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Effect of Ti-Al on microstructures and mechanical properties of plasma arc in-situ welded joint of SiC_p/Al MMCs

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Abstract: The effect of Ti-Al on microstructures and mechanical properties of SiC_p/Al MMC joints produced by plasma arc in-situ weld-alloying was investigated, in which argon-nitrogen mixture was used as plasma gases and Ti-Al alloy as filling composite. The results show that the formation of needle-like harmful phase Al_4C_3 is effectively prevented in the weld by in-situ weld-alloying/plasma arc welding with Ti-Al alloy sheet filler whose titanium content is more than 20%. The fluidity of molten pool is improved, and stable molten pool is gained for the addition of the Ti-Al alloy. The mechanical properties of welded joint are effectively enhanced by the compact-grain structure and the new reinforced composites such as Al_3Ti, TiN, AlN and TiC welded joint. The test results of mechanical property show that the maximum tensile strength of welded joint gained by adding Ti-60Al alloy is up to 235 MPa. The factors influencing the tensile strength were also investigated.

Key words: SiC_p/Al MMCs; plasma arc; in-situ welding; Ti-Al alloy

1 Introduction

At present, aluminum metal matrix composites (Al MMCs) are more and more widely applied in aerospace, spaceflight, auto manufacturing, optical instrument and sports industry due to their excellent combination properties of high specific strength, high specific stiffness, high elastic modulus, better wear-resistance and high temperature resistance[1−2].

But Al MMCs are not applied widely in industry due to their poor weldability. And the welding technique is the key to wide industry application for Al MMCs [3−4]. SiC_p/Al MMCs have been extensively investigated worldwide. Many methods such as brazing[5], diffusion bonding[6], transient liquid phase bonding[7], gas shielded arc welding[8] and laser welding[9] have been used to weld these materials. And fusion welding is the most flexible and versatile one. The previous investigations show that how to prevent the formation of harmful phase Al_4C_3 is the key for the fusion welding of SiC_p/Al MMCs. The defects, such as pores, microfissure and inhomogeneous wild phase would debase the mechanical properties joints, which should be avoided in the welding process[10−12].

In our previous investigation, pure titanium sheet was filled into the molten pool during argon-nitrogen mixture gas plasma arc welding of SiC_p/Al MMCs in order to obtain a particle reinforced composite weld. And the formation of needle-like brittle phases Al_4C_3 is prevented completely because titanium and carbide formed TiC preferably. But the mechanical properties are debased by some defects, such as pores, cracks and incomplete fusion of titanium owing to the high welding current demanded by the high fusion point of titanium and poor fluidity of molten pool[13−14].

Both technics and metallurgy should be taken into consideration in order to improve the weldability of SiC_p/Al MMCs. Decreasing heat input of molten pool is the main approach in technics. But in order to ensure fusion penetration, there is a limitation of reducing the heat input. And some elements that could improve the fluidity of molten pool and inhibit the interface reaction are added into the weld in metallurgy[15]. To improve the structure of weld and performance of welded joint in plasma arc in-situ welding of SiC_p/Al MMCs, Ti-Al was filled into the molten pool and its effects on microstructures and mechanical properties of weld were

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investigated in the present work.

2 Experimental

The morphology of SiC_p/6061Al MMC containing 10% (volume fraction) SiC particle (particle size 6 μm) made by the method of extrusion and foundry is shown in Fig.1. The maximum tensile strength of the base metal was 320 MPa in the state of annealing. It can be seen from Fig.1 that the distribution of reinforcement particles is not even. The chemical compositions of the matrix for experimental materials are listed in Table 1.

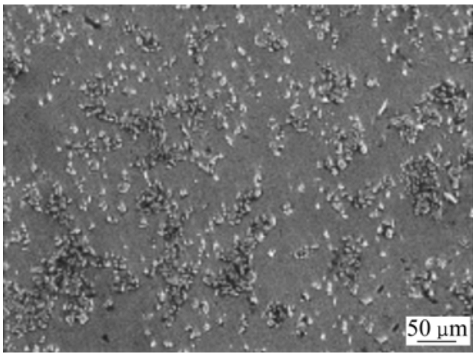

Fig.1 Microstructure of SiC_p/Al MMCs

Table1 Chemical compositions of aluminum alloy (mass fraction, %)

Cu	Mg	Mn	Ni	Si	Ti	Al
0.35	0.76	0.25	<0.05	1.25	<0.05	Bal.

Two kinds of Ti-Al alloys, Ti-60Al and Ti-80Al, prepared by vacuum melting in arc melting and vacuum casting system, were selected as the filled composite in the present work.

Rectangular specimens, 60 mm in length, 20 mm in width and 3 mm in thickness, were cut from long bars of SiC_p/6061Al MMC, burnished using $150^{\#}$ SiC sand paper before weld, and then were cleaned using acetone. The specimens were joined in ion gas of argon and nitrogen by the plasma arc welding torch of Hpt−180 type.

Alloy filler sheet with traverse section size of 0.8 mm×1 mm was cut from a disc-like Ti-Al alloy. And it was cleaned up by ultrasonic vapor in acetone with ultrasonic oscillator so that there is no greasy dirt on the surface.

Metallographic transverse sections of the welds perpendicular to the welding direction were prepared using standard metallographic procedures and etched by Keller's reagent. Microstructure of the weld was characterized by an optical microscope and scanning electron microscope(SEM). Phase analysis was carried out by X-ray diffraction and energy dispersive spectroscopy. The diffraction angle was changed from 20° to 80° (2θ) at an angular velocity of 8 (°)/min.

The tensile strength of the welded joints was measured with electronic universal testing machine. The cross-head velocity was 0.5 mm/min, and the shape and size of tensile specimen are shown in Fig.2.

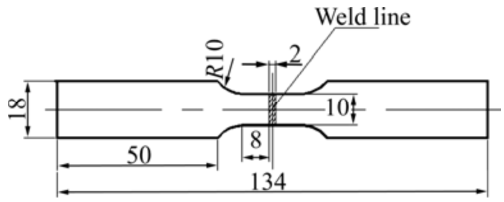

Fig.2 Shape of specimen for tensile test (unit: mm)

3 Results and discussion

3.1 Structural features

Fig.3 shows the OM macrostructure of transverse section of welded joint by plasma arc in-situ weld-alloying welding on SiC_p/6061Al MMC with Ti-60Al alloy sheet filler. No pores, fissures and incomplete fusion of filler are observed in the central zone of weld, and the structure is dense and transits naturally nearby the weld junction, showing that the fluidity of molten pool is improved greatly by the Ti-60Al alloy. Remarkably, high-quality weld in favor of improving the mechanical properties of welded joint is produced by plasma arc in-situ weld-alloying welding with Ti-60Al alloy sheet filler.

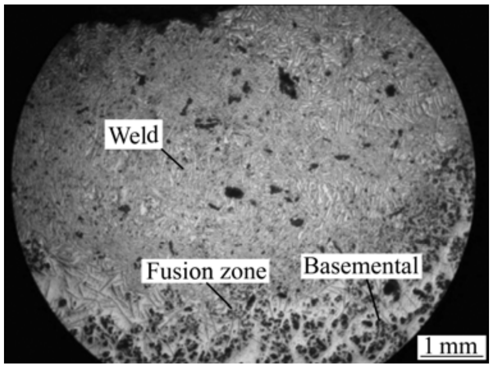

Fig.3 OM macrostructure of welded joint with Ti-60Al alloy sheet filler

The SEM image of welded joint by in-situ welding/ plasma arc welding on SiC_p/6061Al MMC with Ti-40Al alloy sheet filler is shown in Fig.4. Figs.4(a), (b) and (c) show the centre of weld, the bottom of weld and the fusion zone, respectively.

In the microstructure of weld (see Fig.4(a)), a lot of long strip-like phases, 50−200 μm long and 2−5 μm wide, distribute evenly in the weld. And the results of XRD (see Fig.5) and EDS indicate that they are Al_3Ti phases. Much more fine particles with regular shapes are

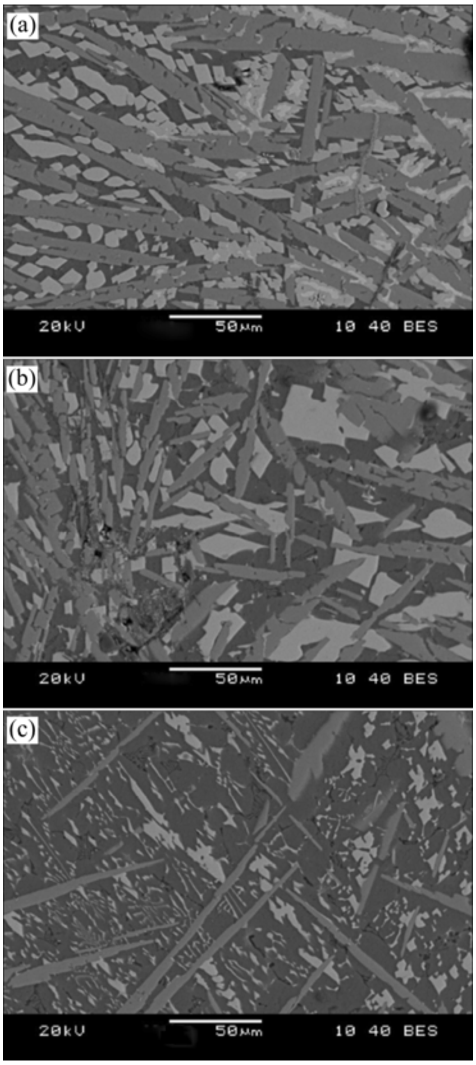

Fig.4 Weld microstructures of welded joint with Ti-60Al alloy sheet filler: (a) In centre of weld; (b) At bottom of weld; (c) In fusion zone

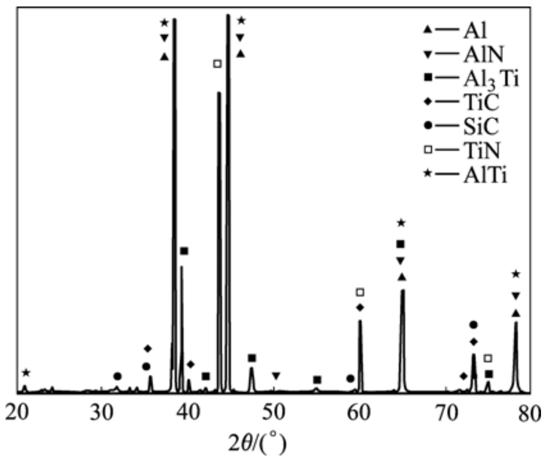

Fig.5 XRD pattern of joint adding Ti-60Al alloy sheet filler

among the phases of Al_3Ti, which are identified to be AlN, TiN and TiC according to the results of XRD and EDS. There is no needle-like Al_4C_3 phase in the weld, and no microporosities and microcracks are observed. However, particle segregation, caused by the settlement of particles[16], is observed at the bottom of the weld (see Fig.4(b)), which could reduce the strength of the grain boundary and debase the properties of welded joint. The particle settlement is caused by the gravity in the molten pool. And the settlement of large bulky and massive phases Al_3Ti oppresses the fine particles to congregate at the bottom of weld because it is much stronger than that of the other fine particles in the molten pool, which bring on the particle segregation at the bottom of weld in final.

Compared with the microstructure of weld, the phases Al_3Ti are less, narrower and shorter, and the size of the other particles is smaller and more homogeneous in the fusion zone (see Fig.4(c)).

The microstructures of weld and fusion zone with Ti-80Al alloy sheet filler are shown in Figs.6(a) and (b), respectively. Many needle-like phases Al_4C_3 are observed in the weld.

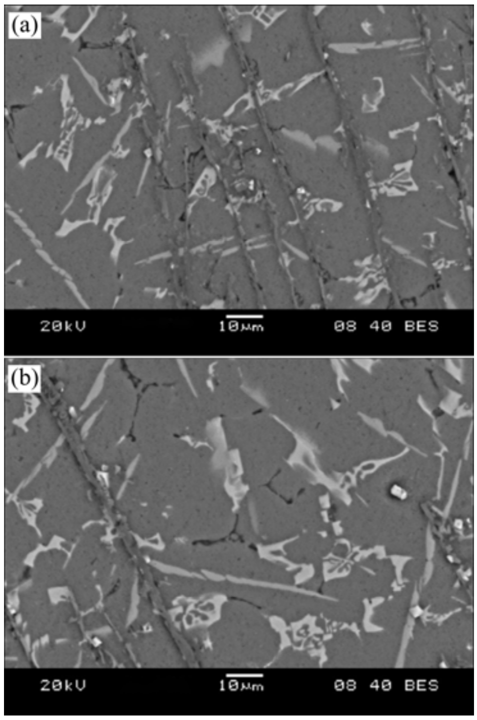

Fig.6 Weld microstructures of welded joint with Ti-80Al alloy sheet filler: (a) Weld; (b) Fusion zone

It can be concluded that the formation of Al_4C_3 phases is effectively prevented by plasma arc in-situ weld-alloying welding with Ti-60Al alloy but it is ineffective with Ti-80Al alloy.

During the welding, the filler was melted into the base metal, forming molten pool. In the molten pool (T≈1 700 K), AlTi was decomposed:

$$AlTi \longrightarrow Al+Ti \quad (1)$$

The formation of Al_4C_3 is effectively suppressed by a series of chemical reactions of Ti and other elements in molten pool[17]. If there is enough amount of titanium, the inhibition mechanisms are as follows:

$$SiC \longrightarrow Si+C \tag{2}$$

$$Al+3C \longrightarrow Al_4C_3\ (\Delta G/(kJ \cdot mol^{-1})=-184\ 000) \tag{3}$$

$$Ti+C \longrightarrow TiC\ (\Delta G/(kJ \cdot mol^{-1})=-186\ 600+13.22T) \tag{4}$$

$$Ti+N_2 \longrightarrow TiN\ (\Delta G/(kJ \cdot mol^{-1})=-676\ 600+190.2T) \tag{5}$$

$$Al+N_2 \longrightarrow AlN\ (\Delta G/(kJ \cdot mol^{-1})=-618\ 000+209.2T) \tag{6}$$

Under the condition of the spontaneous processing for the above reactions, the value of ΔG is smaller, and the reaction processes easily.

By comparing reaction (3) with (4), it can be clearly seen that the free energy of formation of TiC is much more negative than that of Al_4C_3, so the reaction (4) processes earlier than the reaction (3), namely, TiC is preferably formed because the carbide and titanium reacted firstly, leading to the suppression of the reaction (3). In other words, the formation of the needle-like brittle phase is suppressed completely. By comparing reaction (3) with (6), we know that the free energy of formation of aluminum nitrogen is much more negative than that of Al_4C_3. In this way, the matrix aluminum reacts with nitrogen from the ion gas, taking precedence over carbide, which also suppresses the process of the reaction (3) to a certain extent. By comparing reaction (4) with (5), it can be seen that the free energy of formation of titanium nitrogen is much more negative than that of titanium carbide, so the reaction (5) processes earlier than reaction (4), that is to say, the new reinforcement phase TiN is formed because the reaction processes earlier between titanium and nitrogen from the ion gas. If the content of alloying filler titanium is relatively high, which not only causes titanium to react fully with nitrogen, but also guarantees reaction (4) to process successfully, it will lead to the suppression of the formation of the needle-like Al_4C_3 phase.

The formation of Al_4C_3 phases is effectively prevented by plasma arc in-situ weld-alloying with Ti-60Al alloy sheet filler which could supply enough content of titanium and assure that the reactions could carry out successfully in the molten pool in the present work. It can not prevent the formation of Al_4C_3 when Ti-80Al is selected as filler metal, which is caused by low content of titanium. It can be inferred that the content of titanium of Ti-Al alloy should be more than 20% in order to prevent the formation of phase Al_4C_3 effectively during the plasma arc in-situ welding of SiC_p/Al MMCs.

3.2 Effect of Ti-Al on structure and components

The fluidity of molten pool is mainly dependent on the chemical constituents of the alloy system composed with all kinds of elements in the molten pool. As well known, the smaller the solidification interval is, the better the fluidity of alloy is. The fluidity of titanium alloy is commonly worse than pure titanium for the addition of alloying elements can increase its solidification interval. But the crystallization heat increases with increasing the addition of aluminium, which obviously improves the fluidity of titanium alloy[18]. Compared with the previous investigation of welding with pure titanium sheet filler, the fluidity of molten pool is highly improved due to the high content of aluminium, which is propitious to the escape of H. Consequently, the more dense weld structure without defects of pores and microcracks and in favor of improving the mechanical property of welded joint is gained by adding Ti-60Al alloy sheet filler.

The XRD results of the welded joint adding Ti-60Al alloy sheet filler is given in Fig.5. It can be seen that the weld microstructure is composed of Al, TiN, TiC, AlN, Al_3Ti and AlTi. What is different from the previous investigation is that the content of titanium aluminide compound is more in the present work.

3.3 Mechanical properties

The previous investigations show that the maximum tensile strength of welded joint by plasma arc in-situ weld-alloying of SiC_p/6061Al MMCs with titanium sheet filler is 220 MPa[19]. The maximum tensile strength of welded joint with Ti-60Al alloy sheet filler is 235 MPa, which shows that the filler of Al-Ti improves the mechanical properties of joints.

Fig.7 shows a typical fractograph of welded joint by plasma arc in-situ weld-alloying with Ti-60Al alloy filler. A careful inspection of the fracture surface shows that the fracture occurs in the centre of the weld joints. The sheet area, induced by the avulsion of Al_3Ti phases from basal body, shows the brittle fracture, and the others is ductile.

The particle segregation and excessively bulky Al_3Ti phases in the weld undoubtedly have negative effect on the mechanical properties of welded joint. As well known, the interface layer between the wild phases and metal matrix is the key factor that affects the performance of welded joint of composite material. The condition of the interface layer, by which the load on the welded joint transits from the metal matrix Al to the reinforcement particles, is the key factor that influences the mechanical property of composite material[20−21]. The defect of particle segregation breaks the interface layer and becomes the crack source debasing the joint strength under the effect of tension stress. The long strip-like Al_3Ti phase penetrates the crystal grains and could break the continuity of metal matrix[22]. So the joint strength still can not reach the level of the mother material.

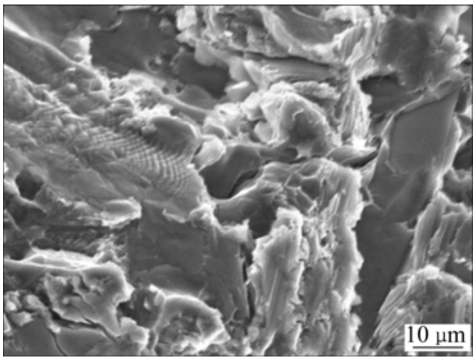

Fig.7 Microfractograph of welded joint with Ti-60Al alloy sheet filler

It can be inferred that the factors which influence the tensile strength of welded joint produced by plasma arc in-situ weld-alloying on SiC_p/6061Al MMCs with Ti-60Al alloy filler are mainly the particle segregation and excessively bulky Al3Ti phase in the weld.

4 Conclusions

1) The needle-like harmful phase Al_4C_3 is effectively eliminated by plasma arc in-situ weld-alloying titanium of SiC_p/Al MMCs with Ti-Al alloy whose titanium content is more than 20%.

2) The maximum tensile strength of welded joint by plasma arc in-situ weld-alloying of SiC_p/6061Al MMCs with Ti-60Al alloy is 235 MPa. The main factors influencing the mechanical performance of joint are the particle segregation and excessively bulky Al_3Ti phase.

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