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Some Investigations on Mechanical and Tribological Characteristics of Industrial Ceramic Coatings.

Mohammed Yunus[1] J.Fazlur Rahman[2]
[1]Department of Mechanical Engineeringt, H.K.B.K. College of Engineering, Bangalore, India-560045.
[2]Department of Mechanical Engineeringt, H.K.B.K. College of Engineering, Bangalore, India-560045.

Abstract: Thermal sprayed coatings are very much attractive for many industrial applications due to their high strength and thermal barrier characteristics at elevated temperatures, resistance to chemical degradation, wear resistance and environmental corrosion protection in engineering components. The design of a surface is concerned with preparation / treatment on the substrate surface of engineering components with suitable surface modification techniques. Among the several surface modification techniques, atmospheric plasma spraying and high velocity oxy-fuel (HVOF) spraying coating techniques are widely used for industrial components. The characterization of TBC requires a better understanding of Mechanical and Tribological properties along with their failure mechanisms which are to be thoroughly investigated to estimate their performance. However the quality and functional requirement of ceramic coated components can further be improved by eliminating the presence of cracks and defects in the coatings by suitable post processing technique (microwave glazing). In this paper, an attempt has been made to study various Mechanical and Tribological characteristics of Tungsten carbide cobalt (WC-CO) HVOF coating as well as ceramic coatings like Alumina (Al_2O_3), Alumina- Titania (Al_2O_3- TiO_2), Partially Stabilized Zirconia (PSZ), Supper-Z alloy produced by APS process. An experimental study is also formulated to evaluate important Mechanical characteristics such as porosity, bond strength, hardness and Tribological characteristics, including fatigue behaviour of the coated components. Based on experimental results, a theoretical modelling has been designed using some special softwares like Minitab and Discipulus to verify the validity of experimental results and also to predict various functional parameters without testing experimentally. This theoretical modelling has also been used for optimization of process parameters using orthogonal array, S/N ratio and ANOVA, besides to predict their values at specific condition.

Keywords: HVOF- APS processes; Ceramic coatings; Tribological and mechanical properties characterization; Microwave glazing of coatings, Taguchi –ANOVA, Genetic Programming.

1.0 INTRODUCTION

Thermal sprayed coatings are very much attractive for many industrial applications due to their high strength and thermal barrier characteristics at elevated temperatures, resistance to chemical degradation, wear resistance and environmental corrosion protection in engineering components. The design of a surface is concerned with preparing a surface with suitable modifications. Among the several surface modification techniques, atmospheric plasma spraying and high velocity oxy-fuel (HVOF) spraying techniques are widely used. It has been observed from previous researchers [1-2], [5-6] that, Tungsten carbide- cobalt (WC-CO)with HVOF process gives comparatively good results compared to other thermal spraying processes producing fine surface finish, high bond strength, higher hardness, lower porosity and low oxide content at larger thickness [3-4], [5-6], [7]. Since oxide ceramics and WC-CO coatings find wider applications, an attempt has been made to study the mechanical and tribological characteristics using HVOF and APS processes. The quality of ceramic coatings further can be enhanced by reducing the presence of cracks and defects by suitable microwave irradiation (glazing) technique by post processing the already coated surfaces. Thermal barrier coating materials have been subjected to thermal tests and suggestions have been made for their characterization for high temperature applications.

1.1. High-velocity oxy-fuel spraying (HVOF) process

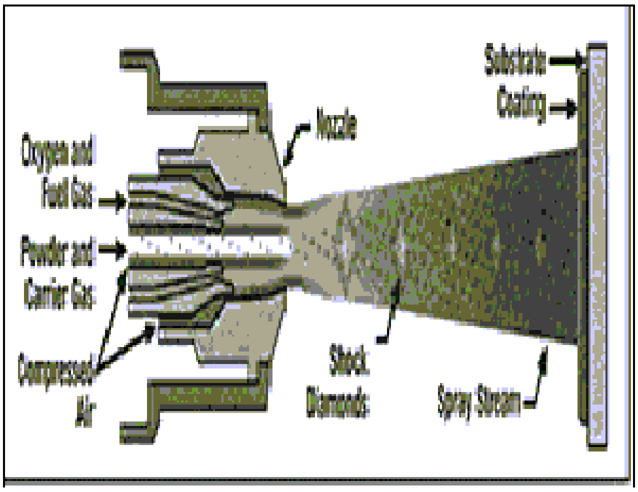

Figure 1.a. HVOF process

In general, the high velocity oxy fuel spraying (HVOF) process can be used for the deposition of the bond coat materials, over which oxide coatings are sprayed for good adherence. This process is based on the combustion of the fuel gas with oxygen at high pressures within the combustion chamber. The exit jet velocity is generally more than 1000 m/s and at this speed, the oxide powder which is axially injected is moderately heated but highly accelerated through the expansion nozzle to large particle velocities beyond 800 m/s. The stream of hot gas and powder is directed towards the surface to be coated. The powder partially melts in the stream, and deposits upon the substrate as shown in figure 1. The process has been most successful for depositing corrosion-resistant alloys (stainless steels, nickel-based alloys, aluminium, etc). HVOF coatings are effectively used in the fields of general manufacturing industry, gas turbine industry, petroleum industry, chemical process industry, pulp industry and automotive industry.

1.2. Atmospheric Plasma spraying process

When a strong electric arc is struck between tungsten electrode (cathode) and a nozzle (anode) in the presence of Argon and nitrogen / hydrogen mixture in the chamber, the gas gets ionized producing high temperature plasma. Injected particles of coating materials are heated inside the plasma jet and molten droplets sprayed on the substrate with high velocities to form the coating. APS ceramic coatings are widely employed in the engineering applications which demand wear resistance, corrosion resistance and high strength at elevated temperatures.

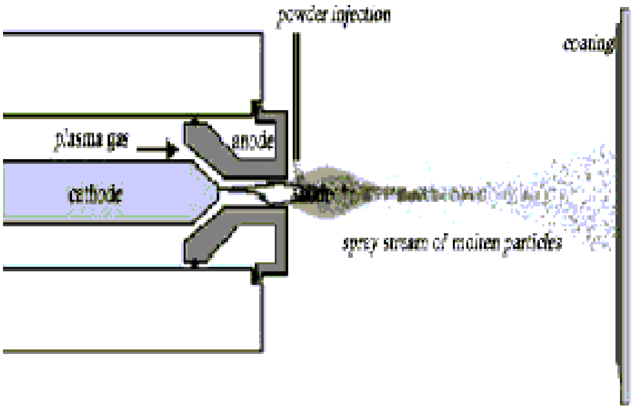

Figure 1.b.Atmospheric plasma spraying process

1.3 Genetic programming

Genetic Programming is a form of machine learning that automatically writes computer programs. It uses the principle of Darwinian Natural [12] Selection to select and reproduce "fitter" programs. GP applies that principle to a population of computer programs and evolves a program that predicts the target output from a data file of inputs and outputs [18-21]. The programs evolved by GP software – Discipulus [22], in this case Java, C/C++ and assembly interpreter programs represents a mapping of input to output data.This is done by Machine Learning that maps a set of input data to known output data. The aims of using the machine learning technique on engineering problems are to determine data mining and knowledge discovery. GP provides a significant benefit in many areas of science and industry [23].

GP solutions are computer programs that can be easily inspected, documented, evaluated, and tested. The GP solutions are easy to understand the nature of the derived relationship between input and output data and to examine the uncover relationships that were unknown before. Genetic Programming evolves both the structure and the constants to the solution simultaneously.

GP has been successfully used to solve problems in a wide range of broad categories [24-33] :

1. Systems Modelling, Curve Fitting, Data Modelling, and Symbolic

Regression

2. Industrial Process Control
3. Financial Trading, Time Series Prediction and Economic Modelling
4. Optimisation and scheduling
5. Medicine, Biology and Bioinformatics
6. Design
7. Image and Signal processing
8. Entertainment and Computer games.

1.4 Taguchi method

Taguchi method is important tool for the robust design in obtaining the process and product conditions which are least sensitive to noise to produce high quality products with low manufacturing costs [16]. It involves various steps of planning, conducting and evaluating the results of specially designed tables called "orthogonal array" experiments to study entire parameter space with minimum number of trials to determine the optimum levels of control parameters [17]. A quality loss function is then designed to evaluate the deviation between experimental value and desired value. Taguchi method combine experiment design theory and quality loss function. Taguchi method recommends the use of loss function which is then transformed into a S/N ratio to measure the performance characteristic deviating from the desired value and then S/N ratio for each level of process parameters is evaluated based on average S/N ratio response analysis and greater S/N ratio is corresponding to better quality characteristic irrespective of category and quality is evaluated based on average S/N ratio response analysis and greater S/N ratio is corresponding to better performance characteristic regardless of category and quality. To find which process parameters are statistically significant, Analysis of Variance (ANOVA) to be performed [8-15]. Finally, to verify the optimal process parameters obtained from the parameter design, confirmation test to be conducted. To find the optimal combinations the following step by step procedure is followed for the DOE [16-17].

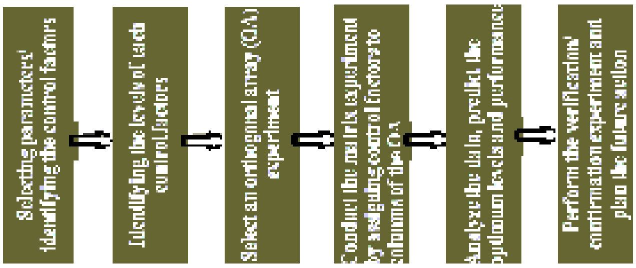

Figure 1.a. Taguchi methodology

2. EXPERIMENTAL PROCEDURES

Five different commercially available ceramic coatings powders namely, Alumina, Alumina-Titania, Partially Stabilized Zirconia, Zirconia Toughened Alumina and Super-Z alloy of two different thicknesses namely 100 to 250 microns were used for the preparation of coatings. A 40 KW Sulzer, Metco plasma spray system with 7MB gun is used for this purpose. Mild steel plates of 50x50x6 mm were used as substrate to spray the ceramic oxides. They were grit blasted, degreased and spray coated with a 50 to 100 micron meter Ni Cr Al bond coat. The ceramic TBC were then plasma sprayed according to spray parameters mentioned in table1. In this study, two response parameters such as thermal barrier and thermal cycling tests were considered.

2.1 Mechanical and tribological tests

Standard specimens are prepared and coated with WC-CO coatings and ceramic coatings materials like A, AT, PSZ with different thicknesses ranging from 100- 400 microns using optimum spray parameters. These specimens were tested for tensile, hardness, porosity, wear and friction and fatigue strength using standard equipments of laboratories.

2.2 Postprocessing of ceramic coatings

The process used here is also called as micro wave glazing. Microwave heating is fundamentally different from conventional heating process. In conventional thermal processing, energy is transferred to the material through conduction, convection and radiation of heat from the surface of the material. In microwave heating, microwave energy is delivered directly to materials through molecular interaction with the electromagnetic field. As microwave radiation penetrates and interacts with molecules, transfer of electromagnetic energy takes place throughout the volume of material, leading to volumetric heating [5], [11], [20]. Microwave material interaction depends on dielectric property of materials. While metals conducting reflect, insulators are transparent to microwaves.

2.3.1. Wear test

The pin-on-disc testing machine was used to measure the wear of material weight loss by conducting dry sliding wear tests [16-21]. This instrument consists of a pin is mounted on a stiff lever, designed as a frictionless force transducer and pressed against a rotating disk. Generally pin surface is coated with ceramic oxide to different thicknesses using plasma spray process, fixed to an arm and pressed with a known force. The measurement includes RPM, Wear and Frictional force to measure effect of sliding speed, applied pressure, and weight loss on the wear characteristics of different types of coatings. As the disc is rotated, resulting frictional forces acting between the pin and the disc are measured by using a strain gage sensor.

2.3.2. Hardness test

The Rockwell hardness number was determined by pressing a hardened steel ball indenter or diamond cone penetrator against a test specimen and resulting indentation depth was measured as a gauge of the specimen hardness using C-scale.

2.4. Taguchi Experimental Design for wear test

In wear characterization of ceramic coatings, the design of experiment using the results of weight loss were carried out with four process parameters [13-15] each at three levels and the feasible space to assess quality of output and values for the four parameters of wear study were defined by varying the applied pressure, sliding velocity, sliding distance and type of coating for a range are tabulated in table2.a. The fractional factorial design layout reduces to L27 type [15] and it requires twenty seven trials are shown in table2.b. The interaction between A and C process parameters were taken to evaluate the effect of PV (product of applied pressure and sliding velocity) factor [1].

Table 2.a. Process parameters and levels of the experimental design

Parameters	Labels	Level 1	Level 2	Level 3
Applied Pressure (MPa)	A	0.1	0.2	0.3
Sliding Distance (m)	B	4	6	8
Sliding velocity (m/sec)	C	2.5	7.5	12.5
Type of Coating	D	PSZ	AT	Alumina

2.4.1. Design of Experiment for hardness test

Table 2.d shows design of experiment for hardness characterization of ceramic coatings with four process parameters each at four levels.

Table 2.b. Experimental layout and results of summary for Wear test.

Experiment trials (Recipes)	A	B	C	D	Weight loss in mg	S/N ratio in dB
1	0.1	4	2.5	PSZ	3.0	9.54
2	0.1	4	7.5	AT	1.8	5.11
3	0.1	4	12.5	A	5.25	14.40
4	0.1	6	2.5	AT	3.8	11.59
5	0.1	6	7.5	A	4.75	13.53
6	0.1	6	12.5	PSZ	8	18.06
7	0.1	8	2.5	A	5.6	14.96
8	0.1	8	7.5	PSZ	8	18.06
9	0.1	8	12.5	AT	8	18.06
10	0.2	4	2.5	AT	3.5	10.88
11	0.2	4	7.5	A	3.6	11.13
12	0.2	4	12.5	PSZ	14	22.9
13	0.2	6	2.5	A	10	20
14	0.2	6	7.5	PSZ	10	20
15	0.2	6	12.5	AT	20	26.02
16	0.2	8	2.5	PSZ	8	18.06
17	0.2	8	7.5	AT	11	20.83
18	0.2	8	12.5	A	25	27.96
19	0.3	4	2.5	A	6.5	16.25
20	0.3	4	7.5	PSZ	12	21.58
21	0.3	4	12.5	AT	16	24.08
22	0.3	6	2.5	PSZ	9	19.08
23	0.3	6	7.5	AT	16	24.08
24	0.3	6	12.5	A	25	27.96
25	0.3	8	2.5	AT	12	21.58
26	0.3	8	7.5	A	16	24.08
27	0.3	8	12.5	PSZ	24	27.6

Table 2.c. Control factors and levels of the experimental design for Hardness.

Factors	Labels	Level 1	Level 2	Level 3
Applied pressure (MPa)	A	0.1	0.2	0.3
Sliding Distance (m)	B	4	6	8
Sliding velocity (m/sec)	C	2.5	7.5	12.5
Type of Coating	D	Partial Stabilized Zirconia (PSZ)	Alumina-Titania (AT)	Alumina (A)

Table 2.d. Experimental layout and summary of results for Hardness test.

S.No.	A	B	C	D	Rockwell hardness no.	S/N ratio in dB
1	16	Super-Z	100	100	110	40.83
2	16	ZTA	110	150	109	40.75
3	16	PSZ	120	200	90	39.08
4	16	AT	140	300	115	41.21
5	25	Super-Z	110	200	116	41.29
6	25	ZTA	100	300	118	41.43
7	25	PSZ	140	100	85	38.59
8	25	AT	120	150	120	41.58
9	30	Super-Z	120	300	120	41.58
10	30	ZTA	140	200	112	40.98
11	30	PSZ	100	150	83	38.38
12	30	AT	110	100	106	40.51
13	40	Super-Z	140	150	125	41.94
14	40	ZTA	120	100	115	41.21
15	40	PSZ	110	300	86	38.69
16	40	AT	100	200	120	41.58

2.5. Genetic Programming methodology

For Prediction of Mechanical and Tribological Properties.Following mechanical and tribological properties of industrial ceramic oxide coatings have been considered.

Process Inputs

Normal Pressure (MPa)
Velocity of Sliding (m/sec),
Sliding Distance (m)
Power Input (KW),
Standoff Distance (mm),
Thickness of Coating (µm),
Toughness (MPa “ m)
Thermal conductivity (W/m K),
Thermal Diffusivity ($10^{-7}m^2$/sec)

Measured Process Outputs

Weight loss (mg)
Hardness (RHC)
Coefficient of friction
Bond strength (MPa)

3. RESULTS AND DISCUSSION

3.1. HVOF spraying process results

Based on experimental results, it was observed that high bond strength and less porosity exist at optimum standoff distance of around 130mm. It is also observed from figure 3.a, 3.b and 3.c, friction and wear test, the wear generally increase with contact pressure, sliding distance, and comparatively less in the case of coated specimens in general.

Table 2.e. Experimental results of evaluating weight loss during under different process parameters for different coatings

	when D = 4Km (V_2)		Alumina		
Normal pressure (V_0)	sliding vel. =2.5 m/s (V_1)	v=5 m/s (V_1)	v=7.5 m/s (V_1)	v=10 m/s (V_1)	v=12.5 m/s (V_1)
0.05	0.17	0.19	0.23	0.3	0.48
0.1	1.6	1.9	2.1	2.3	5.2
0.15	2.1	2.2	2.7	4.7	5.8
0.2	3.4	3.4	3.4	6.5	10
0.25	4.9	5.4	5.8	8.3	16
0.3	6	6.3	6.9	13	18
	when D=6Km (V_2)		Alumina		
0.05	0.8	0.7	0.8	1.2	1.5
0.1	4.3	4.3	4.6	6.8	13
0.15	9.3	7.3	7.3	7.3	14
0.2	12	10.1	10.5	14	17
0.25	14	11	11.6	16	20
0.3	16	13	13.3	18	22
	when D = 8Km (V_2)		Alumina		
0.05	1.4	1.6	1.3	2.2	2.5
0.1	5.6	5	6	7	10
0.15	12	10.5	12.5	14	18
0.2	13	13	12	13	25
0.25	14	14	14	18	28
0.3	15	15	15	23	33

	when D = 4Km (V_2)		Alumina-Titania		
0.05	0.39	0.23	0.18	0.26	0.52
0.1	2.8	2.3	1.8	2.8	7.5
0.15	3	2.8	2.5	6	8.1
0.2	3.8	4.8	5	8.1	15
0.25	4.4	6.3	6.3	9.2	17
0.3	6.5	8	10	14	19
	when D=6Km (V_2)		Alumina- Titania		
0.05	0.7	0.59	0.28	0.32	0.8
0.1	3.7	3.5	2.8	3.7	11
0.15	9.2	9.2	7.8	8.5	14
0.2	10.1	9.8	10.1	11	20
0.25	10.2	10	12	14	22
0.3	11	11	16	16	24
	when D = 8Km (V_2)		Alumina-Titania		
0.05	0.4	0.6	0.375	0.75	0.9
0.1	3.8	4	4	4.2	8
0.15	9	9	8.5	10	15
0.2	10	11	11	12	20
0.25	11	12	13	16	26
0.3	12	13	15	18	29
	when D = 4Km (V_2)		PSZ		
0.05	2.8	2.7	1.8	3	4.5
0.1	3.2	3	2.3	3.5	9.6
0.15	3.5	3.3	3	5.5	11
0.2	4	4.3	6.8	9.2	13
0.25	4.6	4.9	8.8	10	15
0.3	6.2	6.8	10	11	17
	when D = 6Km (V_2)		PSZ		
0.05	3.2	3.2	2.6	4.2	8.6
0.1	7.2	4.7	3.7	4.9	12
0.15	8	7.3	8	8.8	14
0.2	10	8.2	10	12	18
0.25	9.5	9.1	12	13	20
0.3	9	9.5	16	15	22
	when D = 8Km (V_2)		PSZ		
0.05	5	4.75	4.5	4.75	8
0.1	8	6.5	7	8	14
0.15	9	9	9	11	17
0.2	10	9.5	9	11	19
0.25	9	8.5	13	13.5	23
0.3	**8**	**11**	**16**	**17**	**25**

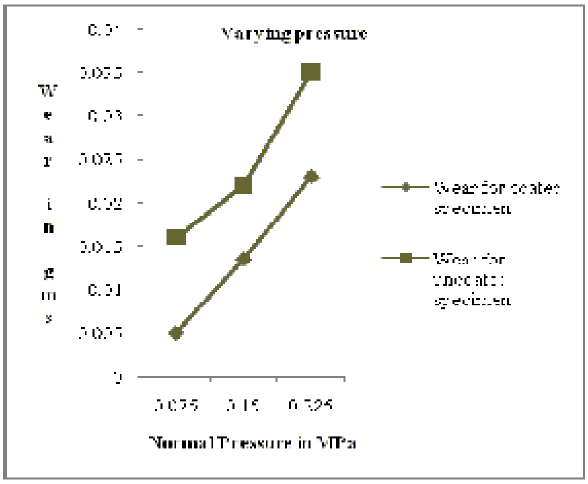

Figure 3.a. Wear v/s pressure

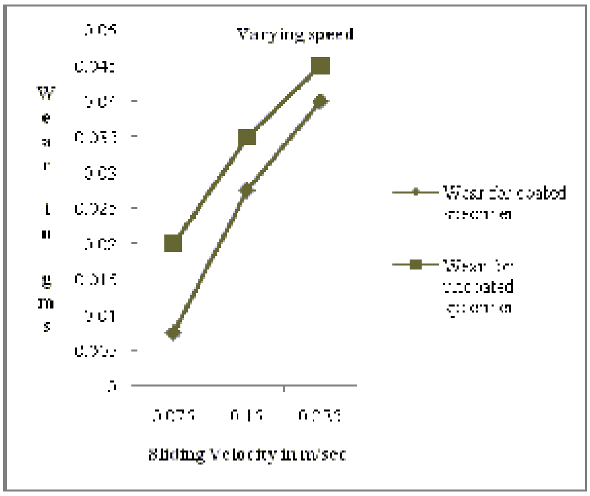

Figure 3.b.Wear v/s sliding velocity

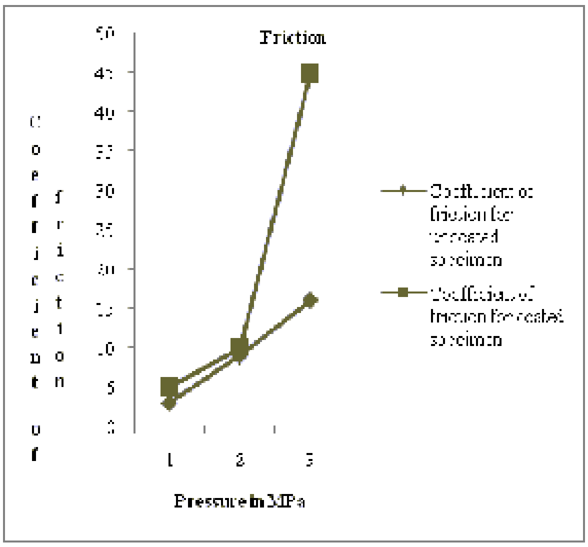

Figure 3.c.Coefficient of friction v/s Pressure

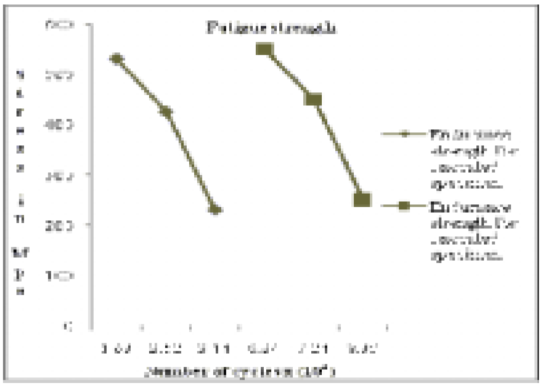

Figure 3.d. Endurance strength v/s Number of cycles

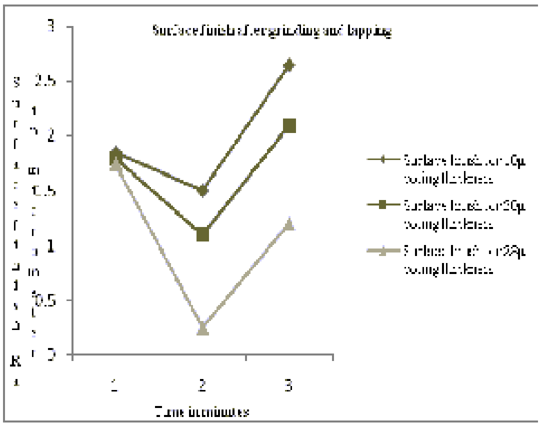

Figure 3.e..Surface finish v/s time of gtinding and lappingfor varying thicknesses

Even though geometry of the substrate and the type of loading influences the fatigue strength, it is observed that the fatigue strength is generally improved on cylindrical coated surface specimens subjected to alternate bending stresses as shown in figure3.d. It was also observed from figures 3.e that, surface finish of the ground and lapped of coated surfaces has favorably improved with the time of machining due to lower porosity and glazing effect.

3.2. Atmospheric plasma spraying results.

An experimental study was conducted on three different types of ceramic coating materials namely, Alumina (A), Alumina-Titania (AT) and partially stabilized zirconia (PSZ) to evaluate the mechanical characteristics such as porosity, hardness, bond strength and tribological characteristics in addition to fatigue behavior of the coated components.

Experimental results also showed that there is a reduction in bond strength with increasing in coating thickness as shown in figure 3.g. For good bond strength of

Atmospheric Plasma Spraying (APS) of ceramic coating was found to exist in the range of 120 to 140mm thicknesses as shown in figure 3.f. In case of PSZ, the highest bond strength was observed to be 50 MPa compared to Alumina (A) and Alumina- Titania (AT).

The friction and wear tests were also conducted on the following coated specimens namely Alumina, Alumina-titania, Partially stabilized Zirconia, Zirconia Toughened alumina (ZTA, having 20% PSZ and 80% Alumina) and Super- Z (having 20% Alumina and 80% PSZ) alloy by varying contact pressure, sliding distance and sliding velocity using pin-on-disc apparatus. It was observed that AT experienced less wear compared with that of Alumina under identical conditions. The wear performance of A, AT and PSZ showed only marginal difference from each other. The kinetic coefficient of friction was dropped down with higher velocity and with longer sliding distance. In the case of ZTA and super-Z alloy, coefficient of friction steadily increases with increasing time, whereas it is not the case with wear at different velocity of sliding as shown in figures 3.n to 3.v.

From the tensile test, it is concluded as coating thickness increases, the bond strength decreases for all types of coatings whereas for PSZ, the bond strength increases up to a thickness of 300µm and then starts decreasing.

It is observed from hardness test for constant power input and standoff distance and coating thickness, hardness increase in the following order PSZ, ZTA, Super-Z and AT. Increase in thickness hardness decreases.fig.

Fatigue test on cylindrical surfaces (alternate bending), reveals that an improvement in fatigue strength of coated substrate metal at all stress conditions, in general.

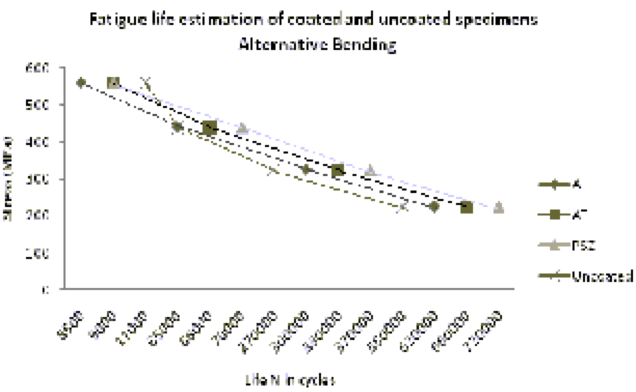

Figure 3.f. Fatigue life estimation under alternate bending

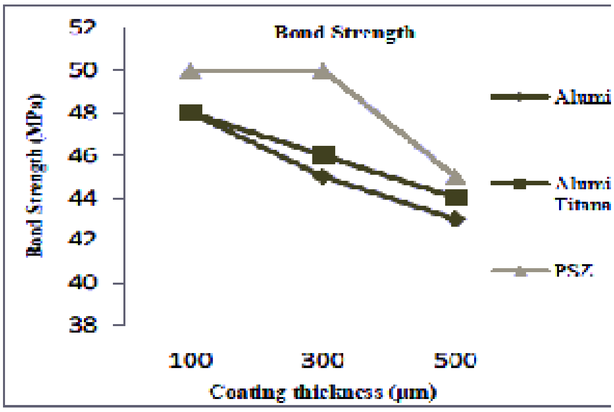

Figure 3.g. .Bond strength of coated componenets

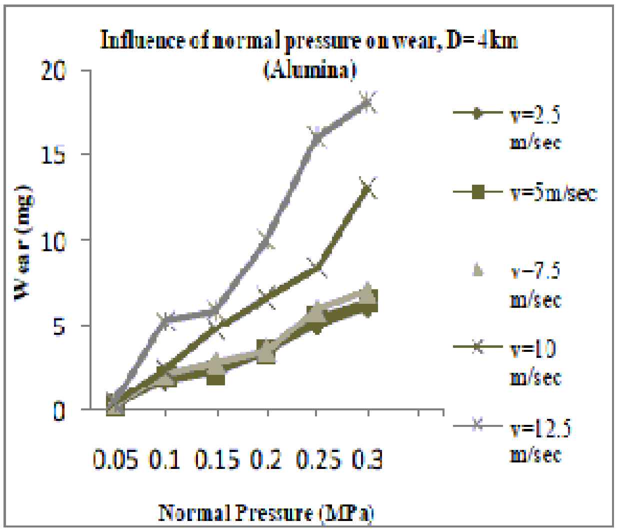

Figure 3.h Wear v/s Normal pressure for Alumina at sliding distance of 4Km

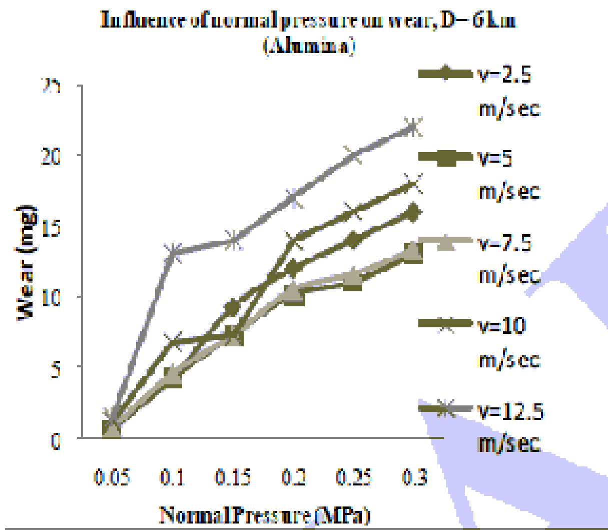

Figure 3.i. Wear v/s Normal pressure for Alumina at sliding distance of 6 Km.

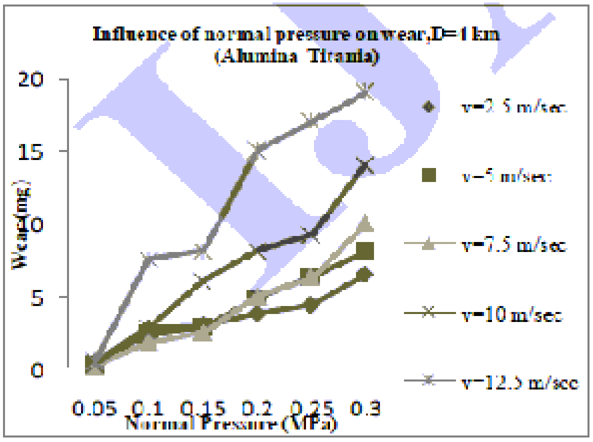

Figure 3.j. Wear v/s Normal pressure for Alumina-Titania at sliding distance of 4Km

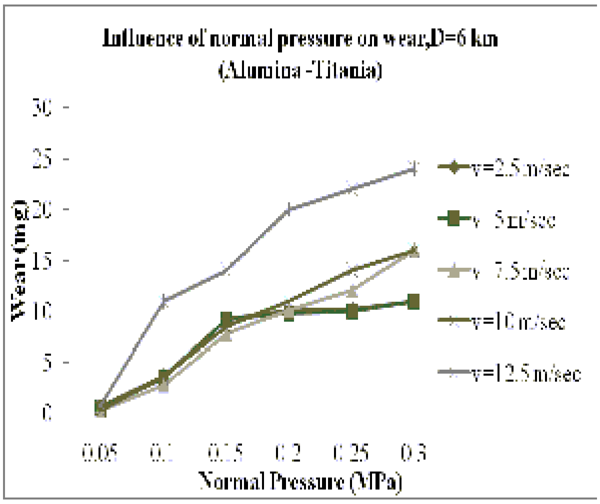

Figure 3.k. Wear v/s Normal pressure for Alumina-Titania at sliding distance of 6Km

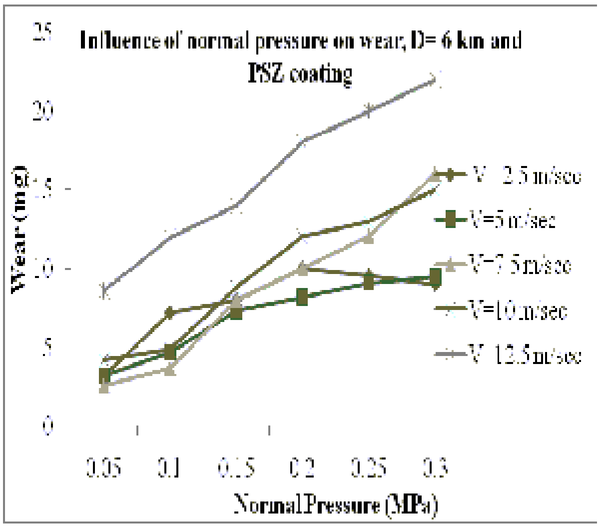

Figure 3.l. Wear v/s Normal pressure for PSZ at sliding distance of 6Km

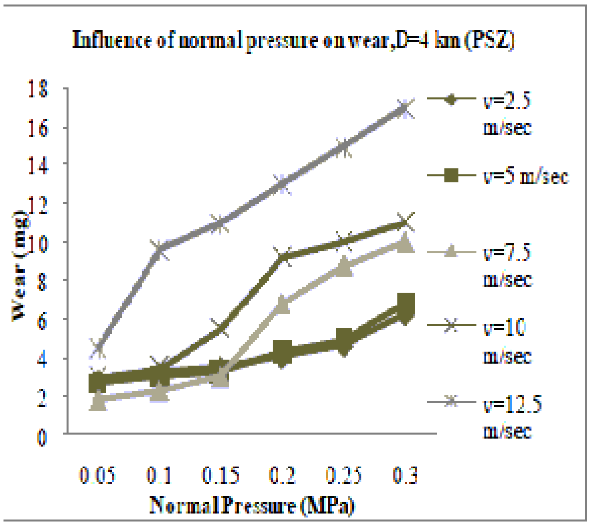

Figure 3.m. Wear v/s Normal pressure for PSZ at sliding distance of 6Km

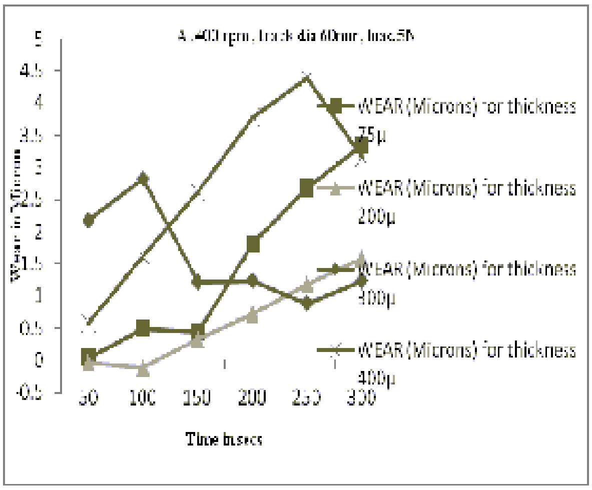

Figure 3.n. Wear v/s Time for Super-Z alloy for 400 rpm

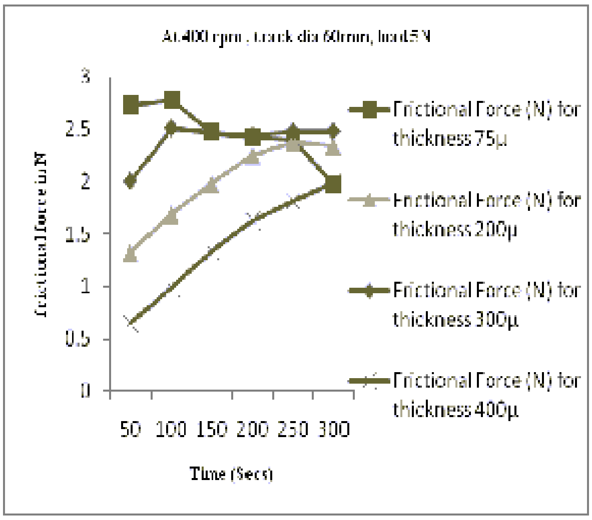

Figure 3.o. Frictional Force v/s Time for Super-Z alloy for 400 rpm

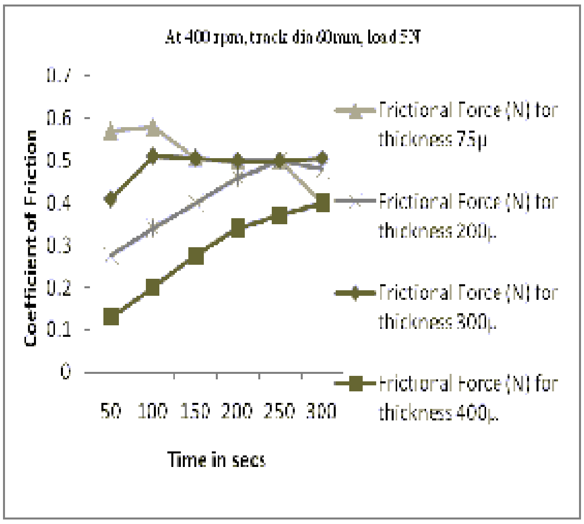

Figure 3.p. Coefficient of Friction v/s Time for Super-Z alloy for 400 rpm

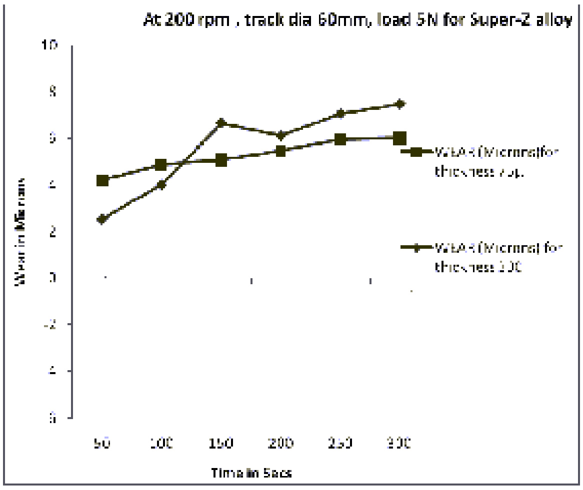

Figure 3.q. Wear v/s Time for Super-Z alloy for 200rpm

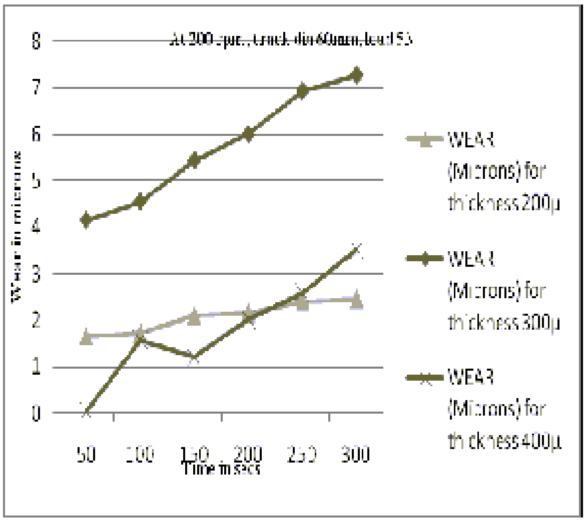

Figure 3.r. Wear v/s Time for ZTA for 200 rpm

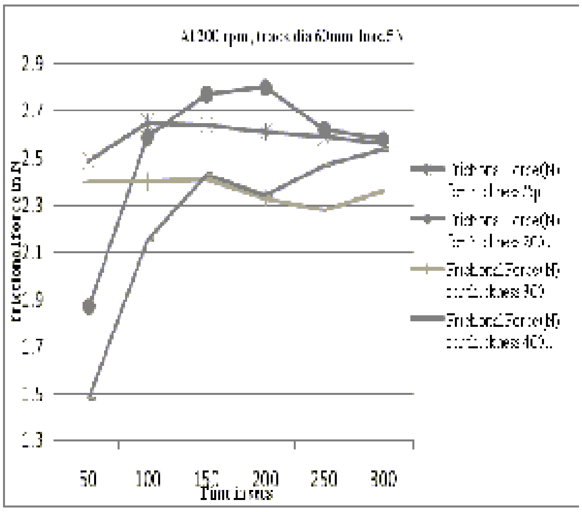

Figure 3.s. Frictional Force v/s Time for ZTA for 200 rpm

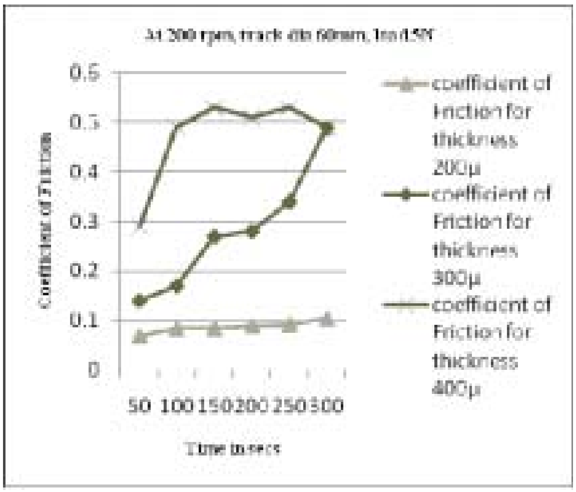

Figure 3.s. Coefficient of Friction v/s Time for ZTA for 200 rpm

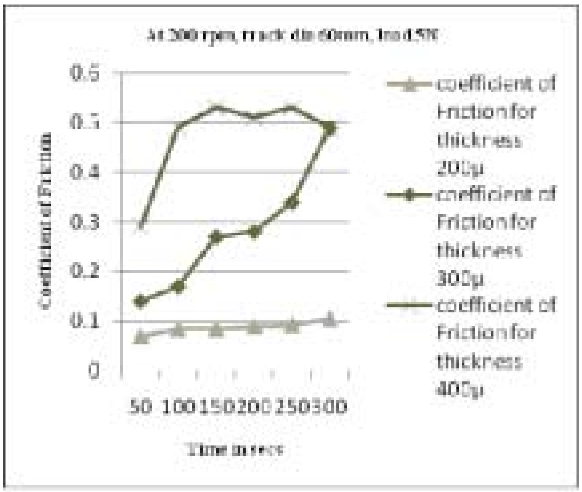

Figure 3.t. Wear v/s Time for ZTA for 400 rpm

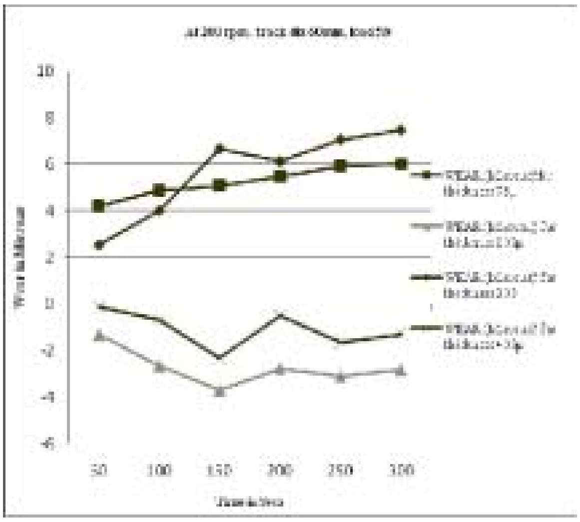

Figure 3.u. Frictional Force v/s Time for ZTA for 400 rpm

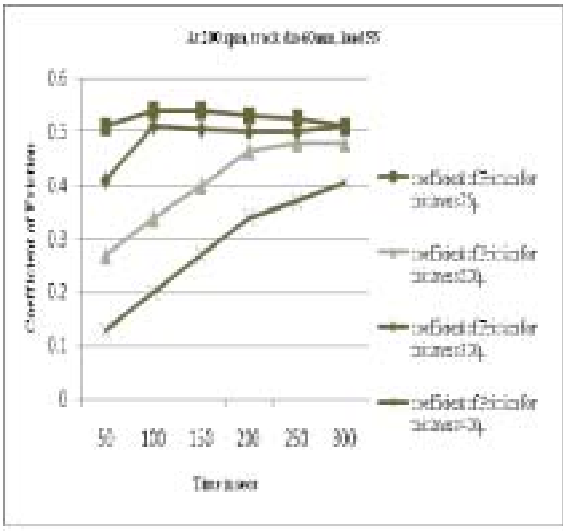

Figure 3.v. Coefficient of Friction v/s Time for ZTA for 400 rpm

3.3. Results of postprocessing of cermaic coatings

The presence of cracks and defects within the coating calls for suitable modification (post processing of the coatings) to improve the microstructure as well as to enhance their performance and quality. In this regard, the post processing of thermally deposited ceramic coated components (PSZ) was done through microwave radiation heating (glazing) and it was found microwave radiation induces phase transformation that influences in the direction of coating microstructure and related properties namely porosity, hardness and surface finish of coatings as shown in figures 3.w, 3.x and 3.y.

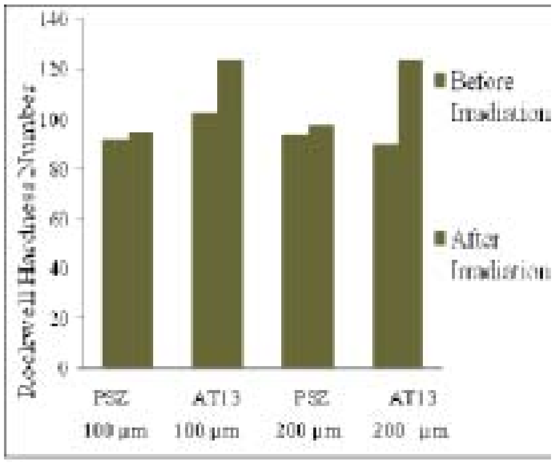

Figure 3.w. Observed reduction in porosity after subjecting to Microwave treatment

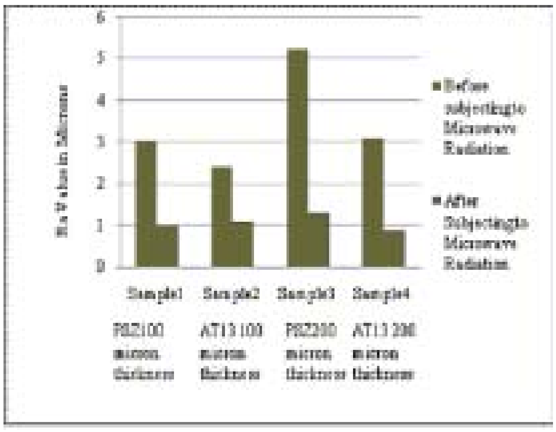

Figure 3.x.Improvement in coating hardness after microwave treatment

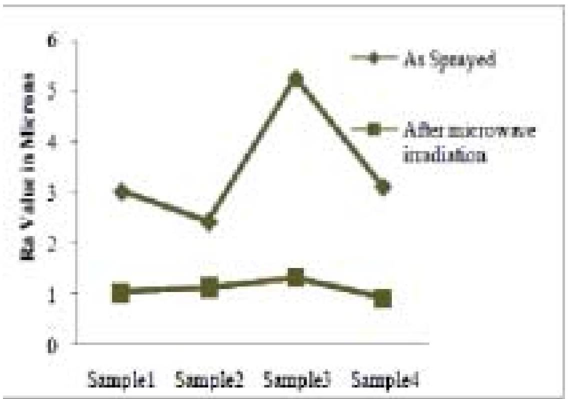

Figure 3.y. Improvement in surface texture after Microwave glazing.

3.4.1. Results of wear test by Taguchi Method and ANOVA

There are twenty seven different tests were conducted using the control factor combinations in the specified orthogonal array table value. Nine specimens were prepared for each set of parameters to prepare complete response table. Taguchi method uses the S/N (signal-to-noise) ratio. S/N ratio is used to determine the most significant factor. There are three types of S/N ratio criteria for optimization; smaller the best, larger the better and nominal the best [5-12]. To get the better performance of results, smaller the weight loss is desired and hence smaller the best criteria has been selected.

Additionally, it is seen that most significant factors can be determined by the larger difference of S/N ratio from figure3.z and table 3.b gives the results of ANOVA, it is found that mostly significant factor with contribution ratio, that decreases the weight loss is Applied pressure followed by the Sliding velocity, sliding distance and the type of coating.Table 3.b, show the results of ANOVA. It is observed that the Applied Pressure (42.13%) is most significantly influences the material or weight loss followed by sliding velocity (27.16%), sliding distance (20.36%) and type of coating (0.9714%) and (3.52%) reveals that the interaction effect of the process parameters is also acceptable.

Table 3.b. Analysis of Variance (ANOVA) results for Wear test.

Factors	SS	Dof	variance	F-ratio	% Contri-bution ratio
A	395.018	2	197.509	50.35	42.13
B	190.897	2	95.4493	24.331	20.36
C	254.622	2	127.3109	32.452	27.16
D	9.10801	2	4.554	1.161	0.9714
AXC	33.02	4	8.255	2.104	03.52
Pooled error	54.968	14	3.923	1	05.862
Total	**937.634**	**26**			**100**

Furthermore, the confirmation test is conducted to verify the improvement of results and to predict the optimum performance at the selected levels (since all factors have a confident level more than 90%) of significant parameters such as A3, C3, B3 and D1. The most optimal set of combination of parameter is found out.

Table 3.c. The comparison between actual and predicted results of Wear test

	Optimum Level		
	Estimation	**Experimental**	**Difference**
Level	$A_3B_3C_3D_1$	$A_3B_3C_3D_1$	
Wear in mg	25.7	24	1.7
S/N Ratio in dB	30.22	27.6	0.6

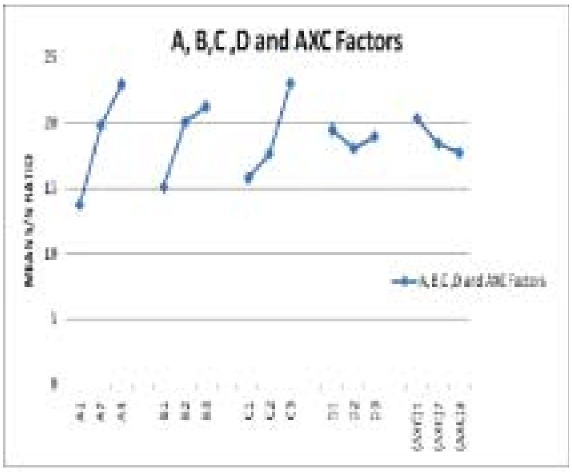

Figure.3.z.. Average Response S/N ratio Graph for Wear test.

3.4.2. Results of wear test by Taguchi Method and ANOVA

Results of Hardness Test Optimization of Parameter For the above test, Twenty seven different hardness tests were conducted using the process parameters combinations in the specified orthogonal array L_{16} as shown in table 9.8. To get the better performance, larger the hardness number is desired and in this case, the larger the best criteria has been selected for S/N ratio in the analysis.

Tabl1e 3.d. ANOVA results of hardness test

Factors	Label	SS	DOF	Variance	F -ratio	Contri-bution ratio (%)
Torch power (KW)	A	0.61592	3	0.20531	6.56	2.84
Type of Coating	B	19.8011	3	6.6	211	91.23
SOD (mm)	C	0.64567	3	0.21522	6.88	2.975
Coating thickness (μm)	D	0.54772	3	0.18257	5.83	2.524
Pooled error		0.094	3	0.0313		
Total		**21.704**	**15**			

The predicted mean (M) of the optimal set of results and confidence interval (C.I.) were obtained.

The predicted mean of the response S/N ratio for the hardness (HRC) lies in the range of 41.294dB <HRC> 42.81dB at the confidence level of 95% (a=0.05).

Table 3.e. Comparison of results between actual and estimated performance of hardness test

	Optimum Level		
	Estimation	**Experimental**	**Difference**
Level	$A_3B_3C_3D_1$	$A_3B_3C_3D_1$	
Wear in mg	116	122	06
S/N Ratio in dB	42.052	41.72	0.6

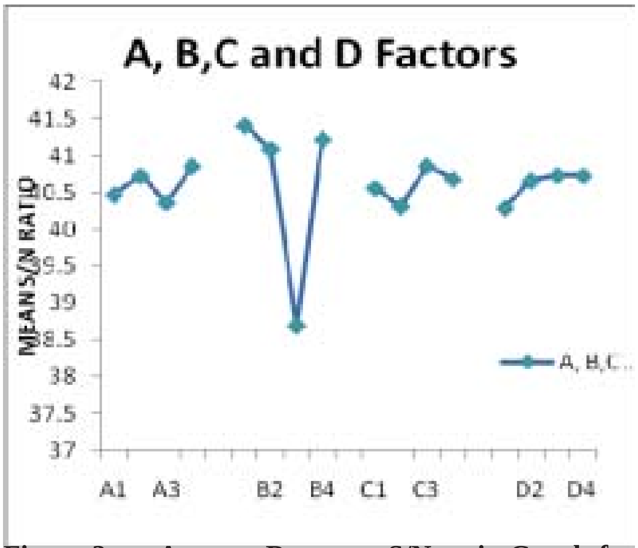

Figure 3.aa. Average Response S/N ratio Graph for Hardness test.

Most significant factor is Super-Z alloy (B1) followed by stndoff distance 120mm, Power of 40KW and least significant factor is when the thickness of coating is 200micron. From ANOVA (table 3.e) results, it is inferred that maximum contribution ratio is for coating (91.23%) followed by standoff distance (2.975%), Power (2.84%) and least significant factor is the thickness of coating (2.524%).

3.2. Genetic models – results and discussion

Using GP simulation, Weight loss in can be determined from the following mathematical model,

$$Weight\ loss = 2V_0\left[C + 2A^2 - \frac{.849828}{V_4} + V_2\right] mg\ C = 2\left[\frac{V_1V_2 - 0.849828}{V_4}\right]$$

(3.1) where,

$$B = 1.6649964V_0^{\ 2}[(2A+V_b)^2 - 1.7448371 - V_1$$

$$A = \left[\frac{(2(V_1+0.963684)^2 + V_5))V_1}{V_3}\right]$$

V_3 =Hardness of coatings, V_5 =Thermal conductivity, V_4 =Thermal diffusivity and V_6= Toughness.

Using GP simulation, Coefficient of Friction can be determined from the following mathematical model,

$$\mu = 2\left[\frac{(4B+0.06551\,V_4)}{V_4^{\ 3}}\right]^2 + 0.06550884 \qquad (3.2)$$

Where $B = (0.79417A4V0 + 0.8277469)V_0 + V_5 - V_2$

$$A = \left[\frac{V_2V_4 - 2.27832}{V_1V_3}\right]^2$$

V4 =Thermal conductivity, V3 =Thermal diffusivity and V5= Toughness

Using GP simulation, Rockwell Hardness number on C-scale can be determined from the following mathematical model,

$$RHC = \left[\frac{128(7.950484 + V_2^{\ 2} + V_0V_2) + 4V_5V_2}{V_2^{\ 2}}\right] - V_5 + V_2 - 3V_0 - V_1 - V_4 \qquad (3.3)$$

Where $A = \left[\frac{-1.7448371V_0V_2}{V_4}\right] - V_5 + V_3 - 3V_0 - V_1 - V_4,$

V_4 = Thermal conductivity, V_1 = Thermal diffusivity and V_0 = Toughness.

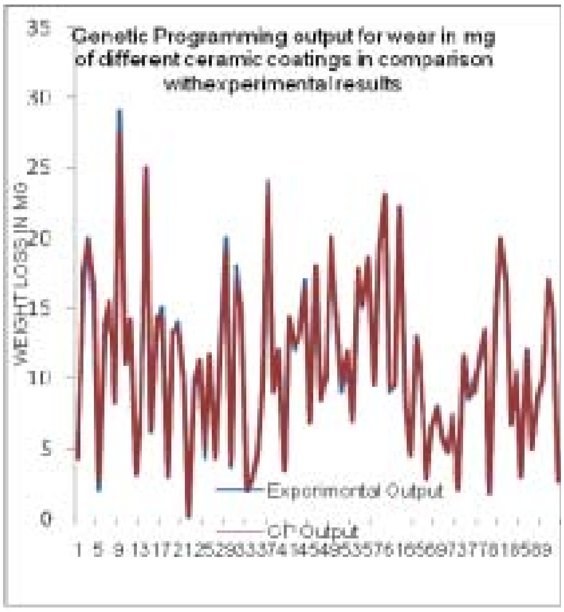

Figure 3.ab. % deviation curve between the best models regarding individual generation and experimental results of wear rate

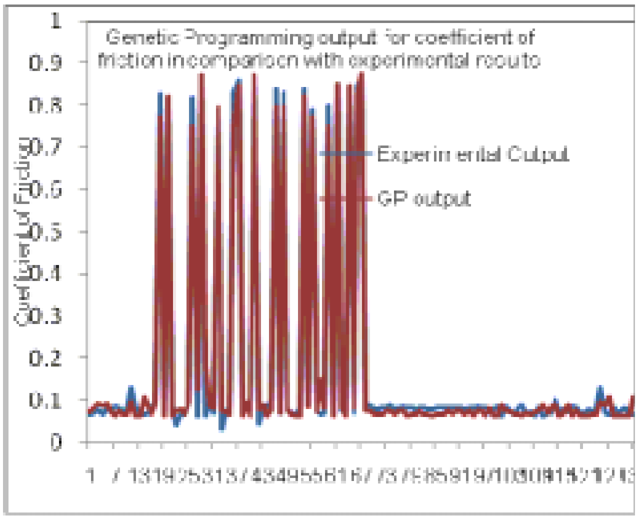

Figure 3.ac, % deviation curve between the best models regarding individual generation and experimental results of coeff. of friction

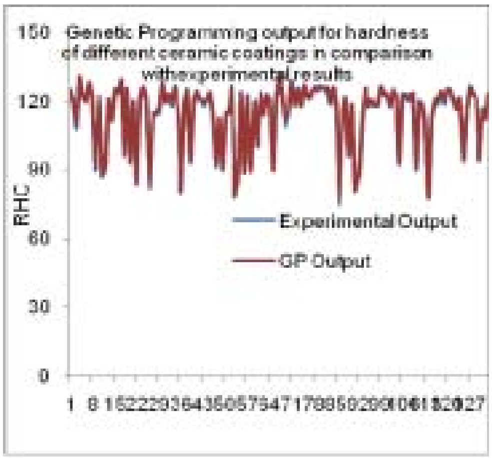

Figure 3.ad. % deviation curve between the best models regarding individual generation and experimental results of hardness.

4. CONCLUSION

The following observations were made based on experimental results. These results are going to be useful from the point of view of characterization of thermally sprayed industrial coating materials.

In HVOF sprayed coatings, it is observed that,

- The amount of wear generally increases with contact pressure and sliding distance.
- Wear is comparatively less in case of coated specimens in comparison with uncoated specimens.
- Fatigue strength is generally improved on coated specimens subjected to alternate bending stresses.
- The ground and lapped finish of coated surface is improved with time of machining, favorably due to lower porosity.

Atmospheric plasma sprayed results showed that,

- Wear performance of A, AT and PSZ shown only marginal difference from each other.
- Coefficient of friction drops down with higher velocity and longer sliding distance in general. In case of ZTA and Super-Z alloy, coefficient of friction steadily increases with time.
- Good bond strength of APS coating was found to exist in the thickness range of 120 to 140mm.With the constant power input and standoff distance of APS process, bond strength decreases with increase in coating thickness for all coatings except for PSZ, where bond strength increases up to a thickness of 300 ìm and then starts decreasing. It is also observed that, an increase in thickness causes reduction in hardness.

Fatigue tests on cylindrical surfaces of APS coatings revealed an improvement in fatigue strength of coated substrate metal, at all stress conditions.

- It is possible to improve the quality of coating (removal of cracks and defects within the coating) by suitable surface modification technique, namely, microwave irradiation. This process helps in the improvement of coated material properties, namely, porosity, hardness and surface finish.
- Results of thermal barrier test and thermal cycling test revealed that, PSZ coating material showed greater thermal barrier, lesser heat transfer coefficient and greater thermal cycling resistance in comparison with A, AT , at high temperatures.

In the light of above findings, PSZ can be used effectively as a coating material on the engineering components whose functional requirements are wear resistance, high hardness, lesser porosity, higher fatigue strength, higher corrosion resistance in addition to higher thermal barrier and thermal cycling resistance at high temperatures.

The following observations were confirmed based on the experimental and Taguchi analysis results, which helps for better performance of ceramic coatings.

- In respect of wear characterization using average response of S/N ratio it is inferred that, the optimum set of parameters are A3, B3, C3 and D1 at optimum conditions of Applied pressure (0.3MPa), sliding distance (8 Km), sliding velocity (12.5 m/sec) and type of coating (PSZ).
- With the above set parameters, the optimal weight loss is 25.7 mg.
- 3. The type of coating i.e. PSZ alloy shows the least significant control parameter, while the applied pressure is the most significant control parameter in case of wear analysis.
- In respect of hardness assessment, type of coating i.e. super-Z alloy, exhibits most significant control parameter for achieving high hardness while the thickness of coating shows least significant parameter.
- From the ANOVA, contribution ratio for wear and hardness tests are tabulated below.

- It is noticed that, there was a good agreement between estimated and actual values obtained in respect of wear and hardness within the preferred significant level.
- Among the three coatings, Alumina, AT and PSZ, PSZ showed maximum wear resistance, whereas super – Z alloy exhibits better when compared to ZTA, PSZ and AT.

Genetic programming (GP) has proved to be a highly versatile and useful tool for identifying relationships in data for which a more precise theoretical construct is unavailable.In this paper, the genetic programming was used for predicting the Mechanical and tribological properties responsible for failure of ceramic coatings. It is inferred from our research findings that the genetic programmingapproach could be well used for the prediction of Mechanical and tribological characteristics of ceramic coatings without conducting the experiments. This helps to establish efficient planning and optimizing of process for the quality production of ceramic coatings depending upon the functional requirements by developing a mathematical model.

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