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Air jet erosion test on plasma sprayed surface by varying erodent impingement pressure and impingement angle

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Abstract
Fly-ash premixed with quartz and illmenite powder in different weight proportions are thermal sprayed on mild steel and copper substrates at various input power levels of the plasma torch ranging from 11 kW to 21 kW DC. The erosion test has done using Air Jet erosion test Reg (As per ASTM G76) with silica erodent typically 150-250 μm in size. Multiple tests were performed at increasing the time duration from 60 sec to 180 sec with increasing pressure (from 1 bar to 2.5 bar) and angle (60° & 90°). This study reveals that the impact velocity and impact angle are two most significant parameters among various factors influencing the wear rate of these coatings. The mechanisms and microstructural changes that arise during erosion wear are studied by using SEM. It is found that, when erodent are impacting the fresh un-eroded surface, material removal occurs by the continuous evolution of craters on the surface. Upper layer splats are removed out after 60 sec and second layer splt erosion starts. Based on these observations Physical models are developed. Some graphs plotted between mass loss-rate versus time period/impact Pressure/impact Angle gives good correlation with surface features observed.


1. Introduction
Solid particle erosion is to be expected whenever hard particles are entrained in a gas or liquid medium impinging on a solid at any significant velocity. Degradation of material by erosion increases operating costs, reduces energy efficiency, increases ideal time, reduces functional life, basically enhance pitting corrosion and decreases productivity across a broad range of applications [1-2]. Many investigations have been studied to increase the surface properties by deposition technique to reduce wear [3-7]. Now-a-days plasma sprayed coatings find broad applications not only in research and development area, but also in the industrial workplaces ranging from textile mills to even medical applications. In the automotive industries of many advanced countries, plasma-sprayed coatings are used to improve the resistance to erosion, abrasion and corrosion of machine components and structural parts [8]. This spray technology has the advantage of being able to process various low-grade minerals to obtain value-added products and to deposit ceramics, metals, and even a combination of these, generating near-homogenous composite coatings with the desired microstructure on a range of substrates [9-11]. Challenges related to thermal spray process concerning the improvement of spray systems and spraying of new materials. These aspects require a better understanding of the involved phenomena, i.e., physical, chemical, thermodynamics, etc. to improve the efficiency of plasma spray coating operation [12-15].
Plasma sprayed fly-ash composite coatings have been widely used in the coatings industry for its superior erosive, sliding and abrasive wear properties. This paper describes about fly-ash+quartz+illmenite composite coating composition. The coatings produced by this thermal spray processes exhibit a broad range of coating hardness, porosity and microstructural features like splat size and volume fraction of different phases. In this study, we have evaluated the coating microstructures of various fly-ash+quartz+illmenite coatings produced from different spraying power level. The objective of our investigation is to explore the erosion wear mechanism of fly-ash+quartz+illmenite coatings in great detail, and determine how these mechanisms are influenced by the coating microstructure.

2. Experimental Procedure

Fly-ash+quartz+illmenite homogeneous mixture having 60:20:20 weight ratios were Plasma sprayed on Mild steel and copper substrates, having dimensions 1 inch diameter and 3 mm thickness. Non-transferred arc mode atmospheric plasma spraying operation was done using a 40 KW plasma spray system at the Laser & Plasma Technology Division, BARC, Mumbai. The major subsystems of plasma set up include the spray torch, powder supply, powder feeder, plasma gas supply, control console, cooling water and spray booth. The plasma input power was varied from 11 to 21 KW by controlling the gas flow rate and arc current. The powder deposited at spraying angle 90°. Operating parameters used for coating deposition are given in table 1. Erosion wear test of these coatings are investigated by using Air Jet erosion test Reg (As per ASTM G76). For erosion study, only a small area of the sample was exposed to particle erosion, while the rest of the sample was wrapped in polyester tape, which allows impact of particle only in the exposed area. The tests were stopped after a short interval of time to calculate the mass loss. Multiple tests were performed at increasing time from 60 sec to 180 sec with increasing pressure from 1 bar to 2.5 bar and constant stand-off-distance of 65 mm. It is known that hard ceramic coating failure occurs at 90° angle [16]. So for high erosion two impact angle 60° & 90° were taken. The morphology of substrate (before worn and after worn) was studied using JOEL T-330 scanning electron microscope. Solid particle erosion test parameters are given in Table-2.

Table 1. Operating parameters during coating deposition of fly-ash+quartz+illmenite.

<table>
<thead>
<tr>
<th>Operating parameters</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma arc current (amp)</td>
<td>260-500</td>
</tr>
<tr>
<td>Arc voltage (volt)</td>
<td>40-44</td>
</tr>
<tr>
<td>Torch input power (kW)</td>
<td>11,15,18,21</td>
</tr>
<tr>
<td>Plasma gas (argon) flow rate (IPM)</td>
<td>28</td>
</tr>
<tr>
<td>Secondary gas (N2) flow rate (IPM)</td>
<td>3</td>
</tr>
<tr>
<td>Carrier gas (Ar) flow rate (IPM)</td>
<td>12</td>
</tr>
<tr>
<td>Powder feed rate (gm/min)</td>
<td>15</td>
</tr>
<tr>
<td>Torch to base distance (TBD) (mm)</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2. Testing parameter during erosion.

<table>
<thead>
<tr>
<th>parameters</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing Temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>Impingement Angle</td>
<td>60° &amp; 90°</td>
</tr>
<tr>
<td>Erodent impingement pressure</td>
<td>1.0, 1.5, 2.0, 2.5 bar</td>
</tr>
<tr>
<td>Test duration</td>
<td>60 sec, 120 sec &amp; 180 sec</td>
</tr>
</tbody>
</table>

3. Results and Discussion

3.1 Investigation on the surface wears during erosion of fly-ash+quartz+illmenite coatings.
After wear test, all the samples have been examined under SEM. Figure 1(a), (b), (c) & (d), show the surface morphology of worn surfaces, when the erodent is impacted at an angle 60° and 90° respectively with varying pressure level of 1 bar and 2 bar. At 60° angle of impact, there are many angular grooves occurs. At 90° angle of impact, sharp vertical groves are seen which is due to dominating effect of perpendicular component of the force of impingement of the erodent. In general, it can be stated that when hard and multifaceted erodent i.e. SiC is used, deeper groves are produced and plastically flow regions are found and also limit the surface crack propagation. It observed that by increasing in erodent impact pressure, there is increasing in removal of coating mass causing exposure of substrate material. By solid particle impingement, there is a formation of grooves called crater. Here crater indicates that the particle indenting the region is more rounded, as an angular particle would have cut deeper into the surface, creating a more prominent crater-lip [17]. SEM micrograph confirms that the damage mechanism is related to single or multiple splat removal through crack propagation along the splat boundaries of single splat or a cluster of splats. This wear mechanism based on piled up of material with gradual loss of mass after subsequent impacts by forming a crater. Initial piled up material is heavily strained and some small cracks are observed & spread along splats boundaries. This is the reason of fragmentation of splat during solid particle erosion.

![Figure 1](image1.png)

**Figure 1.** SEM micrographs of eroded surfaces of coatings deposited at 18 kW, eroded at angle of impact (a) 60° & 1 bar; (b) 60° & 2 bar; (c) 90° & 1 bar; (d) 90° & 2 bar using SiC as the erodent.

### 3.2 XRD Analysis

Figure 2 shows the XRD analysis of (a) raw material which is to be coated, and (b)-(e) shows the coating at a different power level. Here it is observed that by increase in deposition power level, there is increase in different phase formation. These oxide formation is due to the higher energy transformation in the presence of atmospheric air. These different oxide phases act as the ceramic coating and can hinder the corrosion rate.
3.3 Hardness measurement

By micro-hardness testing, it is found that an average hardness is within a range of 532.77 Hv to 659.75 Hv and erosion rate in the range of 60.1×10⁻⁴ to 283.74×10⁻⁴. This variation arises due to distribution of composite coating and due to transformation of different phases in the time of specimen preparation (basically due to different power supply for coating). Additionally, the presence of titanium, iron, and silicon compounds and oxides in the coating phase greatly increased the hardness. These composite phases were more effective in improving wear resistance. Wear behavior of coated composite layers also depends on different powder feed rates and input energy conditions [18]. It is found that the sample prepared by 18 kW power level has a greater hardness and less erosion rate for all test conditions. Figure-3 shows the graph between erosion rate and micro-hardness of plasma sprayed fly-ash+quartz+illmenite coating. The figure indicates erosion rate decreases as increasing in coating hardness. But in some cases, erosion rate becomes a little higher as there is an increase in hardness as compared to others. This is due the presence of larger amount of void present in the coating, semi-molten phases etc.
Figure 3. Erosion rate vs micro-hardness of plasma sprayed fly-ash+quartz+illmenite coating (Erosion at 90° angle of incident).

3.4 Graphical presentation of coating mass with respect to erosion time

Figure 4 shows that mass of coating sample versus time in order to identify the erosion rate. Here time duration taken from 60 sec to 180 sec. Between 60 sec to 120 sec, when the particles impact on the fresh uneroded coating surface, each erodent causes material removal by forming prominent lips and craters [19]. Here it is found that the mass loss increases with increase in time. Mass loss rate can be obtained by the average mass loss at a particular time divided by the time duration. In between 120 sec and 180 sec, in some case, there is a decrease in mass loss. This is due to: (a) strain-aging as sticking of the surface materials [20] or (b) the efficiency of erodent retarded due to the rough uneven surface which absorbs the particle impact energy and hinder for mass loss [21] or (c) due to brittle to ductile transition behavior [22]. The variation of mass loss with time, in case of the coating eroded by SiC for 18 kW are illustrated in Fig 4(a) & (b) and for 21 kW illustrated in Fig 4(c) & (d). From the figures, the mass of the coating material decreases with the time period. The initial mass loss is high and it follows a steady state after a certain time of exposure. Finnie [23] has explained that the drastic drop of erosion rates is due to transition of type of fracture mechanism i.e. from brittle to ductile behavior. From these figures, it is concluded that the initial wear rate is high irrespective of the angle of impact. With increasing exposure time the rate of wear starts decreasing and in the transient regime, a steady state is attended [24]. It is also found that, maximum erosion occurs at a normal impact angle. This behavior is observed in case of brittle materials where the erosion rate continuously increases with increasing impact angle and attains a maximum at normal (90°) impact, in addition, under brittle erosion conditions the magnitude of erosion rate is determined only by the normal component of impact velocity [25].
4. Conclusions

Due to phase transformations and semi-molten powder deposition during plasma spraying, changes the coating characteristic such as erosion rate and hardness. The flyash+quartz+illmenite coating gives much harder than substrate metals for which it can be recommended for tribological applications. It is clear that erosion wear strongly influence by the size of erodent, impact velocity, impact angle standoff distance and hardness, etc. Maximum erosion took place at a normal angle of impact. Here it is found that, this type of erosion mechanism initiates through plastic deformation.

For recommending plasma spraying for a specific application, study of erosion wear behavior is the main requirement. It is concluded that the composite coating materials are more effective for improvement of wear resistance and flyash+quartz+illmenite can be considered as a potential coating material suitable for various tribological applications.

5. References


