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EXPERT SYSTEM FOR PROCESS OPTIMIZATION OF ATMOSPHERIC PLASMA SPRAYING OF HIGH PERFORMANCE CERAMICS

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Abstract

This paper deals with an experimental investigation on the process of atmospheric plasma spraying of high performance ceramics such as Al_2O_3, Al_2O_3-TiO_2, and PSZ on a steel substrate. The ceramic coatings were deposited under different spray conditions and optimal spray parameters were evaluated based on the quality of the coating judged in terms of bond strength and porosity. An expert system, using the above experimental data,developed in Borland C has been demonstrated.

Keywords : Plasma spray-ceramics-process optimization-expert system.

1. Introduction

The life and functional efficiency of ceramic coatings made by the Atmospheric Plasma Spray (APS) method are influenced by the coating properties, amongst which the bond strength, porosity content, hardness etc., of the coating play a dominant role. For satisfactory functioning of the sprayed material, it is essential to maintain adequate bond strength between the coatings and the substrate. From the published literature, it is known that the condition of the surface being sprayed, the stand-off distance, the size of the sprayed particles and the spray parameters are the factors influencing the bond quality. However the mechanism of bonding and the allied strength of plasma deposited coating still remain as a subject of controversy. The porosity content and the hardness of the coating determine its mechanical properties. The values of adhesive bond strength of plasma sprayed metallic and ceramic coatings, stated by different authors, differ considerably because of the highly complex laws of bonding [1]. Hence, the influence of important parameters such as the stand-off distance, power and coating thickness on the bond strength and porosity was determined, the results being given herein.

2. Experimentation

2.1. Plasma spray system

A Plasma Technik MC-1100 unit, Switzerland and a Miller's Plasma Dyne, USA were used to plasma spray the specimens. The spray conditions are given Table 1. Bright drawn steel, the most widely used structural material, was selected as the substrate material and oxide ceramics such as Al_2O_3 (A), Al_2O_3-TiO_2 (AT) and PSZ were selected since they find many industrial applications. Pure Argon (Ar) was used as the plasma gas. A sophisticated, six axis, microprocessor controlled, programmable robot (Motoman, Japan) was used as the spraying equipment for producing very accurate and repeatable ceramic coatings on the steel substrate material.

Table 1
Plasma spray parameters

Spray equipments	1. Millers Plasma Dyne, USA 2. Plasma Technik with 6-axis robot
Powder	Al_2O_3, Al_2O_3-TiO_2 & Y_2O_3-ZrO_2 (PSZ), NiAl - bond coat
Gas	Ar
Gas flow (1/min)	44
Spray rate (g/min)	40
Spray distance(mm)	100-150
Power (kW)	20-40
Nozzle/anode dia. (mm)	6
Powder injector dia.(mm)	1.5
Injector distance (mm)	6
Injector angle (degree)	90

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2.2. Porosity

The cross-sectional surface porosity of the ceramic coating in terms of percentage was measured. The optical micrographs were analyzed with a Vidicom image analyzer for porosity measurement.

2.3. Bond strength

The stand-off distance is the distance between the spray nozzle and the substrate material to be coated. Even though the suppliers of the plasma unit specify a range of stand-off distances, the optimal distance is to be determined by suitable experimental trials [2]. The parameters for good adhesion of coatings are still empirical. The stand-off distance was varied from 100 mm to 150 mm in steps of 10 mm to deposit Al_2O_3, Al_2O_3-TiO_2 and PSZ ceramics. During the process of spraying , the components were cooled by a flow of compressed air, since it is necessary to keep the substrate sufficiently cold to avoid its oxidation during spraying [3].

For each type of ceramics, samples were prepared for testing according to ASTM C633-79, the standard test method for estimating the adhesive or cohesive strength of flame-sprayed coatings. Following spraying, ten pairs of samples without chipping or delamination were separated, desiccated,cleaned and then coated with cyanamid FM73 adhesive. The pairs were then uniaxially aligned and cured. The load at which separation of the pairs took place was noted and the corresponding stress was registered as the adhesive strength of the coating. The arithmetic mean of the ten observations was estimated. Similarly for each type of ceramic coating sprayed at different stand-off distances (for the maximum power of 40 kW), the adhesive bond strength was estimated.

The coating thickness significantly influences the bond strength of ceramic coating. The stress developed and distributed in the coating during the process of spraying increases with increase in the thickness of the coated layer and is assumed to be a significant factor in reducing the adhesive bond strength[1]. Spraying was done at a distance of 120 mm (optimal value resulted from the test) and coatings of Al_2O_3, Al_2O_3-TiO_2, and PSZ ceramics were made for thickness range of 100 μm to 800 μm. Ceramic coated samples were prepared for different plasma power input ranging from 15 to approximately 40 kW. The bond strength of a sprayed ceramic coating depends on the process parameters such as stand-off distance and power input, and also on géometrical parameters such as the coating thickness. The process parameters influence the degree of melting of the ceramic material; thus influencing the spreading of the ceramic on striking the substrate, the porosity of the coating and thereby the bond strength. The observations on porosity, hardness of the sprayed layer and subsequently the bond strength are presented in the following section.

3. Development of an Expert System

An expert system comprises three basic components [4] such as a knowledge base, an inference engine and a user interface as shown in Fig. 1.

3.1. Knowledge base

This comprises a series of facts about the process optimization of atmospheric plasma spraying of high performance ceramics.

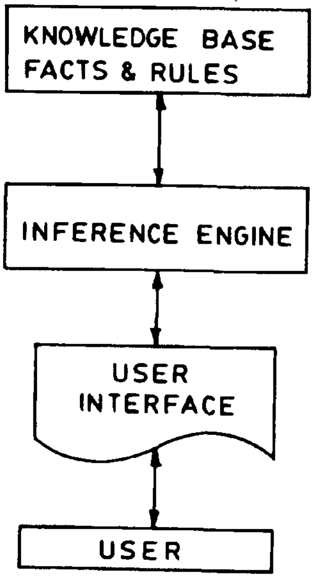


Fig. 1: Components of an Expert system

example: GAS USED IS ARGON
CERAMIC USED IS ALUMINA
BOND STRENGTH IS 20
THICKNESS OF COATING IS 200

3.2. Inference engine

In order to make use of the expertise which is embodied in the knowledge base, the expert system must also posses an element which can scan facts and rules, and provide the answers to the queries given to it by the user. The inference engine has the ability to look through the knowledge base and apply the rules to the solution of a particular problem. The experimental data of the plasma arc spraying of high performance ceramics are stored in the data file. It will accept the queries and give the optimal solution to the queries.

example: POWER IS 40 MW
STAND OF DISTANCE IS 100 MM
POROSITY IS 4%

3.3. User interface

The user interface is the means by which the user communicates with the expert system, i.e., an ideal expert system would allow the user to type his/her queries to the system. The system would then recognize the meaning of the queries, and use its inference engine to apply the rules in the knowledge base to deduce an answer. This answer would then be communicated back to the user.

From the above experimental results it is concluded that a very complex relationship exits amongst various process parameters influencing the plasma spraying. Researches are still being carried out to optimize the various parameters. The complexity of the selection of process parameters makes it an ideal candidate for the application of the expert system, which would aid in the selection of optimum parameters for given conditions, therefore using the above experimental data the expert system '**KRISHPERT**' has been developed. To establish a sound rule base, the experimental data were used in the Statgraphics package and a satisfactory multiple regression model was developed. A semantic net showing the relationship amongst process parameters and measurable parameters has been developed, as shown in Fig. 2.

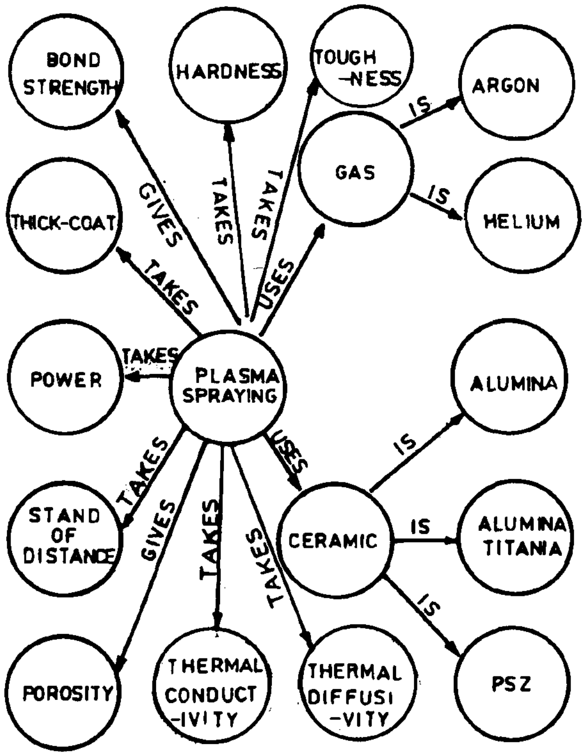


Fig. 2: Semantic net showing the relationship amongst various parameters of the atmospheric plasma spraying of ceramics

4. Results and Discussion

4.1. Porosity

Fig. 3 illustrates a typical variation of porosity with power input to the plasma. It is seen that for all the three types of ceramic coatings, there is a drop in the porosity level with increase in the power input. With increased power input, the quality of melting will improve, resulting thereby in better flattening of the powdered particles, on striking the substrate. This results in denser coatings with reduced porosity. The higher percentage of porosity observed for Al_2O_3 coating is largely due to the poor toughness of the Al_2O_3 and also by the tendency for fragmenting on striking the substrate. The influence of stand-off distance on porosity is presented in Fig. 4. It is seen that as the stand- off distance increases, the porosity level reduces, with shorter stand-off distance, there will be splashing of the molten ceramic on striking the substrate, facilitating entrapment of gases and also void space. The tendency is further enhanced by the possible cracking of the coating material due to faster coating. On striking the substrate with shorter stand-off it is possible that molten material may undergo solidification and subsequent oxidation (open Atmospheric Plasma) resulting in reduced spreading tendency on striking the substrate. This will also result in increase of porosity. Matejka and Benko[1] and P.Fauchias[5] have reported on the influence of velocity and temperatures of molten ceramics.

Porosity is largely influenced by vacant sites/entrapped gases. For a qualitative understanding of the porosity content, the

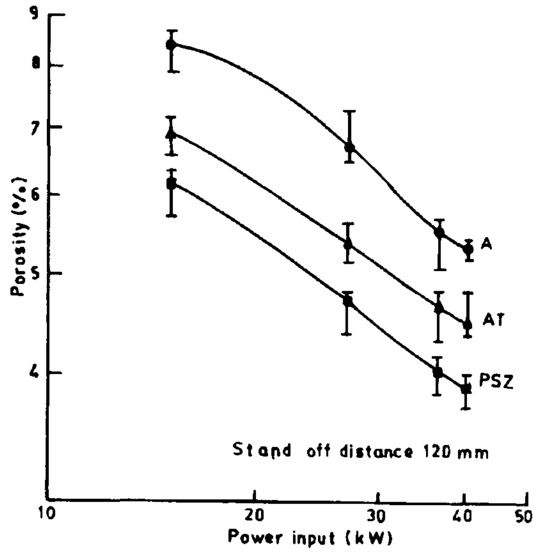


Fig. 3: Influence of power input on porosity

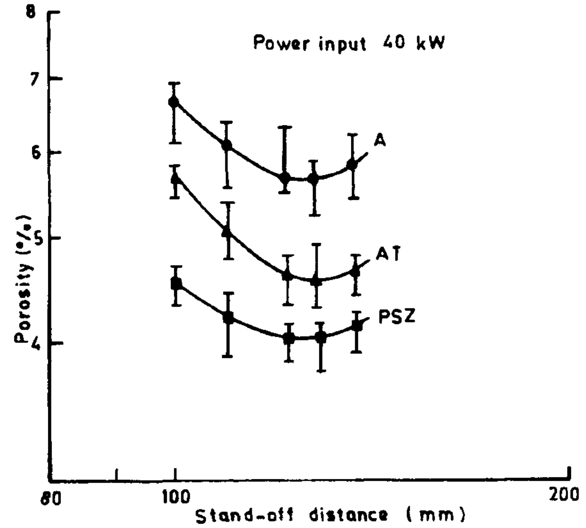


Fig. 4: Influence of stand-off distance on porosity

microstructures for the three types of coatings were taken: a typical micrograph of cut-section of sprayed Al_2O_3-TiO_2 ceramic (Fig. 5) indicates the probable porosity content. During coating, PSZ and Al_2O_3-TiO_2 maintain a fairly compact section owing to their improved toughness parameter.

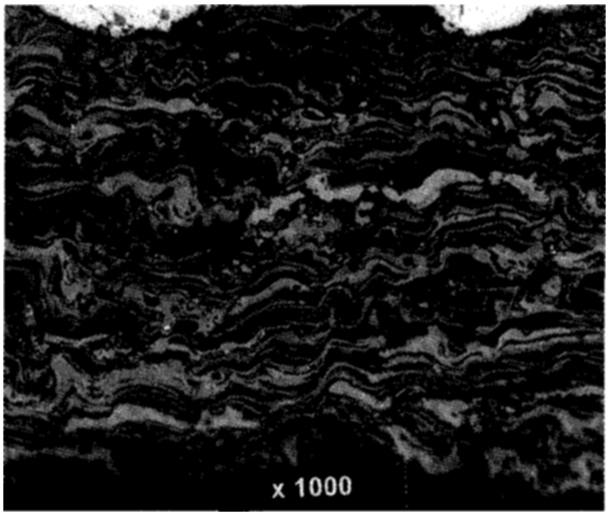


Fig. 5: Typical micrograph of a cut section of sprayed ceramic

4.2. Bond strength

Fig. 6 presents a cross section of a coated layer. As stated earlier, either a bond layer is introduced or the surface is prepared either by grit blasting or machining to provide mechanical locking. Apart from surface preparation, the morphology of the initial powder can influence melting and thereby bond strength.

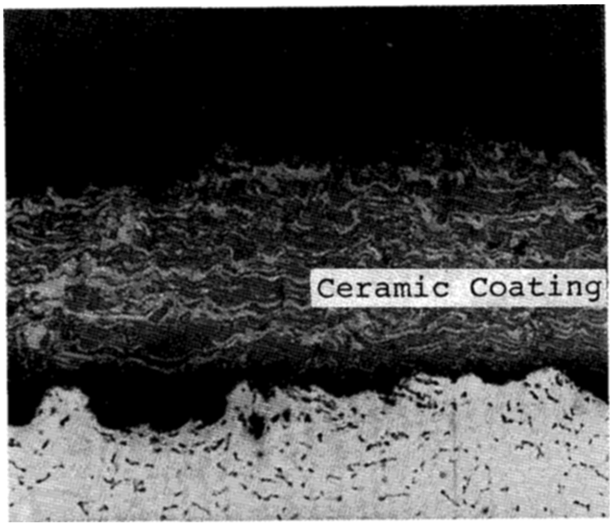
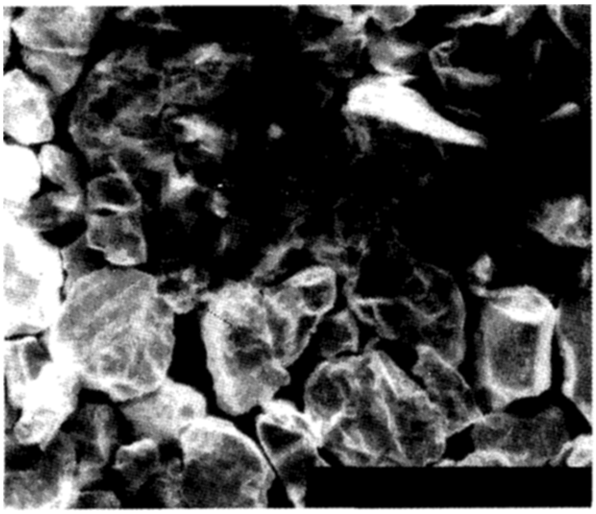
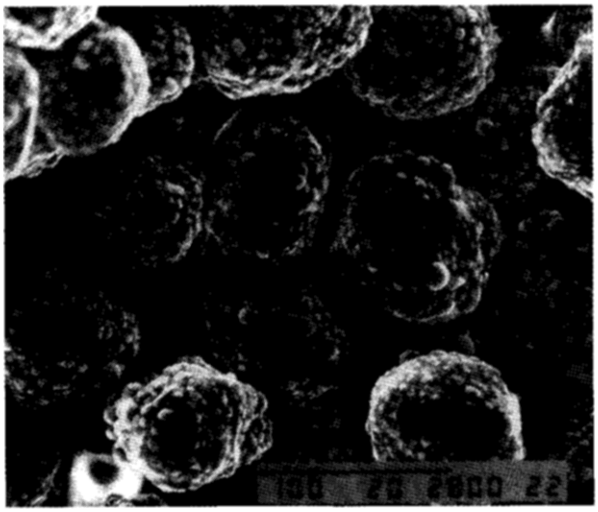


Fig. 6: Cross section of a coated layer

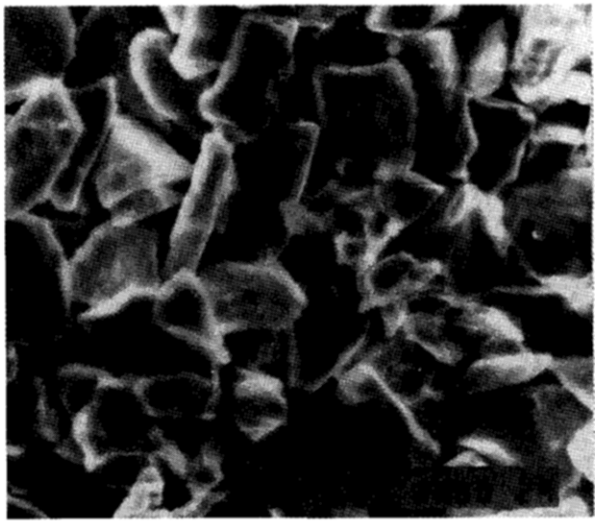
Typical morphology of the initial powder material observed is presented in Fig. 7. It is seen that while both the oxide ceramics (Al_2O_3 and PSZ) present a sharp acicular grit with variation in size, Al_2O_3-TiO_2 was mostly spherical with occasional agglomeration of spheres or layered spheres. The difference in size and shape of



Alumina powder



Alumina - Titania powder



PSZ powder

Fig. 7: Typical morphology of the initial powder material

the particles can influence the melting and thereby the coating strength.

Fig. 8 shows a typical section of a plasma channel illustrating the particle injection and the morphology of the melted particles in the plasma stream. It is seen that depending upon the variations in size and shape of ceramic powder and also the injection altitude, one can obtain fairly uniform and small-sized particles to varying, bigger sized molten particles. This will exert a considerable influence on the bond quality.

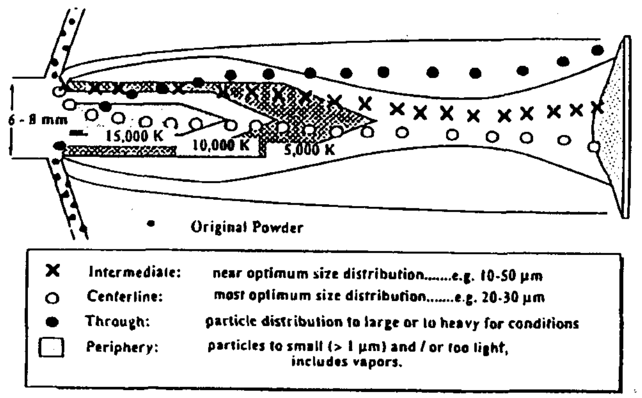


Fig. 8: Section of a plasma channel [5]

4.3. *Influence of stand-off distance on bond strength*

Arata et.al[6], have reported that the spraying distance (stand-off) and the plasma power will effectively change the temperature and velocity, there by influencing the properties of the coating.

Fig. 9 represents a typical variation of bond strength with stand-off distance. It is seen that the bond strength increases with stand-off and attains a maximum at around 115-125 mm stand-off-distance, beyond which a reduction in the bond strength is observed.

As stated earlier with smaller stand-off distance, the splashing of material with possible quenching cracks result (Matejka et al [5], Zhung and Gu, [7] and Kingswel et al [8]); this may promote increased porosity content, reducing the bond strength. However, with higher order stand-off distance, the reduction in the bond strength is due to different attributes. With longer stand-off distance, the enthalpy of the molten ceramic particles is largely lost and the particles are decelerated in a relatively longer flight path promoting oxidation and associated degradation of the melting particles. Under such conditions, the particles on striking the substrate will not be adequately flattened to overlap the layers, resulting in porosity and reduced bond strength.

Typical observations on the influence of stand-off distance on the surface texture and thereby on the bond quality are presented in Fig. 10. With smaller stand-off, the ceramic coatings experience fragmentation and quench cracks. With longer stand-off, the coated surface presents a case of poor melt-particles. In the case of optimum stand-off the surface presents a fairly uniform texture, with striking material experiencing flattening without any cracking.

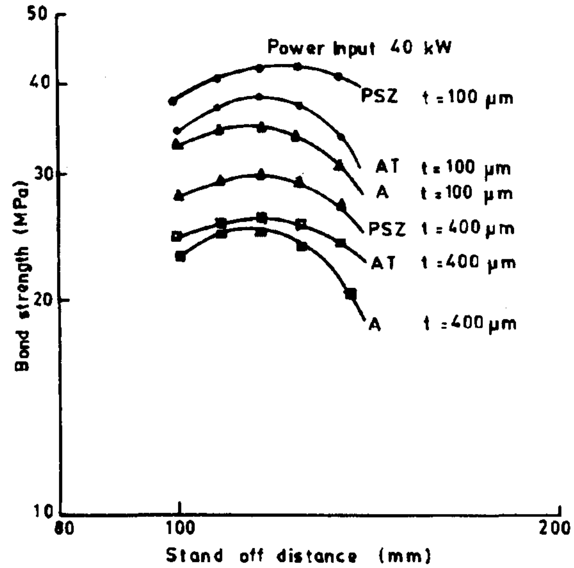


Fig. 9: Influence of stand-off distance on bond strength

Arata et al [6], have studied the influence of stand off distance on the erosion rate of Al_2O_3-TiO_2 ceramic coating; it was observed that erosion rate increased with spraying distance and decreased with increase in plasma power input.

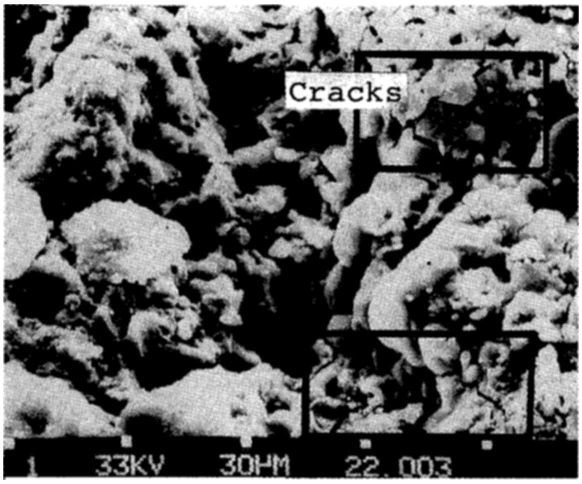
Referring to Fig. 9 showing the influence of stand-off distance on bond strength, it is seen that amongst the three coatings, PSZ and Al_2O_3-TiO_2 exhibited better bond strength compared to Al_2O_3 coatings; further better bonding was realized with smaller coating thickness. The enhanced bond strength of PSZ and Al_2O_3- TiO_2 coatings can be attributed to the higher order toughness. Tougher ceramics can be layered on substrates without quenching cracks and with minimum porosity. This enhances the bond strength.

4.4. *Influence of power input on bond strength*

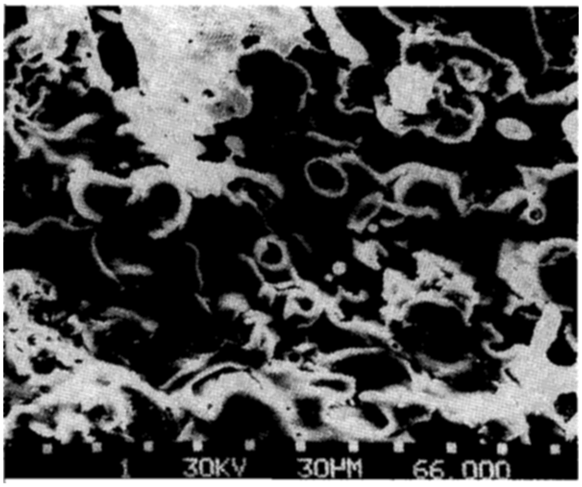
Apart from stand-off, the power input to the plasma can also influence the bond strength. The observations on the influence of input power on bond strength is presented in Fig. 11. It is seen that as the input power increases, the bond strength increases around a specific power input depending upon the coating. There is further improvement in bond strength. This is around a power input of 25 kW for Al_2O_3, while it is around 38 kW for Al_2O_3-TiO_2 and PSZ.

4.5. *Influence of coating thickness on bond strength*

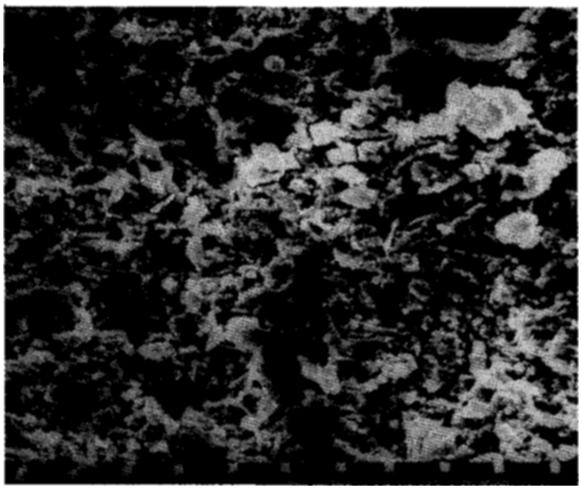
As stated earlier, amongst the factors influencing bond strength, coating thickness is important. The performance of a sprayed coating depends not only on the strength,hardness, porosity and relative factors, but also on its thickness. The



Over heated with crack formation - shorter distance



Poor melting - larger distance



Uniform agglomeration - optimal distance

Fig. 10: Typical observation on the influence of stand-off distance on surface texture (Alumina)

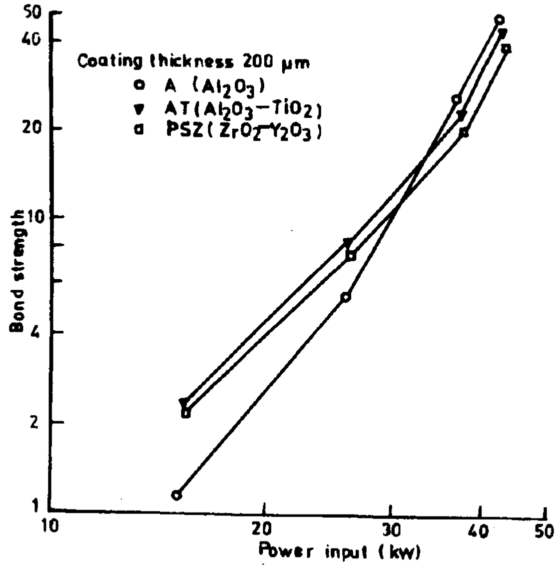


Fig. 11: Influence of power input on bond strength

thickness of a coating is decided mostly based on the strength and deformation characteristics of the substrate. For relatively softer substrate, one has to employ a thinner coating and to ensure a diffusionless interface. In the case of plasma spraying, unlike the case of the PVD or CVD technique, the coatings are usually thicker. Thus one has to employ a better interface such as a bond coat. Hence the thickness has to be limited.

Fig. 12 presents the influence of coating thickness on the bond strength of a plasma sprayed ceramic coating. It is seen that beyond about 150 mm thickness there is drop in bond strength and also a drastic drop beyond a thickness of 400 μm.

Matejka and Benko [1] have reported catastrophic loss of adherence with increasing thickness of coatings. The absolute

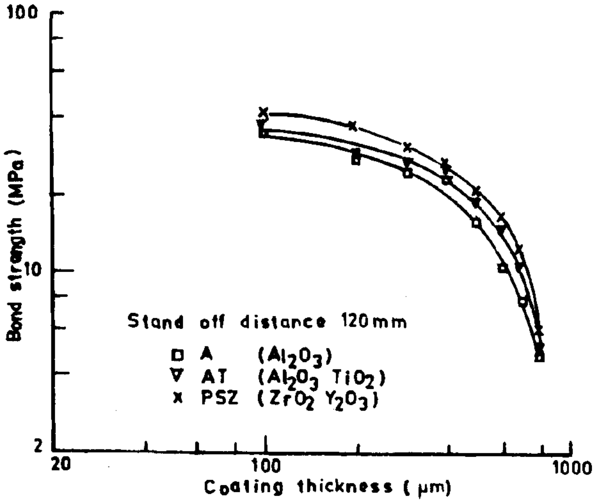


Fig. 12: Influence of coating thickness on bond strength

level of residual stress and its distribution significantly affect the bond strength. Due to stress gradient (maximum stress at the interface) the forces acting normally make tearing off the coating from the substrate easier. The larger is the stress gradient, the easier is the pealing off. Many reported works[8,9] have illustrated that the stress gradient in a thick coating is greater than that in a thin coating. Hence a coating of higher thickness has less adhesive bond strength. Also the greater the size or thickness of the coating, the greater is the flaw and impurities content and this can be one of the factors affecting the bond strength [10].

In thermal spraying, usually the thickness of the coating is built up by multi-layering. The strength of a coating by multi layers depends not only on the bond strength,but also on the cohesive strength between the layers. Since Al_2O_3-TiO_2 and PSZ are tougher grades of ceramics, they could have obtained good conformity with the surface of the substrate, ensuring maximum strength; however, possible oxidation/entrapped gases during layering can influence the inter-layer strength/cohesive of the coating. This might have resulted in the observed cohesive failure. This may be attributed to the difference in thermal properties of the coating materials.

4.6. Expert system

The developed 'KRISHPERT' expert system has been tested for its application and validity. The flow chart for process optimization, as shown in Fig. 13, was drawn and programming was carried out. The process variable and output files are as follows.

Table: 2

Processing the knowledge:

Variable name	Meaning
GAS	Gas used
CERA	Ceramic used
B_S	Bond strength
THICK_COAT	Thickness of coating
POW	Power
SOD	Stand of distance
POR	Porosity

After establishing the knowledge base using the above mentioned table, processing the information using forward chaining principles is possible. The expert technique requires the construction of a number of useful tables or data structures that will aid in answering questions and making decisions about the problems.These data structures, therefore, serve an indispensable purpose as they are derived directly from the knowledge base.

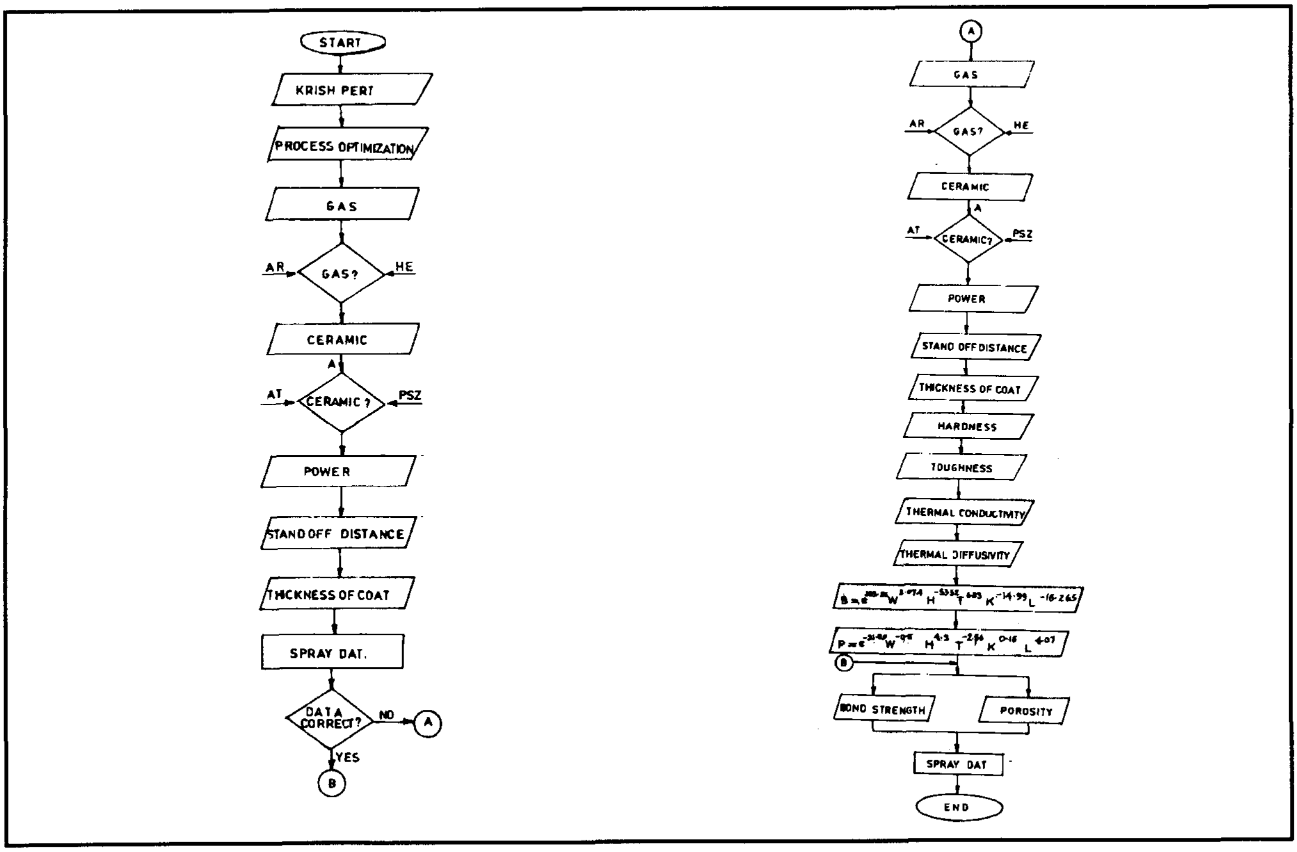


Fig. 13: Flow chart for 'KRISHPERT' system towards process optimization

4.7. Knowledge base of the atmospheric plasma spraying

The following rules can be framed from the experimental database

Rule 1:		
	IF GAS=GAS	1.ARGON
	THEN GAS= ARGON	2.HELIUM
Rule 2:		
	IF CERAMIC=CERA	1.ALUMINA
	THEN CERA=ALUMINA	2.Al_2O_3-TiO_2
		3.PSZ
Rule 3:		
	IF BOND=b-s	
	THEN b-s=20	1. 20 MPa
Rule 4:		
	IF THICKNESS=THICK-COAT	
	THEN THICK-COAT=200	1. 200µm

If the rules, i.e. conclusion variable, match with data in the spray data file, then it displays the output variables. If they do not match so, the developed rule (regression model) is referred automatically and hence the rule base data is displayed as output variable queue.

Conclusion variable queue :

ARGON
ALUMINA
40 kW
120 mm
200 µm

Output variable queue:

BOND STRENGTH	40 MPa
POROSITY	4 %

4.8. Development of rule

The multiple regression models developed for porosity in terms of power and bond strength are as follows.

$$P=e^{-31.89}\, W^{-0.5}\, H^{4.9}\, T^{-2.56}\, K^{0.16}\, L^{4.07}$$

$$B=e^{383.95}\, W^{3.074}\, H^{-53.52}\, T^{6.83}\, K^{-14.99}\, L^{-16.265}$$

Where B - Bond strength (MPa), P-Porosity(%), W - Power (kW), H- Hardness, L -Thermal diffusivity (M^2/sec), K - Thermal conductivity (Kcal/mhr°c), T - Toughness (MPa/$m^{1/2}$)

Similar model can be developed for selection of other spray parameters [11].

5. Conclusions

From the experimental study the following report could be made:

1. High-performance ceramics can be successfully plasma sprayed under atmospheric conditions.
2. Increase in the thickness of the coating reduces the bond strength of the coating.
3. Even though a coating thickness of 100 µm possesses a greater bond strength, a coating of 400-500 µm thickness is found to be optimal from the point of bond strength and further super finishing process (stock available for material removal).
4. The optimal stand-off distance is found to be 115-125 mm for the oxide ceramics under study.
5. A power input of 30-40 kW can melt and form a ceramic coating with least porosity content.
6. A maximum bond strength of 34,39,and 45 MPa for Al_2O_3, Al_2O_3-TiO_2 and PSZ coating can be attained.
7. A bond coat is essential for thicker coatings.
8. Al_2O_3-TiO_2 and PSZ coatings have a greater bond strength than that of Al_2O_3 coatings.
9. The least porosity content in the ceramic coatings was evaluated to be 5.75%, 4.5%,and 4% for Al_2O_3. Al_2O_3-TiO_2 and PSZ respectively.
10. The particle size of the ceramic powders also influences the coating quality. Globular Al_2O_3-TiO_2 ceramics form a coating with least porosity and greater bond strength.
11. The 'KRISHPERT' expert system can be developed with a sound inference engine linking the user with a friendly user interface using the experimental data. A suitable rule based system has been developed and can be used successfully with the expert system.

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