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PLASMA SPRAY TECHNOLOGY
PROCESS PARAMETERS AND APPLICATIONS

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60 Abstract : The current trend in the structural design philosophy is based on the use of substrate with the necessary mechanical properties and a thin coating to exhibit surface properties. Plasma spray process is a versatile surface coating technique which finds extensive application in meeting advanced technologies. This report describes the plasma spray technique and its use in developing coatings for various applications. The spray system is described in detail including the different variables such as power input to the torch, gas flow rate, powder properties, powder injection, etc. and their inter relation in deciding the quality of the coating. A brief write up of the various plasma spray coatings developed for different applications is also included.

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1. INTRODUCTION

In modern technology materials and components are operated under extreme conditions viz. high temperatures, pressures, corrosive – erosive fluid flows, high density energy fluxes etc. Thus structural degradation is a serious problem facing modern industries. The operating conditions in many high technology areas are so demanding in terms of power/weight ratio and life time that the choice of structural components is rather limited. The present design trend is to use composite structures; viz., a core material and a surface material strongly bonded to each other, which complement each other to meet the requirements. This allows the design engineer to select the base material from mechanical and other design considerations and then prepare the surface to meet the requirements by incorporating a surface layer with different properties. Plasma spray technology, the process of preparing an overlay coating onto any surface, is one of the most widely used techniques[1] to prepare such composite structural parts with improved properties and increased lifespan.

In plasma spray process, an electric arc is struck between a rod type cathode and a nozzle anode. When the plasma gas flows through the arc, it gets ignited. The plasma is initiated when electrons are accelerated from the cathode to the anode. As the electrons speed towards the anode they collide with, excite and ionize the atoms or molecules in the gas. The additional electrons freed by the ionisation are also accelerated causing further ionisation These collisions transfer the kinetic energy of the electrons to the other species and raises the temperature of the gas. The ignited gas comes out of the nozzle in the form of a jet whose temperature is above 15,000 K. Any powder which is to be sprayed is injected into the flame were it is melted and accelerated towards the substrate. The molten powder on hitting the substrate cools and anchors together to form a strong adherent coating. This technique is mainly used for preparing many protective coatings of metals, ceramics and alloys for applications like (a) Corrosion/erosion/abrasion resistant coatings, (b) rebuilding worn–out parts and salvaging of mismachined jobs, (c) thermal barrier coatings, high temperature electrically insulating and conducting coatings, (d) preparation of special coatings like superconducting coatings etc. The main advantages of plasma spray process are:

- Any powder which melts without sublimation can be coated.
- The substrate temperature can be as low as 50°C
- There is no restriction on the size and shape of the job.
- The coating process is comparatively fast
- Coating thickness can go from few microns to millimeter
- With additional reinforcement, ceramic coatings with more than 10 mm thick can be prepared
- A mechanical as well as metallurgical bonding is obtained.

In plasma spraying, the quality of coating is affected by many variables [Table I] which are inter related. A careful optimization of the spray parameters is required to obtain good quality reproducible coatings on substrates for any application with specific properties. Figure 1 shows the schematic of the plasma spray system. The system consists of

Plasma Torch
Powder Feeder
Power Supply
Control Console
Plasma Gas and Carrier Gas Supply
Cooling Water System

2. PLASMA SPRAY TORCH SYSTEM AND PROCESS PARAMETERS

2.1 PLASMA TORCH

Plasma torch is the main tool which converts the electrical energy to thermal energy and mixing the coating material with the plasma flame. The normal operating power level is 5 to 20 kW. The ionised gas comes out of the torch in the form of a jet. This flame/effluent can be used for cutting, welding, spraying, melting, heating etc. Plasma spraying is the most effective way of using this jet for preparing protective coatings on substrates for various applications. The critical variables controlling the plasma jet are:

2.1.1 Input to the Torch

The electrical energy given to the torch is converted into thermal energy and is used to melt and accelerate the powder which is to be sprayed. The power input to the torch decides the rate of ionisation of the plasma and the heat flux in the flame. Selection of the power level depends on the type/amount of plasma gas and size/composition of the powder and hence requires a careful optimisation. Normal operating electrical power level varies from 5 – 20 kW.

2.1.2 Type of the plasma gas

The energy available from a plasma flame depends upon the gas which is used to produce the plasma. The gas enthalpy decides the rate of heat transfer to the powder particles used for spraying. The reactivity of the gas with the powder is also to be considered. Normally inert gases are used to produce the plasma jet so that the oxidation inside and outside the torch is reduced. Argon and helium are used as the common plasma gases. Diatomic gases like nitrogen and hydrogen are added to argon and helium to provide optimum heat due to their higher heat enthalpy[2]. A small amount of nitrogen or hydrogen will increase the arc voltage and efficiently increase the heat transfer rate.

2.1.3 Plasma Gas Flow Rate

The arc gas flow rate and the electric power of the plasma torch must be properly balanced. Gas flow must be carefully metered as the current is built up in the arc stream. Improper gas flow may lead to blowing out of the flame or fail to create the necessary thermal pinch effect to force the arc down the nozzle. The zone of stable arc gas flow rate is taken from the arc–gas 'envelope'[3] (figure 2).

2.1.4 Type of Arc

Mainly two types of arc are used for plasma torches. The first one is transferred arc mode, where the work piece is connected to the power supply and the arc is struck between the cathode and the work piece. As the current is drawn through the substrate it will get heated up. This is normally used for plasma cutting and plasma welding where the substrate is required to be heated to a high temperature. The second type is the non–transferred arc. In this method the arc is struck between the cathode and the nozzle anode. Only the plasma jet comes out of the nozzle. This type is mainly used for plasma spraying.

2.1.5. Arc Stabilization

It is required to constrict and stabilize the arc to get a stable flame with proper thermal pinch effect and less arc erosion on the electrodes. The general methods of stabilization can be summarised as:

(a) Wall stabilization. The simplest method of stabilizing the arc is by wall stabilization. The arc column is filled with cooling water which cools the boundary layer of the gas which in turn constricts the arc to the hot center zone. This is useful only for low velocity plasmas. It is mainly used in transferred arc torches for welding.

(b) Sheath stabilization. The gas is passed through a wire mesh kept behind the cathode to reduce the flow and expand equally to produce a gas sheath. The outer periphery of the gas column is always cool and thus the arc stabilizes at the center. This method of stabilizing the arc is used in both transferred arc and non–transferred arc torches.

(c) Vortex stabilization. The most versatile method of stabilizing the arc is by forming a vortex motion of the entering gas. Due to its simplicity in design and fabrication it is widely used. The gas enters behind the cathode tangentially and will form a cyclone inside the chamber and will be pushed out through the nozzle. The outer periphery is always at a high velocity and the center portion provides a stable arc and proper thermal pinch effect.

(d) Magnetic stabilization. In the magnetically stabilized jet the arc strikes radially from an inner electrode to an outer electrode. Gas is blown axially through the annulus. The arc is rapidly rotated with a magnetic field so that at various times it resembles the spoke in a wheel. This design permits operation at high pressures without electrode erosion. Figure 3 shows schematic diagrams of various methods of arc stabilization.

2.1.6. Electrodes

The configuration of the cathode and anode is of paramount importance in the operation of the plasma torch. An improper design of electrodes will result in erratic arcing and unstable operation. The most common and convenient design is a rod type cathode and a nozzle anode. The tip of the cathode is made conical and rounded. This gives better constriction and stabilization of the arc reducing the arc erosion. As the jet has to gain a high velocity the outlet of the anode is made in the form of a nozzle with a conical chamber where the gas forms the cyclone and a small orifice to push out the flame. The port of entry of the powder is at the exit of the nozzle to ensure proper mixing of the powder in the flame. Both the anode and cathode are water cooled. Normally the anode is made of copper because of its better conductivity and the cathode is made of tungsten. 1 to 2 % of thoria is added to the tungsten cathode for better thermionic emission. Cross section of a typical plasma torch is given in figure 4.

2.2. POWDER FEEDER ASSEMBLY AND POWDER CHARECTERISATION.

2.2.1. The powder feeder

This is the component to introduce the powder into the flame at the required rate without any obstruction enroute. The powder feeders which are normally used are (a) The inertia feed type which consists of a conical hopper where the powder is kept and the carrier gas passes through the bottom of the hopper. Due to inertia of the gas the powder falls into the gas stream and is carried away. This is a negative type powder feeder which gives the flow of powder in a pulsed form. This requires more velocity of gas which is a disadvantage. (b) Screw type powder feeder which carries the powder from the container which falls into the screw pitch through an opening. As the screw rotates the powder is trapped in the screw pitch and is carried down to the torch nozzle. Since ceramic powders are more abrasive the powder which goes into the screw pitch wearout the screw faster and chances of powder clogging is much more in this type. (c) The most versatile type is a turn table powder feeder. This is a typical positive type powder feeder which ensures smooth volumetric flow of powder and has much more control over flow rate and requires very low carrier gas velocity. Here the powder kept in a conical chamber falls down to a rotating table through a small orifice whose area is adjustable. The powder carried by the rotating table is wiped and dropped into a small cyclone of gas and is carried away by the carrier gas. The principal advantage of this type of powder feeder is that it does not require large quantity of carrier gas and has a better control over the powder feed rate. Figure 5 gives the schematic diagram of a turn table type powder feeder.

2.2.2. Powder Characterisation

Since the plasma flame temperature is much higher than the melting point of any known material it is possible to coat any material that melts without sublimation. But some flow properties and spray process requirements put some restriction on selection of the powder.

(a) Physical properties.

The heat transfer from the arc to the powder particles depends upon the particle properties like specific heat, density, melting point and boiling point. If the melting and boiling points are very close then some portion of the material will get vapourised reducing the efficiency and bond strength. The powder density controls the particle trajectory into the flame for a given gas flow rate and powder particle size.

(b) Particle size and shape.

Particle size decides the particle trajectory and degree of melting which controls the quality of the coatings. The particle should have enough kinetic energy upon impact on to the substrate to deform and hook to the surface irregularity which in turn increases the bond strength. If the particle size is too big it will not melt fully and if it is too small it will melt and vaporise. So it is required to be sufficient enough to melt and remain deformable until impact and should have a high thermal capacity. This decides the exact size of the powder particle. As it is not practical to have a powder with equally sized particles, it is usually selected in a narrow range of variation.

As the powder is carried by a carrier gas into the torch through a small hose, the particle shape affects the transport properties. Very fine powder will agglomerate and clog up in the supply tube. If the shape of the powder is not spherical its sharp corners will hit the supply tube and will subsequently block the tube by bridge formation. A spherical grain shape is best for trouble-free feeding.

(c) Rate of Powder Addition and Carrier Gas.

The rate of powder injection should be balanced to get the maximum efficiency and quality of the coating. The powder feed rate for a given powder can be varied to a certain range to obtain the optimum spray efficiency. A faster feed rate creates insufficient melting resulting in poor adhesion and density while too slow a flow rate causes over heating and evaporation of the powder. The flow rate of the gas guides the particle trajectory through the plasma. A balance must be maintained between the plasma gas and carrier gas velocity to correctly position the powder particle in the plasma for proper melting.

The type of the carrier gas also is of importance in deciding some chemical reaction with the powder in the plasma flame. This plays a major role in plasma chemical reactors for nitriding, carbiding etc.

(d) Angle and Position of the Powder Entry Port.

The angle of entry of the powder into the flame decides the dwell time of the powder particles in the plasma flame. The dwell time required varies upon the type and size of the powder. The particle size should be such that the powder is just melted and carried on to the substrate. A higher dwell time results in melting and evaporation of the powder and a lower dwell time results in insufficient melting which leads to poor quality spray. The ideal dwell time for a ceramic powder of 40 to 60 micron size is calculated as 4 to 6 milliseconds.

(e). Powder Composition.

Many times the requirement calls for coating with mixture of powders. In some cases the powder material may decompose if melted. For example if tungstencarbide (WC) is sprayed alone it would decarborise, but if it is sprayed together with cobalt only cobalt will be melted during spraying and WC particles will get embedded in it giving a coating with its properties. Thus it is evident that specially prepared powders are required for specific applications.

2.3. PLASMA SPRAY PROCEEDURE

Like any other parameter the plasma spray procedure also contributes much in obtaining required quality and efficiency of the coatings. The main variables to be controlled in the spray procedure are:

2.3.1. Torch to Work Distance & Traverse Rate.

The base to torch distance and traverse rate are selected for a particular type and size of powder to get an optimum efficiency value. If the distance is more than a critical value then the particles will cool before hitting the substrate causing poor adhesion and higher porosity. Too small a distance will lead to overheating resulting in substrate distortion, coating cracks and damage the substrate properties. The normal torch to base distance optimized to get maximum spray efficiency for the powder size 50 to 100 μm is 75 to 100 mm. The traverse rate is set between 100 to 200 cm/min. depending upon the powder size and feed rate. Both these are to be fixed experimentally for a given material.

2.3.2. Angle Of Spray

The convenient spray angle is 90 degrees to the base. However inclined spray upto 45 degrees to the base do not noticeably affect the efficiency. A very low spray angle gives shadow effect (figure 6). To prepare pin reinforced thick coatings the spray angle plays a major role. If the coating angle is 90^{o} it creates a cap formation over the pins which in turn creates a void around the pin making poor adhesion to the pins. Spraying at an angle gives the shadow of the pins. To over come this problem the substrate is rotated by 90^{o} after coating each layer and the caps are removed. Ceramic coatings upto 10 mm have been prepared by this technique[4,5].

2.3.3. Shield Gas.

The need of shield gas is to avoid oxidation of the spray materials. The spray jet will be mixing with ambient air immediately after a short distance from the nozzle. Inorder to avoid the mixing of atmospheric oxygen with the plasma jet a dust proof inert gas shield can be created around the plasma jet to a certain distance which is adequate for spraying. Plasma spray also can be done in a controlled atmosphere like flooded inert gas atmosphere or in vacuum.

2.4. SUBSTRATE FOR PLASMA SPRAY

2.4.1 Composition

Plasma spray can be done onto any substrate. But it is essential to select the material for certain specific applications with desired properties. The mismatch in the thermal properties of the substrate and the coating can weaken the adhesion. This is normally avoided by giving an intermediate layer of coating with a material whose properties are in between those of the base and the coating. Another way is by slowly varying the powder composition from 100% metal to 100% ceramic.

2.4.2. Surface Preparation

A clean dust-free surface should be maintained for plasma spraying to get good adhesion. Degreasing and removing oxide layers and loose particles are to be done before the spray. The general ways of surface preparation are cleaning with a wire brush, chemical etching and sand blasting.

2.4.3. Surface roughness

The bonding in plasma spray is a mainly a mechanical one. The molten particles hitting onto the substrate deforms and anchors onto the surface to form a coating. Hence the surface roughness is important to obtain a good bonding between the substrate and the coating. Sand blasting the substrate with quartz sand or alumina of grit size 10 to 16 gives good adhesion.

2.4.4. Surface temperature.

Surface deformation and oxidation can be avoided by keeping the surface temperature of the substrate between 100 to 150°C. Substrates can be cooled with water cooling jackets to bring down the surface temperature. However to get a metallurgical bonding or to get a reaction with the substrate the surface temperature gas to be increased. Under ideal conditions complete control of all the parameters should yield optimized reproducible coatings at maximum deposition efficiency. The arc gas flow rate, arc power level and torch to base distance are the most critical variables affecting the efficiency. Figure 7 shows the effect of these variables with efficiency. It is necessary that these variables are to be properly regulated inorder to provide the optimum combination of effluent enthalpy and particle dwell time needed.

2.5. COATING EVALUATION

2.5.1. Adhesion

The adherence of the coating to the substrate is of major concern and most particle–substrate interactions are viewed in this perspective. The three categories of the adhesion mechanisms are mechanical, physical and metallurgical. The molten particles hitting the substrate surface deform to the surface topography. The anchoring and interlocking of the particles to the surface is termed the mechanical adhesion. Substrate–coating adherence by Vander walls forces is the physical adherence. The formation of an inter diffusion zone or an intermediate compound between the substrate and the coating is generally termed as the chemical or metallurgical bond. The adherence is always the effect of two or more bonding mechanisms. The degree of the mechanical bonding varies with the spray conditions, pre–spray preparation and the surface topography. Usually undercoat or graded coatings are used successfully to increase the adhesion. Normally plasma spray coating adhesion strength tested as per the ASTM standard is found to be between 20–30 MPa.

2.5.2. Density

The density of the coating can be changed by varying the spray parameters. Coating upto 98% theoretical density can be obtained. Figure 8 shows the variation of density with some coating parameters like spray distance, power level, powder size and and gas flow rate. If the powder particle size is bigger than a certain value then they will not melt fully. If the spray distance is more then the particles will cool before hitting the substrate. An increased power level can cause over heating and the powder may evaporate. Excess gas flow can cool the plasma resulting in the reduction of the temperature and improper melting of the powder.

2.5.3. Thickness

The coating thickness obtained by a single layer is about 25 μm. However multilayer coatings upto 400 μm can be prepared with good adhesion strength. Coatings more than 400 μm will produce internal stress during spraying and will crack or peel off after cooling. Other properties like hardness, thermal conductivity, abrasion resistance, etc., will depend on the coating material.

2.5.4. Stresses developed in the Coating

Various types of stresses are introduced into the coating and substrate during the spray process which have a decided effect on both the cohesive and adhesive strength of the coating. The temperature gradient built up through the substrate and the coating is the major cause for stress development. A typical thermal distribution and the resulting stress on cooling is shown in figure 9a and 9b respectively. The tensile stress at the interface tends to weaken the bond and lead to failure of coating. For thin substrates the compressive stress can cause severe deformation. The technique to reduce the thermal gradients include cooling the back and the front surface during spraying, use a more rapid traverse speed and allowing each layer to cool before spraying the next layer. Other causes of stress are the rapid rate of particle quenching, substrate warpage due to over–heating, design features like sharp corners and mismatch of thermal expansion co–efficient between the substrate and the coating. An intermediate layer having an intermediate expansion co–efficient or graded coatings are normally used to avoid this problem.

3. PLASMA SPRAY RESEARCH WORK CARRIED OUT AT B. A. R. C.

The systems available in Thermal Plasma Section are a 40 kW 'ARCOS' plasma spray unit, and an indigenousely built 20 kW plasma torch with a twin power supply. The general studies conducted on various coatings include density measurement, porosity measurement, adhesion strength, thermal shock resistivity, wear resistance, microstructure, thermal conductivity, electrical properties, etc. Figure 10a and 10b shows various ceramic coatings used in industry and their applications respectively. The optimisation of the spray parameters were carried out for many different coating materials. The major experiments and service coatings carried out with this system are summarized as follows. Typical coatings prepared using this technique include metals like copper, nickel, tungsten; alloys like stainless steel, nichrome, tungsten carbide and ceramics like alumina, titania, yttria, zirconia, composite powders etc. Table II gives a typical optimised spray parameters for a superconducting $Y_1Ba_2Cu_3O_{7-x}$ coating.

3.1. Coating Density Optimisation

As porosity/density is one of the important charecteristics of ceramic coatings, it is very essential to control it to the desired level. For this the spray parameters are to be carefully optimised. As can be seenfrom figure 8, the powder size, spray distance, electrical power level and the gas flow rate contributes great part in controlling the density. Since this variables are inter related and depend on the powder material, it is required to optimise it for specific material and applications.

3.2. Plasma sprayed thick ceramic coatings

10 mm thick ceramic coatings of alumina and calcia stabilized zirconia were prepared by plasma spray technique[4,5]. Metal pins were used as stress relieving agents. Various substrate materials, pin materials, pin diameters and pin matrix were studied.

These pins were spot welded to the substrate and sand blasted before spraying. The samples were rotated by 90° to avoid the shadow effect and the spray angle was kept 60° to the base. After coating 4 layers the spray angle was changed to 90° for the fifth layer. The sequence was maintained till the desired thickness was obtained (figure 11). The coating was allowed to cool to room temperature and caps formed over the pins were removed after each layer. After filling upto the pin level, a coating of 200 μm was given to cover the pins. No cracks were observed even after grinding and polishing. These coating were tested for their microstructure, steady state high temperature performance, thermal shock resistance, adhesion and bonding etc. These coating can be used as high temperature electrodes and insulators for hot wall MHD channel and as protective coatings against high temperature – high velocity flames like in rocket nozzles, combustors etc..

These thick specimens were tested for their high temperature arc erosion [5]. Figure 12 shows the schematic of an electrode test apparatus built in our lab. The equipment consists of a plasma torch to heat the specimen and a water cooled ring through the plasma flame passes. The test specimen is mounted on a water cooled jacket where the temperature rise in the cooling water can be measured. The high temperature plasma flame passes through the ring and impinches on the specimen. An electric arc is struck between the ring and the specimen through the flame. The connections could be changed to make the specimen either anode or cathode as desired. By controlling the power input to the torch and the torch to base distance, the specimen can be heated to test temperatures and the arc is struck between the ring and the specimen. The current density and the arc spots were studied by varying the specimen surface temperature, the discharge current and the arc voltage.

3.3. Thermal barrier coatings

The loss of heat through any metal components exposed to to a hot atmosphere can be reduced by providing a proper ceramic coating[6]. These coatings are called thermal barrier coatings (TBC). Internal combustion engine components like pistons, liner rings, cylinder head, valves etc. have been successfully coated with TBC. The heat loss through these components were reduced and as a result the exhaust gas temperature was increased by 200°C. 1% direct increase in fuel efficiency is observed and an additional 7% efficiency can be obtained by utilising the exhaust gas for running a turbine, compressor or a heat exchanger. TBC on IC engine components yields:

(1) Increase in efficiency due to high temperature operation.

(2) Energy saved by the thermal insulation is transferred to the exhaust gas resulting in rise in exhaust gas temperature which can be used for turbocharging of the engine.

(3) Improved economics due to reduction or elimination of the cooling system as well as increased life of the components.

(4) Increased life of the engine due to resistance of the chemically inert ceramic layer to high temperature corrosion by combustion gas.

3.4. Plasma sprayed superconducting $Y_1Ba_2Cu_3O_{7-x}$ coatings

The effect of powder, spray and coating parameters on superconducting properties of plasma sprayed $Y_1Ba_2Cu_3O_{7-x}$ coatings has been carried out. The spray parameters to yield strong, adherent and dense coatings on many substrates including AISI 304 SS and alumina have been optimised[7]. Coatings show superconductivity after oxygen annealing at 950°C for an hour. Coatings thinner than 100 μm do not show zero resistivity down to 77K due to weak links between granular superconductors. Coatings prepared with fine powder have superior superconducting properties, viz. higher Tc and Jc values than coarse powder coatings. The choice of substrate material strongly affects the Jc values. Use of argon as powder and shield gas led to coatings with room temperature resistance (RTR) in tens of mega ohms range. When oxygen was used as powder and shield gas the RTR was reduced to 10 to 100 kilo ohms. The as sprayed coatings were found to be insulators and annealing studies showed that heat treating the specimens at 950°C for about an hour in flowing oxygen, with heating and cooling rates of 5°C/min.turns the specimen superconducting with a Tc of 82 to 91K depending on the specimen[8]. Figure 13 presents the resistivity–temperature plots of raw material pellet and coated specimens annealed at 950°C for one hour.

The electromagnetic shielding properties of the coatings have been studied in the frequency range 100 Hz to 100 kHz and field intensity range 0.01 mT to 3.0 mT. Results show that the shielding effectiveness increases exponentially with decreasing field intensity. It is also observed that the shielding effectiveness increases with coating thickness and density [9–11], The effect of bending strain on critical current density have been studied to understand the flexibility behaviour of the coating for the use of superconducting magnets [12]. Figures 14 and 15 shows the schematic diagrams of the electromagnetic shielding studies and the flexibility studies setup respectively

3.5. High Temperature Wear Resistant Coatings on Slide Gate Plates.

As a part of the ongoing project with Steel Authoirity of India Ltd. we are collaborating with RDCIS Ranchi to develop wear resistant coatings on slide gate plates. In steel plants severe erosion of the refractory teeming plates (slide gate plates) and generation of macro–micro cracks during teeming of steel has been observed, rendering the plates unusable for re–use. It is being studied to develope plasma sprayed ceramic coatings on refractory plates to minimise the damage and hence increase the life of the slide gate plates. Priliminary experiments have been initiated and coatings of Al_2O_3, $MgZrO_3$, ZrO_2–TiO_2–Y_2O_3 and Calcia Stabilized Zirconia have been coated on refractory substrates for coating evaluation studies.

3.6. Ceramic Probes

Ceramic probes for various applications have been prepared by plasma spray technique [13,14]. They have been made by spray deposition of ceramic layers/blocks over the substrate moulds which were subsiquently removed to yeild free standing ceramic probes. By proper variation of the spray parameters it is possible to control the properties of the probe precisely. This method is an easy and quick method of preparing ceramic probes which are charecterised with adequate mechanical strength and assured electrical contact.

3.7 Plasma Sprayed CSZ–Al_2O_3 Composites.

Plasma sprayed composite coatings of calcia stabilized zircinoa (CSZ) and alumina have been developed by premixing different weight % of CSZ and alumina powders. The effect of annealing and powder composition on the properties of the coatings such as phase composition, thermal shock resistance etc. have been studied[15]. The coatings are found to have excellent thermal shock resistance and are potentially useful in many high temperature applications. The powder composition and other process parameters have been optimised.

4. CONCLUSION

In summary, we have developed plasma sprayed coatings for various applications like: (i) 8 mm thick CSZ coating for MHD electrodes and insulators were prepared by pin reinforcement technique. These electrodes were tested for their electrical conductivity at high temperatures. More than 1000 MHD electrode pins were coated with 100 μm thick Al_2O_3 for inter electrode insulation, (ii) Thermal barrier coatings on IC engine components have been prepared and studied as a part of the collaborative work carried out with IIT Bombay, VRDE Ahmednagar and KOEL Pune. (iii) Al_2O_3 coatings on graphite mould assembly, (iv) Copper coatings on titanium flanges for metal brazing, (v) Corrosion resistant Al_2O_3 coating on stainless steel pipes, (vi) YSZ coatings on turbine blades, (vii) Wear resistant coating on bearing bush, (viii) $Y_1Ba_2Cu_3O_{7-x}$ superconducting coatings, (ix) High temperature corrosion/wear resistant coatings on slide gate valves used in ladles and (x) CSZ – alumina composite coatings for thermal shock resistance etc.

When a conventional plasma spray system is operated in atmosphere the plasma beam get contaminated by the atmospheric air. The substrate also get oxidised during the spraying. These problem can be avoided by the introduction of a controlled environment plasma spray. The modified version of this is the low pressure (vacuum) plasma spray. In vacuum the plasma flame gets longer and broader. A longer flame ensures more residual time for the powder particles which makes it possible to spray with low power level. A broader flame yields larger plasma volume resulting in better efficiency and uniform coating. Plasma sprayed coatings have found wide applications in high technologies like space, aeronautics, defense etc.

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TABLE I

PLASMA SPRAY PROCESS VARIABLES

PLASMA

- Power input
- Type of plasma gas
- Plasma gas flow rate
- Type of arc
- Plasma torch geometry

POWDER

- Composition
- Physical properties
- Method of manufacture
- Particle size

POWDER FEED

- Type of feed system
- Rate of feed
- Type of carrier gas
- Rate of carrier gas
- Angle and port of entry

SPRAY PROCEDURE

- Torch to base distance
- Traverse rate
- Angle of spray
- Shield gas
- Spray atmosphere

SUBSTRATE

- Composition
- Surface preparation
- Surface roughness
- Temperature

TABLE II

PLASMA SPRAY PARAMETERS

Parameter	Study Range	Optimised Value
Power (kW)	6 – 15	9
Plasma Gas (Ar–LPM)	10 – 25	20
Powder Gas 1 (O_2–LPM)	4 – 20	6
Powder Gas 2 (Ar–LPM)	4 – 20	–
Shied Gas 1 (O_2–LPM)	5 – 40	20
Shied Gas 2 (Ar–LPM)	5 – 40	–
Powder Feed Rate (g/min)	5 – 25	16
Torch to Base Dist. (mm)	5 – 150	100
Powder Injection	I, E, NS	I

I: Internal, E: External, NS: Near Substrate

LIST OF FIGURES

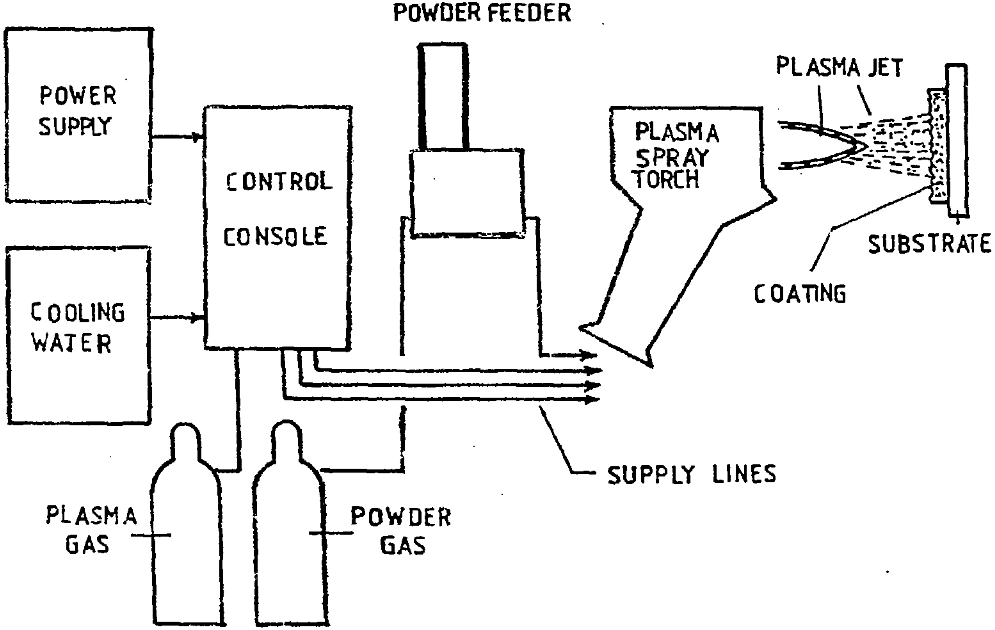

FIG. 1. Schematic diagram of plasma spray system

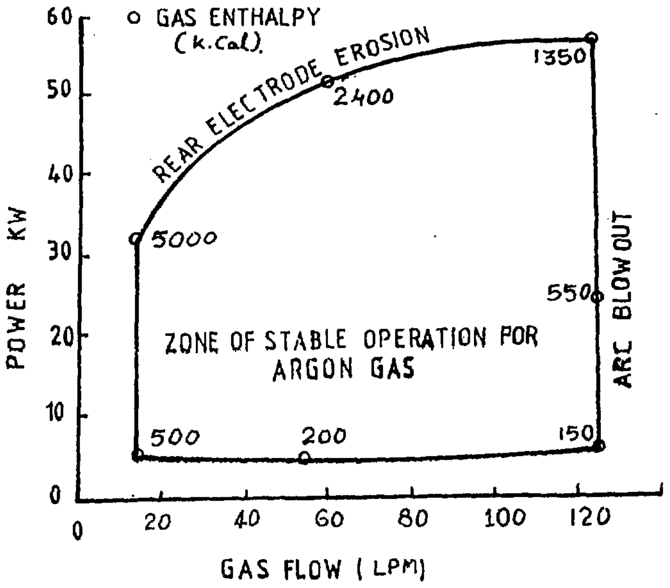

FIG. 2. GAS FLOW RATE - ARC POWER 'ENVELOPE'

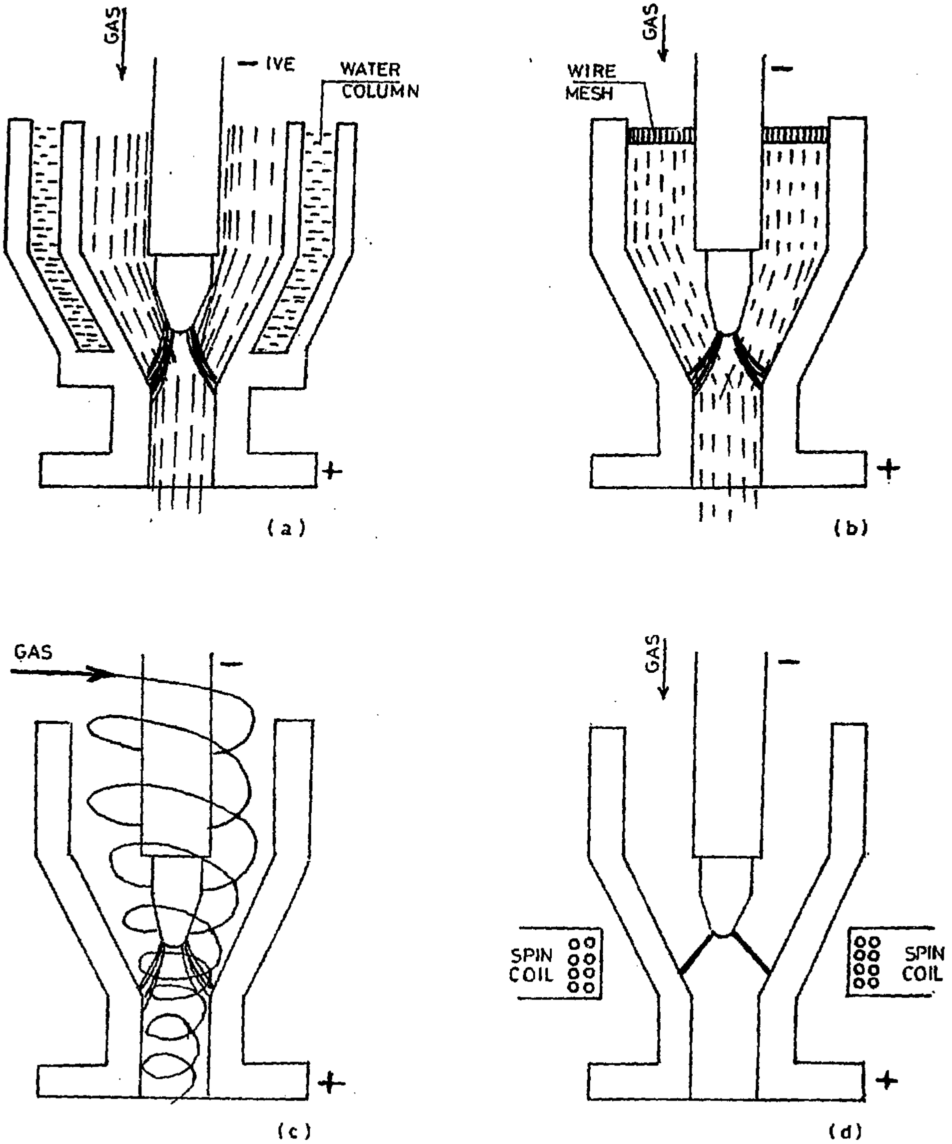

FIG. 3. Schematic diagram of methods of arc stabilization.

a. Wall stabilization b. Sheath stabilization

c. Vortex stabilization d. Magnetic stabilization

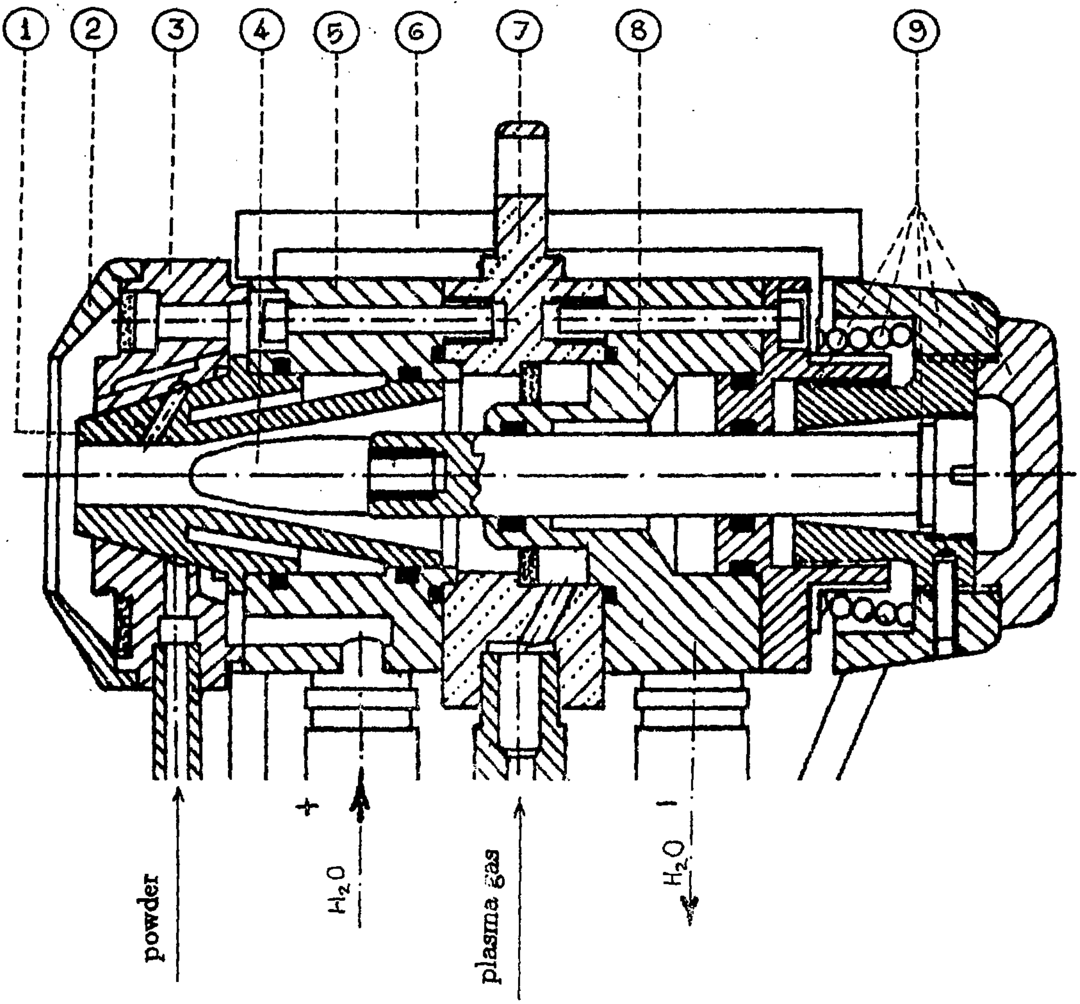

FIG. 4. Cross section of a plasma torch

1. Anode Nozzle
2. Front Cover
3. Powder Injector
4. Cathode
5. Anode Holder
6. Handle
7. Insulator Assembly
8. Cathode Holder
9. Cathode Adjustment Assembly.

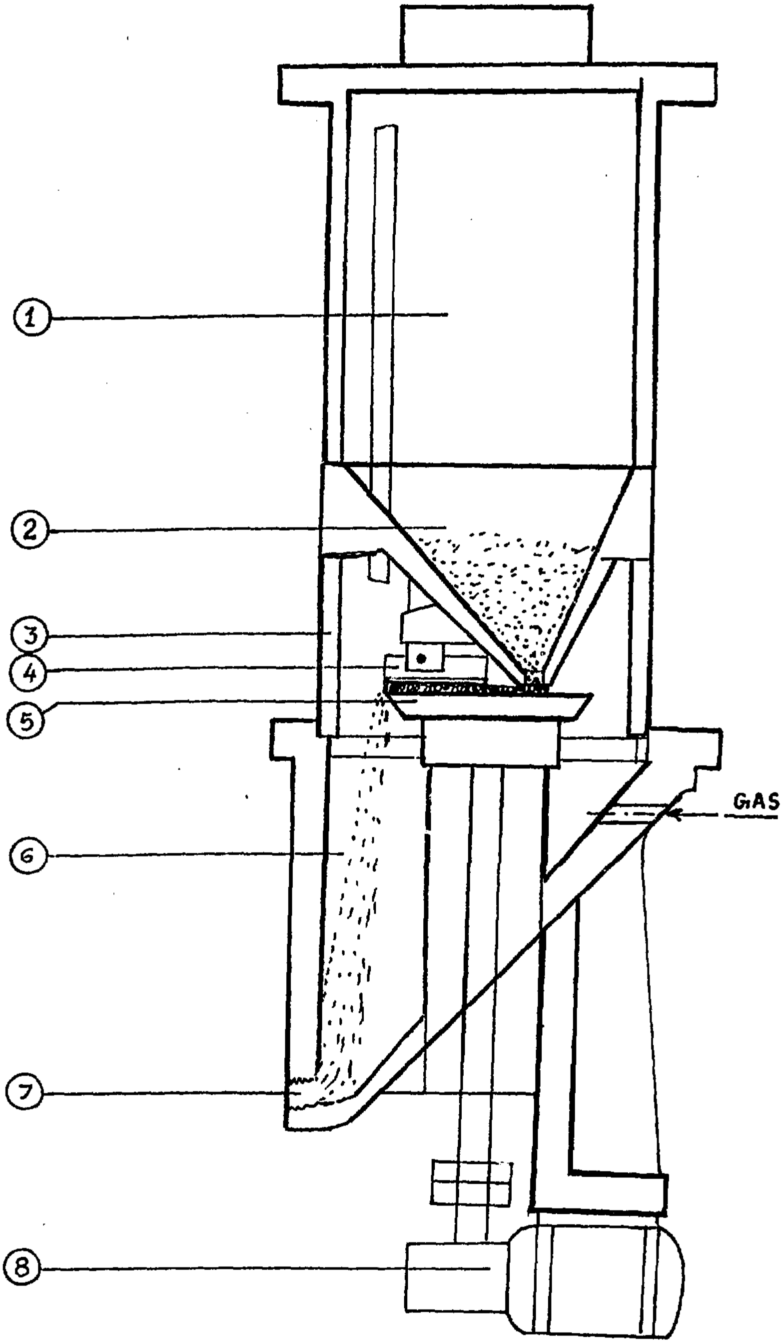

FIG. 5. Schematic diagram of a turn table type powder feeder.

1: Powder container 2: Conical feeder 3: View port 4: Wiper

5: Turn table 6: Gas chamber 7: Powder outlet 8: Motor drive

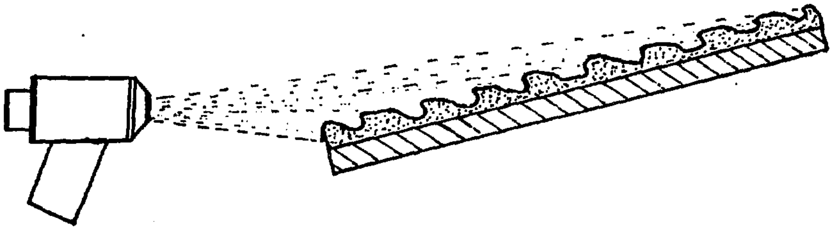

FIG. 6. SHADOW EFFECT ON COATING DUE TO LOW ANGLE SPRAYING

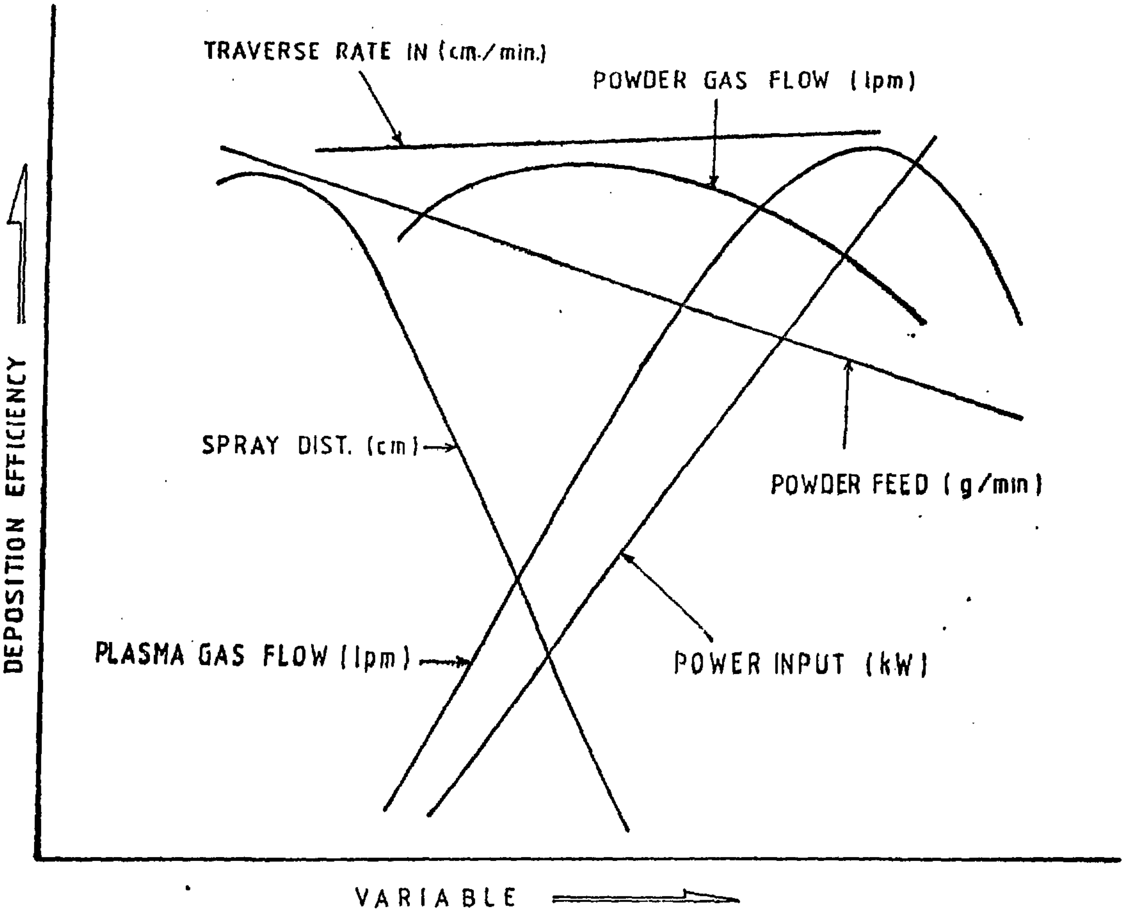

FIG. 7. Dependence of efficiency with Spray Variables.

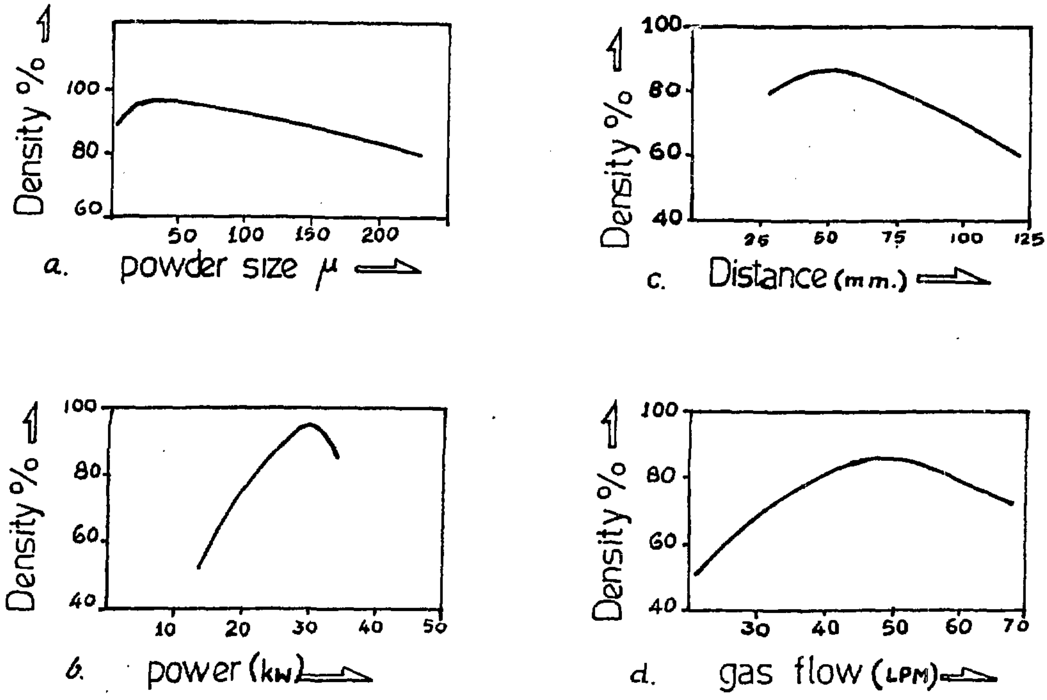

FIG. 8. Variation of coating density with (a) powder size (b) power (c) Base to torch distance (d) gas flow rate

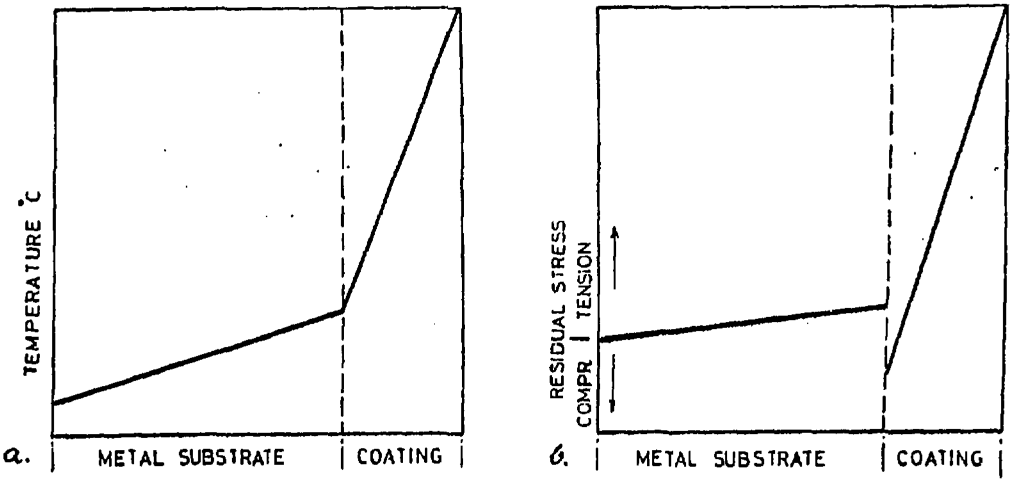

FIG. 9. (a) Thermal distribution through coating and substrate during spraying (b) Stress distribution after cooling

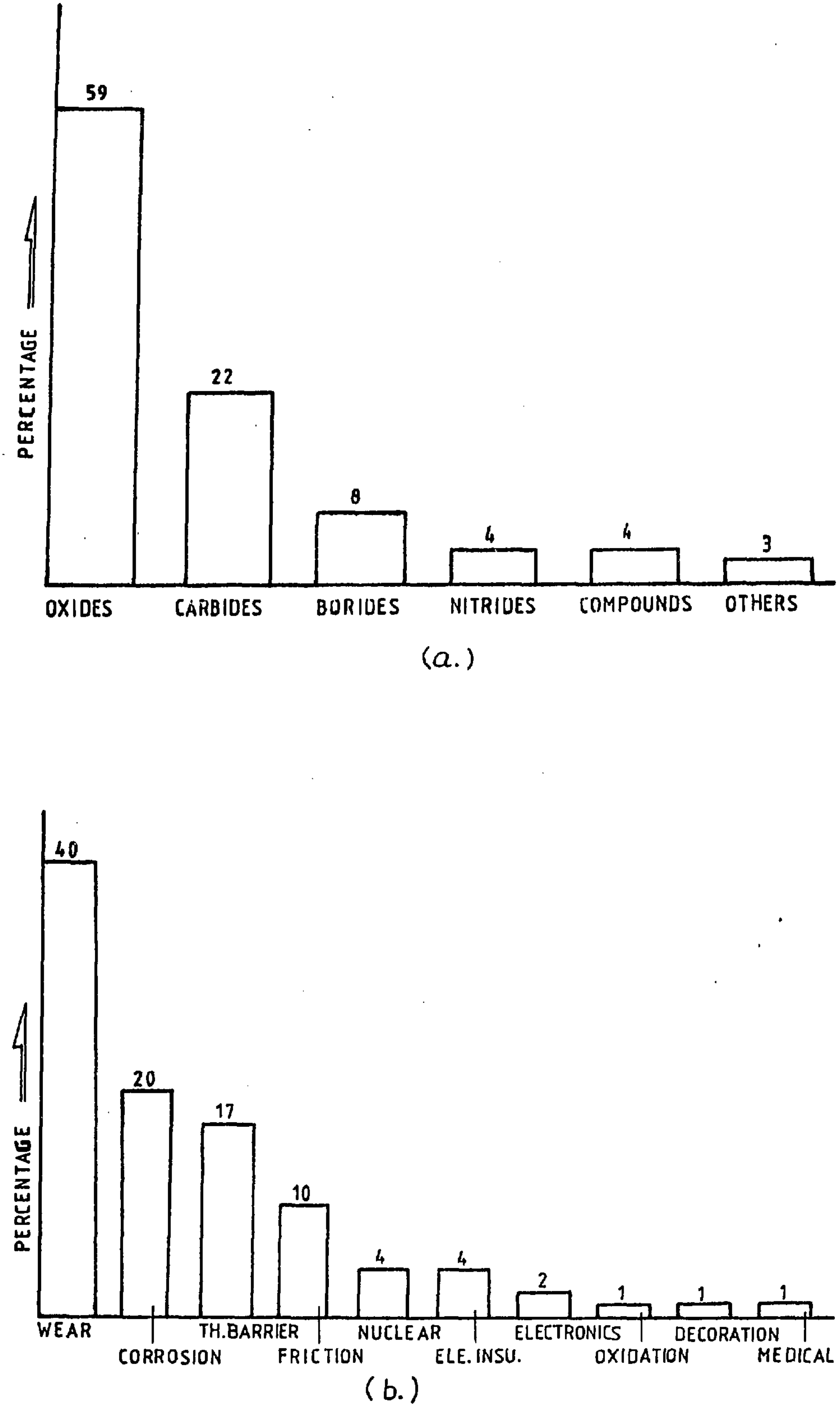

FIG. 10. **(a) Percentage of various ceramic coatings used in industries**

(b) Percentage of ceramics used for various applications.

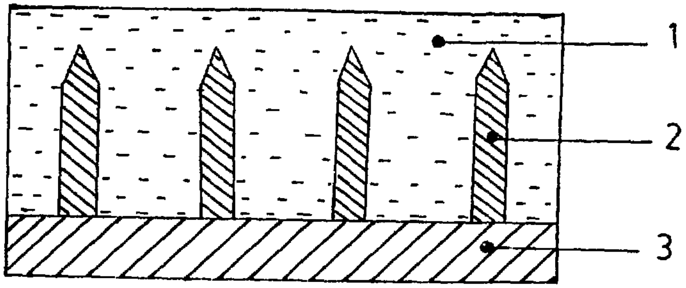

FIG. 11. Schematic of plasma sprayed thick ceramic coating

1. Ceramic coating, 2. Re–inforcement pin, 3. Substrate

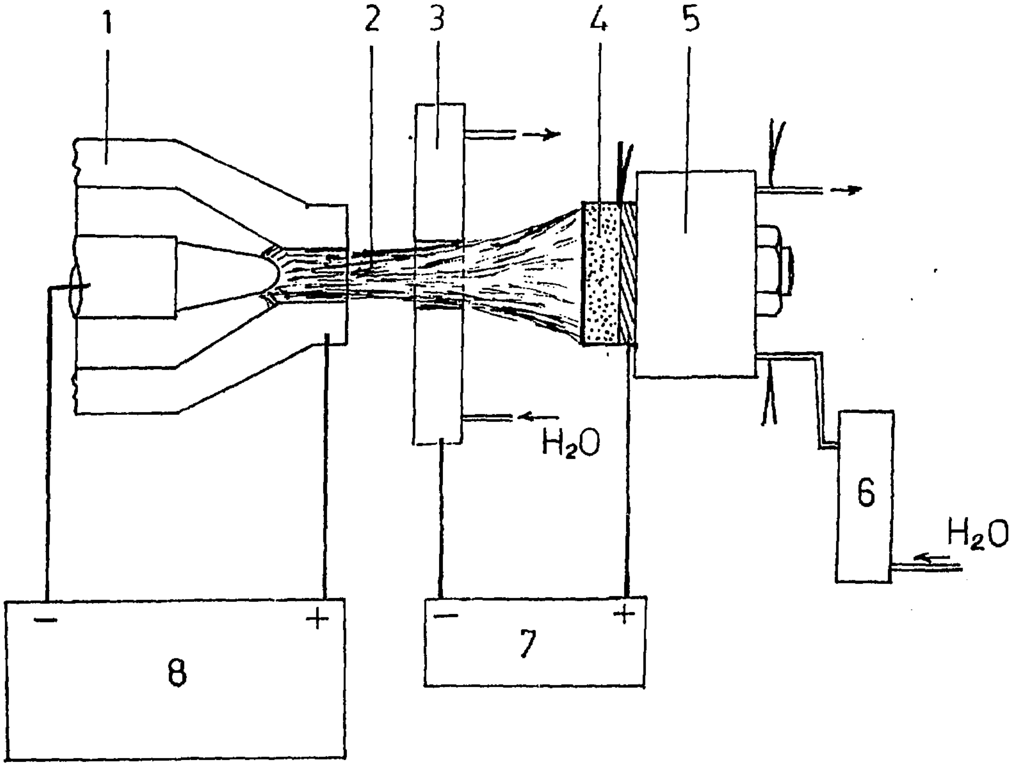

FIG. 12. Schematic of electrode test apparatus.

1.	Plasma Torch	2.	Plasma Flame
3.	Water Cooled ring	4.	Test Specimen
5.	Cooling Jacket	6.	Water Flow Meter
7.	Arc Power Supply	8.	Torch Power Supply

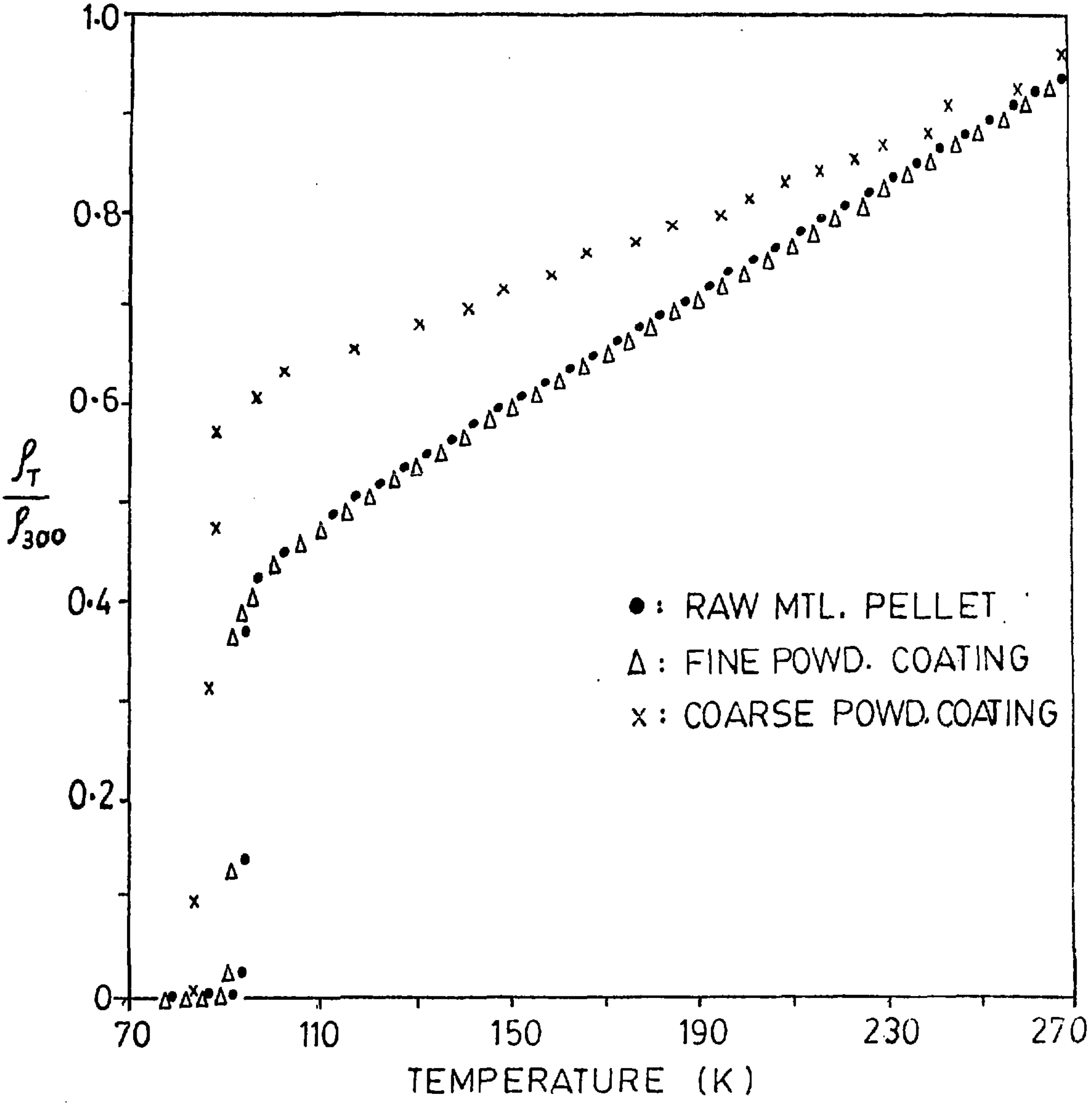

FIG. 13. Temperature dependence of resistivity in superconducting plasma sprayed coatings.

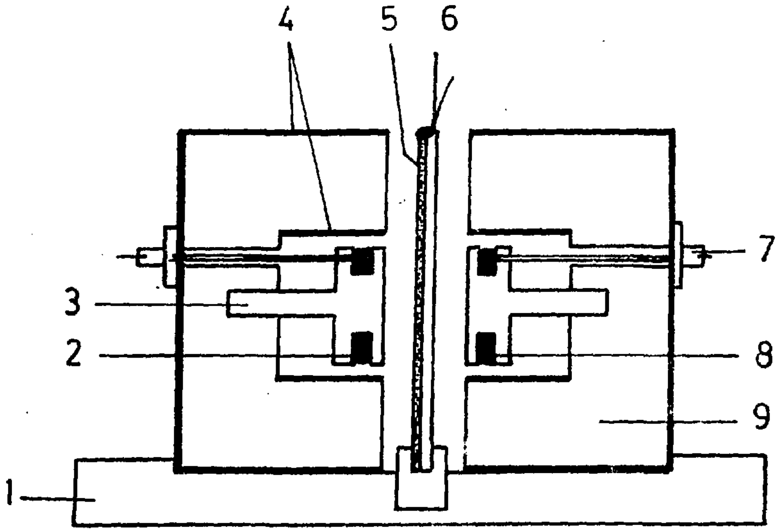

FIG. 14. **Schematic of experimental setup of electromagnetic shieldimg studies.**

1: Teflon base plate 2: Drive coil 3: Teflon coil former

4: μ metal shield 5: Specimen 6: Thermocouple

7: Coaxial connector 8: Receiving coil 9: Coil holder

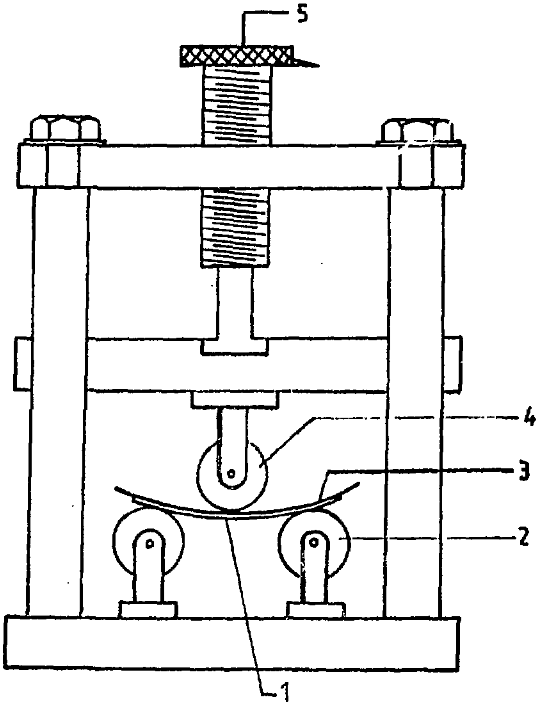

FIG. 15 Schematic of experimental setup of coating flexibility studies.

1: Superconducting coating 2: Support rollers

3: Substrate 4: Bending roller 5: Feed screw

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