Effect of powder particle size on microstructure and properties of low pressure cold sprayed high aluminium bronze coating

Li Feng1,2, Dongting Li3, Guosheng An1,2, Guiping Wang1, Wensheng Li1,2,3 and Jirong Chang1

1 School of Materials and Engineering, Lanzhou University of Technology, Lanzhou, 730050, People’s Republic of China
2 State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals, Lanzhou University of Technology, Lanzhou, 730050, People’s Republic of China
3 Author to whom any correspondence should be addressed.
E-mail: fenglils@lut.edu.cn and Liws@lut.edu.cn

Keywords: low pressure cold spray, high-aluminum bronze, particle size, coating property

Abstract
High-aluminum bronze alloy powder was mixed with 16 wt% Al2O3 powder to prepare low-pressure gas dynamic spray coatings with different sized powder particles. The mechanical properties of coatings were tested and the surface, cross section and stretch section of coatings were observed by scanning electron microscopy. Uniform experiment was performed to analyze the effects of particle size of the high-aluminum bronze and Al2O3 powder on coating performance. Experimental results shows that the degree of deformation of the high-aluminum bronze particle in the coating increased with decreasing particle size in the high-aluminum bronze and Al2O3 in the mixed powder. The degree of deformation of the high-aluminum bronze particle in the coating affected the mechanical properties of the coating showing a linear relationship between powder size and coating performance. When the particle size of Al2O3 and high-aluminum bronze particle ranged between 23–25 μm, the coating has the outstanding mechanical properties.

1. Introduction

High aluminum bronze is a new type of wear-reducing, wear-resistant alloy material which has an alumina content of 12%–16 wt%. This material has high strength and good corrosion resistance, and has been applied as coating material, which can be widely used for surface protection of metal molds, various shafts, pipe fittings, etc [1, 2]. High-aluminum bronze coating is usually prepared by thermal spraying [3]. For example, Lu et al [4] prepared the high-aluminum coating with plasma spraying, they found that coating shows excellent anti-wear performance under high load, and the coating hardness (HV) can reach 500. However, the traditional thermal spraying technology is costly and requires high equipment, which limits the application of high aluminum bronze coating. Therefore, it is of great academic significance and industrial practical value to prepare high-aluminum bronze coating with excellent comprehensive performance by using a simple process to study the structure and application of the prepared coating.

Cold spraying (CS) is a solid-state coating deposition technology. Compared with the traditional thermal spray technology, the cold spray process is simple, avoiding the oxidation, decomposition and phase change of the spray powder, and obtaining a coating with low porosity and good performance [5, 6]. Generally, Cold spraying is divided into high pressure cold spraying (HPCS) and low pressure cold spraying technology (LPCS). However, low-pressure cold spraying is favored by researchers because of its simple and lightweight portable equipment. Compared with high-pressure cold spraying complex equipment, low-pressure cold spraying can not only prepare various metal coatings, but also its economical and portable characteristics are more suitable for industrial fields. Low pressure cold spraying allows mixture of ceramic powder with metal powder. The ceramic powder can improve the deposition rate, density, hardness and bonding force of cold spraying coating [7].

© 2020 The Author(s). Published by IOP Publishing Ltd
Table 1. Composition of the high aluminum bronze alloy powder.

| Alloying element | Al  | Fe  | Cu  | Mn  | Ni  | Others |
|------------------|-----|-----|-----|-----|-----|--------|
| Quality scores (%) | 12~16 | 2.0~4.0 | 70~80 | 0.5~2.0 | 0.2~0.5 | 0.8~2.0 |

Many scholars in the field of cold spray technology show that the factors affecting the quality of cold spray coatings are: carrier gas pressure, spray distance, spray temperature, powder particle size, etc [8–11]. And the particle size of the powder has a significant effect on the performance of the CS coating. For example, Wong et al [12] studied cold-sprayed titanium coatings at different particle sizes and found that when the particle size is 29 μm, the coating has the lowest porosity and the best performance.

In order to prepare high-aluminum bronze coating with high hardness and good wear resistance, the best particle size of the spray powder used for cold spraying is obtained. And based on the size matching and synergistic effect of high-aluminum bronze and alumina particles, the effects of different particle size spray powders on the microstructure and properties of high-aluminum bronze composite coatings were studied. In order to prepare high-aluminum bronze coating with high hardness and good wear resistance. The cold sprayed high aluminum bronze coating with excellent preparation performance is obtained.

2. Experiment materials and methods

2.1. Sample preparation

The high-aluminum bronze powder used in the experiment was prepared by the Lanzhou Polytechnic Powder Metallurgy Co., Ltd, and the compositions are shown in table 1. The alumina powder was a commercial α-Al2O3 powder. After the high-aluminum bronze and the Al2O3 powders were sieved. Figure 1 shows the microscopic morphologies of the high-aluminum bronze and Al2O3 powder. Figures 1(a)–(c) correspond to high-aluminum bronze powder with a particle size of 75–61 μm, 61–48 μm, 48–38 μm, 38–25 μm and 25–23 μm, respectively.

The shape of the particle is similar to that of spherical particle. Figures 1(f)–(j) shows the morphology of Al2O3 particle which were largely lamellae in shape. Figures 1(f)–(j) correspond to Al2O3 with a particle size of 75–61 μm, 61–48 μm, 48–38 μm, 38–25 μm and 25–23 μm, respectively.

The screened high-aluminum bronze powder was mechanically mixed with the Al2O3 powder for 4 h and the mass fraction of the Al2O3 was 16 wt%. The mixed powder was heat treated using vacuum muffle furnace at 400 °C and soaking time of 2 h. The substrate material of the coating was steel G45. The CS coating was prepared using low-pressure CS equipment (GDU-3-15, Belarusian). Compressed air was used as the propulsive gas with the inlet pressure and temperature of 0.6–0.8 MPa and 500 °C, respectively. The standoff distance from the nozzle exit to the substrate surface was 10–20 mm. Table 2 shows number of coating samples prepared by powders with different particle sizes. Uniform experiments were used to study the effect of particle size on the coating properties. The theory and method of uniform experiment can be found in the literature [13].

2.2. Property testing and morphology observations

The morphology of the cross-section and surface structures of the coating were observed using the JSM6700F SEM.

The sample coatings were prepared as prescribed by the standard of GB8642-2002(Thermal spray-Determination of tensile adhesive strength) to test bond strength using the Shimadzu universal material testing machine (AG-10TA, Japan). As shown in the formula: \( R_b = \frac{F_{\text{lim}}}{S} \). The bonding strength \( R_b \) is calculated by the quotient of the maximum load \( F_{\text{lim}} \) and the cross-sectional area \( S \) of the fracture surface. Figure 2 is schematic diagram of the coating sample tensile. Five samples were taken from each group for tensile testing and the average value of the replicates was recorded.

The micro-hardness of the coating was measured using HV-1000 micro-hardness tester. The load was 1.96 N and the loading time was 15 s. Ten different positions were selected for each set of samples for testing, and the results were averaged.

3. Results

3.1. Microscopic morphology of coating

Figure 3 shows the morphology of cold sprayed coating. Figures 3(a)–(e) and (f)–(j) correspond to the morphology of the coating surface and cross-section of samples 1–5 in table 2. As the figure 3 shows the profile of high alumina bronze particles (the dotted line area) can be observed in the coating. It can be seen from the surface morphology of the coating that the metal powder has good spread ability and the coating has small and
dispersed pores (area A in figures 3(a)–(e)). The particle size of the high alumina bronze particles in the cold spray coating samples 1–5 are 75–61 μm, 61–48 μm, 48–38 μm, 38–25 μm and 25–23 μm (the dotted line area of figures 3(a)–(e)), respectively. It can be seen from the cross-sectional morphology of the coating that the high-

Figure 1. The microscopic morphology of the powder: (a)–(e) high-aluminum bronze powder, and (f)–(j) Al₂O₃ powder.
aluminum bronze particles are combined by plastic deformation to form a coating by mechanical occlusion. The cold sprayed coating is dense, and is embedded with flaky Al₂O₃ particles and flat high-aluminum bronze particles of different particle sizes (as shown in figures 3(f)–(j)). When the high aluminum bronze powder has particles size of 75-61 μm, 61-48 μm, and 48-38 μm, the significant pores and cracks can be seen in the coating (arrows in figures 3(f)–(h)). When the high aluminum bronze powder has particles size of 38-25 μm and 25-23 μm, the pores can be seen in the coating, but the crack is not obvious. As the particle size of the high aluminum bronze decreases, the crack in the prepared coating gradually decreases, even disappear. The cold sprayed coating porosity is less than 1%[14]. The average porosity of the coating surface were calculated using ImageJ software and the average porosity of the coating sample 1–5 are 0.74%, 0.65%, 0.81%, 0.61% and 0.49%, respectively. The average value of the ratio of the length to width of the high-aluminum bronze particle in the sample 1–5 cross-section was calculated using the Photoshop software. The calculation results are 3.17, 3.4, 1.67, 4.25 and 6.50, respectively. The aspect ratio of the particle in the coating is large, indicating that the particle are more severe deformation. When high-aluminum bronze and Al₂O₃ powders with a particle size of 23-25 μm, the smallest metal particles would be deformed by the impact maximally. Therefore, the prepared coating has dense structure and the lowest porosity.

3.2. Fracture morphology of coating
Figure 4 shows the tensile fracture morphology of high-aluminum bronze coatings and elemental scanning results. And figures 4(a)–(e) correspond to the cross-sectional microscopic morphology of the sample 1–5. As the figure 4 shows that the fracture occurs at the interface of the high-aluminum bronze particle and on the surface of the Al₂O₃ particle, and the fracture morphology is typically brittle fracture. And the surface of the fracture is inlaid with white particles. It can be seen from the results of the energy spectrum measurement that the particle is Al₂O₃ (the red arrow in figure 4). When the high aluminum bronze powder has particles size of 75-61 μm and 61-48 μm, there are obvious pores and cracks in the prepared coating cross section (yellow circles in figures 4(a) and (b)), and gradually decreases as the particle size decreases. When the particle sizes of the high aluminum bronze powder are 48-38 μm, 38-25 μm, and 25-23 μm, the prepared coating has a neat cross section, and no obvious crack observed. It can be seen from the enlarged area of figure 4(e) that the Al₂O₃ particle on the cross section of the coating are flat and have no deformation (black area in the figure 4), and the high aluminum bronze particle around them have certain degree of deformation.

3.3. Uniform experiment analysis result
According to the theory and method of uniform experiment, the suitable uniform experimental scheme is selected, as shown in table 3.
Figure 3. SEM Morphology of the five coating surfaces (Left) and cross-sections (Right): (a) and (f) sample 1, (b) and (g) sample 2, (c) and (h) sample 3, (d) and (i) sample 4, (e) and (j) sample 5.
Linear regression analysis on the experimental data in table 3 was made using SPSS date analysis software. According to the uniform experimental analysis [15], the relationship between micro-hardness and bond strength with the size of powder is obtained as shown in equations (1) and (2). $X_1$ is the size of high-aluminum bronze powder, $X_2$ represents the size of Al$_2$O$_3$ powder, $Y_1$ denotes bonding strength and $Y_2$ is micro-hardness. Equations (1) and (2) only apply to the situation when particles sizes are in the range of 23–75 $\mu$m.

Figure 4. SEM images of tensile fracture morphology and area scanning analysis of the coating: (a) sample 1, (b) sample 2, (c) sample 3, (d) sample 4, (e) sample 5.
Based on equations (1) and (2), and data in table 3, the respond surface diagram of the relationship between the mechanical property of coatings and the size of powder is obtained. Figure 5(a) shows the relationship of high-aluminum bronze particle size and Al2O3 particle size on the bond strength of the coating. Figure 5(b) shows the relationship of high-aluminum bronze particle size and Al2O3 particle size on the micro-hardness of the coating.

According to the figure 5, when the Al2O3 particle size is constant, the bond strength and micro-hardness of the coating increase with decreasing particle size of the high-aluminum bronze. When the particle size of the high aluminum bronze powder is constant, the bond strength and micro-hardness of the coating increase as the particle size of Al2O3 decreases. When the particle size of high aluminum bronze and Al2O3 powder is 25-23 μm, the prepared coating has the largest bond strength (32Mpa) and micro hardness value (HV514).

In order to verify the accuracy of the linear relationship between particle size and mechanical property. In the range of powder particle size of 75-23 μm, three sets of powder were used to prepare the coating and the mechanical properties of the coating were tested. Compared with the calculation results (table 4), it is found that there is error between the measured bond strength and the micro-hardness value and the theoretically calculated value. Respectively, the error range is 1–3 MPa and HV3-11. The error is in a small range, and the experimental values are basically matched with the theoretical values. In summary, in the range of powder particle size of 75-23 μm, the linear relationship between powder particle size and mechanical property is accurate.
4. Discussion

4.1. The effect of powder particle size on the microstructure of the coating

In this study, the ratio of the length to width of the high-aluminum bronze particle in the coating was used to characterize the deformation of the high-aluminum bronze particle. The larger the aspect ratio of the cold spray powder particles in the coating, the greater the degree of plastic deformation of the particles and the closer the particles combined. According to section 3.1, the deformation of high aluminum bronze particles in the coating of sample 5 is the largest, and the deformation of high aluminum bronze particles in the coating of sample 3 is the smallest, as shown in figures 3(f)–(j). Combining the data in table 2 and figures 3(f)–(j), the deformation of the high-aluminum bronze particle depended not only on the size of high-aluminum bronze, but also on the size of the Al2O3 particle. The smaller the particles size of high-aluminum bronze particle, the greater the amount of deformation. Due to the smaller the particle size, the greater the particle acquisition speed during cold spray process [16]. And the greater kinetic energy can cause severe plastic deformation of metal particles [11]. The larger the deformation of the high-alumina bronze particles, the more sufficient the pores around the high-alumina bronze particles are filled, resulting in a decrease in the pores in the coating. So, the 23–25 μm high-aluminum bronze particles with highest velocity would be deformed by the impact maximally in cold spray process, which results in the coating with lower porosity and denser structure.

In the coating, the Al2O3 particle can promote the deformation of high-aluminum bronze particles. However, the Al2O3 particle is not deformed. As shown in the enlarged view in the upper right corner of figure 4(e), there are fine pores around the semi-embedded Al2O3 particles. During the coating deposition process, subsequent powder particles can squeeze the deposited Al2O3 particles and high-aluminum bronze particles. During the extrusion process, the deposited particles will also be driven to fill the surrounding pores. The larger the particle size of Al2O3 particles and high-aluminum bronze particles, the smaller the velocity and kinetic energy obtained by the particles. So, the impact on the high alumina bronze particle is weakened, which will result in poor pore filling effect. Poor filling effect will lead to increased porosity of the coating.

Combining the data in table 3 with that in figures 3(f)–(j), it can be seen that with increasing size of the high-aluminum bronze particle in the sprayed powder, the micro cracks in the obtained coating are more obvious, as indicated by the yellow areas in figure 4. The smaller the particle velocity during cold spray, the greater the stress in the coating and the concentration [17], which leads to crack propagation [18]. Therefore, under the same spraying conditions, the low kinetic energy of the high-aluminum bronze particle having large particle size results in stress concentration and the larger the crack.

4.2. Effect of powder particle size on the coating property

As can be seen from figures 3 and 4, there are pores in the coating and obvious cracks in the section. The pores and cracks in the coating reduce the bond strength between the coating and the substrate and the cohesive strength of the coating [19]. As the particle size of the high aluminum bronze and Al2O3 particles in the sprayed powder decreases, the porosity of the coating decreases and the crack decreases. Therefore, as the particle size of the high aluminum bronze and Al2O3 particles in the sprayed powder is reduced, the bond strength of the coating is increased.

From the table 3, it can be seen that the micro-hardness of the coating increase with decreasing particle size of the high-aluminum bronze and Al2O3 particles in the original powder. The micro-hardness of the coating is mainly related to the porosity and work hardening of the coating [20]. According to the principle of work hardening, with the increase of the degree of cold deformation of metal materials, the strength and hardness indicators have improved. As known in section 3.1, with a reduction in size of the high-aluminum bronze and Al2O3 particles, the deformation of the high-aluminum bronze particles during spraying is more sufficient. The more fully deformed the high aluminum bronze particles and the lower the porosity of the coating results in an increase in the micro-hardness of the coating.

5. Conclusions

In this manuscript, a low-pressure cold sprayed coating was prepared using a high-aluminum bronze powder with 16 wt% Al2O3 content. A uniform experimental method was used to study the effect of the particle sizes for Al2O3 and high-aluminum bronze powders on the mechanical property of low-pressure cold sprayed high-aluminum bronze composite coating. The respond surface of the relationship between bonding strength, micro-hardness and particles size was obtained. With decreasing particle size of the high-aluminum bronze and the Al2O3 powders in the spraying material, deformation of the high-aluminum bronze particles in the coating increase, and the porosity and cracks in the coating decrease. The increased deformation of the high-aluminum bronze particle and the reduced porosity and cracks in the coating lead to increase in the mechanical property of...
the coating. When the particle size of the high-aluminum bronze and Al2O3 powders are both in the range of 23–25 μm, the coating obtains outstanding mechanical properties.

Acknowledgments

The paper was financially supported by National Key Research and Development Program of China (2016YFE0111400), Program on Key Research Project of Gansu Province (17YFJWA159), Project of China Postdoctoral Science Foundation (2018-63-200618-34), Natural Science Foundation of Gansu Province of China (18JR3RA147), he program of 'Science & Technology International Cooperation Demonstrative Base of Metal Surface Engineering along the Silk Road’.

ORCID iDs

Li Feng @ https://orcid.org/0000-0001-5496-847X

References

[1] Li W S, Wang Z P, Lu Y and Xu J L 2006 Preparation, mechanical properties and wear behaviors of novel aluminum bronze for dies T Nonferr Metal Soc. 16 607
[2] Li W S 2006 Mechanical and tribological properties of a novel aluminum bronze material for drawing dies Wear 261 155
[3] Lu Y, Deng G, Yang X T, Guo W J and Shi X Y 2014 Microstructure and properties of high-aluminum bronze coatings after induction remelting prepared by supersonic plasma spraying J. Univ. Sci. Technol. B. 36 333
[4] Lu Y, Zhou J J, Yang X T and Ding M H 2011 Friction and wear properties of HVOF high aluminum bronze coating under sliding dry friction condition Special Casting & Nonferrous Alloys. 31 583
[5] Li W Y, Huang C J, Yu M and Liao H L 2013 Research status of cold spraying composite coatings J. Mater. Eng. 8 1
[6] Assadi H, Kreys H, Gartner F and Klassen T 2016 Cold spraying—a materials perspective Acta Mater. 116 382
[7] Koivuluoto H and Vuorio P 2010 Effect of powder type and composition on structure and mechanical properties of Cu J Therm Spray Techn. 19 1081
[8] Li C J and Li W Y 2002 Cold spray characteristics Surf. Eng. 1 12
[9] Bu H Y and Lu C 2010 Research and development of cold spray technology J. Mater. Eng. 1 94
[10] Jodoin B 2002 Cold spray nozzle mach number limitation J Therm Spray Techn. 11 496
[11] Li W Y, Li C J, Wang Y Y and Yang G J 2005 Effect of parameters cold sprayed Cu particle on its impacring behavior Acta Metall Sin. 41 282
[12] Li W S, Wang Z P, Lu Y and Yuan L H 2006 Corrosion wear behavior of al-bronzes in 3.5% nacl solution J. Mater. Eng. Perform. 15 102