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An Investigation on the Parameter Sensitive Performance of Detonation Sprayed Alumina on EN19 Steel

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Abstract

Modern technology has evinced keen interest on development of advanced materials for a variety of surface technologies. Detonation gun (d-gun) spraying has been considered as one of the promising thermal spraying technologies. The study focuses the investigation on the parameter sensitive performance of detonation sprayed alumina on EN19 steel. Accordingly, the effects of process parameters viz. fuel ratio and standoff are studied on performance indicators such as micro hardness, wear, friction force and coating thickness. Experimental results suggest that the variation in the standoff distance causes alteration in the duration of residency, which has a pivotal role in producing durable surface coatings that can resist wear using the d-gun spraying process. It is preferable to adopt a standoff of 200 mm with 1:2.5 fuel ratio to get a surface coating with optimum thickness and hardness. Presence of finer surface cracks is observed at higher standoff due to induction of compressive residual stress during detonation followed by tensile rarefaction.

Keywords: alumina, detonation, spray, standoff, micro hardness, plasticized, wear.

INTRODUCTION

Modern technology has evinced interest on development of advanced materials for a variety of technological uses. Despite development of the bulk of engineered parts, there is a limit to their surface integrity calling for suitable surface coatings/depositions. Hence in recent times components are coated with suitable ceramic materials to modify and safeguard surface properties against hazardous environments such as abrasion, erosion, and corrosion [1]. Among the various coating technologies, detonation gun (d-gun) spraying has been considered as promising thermal spraying technology to produce different protective coatings such as thermal barrier coatings, wear resistant coatings, and corrosion resistant coatings, etc. [2]. Detonation gun spraying is a high velocity (up to 1200ms^{-1}) deposition process wherein material to be deposited is injected as smaller particles into a combustion flame; the injected particles become plasticized due to heating and detonated subsequently on the chosen substrate material. The high velocity impingement causes splat cooling of the plasticized particles leading to deposition. In the case of coating material, diverse types of ceramic compounds (oxides, carbides, borides) are used individually or in combination. Of the oxide ceramic compounds, aluminum oxide (Al_2O_3) coatings are used for a wide range of applications. This rapid introduction of tribological coatings necessitates study of the effect of process parameters on the response coatings. In the case of plasma spraying the particles injected into the plasma melt and get deposited on the substrate, while with detonation spraying the injected particles get plasticized and deposited. This necessitates selection of particle-size and residence time depending on the type of spraying/deposition. This study focuses on the effect of process parameters on the d-gun sprayed alumina coatings.

Thermal spraying using Detonation gun is beneficial in the manufacture of aircraft turbines parts [3]. The working temperature of d-gun spraying is relatively low when compared to other thermal coating processes and coating thickness is an important factor when protection of the base material is with cermet coatings [4]. L4 orthogonal type array was adopted to find the ideal mix of the process parameters for different coating materials [5]. High hardness with significant adherence strength, superior modulus of rupture, and reduced porosity are reported as important characteristics of d-gun coatings [6]. Higher hardness and lower wear result with increasing fuel ratio and decreasing standoff, when the effect of process parameters on the quality of alumina coating using d-gun spraying is considered [7, 8]. At higher fuel ratio, deposits were harder with an enhanced resistance to wear. Likewise the stand-off distance in terms of time of residency also plays a significant role in d-gun spraying [9]. The distance of the spray gun from target and the fuel ratio influence the state of the plasticized particle and consequent formation of splats and inter splat cohesion;further the residual stresses on the interface is also influenced affecting the performance of the coatings [10]. Lamellar structure was observed when Al_2O_3 was deposited using d-gun process [11, 12]. Inter-lamellar cohesion associated with voids dictate the soundness of the Al_2O_3 deposits. D-gun-sprayed hard coatings had higher hardness, density and wear resistance than the corresponding plasma-sprayed coatings. The wear resistance of D-gun-sprayed deposits is higher than that obtained with sintering [13].Porosity of sintered product is a serious concern calling for selection of the type of compaction and subsequent sintering. Commercial alumina powder exhibits thick splats, higher wear rate and frictional coefficient than nanocrystalline powder d-gun coating [14]. This could be attributed to the size effect. Normally reduced order of porosity was observed while d-gun spraying of alumina [15]. Alumina deposits when paired with hardened steel exhibit increased sliding wear due to chemical interaction at higher temperature and the strain associated wear mechanism [16].This could be due to the status of the deposition including porosity and interlamellar cohesion since alumina is thermally stable. This paper discusses the parametric influence on the d-gun sprayed alumina coatings on EN19 steel substrate. The microstructure of d-gun sprayed samples was initially studied through Scanning Electron Microscope (SEM) followed by assessment of micro hardness, frictional force and wear.

MATERIALS AND METHODS

The performance characteristics of the d-gun sprayed coating largely depend on the ratio of combustion gases, the particle size of powder, the flow rate of Nitrogen (carrier gas), detonation frequency, and standoff distance. In this study, Fuel-Oxygen ratio (Fuel ratio) and standoff distance were taken as process parameters and coating thickness, micro hardness, frictional force, and wear as response parameters. The entire experimental study utilized the identical particle size of the coating powder. EN19 steel (BS: 970) whose composition is given in Table 1, has been taken as substrate material. Cylindrical specimens of size 10 mm diameter and 30 mm length were prepared and subsequently grit blasted to

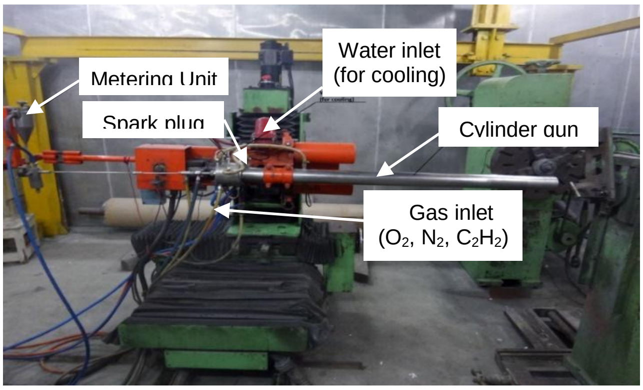


Figure 1: D-gun coating set-up

to roughen the outer layer of the substrates to facilitate better mechanical keying/locking of the sprayed layers. The experimental setup of d-gun spraying is given in Figure 1. The purity of alumina powder is 99.97 and the size of the alumina powder is 20 to 30 µm of CUMI make. The spraying is performed at different combinations of fuel ratios and standoff distances. The experimental details are given in Table 2. The

Table 1: Chemical composition of work material

Material	C%	Mn%	Cr%	Mo%	Si%	S%	P%
En19 steel to BS:970	0.35 to 0.45	0.50 to 0.80	0.90 to 1.40	0.20 to 0.40	0.10 to 0.35	0.40	0.40

size and shape distribution of alumina powder was assessed before spraying through EDS. Typical morphology and EDS spectra are illustrated in Figure 2 and Figure 3. The hardness on the sprayed surface was measured using Vickers Hardness Tester, Model No. VM50 (Fuel Instruments Engineers Pvt. Ltd.) at a load of 200gf. The microstructure of the sprayed coatings was observed by using Quanta FEG scanning electron microscope, Model No. 200. Frictional force and wear of the coating was measured Utilizing rotary tribometer, Model No. TR-201 (DUCOM instruments Pvt. Ltd, India). Wear test were performed by keeping wear track as 80mm, load as 15N and sliding velocity as 1ms-1.

Table 2: Experimental details..

Workpiece	Material Size	- En 19 steel (normalised) - Ø10mm X 30mm long
Coating material	Alumina powder Size	- (99.97%purity) - 20 to 30 µm
Coating conditions	Fuel Oxygen Ratio Standoff	- 1:2.5, 1:3.0, 1:3.5 - 180, 200, 220 mm
Purging gas	Nitrogen	

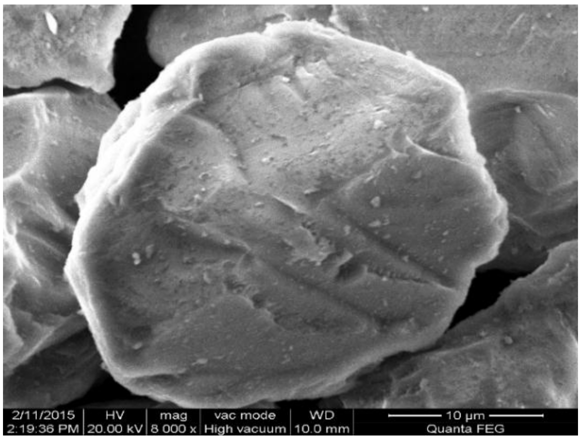


Figure 2: SEM of Alumina powder sample

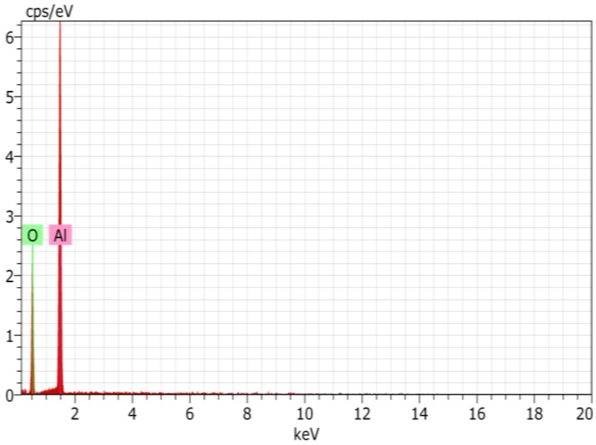


Figure 3: EDS Analysis of Alumina powder sample

RESULTS

Parametric Influence on hardness

Typical monitored dependency of hardness on spray parameters fuel ratio and standoff distance is illustrated in Figure 4. For a given standoff, increasing the fuel ratio from 1:2.5 to 1:3.5 results in drop in hardness. With increasing fuel ratio the temperature of the combustion flame drops down resulting in reduced spreading of the splats and a coating with discrete pores; this leads to drop in hardness of the deposition. However in the case of standoff, a critical value (200 mm) has been observed above which a drop in hardness results, unlike the case of plasma spraying wherein the molten droplets/particles travelling in air (atmospheric plasma). With detonation spraying the injected particles in the combustion flame impinge on the surface of the substrate on detonation. The standoff decides the period of residency influencing the plasticizing. With higher standoff the injected particles encounter more heating due to increased period of residency. On detonation the interface experiences more heating with induction of compressive residual stress, followed by tensile

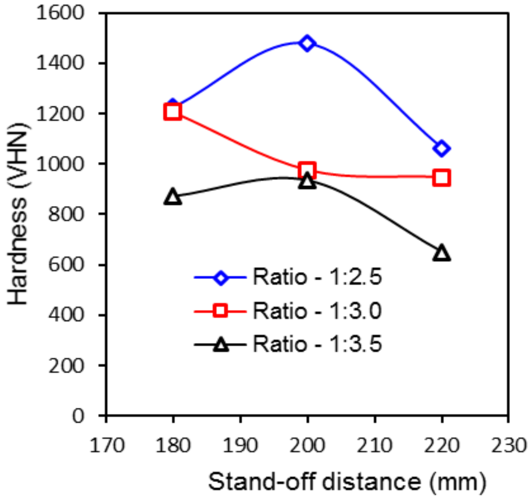


Figure 4: Parametric influence on hardness

rarefaction. This results in cracking and reduced hardness of the deposition.

Parametric Influence on wear

Typical monitored variation of wear of the depositions is illustrated in the Figure 5. It is seen that for a given standoff, with increasing oxy fuel ratio (1:2.5 to 1:3.5) the associated reduction in hardness results in increased wear. However with standoff a mixed mode of wear response was observed. For all the fuel ratios, up to a critical standoff, a rise in hardness was monitored with a reduction in wear. However with increasing fuel ratio a reduction in wear up to the critical standoff of 200 mm, followed by a rise with higher standoff was noticed.

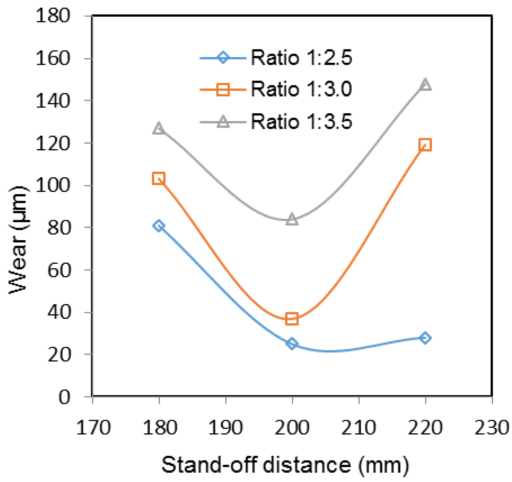


Figure 5: Parametric influence on wear

Figure 6 illustrates the variation of attainable thickness of the deposition influenced by the standoff and fuel ratios. For a given value of feed, the process exhibits a rise in thickness. With an increase in standoff a reduction in coating deposition is observed with standoff for 1:3.5 ratio; with 1:3.0 ratio a rise in thickness is observed up to 200mm standoff followed by a

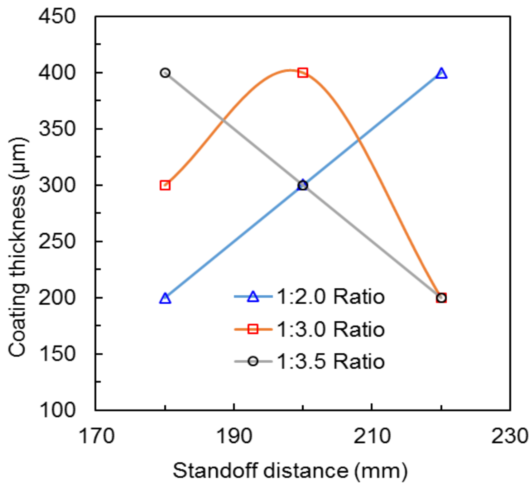


Figure 6: Parametric influence on coating thickness

reduction with increased standoff. During detonation depending on (thermal) status of the impinging particles the deposition will be full without any scattering leading to higher thickness of deposition. Also with increasing fuel ratios the deposition can be partial due to scattering of material during detonation increasing thickness of the deposition with 1:2.5 fuel ratio with increasing standoff results in denser deposition and higher hardness. A reduction in thickness with standoff in the case of higher fuel ratio is associated with reduced hardness and higher order wear.

Parametric influence on frictional force

Typical parametric influence on frictional force is illustrated in Figure 7. The observation on the frictional force pattern almost follows the trend of variation of hardness (Figure 4).

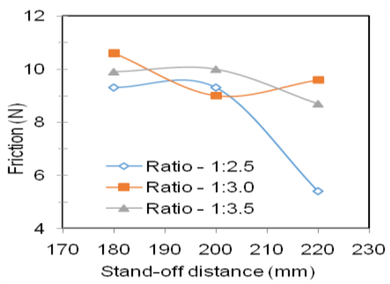
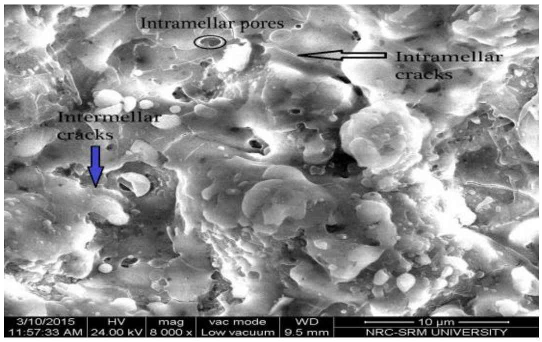


Figure 6: Parametric influence on frictional force

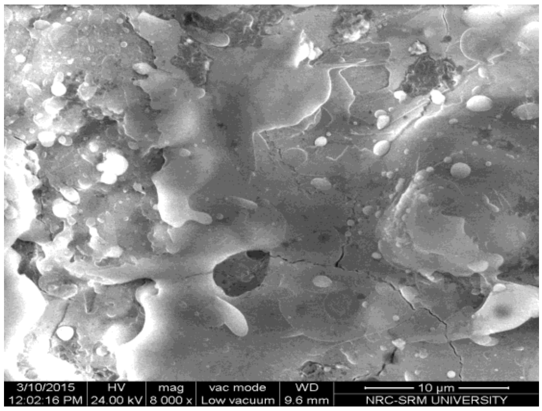
With increasing standoff, the frictional force increases very marginally till 200 mm, beyond this point it reduces, except at fuel ratio of 1:3, where a marginal increase in frictional force is observed. Technically, it is not easy to predict wear of ceramic deposition with structural defects like porosity, presence of un-melted grains (both gamma and alpha phases) and spraying induced cracking.

Microstructure characterization of sprayed surface

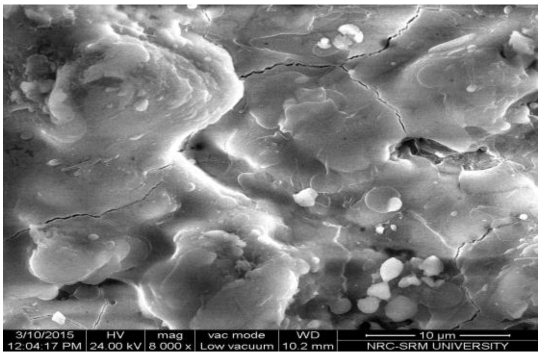
Micrograph of sprayed surfaces supplement the above observations. Typical micro graphs obtained on the coatings at 1:2.5 fuel ratio are illustrated in Figure 8. With 180 mm standoff, micrograph (Figure 8(a)) pertaining to coating thickness of 200 μm shows splats of mixed size of plasticized material with discrete cavities and inter splat /surface cracks. With increasing standoff (period of residency), due to higher heat input the micrograph is relatively denser with solidified and layered splats. This is associated with higher hardness of 1500 VHN as observed in the hardness (Refer Figure 4). With 220 mm standoff longer residency facilitates enhanced heating of the charged powder particles resulting in coarser splats and



(a) Standoff - 180mm, Coating thickness - 200 μm



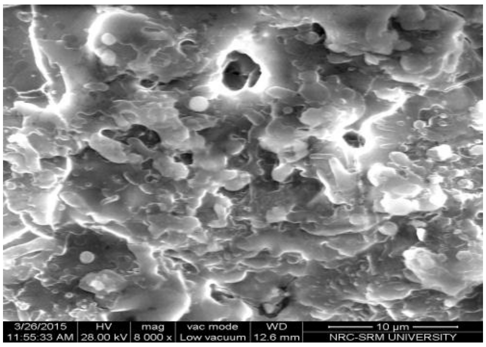
(b) Standoff - 180mm, coating thickness - 200 μm



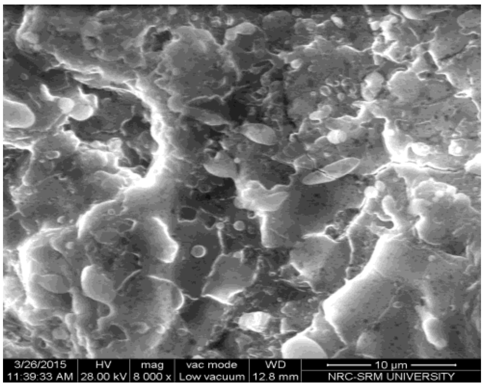
(c) Standoff - 220mm, Coating thickness - 400 µm

Figure 8: SEM micrographs of sprayed surfaces with Fuel/oxygen ratio - 1:2.5

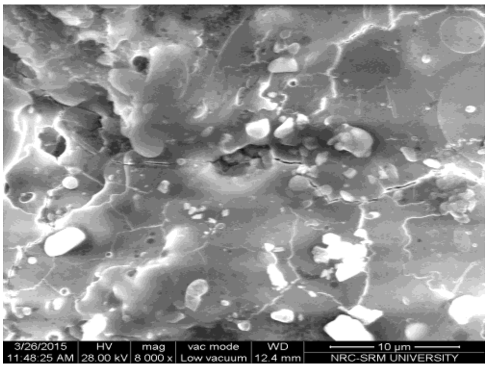
surface cracks as seen from Figure 8(c). The surface cracks in the deposition could be attributed to the interface residual stress; incidence of compressive stress followed by tensile rarefaction can induce finer cracking in the mechanically adhering coating. Also relatively slower cooling of the outer layer of thick deposition could have resulted into reduced hardness of 1100 VHN as seen in Figure 4.



(a) Standoff - 80 mm, Coating thickness - 300 µm



(b) Standoff – 200 mm, Coating thickness – 400 µm



(c) Standoff - 220 mm, Coating thickness - 200 µm

Figure 9: SEM micrographs of sprayed surfaces with Fuel/oxygen ratio - 1:3

Typical micrographs obtained from coatings done at 1:3 fuel ratio are shown in Figure 9. At 1:3 fuel ratio with 180 mm standoff (Figure 9(a)), unlike the case of 1:2.5 ratio, relatively thicker deposition (300 µm) results with deformed /elongated streaks; with increasing standoff and consequent higher heating, a thicker deposition (400 µm) with a microstructure comprising of coarser solidified splats results (Figure 9(b)). The presence of surface cracks at higher standoff of 220mm (Figure 9(c)) could be due to the relaxation of the coating. The thinner deposition is possibly due to partial scattering / rebouncing at higher standoff.

Micrographs of sprayed surfaces with 1:3.5 fuel ratio are illustrated in Figure 10. With lower standoff of 180 mm, the

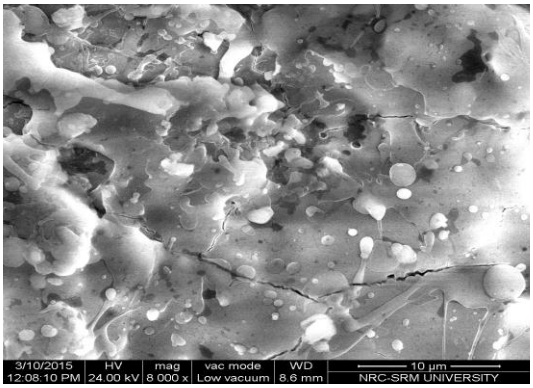


Fig. 8 (a) Standoff -180 mm, Coating thickness - 200 µm

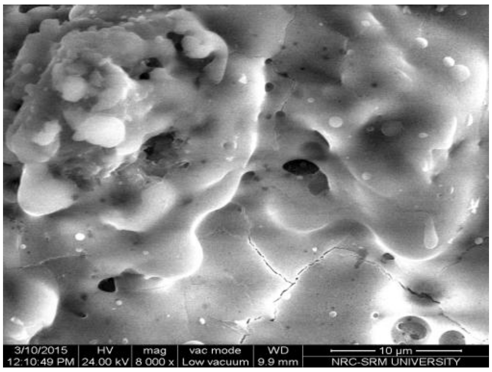


Fig. 8 (b) Standoff - 200 mm, Coating thickness - 300 µm

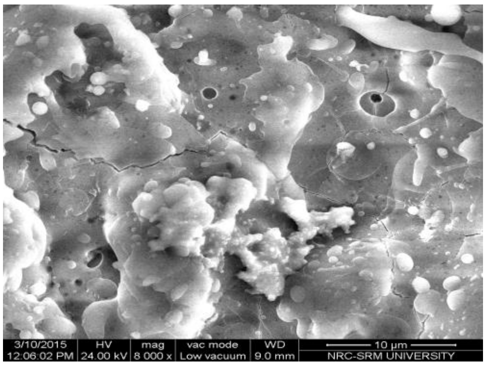


Fig. 8 (c) Standoff - 220 mm, Coating thickness - 200 µm

Figure 10: SEM micrographs of sprayed surfaces with Fuel/oxygen ratio - 1:3.5

injected particles will encounter less thermal energy and gets plasticized, resulting into mixed mode of solidified and plasticized splats. With increasing standoff and higher fuel ratio, more heat input to the charge facilitating easier spreading of splats and forming deposition of 300mm thick and only marginally varying in hardness are seen. With a higher period of residency at 220 mm, the plasticized particles spread out as coarse splats with isolated porous sites and surface cracking (Figure 10(c)), resulting into reduction in thickness of deposition. The coarse splats with surface cracks could have resulted in coatings associated with inferior hardness of about 600 VHN (Refer Figure 4).

Considering the influence of stand-off on the microstructure and micro hardness, it is preferable to adopt a stand-off of 200 mm with 1:2.5 fuel ratio to obtain a good coating with higher thickness and hardness. As regards the deposition thickness, it is preferable to select 180 mm stand-off with 1:3.5 fuel ratio, 200 mm standoff distance with 1:3 fuel ratio and 220mm stand-off distance with a fuel ratio of 1:3.5. A combination that balances both stand-off distance and fuel ratio, results in a thicker deposition. Also, 200 mm standoff with 1:2.5 fuel ratio yields deposition of medium thickness and higher hardness.

CONCLUSION

The following are the findings of the experimental study and analysis of the d-gun sprayed alumina coatings low alloy EN19 steel material:

- With regard to hardness, a reduction is noticed beyond 200 mm standoff indicating optimum level of standoff.
- With respect to wear, it is seen that wear tends to drop down over 180-200 mm standoff while it rises over 200-220 mm range.
- The pattern of the frictional force almost follows a similar trend of variation of hardness.
- With regards to deposition thickness, it is preferable to select 180 mm standoff with 1: 3.5 fuel ratio, 200 mm standoff with fuel ratio of 1:3 and 220 mm standoff with fuel ratio of 1:3.5.
- It is preferable to adopt a standoff of 180 mm with 1:2.5 fuel ratio to get a surface coating with optimum thickness and hardness.
- From the microstructure finer surface cracks in the deposition are observed at higher standoff almost at all fuel ratios, which could be due to induction of compressive residual stress during detonation followed by tensile rarefaction.

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