlikely to be affected by the slightly raised substrate temperature created by the flame. This is in marked contrast to the plasma spraying situation where Houben and van Liempd (43) find that two thirds of the heat input to the substrate is due to the plasma itself and that surface diffusion of plasma sprayed molybdenum would not be possible without this heat input. It should be noted that flame sprayed molybdenum particles may be much larger with much higher heat contents. Thus Houben's work cannot infer that surface diffusion does not take place with flame wire sprayed molybdenum.

7.3.6. Heat input to the substrate.

The heat input to the workpiece from the flame was shown to be much less than that of the spray particles and it could be ignored for all likely applications of the process. It should be recalled that when the various options for improvement were originally discussed in chapter 3, it was understood that the process would not be suitable for applications such as mould production or electromagnetic screening, where substrates are easily damaged by heat. By comparison with the Jet-Kote process and Plasma spraying the level of heat input to the substrate appeared small.

7.3.7. Strength of the coating.

In addition to improving the coating density, higher velocity particles should increase the cohesive strength of the coating. Bend tests, as performed in this work and by Overs (85), are really a comparative test of the adhesive and cohesive strength of the deposit, the higher the cohesive strength the more likely that the coating will fail with a single crack followed by delamination along the interface with the substrate. If the adhesive strength is high by comparison, failure is by multiple transverse cracks without peeling. However, the force required to delaminate the coating will be roughly constant, whereas the force to crack the deposit normal to the substrate is proportional to the thickness. Furthermore, the presence of residual stresses affects the effective adhesive strength with the effect increasing with thickness. Thus the test is coating thickness dependent. Nevertheless, for similar thicknesses, coatings produced by H.S.G. spraying all failed with a single crack, whereas the standard arc-spray produced multiple cracks and if similar bond strengths are assumed, this implies a higher cohesive strength, which was not supported by later work.

The direct tensile tests on samples of coating material showed considerable scatter and this is to be expected from the defect rich nature of the microstructure. Nevertheless, it was clear that the coatings produced by H.S.G. were weaker than their standard counterparts. In terms of energy per unit volume absorbed at failure, the H.S.G. coating failed at less than half the energy absorbed by the normal coating for the same range. At greater range, H.S.G. performed better, reaching 86% of standard energy absorbed. This suggests a surprising dependence of strength on range.

The fracture faces of two of the coatings were examined by S.E.M. looking for signs of ductile failure but none was apparent. All failures were, as expected, brittle cleavage fractures or associated with failure of the oxide layers between particles. Nevertheless the coatings are not perfectly elastic. In cases where failure did not occur through the strain gauge a residual strain of around 15% remained. Berndt (86) explains such an occurrence in plasma sprayed ceramics by slippage between individual lammellae and similar effects have been noted in testing of sintered materials.

In comparison with previously published results the values of modulus fall between those of Johnston (64) and Overs (85) and the ultimate tensile strength is significantly higher than either previous work records. The difference may be attributed to the spraying technique involved. Johnston had produced samples from coating material by cutting a piece from a coating, machining and gritblasting, and then building up new layers of sprayed metal until the required dimensions were achieved prior to re-machining the final test piece. This process will lead to errors because:

1/. There is a layer of weakness between the core and the new layers.

2/. Since their thermal histories and original geometries are different, the core will have different mechanical properties.

3/. Residual stress levels in the core and the new layers will be different.

All these factors will cause the samples to behave as composite bars and must cause an unusual stress distribution leading to premature failure in the most highly stressed region.

Overs used a test on composite bars of steel substrate and sprayed coating and this must also suffer similar shortcomings due to uncertainty about the true stress distribution.

Both these previous works used coatings sprayed using an outdated spraying system which was more prone to inconsistencies and both sets of samples were produced using a multi-pass technique which gave inter-pass oxide layers and higher levels of dust inclusion.

7.4. Comparisons with other systems

As has been discussed previously there are six general forms of thermal spraying equipment. However one way of classifying such systems would be on the basis of the principle form of energy produced, thermal or kinetic. If they are arranged in ascending order of kinetic energy it can be seen that this is also in ascending order of general coating quality thus.

1/. Powder flame spraying.

2/. Wire flame spraying.

3/. Arc-spraying.

4/. Plasma spraying.

5/. Hypersonic flame spraying.

6/. Detonation gun.

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Having said that it must be remembered that certain equipment excels in particular areas. For instance Hypersonic flame spray produces outstanding metal and Tungsten carbide based coatings but is incapable of spraying ceramics since it cannot produce the required temperatures and dwell times for softening to occur. Those systems which rely upon thermal energy must ensure that the material is thoroughly melted so that particles can flow over the surface and fill pores to create a dense coating. This is one reason why exothermicly reacting powders are often used in powder flame spraying. On the other hand systems which produce high particle velocities and hence kinetic energies, do not require complete melting, indeed overheating can be a disadvantage as the particles can splatter instead of spreading evenly over the surface.

Arc-spraying falls between these extremes. On the one hand it is very effective in melting material and is the most energy efficient system. Clearly since it is a wire fed process no material can leave the wire without being melted. However, it achieves a superior coating quality over powder flame spraying due to the much higher particle projection velocities. The principle question which this work attempts to address is whether the coating quality of arc-spraying could be further enhanced by significantly increasing these velocities. It would appear that increased velocity has not greatly improved coating density and a more detailed study of the reasons for the integrity of high velocity combustion sprayed (H.V.C.S.) coatings may reveal why this is so.

Metal coatings produced by HVCS have very low porosity and low levels of oxidation and there are two possible reasons why this is so. Firstly the flame is very long and is allowed to impinge upon the workpiece. It has been suggested that this may shield the hot particles from the air and thus reduce oxidation. However studies on the mixing of jets such as by Forstall and Shapiro (44) have shown that air is rapidly entrained into the spraystream and furthermore attempts to reduce oxidation in flame wire sprayed coatings by using inert atomising gases have also shown limited success due to the free oxygen which is always present in the flame. The second theory proposed by Browning (78) and others, suggests that due to the high velocities the particle dwell time in the flame and in flight is very short and that particles are not heated to the same degree as with other systems. In this way both the reaction rate and the time for reaction are reduced and by correct selection of powder size and flame parameters high velocity particles which are softened but not melted will be produced.

If this second argument is transferred to the HSG arc-spraying system clear differences can be seen. Firstly the particles are fully molten, many will be superheated and highly reactive. The particles will be exothermically oxidising in flight and will retain their temperature until impact. This is demonstrated by the fact that arc-sprayed steels retain a deposit efficiency of over 70% at a range of 2 metres as found by Blewitt (47). Also the arc-sprayed particles will have a much lower viscosity and surface tension and will be more likely to splatter on the substrate surface than spread in a uniform way. Increasing the particle velocity will increase the degree of splattering. Also the impact stress imparted to the substrate will be much greater with a solid or semi-solid particle than with a liquid droplet for the same impact velocity. This factor is very important to the bond strength and cohesive strength of the coating.

On the other hand it would have been expected that since impact stress will be proportional to the square of the impact velocity some increase in bond strength and cohesive strength would have occurred.

7.5. Economic and commercial aspects.

7.5.1. The primary economic case for improving arc-spraying.

There is a case for improving the quality of the coatings produced by arc-spraying to a level where these could compete with some plasma sprayed coatings.

Plasma spraying can deposit a wide range of materials allowing many surfacing problems to be solved by thermal spraying. Also it must be conceded that in almost all circumstances the quality of plasma deposited coatings cannot be matched by present day arc-spraying. However when compared with arc-spraying, the capital and operating costs of the plasma system are high. Arc-spraying has considerable advantages in terms of spraying rate and the cost of consumables and in capital cost. Arc-spraying can be over 14 times cheaper than plasma spraying per kilogram deposited as shown by Gustafson (87) referring to boiler protection coatings.

In many cases the full quality afforded by plasma coatings will not be required, in other words, some users are forced to use plasma because arc-sprayed coatings are marginally unacceptable.

7.5.2. Cost benefit characteristics of H.S.G. spray system.

7.5.2.1. Capital and running costs of H.S.G.

Capital costs:

Liner	@ £50 ea
Shell	@ £25 ea
Front holder	@ £50
Nozzle	@ £30 ea
Swirl	@ £50 ea
Traps	@ £15 ea x 2
pipes	@ £30 set
Flowmeters	@ £150
Igniter	@ £25

Total added cost:

£440 for a minimum system

Discussion

Running costs:

As per std Arc-spray plus:

5 l/min Propane @ £5/hr

envisaged increased spares cost £10/hr.

The capital cost is well within the limit of £1000 proposed in the original specification and no constructive modification can be envisaged which would take the cost over this amount. The running cost due to gas consumption is almost exactly as predicted but the actual cost of spares is much higher than could be accepted at around £100. This is the area in which constructive modification could be made, adding about £100 to the capital cost but hopefully bringing the spares usage to the envisaged level.

7.5.2.2. The benefits of H.S.G. spraying

Unfortunately there appear to be no outstanding benefits to be gained from H.S.G. except that the spray is significantly more concentrated. However it may be that re-design of the conventional atomising head could achieve this result at lower running costs. Nevertheless were the system to provide significant advantages it is interesting to assess the reaction of competing companies and discuss the system's future.

7.5.3. Longer term economic assessment

In general, the metal spraying industry is very conservative and it would be some years before a new system was generally accepted, presuming that trials were successful. A case in point is the acceptance of hypersonic flame spraying which has only been widely accepted in the last 5 years even though the initial idea was presented in around 1956 by Buffington and Browning (84). If it is produced, sales ofthe device would be small in the first few years. As an example Metallisation began to market plastic spraying equipment in recent years and it was almost a year after the launch before any units were sold.

7.5.3.1. Reaction of competing manufacturers.

If the improved process is combined with spraying of cored wires to produce dense carbide coatings some plasma business could be threatened. There is a good deal of scope for price reductions in plasma equipment if protection was felt to be neccessary but this will only occur some distance into the future and only if H.S.G. sells well in the face of an antagonistic marketing effort by plasma producers. Clearly the price cut must be significant to be effective against a device costing less than half as much . It may well be thought better to lose a few sales at a high price than to begin to offer systems at a generally reduced price. Furthermore, a loss of 1% of the market to H.S.G. would be of little significance to the plasma producers collectively, compared to the gain to the H.S.G. producer. Therefore competitive reaction would probably take the form of concentrating on the benefits peculiar to plasma spraying and exposing any weaknesses the new system might have, in much the same way as they have reacted to Hypersonic flame spraying.

7.5.3.2. Marketing method

With regard to the method of sale of the process, Metallisation has never promoted leasing, preferring an outright sale. Were the service and equipment divisions working more closely together it might be possible to offer the process on a contract service basis as do Union Carbide with their "D" gun and Plasma spray systems. However such a marketing approach would probably require the setting up of a new contracting wing by the equipment division. Unless the benefits of the process are remarkable, this is unlikely to be taken up in preference to the relatively cheap option of direct sale.

Concluding Summary

8.1. Possible improvements to arc spraying.

Several areas of improvement were identified and three were selected for closer scrutiny. These were firstly increasing the particle velocity to increase coating density, secondly using induction melting to improve the environmental acceptability of the process and thirdly the use of close automatic process control to reduce inconsistency in arc spraying. Of these the first option was finally selected for further development, after some preliminary testing, as it was thought to offer the greatest potential financial return.

8.2. Development of the High Speed Gas (H.S.G.) burner.

To acheive high particle velocities high gas velocities are required and this necessitates high gas temperatures. A propane air burner was developed to provide the gas stream, with not only the correct gas quantities and velocities, but also a usable disposition of flow around the arc spray wires. This severely constrained the dimensions of the burner and cost constraints required air cooling to be used. These problems combined to make overheating of the burner shell a serious problem and further work is needed to overcome problems in this area.

8.3. Coating comparisons.

In order to compare coatings produced by the new process and arc spraying, several coatings were made and tested for porosity, hardness and strength, by various techniques. However, little difference could be seen between H.S.G. produced coatings and best quality standard arc-spray coatings. Thus, if the hypothesis is that increasing particle velocity increases coating density, then this work has not proven the hypothesis. However, due toe practical difficulties with the equipment, resulting in a limited number of different parameters being used, it cannot definiely be said that the hypothesis is disproved.

8.4. Future prospects for H.S.G. arc-spraying.

In view of the similarity between the coatings of H.S.G. and standard arc-spraying there is no immediate likelihood of H.S.G. being developed along the present lines. However a compact, high velocity burner has been produced and this may be effective in projecting powdered material to produce good quality coatings at lower cost than Jet-kote.

8.5. Other matters arising from the project.

The quality of arc-sprayed coatings has been shown to vary greatly, not only with pistol parameters, but also with the handling parameters. In particular there are obvious differences between hand sprayed and machine sprayed coatings and also between single pass and multi-pass deposits. If the dust concentrations at the interface can be avoided or removed then single pass coatings may provide the most dense arc-sprayed deposits.

The modelling of the spraying process must generalise about the properties of particles and this is a serious weakness in view of the wide distribution of these properties. Nevertheless if it is accepted as only an indicator of trends then it can be very informative.

It has been shown that the toluene immersion method for porosity determination is effective if care is taken to ensure that the sample section can be fully penetrated by the liquid. If this is not so, then low values of porosity are given. However if the section is not fully penetrated, and the true porosity is known then this method can be used to give an idea of the penetration depth.

Direct tensile testing of one-piece coating samples was shown to be a straightforward technique, having selected a sample piece geometry which was easy to produce and mount for testing.

Recommendations for further work

It is recommended that the following work be done.

1/. The effects of handling parameters such as traverse rate and pass thickness should be investigated more thoroughly. Also the use of secondary air jets to remove dust and slow moving particles may be beneficial.

2/. The H.S.G. system should not be proceeded with in its present form.

3/. The H.S.G. burner be modified such that the full air flow to the burner passes first between the liner and the shell to provide better cooling. If the cooling is still not adequate then water cooling should be introduced.
The nozzle should be modified to allow injection of powder and trials made to produce coatings in this way.

Appendix 1

Calculation of Particle Velocity and Temperature.

Principle equation no.1

$$\frac{dVp}{dZ} = \frac{18Ug}{DpRp} \quad \frac{(Vg - Vp)}{Vp} \quad (1 + 0.15Re^{.687})$$

Describes the relationship between particle velocity and range.

Where:

Vp is the particle velocity

Z is the range from the pistol nozzle

Ug is the gas viscosity

Vg is the gas velocity

Re is the particle Reynolds Number

Dp is the particle diameter

Rp is the particle density

Principle equation no. 2

$$\frac{dTp}{dZ} = \frac{12Kg(Tg - Tp)}{Dp^2 \; RpCp}$$

Describes the relationship between particle temperature and range.

Where:

Kg is the gas conductivity

Cp is the particle specific heat

Appendix 1

The above differential equations were numerically solved using a fourth order Runge - Kutta technique as follows:

$$Y_{r+1} = Y_r \ {}^{1}/_{6}(k_0 + 2k_1 + 2k_2 + k_3)$$

$$k_0 = h\ Fn(X_r,\ Y_r)$$

$$k_1 = h\ Fn(X_r + {}^{1}/_{2}h,\ Y_r + {}^{1}/_{2}k_0)$$

$$k_2 = h\ Fn(X_r + {}^{1}/_{2}h,\ Y_r + {}^{1}/_{2}k_1)$$

$$k_3 = h\ Fn(X_r + h,\ Y_r + k_2)$$

In order to facilitate analysis and to substitute for incomplete experimental data some simplifying assumptions had to be made as follows:

1/. Particles are assumed to be solid spheres with homogenious internal properties.

2/. Since the conductivity of the particle is so much greater than that of the gas, the particle is assumed to be at one temperature throughout.

3/. The gas is presumed to follow a simplified velocity profile

4/. Only the centre line conditions are evaluated

Appendix 1

Variable list and description.

Zz	Range millimetres
V	Particle velocity metres /sec
Vf	Fluid velocity metres /sec
Tp	Particle temperature K
N$	Input string to allow options
De	Particle density kgm^{-3}
Fv	Fluid viscosity Nsm^{-2}
Kg	Fluid conductivity Wm^{-2}
Cp	Particle specific heat Joules/kg/K
Tgas	Initial gas temperature K
Vg	Initial gas velocity metres/sec
D	Current particle size in microns
Dd	Current particle size in metres
A1,A2,A3,	Start, end and increment diameters in microns
Co	Counter for fluid property reading.

All other variables are temporary and are defined within the program.

Appendix 1

```
10 Cb=0
20 DIM Zz(30)
30 DIM V(30)
40   DIM Vf(30)
50 DIM Tp(30)
60   INPUT "COMMINUTION ?",N$
70   IF N$="N" THEN Cb=-1
80   INPUT "STEEL ATOMISED BY AIR",N$
90   IF N$="Y" THEN GOTO 120
100  INPUT "PART DENS,FLUID VIS,FLUID DENS,FLUID COND,PART SPEC HEAT,INITIAL GAS
 TEMP.",De,Fv,Fd,Kg,Cp,Tgas
110  GOTO 210
120  INPUT "HOT OR COLD AIR H/C",N$
130  IF N$="H" THEN GOTO 190
140  IF N$="C" THEN Ca=0
150  Tgas=300
160  Vg=300
170  GOSUB 1160
180  GOTO 210
190  Tgas=1500
200  Vg=1E3
230  Tp=2000
250  GOSUB 1150
260  INPUT "STEP LENGTH mm",H
261  Zz=0
262  GOSUB Comminute
320  PRINTER IS 0
330  PRINT "SCOTT & CANNELL TYPE VELOCITY DISTRIBUTION CENTRE LINE ONLY"
350  PRINT "INITIAL GAS SPEED IS ";Vg;"METRES/SEC"
360  PRINT "INITIAL TEMPERATURE IS ";Tp;"DEGREES"
370  PRINT "INITIAL GAS TEMPERATURE IS ";Tgas;"DEGREES"
380  PRINT "DISTANCE          GAS          PART.         PART.         PART."
390  PRINT "                  SPEED        SPEED         TEMPERATURE   SIZE um"
400  IF Tgas<400 THEN GOTO 510
410  RESTORE
420  GOTO 510
430  M=18*Fv/Dd^2/De
440  G=.15*Fd*Dd/Fv
450  X2=.687
460  X1=M/1E4
470  X3=50*12*Kg/1E4
480  X4=Cp*De*Dd^2
490  Ca=Co
500  RETURN
510  V=1
520  GOSUB 1150
530  GOSUB 430
540  H1=H*1E-3/50
550  H2=H1/2
560  FOR Z=0 TO .15 STEP H1
570  Zz=Z*1E3
571  GOSUB Comminute
580  GOSUB 1150
590 GOSUB 430
600  IF Vf<3 THEN Vf=0
610  IF Tg<300 THEN Tg=300
620  N=N+1
630  IF Z<1.2E-2 THEN GOTO 730
640  IF Cb=0 THEN GOSUB Comminute
650  K0=X1*((Vf-V)/V)*(1+(G*ABS(Vf-V))^X2)
660  Z=Z+H2
670  K1=X1*(Vf-(V+K0/2))/(V+K0/2)*(1+G*ABS(Vf-(V+K0/2))^X2)
680  K2=X1*(Vf-(V+K1/2))/(V+K1/2)*(1+G*ABS(Vf-(V+K1/2))^X2)
690  Z=Z+H2
700  K3=X1*(Vf-(V+K2))*(1+G+ABS(Vf-(V+K2))^X2)
710  Z=Z-H1
720  V=V+(K0+2*K1+2*K2+K3)/6
730  IF V<2 THEN V=1
740  Ka=X3*(Tg-Tp)/(V*X4)
750  Kb=X3*(Tg-(Tp+Ka/2))/(V*X4)
```

Appendix 1

```
760  Kc=X3*(Tg-(Tp+Kb/2))/(V*X4)
770  Kd=X3*(Tg-(Tp+Kc))/(V*X4)
780  Tp=Tp+(Ka+Kb*2+Kc*2+Kd)/6
790  IF Z<1.2E-2 THEN Tp=2000
800  IF N=50 THEN GOSUB 1070
810  NEXT Z
820  Cb=Cb-1
830  GOSUB 1270
840  DUMP GRAPHICS
850  L=0
860  GOSUB 1640
870  L=0
890 PLOTTER IS 13,"GRAPHICS"
900  GRAPHICS
910  FRAME
920  LOCATE 20,110,20,90
930  GOSUB Labelx
940  SCALE 0,150,0,1E3
950  AXES 10,25,0,0,5,4,2
960  GOSUB Labely
970  MOVE 0,0
980  FOR L=0 TO 30
990  PLOT Zz(L),Vf(L)
1000 NEXT L
1010 END
1020 Comminute:Th=13*EXP(-7.4555E-3*Zz)
1030 Th=Th/1E6
1040 Dd=Th*5
1050 GOSUB 430
1060 RETURN
1070 L=L+1
1080 Vf(L)=Vf
1090 Zz(L)=Zz
1100 V(L)=V
1110 Tp(L)=Tp
1120 PRINT USING "DDD,13X,DDDD,13X,DDD,13X,DDDD,5X,DDD,1X";Zz,Vf,V,Tp,Dd*1E6
1130 N=0
1140 RETURN
1150 IF Z>2.4E-2 THEN GOTO 1190
1160 Vf=Vg
1170 Tg=Tgas
1180 GOTO 1210
1190 Vf=2.4E-2*Vg/Z
1200 Tg=2.4E-2*Tgas/Z
1210 Fv=(4.092241E-10*Tg^3-2.064823E-6*Tg^2+.0053927*Tg+.425315)/1E5
1220 Cp=(-4.8143E-11*Tg^3+9.9378E-8*Tg^2+.000137603*Tg+.948074734)*1E3
1230 Kg=(5.62E-10*Tg^3-3.05762976E-6*Tg^2+.0090817*Tg+.1794473)/1E5
1240 De=7E3
1250 Fd=353/Tg
1260 RETURN
1270 PLOTTER IS 13,"GRAPHICS"
1280 GRAPHICS
1290 FRAME
1300 LOCATE 25,115,20,90
1310 MOVE 0,0
1320 GOSUB Labelx
1330 SCALE 0,150,0,Vg
1340 GOSUB Labely
1350 AXES 10,25,0,0,5,4,2
1360 GOTO Vplot
1370 Labelx:CSIZE 3
1380 SCALE 0,150,0,400
1390 LORG 4
1400 LDIR 0
1410 FOR Range=0 TO 150 STEP 10
1420 MOVE Range,-20
1430 LABEL USING "K";Range
1440 NEXT Range
1450 MOVE 75,-55
1460 LABEL USING "K";"RANGE IN MILLIMETRES"
1470 RETURN
```

Appendix 1

```
1480 Labely:LORG 6
1490 FOR Value=0 TO Vg STEP 50
1500 MOVE -15,Value+5
1510 LABEL ,Value
1520 NEXT Value
1530 DEG
1540 MOVE -25,300
1550 LDIR 90
1560 LABEL USING "K";"VELOCITY IN METRES PER SECOND"
1570 RETURN
1580 Vplot:MOVE 0,0
1590 FOR L=0 TO 30
1600 PLOT Zz(L),V(L)
1610 NEXT L
1620 RETURN
1630 END
1640 PLOTTER IS 13,"GRAPHICS"
1650 GRAPHICS
1660 FRAME
1670 LOCATE 25,115,20,90
1680 SCALE 0,150,0,400
1690 GOSUB Labelx
1700 SCALE 0,150,0,3E3
1710 AXES 10,100,0,0,5,10,2
1720 GOSUB Labelty
1730 MOVE 0,0
1740 FOR L=0 TO 30
1750 PLOT Zz(L),Tp(L)
1760 NEXT L
1770 RETURN
1780 Labelty:MOVE -15,0
1790 FOR Value=0 TO 3E3 STEP 200
1800 MOVE -20,Value
1810 LABEL ,Value
1820 NEXT Value
1830 MOVE -25,1500
1840 DEG
1850 LDIR 90
1860 LABEL USING "K";"TEMPERATURE IN KELVIN"
1870 RETURN
```

Appendix 2

Calculation of heat transfer through burner walls.

Resistance of outer gas film $R = 1/hA$ per metre of tube.

where h is the heat transfer coefficient and

A is the surface area per metre length.

Taking $h = 15\ Wm^{-2}K$ and a diameter of 50 millimetres.

$A = 0.157\ m^2$ per metre length

$R = 0.424\ K/W$

For the steel shell $k = 50\ Wm^{-2}K$, the o.d. is 50 mm and the i.d. is 42 mm then the logarithmic mean area is:

$$Am = \frac{Ao - Ai}{\ln(Do/Di)}$$

where Ao is the area of the outer surface

Ai is the area of the inner surface

Do is the outer diameter

Di is the inner diameter

thus $Am = 0.144\ m^2$ per metre length

and $R = 0.55e-3\ K/W$

Similarly for the mullite liner $k = 10\ Wm^{-2}K$, the o.d. is 42 mm and the i.d. is 32 mm.

$Am = 0.115 m^2$

and $R = 2.61e-3\ K/W$

For the inner film $h = 250$ and the diameter as 32 mm

$A = 0.100\ m^2$

and $R = 0.04\ K/W$

Thus the total resistance is 0.467 K/W. (Note that this is dominated by the outer film resistance at 0.424.)

Appendix 2

Total heat flow Qtot = Total temperature difference / total resistance

thus Qtot = 1500 - 300 / 0.467 = 2568 W

To find the steel surface temperature once again:

Qtot = temperature difference / film resistance

thus 2568 = surface temperature - 300 / 0.424

and the surface temperature of the steel shell is 1389 K

Clearly the mullite alone is ineffective in reducing the surface temperature because of the low heat extraction rate at the surface.

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