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Abrasive wear behavior of detonation sprayed WC–12Co coatings: Influence of decarburization and abrasive characteristics

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ABSTRACT

The major objective of the present work is to evaluate the influence of decarburization of the WC–12Co coatings and also the abrasive characteristics on its abrasive wear behavior using a planned set of dry sand rubber wheel abrasion tests. Towards this purpose, detonation sprayed coatings have been deposited at three levels of oxygen to fuel ratios so as to obtain WC–12Co coatings with decarburization lying in the wide range of 4.4–45%. Additionally, to study the interrelationship between the abrasive characteristics and decarburization on abrasive wear, the abrasive wear tests have been conducted on WC–12Co coatings using three abrasives, i.e. SiO_2, Al_2O_3 and SiC. The results indicate that WC–12Co coatings with the decarburization levels of 4.4 and 34% results in similar abrasion rates irrespective of the type of abrasive used. However, WC–12Co coatings with a decarburization of 45% exhibited high abrasion rate and the observed increase in wear rate was also associated with a change in abrasion mechanism from one dominated by WC cuboid pullout to that of inter-splat cracking induced delamination. The wear induced subsurface damage has also been investigated.

1. Introduction

In order to assess the performance for various engineering applications, the abrasive wear behavior of thermal sprayed WC–Co coatings has been widely investigated [1–12]. It has been consistently observed that the abrasion resistance of thermal sprayed WC–Co coatings is always inferior to that of liquid phase sintered bulk WC–Co of identical composition [8]. Such difference in performance arises primarily because of the extensive decarburization experienced by the powder particles during the spray process, prior to their incorporation in the coatings in the form of splats [1,6]. The decarburization reduces the volume fraction of WC in the coatings (as compared to that in the powder), allows the formation of undesirable phases like W_2C, W and also causes the dissolution of C and W in the Co binder phase, thereby making it hard and brittle [6,9]. In addition, the inter-splat boundaries, characteristic of thermal spray coatings, have also been identified as mechanically weaker regions in the coatings [6,8].

The extent of decarburization experienced by the powder particle during the spray process depends on the thermal spray technique employed as well as the characteristics of the WC–Co powder feedstock. For example, it has been observed that the WC–Co powder experiences substantial decarburization, when air plasma technique has been used [4,13]. In contrast, in cases where WC–Co is deposited using HVOF or detonation spray coating (DSC) process, the extent of decarburization is substantially lower [6,14–17]. Similarly, the use of nanostructured WC–Co powders, instead of conventional WC–Co powder as feedstock, also causes an enhanced decarburization [6,7].

Though it is accepted that the extent of decarburization of the WC–Co powder particles, constituting the coating, should influence its abrasion behavior, the trend is not very clear. For example, Schwetzke and Kreye [9] obtained thermal sprayed coatings using WC–17Co feedstock but by employing a variety of coating techniques. These authors observed that the abrasive wear rate of WC–17Co coatings was hardly affected by decarburization as long as the carbon loss was lower than 60%. Chen and Hutchings [1] compared the rubber wheel abrasion resistance of air plasma sprayed (APS) and vacuum plasma sprayed (VPS) WC–17Co coatings and noted VPS WC–17Co coatings to be superior in performance. Such difference in wear behavior was rationalized on the basis that while decarburization was negligible in the case of VPS coatings, the reverse was true in the case of APS coatings wherein W_2C and W phases were present with a concomitant decrease in the volume fraction of WC.

Stewart et al. [6] carried out abrasive wear studies on conventional and nanostructured WC–Co HVOF coatings and observed that nanostructured WC–Co coating had a poorer abrasion resistance compared to conventional WC–Co coatings mainly due to

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the fact that decarburization resulting in Co binder with poor ductility was much more extensive in the nanostructured WC–Co coatings. A similar result has also been obtained by Guilemany et al. [7] and they also noticed an enhanced decarburization in the nanostructured HVOF WC–Co coatings as compared to conventional HVOF WC–Co coatings. However, these authors obtained the same abrasion rate with nanostructured and conventional WC–Co coatings in line with the observations of Schwetzke and Kreye [9]. The carbide size in the coatings also influences the extent of decarburization and in turn, abrasive wear. Usmani et al. [2] evaluated the abrasion resistance of WC–17Co HVOF coatings with the average carbide sizes of 1.2, 3.8 and 7.9 μm and observed that coatings with finer carbides displayed higher degree of decomposition of WC to W_2C phase and hence, lower abrasion resistance.

The abrasion rate of the thermal sprayed coatings is also a strong function of the nature of abrasives used. It is generally accepted that as the hardness of the abrasive increases, so does the abrasion of the coating. However, as pointed out Bozzi and Biasoli de Mello [5], the nature of abrasion mechanism in WC–Co coatings changes from micropolishing to microploughing and cutting and finally to interlamellar brittle fracture as the abrasives used are SiO_2, Al_2O_3 and SiC, respectively.

On the basis of the above survey the following conclusions can be drawn:

(a) There is no general agreement as far as the influence of the extent of decarburization of the WC–Co coatings on its abrasion resistance is concerned, with some investigators reporting no effect while others have noticed a substantial deterioration of abrasion resistance with decarburization. One of the reasons for such an ambiguous result could be that earlier investigators have achieved different levels of decarburization by either changing the coating technique itself or by powder feedstock and in both cases, additional (uncontrolled) process/feedstock variables have been inadvertently brought in. Therefore, it should be ideal if the levels of decarburization of the WC–Co coatings can be varied using the same powder feedstock and same coating technique. In this regard, the detonation sprayed coating (DSC) process provides a distinct advantage, since by changing the oxygen to fuel ratio during the coating process, the extent of decarburization of the coatings can be varied for the same powder feedstock.
(b) Earlier investigators have achieved decarburization levels, as measured using the combustion method in the range of 24–70%, but not lower. The DSC process is capable of producing WC–Co coatings with decarburization levels as low as 5% and thus should help in improving our understanding regarding the abrasive wear mechanisms of WC–Co coatings at low decarburization levels.
(c) Earlier studies indicate that the abrasive wear mechanisms depend on the type of abrasives. However, it is not clear as to how the extent of decarburization influences the abrasion mechanism of WC–Co coatings, when tested with different type of abrasives.

With a view to provide answers to the three questions/points raised above, three levels of decarburization have been obtained in the WC–12Co coatings after deposition using the same coating technique (detonation spray) and the same powder feedstock. These coatings have been subjected to abrasive wear using three abrasives (i.e. SiO_2, Al_2O_3 and SiC) and the results from such a study are presented in this paper.

2. Experimental details

2.1. Materials and coatings

WC–Co powder (Sulzer Metco, USA) having the size range 10–41 μm and an average size of 27 μm was used as the powder feedstock. Using this powder having 12 wt.% Co (WC–12Co) coatings were deposited at three levels of oxygen to fuel ratio (referred to as OF ratio) on a mild steel substrate using the detonation spray process, as described in detail elsewhere [18]. The coatings were built up to a thickness of 350 μm (±20 μm) at each OF ratio. In addition, WC–Co bulk cermet samples (Sandvik Asia, Pune) and uncoated mild steel were also subjected to abrasion tests to provide comparative data. All through this paper, the WC–Co detonation sprayed coatings obtained at OF ratios of 1.16, 1.50 and 2.0 will be referred to as OF-1.16, OF-1.50 and OF-2.0 coatings while the bulk WC–Co material will be referred to as bulk WC–12Co.

2.2. Dry sand rubber wheel abrasion test

To evaluate the abrasion resistance of detonation sprayed WC–12Co coatings, a dry rubber wheel abrasion test rig was used and the tests were carried out as per ASTM G65 [19]. The specimens were ultrasonically cleaned in acetone and weighed before and after each test. The tests were done at normal load of 5 kg. The weight loss experienced by the specimens was measured after every 200 revolutions of the rubber wheel and the cumulative weight loss per revolution was computed. This parameter reached a constant value after the first 200 revolutions and this constant value converted to volumetric rate using the density value of the test material measured using the pycnometric technique is defined as the steady state abrasion rate (henceforth referred to as abrasion rate). Tests were carried out on three samples at each condition and an average of these three values has been reported. In addition, to benchmark the abrasion data of WC–12Co coatings, baseline experiments were carried out under identical abrasion conditions using uncoated mild steel samples and also WC–12Co bulk cermet samples.

In the dry sand rubber wheel abrasion test, the nature of the abrasive used is an important variable especially since it is expected that both the abrasive characteristics and extent of decarburization of the WC–12Co coatings will strongly influence the abrasion resistance. Therefore, three abrasive particles namely SiO_2, Al_2O_3 and SiC having varying hardness values were used. The properties of the abrasive used are provided in Section 3.

2.3. Coating characterization

The morphology of the abrasives used in the abrasion test, the microstructure of the WC–Co coatings including WC cuboid size, the morphological features of the abraded surface and also the extent of subsurface damage beneath the abraded surfaces of the coatings were assessed using the Scanning Electron Microscope (SEM) [Model:S-4300SE/N, Hitachi, Japan]. The phases present in the coatings and their proportions were obtained using X-ray diffraction (Model ADX D8, Bruckers, Germany) and also by SEM analysis in conjunction with Electron Back Scattering Diffraction (EBSD) as described in detailed elsewhere [16]. Carbon content and hence the extent of decarburization of the WC–Co coatings obtained at different OF ratios as well as feedstock, were determined by the combustion method (LECO Carbon-Sulfur analyzer, USA, Model-CS-444).

During abrasion testing of the WC–Co coatings, the abrasives indent the coating surface and the indentation direction is perpendicular to the coating surface. Thus, it is important that the evaluation of the hardness of the coatings is carried out on the