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Friction and wear properties of WC-Co and Mo-Mo_2C based functionally graded materials

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Abstract

Wear resistant coatings based on functionally graded materials (FGMs) applied on industrial machinery components can reduce weight, increase adhesion strength, decrease internal stresses and improve the resistance against propagation of surface defects. Macroscale FGMs offer a new method of surface engineering to produce tailored tribological properties. In order to fully exploit the FGM concepts, an efficient fabrication with advanced process control assuring the stability of the resulting properties is desirable. The fundamental understanding of wear damage modes of each layer, as well as the development of predictive models for through-thickness behavior can increase the industrial applicability of graded coatings.

In the present study, two industrially relevant FGM coatings were investigated: high-velocity-oxygen-fuel (HVOF) deposited WC-Co/stainless steel and plasma sprayed Mo-Mo_2C/stainless steel FGMs. For both deposition processes, high degree of automation was achieved and linearly graded coatings were successfully prepared. Sliding friction and abrasive wear responses were evaluated through thickness and damage mechanisms controlling the coefficient of friction and wear rates were described. A correlation between composition, microstructure characteristics and damage modes was established. The enhancement of Mo-Mo_2C coating properties through FGM approach with stainless steel was reported.

Keywords: Wear; Fgms; Thermal spraying; Carbides

1. Introduction

There is a constant demand in engineering industry to improve operating performance of machinery, while maintaining or reducing the manufacturing costs. In many types of industrial machinery, surface damage generated by sliding or abrasive contact limits the life of the component and therefore reduces durability and product reliability. This drives the development and implementation of intelligent surface coatings and films that enable to improve the performance of engineering components under contact loading, while retaining or reducing the material and manufacturing requirements for the base material. Protective coatings on components of industrial machinery are expected to meet stringent requirements for adhesion, surface impact tolerance and wear resistance.

Composite and cermet materials have been used for the number of years as a solution to a variety of engineering problems. When such a material is applied in the form of a protective coating, difficulties arise due to the mismatch in elastic modulii, thermal expansion coefficients and hardness between the surface layer and the base material. Such differences in materials properties lead to the generation of residual (process induced) or operation-related internal stresses and may cause coating to delaminate or form a crack network with the implications for the component performance. Temperature changes and high-energy impact loading appear to be especially critical. This may limit the application of certain hardfacing materials with otherwise excellent wear characteristics.

The FGM approach, when successfully applied, can enhance the materials performance, while maintaining or reducing fabrication costs. Several processing techniques have been explored for the fabrication of multilayered and functionally graded materials, e.g. powder metallurgy, adhesive bonding, in-situ synthesis, self-propagating high temperature synthesis, and thermal spraying [1–4].

Thermal spray processing represents industrially well-established method and offers versatility and flexibility essential for the FGMs design and process development. Hard cermet coatings produced by thermal spraying are

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used in industry to minimize friction, lower wear and reduce the tribological requirements for the base material of protected components. They have been successfully applied in many industrial sectors: aerospace, pulp and paper, marine, diesel engine, and oil industries. These coatings, usually deposited through high velocity oxy-fuel or plasma spray processes are based on cermet compositions such as WC-Co, Cr_3C_2-Mo, (W, Ti)-Ni, and Mo_2C-Mo and perform well in abrasive and sliding wear [5–10]. In recent years, there has been an increased need for design-based implementation of coatings, where the surface hardness, sliding friction and compatibility between mating surfaces play a key role in the system performance.

The goal of this study is to examine contact damage and wear behavior of selected carbide reinforced metallic composite and graded materials as function of their composition/depth. Specifically, Mo-Mo_2C/stainless steel (Mo-Mo_2C/SS) and WC-Co/SS FGMs have been produced and studied. The choice of the FGM components is based on their relevance to sliding wear applications in automotive and other important industries [8,9]. For example, Mo-based alloy coatings offer excellent scuff resistance in dry unlubricated sliding contact, however, they are prone to brittle breakout of the coating and spallation [10–12]. Preliminary studies showed that the soft ferrous materials, when used as a matrix, can reduce this limitation [13]. In the case of WC-Co/SS FGMs, weight reduction and adhesion improvement due to increased material compatibility is expected.

2. Experimental methods

2.1. Processing

Two FGM coatings were fabricated using the setup from Fig. 1: (i) HVOF deposited WC-Co/SS and (ii) plasma sprayed Mo-Mo_2C/SS. In the first case, commercial grade stainless steel powder (ANVAL 316, particle size −42/+18 μm) and a WC-Co composite powder (Diamalloy 2004, particle size −45/+5 μm) were used to prepare graded and composite coatings. These coatings were deposited on mild steel substrates with the HV 2000 HVOF system (Tafa-Praxair, 146 Pembroke Road, Concorde, New Hampshire). Spraying was carried out using propylene as the fuel gas and nitrogen as the powder carrier gas. The gun was kept at a fixed spray distance of 230 mm and traversed vertically at 6 mm/s during the coating process. The substrates were mounted on a carousel of 190 mm diameter, rotating at 400 rpm. The FGMs consisted of six uniform layers of approximately same thickness, graded in 20% composition steps. Prior to the deposition of FGMs, deposition rates of both single components were measured. Based on these measurements, powder feed-rates and the number of passes were adjusted appropriately to achieve the required phase content and the thickness of each layer. The FGM coating was graded from 100% stainless steel (near the substrate) to 100% WC-Co (on the surface). Table 1 lists the spraying parameters used for each step of the graded coating.

The Mo-Mo_2C/SS coatings were sprayed with stainless steel powder (ANVAL 316, particle size −42/+18 μm) and Mo-Mo_2C powder (OSRAM Sylvania SX 274, particle size −108/+48 μm). The coatings were prepared on mild steel substrates with a plasma gun F4-MB (Plasma Technik, Switzerland). The spray parameters are summarized in Table 2. Graded coatings were prepared in five 25 wt.% composition steps. Similarly as in the case of HVOF deposits, deposition rates were measured and feed rates and the number of passes were adjusted to achieve the desired linear grading profile.

2.2. Testing and characterization

Coating microstructures and properties were evaluated using SEM, optical microscopy and microhardness

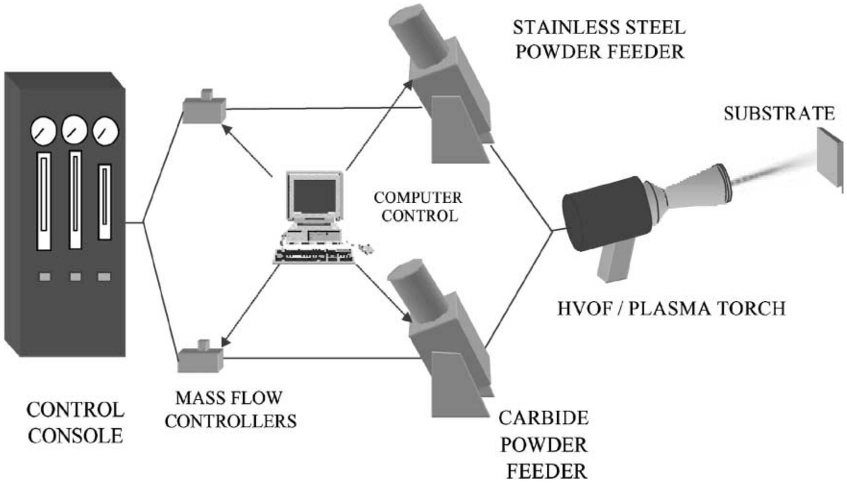

Fig. 1. Schematic of the FGM processing setup.

Table 1
Spray parameters used for HVOF processing of WC-Co/stainless steel coatings

Composition steel/WC-Co	Propylene flow (scfh/slm)	Oxygen flow (scfh/slm)	Feed rate (g/min) SS/WC-Co	Deposition rate (mm/pass)	Number of passes (for FGM)
100%/0%	1400/658	350/165	40/0	0.0127	14
80%/20%	1400/658	350/165	32/8	0.0111	16
60%/40%	1400/658	400/188	24/16	0.0096	18
40%/60%	1400/658	400/188	16/24	0.086	20
20%/80%	1485/698	450/212	8/32	0.0074	24
0%/100%	1485/698	450/212	0/40	0.0065	28

Table 2
Spraying parameters for Mo-Mo_2C composites and FGM

Parameter	Description/value
Gun	F4-MB
Gun Nozzle	8 mm
Gun Power	500 A
Gun Voltage	69 V
Primary (Ar) gas flow	40–48 slpm
Secondary (H_2) gas flow	10–8 slpm
Carrier (Ar) gas flow	2.5 slpm
Spraying distance	110 mm
Vertical traverse speed	30 mm/s
Spindle speed/diameter	160 rpm/∅ 140 mm
Total feed rate (Carbide + Stainless Steel)	16 g/min

measurements. For Mo-Mo_2C/SS coatings, energy dispersive X-ray microanalysis (EDX) and quantitative X-ray analysis were used for the composition measurements. For the composition evaluation of WC-Co/SS coatings, the image analysis of back-scattered electron microscopy images and EDX were employed. Indentation fracture toughness was measured on selected composite coatings according to [14].

Room temperature dry sliding friction/wear tests were carried out in air with silicon nitride balls at 50 N load on a Universal Micro-Tribometer tester (Center for Tribology, 625-A Clyde Ave., Mountain View, California). The eccentric position of stationary balls produced wear scar of 7 mm diameter, which for a rotational speed 27.4 rpm, and 120 min of testing resulted in 72 m of effective sliding distance at the velocity of 0.01 m/s. The profiles of wear scars were evaluated with an optical 3D scanning white light interferometer (Zygo Corporation, Laurel Brook Rd., Connecticut), which has the lateral resolution of 0.7 μm and the effective vertical resolution of 0.01 μm. Prior to wear testing, coatings surfaces were polished using the following procedure: (i) fine wet grinding on 45 μm diamond abrasive wheel; (ii) polishing by diamond suspension emulsions 9, 3, and 1 μm; (iii) ultrasonic cleaning in methanol for 15 s; (iv) drying at 100°C for 10 min. The final surface roughness of specimens was measured, and the R_a values were lower than 0.1 μm. Two-body abrasion tests were performed in the configuration depicted on Fig. 2. Three rectangular specimens (160 mm^2 each) were affixed to a holder, rotating at 40 rpm in same direction as the disc with grinding paper, and dividing the load evenly among all the specimens. The 180 grit SiC paper, rotating at 300 rpm, was changed every 30 s. The load was adjusted so that the average pressure on the surface of each specimen was 80 kPa. Weight measurements were taken five times in 1-min intervals. The samples were washed quickly in an ultrasonic bath to remove entrapped grit and dried for 5 min at 100°C before the weigh measurements.

Single point scratch tests have been used as a complimentary technique to the friction and abrasion wear tests. A specially designed scratch system was used. The device, described in detail in [15], permits computer controlled scratching at low loads using various indentation tools. In this case, a standard Vickers diamond tool with 136° apex angle was used. The wide range of loads chosen (15, 35, 65, and 125 g) enabled to reveal damage mechanisms on different levels of the coating microstructure. The scratch tests

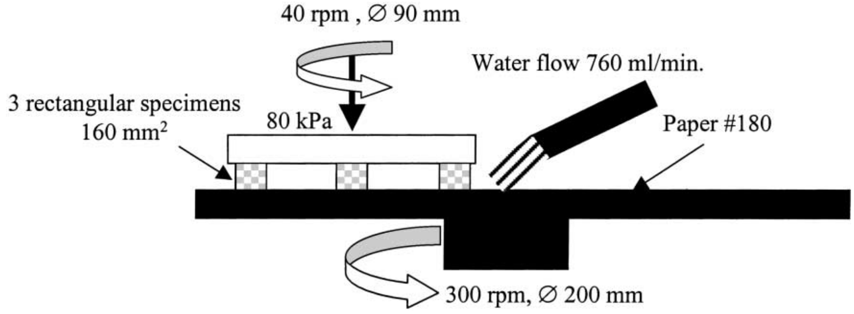

Fig. 2. Schematic of the wet two-body abrasion test.