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Diffusion bonding mechanism and microstructure of welded joint of aluminium matrix composite $Al_2O_{3p}/6061$ ①

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Abstract: Relationships between microstructures of welded joint and welding parameters or weld strength of aluminium matrix composite $Al_2O_{3p}/6061$ subjected to diffusion welding were studied. The results are as follows: key factor affecting strength of welded joint is oxide in the weld zone. The existence of oxide in the welded joint not only hinders the diffusion of the matrix atoms, but also destroys the good interface between the matrix and the reinforced phase. The oxides turn into fine particles from film with increasing welding temperature, and the destroying effect on welded joint decreases, which increases the strength of the welded joint. On the basis of this, the diffusion welding of aluminium matrix composite $Al_2O_{3p}/6061$ was successfully realized.

Key words: aluminium matrix composite; oxide; welded joints; microstructure **Document code**: A

1 INTRODUCTION

Aluminium matrix composite, thanks to its outstanding physical and mechanical performance, has attracted great attentions from material scientists both at home and abroad. Especially the particle reinforced aluminium matrix composites, cost-effective, isotropical, wear-resistant and flexible with functional design, have wide applications in aerospace and aviation structural components etc[1~6]. The study on the weldability of aluminium matrix composites and welding technique is far from enough, compared with the remarkable achievements on their manufacture techniques, plasticitical formation, cold machanical processing, heat treatment and surface treatment. Any advanced materials remain impractical until they are processed into structural components, and welding plays an essential role. The inadequate study on the welding of aluminium matrix composite attributes to big difference in physical and chemical performances between matrix and reinforced phase, resulting in neither good welding nor high quality of welded joint[7~11]. At present, study on diffusion welding of aluminium matrix composites is much fewer in both China and other countries, especially for thorough analysis of microstructure of welded joint. However, the microstructure is a key factor affecting the property of welded joint. This paper, based on series of experiments on particle reinforced phase aluminium matrix composite $Al_2O_{3p}/6061$, conducts the study of the effects of diffusion welding parameters on the strength of joint, and further analysis of the microstructure in the weld zone. It is intended to provide the theoretical and experimental basis for the welding parameter optimization of particle reinforced aluminium matrix composite.

2 EXPERIMENTAL

2.1 Experimental materials

Particle reinforced aluminium matrix com-

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posite was prepared by means of extrusion casting. Its mechanical properties are listed in Table 1. Average size of reinforced phase is 0.4 μm, and the fraction factor is 30%. Its microstructure is shown in Fig. 1.

Table 1 Mechanical properties of $Al_2O_{3p}/6061$ composite and 6061

Material	Tensile strength/MPa	
	M	CS
$Al_2O_3/6061$	300	504
6061	125	310

M—annealing; CS—artificial ageing.

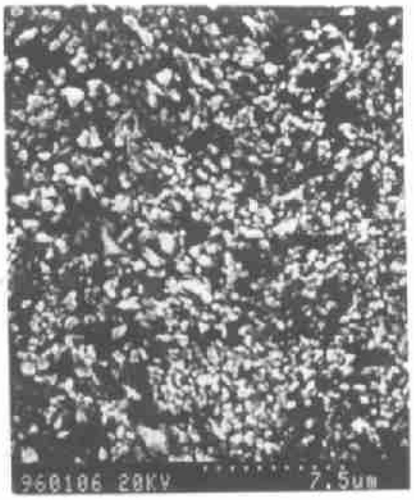

Fig. 1 Microstructure of aluminium matrix composite $Al_2O_{3p}/6061$

2.2 Experimental procedure

(1) By wire cutting, the material was processed into 30 mm × 5 mm × 10 mm welding specimens.

(2) Diffusion welding through heating electric resistance was conducted in a 10^{-1} Pa vaccum chamber. The welding process is shown in Fig. 2.

(3) Tensile test of the welded joint was carried out on an electronic universal testing machine at a tensile speed of 0.5 mm/min.

(4) The analysis on microstructure of the welded joint was accomplished through SEM and TEM.

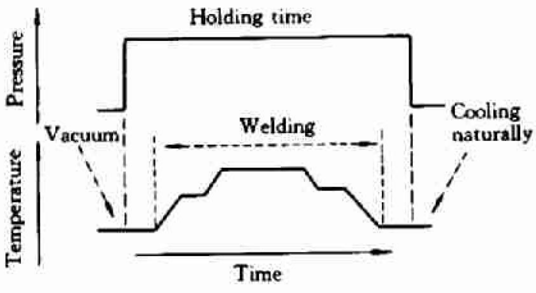

Fig. 2 Process flow diagram for diffusion welding of aluminium matrix composite $Al_2O_{3p}/6061$

3 EXPERIMENTAL RESULTS AND ANALYSIS

Fig. 3 shows the relationship between welding parameter and strength of joint subjected to diffusion welding. It is obvious that the strength of joint increases with the increase of temperature and pressure, especially the temperature. The strength of joint is enhanced especially fast at the temperature higher than the solidus temperature of the matrix (580 ℃), while the strength becomes constant at the temperature

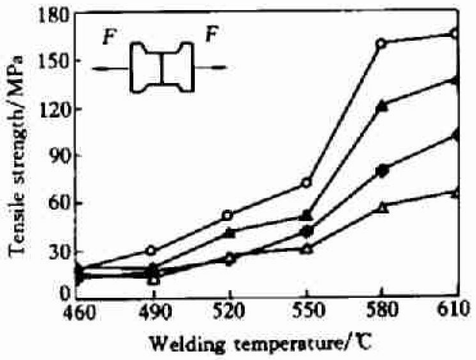

Fig. 3 Relationship between strength of welded joint and welding parameters

(30% $Al_2O_{3p}/6061$ composite, t = 30 min)

○—Abraded using 360# emery paper, p = 5 MPa;
▲—Abraded using 1800# emery paper, p = 5 MPa;
◆—Abraded using 360# emery paper, p = 2 MPa;
△—Abraded using 1800# emery paper, p = 2 MPa

close to the liquidus temperature of the matrix (650 ℃). Under the same welding temperature, the strength of joint for the composite polished by 1800# emery paper before welding is obviously inferior to that of the composite by 360# emery paper. Additionally, it can be seen from Fig. 3 that change of temperature in the range of 10 ℃ and welding pressure in the ranges of 2 MPa both have obvious effects on the strength of the welded joint.

It is thus clear that the optimum parameters used in this experiment are as follows: $\theta_w = 580 \sim 650$ ℃, $t_w = 30$ min, $p_w = 5$ MPa. High quality of welded joint polished by 360# emery paper before welding can be obtained. Maximum tensile strength can reach 170 MPa, close to 60% of that of base metal.

In order to further analyze the mechanism of aluminium matrix composite subjected to diffusion welding, microstructure of welds was studied through SEM and TEM.

As seen in the scanning electron micrograph in Fig. 4, there is an easily detected bond line as shown in Fig. 4(a) in the joint under low welding temperature, where lamellar white substances gather, causing lower tensile strength. Through EDX energy spectral analysis, the substances turn out to be oxide film, which prevents atom diffusion in the matrix , and consequently reduces the tensile strength. As the welding temperature increases, the plastic deformation of the joint becomes more active.

The spliting of oxide film under pressure hinders the atom diffusion to a less extent as shown in Fig. 4(b) thus improving the tensile strength. When the temperature rises beyond the solidus temperature, the bond line vanishes, and the welded zone with certain thickness as shown in Fig. 4(c) is formed there after certain holding time. The strength of the joint reaches its maximum. The oxide film is not detectable through SEM in the welded joint.

TEM is used to further analyze the microstructure of the welded joint. Fig. 5 shows the transmission electron micrographs of the parent and the welded joint. We can see obvious honeycomb texture made up of fine particles in the parent as well as the welded joint. The results of electron diffraction analysis show that such honeycomb texture is oxide of aluminium Al_2O_3.

To sum up, the shape of oxide Al_2O_3 on the bond interface at different temperatures is shown in Fig. 6. The shape of oxide gradually turned into fine particle from film with increasing welding temperature. Especially when the welding temperature is beyond the solidus of matrix alloy, the oxide turns into honeycomb texture made up of fine particles completely. The interface layer between the matrix and the reinforced phase is known as the main factor affecting the

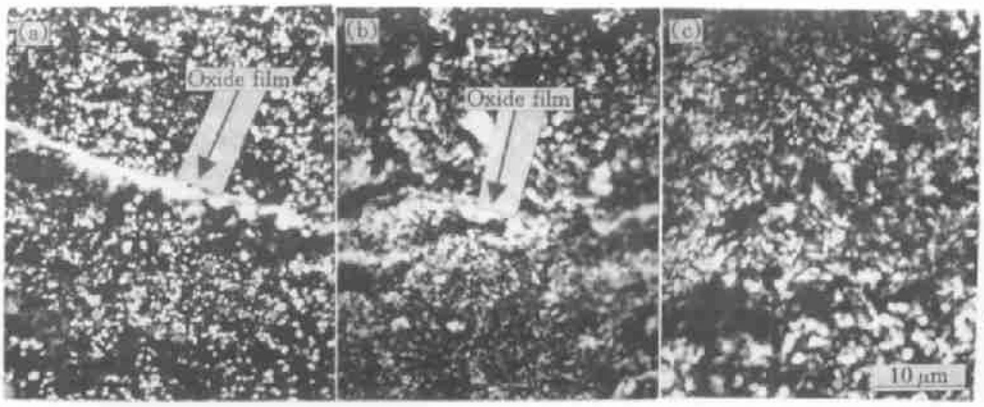

Fig. 4 Scanning electron micrographs of welded joint at different welding temperatures
(a)—$\theta_w = 550$ ℃, $p = 5$ MPa, $t = 30$ min, $\sigma_b = 74$ MPa; (b)—$\theta_w = 580$ ℃, $p = 5$ MPa, $t = 30$ min, $\sigma_b = 118$ MPa;
(c)—$\theta_w = 620$ ℃, $p = 5$ MPa, $t = 30$ min, $\sigma_b = 165$ MPa;

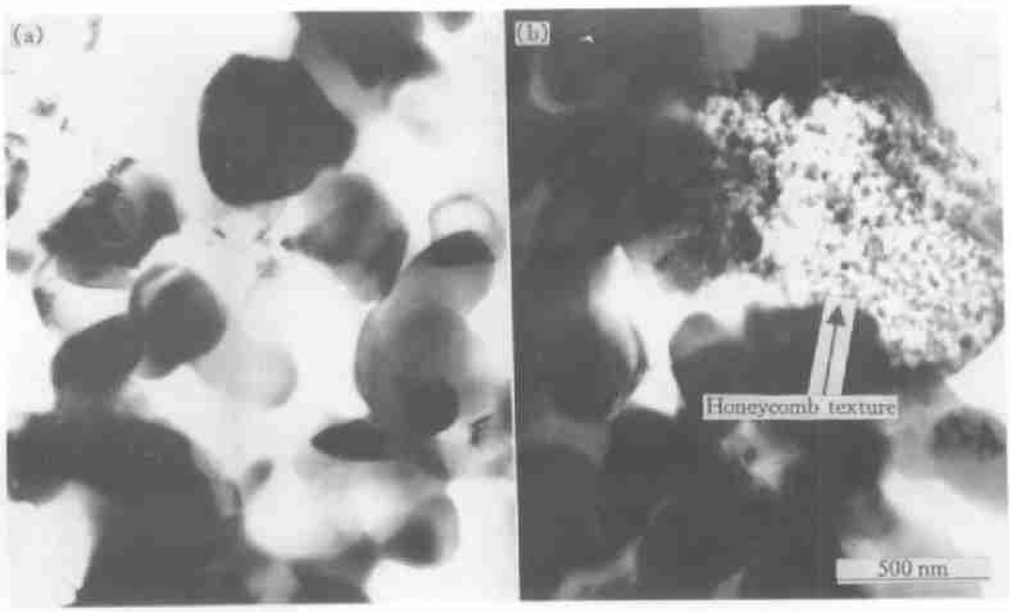

Fig.5 Transmission electron micrographs of base metal and welded joint
(a)— Base metal; (b)— Welded joint
($\theta_w = 600$ ℃, $p = 5$ MPa, $t_w = 30$ min)

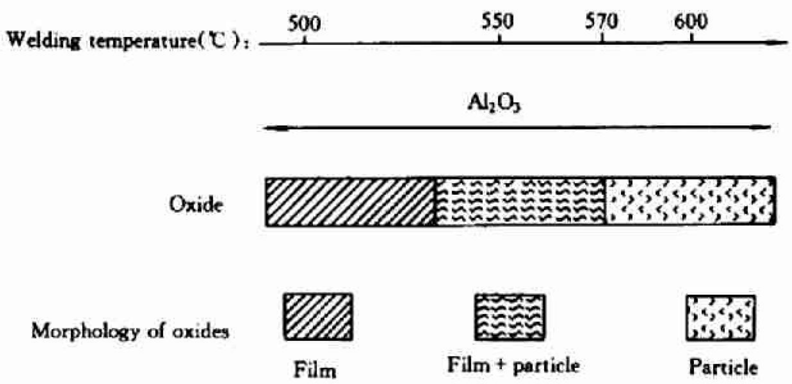

Fig.6 Scheme of oxide in weld zone changing with welding temperature

performance of the composite. The load the joint endures is transmitted to the reinforced phase Al_2O_3 particles from the matrix through the interface layer. The condition of interface layer in the welded joint, the key to optimization of element effect, is also directly related to the performance of the composite. Because of certain quantity of honeycomb texture in the welded joint, the good interface layer between the matrix and the reinforced phase is not available. Moreover, such defects will turn into crack source under stress, reducing the strength of the welded joint, and become direct reason for poor weldability of the composite. With the increase of temperature, the oxide turns into fine particles from film gradually, the destroying effect to the welded joint of Al matrix composite subjected to diffusion welding decreases, and the strength of the welded joint increases. This is why the strength of the welded joint increases obviously when the welding temperature is beyond the solidus temperature of the matrix.

4 CONCLUSIONS

(1) Welded joint of high quality for aluminium matrix composite $Al_2O_{3p}/6061$ can be successfully obtained through vacuum diffusion welding. Under appropriate welding parameters, the tensile strength of welded joint can reach 170 MPa, close to 60 % of that of the base metal.

(2) Appearance of oxide in the weld zone is the key factor affecting the strength of the joint. With increasing welding temperature , the oxide gradually turns into fine particles, then the destroying effect on the welded joint of the Al matrix composite is decreased, and the strength of the welded joint is increased.

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