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ARTICLE

Effect of Feedstock Size on the Properties of WC-17Co Coatings

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Abstract: High velocity oxy-fuel (HVOF) spray technique has been employed to fabricate WC-17Co coatings. To achieve a high performance of mechanical properties and abrasive wear resistance, four types of WC-17Co powders with different feedstock particle sizes were investigated. The results show that the feedstock powder with finer particle size has higher velocity and temperature during the spraying process, resulting in a denser coating and a stronger splat-splat bonding. The micro-hardness of WC-17Co coating increases with the decreasing of feedstock size. The coating deposited by finer feedstock powder has superior abrasive wear resistance, due to the smaller porosity and boundary flaws on coating surface. However, coating fracture toughness could be affected by feedstock size if it is too small. Among all those investigated coatings, the one with medium particle size and narrow size distribution exhibits both excellent mechanical properties and wear resistance.

Key words: feedstock size; HVOF; WC-17Co; mechanical properties; abrasive wear

Thermally sprayed carbide-based cermet coatings have been widely used in many industries for their high wear resistance. In particular, a WC-17Co coating has been chosen as one of the best candidates[1]. In order to suppress the decarburization of WC, this coating is usually deposited by high velocity oxy-fuel (HVOF) method, which is characterized by a high velocity and low temperature flame[2]. The powder particles used as the feedstock are heated and accelerated by the flame, and then impact on the substrate surface to form coatings[3]. Since the distribution of the feedstock size is closely related to the characters of the in-flight particles, it is important to the coating performance. A narrow and fine powder size distribution is beneficial to hardness of the coatings[4]. However, such distribution may be harmful to other properties, such as the wear resistance of coatings, because of more W_2C generation during spraying[5]. So far, the work in this area has been quite limited. The effect of particle size distribution on coating properties, especially wear resistance, has not been described exactly. Due to cost consideration, commercially available thermal spray powders have to use a wide particle size distribution ranging from 10 to 53 μm. In the present work, the effect of the feedstock size of WC-17Co on the coating properties (porosity, hardness, toughness and wear resistance) has been fully investigated. The purpose of this work is to provide help for feedstock size option and optimization.

1 Experiment

The feedstock powders were manufactured by spray drying of slurries containing WC, Co and Cr particles, followed by sintering and classification. Four types of WC-17Co powders including fine (-25+10 μm), medium (-38+25 μm), coarse (-53+38 μm), and as-received (-53+10 μm) ones were prepared. The former three types of powders were obtained by screening from the last one. The shape and size of the four sets of WC-17Co powders are shown in Fig.1. All powders have typically spherical shape with some amounts of pores distributing on the surface.

The WC-17Co coating was deposited on a Ti-6Al-4V alloy substrate through a HVOF thermal-spray process. The JP5000

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HVOF system (TAFA, US) was used to spray the cermet coating. This system was based on a liquid fuel (kerosene of aviation grade) and oxygen gas. A gun mounted on a six-axis ABB 2400M robot was used to carry out the process. The HVOF spraying parameters are presented in Table 1.

Prior to spraying, the substrate was degreased in ethanol and blasted with alumina grit with an average size of 0.25 mm at an air pressure of 0.6 MPa. The average roughness value (Ra), determined by optical profilometry of the substrate after grit blasting was ~8 μm. Specimens with 0.30 mm coating thickness were prepared.

The Spraywatch 2i system (Oseir, Finland) was used to measure the mean velocity and temperature of particles. Eight measurement points were distributed evenly between the nozzle exit and the depositing point along the central axis of the flame. A QUANTA-200 SEM (FEI, Netherlands) was used to monitor the particle and coating morphology. A D8 Advance X-ray diffraction (XRD) meter (Bruker, Germany, Cu Kα radiation, 40 kV, 40 mA, 1 °/min scan rate) was used to identify the present phases. The micro-hardness of the coatings was measured by a HVS-1000 micro-hardness tester with a Vickers diamond indenter under a load of 0.3 kg, according to ASTM E384 standard. The Vickers indentation at the load of 1 kg was used to evaluate the fracture toughness of the coatings. The fracture toughness (K_c) can be calculated by the Evans Wilshaw equation in Eq. (1)[6]

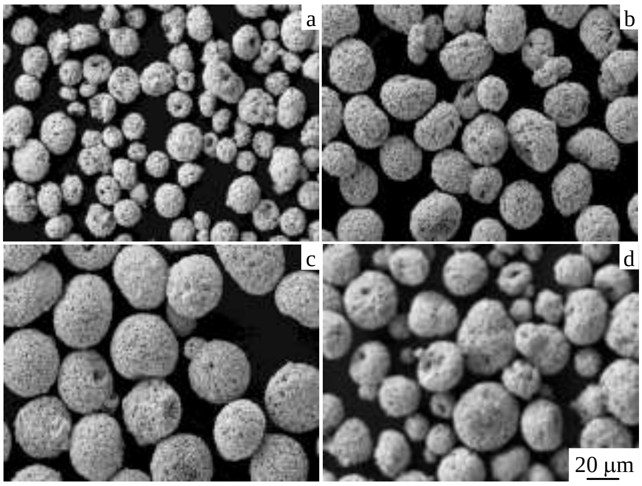

Fig. 1 SEM morphologies of fine (a), medium (b), coarse (c), and as-received (d) WC-17Co feedstock powders

Table 1 HVOF coating spray parameters

Spray parameters	Values
Oxygen flow rate/L·h^{-1}	53000 (pressure: 1.45 MPa)
Fuel flow rate/L·h^{-1}	23.5
Powder flow rate/g·min^{-1}	65
Spray distance/mm	380
Gun movement speed/mm·s^{-1}	350
Offset per pass/mm	4.0

$$K_c = 0.079 \frac{P}{a^{3/2}} \lg \frac{4.5a}{c} \quad (1)$$

where, P is the press load in the unit of mN, a is half of the average diagonal length (μm) of micro-indentation, and c is the average length (μm) from the center of indentation to crack end.

Abrasive wear test for the coated samples was conducted by ASTM G65[7]. The samples were mounted firmly in the sample holder and were allowed to press against the rim of the rubber wheel with the force of 130 N. Dry silica with a particle size of 250~400 μm was used as an abrasive. The dry silica sand then fell freely between the wheel and the coated surface while the rubber wheel was rubbing against the coated surface. The wheel with a diameter of 220 mm was running at a rate of 200 r/min. The abrasive particles used were not recycled. Prior to the test, the coated samples were ultrasonically cleaned with acetone, dried and then weighed by an electronic weighing balance with an accuracy of 0.001 g. The coating mass loss was measured every two minute interval. The total time of the test was 30 min. Parameters of the test conditions are listed in Table 2.

2 Results and Discussion

The cross-section morphologies of the WC-17Co coatings deposited by powders with different particle sizes is shown in Fig.2. All coatings have homogenous structures with

Table 2 Abrasive wear test conditions

Parameters	Values
Abrasive material	Silica
Particle size/μm	250~400
Load/N	130
Wheel speed/r·min^{-1}	200
Wheel diameter/mm	228.6
Feed rate/g·min^{-1}	300~400

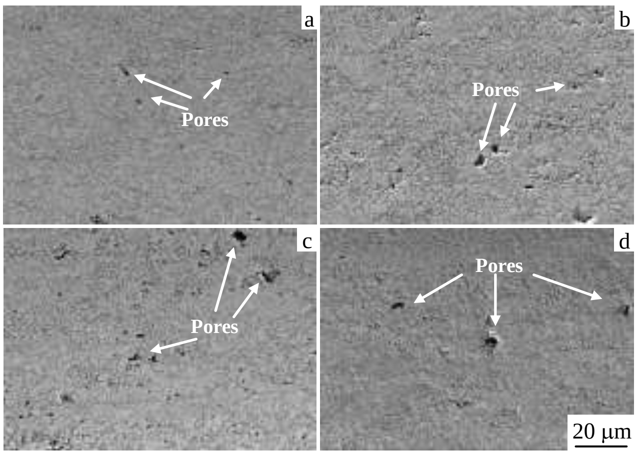

Fig. 2 SEM morphologies of coatings deposited by powders with different particle sizes: (a) fine, (b) medium, (c) coarse, and (d) as-received

polygonal tungsten carbide embodying in the Co metal matrix. Some pores distribute on the coating cross-section. Both the pores size and porosity increase with the increase in the particle size of the feedstock powder. The porosity in the coating deposited by as-received powder is between those of the coatings deposited by medium and by coarse powders.

Coating properties, such as porosity, micro-hardness and fracture toughness are shown in Table 3. As shown in Table 3, the coating deposited by fine powders exhibits the lowest porosity of about 0.53%, and the coating deposited by coarse powders shows the highest porosity of about 1.13%. It has been reported that coating porosity could be affected by the velocity and temperature of in-flight particles[8]. The characters of different types of in-flight particles are shown in Fig.3.

As shown in Table 3, the coating deposited by coarse powder exhibits the lowest density (porosity=1.13%), but the largest fracture toughness (K_c=5.78 MPa m$^{1/2}$). On the contrary, the coating deposited by fine powder presents the highest density (porosity=0.53%), but the lowest fracture toughness (K_c=4.25 MPa m$^{1/2}$), which is attributed to the generation of W_2C phase.

Table 3 Properties of WC-17Co coatings deposited by different feedstock size powders

Types	Porosity/%	$HV_{0.3}$/MPa	K_c/MPa m$^{1/2}$
Fine	0.53±0.05	12760±460	4.25±0.86
Medium	0.76±0.06	11020±540	5.36±0.76
Coarse	1.13±0.07	9900±820	5.78±0.65
As-received	0.81±0.05	12350±650	4.97±0.83

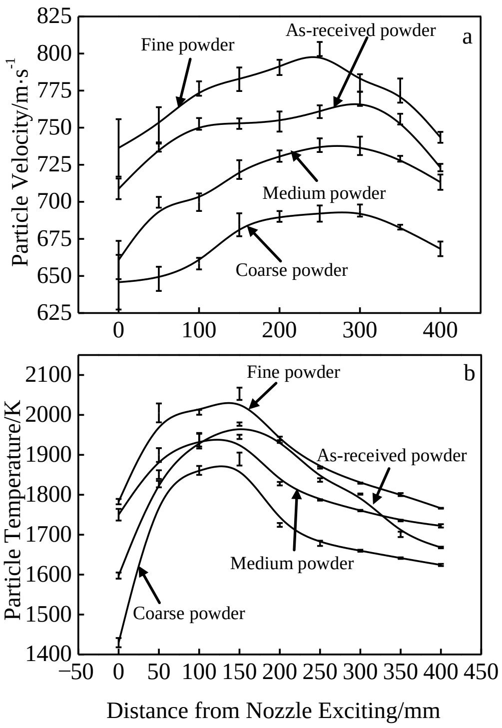

Fig. 3 Effect of the feedstock size on particle velocity (a) and particle temperature (b) during spraying process

All types of powders were accelerated and heated up at the initial flight trip and then declined when they reached to peak values. The powder with smaller diameter size presents higher velocity and temperature during the whole flight trip, especially on the impact point. Therefore, such powder can deform better to achieve a denser coating and a stronger splat-splat bonding.

As shown in Table 3, the micro-hardness of coatings increases with the decrease in feedstock size. One explanation is ascribed to the reduction of porosity in the coating deposited by finer powders. Another one is ascribed to the increase of W_2C and amorphous phase[9]. Illustrative examples of XRD patterns of different series of coatings are shown in Fig.4. There are some differences in the phase presences. It is revealed the peak relative to that of pure cobalt (2θ=44.21°) is present in the coating deposited by coarse powder (‘C’-coatings) besides the peak of tungsten carbide. The peak height associated with cobalt is lower in the coating deposited by medium powder (‘M’-coatings) than that in ‘C’-coatings. This is likely due to the fact that part of tungsten dissolves in the metallic matrix to generate Co-rich amorphous phase after the high temperature spraying process[10]. In the coating deposited by fine powder (‘F’-coatings), there is an appearance of obvious line broadening, which can be attributed to the further dissolution of WC into the Co matrix. Meanwhile W_2C phase arise in ‘F’-coating due to the presence of tungsten carbide decomposition in high temperature and oxidizing conditions[11]. W_2C and amorphous phase possess higher hardness than original phases, so ‘F’-coatings exhibit the higher micro-hardness than the former coatings. Since W_2C is harder but more brittle than WC phase, the fracture toughness of ‘F’-coatings is lower than others[12,13]. Micro-hardness and fracture toughness from the coating deposited by as-received powder (‘A’-coating) are between those from ‘F’-coatings and ‘M’-coatings.

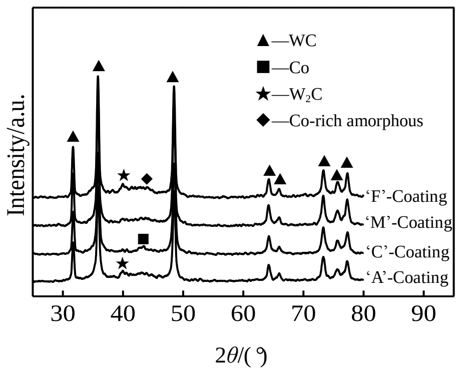

Fig.4 XRD patterns of the coatings deposited by fine (‘F’-Coating), medium (‘M’-Coating), coarse (‘C’-Coating), and as-received

('A'-Coating) powders

Wear resistance of cermet coating is closely related to the mechanical properties. An abrasive wear testing was used to estimate coating wear resistance. The coating mass loss corresponding to the wearing time is shown in Fig. 5. It is observed that the mass loss increase with the increase of the feedstock size after the same wear rounds. The mean mass losses are 2.47, 2.18, 2.03 mg per 100 rounds, for 'C', 'M' and 'F' -coatings, respectively. The curve attributed to 'A'-coatings are located between those of 'M'-coatings and 'C'-coatings, for mass loss.

Abrasive wear mechanism of WC-Co coating from previous studies can be summarized as three steps[14-16]. The first is microcutting and removal of the soft binder by abrasive particles. The second is fragmentation of carbide grains as a whole or in part. The last is primary related to pull out of fragments. The wear surface of 'C'-coatings is shown in Fig.6. Some grooves are observed in 'C'-coatings indicated by arrows in Fig. 6a. High magnification of these grooves is shown in Fig. 6b. The above-mentioned wear mechanism presents well in this area. Individual WC grains (bright areas) standing in relief indicate that the Co-rich matrix around the WC grains has been partially removed. WC grain fragmentation and eventually pull out are also observed in this area. Besides grooves, porous and lack-bonding areas appear on the coating surface. The formation and propagation of cracks are obviousl around such weak points (Fig.6c). The cracks propagate along splat boundaries, leading to WC grains pull out directly from the Co-rich matrix (Fig.6d). 'C'-coatings possess more pores and lack-bonding defects than other series of coatings. Therefore more WC grains pull out from the binder directly, resulting in the largest mass loss in 'C'-coatings during the abrasive wear process.

Some studies in the literature have reported that the wear mass loss increased with the increase of W_2C, which is harder but more brittle than WC[17-19]. However, this phenomenon did not emerge in the present study. This is probably attributed to the low amount of W_2C in those series of coatings. The pores and boundary defects decrease the coating hardness. Furthermore, the coating wear performance deteriorates, when pores and boundary defects appeared on the coating surface. To reduce the porosity and boundary defects, a narrow and fine particle size distribution should be selected. However, it has to be carefully selected because the coating fracture toughness could decrease if the particle size is too small. In this study, the coating deposited by the medium powder (–38+25 μm) exhibits superior mechanical properties and wear resistance.

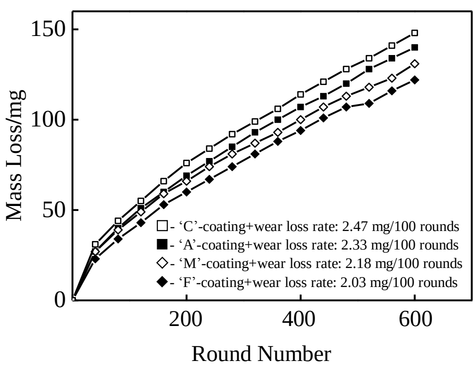

Fig. 5 Mass loss versus rounds curves of different series coatings

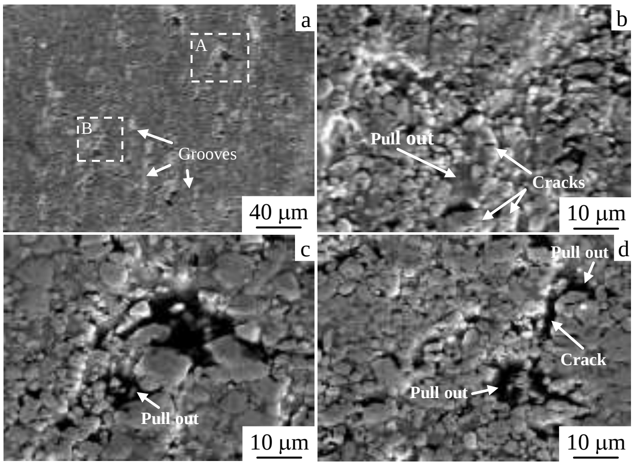

Fig. 6 SEM morphologies of the general surface of 'C'-coating after 6000 abrasive wear rounds (a): (b) higher magnification of the grooves in Fig.6a, (c) higher magnification of region A in Fig. 6a, (d) higher magnification of the region B in Fig. 6a

3 Conclusions

1) The coating deposited by coarse powder exhibits the lowest density (porosity: 1.13%), but the largest fracture toughness (K_c: 5.78 MPa $m^{1/2}$). On the contrary, the coating deposited by fine powder exhibits the highest density (porosity: 0.53%), but the lowest fracture toughness (K_c: 4.25 MPa $m^{1/2}$), which is attributed to the generation of W_2C phase.

2) During the abrasive wear test process, the mass loss rate was mainly related to the porosity and lack-bonding defects on the coating surface. The coating deposited by fine (–25+10 μm) feedstock powder has the lowest wear loss rate, followed by 'M'-coating, 'A'-coating, and 'C'-coating.

3) Compared with as-received feedstock with particle size ranging from 10 to 53 μm, the feedstock with medium particle size and narrow size distribution ranging from 25 to 38 μm exhibits both excellent mechanical properties and wear resistance.

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粉末原料粒径对 WC-17Co 涂层性能的影响

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摘　要：利用超音速火焰喷涂技术喷涂 4 种不同粒径的 WC-17Co 粉末，评价粉末粒径对涂层机械性能和抗磨粒磨损性能的影响。结果表明，粉末的粒径越小，在超音速焰流作用下获得的速度和温度越高，形成的涂层越致密，颗粒间的粘接强度越高，同时涂层的显微硬度也越高。WC-17Co 粉末的粒径越小，获得涂层的孔隙直径越小，颗粒间的粘接缺陷越少，因此涂层的抗磨粒磨损性能越好。但是当 WC-17Co 粉末的粒径过于微小时，涂层的断裂韧性将受到影响。在本研究的 4 种粒径分布的 WC-17Co 粉末中，中间粒径且分布范围集中的粉末制得的涂层兼具良好的机械性能和抗磨粒磨损性能。

关键词：原料粒径；超音速火焰喷涂； WC-17Co；机械性能；磨粒磨损

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