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Studying of micro-bonding in diffusion welding joint for composite

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Abstract

This paper reports the preliminary investigation of the micro-bonding of reinforcement/matrix and reinforcement/reinforcement in a diffusion welded joint for Al_2O_3p/6061Al composite and analyzes the microstructure and performance of the welded joint. Experimental results show that the interface of the matrix/reinforcement has better bonding only when the diffusion welding temperature is higher than the solid phase line of Al_2O_3p/6061Al composite. It is found that a critical temperature exists between solid and liquid phase line of the aluminum matrix composite. When the diffusion welding temperature reaches this value, not only the interface of the matrix/reinforcement exhibits better bonding, but also the welded joint can be greatly strengthened, the molten matrix penetrating into the interface of the reinforcement/reinforcement can change the bonding of reinforcement/reinforcement into reinforcement/matrix/reinforcement. Based on the experimental results, the authors firstly point out that the technology on non-interlayer liquid phase diffusion welding can successfully bond Al_2O_3p/6061Al composite.

Keywords: Aluminum matrix composite; Diffusion welding; Matrix metal; Reinforcement

1. Introduction

Aluminum matrix composites have a widely applied prospect because of their high specific strength, stiffness and wear resistance. Welding, a second working technology is also stressed. However, it is difficult to obtain a good quality welded joint adopting molten welding methods, some defects exist such as pore and interface reactant because of the great difference between aluminum matrix and reinforcement in physical and chemical properties [1]. Diffusion welding, as one solid bond method, has widely been recognized all over the world, because the lower welding temperature can resist the interface reaction and is beneficial in obtaining a competent welded joint [2]. Among the three bonding interfaces: matrix/matrix, matrix/reinforcement and reinforcement/reinforcement, during the aluminum matrix composite diffusion welding, only the matrix/matrix can easily obtain a better joint, while the matrix/reinforcement and reinforcement/reinforcement impede the diffusion welding joint to have a high strength joint [3–5]. Therefore, how to solve the micro-bonding of matrix/reinforcement and reinforcement/reinforcement is the key to obtaining good quality diffusion welding for an aluminum matrix composite. Up to now, there is no report about it.

This paper will systematically study the micro-bonding of matrix/reinforcement and reinforcement/reinforcement, and try to discover a new technology, 'non-interlayer liquid phase diffusion welding', which the temperature being between solid phase line and liquid phase line of the aluminium matrix composite can greatly improve the joint strength.

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Table 1
Chemical compositions of 6061Al alloy (wt.%)

Cu	Mg	Mn	Fe	Si	Zn	Ti	Ni	Al
0.34	0.75	0.22	0.36	1.26	<0.15	<0.05	<0.05	Bal

2. Experimental material and process

2.1. Experimental material

The Al_2O_3p/6061Al composite, whose tension strength is 300 MPa under the annealed state, was made by the method of squeeze casting. The mean size of Al_2O_3 particulate reinforcement is 0.4 m and the ratio of volume is 30%. The aluminum alloy used in comparative tests is the same as the matrix metal of Al_2O_3p/6061Al composite, and their chemical composition is listed in Table 1. The solid phase line and liquid phase line for the aluminum matrix composite measured by the way of TG-DTA is, respectively, 855 and 920 K (Fig. 1), the variation for the volume ratio of liquid composite with temperature between solid phase and liquid phase is shown in Fig. 2.

2.2. Experimental process

Specimen size is 5 × 10 × 30 mm made by the way of wire cutting. Specimen is welded by the way of diffusion welding at the constant temperature controlled by the thermocouple in the 1.33×10^{-1} vacuum chamber. Tension test of the welded joint was measured with the electron-mechanical universal material testing machine made in Instron Company (USA).

Joint fracture surface was scanned with SEM, and its chemical composition was analyzed with EDX in SEM in order to check the bonding state in diffusion welding joint, the parent microstructure was analyzed with TEM in order to develop welding technology on the composite.

3. Results and discussion

In order to know the micro-bonding state of diffusion welding joint in Al_2O_3p/6061Al composite, the composite–composite (MMC–MMC), composite–matrix metal (MMC–6061Al) and matrix metal–matrix metal (6061Al–6061Al) were bonded with diffusion welding, respectively (Fig. 3). In the micro-bonding of diffusion welding joint, there are three micro-bonding states of matrix/matrix, matrix/reinforcement and reinforcement/reinforcement in MMC–MMC and two micro-bonding states of matrix/matrix, matrix/reinforcement in MMC–6061Al.

In Fig. 3, the strength of the joint of 6061Al–6061Al is equal to 90% of that of 6061Al–parent alloy, showing that the effect of oxide on the strength of the joint can be neglected. When the diffusion welding temperature is lower than that of the composite solid phase line, the strengths of three kinds of welded joint all increase with increasing temperature, and the joint strengths of MMC–MMC, MMC–6061Al are obviously lower than that of 6061Al–6061Al. This shows that the micro-bonding of reinforcement/reinforcement and matrix /reinforcement belong to weak-bonding in which the reinforcement doesn't play any role of strength, but become a crack origin at the interfaces of reinforcement/reinforcement and matrix /reinforcement.

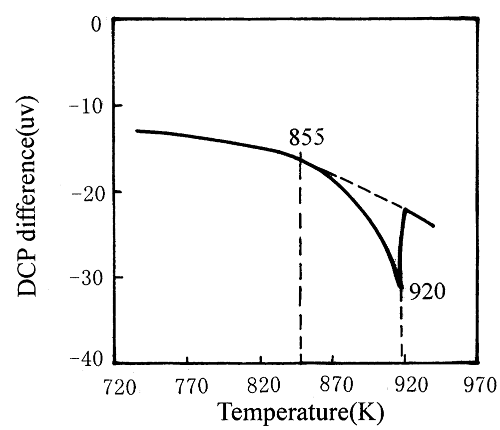

Fig. 1. Determination of the liquid-solid co-existing range of Al_2O_3/6061Al composite by differential scanning calorimetry.

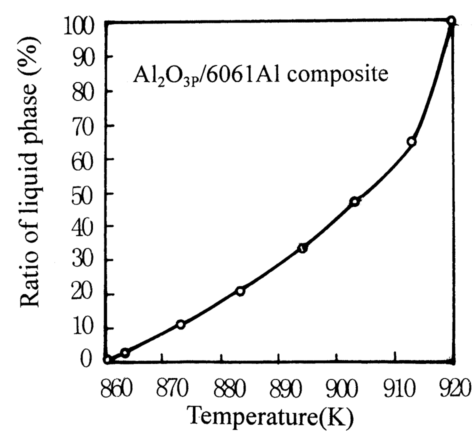

Fig. 2. Volume fraction of the liquid phase matrix as a function of temperature.

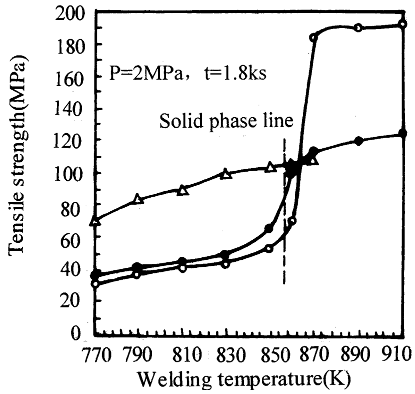

Fig. 3. Relationship between temperature and tensile strength of welded joint □, 6061Al–6061Al, ●, MMC–6061Al, ○, MMC–MMC.

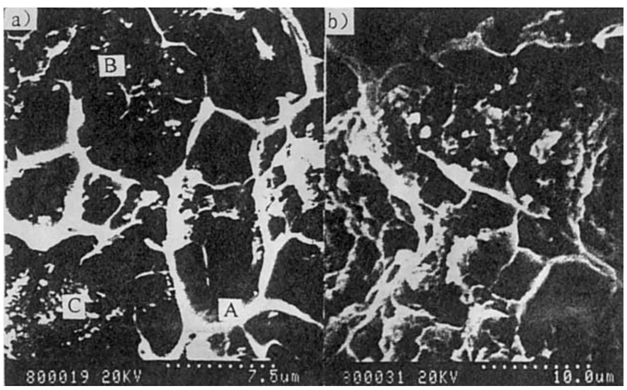

Fig. 4. Effect welding temperature on fractograph of MMC–6061Al, (a) 850 K, (b) 860 K.

Table 2
Analysis result of SEM and EDX on the fractured surface (wt.%)

Analysis point	Mg	Si	Fe	Cu	Mn	Al
Particulate	0.78	1.48	0.29	0.21	0.13	Bal
Matrix	0.70	1.39	0.18	0.23	0.11	Bal

When the diffusion welding temperature is between the solid phase line and liquid phase line, joint strengths of MMC–MMC and MMC–6061Al are increased rapidly, and exceed that of 6061Al/6061Al, and have an obvious threshold value of temperature, about 860 K for MMC–6061Al (liquid volume fraction 2%), about 870 K for MMC–MMC (liquid volume fraction 15%). The results show that the reinforcement of Al_2O_3 particulate has played a role of strengthening in the diffusion welding joint.

To further study the micro-bonding variation in the interface of matrix/reinforcement, the state of MMC side in the joint fracture of MMC/6061Al was scanned with SEM. When the diffusion welding temperature was lower than the solid phase line temperature of the composite, there are three zones (A, B and C) on the fracture surfaces as shown in Fig. 4a. Zone A shows an obvious ductile fracture of aluminum fracture, meaning a good bonding in the interface of matrix/matrix. Zone B shows a ductile fracture with low and small dimples and some uncovered Al_2O_3 particulates, indicating that the interface of matrix/reinforcement could not bond well. Zone C shows a brittle fracture with a layer of oxides, indicating that zone C was not welded well. However, when the diffusion welding temperature was higher than the solid phase line of composite, an obvious ductile fracture took place in 6061Al aluminum alloy side of the bonding interface as shown in Fig. 4b and Al_2O_3 particulates are found only at the bottom of the dimples. Table 2 is the analyzed results of the Al_2O_3 particulates and the matrix nearby the Al_2O_3 particulates with EXD of SEM. Since the chemical composition of Al_2O_3 particulate is the same as that of the matrix nearby, it is reasonably thought that a layer of matrix was adhered on the Al_2O_3 particulate surface. This can be explained because the atom in the interface deformed a little and had a high energy during diffusion welding. When the diffusion welding temperature reached 860 K, the interface of matrix/reinforcement had been bonded well because the reinforcement was wetted by the molten matrix, which had a high energy and had priority to melt during diffusion welding.

In order to deeply investigate the micro-bonding of reinforcement/reinforcement, the fracture of MMC–MMC was analyzed with SEM and the results were shown in Fig. 5. When the welding temperature was 830 K, there were some uncovered Al_2O_3 particulates in fracture zone A of Fig. 5a, while zone B showed a brittle fracture and a layer of oxide. When the temperature increased, the oxides gradually disappeared and a ductile fracture gradually occurred. At the temperature of 860 K, both at the bottom and the edge of the dimples Al_2O_3 particulates could be seen (Fig. 5b). The general feature in Fig. 5b showed that the Al_2O_3 particulates at the bottom of the dimples bonded well with the matrix, coinciding with the result in Fig. 4. It is estimated that the bad bonding of reinforcement/reinforcement caused the uncovered Al_2O_3 particulates at the edge of the dimples. When the diffusion welding temperature reached 870 K, the general feature in Fig. 5c was similar to that in 860 K except the amount of uncovered Al_2O_3 particulates at the edge of the dimples obviously decreased. It shows that not only the interface of matrix/reinforcement could be bonded well, but also could improve the bonding of reinforcement/reinforcement. It should be noted that it was impossible to succeed in bonding the interface of reinforcement/reinforcement because the molten temperature of reinforcement was much higher than that of matrix. In fact, when the welding temperature reached 870 K, the matrix would change into liquid from solid and penetrate into the interface of reinforcement/reinforcement dur-

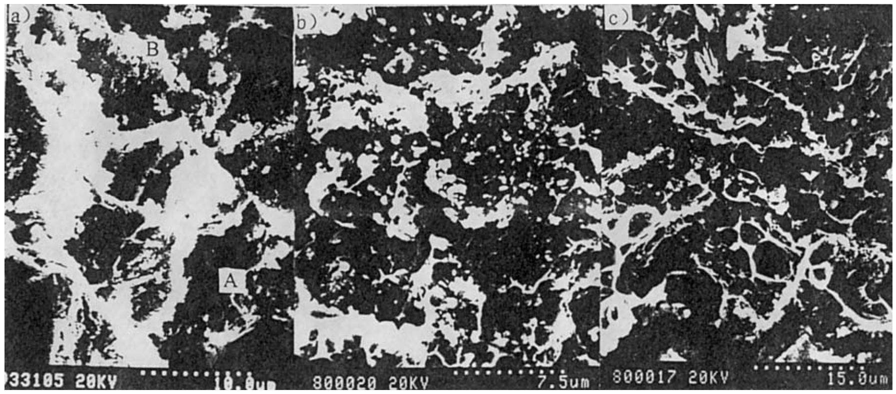

Fig. 5. Effect welding temperature on fractograph of MMC–MMC, (a) 830 K, (b) 860 K, (c) 870 K.

ing diffusion welding, as a result, the bonding of most reinforcement/reinforcement interface would change into the bonding of reinforcement/matrix/reinforcement. This shows that the welding temperature is an important parameter for MMC weldability, as long as the welding temperature reached 870 K, the strength of the welded joint improved, otherwise, the strength deteriorated. Therefore, 870 K is a threshold value for diffusion welding as a critical temperature.

However, compared with the composite parent fracture (Fig. 6), the general feature in the welded joint of Fig. 5c has smaller and shallower dimples. This shows that although the weldability was improved at the welding temperature of 870 K, there were more defects in welded joint comparison with the composite parent. Due to the difficulty and complexity, the weldability of the composite needs to be studied more.

4. Reasonable welding technology for Al_2O_3p/6061Al composite

On the Basis of foregoing analysis, a new welding technology of Al_2O_3p/6061Al composite has been pointed out as shown in Fig. 7. When the welding temperature reaches 870 K the strength of the welded joint increases rapidly, up until the liquid phase line temperature of composite. The strength of the welded joint is 200–210 MPa, about 70% of the composite parent, and the deformation of welded joint is less than 2%. When the welding temperature is over the liquid phase line of the composite, the welded joint strength does not increase any more; on the contrary, the deformation increases obviously, so this temperature is not suitable to weld the high-precision weld. Comparison with the solid diffusion welding and liquid diffusion welding with a layer (TLP), this mew method could be called non-interlayer liquid phase diffusion welding.

The strength of the composite parent, with the same heating loop of bonding as the non-interlayer liquid phase diffusion welding, did not vary too much (Fig. 7). Fig. 8 shows no reaction had token place in the interface of matrix/reinforcement, coinciding with the published date [6].

Fig. 6. Fracture surface of aluminium matrix composite Al_2O_3/6061Al.

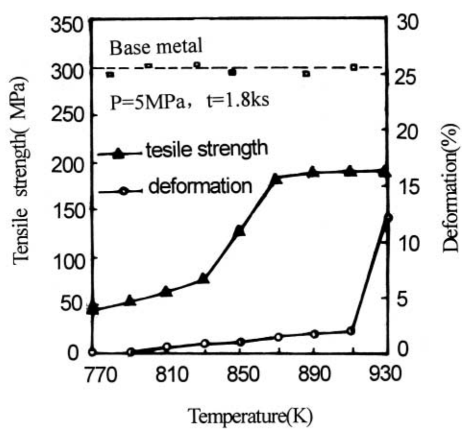

Fig. 7. Relationship between temperature and tensile strength of welded joint.

Fig. 8. Transmission electron micrographs of the composite parent.

5. Conclusions

Under the condition of solid state diffusion welding, Al_2O_3p/6061Al composite could not be bonded well in the interfaces of matrix/reinforcement and reinforcement/reinforcement and the reinforcement could not play the role of strengthening.

The interface of matrix/reinforcement could be bonded well only when the welding temperature was higher than that of composite solid phase line, and the strength of welded joint for MMC–6061Al had an obvious threshold value near this realm.

A critical temperature was found to exist between the solid and liquid phase line temperature of composite. When the welding temperature reached the critical temperature, the liquid phase matrix would change the bonding of reinforcement/reinforcement into reinforcement/matrix/reinforcement by penetrating into the interface of reinforcement/reinforcement.

A new technology on non-interlayer liquid phase diffusion welding was made out according to the critical temperature value, and successfully used to weld the Al_2O_3p/6061Al composite. The technology could avoid forming the brittle phase and non-reinforcement strip just as in the welded joint, but also make the reinforcement play a role of strength. So that the welded joint strength reached 200–210 MPa, about to 70% of the strength of the composite parent and the deformation was less than 2%.

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