Thermal deformation strengthening of WC-10Co4Cr coating prepared by high velocity air-fule process

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Abstract
In this paper, WC-10Co4Cr coating was prepared on the surface of LC9 aluminum alloy by high velocity air-fule (HVAF) process. And a thermal deformation method was developed to enhance the coating properties. Experimental results show that, during the process of thermal deformation, the increase of temperature and deformation amount could improve the microhardness of coating surface. With temperature of 480 °C and deformation amount of 16\% (0.8 mm), the microhardness reached the maximum value of 1349 HV0.3, which increased nearly 20\% compared with that of specimen (1137 HV0.3) without compressive deformation. Besides, the strengthening effects of thermal deformation temperature and deformation amount on the bonding strength of coating were obvious. With deformation temperature of 450 °C and deformation amount of 8\% (4 mm), the bonding strength reached the maximum critical load of 188 N, which was 17.5\% higher than that of initial state.

1. Introduction

With the rapid improvement of industrial technology, aluminum (Al) alloy has been widely used in the manufacturing field [1–4]. As a kind of high strength Al alloy, LC9 (7A09) alloy is one of the most remarkable alloys in China. LC9 alloy has been widely used in automobile, ship, machinery manufacturing and defense industry owing to the excellent specific strength, specific stiffness and excellent machining performance [5–8]. However, although ultra-high strength LC9 alloy is characterized by many advantages, the disadvantages of wear resistance and poor corrosion resistance are the main reasons for limiting its application.

In the recent years, the surface modification technology is one of the hotspots in the application research of Al alloy. Surface treatment methods of Al alloy mainly include surface spraying, surface alloying, laser surface modification, electrochemical method, ionomer injection method and micro plasma oxidation method [9–14]. During the above methods, surface spraying technology is widely used in industrial production, attributed to the excellent comprehensive performances of application range, various coating functions, high production efficiency and other unique advantages.

High velocity air-fuel is an excellent coating technology in the field of thermal spraying [15, 16]. Under the action of flame heating, the powdered materials were heated to a molten/semi-melting state and accelerated to form high-speed droplets, which deposited onto the surface of the workpiece. Eventually resulting in the formation of dense coating with certain special properties on specimen’s surface. HVAF technology could strengthen or regenerate the surface properties of materials, compensate the size reduction of parts caused by machining, and form a covering layer with various functions.

However, the bonding strength between the thermal spraying coating and the substrate was weak, and the coating contained some pores and inclusions. Besides, anisotropy of coating occurred owing to lamellar structure, which resulted in the decrease of friction resistance and corrosion resistance. In recent years, with the continuous development of coating strengthening technology, a variety of processes have been applied to strengthen coating performance. Such as composite shot peening, electric contact method, laser remelting and
laser cladding, etc [17–20]. Deng et al [21] reinforced Co–Cr–Al–Y coating with composite shot peening, and results revealed that the hardness and oxidation resistance of the coating were significantly improved. Wang et al [22] remelted the Ni–W–C composite coating by flame spraying with CO₂ laser, which effectively enhanced the microhardness and wear resistance of coating.

In this paper, HVAF equipment was used to prepare WC-10Co4Cr coating on the surface of LC9 Al alloy, and the microstructures and mechanical properties of the coating were analyzed. LC9 Al alloy with WC-10Co4Cr coating was subjected to hot pressing deformation to obtain the stress-strain curve. The influencing factors and rules of coating quality evolution during hot pressing deformation were investigated.

2. Experimental materials and methods

2.1. Experimental materials

Matrix materials: The matrix material selected in this paper is Al–Zn–Mg–Cu aluminum alloy (LC9), which is a typical ultra-high strength aluminum alloy. The chemical composition, physical properties and mechanical properties of LC9 aluminum alloy are respectively shown in tables 1–3. In this paper, LC9 matrix materials were processed into round rods (ϕ 25.4 mm × 10 mm) for coating bonding strength testing and plates for other properties testing (150 mm × 90 mm × 5 mm) according to ASTM C633.

Spraying material: In the present study, agglomerated and sintered ball-type WC-10Co-4Cr powder with particle size of 15–38 μm was used. The main chemical compositions of spray powder are shown in table 4.

Spraying equipment: In this experiment, the supersonic thermal spraying device of Kermetico from the United States (AcuKote HVAF) was used, as shown in figure 1. Table 5 shows the parameters selected for the spray gun. According to orthogonal table L9 (34), three parameters of traverse speed, spraying distance and step distance were set reasonably, as shown in table 6.

2.2. Coating preparation method

The coated surfaces of the samples were cleaned with acetone and polished with sand blast. Then the specimens were mounted on the tooling and sprayed with the surface perpendicular to spray gun. After spraying, a thermometer was used to measure the temperature of substrate, and carried out the second spraying until the substrate temperature dropped below 40 °C, which circulated until the coating thickness reached 200μm. Five samples were prepared for each experimental parameter.

2.3. Hot pressing deformation

In this study, Gleeble-1500 dynamic thermal simulation machine was applied to conduct unidirectional compression experiment, with the coating facing upward in contact with the pressure head. The deformation
temperature was 360 °C, 390 °C, 420 °C, 450 °C and 480 °C, respectively. The deformation was 4% (0.2 mm), 8% (0.4 mm), 12% (0.6 mm), 16% (0.8 mm) and 20% (1 mm) respectively. In order to simplify the experimental model, the compressive deformation of the coating is not considered in the deformation experiment.

3. Results and discussion

3.1. The coating performance
During the preparation of coating with thermal spraying technology, the process parameters have a great influence on the coating properties. In this study, the three indexes of porosity, microhardness and bonding strength were combined into one index by weight method. Among the three performance indexes, bonding strength is an important index of coating properties, which accounting for 60% of the coating performance. In this paper, the tensile method is used to test the bonding strength. In order to facilitate comparison, the minimum value of 70 MPa was selected as the reference value. Secondly, the microhardness is of great practical significance to evaluate the wear resistance of WC series coating, accounting for 30% of the coating performance. Finally, the porosity of the coating prepared by this process is generally low, which accounting for 10% of the coating properties. And porosity has a negative effect on the coating performance with a value of ‘−’. Eventually, the performance of coating was assessed as 60% of the bonding strength + 30% of the microhardness −10% of the porosity. It is worth noting that the microhardness value is thousands. In order to adapt to the
bonding strength and porosity data, the microhardness values were reduced by 100 times as the calculation parameter in the numerical processing.

The testing results of thermal spraying coating of LC9 aluminum alloy are shown in orthogonal test table 7. The range analysis method could be used to determine the influence degree of the coating performance from large to small, including transverse velocity, step distance, spraying distance and combustion chamber pressure. Table 7 indicates that the optimal thermal spraying parameters are the transverse velocity of 1,500 mm s$^{-1}$, spraying distance of 180 mm, step distance of 2 mm, and the combustor pressure of 80.4 MPa. Under the optimal process parameters, the main performances of WC-10Co4Cr coating prepared on LC9 Al alloy surface by HVAF process are shown in table 8.

### 3.2. Thermal deformation

Figure 2 shows the load-displacement curves of the materials during compression deformation at different temperatures. As shown in figure 2, with the strain of 4% (0.2 mm), the maximum stress of specimen occurred at 450 °C. This is because the specimen is in the stage of plastic deformation hardening. At this point, under the influence of temperature, the resistance during the hardening process of aluminum alloy would increase at a certain temperature. A similar variation was observed with the deformation amount of 8% (0.4 mm). When the deformation is greater than 8%, the specimen has the maximum stress value at 360 °C. After that, with the increase of temperature, the material completely entered the steady-state rheological stage, and the compressive stress decreased with the increase of temperature, as shown in figure 2.

The above results show that the deformation temperature has a significant effect on the rheological stress of metal plastic deformation. In the process of plastic deformation, the atomic kinetic energy increased with the increase of temperature, while the interatomic shear stress weakened. The diffusion of point defects was accelerated and dislocations were more easily generated. The reduction of effective stress of thermal activation energy dislocations led to the decrease of rheological stress. At this point, the softening effect of dynamic recovery and recrystallization was enhanced, which could reduce or even eliminate the work hardening of metal materials in the process of plastic deformation. Therefore, the rheological stress decreased with the increase of temperature during the process of thermal compression deformation.

In addition, it can be found that with the increase of temperature, the deformation amount of aluminum alloy into steady state rheology decreased. For example, the hardening process of aluminum alloy was significantly shortened at 450 °C, and the deformation amount is minimized when it enters steady state rheology. However, as the temperature rose to 480 °C, although the compression load was small in the
deformation process, the deformation amount increased from the hardening stage to the steady-state rheological stage.

3.3. Micro hardness

Table 9 shows the micro hardness distribution of coating after thermal compression deformation process. As shown in table 9, the micro hardness generally increased with the increase of deformation amount when the deformation was less than 16% (0.8 mm). For all deformation temperatures (except 360 °C), the specimen has the highest micro hardness with deformation amount of 16% (0.8 mm). The micro hardness increased by about 10% and then decreased slightly. In addition, it can be found that the micro hardness of the coating increased fastest with the increase of deformation at 360 °C. The maximum micro hardness (1349 HV0.3) was detected with temperature of 480 °C and deformation amount of 16% (0.8 mm). Compared with the sample without compression deformation treatment (1137 HV0.3), the micro hardness increased nearly 20%. The above results indicate that the surface hardness of thermal spray coating can be effectively improved by thermal compression deformation process.

![Figure 2. The load-displacement curves of the material during compression deformation at different temperatures.](image)

| Temperature (°C) | 4% (0.2 mm) | 8% (0.4 mm) | 12% (0.6 mm) | 16% (0.8 mm) | 20% (1 mm) |
|-----------------|-------------|-------------|--------------|--------------|------------|
| 360 °C          | 1131.8      | 1216.5      | 1295.9       | 1248.7       | —          |
| 390 °C          | 1125.2      | 1156.7      | 1205.2       | 1260.1       | 1258       |
| 420 °C          | 1169.3      | 1191.2      | 1222.7       | 1240.7       | 1237.5     |
| 450 °C          | 1144.2      | 1238.3      | 1236.6       | 1287.8       | 1283.2     |
| 480 °C          | 1123.5      | 1234.6      | 1235.4       | 1349.0       | 1306.9     |

Figure 3 shows the typical surface microstructure images of the sample (360 °C). As shown in figure 3(a), micro cracks appeared on the surface of coating with deformation amount of 16% (0.8 mm). Besides, the number and size of cracks on the coating surface increased with the increasing of deformation. When the deformation amount reached 20% (1 mm), a large number of cracks appeared on the surface of the coating, as shown in figure 3(b). At this time, the study of microhardness was meaningless, so it will not be discussed here.

The literatures reveal that the particle density and pore distribution are closely related to the micro hardness of the coating. Under the action of pressure and heat, on the one hand, it will increase the density of coating particles. On the other hand, it will produce a certain degree of work hardening on the surface of WC-10Co4Cr coating. These factors which can improve the surface hardness of the coating during thermal compression are beneficial to quality strengthening of the coating.

3.4. Bonding strength

Table 10 shows the effects of temperature and compression deformation on the critical load value of WC-10Co4Cr coating. It can be seen from the table that temperature and thermal deformation has a significant effect
During the process of thermal deformation strengthening, as the temperature was lower than 420 °C, the effect of compression deformation on the coating is not obvious. With the deformation temperature of 420 °C and the deformation amount of 12%, the bonding strength of coating reached an acceptable state (180 N). With the temperature increasing to 450 °C, even if the minimum deformation was 4%, the bonding strength of the coating showed effective enhancement (184 N). After that, with the increase of compression deformation, the bonding strength of the coating also continued to improve. With the deformation amount of 8%, the critical load of the coating has a maximum value of 188 N, which subsequently decreased with the deformation amount furtherly increased to 12%. However, when the temperature rose to 480 °C, the compressive deformation has no obvious effect on the bonding strength of the coating. Of particular noting that, when the deformation amount were 16% and 20%, it was difficult to detect the bonding strength of the coating by the scratch method because of cracks on the surface of the material.

### Table 10. Critical load Lc of coating under thermal compression deformation.

| Temperature (°C) | 4% (0.2 mm) | 8% (0.4 mm) | 12% (0.6 mm) | 16% (0.8 mm) | 20% (1 mm) |
|------------------|------------|------------|-------------|-------------|------------|
| 360              | 164        | 150        | 140         | —           | —          |
| 390              | 165        | 165        | 165         | 150         | 140        |
| 420              | 170        | 176        | 180         | 150         | 140        |
| 450              | 184        | 188        | 179         | 170         | 155        |
| 480              | 170        | 170        | 176         | 172         | 155        |

4. Conclusions

(1) The process parameters of thermal spraying coating on the surface of LC9 aluminum alloy were optimized by orthogonal method, and the optimal process parameters were obtained as follows: air pressure of 89 MPa, propane pressure of 91 MPa, combustor pressure of 80.4 MPa, powder feeder speed of 6 Rpm, transverse speed of 1500 mm s⁻¹, spraying distance of 180 mm and step distance of 2 mm.

(2) During the process of thermal deformation, the increase of temperature and deformation amount could improve the micro hardness of coating surface. With temperature of 480 °C and deformation amount of 16% (0.8 mm), the micro hardness reached the maximum value of 1349 HV0.3, which increased by nearly 20% compared with that of specimen (1137 HV0.3) without compressive deformation.

(3) The strengthening effects of thermal deformation temperature and deformation amount on the bonding strength of coating were obvious. With deformation temperature of 450 °C and deformation amount of 8% (4 mm), the bonding strength reached the maximum critical load of 188 N, which was 17.5% higher than that of initial state.
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