INVESTIGATION OF EROSION AND CORROSION OF CERAMIC COATED TITANIUM ALLOY FOR AIRCRAFT ENGINE NOZZLE APPLICATIONS

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Abstract— In ages Aircraft Engine is being manufactured with heavy metals and alloys which is responsible for 20% aircraft's weight. In order to reduce weight and increase the efficiency of the engine, grade 5 titanium alloy is coated with ceramics. Titanium alloy is well-known for its light weight, high strength to weight ratio and with lot of other advantages. In this investigation, testing of four different compositions of silicon carbide and yttria stabilize zirconia are coated over titanium alloy is done. The titanium which we are coating can used in aircraft engine nozzle which is dealing with high temperature. This coated alloy has the responsibility to withstand high temperature. The material is undergone through extreme high temperature testing (up to 1000°C) to find the corrosion and erosion rate. Thermal shock, hot corrosion test and gas jet erosion are the major tests. Results have shown that the coating can improve the corrosion and erosion resistance.

Keywords—nozzle, titanium, ceramic, corrosion, erosion

1. INTRODUCTION

Titanium alloys (specifically Ti6Al4V alloy) find extensive use in aerospace and aircraft applications due to its good mechanical, chemical and physical properties such as high strength to weight ratio, high toughness, low density and excellent corrosion resistance. However, it has relatively poor wear resistance due to its poor tribological properties. Light weight and good mechanical properties of Titanium alloy, can increase the engine power to weight ratio of an aircraft engine and also it can increase the fuel efficiency. But, due to its poor wear resistance, it may make the condition worse by failure. We cannot afford to such losses. Since Titanium alloy is used in parts of aircraft such as landing gear, airframes where contact with the heat (>600° C) and atmosphere is low. But when it comes to aircraft engine, Titanium has to deal with high temperature. The main cause of wear (may be of corrosion or erosion) is due to heat and atmospheric reaction (either physical or chemical reaction).

Corrosion is a natural process. It is the gradual destruction of metals/alloys by chemical reaction with their environment. Hot corrosion is a type of corrosion which takes place where the temperature is higher than 500° C. Hot corrosion is a form of accelerated oxidation that is produced by the chemical reaction between a metal or alloy and molten salts deposited on its surface. The combination of high temperature with a metal that contains contaminants such as sodium, sulfur and vanadium over it, results in the phenomenon of hot corrosion. Hot corrosion comprises a complex series of chemical reactions, making corrosion rates very difficult to predict and it is at rapid rate. The inability to either totally prevent or detect it in early stages leads to the failure of the material. According to the temperature that the hot corrosion occurs, it is classified into two types. They are,

- Type I HTHC (High Temperature Hot Corrosion) – It occurs between Temperature 850 - 1000°C.
- Type II LTHC (Low Temperature Hot Corrosion) – It occurs between Temperature 550 - 800°C.

Erosion is a gradual, layer-by-layer degradation of material surface due to mechanical action, by frictional rubbing of surfaces, impinging liquid, abrasion by a slurry, particles suspended in fast flowing liquid or gas. It is also caused by the repeated application of high localized stresses. Erosion by solid particle impact is a problem of great practical significance which can result in component failures. For example, turbines. In aircraft engines, Erosion occurs mainly due to the entering of impurities and foreign bodies into engine. One of the erosions causing agent in aircraft engine is volcanic ash. Erosion is a serious problem that could lead to Erosion Corrosion. Erosion corrosion means degradation of layer of metal/alloy in a corrosive environment. If erosion degrades the layer of a metal then corrosion takes place easily.

In this investigation, to increase the corrosion and erosion resistance, titanium alloy is coated with four different compositions of silicon carbide and yttria stabilized zirconia. The compositions are seen in table 1.

TABLE 1 – COATING COMPOSITIONS OF SAMPLES

Sample No	Percentage of SiC	Percentage of 7YSZ
1.	25	75
2.	50	50
3.	75	25
4.	100	0

2. MATREIALS AND METHODOLOY

2.1. Materials.

The materials used for our investigation are grade 5 Titanium alloy (Ti6Al4V), Silicon carbide powder (SiC) and 7% Yttria Stabilized Zirconia (7YSZ).

The grade 5 Titanium Alloy (Ti6Al4V) is chosen because it is widely used in aircraft industry and aerospace applications. It has a chemical composition of 6% aluminum, 4% vanadium, 0.25% iron, 0.2% oxygen, and the remaining titanium. It is significantly stronger than commercially pure titanium while having the same stiffness and thermal properties. Among its advantages, it is heat treatable. This grade is an excellent combination of strength, corrosion resistance, weld and fabricability.

We have chosen Silicon Carbide (SiC), a Ceramic. Because the grains of silicon carbide will form very strong ceramic which is use in the applications where high endurance is required. The operating temperature of SiC is nearly 1800°C. 7% Yttria Stabilized Zirconia (7YSZ) is also a ceramic. It is formed by stabilization of Zirconia Oxide (ZrO_2) with 7% weight of Yttria Oxide (Y_2O_3). It is well known as thermal barrier. It has high melting point i.e. nearly 2000°C and operating temperature up to 1400°C. The chemical composition of 7YSZ is 94% ZrO_2 + 7% Y_2O_3.

2.2. Method of Coating

Plasma spray coating is chosen to coat our titanium alloy because it is one of the best methods to coat thermal barrier coating. TBC provide not only corrosive and erosion resistance, it also provides thermal resistance to the alloy due to its Ni-Cr bond coat. It can reduce heat up to nearly 200° C which reaching alloy. One surface of Titanium alloy is coated in four different compositions of Silicon Carbide and Zirconia using Plasma Spray Coating. The compositions are seen in tab 1.1. The coating parameters are seen in table 2.

TABLE 2.1 – COATING PARAMETERS

Base Metal	Titanium Alloy (Ti6Al4V)
Bond Coat	Ni-Cr Alloy
Base Metal Thickness	3 mm
Bond Coat Thickness	45 µm
Ceramic Thickness	180 µm
Coating Thickness	225 µm
Overall Thickness	3.225 mm

2.1. Experimental Tests

To find out the Corrosion and Erosion rate of our coated Titanium alloy, four analysis/tests are done.

2.2.1. SEM and EDS Analysis

SEM is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons. EDS Analysis is accompanied with SEM. The data that is generated by EDS analysis consists of spectra with peaks corresponding to all the different elements that are present in the sample. SEM is used to study the surface morphology and characterization of the coated surface. EDS give the weight and atomic percentage of the elements present in the coated sample. SEM and EDS analysis is done in IIT, Madras, by using FEI Quanta FEG 200- High Resolution Electron Microscope. The dimension suggested for SEM and EDS is 10 mm diameter and 3 mm thickness. Before undergoing microscopy, the specimen is first coated with ultra-thin coating of Gold-Chromium alloy to enhance the electron conductivity. SEM is taken in three different magnification for each sample *1000, *2500 and *5000.

2.2.2. Thermal Shock

Thermal shock testing is a fatigue test, in which the material is exposes to alternating low and high temperatures to accelerate failures caused by temperature cycles or during normal use. The transition between temperature extremes occurs very rapidly. We conducted this test in Material Testing Laboratory, Sathyabama Institute of Science and Technology and there SEMCO MUFFLE FURNACE is used for Thermal Shock testing. Sample dimension for Thermal Shock testing is 10mm Diameter with 3mm Thickness. Each piece of material from four different composition of 7YSZ and SiC coating is heated up to 1000° C and it rapidly cools atmospheric temperature. The timing of each cycle is 15 minutes. Thereby it undergoes Thermal Shock. 250 cycles of thermal shock are given to each material until the material reaches failure. For us it took nearly 15 days (20 cycles/day) to achieve 250 cycles.

2.2.3. Hot Corrosion

Hot Corrosion Test (i.e. Type I High Temperature Hot Corrosion, 850 - 1000°C) is done in Material Testing Laboratory, Sathyabama Institute of Science and Technology by Using SEMCO MUFFLE FURNANCE. In the Hot Corrosion Testing, the materials are applied with Sodium Sulphate and Vanadium Pentoxide salts on the coated surface and kept at 1000° C for 50 hours. The Sample is sprinkled with Sodium Sulphate (55%) and Vanadium Pentoxide salts (45%) over the coated surface. Both Sodium Sulphate and Vandium Pentoxide combined to form a weight of 0.1g for 1cm area.

2.2.4. Hot Air Jet Erosion

Erosion is a wear process, in which surface damage is caused by the repeated application of high localized stresses.

TABLE 3 – ASTM G 76- PARAMETERS OF EROSION TEST

PARAMETER	SPECIFICATION
Velocity	100 m/s
Erodent Feed Rate	4 g/min
Angle of Impingement	90 °

Nozzle Diameter	1.5 mm
Temperature	800° C
Erodent Size	50 µm
Erodent Material	Alumina (Angular)
Time	10 mins

The test is done according to ASTM G76 Test standards table-3. In testing erodent is made to strike the sample at 100 m/s and at 800° C atmosphere. Hot Air Jet Erosion Test is done in Surface Engineering Division, CSIR- National Aerospace Laboratories, Bangalore. There DUCOM INSTRUMENT, TR 471-1000 DEG is used for Hot Air Jet Erosion Test

3. RESULTS AND DISCUSSION

3.1. SEM and EDS Analysis

With the SEM figures, the surface morphology of the samples are studied. All samples have imperfection and ununiform layer of coating. Craters are seen in all samples. In fig 1. showing that there is imperfection in the coating of sample 1. There is also a crack in the surface that be due to physical shock. From fig 2. we can say that there are lot of imperfections in the coating. Pores are also seen in the figure. SiC and 7YSZ particles are not completely merged. This may be least corrosive and erosive resistant compared to other samples.

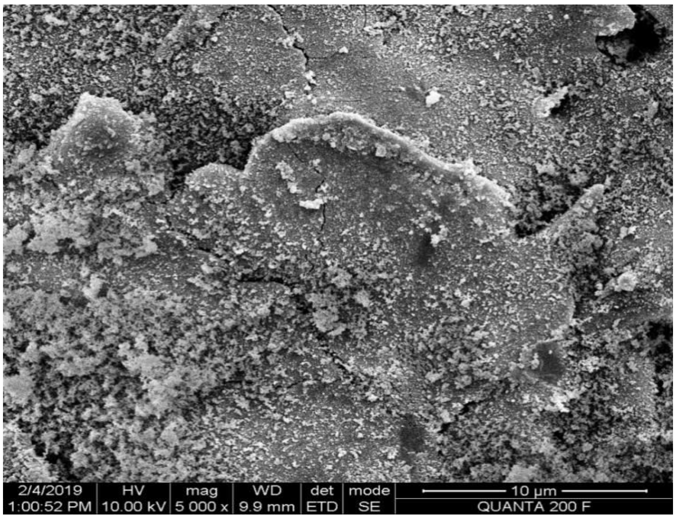


Fig 1- *SEM of Sample 1 at *5000 magnification*

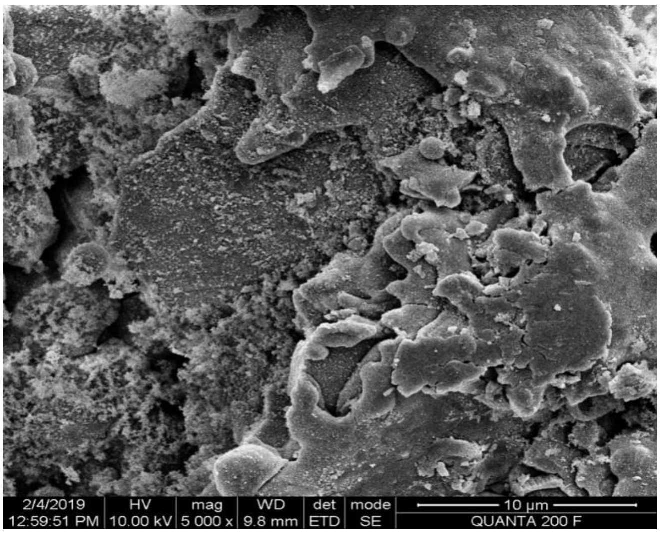


Fig 2 - *SEM of Sample 2 at *5000 magnification*

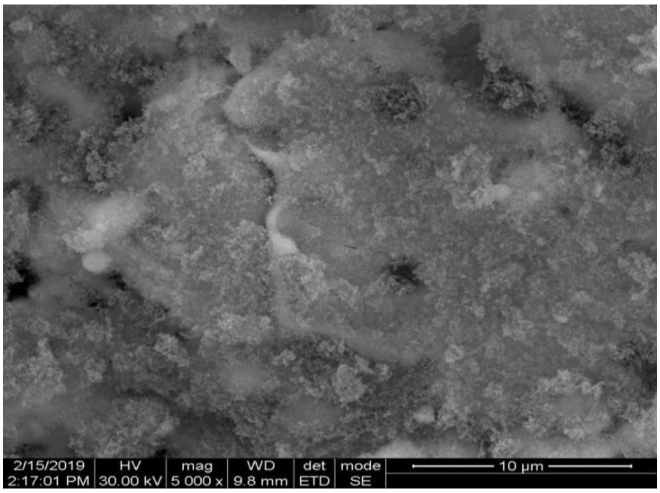


Fig 3 - *SEM of Sample 3 at *5000 magnification*

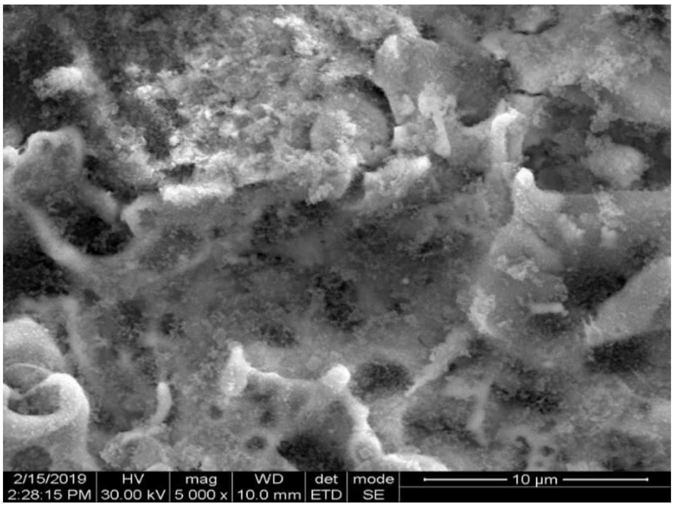


Fig 4 - *SEM of Sample 4 at *5000 magnification*

In Sample 3, imperfections are seen from fig 3. Ups and downs are seen in the figure. Some of the particles are larger in size that may be SiC particles. Lots of clusters and pores are seen in fig 4.

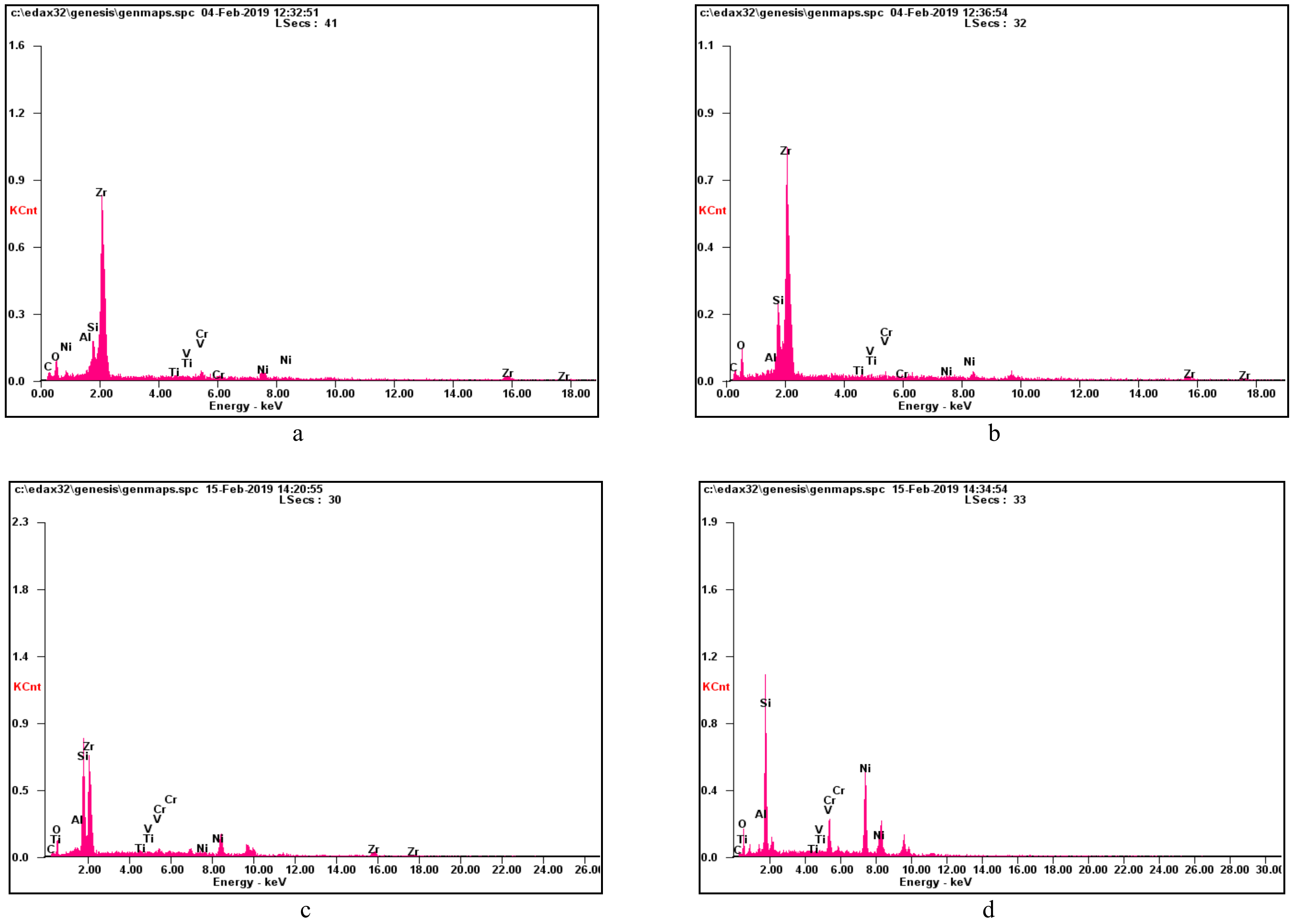


Fig 4 – a, b, c & d are spectra obtained from EDS analysis of sample 1, 2, 3 & 4 respectively.

The data generated by EDX analysis consists of spectra with peaks corresponding to the different elements that are present in the sample 1, 2, 3 & 4. These spectra of sample 1, 2, 3 and 4 can see in Fig 5 respectively.

The amount and weight percentage and atomic percentage of elements obtained from the Spectra are in the table 4.

TABLE 4 -WEIGHT AND ATOMIC PERENTAGE OF SAMPLE 1, 2, 3 & 4

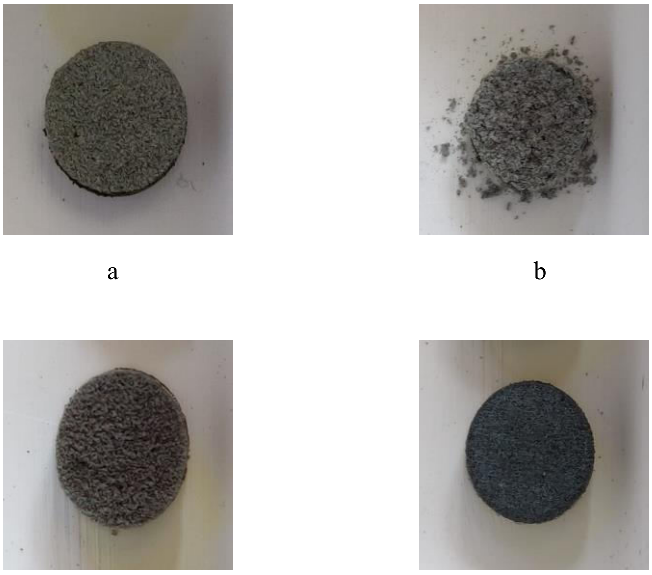
ELEMENT	SAMPLE 1		SAMPLE 2		SAMPLE 3		SAMPLE 4	
	Wt%	At%	Wt%	At%	Wt%	At%	Wt%	At%
CK	32.92	56.13	22.53	46.46	19.61	38.71	10.83	24.22
OK	23.34	29.87	21.54	33.35	24.40	36.16	15.64	26.26
AlK	00.71	00.54	00.21	00.19	00.55	00.48	00.67	00.67
SiK	05.21	03.80	06.83	06.02	16.27	13.74	30.01	28.70
Tik	00.74	00.32	00.58	00.30	00.95	00.47	00.22	00.21
VK	00.54	00.22	00.77	00.37	00.22	00.10	00.28	00.15
CrK	02.08	00.82	00.84	00.40	01.45	00.66	08.73	04.51
NiK	04.57	01.59	01.46	00.62	01.20	00.48	3.62	15.36
Zrk	29.90	06.71	45.25	12.29	35.35	09.19	-	-

3.2. Thermal Shock

Thermal shock test is a fatigue test which test the endurance of samples at cycles of high and low temperature. The after effects in the sample due to thermal shock test are seen in Fig 6 respectively. Even at 250 cycles, the layer of coating remained in sample 1 and 4. There were minimum distortion in the coating that you can see in the figure.

The sample 1 and sample 4 have proven its capacity up to 250 cycles to withstand the extreme temperature ranging 1000°c. The sample 2 have started showing the deformation from 125 cycle, which is considered to be failure. The sample 3 has a moderate resistance to thermal shock as it with stand 180 cycles.

From this Thermal Shock Test, we can understand that both sample 1 and 4 are performed well and also has good endurance to withstand high number of thermal shocks.



a b

c d

Fig 6 – a, b, c & d are samples 1,2,3 & 4 after Thermal shock test

TABLE 5 – NO. OF CYCLES WITHSTAND BY SAMPLES

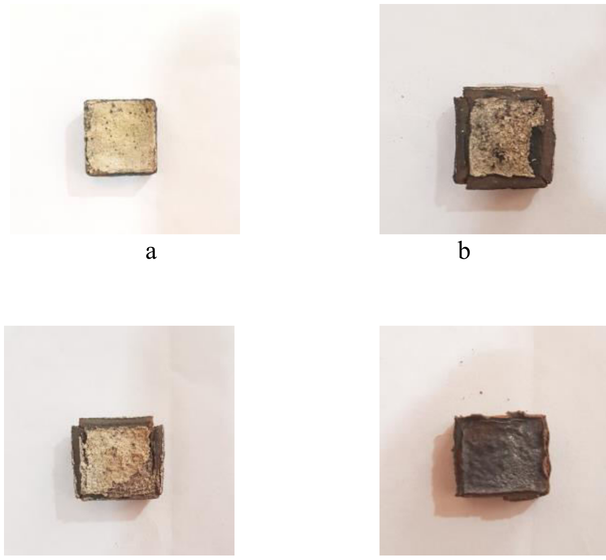
`SAMPLE NO	COMPOSITION OF COATING	NO. OF CYCLES WITHSTAND
1	75% 7YSZ + 25% SiC	250
2	50% 7YSZ + 50% SiC	125
3	25% 7YSZ + 75% SiC	180
4	100% SiC	250

3.3. Hot Corrosion

Hot Corrosion is the most aggressive method of degradation of metals and alloys. The samples are applied with Sodium Sulphate and Vanadium Pentoxide salts on the coated surface and kept at 1000° C for 50 hours. After 50 hours, the corroded samples are seen in Fig 7 respectively. Initially, each sample is weighed and noted. Sample 2 & 3 suffered a lot due to hot corrosion. The coating is fully corroded and titanium alloy also slightly distorted. Sample 1 endures hot corrosion and the coating does not allow the salts to react with titanium alloy. In Sample 4, silicon carbide layer still remains in the alloy. So it performed well. But the edges are distorted.

At the end of each day (8 hours/day), again the samples are weighed and noted. With these values a table and graph are made. The vales are in table 5 and the graph is seen in Fig 8 respectively.

After 50 hours of Hot Corrosion Test,



a b

c d

Fig 7 – a, b, c & d are samples 1, 2, 3 & 4 after 50hrs of hot corrosion test

TABLE 6– HOT CORROSION RATE

Sample no	0 hour	8 hours	16 hours	24 hours	36 hours	44 hours	50 hours
1	1.44	1.46	1.49	1.53	1.56	1.61	1.64
2	1.41	1.46	1.5	1.56	1.59	1.71	1.75
3	1.42	1.47	1.51	1.57	1.63	1.69	1.74
4	1.39	1.42	1.46	1.51	1.57	1.63	1.68

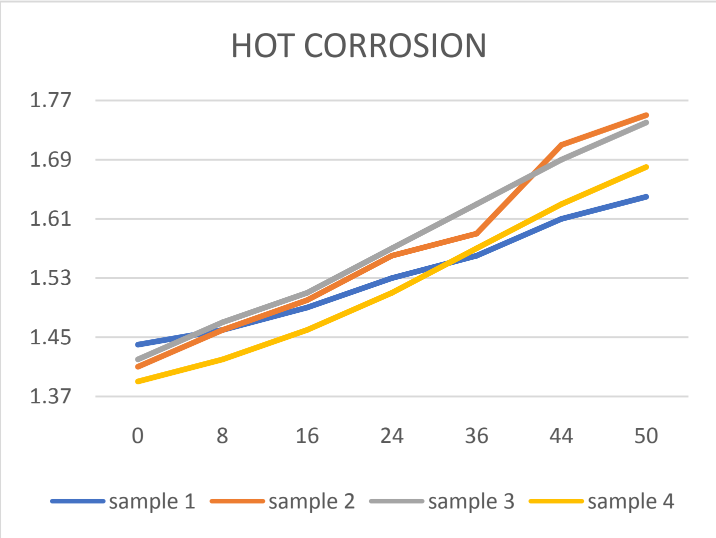
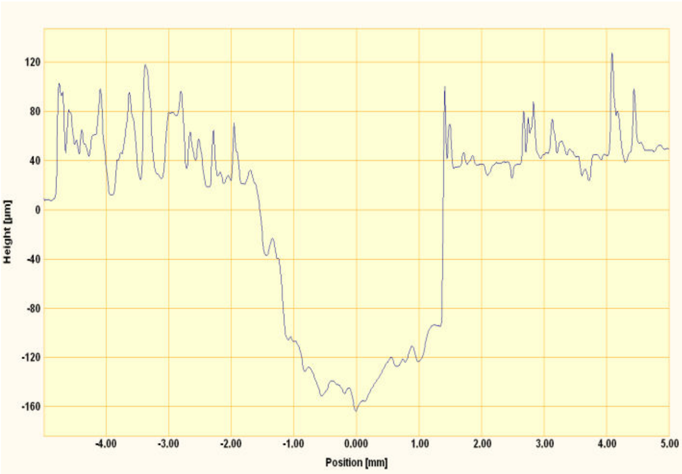


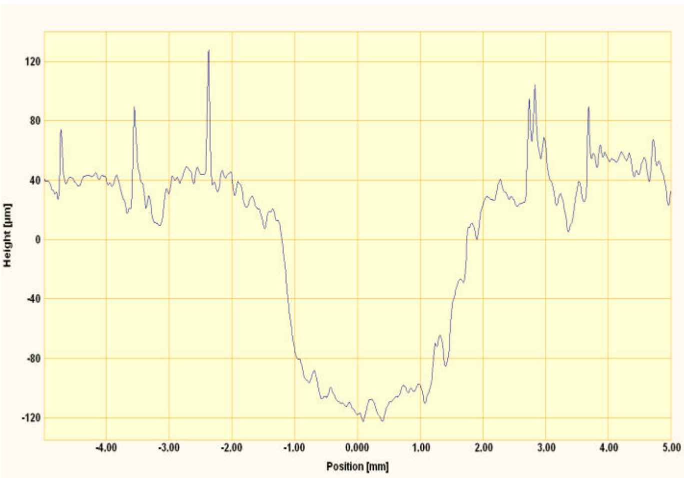
Fig 8 – Graph showing hot corrosion rate

3.2. Hot Air Jet Erosion Test

After hot air jet erosion test, the eroded section of samples are scanned in Profilometer to get wear track profiles.



a



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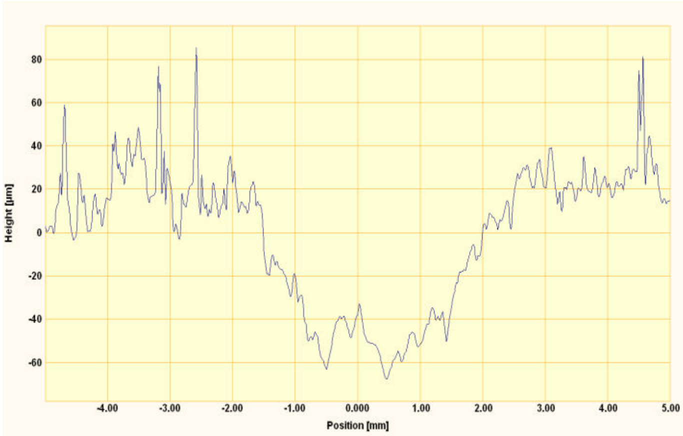

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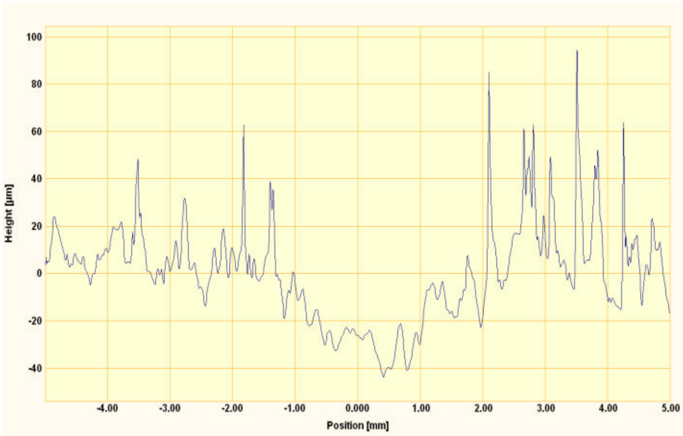

d

Fig 9 – a, b, c & d are the wear track profile of sample 1, 2, 3 & 4

Using Wear Track Profile, the diameter and depth of erosion surface is noted. From this volume of eroded layer is calculated (table 7). From that volume, Erosion Rate per gram of erodent is calculated (table 8). A bar graph is drawn to show comparison between the erosion rate of four samples with respect to the above Table. 8. The graph can be seen in Fig 9.

TABLE 7 – VOLUME OF ERODED LAYER

SAMPLE No.	VOLUME OF ERODED LAYER (mm^3)
1	0.37699
2	0.28274
3	0.19242
4	0.0821

TABLE 8 – EROSION RATE PER GRAM OF ERODENT

SAMPLE No.	EROSION RATE PER GRAM OF ERODENT ($*10^{-4}$ g/g)
1	4.9025
2	3.1931
3	1.8439
4	0.6463

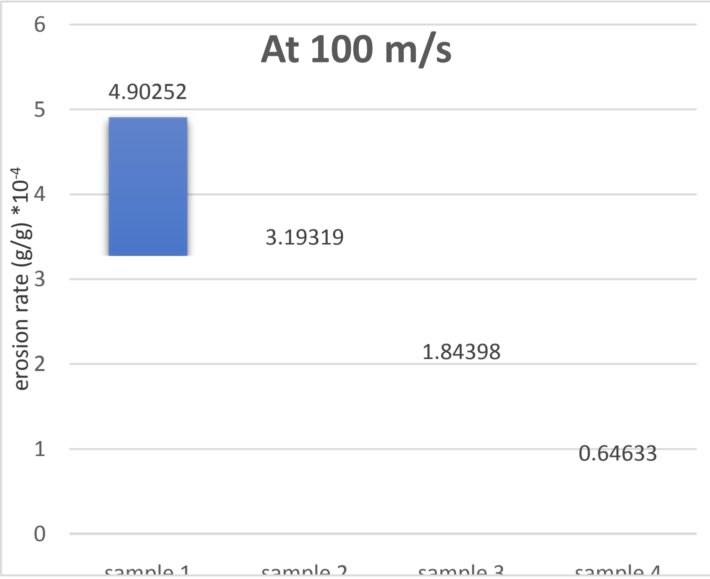

Fig 10 – Bar graph showing erosion rate of sample 1, 2, 3 & 4

From the graph we observed that Sample 4 (100% SiC) has very less erosion rate compared to other samples. The erosion rates are highly reduced by SiC. But whereas, increase in 7YSZ in amount, decrease in erosion resistance is reduced accordingly.

4. CONCLUSON

The high temperature corrosion and erosion tests of ceramic coated titanium alloy has proven the ability to withstand the extreme conditions involving high temperature. In Thermal shock test, sample 1 & 4 withstands 250 cycles. The Hot corrosion rate also impressive for sample 1 & 4. In hot air jet erosion test the erosion rate of sample 4 is lower than the other three samples. However, the erosion rates of all four samples are less when compared to Inconel 718 alloy [ref 5] which is used in high temperature jet engine components. From the results of thermal shock and hot corrosion tests, both samples 1 & 4 have performed well. But by looking at the result of all the tests together, the sample 4 (100% silicon carbide coated titanium alloy) is the best among four samples and the mechanical properties of titanium alloy will remain unchanged [ref 8] and can be proposed as an alternative material for nozzle manufacturing, which is having half the weight as Inconel 718. With this TBC, the efficiency of aircraft jet engine will increase [ref 7]. The coating has helped to increase the efficiency of the engine by reducing the material weight by replacing Inconel 718. Ceramic coated titanium is half the weight of Inconel 718.

REFERENCES

[1] *A. Marcocchi, A. Bartz*. "PVD TBC experience on GE aircraft engine", ASM international 1997, p 193-197

[2] *D.M.Nissley*. "Thermal barrier coating life modeling in aircraft gas turbine engines". ASM international. 1997, p 91 - 97

[3] *Nitin P. Padture, Maurice Gell*. "Thermal barrier coatings for gas-turbine engine application". Science compass April 2002, p 280 - 284

[4] *R.R. Boyer*., "An overview on the titanium in the aerospace industry". Elsevier material science and engineering. 1996, p 103 - 112

[5] *K.G. Thirugnansambanthan and S. Natrajan*., "Degradation through erosion: Mechanistic studies on IN-718 superalloy under hot air jet conditions. ASM International. November 2014, p 1 - 5

[6] *Robert E. Schafrik, Douglas D.*, "Application of alloy 718 in GE aircraft engines: past, present and next five years". TMS, 2001, p 1 - 11

[7] *David R. Clarke, Matthias Oechsner*., "Thermal barrier coating for more efficient gas turbine engines". MRS Bulletin, oct 2012, p 891 - 941

[8] *Milton levy and Joseph L.Morrossi*., "Erosion and fatigue behavior of coating titanium alloys for gas turbine engine compressor application" feb 1976, p 1 - 15

[9] *E.Avcu, S.Fidan*., " Solid particle erosionbehaviour of Ti6Al4V alloy" W.S.Maney& son Ltd., July 2013, p 201 - 209

[10] *Bartosz Olzak, JanuszSzymczak*., "Gaseous erosion an corrosion of turbines"., researchgate., jan 2007.

[11] *N.Eliaz, G.Shemesh*. "Hot corrosion in gas turbine components". PERGAMON., 2002.

[12] *A.J.A.Mom* and *H.J. Kolkman*., " Corrosion and corrosion prevention in gas turbines"., NASA., November 1985.

[13] *U.S. Titanium industry*, "Titanium alloys – Ti6Al4V Grade 5:., July 2002.

[14] *Aleksander Lisiecki*., "Erosion wear resistance of titanium matrix composite ti/tin produced by diode-laser gas nitriding"., UDK, 2017, p 29 - 34

[15] *J. T. DeMasi-Marein*., "Mechanisms of Degradation and Failure in a Plasma-Deposited Thermal Barrier Coating"., asme.org., 1990, p 1 - 15