Microstructure and Wear Behavior of Microwave Treated WC-10Co-4Cr Composite Coating on AISI 4140 Alloy Steel

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Abstract. WC-10Co-4Cr composite coatings have been coated with AISI 4140 low alloy steel substrate using high-speed oxygen fuel (HVOF) technology with a particle size from 0 to 50 microns. Microwave heating energy is used to enhance the mechanical and tribological properties of sprayed coatings as post-heat treatment technique. Microwave fused coatings exhibit greater surface roughness, porosity, micro hardness, and wear strength than the as sprayed deposition. The as coated and fused coatings have been characterized by x-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) procedure. Wear behaviors under normal loads of 5N, 10N and 15N have been investigated by a pin on a disc device at temperatures of 30 °C, 100 °C and 200 °C. The results revealed that microwave-treated coatings are highly recommended to protect the sliding surface, such as a high-speed spindle, under different environmental conditions.

Keywords: HVOF; Wear; WC-10Co-4Cr; Microwave Treated.

1. Introduction

In many applications, for example, automotive, aerospace, power plants and various industrial sectors, wear, corrosion, and thermal stability are anticipated phenomena. Therefore, in such applications, improved wear and dynamic resistance are crucial. These can be improved by hard thermal spray coatings in an effective and reasonable manner. These coatings may be formulated in a defensive atmosphere or in the air, preserving fair deposition efficiency at moderately low costs [1]. Thermal spray technique has been used for a long time to produce wear-resistant materials on the surface [2-3]. Accordingly, several studies have shown that, the wear phenomena is influenced by various possessions such as geometry, normal load, relative surface motion, rubbing surface texture, sliding speed, device rigidity, material type, lubrication and vibration [4-5].

Consequently, several research issues relating to friction and wear by sliding fields were created to address Wear Mechanism [6]. In many applications steel alloy AISI 4140 is commonly used as a result of high mechanical strength at high temperatures [7-9]. Carbide-based coatings are most suitable for wear applications. The HVOF technique is most preferable for carbide coatings, since it exhibits low temperature flame with high velocity compared to other thermal spray processes. Therefore, WC decarburization is significantly reduced during spraying [10-11]. WC-10Co-4Cr coating composition is widely used composite coatings for sliding and abrasive wear and slurry erosion because of higher hardness and fracture toughness [12-14]. Furnace heating is most often and conventional post treatment technique used to for thermal spray coatings to homogenies and strength the coating structure [15]. Microwave heating is the modern post treatment technique reported as cost effective solution for enhancing the thermal spray coatings [16-18]. The researcher reported that, Microwave fused Tribaloy-T400 and Cr3C2 reinforced Tribaloy-T400 composite coatings exhibited better mechanical and wear properties than as-sprayed coatings [19]. Hence, investigation on the effect of microwave fusing on carbide coatings is of high interest. In the present study, WC-12Co-4Cr is coated using HVOF technique over AISI4140 steel alloy. The as-sprayed coating is post treated using a domestic microwave oven. The sliding wear behavior of both as-sprayed and microwave fused WC-12Co-4Cr coatings are investigated at room temperature, 100 °C and 200 °C. The phase, microstructure analysis and wear mechanism is examined using XRD, SEM and EDS techniques.
2. Experimentation

2.1 Materials and development of coating

In the present work, AISI 4140 low alloy steel was used as a substrate. The procured substrate was in the form of a rolled plate and plate was sectioned for the dimension of 75 mm x 75 mm x 25 mm in size. The base metal was blown at a pressure of 0.5 MPa with 16 # grit before spraying to achieve surface roughness, $R_a$ 8–10μm for stronger bonding strength between the surface of the substrate as well as the coating. The WC-10Co-4Cr coating powder of 0 to 50 μm was deposited over the substrate by HVOF method and the parameters are shown in table 1. The composite feedstock powder was developed through agglomeration and sintering and had spherical grains.

| Powder      | WC-10Co-4Cr |
|-------------|-------------|
| Hydrogen (lpm) | 600         |
| Oxygen (lpm)   | 300         |
| Air (lpm)      | 200         |
| Nitrogen (lpm) | Carrier gas 40 |
| Distance (mm)  | 300         |
| Traverse velocity (m/min) | 80         |
| Angle between gun to job | 90º        |
| Coating thickness (μm) | 200        |

2.2 Microwave energy post treatment

Use of Microwave energy for post-treatment is designated as microwave fusing in the present investigation. Microwave fusing focused on the development of homogenized surface coating characteristics for a various application. As-coated WC-10Co-4Cr samples were cut into 10mm×10mm×5 mm form for the domestic microwave fuse. Figure 1 represents the as-sprayed coated samples were properly positioned on the refractory brick. Graphite sheet (extractor) of 1 mm thick with 99% purity was placed above the coated sample to produce carbon.

Silicon carbide used as a susceptor and placed above the graphite sheet and heats the coated sample through the absorption of microwaves. As soon as the setup is ready, the power 900W and frequency of 2.45 GHz has been set to start the fusion of as sprayed coating about 10 min. The fused coated samples were slowly cooled under atmospheric conditions. Scanning electron microscope (SEM) and
x-ray diffractometer (XRD) was used to observe the morphology and phase analysis for both as-coated and fused coatings.

2.3 Wear studies
Sliding wear test was carried out using pin on disc tribometer (TR-20LE-PHM 400-Ducom) at different temperatures under dry conditions as per ASTM G99-05. The test temperatures are RT, 200°C and 400°C. Wear test was conducted with normal loads of 5N, 10N and 15N. A computerized interpretation system is utilized for continuous record of both height loss and frictional force. Wear rate is expressed in mm$^3$/m by converting the height loss into volume loss using the pin cross section area. Alumina disc is used as the counter body. Wear mechanism was observed by witnessing the worn surfaces and wear debris through SEM. The elemental composition of wear debris is determined using EDS (JSM 6380LA, JEOL, JAPAN). Dry sliding wear study parameters as shown in Table 2.

| Wear test method | weight loss method |
|------------------|--------------------|
| Speed of disc    | 420 rpm            |
| Normal load applied in steps | 5N, 10N, 15N |
| Sliding temperature | Room temp, 100 c, 200 c |
| Duration considered | 6 min             |
| Sliding distance | 700 m              |
| Track diameter   | 90 mm              |

3. Results and Discussions

3.1 Microstructural Characterization
Figure 2 (a) and (b) illustrate the microstructure of as sprayed and microwave fused coatings respectively. The as sprayed deposition reveals a usually heterogeneous microstructure with several micro pores, microcracks and unmelted/partial melted particles as shown in the figure 2(a).

Compared to the as sprayed coated samples, the microwave fused coating showed reduced pores and dense microstructures (Figure. 2b). A progressive effect on the characteristics of the HVOF coating was noticed via the microwave fusing. The Unmelted and partially melted particles leads to melting and flowed due to constant microwave exposure, likely filling up the pores. As a result of fusing a relative compact, uniform microstructure is observed in the post processed samples. The cross-sectioned morphology as-sprayed and microwave fused WC-10Co-4Cr coating is shown in Figure 3 (a) and (b) respectively. The porosity and surface roughness of the as-sprayed coating was 1.2 ± 0.20% and 6.52 μm respectively.
Throughout the sprayed coating, the microwave reels the unmelted and partially melted particles for a period of 10 min. Microwave fusing removes the micro cracks, pores and voids which are present in the as-sprayed coating. Fusing leads to the growth of diffusion layer at the interface of the substrate-coating which is observed Figure 3(b). Metallurgical bonding has been formed between the coating and the substrate, thereby improving the adhesion to the substrate. Microwave fused coating shows the porosity of 0.70 ± 0.3 and surface roughness Ra 4.21 μm. The rapid cooling processes of the microwave resulted in finer coating structure than those of conventional post-heat processes [20].

3.2 XRD analysis

Figure 4(a) and (b) represents the XRD patterns of as-sprayed and fused WC-10Co-4Cr coating on AISI 4140 steel alloy. In coated samples, the major presence of the WC phase was detected [21]. The various phases such as W₂C, WO₃ and Co₃W₉C₄ corresponds to minor peaks. Occurrence of WC oxidation and decomposition during inflight time coating process leads to above mentioned phases. The chemical reaction described below is more likely to occur when the WC to W₂C oxidants relative to other potential reactions [22]. A cobalt and chromium binding phase of the amorphous is attributed to the curve between 20 ° and 50 ° angles in 2θ (Figure 4.a). The amorphous phase of this coating is mostly found due to its rapid cooling effect [23]. In microwave fused coatings, no significant change in constituents is observed in as that of the as-sprayed coatings. The XRD pattern of fused coating indicate that effect of oxidation and decarburization are negligible. While tungsten is oxidized into metallic oxide during microwave fusing and also carbon entry occurs from graphite seperator [24].
3.3 Microhardness studies

The microhardness test was carried out across the thickness of both as sprayed and microwave fused coatings. The microhardness report for the different loads of both coatings is shown in the figure 5. For 10N load, the microhardness of both as sprayed and fused coatings were 645 ± 20 HV1 and 738.7 ± 15 HV1 respectively. Similarly, for the load of 20N, 621.3 ± 15 HV1 and 715.0 ± 15 HV1 were detected for both as sprayed and fused coatings respectively. The bare metal microhardness test was also performed and 199 ± 15 HV1 and 194.3 ± 10 HV1 values were found for both 10N and 20N loads respectively. For both the loads the microwave fused coating exhibited better micro hardness than the as-sprayed coating. Effective metallurgical bonding and uniform homogenized coating structure are the potential descriptions for an improvement in microhardness of the fused coating.

![Figure 5. Microhardness of coatings with substrate for different loads](image)

3.4 Dry sliding wear behavior

Figure. 6(a, b and c) demonstrates the friction coefficients of AISI 4140 steel, WC-10Co-4Cr coating and Fused coating at RT, 100 and 200 °C with 5N, 10N and 15N normal loads respectively. Tribological properties of as-sprayed and fused coatings are compared. Wear rate was determined considering the weight loss for all the loads and wear is represented in mm3/m.

![Figure 6a. Wear rate of room temperature for various loads](image)

![Figure 6b. Wear rate of 100 °C for various loads](image)
Figure 6. Wear rate of 200 °C for various loads

From the figure 7 indicates that, fused coatings shows better wear resistance comparatively in all the test temperatures and loads. Fused coating shows the highest wear resistance at RT condition. Also the wear graph indicates that significant wear rate change is not observed with respect to load. Similar observation have been made in all the test temperature. The flow of metallic binder during fusing resulted in strengthening the coating structure by adhering the carbide particles [25].

This was due to the high stiffness caused by the metallurgical bonding during the microwave fusing through diffusion of elements from the substrate to the coating. However, carbides like WC, W2C and Cr2C give high temperature strength and prevent more material loss during sliding [26].

Substrate, as coated and microwave fused wear rate values are listed in Table 3.

Table 3. Wear rate values for normal load and temperature

| Samples   | Room temperature | 100 °C | 200 °C |
|-----------|------------------|--------|--------|
|           | 5 N | 10 N | 15 N | 5 N | 10 N | 15 N | 5 N | 10 N | 15 N |
| Substrate | 3.51* 10⁻⁶ 3.50* 10⁻⁶ 3.53* 10⁻⁶ | 6.32* 10⁻⁶ 6.31* 10⁻⁶ 6.30* 10⁻⁶ | 9.81* 10⁻⁶ 9.82* 10⁻⁶ 9.83* 10⁻⁶ |
| As coated  | 1.20* 10⁻⁶ 1.22* 10⁻⁶ 1.24* 10⁻⁶ | 2.79* 10⁻⁶ 2.80* 10⁻⁶ 2.83* 10⁻⁶ | 5.60* 10⁻⁶ 5.61* 10⁻⁶ 5.63* 10⁻⁶ |
| Microwave fused | 7.017* 10⁻⁶ 7.015* 10⁻⁶ 7.020* 10⁻⁶ | 1.80* 10⁻⁶ 1.82* 10⁻⁶ 1.83* 10⁻⁶ | 4.89* 10⁻⁶ 4.31* 10⁻⁶ 4.33* 10⁻⁶ |

Figure 7a and 7b represents the SEM images of the worn surface of as-sprayed and fused WC-10Co-4Cr coatings under 20 N normal load at 200 °C temperature respectively. It is observed from the worn surface that the coatings are characterized by groove, delamination and flaking pit for both as sprayed and fused condition. Whereas the fused coating shows the smoother wear surface as compared to as-sprayed coating. Micro cracks are observed for both worn surfaces, as a result of fracture of metal oxide formed due to oxidation of coating elements during high temperature wear exposure. Flaking pits are more frequently observed in as-sprayed worn surface which leads to severe material loss. Fused coating shows the smoother worn surface and experiencing the minimal delamination and micro crack areas. The microwave fusing of the coating leads to better adherence between the coating splats, this prevents the coating from flaking and delamination [27]. Also, the dispersion of carbon form the graphite separator enhances the wear property of the fused coating.
4. Conclusions

1. WC-10Co-4Cr feedstock was successfully coated over AISI4140 low steel alloy using HVOF spray technique with a particle size of 0 to 50 μm and an average coating thickness of 250 μm.

2. The micro hardness for 10N was 645 ± 20 HV1 and 738.7 ± 15 HV1 for both as sprayed and microwave fused coatings. Furthermore, both as sprayed and fused coatings were observed for loads of 20N, 621.3 ± 15 HV1 and 715.0 ± 15 HV1 respectively.

3. In comparison, the microwave-treated coating showed a lower rate of wear than the substrate and spray coatings for specific temperature-related to applied loads.

4. Microwave fusing resulted in the development of metallurgical bonding between coating-substrate interfaces and fusing leads to better cohesion between the splats.

5. The dispersion of carbon to the coating from the graphite separator sheet during the fusing process will be beneficial for wear resistance.

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