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Tribology of FeVCrC coatings deposited by HVOF and HVAF thermal spray processes

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ABSTRACT

This work studies FeVCrC-based coatings as potential alternatives to conventional Ni- and Co-based alloys for wear protection. Specifically, the microstructure and tribological properties of the coatings are characterized as a function of the particle size distribution of the feedstock powder, of the deposition technique – High Velocity Oxygen-Fuel (HVOF) or High Velocity Air-Fuel (HVAF) spraying – and of specific processing parameters.

HVOF-sprayed coatings obtained from fine feedstock powder exhibit numerous oxide inclusions, which provide high hardness (≈ 900 $HV_{0.3}$) but do not excessively impair fracture toughness, as determined through scratch testing techniques. HVAF-sprayed coatings obtained from the same feedstock powder contain much fewer oxide inclusions, and some of them possess simultaneously high hardness and high toughness. Defects (e.g. speckles) are instead formed in case unsuitable HVAF torch hardware is employed. A coarse feedstock powder always results in unmelted inclusions, which impair the cohesion of the coatings, particularly of the HVAF-sprayed ones.

Most coatings anyway exhibit very low sliding wear rates < 3 × 10^{-6} mm^3/(N m); abrasive grooving and surface fatigue-induced pitting are the main wear mechanisms. Oxide inclusions do not affect negatively the response of HVOF coatings, whereas too many unmolten particles increase pitting under severe test conditions. Rubber-wheel abrasion testing produces comparatively more severe grooving.

1. Introduction

Fe-based alloys have recently attracted considerable interest as materials for the production of wear-and corrosion-resistant coatings.

On the one hand, Fe as the main alloy constituent is a relatively inexpensive material, particularly when compared to elements such as Co [1], which is the basis of many hardfacing alloys currently on the market (Stellites, Tribaloys, etc.) [2,3]. The latter has also been regarded as a critical raw material at least since the 80's [4], the concern having grown in recent years [5–8] due to factors such as supply scarcity combined with strategic importance. Cobalt is indeed a key constituent not only of hardfacing materials, hardmetals, and heat-resistant alloys for aeronautical and energy production applications [2,3,9,10], but also of batteries and catalysts [6,8,9,11].

On the other hand, alloy constituents such as Ni and Co are toxic, allergenic elements, especially hazardous for human health when in inhalable powder form [12–14]. Handling of powdered feedstock materials therefore requires additional risk management procedures at the workplace; a second, subtler risk might be envisaged in case solid Ni- or Co-based materials (included coated mechanical parts) release fine wear debris during service.

Most of the research, as inferable from a representative sample of the recent literature [15–24], is concerned with Fe-Cr-C [17,23] or Fe-Cr-B(-C) [18–22,24] coating systems, either in (nano)crystalline [18,23], glassy [15,19,20], or composite (glass + nanocrystals) [24] form, processed by thermal spraying [17,19–21] or by cladding [16,22,23].

Cladded layers can be grown up to several millimeters in thickness, they are dense and metallurgically bonded to the substrate [3,10,25]; hence, they are well suited to the most severe wear and corrosion conditions. Depending on whether a hypo- or hyper-eutectic composition is employed, their relatively coarse microstructure comprises either

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primary α- and/or γ-Fe solid solution dendrites with interdendritic, eutectic hard phases (carbides and/or borides) [23,26–28], or primary carbides/borides in a eutectic matrix containing α- and/or γ-Fe phases [16,28,29]. In either case, literature sources show that the ductile metal phase tends to suffer grooving (through micro-cutting and/or micro-ploughing) by hard asperities and abrasive particles, or adhesive/delaminative wear by contact with counterbodies. Carbides and/or borides restrain the above phenomena, due to their hardness, but they are also prone to brittle fracture, leading to pull-outs [23,26,29–31]. Clearly, the extent of each process and the overall wear rate depend on the interplay between contact conditions and microstructural features such as the volume fraction, size, shape and distribution of each phase.

In comparison to cladded layers, thermally sprayed coatings possess a lamellar architecture, with finer intra-lamellar microstructure but weaker inter-lamellar cohesion. Their wear mechanisms are therefore substantially different: all pertinent studies highlight a mix of grooving and lamellar delamination under both abrasive and sliding wear conditions, though the extent of each clearly varies with the coating properties and the contact conditions [19–21,32,33]. Trying to improve their interlamellar cohesion is indeed a significant issue; some authors for instance reported on attempts to engineer the feedstock powder for this purpose [24].

Thermal spraying can however be applied to more complex geometries; it can deposit layers of a few hundreds of micrometers in thickness, better suited when dimensional tolerances must be respected; it causes no dilution of the coating material, and delivers less heat to the substrate, thus reducing the risk for distortions and thermal alterations [34]. Thermal spraying is therefore employed for such components as petrochemical valves, pistons, impellers, shafts and journal bearings, automatic machine parts, cylinders and rolls, etc. [35].

The present research is specifically concerned with thermal spray techniques, and its originality stems from the use of a novel Fe-V-Cr-C alloy system, which has recently become available as a feedstock powder. This paper follows a previous work on the deposition of Fe-V-Cr-C-type coatings by gas-fueled High-Velocity Oxygen Fuel (HVOF) spraying [36]. Their sliding wear rates of $\approx 2 \times 10^{-6}\ mm^3/(N\ m)$ were found to compare favorably with state-of-the-art, HVOF-sprayed Stellite-6 and NiCrBSi alloys. It was therefore concluded that Fe-V-Cr-C-based coatings are well suited for tribological applications (e.g. engine parts, hydraulic/pneumatic pistons, etc.), although they are unfit for corrosion protection. In spite of the dense, watertight coating microstructure, the alloy itself indeed has intrinsically poor corrosion resistance.

The topic is now deepened by focusing on the mechanical and tribological properties of Fe-V-Cr-C-type coatings as a function of (i) the tribological process (particle abrasion or sliding wear under different load and speed conditions), (ii) the particle size distribution of the feedstock powder, and (iii) the use of HVOF or HVAF (High-Velocity Air Fuel) spraying as deposition techniques. The latter is a novel process which, especially through its most recent advancements [37], is able to drag the powder particles to high speeds, simultaneously conferring them enough plasticity for proper deposition upon impact onto the substrate in the solid or semi-solid state. Apart from cost and productivity considerations, HVAF could therefore provide specific technical advantages over HVOF in terms of lower oxidation and higher cohesive strength of the resulting coatings.

2. Experimental

2.1. Coating manufacturing

A feedstock powder with nominal chemical composition 17% V, 12% Cr, 4% C, 1.5%W, 1% Mo, 0.5% Mn, 1% Si, balance Fe (values in weight %), hereafter referred to as a FeVCrC alloy, was commercially procured from H.C. Starck GmbH (Laufenburg, Germany) in two distinct nominal particle size distributions: −53 + 20 μm (commercially designated as Amperit 381.088) and −25 + 5 μm (Amperit 381.071).

Both particle size distributions were thermally sprayed using a Diamond Jet 2600 hybrid HVOF torch (Oerlikon Metco, Wohlen, Switzerland), operated with a hydrogen + oxygen + air mixture, and an M3 HVAF torch (Uniquecoat Technologies LLC, VA, USA). Moreover, for the HVAF process only, a third particle size distribution was obtained by air classifying the fine powder to remove the smallest particles (see the discussion in Section 3.2.2 for details and explanations on the rationale for air classification). The coatings were deposited onto AISI 304 stainless steel plates of 60 × 25 × 3 mm size. As previously described in [36], the plates were manually sandblasted with 36 mesh brown corundum at 6 bar pressure to achieve a surface roughness Ra ≈ 6 μm, which was determined using a stylus profilometer (TR200, Rupac, Milano, Italy). HVAF deposition was performed immediately after blasting, whilst, for HVOF deposition, plates were pre-heated in a stove at 60 °C.

The M3-HVAF torch is designed in order to allow distinct hardware settings to modify the particles' acceleration and heating. Notably, it features a secondary air + fuel injection in a (replaceable) convergent/divergent extended nozzle, downstream of the primary combustion chamber [37]. Supersonic expansion of the gas stream in this nozzle is therefore coupled to an additional input of combustion heat to counter the cooling that comes with such expansion. In the present case, HVAF depositions were carried out using three distinct types of extended nozzles, with various lengths and inner diameters (Table 1), in order to obtain three different particles' heating conditions. The long 4L2 nozzle with smaller exit diameter heats the particles effectively; the shorter 3L2 nozzle with the same exit diameter decreases the particles' heating time but also causes the gas to emerge at higher temperature from the torch. The long 4L4 nozzle with increased exit diameter expands the gases to the highest velocity, thus producing low particle temperatures and high velocities according to the manufacturer's own specifications. Short combustion chamber and short powder injector (type #2) were used as hardware for all sprayings. Overall, nine distinct coating types were obtained, as listed in Table 2.

HVAF process parameters are shown in Table 3, where “Fuel 1” refers to the primary fuel flow inside the combustion chamber, whereas “Fuel 2” refers to the secondary fuel inlet into the extended nozzle. Fuel pressures were slightly adjusted to match the needs of each nozzle, whereas the air pressure was constant for all processing conditions. It is reminded that gas flows are pressure-controlled in HVAF systems, unlike HVOF torches, where they are flow rate-controlled.

The fine feedstock powder was processed by HVOF spraying using two distinct sets of parameters featuring different oxygen/fuel ratios (Table 4). It is reminded that gun hardware is unmodifiable in this type of torch.

HVOF processing of the coarse powder had already been studied in [36] through a Design of Experiment (DoE) methodology, coming to the conclusion that coating properties were little affected by the choice of deposition conditions unless extreme parameters (e.g. excessively high oxygen/fuel ratio) are set. Therefore, HVOF-sprayed coarse-powder samples obtained with process parameters corresponding to the center point conditions of the previous DoE plan (recalled in Table 4) are considered in this study.

Table 1
Extended nozzle types employed for HVAF spraying.

Nozzle type	*Material*	*Length, l* (mm)	*Inner exit diameter, a* (mm)	*Outer exit diameter, b* (mm)
3L2	Stainless steel	205	22.5	30
4L2	Stainless steel	255	22.5	30
4L4	Stainless steel	255	26	30