Effect of Annealing on Erosion Behavior of Atmospheric Plasma Spray and High Velocity Oxy Fuel Sprayed WC-Cr3C2-Ni Coatings.

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ABSTRACT - *High temperature solid particle erosion is a major problem in pressure vessels and turbo machineries. A detailed tribological study becomes essential to investigate the right coating method to prevent it and enhance its mechanical and physical properties. The study focuses on Wc-Cr3C2Ni coating, thermally sprayed APS and HVOF considering pre available literature. The coating was subjected to heat treatment and then to solid particle erosion testing. Annealing was done in cycles at 550-degree temperature at intervals to influence its properties. Solid particle erosion was done at 450- and 575-degree temperature using Alumina powder as eroded at 30- and 90-degree impact angles. SEM and EDX analysis were done as a part of characterization and hardness was noted before and after testing. It was observed that Wc-Cr3C2Ni coating superior hardness makes them ideal for use on steel substrates to improve erosion resistance. Also, both coatings showed improved hardness, HVOF has more wear resistance and hardness gain than APS. Thus, making the coating suitable for boiler tubes, turbine valves and other pressure vessels and turbo machineries to resist erosion and enhance properties*

Key Words: **Annealing, Elevated temperature, Air particle erosion, Thermal spray coating, Microhardness, SEM.**

1. INTRODUCTION

In most fluid interaction engineering applications, high-temperature erosion produced by impingement of solid particles suspended in the fluid is a serious concern. The high temperature solid particle erosion has a significant contribution to the failure of components in a coal-fired power plant like steam gas turbines, boiler tubes. As a result, substantial financial losses are unavoidable during component maintenance and replacement. Stainless steel and nickel alloys are the most widely utilised materials for these components. Tungsten carbide-based coatings' superior hardness makes them ideal for use on steel substrates to improve erosion resistance. For the deposition of carbide-based coatings, thermal spray versions are useful. Because they offer outstanding mechanical features such as increased hardness, fracture toughness, and cohesive strength, atmospheric plasma spray (APS) and high-velocity oxy-fuel (HVOF) are favoured variations.

As a result, examining the erosion resistance of coatings under varying operating conditions such as temperature, impact angle, and impingement velocity is more important than the other characteristics. Among commercially available formulations, WC-Cr3C2–Ni outperforms other WC compositions in terms of high-temperature wear and oxidation resistance. The research focuses on the erosion performance of WC-Cr3C2–Ni coatings coated by atmospheric plasma spray (APS) and high velocity oxy-fuel (HVOF) in the presence of alumina (Al2O3) entrained in the air stream.

1.1 LITERATURE REVIEW

The HVOF coating exhibits the best wear resistance because of its higher hardness and toughness and better oxidation characteristics. The tribological performance of the APS coating is unsatisfactory because of its inferior mechanical property and oxidation resistance. With increasing annealing temperature, annealed coatings show a minor increase in hardness and better toughness, as well as a steady decrease in internal stress, which is especially noticeable beyond 200 C. The wear rate reduces as the annealing temperature rises, reaching its lowest point at 400 C before recovering to a high point at 500 C [(25)]. WC-Co coatings of different thickness (250, 350, 400 μm) were deposited onto the steel 45 Tungsten carbide/cobalt (WC-Co) coatings deposited by thermal spray technique. Air annealing at 500 °C temperature resulted in surface morphology changes similar for all WC-Co coating [(18)]. The substrate steels' solid particle erosion rate is highest at 30° impact angles, indicating that they are behaving in a ductile manner. The substrate steels have shown little low mass loss as compared to the HVOF coatings due to embedment of sand particles. [(20)]

2. MATERIAL SELECTION

The high temperature solid particle erosion has a significant contribution to the failure of components in a coal-fired power plant like steam and gas turbines, boiler tubes. Stainless steel and nickel alloys are the most widely utilized materials for these components. Due to inferior erosion and high-temperature corrosion resistance, the useful service life of these components is low. Superior hardness of tungsten carbide-based coatings makes them favorable on steel substrate to enhance erosion resistance. Because to catastrophic oxidation, the majority of WC-based coatings lost their functional capabilities over 500°C. Mixed carbide-based coating, such as WC-Cr3C2–Ni, is an exception because the presence of Cr or Cr3C2 helps to increase oxidation resistance. In the as-received powder, there are 20% chromium carbides, 7% nickel, and tungsten carbide to balance things out.

The properties of WC-Cr3C2-Ni are Superior wear properties at elevated temperature. They can operate up to 760°C. Excellent oxidation and corrosion properties than other tungsten-based material. Better chemical resistance. They have Higher deposition efficiency (DE) and lower porosity and Finer microstructure, dense and smooth coatings.

3. COATING METHOD - APS AND HVOF

APS: Plasma is an electrically conductive gas containing electrically charged particles, ions and electrons. [11]

Thermal spray is a series of processes that includes atmospheric plasma spray. The plasma spray process consists of forming the plasma jet, which interacts with the particles with the plasma. By guiding the material to be deposited to a substrate, the plasma jet imparts thermal and kinetic energy to the material to be deposited, resulting in a coating. The substrate is normally prepared to accept the coating in the plasma spray deposition process by executing cleaning techniques that induce surface roughness, preheating, and regulating movement. Preheating, which is usually done using the plasma jet itself. Preheating, generally performed with the plasma jet itself. [11]

HVOF: In the HVOF spraying process, the pressure in the spraying gun's combustion chamber is raised to produce a high-speed flame that is similar to a detonative combustion flame. The powder materials are fed and melted, or half-melted in the flame jet stream, then accelerated and continuously sprayed at supersonic speed. This method allows for the creation of a covering with a very high density and bonding strength. Compared with detonation spraying, HVOF coating has more homogeneous characteristics for its continuous formation process, and exerts more effectively in forming wear resistant coatings with carbide cermets. [12]

4. SAMPLE PREPARATION

Samples are prepared by using wire EDM method. Electrical discharge machining (EDM) is a metal-cutting method that uses electrical sparks to create a shape. When current discharges, or sparks, occur between two electrodes in this process, the desired form is cut from the metal; where the sparking happens, cuts are created into the metal, generating the desired shape and detaching it from the metal sheet. The samples dimensions are depending on the size of air erosion holder. Dimensions of the samples are square samples of 25 mm X 25 mm, 10 mm thick and total 14 samples are cut 25*25 6 nos ,20*20 5 nos ,10*10 3 nos.

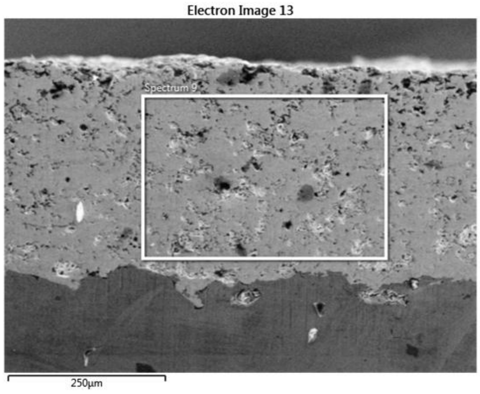


Fig -1: Microstructure of a cross- section of APS coated specimen.

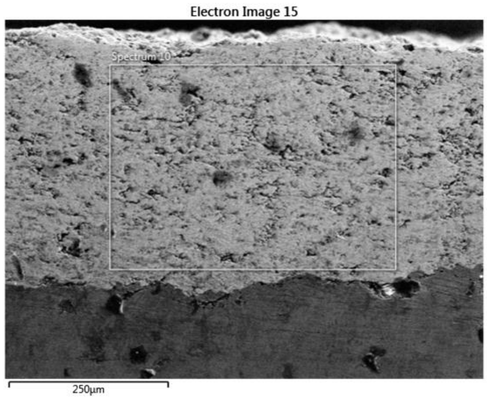


Fig -2: Microstructure of a cross- section of HVOF coated specimen

5. EXPERIMENTAL DETAILS

A) ANNEALING

Annealing is a heat treatment procedure that alters a material's physical and, in some cases, chemical qualities to improve ductility and reduce hardness, making it easier to work with. The annealing process needs the material to be heated above its recrystallization temperature for a certain length of time before cooling. The cooling rate is determined by the type of metal being annealed. The heating process causes atoms to move in the crystal lattice and decreases the number of dislocations, resulting in a change in ductility and hardness. Annealing is done by using Muffle Furnace. The coated specimens when heated at 500-degree Celsius for 5.5 hrs. then there are no significant changes on surface and annealing is uneven when they heated for 24 hrs they underwent delamination. So, specimens are annealed at 500 degrees Celsius for 8 hrs. followed by 24 hrs furnace cooling and then same specimen at again heated at same temperature for 12 hrs. followed by 48 hrs. furnace cooling.

B) AIR EROSION TEST

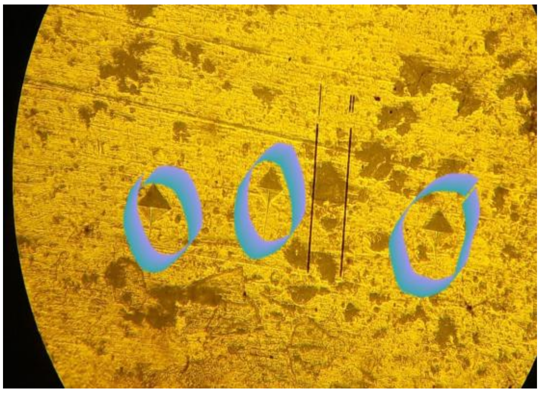
The solid particle erosion behavior of both APS and HVOF coated specimens were investigated by air-jet erosion tester (Model: TR-471- 600, Make: Ducom Instruments, Bengaluru, India) as per ASTM G76.The literature review suggested that the solid particle erosion performance of coatings is dominantly influenced by operating temperature and impact angle. The limitation temperature for WC-Cr3C2–Ni coatings in high-temperature applications is 750 C. The operating temperature range for most high-efficiency steam turbines is 500 C–600 C, whereas the maximum temperature for boiler economizer tubes is 450 C. As a result, the operating temperature range considered for simulating these circumstances is 450 C–575 C.The erodent used for this study was alumina(99.9% pure) with hardness 27 GPa, and the average particle size is 50 µm. The specimens used for this study are 25 mm × 25 mm x 5 mm and 20 mm × 20 mm x 5 mm as per tribo-tester requirements. The 30 and 90 degrees is selected as impact angle. Erosion rate is the ratio of mass loss to the unit mass of erodent.

C) WEIGHING

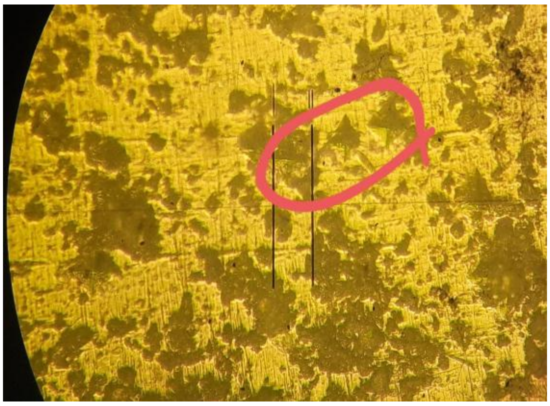
Weights are obtained with a High Precision balance machine (Accuracy - 0,0001gm) (Model CAS-234, Manufacturer Contech Instruments Limited). Weights are taken at each stage of the Heat Treatment procedure, as well as after the Air Erosion Test. Before any heat treatment. The weights are then compared to check if annealing has any influence on mass and to calculate mass loss post erosion.

D) MICROHARDNESS

The HMV 2T manufactured by Shimadzu, JAPAN is used to measure hardness. Vickers hardness testing, also known as microhardness testing, is commonly utilized for tiny components, thin sections, or case depth work. The Vickers technique is based on an optical measuring device. ASTM E384 Microhardness test protocol provides a range of low loads utilizing a diamond indenter to create an indentation that is measured and translated to a hardness value.



(a)



(b)

Fig -3: Indentation to check microhardness

8. RESULTS

a) Aps sprayed coating: The average thickness of the coating assessed from a cross-section picture is 345 micro mm. As shown in fig 1, The coating-substrate interface is continuous and devoid of flaws, indicating excellent adhesion. The surface morphology of the coating depicted in shows that it has a homogeneous microstructure with little micro-voids. The laminar splat-like microstructure of APS sprayed coatings is an inherent characteristic. During the deposition of APS coating, the carbide phases were almost completely melted. As per literature review there is higher degree of decarburisation of WC. The sprayed coating contained traces of Cr3C2 and WC1-x. The existence of cubic WC1-x is caused by a high process temperature and a quick cooling rate. The W2C are most likely related to the addition of Cr.

b) HVOF sprayed coating: The average thickness of the coating assessed from a cross-section picture is 387 micro mm. The surface morphology of the coating seen in Fig 2 is made up of partly melted particles mixed in with totally melted particles, with no distinct boundary. Some of the unmelted and partially melted particles on the surface are due to the lower temperature associated with the HVOF process. As per literature review Due to the general lower process temperature, the degree of WC decarburisation and binder interaction of WC with Cr3C2 is substantially reduced in HVOF coating. Chromium oxide peaks can also be seen. The percentage decarburisation in thermal sprayed coatings is temperature dependent. The increased deposition temperature hastened the decarburisation process, resulting in the brittle W2C phase. The fracture toughness and hardness of the W2C phase are lower than those of the WC phase. This entails more fragility, making their presence undesirable.

Table 1 - Weightage of specimens after each stage and effect of annealing on mass

Sample	Samples Dimension	Before Heat Treatment	8 hrs Heat Treatment	12 hrs Heat Treatment	After Air Erosion Test
APS Coated sample	2.5 * 2.5	38.1056	38.1099	38.1128	38.0776
	2.5 * 2.5	37.8903	37.8912	37.8914	37.8483
	2 * 2	24.3621	24.3637	24.0853	24.0615
	2 * 2	24.0811	24.0853	24.3637	24.3469
HVOF Coated sample	2.5 * 2.5	36.2488	36.2583	36.2602	36.2334
	2.5 * 2.5	35.8960	35.8963	35.8970	35.8732
	2 * 2	22.6397	22.6494	22.6510	22.6332
	2 * 2	23.0328	23.0375	23.0367	23.0231

As shown in Table 1 after each cycle of annealing there is increase in weights of samples. the main reason behind the increase in wights is oxidation. as temperature and time for annealing increases the rate of oxidation also increases which results in the increase in mass due to addition of oxygen. Annealing causes change in grain boundary and orientation of grain in microstructure.

As per literature review, for coated specimens, the mass loss due to erosion rises as the impingement angle increases and decreases for uncoated specimens. Remarkably, the maximum mass loss for the uncoated specimen occurs at 30 impact angle and less than 650 C rather than at 90. Uncoated specimens lose much more mass at 650 C than at 500 C at 30 and 90 degrees Celsius. The growth of the oxide layer on the uncoated specimens is caused by a rise in temperature, however it is unable to withstand the high impact energy of hard erodent. As a result, the brittle oxide layer cracks, resulting in direct contact with the erodent.

Table 2- Experimental parameters of Air erosion Test and mass loss.

Specimen	Temperature (◦C)	Impact angle	Mass loss (mg)	Erosion Rate *10^3 (g/g of erodent).
APS	450	90	35.2	0.586
	575	90	43.1	0.718
	450	30	23.8	0.396
	575	30	16.8	0.280
HVOF	450	90	26.8	0.446
	575	90	23.8	0.396
	450	30	17.8	0.296
	575	30	13.6	0.226

As seen in table 2, both APS and HVOF coatings have much reduced erosion rates. Under all test circumstances, coated specimens outperformed untreated specimens. The increased hardness and stability of carbides at high temperatures are the reasons for the variation. Coated specimens' mass loss does not rise linearly with temperature and impact angle, as it does with untreated specimens. A distinct drop of the mass loss by approximately 30% occurs

for the APS coating tested at 30◦ impact angle with an increase in temperature from 500 ◦C to 650 ◦C. Furthermore, for impact angles 30 and 90, mass loss is smaller at 650 C than at 500 C for the HVOF coating. At 650 C and 90 impact angles, the erosion resistance of APS and HVOF coatings is roughly two and four times that of the substrate, respectively. The inclusion of a larger percentage of hard carbides in coatings allows them to keep their hardness at higher temperatures. The comparably well-retained WC phase during deposition of the HVOF coating as opposed to the APS coating is a differentiating feature for the former's lower erosion rate. Additionally, in the case of HVOF coating, sintering of the intersplat area serves to improve inter-splat adhesion, and therefore the erosion rate lowers as the test temperature rises.

Table3- Experimental parameters of Air erosion Test and mass loss

Sample	Load (N)	Time (Sec)	Hardness (HV) (Before annealing and testing)	Hardness (HV) (After Annealing and Erosion Test)
APS Coated samples	2.949	15	942	Indent 1: 1098 Indent 2: 918 Indent 3: 1045
			939	Indent 1: 959 Indent 2: 1056 Indent 3: 966
HVOF Coated samples	2.949	15	930	Indent 1: 1489 Indent 2: 1554 Indent 3: 1406
			1162	Indent 1: 1596 Indent 2: 1685 Indent 3: 1622 Indent 4: 1555

Before the annealing as shown in Table 3 hardness of HVOF coating is more as compared to APS coating. this is due to the presence of oxygen. The main purpose of Annealing to decrease the porosity and increase the hardness of a material. as seen in Table 3 after annealing there is increase in hardness of both coating specimens. HVOF coated specimens are harder as compared to APS coated Specimens. The reason behind this is presence of an oxide clusters and presence of WC phase .

11. CONCLUSIONS

1) The annealing process cause increase of the value of microhardness HVOF as well as APS sprayed coating.

2) HVOF coating has higher hardness before and after annealing due to the presence of oxygen. as annealing temperature and time required the rate of oxidation is also increased.

3) After annealing temperature 450ºC, the voids and pores disappeared almost completely.

4) The microstructure and phase composition of the as deposited APS and HVOF coatings differ. The morphological structure of the HVOF coating is quite dense. The (W, Cr)2C phase is a significant phase due to the substantial interaction of WC with Cr3C2 and the increased degree of decarburization of WC in the APS coating. In contrast to the APS coating, the (W, Cr)2C phase is substantially reduced in the HVOF coating due to the lower process temperature. In the HVOF coating, the WC phase is a primary phase.

5) Because of its smaller porosity, stronger splat adhesion, lower degree of decarburization, and faster inter-splat sintering at increased temperatures, the HVOF coating has a lower material loss rate through erosion than the APS coating.

6) As a result, APS and HVOF sprayed WC-Cr3C2–Ni coatings are useful for improving the erosion resistance of base material steel in steam turbines and boiler tubes working at temperatures up to 650 C.

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