Effect of Bauxite addition on Adhesion Strength and Surface Roughness of Fly ash based Plasma Sprayed Coatings

S K Bhuyan1*, S Samal1, D Pattnaik1, A Sahu1, B Swain1, T K Thiagarajan2 and S C Mishra1
1Metallurgical & Materials Engineering Department, N.I.T. Rourkela.
2Laser and Plasma Technology Division, BARC, Mumbai.
Email: subratbhuyan2014@gmail.com

Abstract
The environment is being contaminated with advancement of new technology, day by day. One of the primary sources for this contamination is the industrial waste. Industrialization is the prime reason behind the prosperity of any country to meet the materialistic demand. To run the industries, a huge amount of (electric) power is needed and hence need for thermal power plants to serve the purpose. In present scenario, coal fired thermal power plants are set up which generates a huge quantity of Fly ash. Consumption of industrial waste (Fly ash), continually a major concern for human race. In recent years, fly ash is being utilized for various purposes i.e. making bricks, mine reclamation, production of cements etc. The presence of Silica and Alumina in fly ash makes it useful for thermal barrier applications also. The plasma spray technology has the advantage of being able to process any types of metal/ceramic mineral, low-grade-ore minerals etc. to make value-added products and also to deposit ceramics, metals and a combination of these to deposit composite coatings with desired microstructure and required properties on a range of substrate materials. The present work focuses on utilization of fly ash mixing with bauxite (ore mineral) for a high valued application. Fly ash with 10 and 20% bauxite addition is used to deposit plasma spray overlay coatings at different power levels (10-20kW) on aluminum and mild steel substrates. Adhesion strength and surface roughness of the coatings are evaluated. Phase composition analysis of the coatings were done using X-ray diffraction analysis. Surface morphology of the coatings was studied using a scanning electron microscope (SEM). Maximum adhesion strength of 4.924 MPa is obtained for the composition fly ash and bauxite (10%), coated on mild steel at 16kW torch power level. The surface roughness (Ra) of the coatings is found to vary between 10.0102 to 17.2341 micron.

Keywords: Fly ash; Bauxite Ore; Plasma Spraying; Adhesion Strength.

1. Introduction
Coal is an indispensable part in electricity generation around the world. As per the World Coal Institute, coal fuelled power plants generates 41% of worldwide electricity. It is estimated that coal fuelling 44% of electricity generation worldwide by 2030 [1]. Huge amounts of fly ash is generated in coal-fired thermal power stations [2]. In the year 2016-17 it is expected that the production of fly-ash increases around 300-400 MT/year. Now a days, in manufacturing of concrete, bricks, cement and tiles fly ash is used. Also it finds a remarkable contribution in mine filling and road embankment [3]. In recent years, industrial wastes are used for making value-added products [4, 5]. Some research have been done to develop plasma spray
coatings using these wastes [6, 7]. Also these wastes finds application in wear resistant coatings [8]. Plasma spray technology is one of the most widely used techniques of preparing overlay coating on any surface to improve properties and increase life span of parts [9]. The plasma spray technology can apply various minerals, metals and ceramics to obtain the desired microstructure of the near homogenous composite coatings. While considerable emphasis is being placed to process low-grade ore minerals through plasma spray process, fly ash was found to be a productive substitute for conventional extenders in high performance industrial coatings [10].

Bauxite ore contains alumina, silica, iron oxide and titania as the major oxides. The two very important properties of protective coatings are adhesion and thermal shock resistance. The adhesion strength of the coating strongly determines the performance and quality of protective coatings. Here, in the present work, an attempt has been made to utilize an industrial waste in addition of an ore mineral to examine its usefulness and functionality. The overlay coatings of 10% and 20% bauxite addition with fly-ash on metals are developed using plasma spray technique. The objective of the current work is to use an industrial waste to develop a ceramic coating on metal substrates.

2. Materials and Methods
Fly-ash (FA) and bauxite ore are the major raw materials used in the present research work. Sieve analysis method is used particle size analysis where both materials contains particles in the range of 20 to 100 micron. Raw materials of three different compositions are homogeneously mixed prior to plasma spraying and are; FA, FA + 10% bauxite and FA + 20% bauxite. The detailed chemical compositions of two raw materials as mentioned above are listed in table 1 given below.

| Table 1 Chemical analysis of raw materials. |
|------------------------------------------------|
| Raw material | Compounds (Oxides) | Wt. % | LOI |
| ------------ | ------------------ | ------ | ---- |
|              | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | TiO$_2$ | CaO |
| FA          |       |   |   |   |    |     |
| Bauxite Ore |       |   |   |   |    |     |

| Raw material | Wt. % | At. % |
| ------------ | ------ | ----- |
| FA          |       |       |
| Bauxite Ore |       |       |

Figure.1 Scanning Electron images of a) FA and b) Bauxite ore with their respective EDS spectrums.
SEM images and EDS analysis of raw fly ash and bauxite samples are given in figure 1. Both materials contain oxides of silicon and aluminium but significant amount of iron oxide is found to be present in bauxite.

Mild steel and aluminium plates of size 25.4mm x 25.4 x 3mm are taken as the substrate material. Sand blasting was adopted to obtain a minimum surface roughness value of ~3.5 micron Ra. 10, 12, 16 and 20 kW DC power level was maintained for plasma spraying with a non-transferred arc. Argon is chosen for both carrier as well as plasma forming gas where flow rates of 30 and 6 LPM are maintained for plasma forming and carrier gases respectively. Apart from this nitrogen gas of flow rate 2LPM are included as secondary carrier gas for enhancement of flame enthalpy.

The input feeding of powder was maintained at a rate of 10gm/min. A distance of 80mm is maintained from plasma torch to substrate. The surface morphology and phase identification studies were done by using JEOL (JSM-6480LV) scanning electron microscope and BRUKER D8 Advance type diffractometer with a Co-Kα radiation (1.79285 Å) respectively. A jig is fabricated to evaluate the adhesion strength of coating. Cylindrical dummy samples with 13 mm top diameter was prepared for the same purpose. The adhesive used for the test was Epoxy 900-C. Coating pull out method in INSTRON machine was adopted to evaluate the adhesion strength. The surface roughness was measured with Stylus Surface Profilometer.

3. Results and discussion
Further all coating surfaces are observed in scanning electron microscope and are shown in the figure 2 where figures are in increasing order of power level i.e. coated with application of 10 to 20 KW.

![Figure 2 SEM images of FA + bauxite 10% coated samples](image)

Figure 2 SEM images of FA + bauxite 10% coated samples (a-10kW, b-12kW, c-16kW, d-20kW).

With increase in power level the densification rate is increased which can be clearly seen from the above micrographs. Highest flattening of deposited coatings is observed at 16 kW. In figure 2d the lesser flattening is observed as that of 16kW coated surface; may be due to the faster quenching rate as occurs in plasma spraying. The temperature difference in the axial zone of plasma jet and flame tip is the key reason behind the rapid cooling rate; which in turn resulted in deposition of small fragmented particles at some regions [4].

Further X-Ray analysis was performed for proper understanding of spraying kinetics and are the diffractograms thus obtained are shown in figures 3 and 4. The presence of Quartz, Mullite, Iron Oxide (Fe₂O₃) and Corundum phases are detected in the XRD pattern of raw FA. After spraying transformation of quartz has into tridymite (the high temperature polymer) and Iron Oxide (Fe₂O₃) to Iron Oxide (Fe₃O₄) is observed. Also, with increase in power level the intensities of tridymite, mullite and Iron Oxide (Fe₃O₄) phases are increased as evident from the XRD patterns shown in figure 3.

The XRD patterns of raw composition (fly ash 80 + bauxite 20%) as well as coatings at different power levels viz. 10 to 20 kW are shown in the figure 4. With bauxite addition to fly ash, along with Quartz,
Mullite, Iron Oxide (Fe2O3) and Corundum, presence of gibbsite phase is also found. From figure 4 it observed that, with 20% addition of bauxite to fly ash, the intensities of mullite and corundum phases increases with increase in power level.

Figure 3 XRD patterns of Raw FA and FA coatings made 10, 12, 16 and 20 kW.

The adhesion strength of the coatings were evaluated with implementation of coating pull out technique following ASTM C-633 standard. While performing the test, it is observed that at the interface of coating and substrate gets fractured in case of all coated samples. Figure 5 represents the plot showing the variation in coating adhesion strength w.r.t operating power level. In both the cases the adhesion strength shows an increasing trend up to 16kW power level and after that the bond strength decreases i.e. at 20kW. This may be due to the reason that the melting of raw/fused particles is favored by high temperature plasma flame, but at upper power input the plasma jet velocity is too high with the elevated temperature which causes/enhances particle fragmentation [9]. Maximum adhesion strength values of 4.924 MPa is achieved for the fly ash 90+ bauxite 10% coatings on Mild steel substrate at 16kW. This may be due to the reason that aluminium has higher thermal conductivity than mild steel substrate. For this reason in mild steel substrate the molten/semi molten particles get more heat at the interface of the coating and substrate resulting a better interlocking [10].

Figure 4 XRD patterns of Raw (FA + bauxite 20%) and coatings 10, 12, 16 and 20kW.
Figure. 5 Adhesion Strength Comparison between FA, FA+ Bauxite 10% and FA + Bauxite 20% coatings made at various power levels for Al and MS substrate.

The variation of surface roughness for various compositions w.r.t operating power levels is shown below in figure. 6.

Figure. 6 Surface Roughness Comparison between FA, FA+ Bauxite 10% and FA + Bauxite 20% coatings at different operating power levels.

In figure 6, it is clearly observed that surface roughness of the each composition decrease with rise in torch power. Surface roughness value is minimum i.e. 10.01 micron (Ra) for fly ash coating at 20kW power level and maximum in fly ash 80 + bauxite 20% coatings i.e.17.23 micron (Ra) at 10kW. It may be because of; with increase in power level, high temperature-high enthalpy plasma flame favors the softening/melting of the particle, creates more homogenous distribution of sprayed particles from molten state.

Conclusions
1. Efficient melting of particles occurs at 16kW power level as seen from SEM images and proper bonding/melting etc. is restricted at higher power level.
2. The intensities of tridymite, mullite and iron oxide (Fe₂O₃) peaks increase with increased operating power level. When Bauxite is added to fly ash, it also favours the increase in formation of corundum phase (i.e. alpha alumina).
3. The adhesion strength shows an increasing trend up to 16kW power level and after that the bond strength decreases except for fly ash coating, on MS substrate. This may be due to uniform melting of charge composition (Fly ash ) and increase in power level favoring the melting/bonding of particles with MS substrate.
4. Minimum surface roughness value of 10.01 micron (Ra) is obtained for fly ash coating (without bauxite) at 20kW.
References

[1] A. A. Cha´vez-Valdez, A. Arizmendi-Morquecho, G. Vargas, J.M. Almanza, J. Alvarez-Quintana, 2011 Ultra-low thermal conductivity thermal barrier coatings from recycled fly-ash cenospheres 59 2556-2562.

[2] Openshaw SC 1992 Utilization of coal fly ash Ph.D. Thesis University of Florida.

[3] Haque Md 2013 Waste Resources 3 22-25.

[4] Mishra S C, Mishra P C, Rout K Cand Anantapadanabahn P V 1999 Fly ash utilization for value added products NML. Jamshedpur 131-135.

[5] Sathpathy A 2005 Thermal Spray Coating of Red Mud on Metals PhD Thesis, NIT Rourkela, India.

[6] Sathpathy A and Mishra S C 2003 National Conference on Materials and Related Technology, TIET.

[7] Mishra, S. C., Das, S., Satapathy, A., Sarkar, S., Ananthapadanabahn, P. V., and Sreekumar, K. P. (2009), “Investigation on Composite Coating of Low Grade Minerals,” Journal of Reinforced Plastics and Composites 24 3061-3067.

[8] Mishra, S.C., Rout, K.C., Padmanabhan, P.V.A. & Mills, B. 2000 Plasma spray coating of fly ash pre-mixed with aluminium powder deposited on metal substrates. Journal of Materials Processing Technology 102 9–13.

[9] Satapathy A, Mishra SC, Mohanty U, Mishra TK, Anantha padmanabhan P V and Sreekumar K P 2004 Proceedings of the International Conference on Industrial Tribology, Tribological Society of India, Mumbai.

[10] Mishra S C, Praharaj S and Satapathy A 2009 Journal of Manufacturing Engineering 4 241-246.