Front. Mech. Eng. China 2010, 5(3): 256–260
DOI 10.1007/s11465-010-0095-9

RESEARCH ARTICLE

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Application of cold spraying for flux-free brazing of aluminium alloy 6060

Abstract In the present study, samples of aluminium alloy 6060 were coated by cold spraying with a powder of brazing alloy Al12Si. The influence of the process gas temperature on particle velocities and coating build-up was investigated. The coated samples were heat-treated in air and under argon atmosphere to investigate the wetting behaviour of the deposited Al12Si and the diffusion processes between Al12Si coatings and substrates. Coated samples were brazed flux-free under argon atmosphere by an induction heating system. The microstructure of the coated, heat-treated, and brazed samples was investigated. The shear strength of the brazed joints was determined. The results show that the brazing alloy Al12Si could be very well deposited on the substrate by cold spraying. The particle velocity increased with increasing process temperature. Correspondingly, the thickness of Al12Si coatings increased with increasing process temperature. The heat treatments showed that a very good metallurgical bond between the Al12Si coatings and the substrate could be realized by the deposition using cold spraying. The coated samples could be well brazed without fluxes. The coating thickness and overlap width influenced the shear strength of the brazed joints. The highest shear strength of brazed joints amounts to 80 MPa.

Keywords aluminium alloy, flux-free brazing, cold spraying, shear strength

1 Introduction

Cold spraying uses an electrically heated high pressure gas to accelerate powder particles to high velocities. When solid powder particles impact target surfaces, they undergo plastic deformation and bond to the surfaces, rapidly building up a layer of the deposited material. Due to their strong impact, local rupture of oxide scales on particles and substrate surfaces occurs. Because the particles are in a solid state, the spray materials are hardly oxidized despite the deposition in air [1,2]. These properties of cold spraying are very interesting for brazing technology because the local rupture of oxide scales can favour the wetting of deposited filler materials [3,4].

Aluminium and its alloys are brazed in air or under controlled atmospheres using fluxes or in vacuum without fluxes. Of these brazing techniques, brazing under controlled atmosphere represents the most modern trend-setting technique [5]. Due to stable oxide scales on aluminium alloys, flux-free brazing of aluminium alloys under controlled atmospheres has remained a big challenge to material engineers. In the present study, flux-free brazing of aluminium alloy 6060 under argon atmosphere with the aid of cold spraying has been investigated. Samples of aluminium alloy 6060 were coated with a brazing alloy Al12Si. The influence of the process gas temperature on the particle velocities and coating build-up was investigated by means of a particle online monitoring device DPV 2000 with an integrated CPS-function (CPS: cold particle sensor). Some Al12Si-coated samples were heat-treated to investigate the wetting behaviour of deposited Al12Si coatings and diffusion processes between the Al12Si coatings and the substrates. Then, the coated samples were brazed under argon atmosphere without fluxes using an induction heating system. The shear strength of the brazed joints was determined. The microstructure of the coated, heat-treated and brazed samples was investigated by means of optical microscopy and scanning electron microscopy (SEM).

2 Experiments

In this study, plates of aluminium alloy 6060 (2 mm ×

Received December 16, 2009; accepted March 16, 2010

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20 mm × 60 mm) were used as substrate samples. A powder of brazing alloy Al12Si (−45 μm) delivered by Sulzer Metco Europe GmbH, Germany, was used to coat the samples. A cold-spray system Kinetiks 3000 by Cold Gas Technology GmbH (CGT), Germany, was employed for deposition. Nitrogen was used both as process gas and as powder carrier gas. The process gas temperature was varied in order to investigate its influence on particle velocities and coating build-up using a particle online monitoring device DPV 2000 with an integrated CPS-function by Tecnar Automation Ltée, Canada. The CPS-function allows measuring particle velocities of cold particles with low radiation intensities by using an additional laser beam. The point measurements were carried out. For a point measurement, 2500 particles were measured. The spray parameters are listed in Table 1.

Table 1 Spray parameters

parameters	value
gas temperature/°C	200–310
process gas/($L \cdot min^{-1}$)	500
carrier gas/($L \cdot min^{-1}$)	50
spray distance/mm	15
gun velocity/($mm \cdot s^{-1}$)	200–600
layer number	1–3

Some of the coated samples were heat-treated in air without fluxes to investigate the effect of the deposition by cold spraying on the wetting performance of Al12Si and under argon atmosphere to investigate the diffusion processes between the coatings and the substrate. The temperature for the heat treatment in air was 600°C and, for the heat treatment under argon atmosphere, 520°C and 580°C, respectively.

Some coated samples were brazed under argon atmosphere using an induction heating system. Two coated samples were used to produce a brazed joint. Both samples were pressed by two finished steel plates from their back sides. These steel plates were heated to 600°C and held for 15–20 s at this working temperature. The shear strengths of the joints were determined according to the standard DIN EN 12797. The samples for shear tests had an overlap of 2, 4 and 6 mm. The shear strength of the brazed joints was determined by means of an MTS tensile test machine.

The powder, coated, heat-treated, and brazed samples were prepared metallographically and investigated in terms of their microstructure by optical microscopy and SEM. On the cross-sections of the coatings, the coating porosity and thickness were measured by means of a picture analysis system.

3 Results and discussion

The cross-sections of the Al12Si powder are shown in Fig. 1. It can be seen that the particles of the powder are almost spherical. Because the composition of the powder is close to that of the eutectic reaction in the Al-Si system, the particles show a eutectic-similar dendritic microstructure.

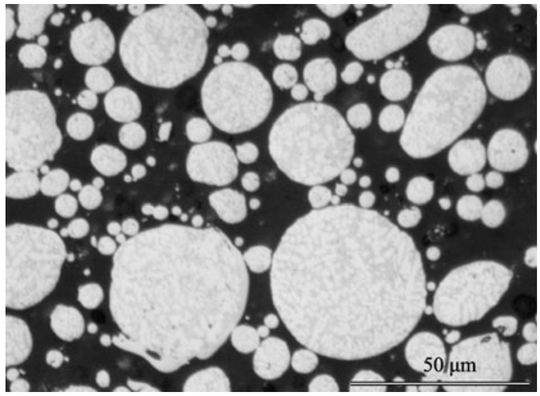

Fig. 1 Cross-sections of Al12Si particles

The spray trials showed that no coatings could be deposited with a gas temperature of 200°C under the given conditions as shown in Table 1. The DPV 2000 measurements revealed that the average velocity of the particles with the gas temperature of 200°C was 629 m/s, which indicates that higher particle velocities are essential for coating build-up. Figure 2 shows the particle velocity distributions via gas temperature. It can be seen that more than 20% of the particles had a velocity higher than 700 m/s; more than 10% of the particles had a velocity higher than 800 m/s. The reason for the lack of coating build-up was assumed to be that the total amount of the particles that were faster than their critical velocities was too low because of the fast-moving spray gun. To prove this assumption, a sample was sprayed under the same spray condition but without moving the spray gun. After a short time, a spray spot formed on the sample, which indicates that even with the gas temperature of 200°C, Al12Si coatings can be produced but only with a very low deposition efficiency of the powder. When increasing the gas temperature from 200°C to 250°C, the deposition performance of the particles improved significantly so that coatings formed on the samples. When further increasing the gas temperature from 250°C to 310°C, the deposition performance significantly improved again so that the coating thickness increased by over 200% compared to the coatings deposited at 250°C. Based on these results, samples for heat-treatments and brazing tests were then coated at the process temperature of 310°C. The coating thickness of the samples was varied between about 50 μm and 100 μm by changing the gun velocity and layer number. The DPV 2000 measurements revealed that the average velocity of the particles with a gas temperature of 250°C and 310°C was 658 m/s and 681 m/s, respectively, corresponding to an increase by 4.6% and 8.2%. It can be seen in Fig. 2 that the amount of particles that were faster than 600 m/s increased by less than 20% when increasing the gas temperature from 250°C to 310°C. In contrast, the coating thickness increased by over 200%, which indicates that the critical velocities for deposition decreased with increasing gas temperature. The porosity measurements revealed that the coatings deposited at 310°C had porosity values between 2.4% and 4.3%. Figure 3 shows a cross-section of an Al12Si coating. It can be seen that Al12Si particles and substrate surface deformed plastically during the deposition process. A good connection between the coating and the substrate is recognizable. Because the particles remained in solid state during spraying, some particles did not flatten enough so that pores formed within the coatings. Due to the solid-state process, the microstructure of the particles is still recognizable in the coatings, but it is difficult to detect the particle boundaries between the single particles.

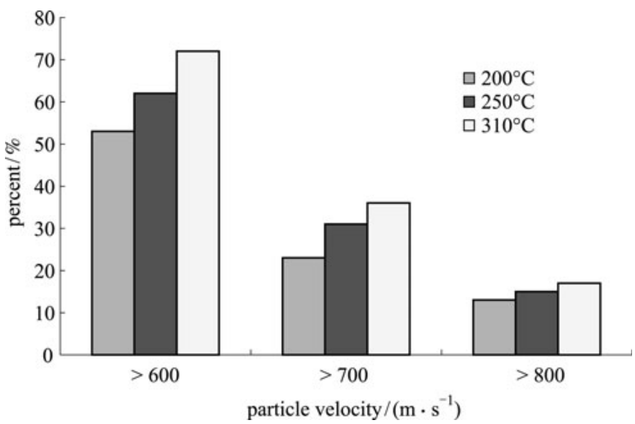

Fig. 2 Particle velocity distribution via process gas temperature

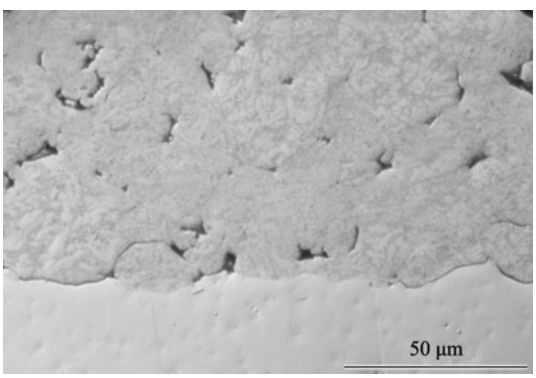

Fig. 3 Cross-section of Al12Si deposited sample

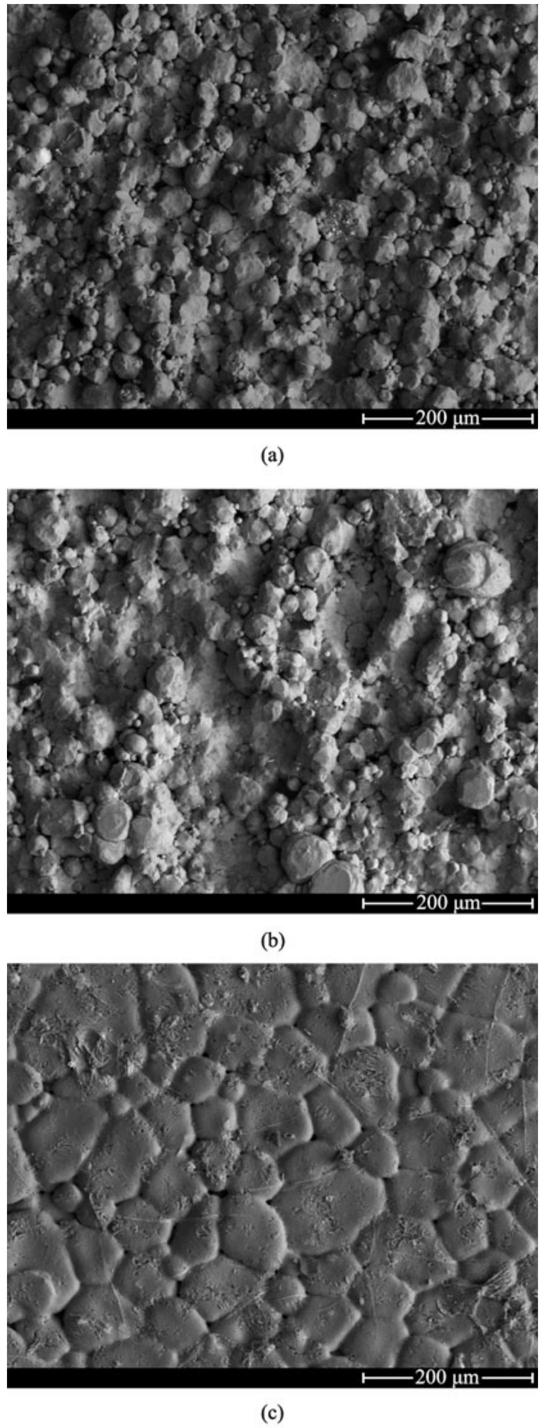

Fig. 4 Topography of Al12Si coating in as-sprayed state (a), after heat-treatment at 520°C (b) and 580°C under argon atmosphere (c)

Figure 4 shows the topography of an Al12Si coating in the as-sprayed state and after a heat treatment at 520°C and 580°C under argon atmosphere. It is obvious that after the heat treatment at 520°C, the coating was densified compared to the as-sprayed coating, which indicates that the sintering process occurred during the heat treatment due to the diffusion processes between the single particles. Energy dispersive X-ray spectroscopy (EDS)-measurements were carried out on the coating surface. The results showed that Si-contents varied between 10.70 wt.% and 14.29 wt.%, very similar to those measured on the surface of the as-sprayed coating. Oxygen and magnesium could not be identified by the EDS-measurements. Because of the eutectic reaction in the Al-Si system at 577°C, the coating melted during the heat treatment at 580°C, so that particles (as shown in Fig. 4(a)) disappeared, and the grains of the substrate were visible. At some locations, the solidified coating material can still be recognized. The EDS-measurements revealed Si-contents between 2.73 wt.% and 5.64 wt.% and Mg-contents between 1.75 wt.% and 2.39 wt.%, which indicates that Si in the coating diffused into the substrate, and Mg in the substrate diffused into the coating during the heat treatment. Figure 5 shows a cross-section of the Al12Si-deposited sample after a heat treatment at 600°C in air. It is obvious that the coating was completely melted during the heat treatment. The dark Si-dendrites formed due to the eutectic reaction during solidification. In the coating, there are light areas, in which no dendrites exist. Because of the diffusion of Si into the substrate, the Si-content in the coating decreased, so that the primary Al solidified in the coating prior to the eutectic reaction at 577°C, leading to formation of such light areas without dendrites. In Fig. 5, a very good metallurgical connection of the coating to the substrate is recognizable, although the heat treatment was carried out in air. This indicates that the deposition of the brazing alloy by cold spraying allows a good metallurgical bond between the brazing alloy and the substrate. Hence, it can be expected that the challenge for flux-free brazing of the deposited samples lies mainly in rupturing of the oxide scales on the coating of Al12Si during brazing.

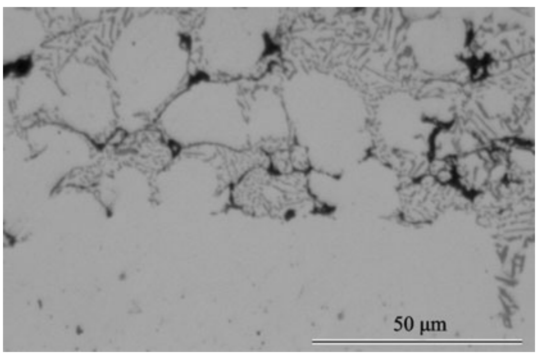

Fig. 5 Cross-section of Al12Si-deposited sample after heat-treatment at 600°C in air

The brazing experiments showed that the samples deposited with Al12Si could be well brazed under argon atmosphere without fluxes. Figure 6 shows a cross-section of a brazed joint produced using two samples with about 50-μm-thick coatings. It can be seen that the brazed seam is very narrow. At some location, dark Si dendrites are visible, which are attributed to the eutectic reaction of the Al12Si filler material at 577°C. The very narrow brazed beam indicates that Si in the coatings strongly diffused into the two substrates during the brazing process. As a result of

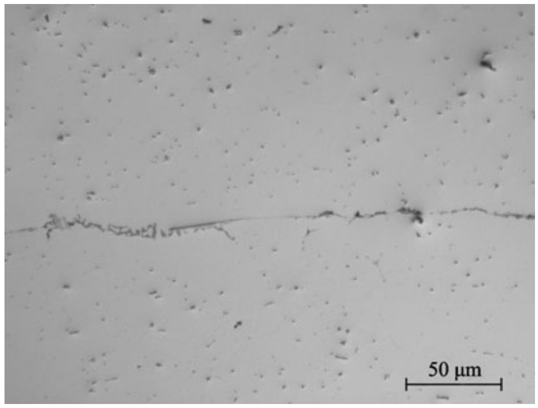

Fig. 6 Cross-section of a joint brazed of samples with two about 50-μm-thick coatings

the strong diffusion of Si into the substrates, the brazed seam is almost not recognizable at some locations.

Figure 7 shows the determined shear strengths of brazed joints depending on the overlap width and coating thickness. The shear strength decreased with increasing overlap width. It is known that the total defect area in brazed joints increases with increasing brazed area. It is assumable that this phenomenon occurs also with flux-free brazing of aluminium alloys. The defect area in the brazed joints increased with increasing overlap width, leading to the reduction in the shear strength of the brazed joints. It can be seen in Fig. 7 that the 50-μm-thick coatings led to higher shear strengths than the 100-μm-thick coatings. The wider brazed seam containing more Si-dendrites could be the reason for the lower shear strengths of the samples with 100-μm-thick coatings.

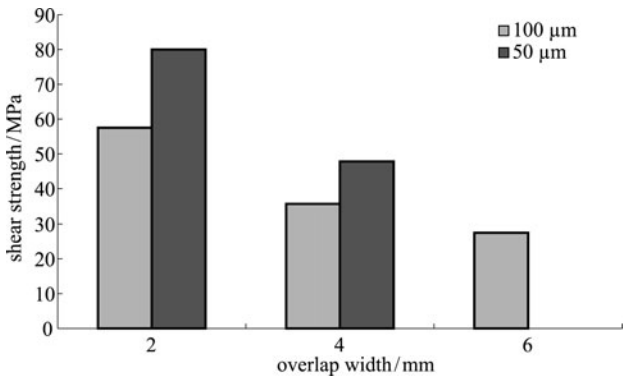

Fig. 7 Shear strength of brazed joints depending on overlap width and coating thickness

4 Conclusions

In the present study, samples of aluminium alloy 6060 were coated by cold spraying with a powder of the brazing alloy Al12Si. The influence of the process gas temperature on particle velocities and coating build-up was investigated. The deposition performance of the powder improved significantly with increasing gas temperature. An increase in the gas temperature from 250°C to 310°C led to an increase in the average particle velocity by below 4%, but an increase in the coating thickness by over 200%. The heat treatments showed that a very good metallurgical bond between the brazing alloy Al12Si and the substrate could be realized by deposition using cold spraying. The Al12Si-coated samples could be well brazed without fluxes. The coating thickness and overlap width influenced the shear strength of the brazed joints. The highest shear strength of the brazed joints amounts to 80 MPa.

Acknowledgements The authors would like to thank the German Science Foundation (DFG) for financially supporting the research work within the scope of DFG project Lu232/94-2.

References

1. Gärtner F, Stoltenhoff T, Schmidt T, Kreye H. The cold spray process and its potential for industrial applications. Journal of Thermal Spray Technology, 2006, 15(2): 223–232
2. Morgan R, Fox P, Pattison J, Sutcliffe C, ÓNeil W. Analysis of cold gas dynamically sprayed aluminium deposits. Materials Letter, 2004, 58(7–8): 1317–1320
3. Zhao L, Bobzin K, Ernst F, Zwick J, Roesing J, Lugscheider E. Feasibility study of brazing aluminium alloys through pre-deposition of a braze alloy by cold spray process. Advanced Engineering Materials, 2006, 8(8): 751–753
4. Bobzin K, Zhao L, Ernst F, Richardt K, Lugscheider E. Investigation into the flux-free brazing of an AlMg3 alloy with the aid of cold gas braze. Metal Application, 2008, (1): 50–54
5. Kohlweiler W. Brazing aluminium. http://www.BrazeTec.de