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Microstructural response of various chromium carbide based coatings to erosion and nano impact testing

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ABSTRACT

In this study, we demonstrate the microstructure dependency of erosion behaviour of laser clad, detonation sprayed and atmospheric plasma sprayed chromium carbide based coatings. The final chromium carbide content in all the coatings was a strong function of rapid solidification rate associated with the processes. In the laser clad coating majority of the chromium carbides re-solidified while in the thermally sprayed coatings chromium carbide re-solidification was hindered to a large extent. Hence, the final chromium carbide content in the thermally sprayed coating decreased with increased extent of particle melting during spraying. Decarburisation and oxidation during thermal spraying lead to the formation of chromium carbides with lower carbon content and chromium oxide(s). Laser clad and detonation sprayed coatings, with higher chromium carbide content, showed lower erosion rates and exhibited fewer brittle erosion events. Embrittlement due to excessive dissolution of chromium carbides into the matrix and poor splat bonding were found to be the reasons for higher erosion rate of the plasma sprayed coating. Scanning electron microscopy and quantification of single erodent impact events clearly established ductile material removal in the laser clad and detonation sprayed coating and brittle material removal in the plasma sprayed coating as the dominant mechanism(s). A good agreement was found between solid particle erosion testing and nano impact testing results.

1. Introduction

Degradation of components by solid particle erosion during service is a common phenomenon in various industrial processes. Since erosion is a surface degradation process, protective coatings are often employed to increase their useful service period. Chromium carbide-NiCr based coatings are one of the most widely applied coatings for erosion wear resistance applications [1]. These coatings can be deposited by a variety of thermal spraying techniques as well as by laser cladding [2–13]. The common screening test for ranking erosion rates of these coatings is erosion testing by solid particle impingement [5–8]. Solid particle erosion in these coatings is found to be strongly dependent on the microstructure and splat bonding [6–8]. Different coating methods generate considerably varying coating microstructures [2–13]. Therefore, it is expected that their erosion behaviours would also be different. Although erosion rate determination of chromium carbide-NiCr coatings through mass loss measurements is routinely performed, studies focusing on understanding the underlying mechanism(s) of material removal during erosion have been very limited. Such studies have been reported only on coatings generated by high velocity oxy fuel spraying process [6,7] and sintered composites [14,15]. This manuscript attempts to highlight the microstructure dependency of erosion behaviour of coatings deposited by laser cladding, detonation spraying and plasma spraying. Literature has shown the effectiveness of careful examination of surface topography after single erodent impacts in providing useful insight into the erosion behaviour. The different single erodent impact features observed under a scanning electron microscope have been characteristically termed [16–19]. However, the past studies did not include quantification of such features and their effective linkage with the bulk erosion data and this constitutes a major novelty of the present study.

In the recent past, there has been increasing interest in exploring mechanical properties of thin films using instrumented indentation systems under dynamic loading conditions [20–22]. Such studies have also been extended to understand the behaviour of thicker coatings at the microscopic level. One such study [23] reported good correlation

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between erosion performance and nano impact testing of a coating produced by electron beam physical vapour deposition process. The authors attributed the correlation to the dynamic character of nano impact testing, which was responsible for producing deformation with a similar contact footprint to that produced in erosion tests. Another study [24] has focussed on understanding the microstructure dependent inelastic behaviour of NiAl coatings generated by different thermal spray processes. Nevertheless, materials characterization using instrumented indentation techniques based on dynamic loading are still evolving. Given that the hardness obtained by quasi-static indentation loading is a very poor indicator of erosion performance [25,26], an effort to relate solid particle erosion testing results to nano impact testing outcome using an instrumented indentation system has also been made in this study. Particular emphasis has also been placed on examining the microstructure dependency of erosion and nano impact behaviour and determining possible correlation between the two testing methods.

2. Experimental

2.1. Coating deposition

Agglomerated and sintered chromium carbide-NiCrMoNb powder (Cr-31Ni-4.5Mo-1.75Nb-7C mass%) from H.C. Stark ltd. was used as feedstock. The average size of the powder was 21 μm as measured by the particle size analyser. Steel with 0.27% carbon was used as substrate. The microstructure and phase constitution of the powder and details about laser cladding process parameter optimization and overlapping have been discussed in detail in our earlier work [13]. Thermal spraying was carried out on grit blasted substrates using detonation spraying and plasma spraying processes. The configuration of the detonation spraying and plasma spraying systems have been described elsewhere [27,28]. The process parameters used for deposition of the three coatings are summarised in Table 1.

2.2. Microstructural characterisation and hardness measurement

The surface of the coatings was ground and subsequently metallographically polished before secondary electron (SE) imaging, back scattered electron (BSE) imaging and energy dispersive spectroscopy (EDS) (in a Neon 40 Zeiss field emission gun (FEG) scanning electron microscope (SEM)) and diamond pyramid hardness (DPH) testing using a microhardness tester (VMHT, Walter Uhl). The hardness values reported in this study are average of at least 10 indentations using 100 g load. Phase constitution of the starting powder and the coatings was determined by X-ray diffraction (in a Bruker D-8 Advance diffractometer). The degree of crystallinity of the coatings was ascertained from the XRD patterns after performing peaks splitting in order to separate the crystalline peaks and broad amorphous halo in the 2θ range of 42–45°. The estimation was carried out by the standard procedure of dividing the area of crystalline peaks by total area (crystalline and amorphous) under the XRD profile within the 2θ range mentioned above. Phase quantification in the BSE images were carried out using an image analysis software (Olympus analySIS FIVE). The image analysis software converted the BSE image into a false colour image helping the human eye distinguish subtle variations by expanding the range of visible hues. This method facilitated a reasonably reliable quantification of the phases. The values reported are average of analysis carried out on minimum of 10 BSE images recorded at a suitable magnification. For cross-sectional examination, the coatings were cut in transverse and the sectioned surface was mounted in bakelite and metallographically polished.

2.3. Erosion testing

Erosion testing was carried out using an air jet type solid particle erosion rig as per the procedure described in ASTM G76-83 [29]. Silica particles with average size of ≈ 200 μm were used as erodent material at a flux rate of 2 g/min. SE image along with its granulometric curve of the silica particles used in this study is shown in Fig. 1. The tests were performed at 90° impact angle with an average erodent particle velocity of 82 m/s. The method of measuring the velocity has been described elsewhere [30]. Compressed air was used to accelerate the silica erodent particles through a nozzle of 100 mm length and 4 mm diameter. The distance between the nozzle and the sample surface (stand-off distance) was maintained at 10 mm. Normal impact angle was chosen so that a fair comparison with nano impact testing, also carried out at 90° impact angle could be carried out. The mass loss was measured by weighing the sample at regular intervals and a steady state erosion rate was achieved for all the coatings. Before measuring the weight loss, eroded surface was thoroughly cleaned using compressed air followed by ultrasonic cleaning in alcohol for about five minutes. This procedure effectively removed the wear debris without inducing any new damage to the surface. The steady state erosion rate values reported are average of three tests. Further, to understand the microstructural response of the coatings to solid particle erosion, the test was carried out for very short durations (2 s) to produce several single erodent impacts for examination.

2.4. Nano impact testing

Nano impact testing was carried out using an instrumented indentation system (Nano-Test Vantage System, Micro Materials). The instrument is a pendulum-based depth sensing system capable of impacting precisely at the same location repeatedly at regular intervals. Details about the configuration of the system are available in the cited references [20–22]. A cube-corner diamond indenter test probe was accelerated from a distance of 15 μm from the surface to produce each impact at an applied load of 400 mN. 30 repeat tests were performed at different locations on each sample and average of the depth value and SE images of the representative indentations are reported in the present study.

3. Results and discussion

3.1. Microstructure

The microstructures of the coatings' polished surfaces and cross sections are shown in Fig. 2. BSE image of the laser clad coating shows well-defined contrast between the darker chromium carbide and the

Table 1
Important process parameters used for generating laser clad, detonation sprayed and plasma sprayed coatings.

Laser cladding		Detonation spraying		Plasma spraying	
Laser power (W)	1600	Frequency (shots/s)	3	Plasma Power (kW)	37
Laser beam spot size (mm)	3	Oxygen flow rate (l h^{-1})	2960	Primary gas (Ar) flow rate @5.5 bar (NLPM)	45
Carrier gas (Ar) flow rate @4 bar (l min^{-1})	5	Acetylene flow rate,(l h^{-1})	2240	Secondary gas (H_2) flow rate @3.5 bar (NLPM)	5
		Powder carrier (N_2) flow rate (l h^{-1})	960		
Scanning speed (mm/s)	8	Spray distance (mm)	165	Spray distance (mm)	110
Powder feed rate (g/min)	14	Powder feed rate (g/min)	10	Powder feed rate (g/min)	35