JTTEE5 2:133-136

Plasma Spraying of WC-Co Part II: Experimental Study of Particle Deposition and Coating Microstructure

S.V. Joshi and M.P. Srivastava

WC-Co base wear-resistant coatings deposited by plasma spraying are widely used to enhance component longevity in a variety of wear environments. During spraying of WC-Co, ideally only the cobalt phase should melt and act as a binder for the WC particles. Although it is undesirable to fully melt WC because it can cause decarburization, complete melting of the cobalt phase and its satisfactory flattening on impacting the substrate is necessary to minimize porosity and achieve good substrate/coating adhesion. In this article, the influence of the primary plasma spray variables on the melting characteristics of WC-Co powders is investigated with respect to the microstructure of these coatings. This experimental work complements an analytical study on plasma spraying of WC-Co, and thus, observations are presented to support the predictions of the modeling effort.

1. Introduction

THERMALLY sprayed protective coatings find application in many aggressive environments to enhance performance and improve durability of engineering components. Of the thermal spray coatings intended to combat extreme wear conditions, WC-Co deposits are the most widely used.[1] The more recently developed high-velocity oxyfuel (HVOF) techniques and the detonation gun process are well suited for generating dense and well-bonded coatings of relatively low-melting-point materials such as WC-Co.[2,3] However, plasma spraying is still extensively used for wear-resistant applications as a plasma coating system (by virtue of its versatility in producing good ceramic deposits) and is nearly always the spraying unit of choice in single-spray-equipment coating installations worldwide.

Cemented carbides, such as sintered WC-Co compacts, derived from the powder metallurgy route are used extensively in the industry because of their excellent wear resistance. However, the properties of plasma-sprayed WC-Co coatings are inferior to the cemented carbide, and this is presumably due to the included porosity in the coatings, the limitation on the bond strength of the sprayed deposits, and also due to decomposition of the WC phase during plasma spraying. Both adhesion of the coating to the substrate as well as the coating density are governed primarily by the extent of particle melting at the moment of impact with the substrate and the velocity with which the particles strike the substrate. The velocity and temperature evolution of powder particles, in turn, depend on the powder characteristics and the spray parameters used.

A theoretical study of particle heatup and acceleration during plasma spraying of WC-Co is presented in Part I of this article.[4] The above study, based on a one-dimensional prediction model,[5] highlights the influence of particle size characteristics on the evolution of particle temperature and velocity during spraying. The results[4] show that the trajectory assumed by the powder particles while traversing through the plasma flame also influences gas-particle heat and momentum transfer. The present study (Part II) deals with an experimental investigation of particle deposition and coating microstructure during plasma spraying of WC-Co. It will be shown that the predictions of the analytical model can explain many of the observations noted during the current experimental investigation. Considering the obvious difficulties associated with experimental measurement of the temperature and velocity of particles traversing through a plasma flame, an analytical approach to the spraying process in conjunction with simple qualitative methods of confirming the model-predicted trends can play a significant role in further advancement of the plasma spray technology.

Keywords: optimization, particle heating and acceleration, plasma spray variables, splat microstructure, tungsten carbide/cobalt

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2. Experimental Procedure

The present work was carried out using WC-Co powders containing 12% cobalt. Powders of two different sizes were used during the study, i.e., 45 to 90 μm (from Hermann C. Starck, Berlin, Germany) and –45 μm (from Cabot Corporation, Indiana). A METCO 7MB plasma spraying unit was used for spraying the powders, and unless otherwise stated, the parameters listed in Table 1 were used.

Powder splats were collected on polished 25-mm diameter brass rounds to observe the powder deposition characteristics. The WC-Co coatings were deposited on mild steel sheet substrates of approximate dimensions $2 \times 30 \times 60$ mm. The substrate surface was grit blasted with –30 mesh alumina particles at about 0.5 MPa and then ultrasonically cleaned prior to coating. The spreading and flattening characteristics of the impacting WC-Co particles at different plasma arc currents and spray distances were investigated by scanning electron microscopy. The effect of these spray variables on the microstructures of the sprayed WC-Co deposits was also studied.

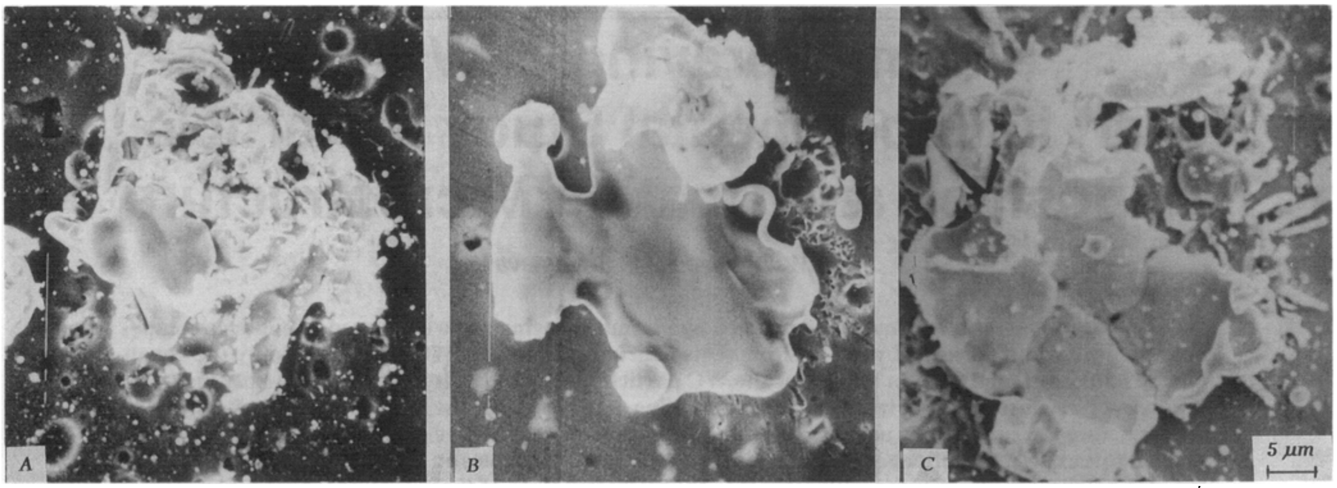

Fig. 1 Scanning electron micrographs of WC-Co splats collected on polished brass surfaces at a spray distance of 75 mm using different plasma arc currents. (a) 300 A. (b) 400 A. (c) 500 A. Note that all three micrographs have the same magnification.

Table 1 Plasma spray parameters for spraying of WC-Co powders

Spray gun	METCO Type 7 MB
Gases	
Primary gas	Ar
Pressure, psi	100
Flow, ft^3/h	100
Secondary gas	H_2
Pressure, psi	50
Flow, ft^3/h	10
Carrier gas	Ar
Flow, ft^3/h	37
Powder feed rate, g/min	40
Arc current,A	400
Spray distance, mm	75

3. Results and Discussion

Observation of splats by microscopy, under the same spray conditions as those likely to be used to develop the coatings, can provide information regarding particle melting and acceleration.[6] For instance, Fig. 1 shows the scanning electron micrographs (SEM) of similarly sized WC-Co splats collected at a distance of 75 mm from the plasma gun nozzle tip using three different plasma arc currents of 300, 400, and 500 A. It is assumed that the SEM photographs in each case contain one complete particle, i.e., none of the splat has been removed, and there is no compositional variation among the splats. The typical photographs shown in Fig. 1 suggest that the WC-Co powder is molten at all three arc currents. However, the molten particle flow patterns vary substantially in each case, with the spreading being rather poor at 300 A (Fig. 1a). The spreading improves considerably by increasing the arc current to 400 A (Fig. 1b) or 500 A (Fig. 1c). In the case of the splat collected at 500 A (Fig. 1c), the streaks of solidified material and other fragmented particles observed around the main splat indicate that the molten particle must have impacted the surface with somewhat greater velocity than in the case of the 400-A splat. This is explained and substantiated by reports in the literature that the velocity attained by particles during spraying increases with the power level at which the plasma gun is operated.[7]

Particle acceleration during spraying also depends greatly on the particle size,[4] with the finer particles attaining higher velocities before impacting a substrate. Thus, satisfactory spreading of the molten particle, as shown in Fig. 1(c) taken from the splats collected at 500 A, should also be obtainable at lower arc currents if the particle size is fine enough. Observation of the splats collected at 400 A does reveal numerous smaller sized particles (compared to the particle shown in Fig. 1b), exhibiting good spreading on impact (Fig. 2). The observation of such splats, besides qualitatively validating prediction models, can be a useful step in optimizing various plasma spray variables. However, it is pertinent to make a general remark advocating caution, particularly in light of the results presented in Fig. 1 and 2. Any commercially available spray-grade powder typically has a wide particle size distribution, and examination of numerous individual particle splats is essential to draw any meaningful conclusion. Additionally, there is also the need to perform a complete mass balance of the feedstock material compared to the final deposit and any material that may be lost due to less than optimum deposit efficiencies.

When the spray distance is increased from 75 to 125 mm, the nature of the splats is largely unchanged. This conforms to the results that would be expected after referring to the predictions of the modeling study,[4] which show that, irrespective of the size of the particle, there is little change in its velocity at impact over the spray distance in question. However, Fig. 3 reveals a scanning electron micrograph of a donut-shaped splat sprayed at 400 A and collected at a distance of 125 mm. It is proposed that this donut shape results from the rebound of an unmolten particle core, as is predicted[4] for a particle that is coarse and/or travels too far in the fringe of the plasma flame.

Figure 4 shows the cross-sectional microstructures of the plasma sprayed WC-Co coatings formed using a powder with a particle size range of −90 +45 μm. In accordance with the observed influence of the plasma arc current on the particle deposition characteristics (Fig. 1), Fig. 4(a) shows that the coating formed at 300 A consists of very large pores. On the other hand,

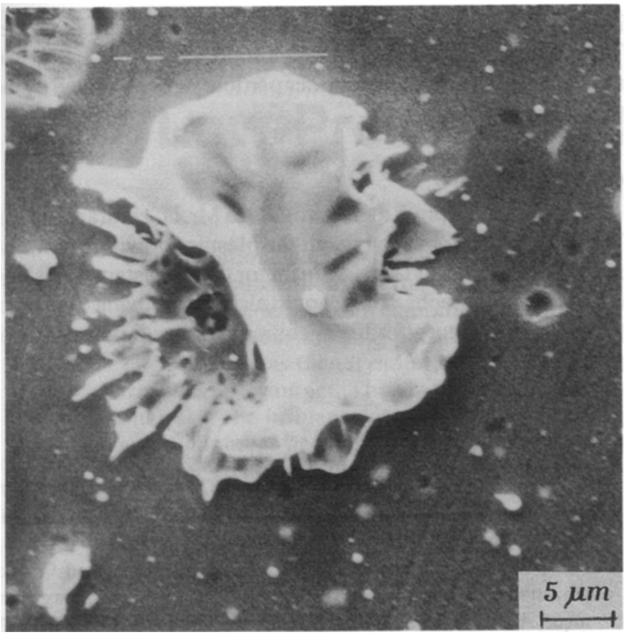

Fig. 2 Splat of a finer WC-Co particle at a 75-mm spray distance and a 400-A arc current, revealing improved particle spreading.

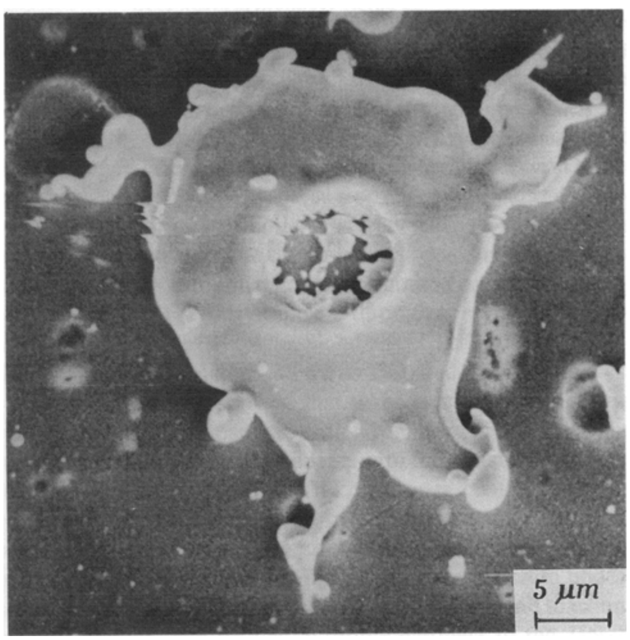

Fig. 3 Unusual splat, formed at 400 A, of a WC-Co particle at a 125-mm spray distance, exhibiting a hole in the middle, presumably due to incomplete melting of a particle having traveled in the fringe of the plasma flame.

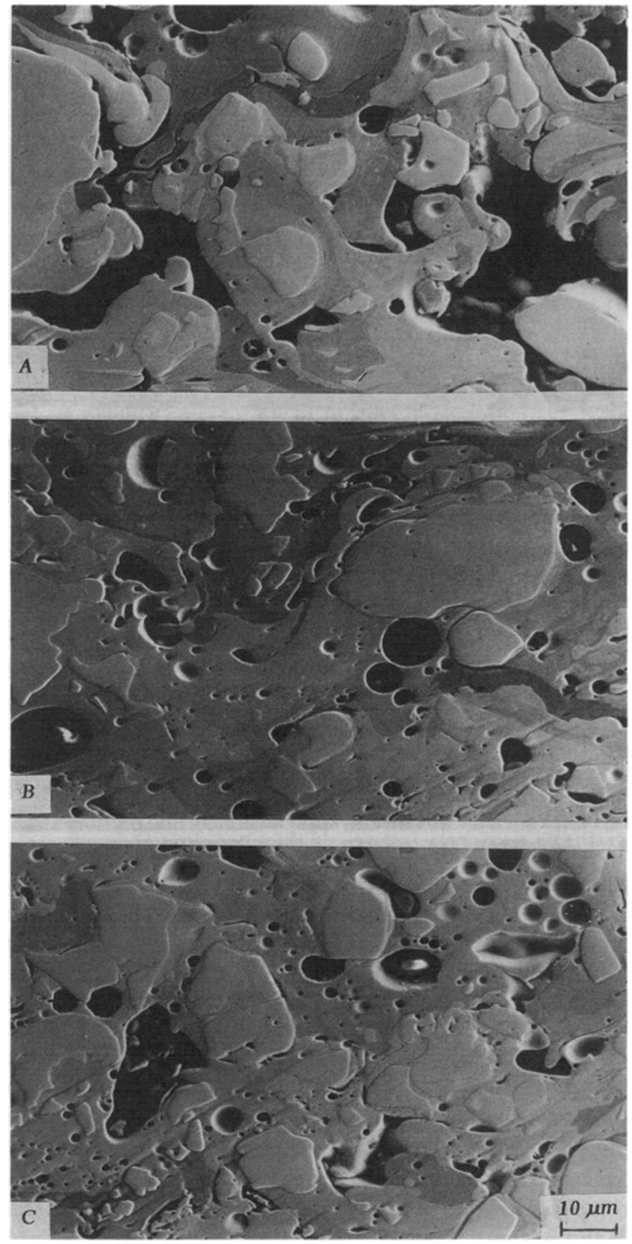

Fig. 4 Typical cross-sectional microstructures of WC-Co coatings sprayed using different plasma arc currents. (a) 300 A. (b) 400 A. (c) 500 A.

there is no significant difference between the coatings developed at 400 A (Fig. 4b) and 500 A (Fig. 4c), in terms of the amount of visible porosity. In both cases, the pore size is typically under 10 μm and considerably reduced compared to the 300-A coating. The greater amount of porosity in the coating formed at the low current can be attributed to poor particle flattening on impact.

Because a lower particle size leads to both more rapid particle heatup and particle acceleration, indicated by the results of the modeling effort,[4] the use of a finer powder for coating formation leads to a marked change in the microstructure of the plasma sprayed coating. This is evident from Fig. 5, which illustrates the cross-sectional microphotograph of a plasma-sprayed WC-Co coating generated at a plasma arc current of 400 A using a powder of –45 μm cut. The coating microstructure is much denser than that in Fig. 4(b). Note that, except for the difference in particle size distribution of the powders used for coating formation, identical spray variables (shown in Table 1) were used to deposit both the coatings.

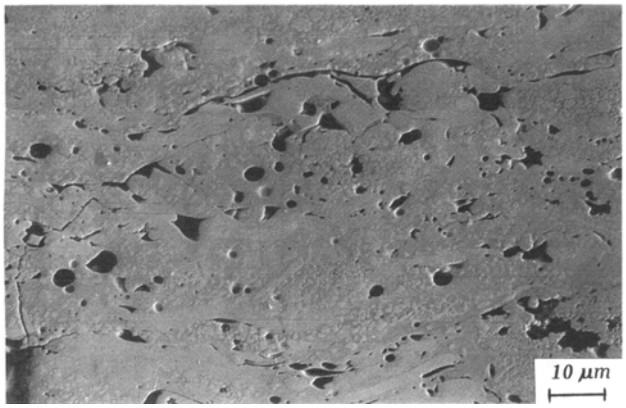

Fig. 5 Denser coating microstructure resulting from a finer (–45 μm) WC-Co powder plasma sprayed at a 400-A arc current.

4. Conclusions

This article deals with an experimental study of particle deposition and coating microstructure during plasma spraying of WC-Co. This work is intended to complement the analytical study of heatup and acceleration of WC-Co particles in the plasma flame detailed in Part I of this article.[4] The study is designed to investigate the influence of the primary plasma spray variables such as arc current, spray distance, and particle size on the particle deposition characteristics, which in turn have an important bearing on the microstructure of the developed coating. The observation of splats, collected on polished brass surfaces, suggests that a plasma arc current of at least 400 A is required to obtain satisfactory flattening of the WC-Co particles on impacting the substrate. Finer WC-Co particles exhibit better spreading characteristics and lead to a denser coating microstructure. These are manifestations of the improved gas-particle heat and momentum transfer rates for finer particle sizes predicted by the theoretical study.

Acknowledgments

The authors express their gratitude to Mr. D. Jayaram and Mr. V.S.R.A. Sarma for carrying out the plasma spraying work, and to Mr. S.M. Gupta and Mrs. V. Joshi for their assistance in taking the SEM photographs. They would also like to thank the Director of this laboratory for his encouragement and permission to publish this work.

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