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Experimental study of high velocity oxy-fuel sprayed WC-17Co coatings applied on complex geometries. Part A: Influence of kinematic spray parameters on thickness, porosity, residual stresses and microhardness

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ABSTRACT

When a complex geometry is rotated in front of the thermal spray gun, the following kinematic parameters vary in a coupled fashion dictated by the geometry: Stand-off distance, spray angle and gun traverse speed. These fluctuations affect the conditions of particle impact with major implications on the coating's properties. This work aims to probe into the interplay and isolated effect of these parameters on vital coating characteristics in applications requiring variable stand-off distance and spray angles. WC-17Co powders are sprayed via HVOF on steel substrates in a set of experiments that simulates the spray process of a non-circular cross section, while it allows for individual control of the kinematic parameters. Comprehensive investigation of their influence is made on deposition rate, residual stresses, porosity and microhardness of the final coating. It was determined that oblique spray angles and long stand-off distances compromise the coating properties but in some cases, the interplay of the kinematic parameters produced non-linear behaviours. Microhardness is related negatively with oblique spray angles at short distances while a positive correlation emerges as the stand-off distance is increased. Porosity and residual stresses are sensitive to the spray angle only in relatively short stand-off distances.

1. Introduction

The past decades, hardmetals or cermet coatings have been successfully applied to protect parts that experience intense mechanical wear, erosion and corrosion in their working life. These coatings can be deposited via various thermal spray methods, of which, combustion methods such as HVOF and HVAF are preferred due to their high velocity gas streams at low deposition temperatures. This combination of spray parameters is vital in achieving dense coatings with minimum thermal decomposition and good bond strength with the substrate [1–3]. Conventionally, thermal spray processes are employed to coat large, axisymmetric components either by linear translation of the gun over the surface or by rotation of the part in front of the gun. However, there is an increasingly pressing demand to coat complex parts, either externally or internally. These parts are typically, non-symmetric and may possess edges, corners and curvature. Examples of such parts include turbine compressor blades, aircraft landing gear, water turbine blades, casting machine parts, forming tools, bolts and many other [4]. When coating a complex geometry via a line of sight process, such as thermal spray, there are fluctuations in (i) the angle of spray, (ii) the stand-off distance (SoD) between the nozzle and the substrate and (iii) gun traverse speed. These are defined as the spray kinematic parameters since they depend on the relative motion of the robot operating the spray gun and the coated surface and are major factors of the quality and characteristics of the final coating.

At the moment, when the shape of part is considered too complex to be thermally sprayed, an alternative is to be coated via hard chrome plating (HCP) in which coating is deposited isometrically on all surfaces via an electroplating bath. Yet, HCP does not pose a viable solution due to its toxicity, regulatory limitations and mediocre performance [5,6]. Thermal sprayed hardmetal coatings are considered the most viable alternative for HCP due to their ability to produce coatings of better quality, low environmental footprint and ease of scaling up production [5]. Towards that end, it is crucial to extend the range of thermal spray applications in an economical and reliable manner.

Off-line programming of the industrial robots that control the spray guns is gaining popularity as an approach to achieve uniform and invariable coatings via thermal spray onto complex parts [7,8]. This technique aims at maintaining the spray kinematic parameters stable during coating process. The main disadvantage of complex robot paths is increased process time per part and ultimately process cost. Even so, there are significant issues in achieving a near-net-shape and adequate consistency over the coated surface in an economically attractive manner [4]. Most often, these issues emerge from the complexity and small dimensions

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of the sprayed geometry making the variation in spray angle, SoD or traverse speed unavoidable [9].

Therefore, there is significant interest in the literature to deepen the understanding of the influence of spray kinematic parameters to coating properties. Even though there have been considerable efforts to study kinematic spray parameters in various thermal spray processes and powders [4,9–17], almost all of the precedent work examines the kinematic parameters in isolation from each other and the discussion revolves around their individual role in the coating process. Yet, this approach may produce misleading conclusions for real applications since the kinematic parameters always fluctuate simultaneously in a manner dictated by the geometry sprayed and the relative movement of the gun on the sprayed surface. In order to extend the capabilities of current thermal spray systems, attention should be given not only in the effect of angle, stand-off distance and traverse speed individually but also, on their interplay.

This work takes a different approach from the relevant literature, investigating the influence of kinematic parameters individually as well as their interplay (systemically) on several important coating properties. It is of interest to accurately define the space (Angle × SoD × Traverse speed) in which the effect of varying kinematic parameters during thermal spraying is not detrimental, considering the needs of the end application. This will ultimately provide another option in the hands of decision makers in thermal spray industry when considering the feasibility of thermal spray in new applications involving complex geometries. There are many complex components in applications that could benefit from thermal spray coatings, not necessarily requiring top coating performances. These cases could afford being thermally sprayed without the extra cost of off-line robot programming tailored to their shape. In this work, deposition efficiency (coating thickness), porosity, micro hardness, and residual stresses are examined as well as some elements of the coating microstructure.

2. Experimental

2.1. Feedstock

A commercially available agglomerate sintered powder of WC- 17Co mass fraction (H.C. Starck, AMPERIT 526) [18] was used for the deposition of coatings. The detailed chemical composition and size distribution of the powder are presented in Table 1. From the XRD spectrum of the feedstock powder only peaks from the primary phases, WC (hexagonal) and Co (FCC) were detected. The powder used shows the median size to equal about 18.9 μm. The measured particle size distribution ranges from 12.5 μm–28.1 μm at 10% and 90% of the cumulative respectively.

2.2. Substrate preparation & coating deposition

The coatings were deposited onto steel substrates of dimensions 160 × 80 × 3 mm^3 and one substrate of dimensions 214 × 80 × 3 mm^3. The larger substrate was used for the rotational spray part of the experiment as described later on. The substrates where grit blasted with alumna particles of 46 μm at a distance of 100 mm, subsequently they were blasted with high pressure air and mechanically cleaned to remove any remaining grit on the surface.

The samples were sprayed using Monitor Coatings (UK) HVOF torch which has been designed and built in-house. The patented technology (EP2411554A1) comprises of an isentropic plug nozzle to accelerate the exhaust gases to supersonic velocities reaching Mach 2.7. The torch uses a mixture of gas fuels and oxidisers. The process parameters for the gun were previously optimised in-house using Oseir's SprayWatch system for achieving the best microstructure, the highest microhardness and optimum deposition efficiency (Fig. 1, Table 2).

Table 1
Powder properties.

Powder chemical composition				Size distribution		
Co	C	Fe	W	D90% (μm)	D10% (μm)	Apparent density (g/cm^3)
15–18%	4.9–5.3%	Max. 0.2%	Balance	28.1	12.5	4.4–5.2

2.3. Experimental configuration

The dynamic behaviour of the kinematic parameters studied in this work stems from the rotation of a plate substrate around the spray gun's fixed position. This is a generic approach for the study of the case of spraying a complex geometry internally. When spraying a complex geometry via part rotation, the changes in the kinematic parameters are coupled with one another. This coupling is a function only of the shape, dimensions of the part and the gun position in regards to the axis of rotation. In that way, every different shape sprayed has its own specific combination of simultaneously changing kinematic parameters during part rotation. Two sets of experiments were conducted in order to produce results that exhibit the individual influence of each one of the kinematic parameters as well as their interplay.

First, a rectangular substrate was fixed on a turntable and rotated around the HVOF gun. The gun itself was fixed so that its nozzle was on the centre of rotation as seen in Fig. 2A, B. The minimum stand-off distance during rotation occurs at the centre point of the substrate where the spray plume hits it at 90° (small circle in Fig. 2B). Respectively, the maximum SoD occurs at the edge of the rotating substrate where sprayed particles impact at an angle of 30° (large circle in Fig. 2B). The minimum SoD was set at 120 mm which is the optimum spray distance of the used equipment/process parameters. The rotation speed was 40 rpm and the HVOF gun had a vertical velocity of 2 mm/s, this resulted in a steady vertical step between the passes (track pitch) of 3 mm. The spray process lasted for 20 cycles aiming to deposit 25 μm/cycle at 90° and 120 mm SoD. After the process, five sites (S1, S2, S3, S4 and S5) were marked on the specimen from its centre point to its edge indicating areas where the impact angle was 90°, 75°, 60°, 45° and 30° accordingly. Beyond the changing impact angle, each of those sites corresponded to different SoD and gun traverse speed as seen on Table 3.

The second set of experiments was performed with the HVOF gun traversing linearly over the substrates as seen in Fig. 2C. The spray angle, SoD and Traverse speed were individually controlled. This allowed for studying the influence of each one, while the two others were held constant. Table 4 outlines twenty linear experiments conducted with traverse speed of 502 mm/s and three experiments with increasing gun traverse speed. The first twenty experiments in Table 4 aim to study the influence of SoD, spray angle and their interplay and the second part of three experiments to evaluate the effect of gun traverse speed. The increments in spray angles and SoDs were the same as the sites of interest taken from the rotating experiment (S1, S2, S3, S4 and S5) so that a comparison between them would be possible. The SoD of 124 mm (S2) was not included in the linear experiments because

Fig. 1. Spray optimisation using Oseir's SprayWatch system.