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Sliding wear investigation of suspension sprayed WC–Co nanocomposite coatings

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ABSTRACT

Sliding wear evaluation of nanostructured coatings deposited by Suspension High Velocity Oxy-Fuel (S-HVOF) and conventional HVOF (Jet Kote (HVOF-JK) and JP5000 (HVOF-JP)) spraying were evaluated. S-HVOF coatings were nanostructured and deposited via an aqueous based suspension of the WC–Co powder, using modified HVOF (TopGun) spraying. Microstructural evaluations of these hardmetal coatings included X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) equipped with Energy Dispersive X-ray Spectroscopy (EDX). Sliding wear tests on coatings were conducted using a ball-on-flat test rig against steel, silicon nitride (Si_3N_4) ceramic and WC–6Co balls. Results indicated that nanosized particles inherited from the starting powder in S-HVOF spraying were retained in the resulting coatings. Significant changes in the chemical and phase composition were observed in the S-HVOF coatings. Despite decarburization, the hardness and sliding wear resistance of the S-HVOF coatings was comparable to the HVOF-JK and HVOF-JP coatings. The sliding wear performance was dependent on the ball-coating test couple. In general a higher ball wear rate was observed with lower coating wear rate. Comparison of the total (ball and coating) wear rate indicated that for steel and ceramic balls, HVOF-JP coatings performed the best followed by the S-HVOF and HVOF-JK coatings. For the WC–Co ball tests, average performance of S-HVOF was better than that of HVOF-JK and HVOF-JP coatings. Changes in sliding wear behavior were attributed to the support of metal matrix due to relatively higher tungsten content, and uniform distribution of nanoparticles in the S-HVOF coating microstructure. The presence of tribofilm was also observed for all test couples.

Introduction

Hardmetals, such as WC–Co, Cr_3C_2–NiCr, WC–$(W,Cr)_2$C–Ni, WC–NiCrBSi belong to one of the most important group of materials processed by thermal spray processes into coatings, which are predominantly applied for the protection against wear, such as abrasion, erosion and sliding [1–13]. Third generation high velocity oxy-fuel spraying (HVOF) is currently the industrial state-of-the-art process for the preparation of high quality hardmetal coatings. Tribomechanical properties such as hardness, wear resistance, and strength are influenced primarily by the size and distribution of WC grains, the porosity, the volume fraction and thermo-mechanical properties of the metal matrix, and post-treatments of the composite hardmetal coating [1–6,14–22]. Both room temperature and higher temperature investigations have been conducted [23–26]. These coatings are used in many industrial applications ranging from aerospace, transportation, off-shore and civil engineering to biomedical industries. During spraying of WC–Co powders, significant changes in the chemical and phase compositions can occur [8]. He and Schoenung [27] indicated the potential benefits of nanostructured WC–Co coatings over conventional WC–Co coatings. However in the past, coatings deposited from nanostructured powders often displayed a much less real gain in coating properties than expected, e.g. WC–Co coatings usually showed higher hardness but lower wear resistance than conventional coatings and thus a disappointing performance [28].

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The past two decades have seen extensive research in optimizing the feedstock powder characteristics, process parameters, and post-treatments of wear resistant hardmetal coatings [1–6,12,14–19]. Most research however has related to coatings sprayed from agglomerated and sintered powders, with the average particle size ranging from 10 µm to 50 µm and WC grain size ranging from 0.8 to 3.5 µm [1–6]. Optimization of these coatings has resulted in coating microstructures with negligible porosity, high fracture toughness and minimization of secondary carbide phases [1–6, 9–16].

Nanostructured feedstock powders cannot be directly fed into spray processes, e.g. the initial hardmetal constituents can firstly be agglomerated into spherical particles with µm-particle sizes for spraying. Many researchers have used conventional thermal spray systems to deposit coatings from nanostructured WC–Co feedstocks [14–15,29–31]. In these previous investigations, the problems associated with the injection of submicron particles have been addressed via agglomeration of nanoparticles to micron sized powder for thermal spraying [14–15,29–31]. For conventional spraying systems, the use of agglomerated nanosized particles for nanostructured thermal spray coatings can result in a predominantly bimodal coating structure where the coating architecture exhibits micrometer-sized zones with nanometer-sized structure [29].

Suspensions are an emerging type of feedstock for thermal spray processes, which allows the direct injection of very fine powders (from nm- up to several µm-sizes), thus avoiding the necessity of powder agglomeration [29,30,32]. Using suspensions, finely structured coatings can be produced, but their use is limited so far to oxide materials [33–35]. Mostly water [29,13,36–37] and alcohols e.g. isopropanol and ethanol [29,38], have been employed as transport media to inject fine nanosized and submicron-sized particles directly into the thermal spray process. Suspension sprayed coatings, because of the relatively smaller powder particle size, also result in lower as-sprayed surface roughness and additionally provide the ability to deposit thinner thermal spray coatings [33–34]. Apart from powder particle size, other differences also occur in terms of particle temperature and velocity e.g. between HVOF and APS systems adapted for suspension spraying.

Suspension spraying can result in either a truly nanocomposite coating, or a bimodal coating i.e. a lamellar coating with nanostructured zones [29]. The microstructure features of the suspension sprayed coatings are not only strongly depended to the suspensions characteristics (i.e. particle sizes, agglomeration degree of very fine nano-sized particles, stability, and viscosity) but also the spray processes and parameters. The bimodal coating in suspension spraying results from the thermal kinetics of nanosized particles which agglomerated during preparation in suspension. These agglomerates/aggregates cannot be completely de-agglomerated (up to nano-size as primary particle size) during spraying. When using "cold" spray parameters, these agglomerated nanoparticle zones may be observed in the coating microstructure. When spraying with “hot” parameters, these regions are less evident because the agglomerates are completely or mostly melted resulting in splats of several µm.

Even for oxides, there are only few studies on the dry sliding wear resistance of coatings sprayed from suspensions. Some results have been reported for Al_2O_3 and TiO_2 coatings against sintered alumina [39–40]. However, these coatings were produced from suspensions with low solids content, thus representing uneconomic conditions for coating deposition compared to conventional coatings.

In the case of conventional HVOF-sprayed hardmetal coatings all metal binder areas are nanostructured due to rapid solidification of powder particles, however their concentration can be increased by the use of suspensions of nanocomposite powders. In the literature, there is only one study by Oberste Berghaus et al. [32], dealing with the preparation of WC–12Co coatings by plasma spraying using suspensions. They have used a mixture of ethanol and ethylene glycol for suspension preparation and studied coating microstructure and phase composition in detail, but no experiments of wear properties were reported.

The dry sliding wear resistance of a new generation suspension thermal spray WC–Co coatings has not been reported in the published literature. Prior studies on the effect of grain size on the sliding wear resistance have shown wear rates which are very dependent on the tribological test conditions, e.g. it has generally been reported that the wear resistance of thermally sprayed WC–Co coatings increases with a decrease in the volume fraction of Co, and increases dramatically as the WC grain size is reduced [1–6]. Contrary to this, it has also been reported that the wear rate increases with the increasing carbide grain size, as the finer carbides in the wear debris relatively reduce the three-body abrasion wear process [2]. Similarly, the results are dependent on the counter-body (ball or pin) material, which makes the comparison of wear rates and failure mechanisms for different test couples difficult.

Previously, the authors reported investigations of another nanostructured WC–12Co coating deposited by S-HVOF spraying using suspension made from milled agglomerated and sintered conventional powder [41]. As it is advantageous to avoid milling operations, in this paper, a WC–12Co nanocomposite powder was employed. The current paper which aims to address some of these issues, has three specific objectives (i) investigate the sliding wear resistance of a nanocomposite WC–Co coating deposited by suspension thermal spraying, (ii) comparison of sliding wear performance of suspension sprayed coatings with first (Jet Kote) and third generation (JP5000) conventional HVOF coatings, and (iii) influence of counter-body as steel, ceramic and sintered carbide on the relative sliding wear performance under test conditions similar to ASTM G133-02. Tribo-mechanical investigations included Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), X-Ray Diffractometry (XRD), nanohardness and sliding wear evaluations.

Technological challenges – suspension spraying of WC–Co coatings

There are seven major technological challenges associated with the direct use of nanoparticles such as WC–Co in thermal spraying systems [29–30,32], which have so far limited the development of WC–Co nanocomposite coatings by spraying with suspensions for industrial applications. The first four can be overcome by the use suspension thermal spraying, whereas the remaining three require careful considerations of suspension composition [41].

i. Direct injection of nanoparticles in thermal spray process cannot be done using conventional conditions due to their lower mass relative to conventional powders.
ii. Even if the nanoparticles are injected, they can decompose quickly owing to the high thermal energy imparted as a result of their smaller size.
iii. The atmosphere of thermal spraying can lead to carbon loss in high temperature environments, which can increase due to the small grain size of WC compared to conventional feedstocks.
iv. There is generally an uneven distribution of nanocomposite particles in the spray stream. These challenges can however be somewhat addressed by employing a suspension feed system and carefully controlling the coating process parameters.
v. Suspension development and its feed-mechanism need to be optimized before improved coating quality can be achieved i.e. the high density of WC (15.7 g/cm^3) makes suspension development difficult in comparison to other carbides as it is almost three times the density of TiC (4.93 g/cm^3) and more than twice that of Cr_3C_2 (6.68 g/cm^3).