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ScienceDirect
Trans. Nonferrous Met. Soc. China 21(2011) s274−s279
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Effects of stirring parameters on microstructure and tensile properties of (ABO_w+SiC_p)/6061Al composites fabricated by semi-solid stirring technique

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Received 10 May 2011; accepted 25 July 2011

Abstract: Aluminum borate whisker (ABO_w) and silicon carbide particle (SiC_p) hybrid reinforced 6061Al matrix composites ((ABO_w+SiC_p)/6061Al) were fabricated by semi-solid mechanical stirring technique with different stirring temperatures and different stirring time. The influence of stirring parameters on microstructure and mechanical properties of the composites was investigated using scanning electron microscopy (SEM), X-ray diffractometry (XRD), transmission electron microscopy (TEM) and tensile tests. The results reveal that the homogeneity of reinforcement and tensile properties increase with decreasing the stirring temperature and increasing the stirring time. The optimal stirring parameters of 640 °C and 30 min are exploited based on the microstructure observation and tensile properties of the composites.

Key words: aluminum matrix composites; semi-solid stirring; stirring parameter; mechanical properties

1 Introduction

Aluminum matrix composites attract more and more interest due to their low density, high specific strength and good wear resistance. In particular, the hybrid composites were considered to possess superior properties to single reinforced composites [1−2]. Recently, various hybrid composites have been designed to get a better wear resistance, lower coefficient of thermal expansion (CTE), higher mechanical properties [3−5] and so on. Generally, ABO_w and SiC_p are considered to be effective reinforcements for aluminum alloy [6−8]. The addition of SiC_p can decrease the CTE of the composites while the addition of ABO_w is more effective in improving the combination of mechanical properties of the composites than SiC_p.

There are many methods for fabrication of metal matrix composites, such as liquid metal infiltration, squeeze casting, powder metallurgy, and semi-solid stirring [9−10]. Among these processing techniques available for discontinuously reinforced metal matrix composites, semi-solid stirring attracts more attention because of simplicity, flexibility and being most economical for large sized components to be fabricated [11]. However, the inferior wettability and serious interfacial reaction between reinforcement and matrix alloy are two problems for semi-solid stirring technique. Finally, semi-solid stirring process parameters, such as the stirring temperature, stirring time and stirring speed significantly influence the microstructure and mechanical properties of the composites [12]. As a result, optimizing process parameters is necessary to fabricate hybrid reinforced metal matrix composites with a homogeneous microstructure and superior mechanical properties.

In the present study, the hybrid (5%ABO_w+ 15%SiC_p, volume fraction)/6061Al composites were successfully fabricated by semi-solid stirring technique. Subsequently, effects of stirring parameters on the microstructure and mechanical properties of (ABO_w+SiC_p)/6061Al composite were investigated.

2 Experimental

The reinforcements of composites selected in this study were ABO_w with a diameter of 0.5−1 μm and a length of 10−30 μm and SiC_p with a narrow particle size distribution in the range of 8−14 μm. The composition of the selected 6061 alloy was as follows: 0.6%Si, 0.7%Fe, 0.3%Cu, 0.15%Mn, 0.8%Mg, 0.25%Zn and balance Al (mass fraction).

Before semi-solid stirring process, ABO_w and SiC_p were pretreated. ABO_w was coated with ZnO layer using a precipitation process and SiC_p was pretreated to form a

Foundation item: Project (2006CB605203-3) supported by the National Basic Research Program of China
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layer of SiO_2 film on it, which prevented the interfacial reaction with molten aluminum and improved the wettability between reinforcements and matrix alloy.

The fabrication process of the hybrid (ABO_w+SiC_p)/6061Al composites consisted of the following steps: 1) 6061Al alloy was molten at 800 °C in stainless steel crucible and then cooled to semi-solid temperature. In order to investigate the effects of stirring temperature on the whisker distribution, the semi-solid temperatures were selected as 680 °C, 650 °C, 640 °C and 630 °C, respectively; 2) The preheated SiC_p at 600 °C was added into the semi-solid matrix alloy, stirred at 300 r/min for 10 min, and then the preheated ABO_w at 600 °C was also added into the matrix alloy. The slurry charged with ABO_w was mixed in the semi-solid state isothermally for another 10 min and 20 min, respectively; 3) The semi-solid slurry was then poured into a preheated container (480 °C) and allowed to solidify under 100 MPa to obtain composite billets without porosity; 4) The billet was extruded with an extrusion ratio of 25:1 and a constant ram speed of 15 mm/s and then cooled in air.

The phase composition of pretreated SiC_p/6061Al composite was identified using a Philips X'Pert X-ray diffractometer with Cu K_α radiation. The morphologies of the composites and tensile fractographs of composites were examined by a FEI Sirion type scanning electronic microscope (SEM). The interfacial microstructure of composites was observed using a Philips CM−12 transmission electron microscope (TEM). The tensile tests were carried out using an Instron Series 5569 universal testing machine at room temperature and the tensile rate was 0.5 mm/min.

3 Results and discussion

3.1 Effects of stirring parameters on microstructure of hybrid composites

According to the binary phase diagram of 6061Al alloy, the solid-liquid interval of 6061Al alloy ranges from 582 °C to 652 °C. At 680 °C, the metal is fully molten. While at 650 °C, 640 °C and 630 °C, the metal consists of 20.3%, 52.7% and 73.8% solid in the semi-solid slurry, respectively.

Figure 1 shows the SEM micrographs of composites fabricated at different stirring temperatures (stirring time and speed are 30 min and 300 r/min, respectively). In Figs. 1(a) and (d), ABO_w and SiC_p agglomerations can be observed in composites. By comparison, it can be seen that the uniformity of the reinforcement distribution in the composites initially increases and later declines with decreasing the stirring temperature, which indicates that an optimal stirring temperature exists in the semi-solid stirring fabrication of the composites. The ABO_w and SiC_p are uniformly distributed in the composites with the stirring temperature of 640 °C.

The effect of stirring temperatures on ABO_w and SiC_p distribution in the composites is related to the

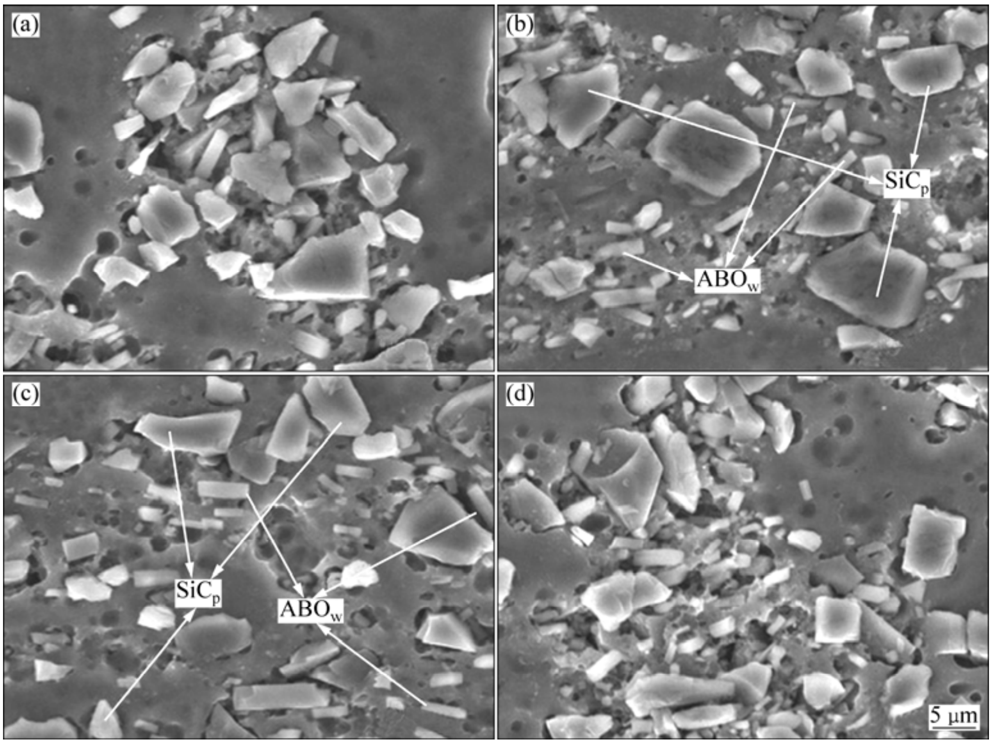

Fig. 1 SEM micrographs of $(5\%ABO_w+15\%SiC_p)$/6061Al composites fabricated at different stirring temperatures for 30 min: (a) 680 °C; (b) 650 °C; (c) 640 °C; (d) 630 °C

friction and shear between reinforcements and semi-solid slurry, which is related to the viscosity. The solid fraction and viscosity of the semi-solid slurry increase with reducing the stirring temperature. At 680 °C, the low viscosity and friction between liquid metal and reinforcements are harmful to the distribution of the reinforcements in the composites. In addition, oxidation of molten metal and injurious interfacial reaction between SiC_p and matrix alloy also happen at a high temperature, which leads to particle agglomeration as well [13]. At a lower stirring temperature of 640 °C, the solid fraction (52.7%) and viscosity of the semi-solid slurry significantly increase, but still maintain in a liquid state during stirring. The vortex generated in the stirring process breaks solid dendrites due to higher friction and shear between reinforcements and 6061Al matrix alloy, which induces a homogeneous distribution of ABO_w and SiC_p. In addition, the sedimentation of reinforcements in metal matrix decreases with decreasing the stirring temperature, which can further cause the homogeneous distribution of reinforcements due to the increasing solid fraction. With further decreasing the stirring temperature to 630 °C, the matrix alloy is no longer in a liquid state during stirring, and it is difficult to stir completely due to significantly enhanced viscosity or friction resistance, which makes it impossible for the uniform distribution of the reinforcements in the composites.

Figure 2 shows the SEM micrographs of $(5\%ABO_w+15\%SiC_p)$/6061Al composites stirred for 20 min and 30 min (stirring temperature and speed are 640 °C and 300 r/min, respectively). From Fig. 2(a), reinforcement agglomeration can be observed obviously in the composite fabricated with a shorter stirring time of 20 min. Increasing the stirring time to 30 min, an improved distribution of the ABO_w and SiC_p reinforcements can be obviously observed compared with that of the composite fabricated with a stirring time of 20 min (as shown in Fig. 2(b)). The results indicate that the distribution of the ABO_w and SiC_p in the composites can be improved with increasing the stirring time. However, further increasing stirring time certainly increases gas absorbability and oxidation of the prepared composites, which can remarkably decrease the mechanical properties [14]. Therefore, it is important to select a suitable stirring time.

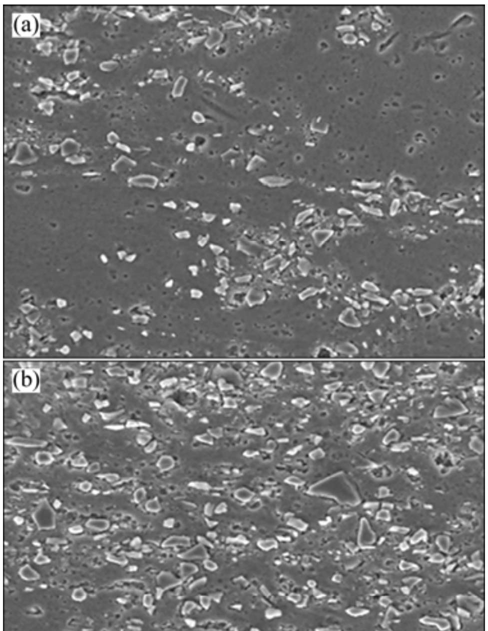

Fig. 2 SEM micrographs of $(5\%ABO_w+15\%SiC_p)$/6061Al composites fabricated with different stirring time: (a) 20 min; (b) 30 min

The potential chemical reaction products between matrix and reinforcement of the present hybrid system are Al_4C_3 and $MgAl_2O_4$ compounds, which are harmful to the properties of the composites [15−16]. Figure 3 shows the XRD result of the composite fabricated at 640 °C for 30 min. It can be seen that no Al_4C_3 and $MgAl_2O_4$ exist in the composites, that is to say, the pretreatment of the ABO_w and SiC_p can effectively prevent the interfacial reaction with the matrix alloy. However, the diffraction peak of ABO_w is not observed in Fig. 3 due to the low content of ABO_w in the composite. Figure 4 shows the TEM micrograph of the hybrid composite, which shows that ABO_w exists in the composite and Al_2O_3 interlayer appears between matrix and ABO_w reinforcement. This indicates that ZnO can react with molten aluminum during the stirring and squeeze casting. The reaction can improve the wettability between ABO_w and matrix alloy and prevent the damage of ABO_w effectively.

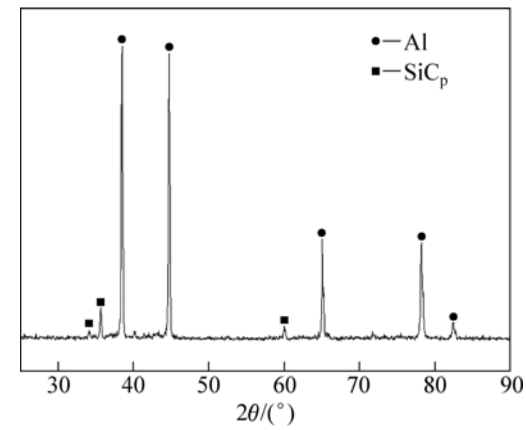

Fig. 3 X-ray diffraction pattern of composite

3.2 Effects of stirring parameters on tensile properties of composites

The comparative tensile properties of the prepared composites are shown in Fig. 5. Figure 5(a) shows the

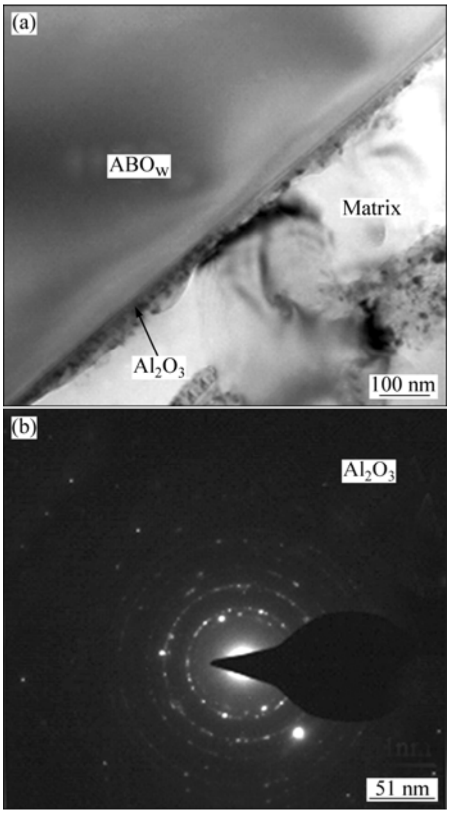

Fig. 4 TEM micrographs of composite: (a) Interface; (b) Diffraction pattern

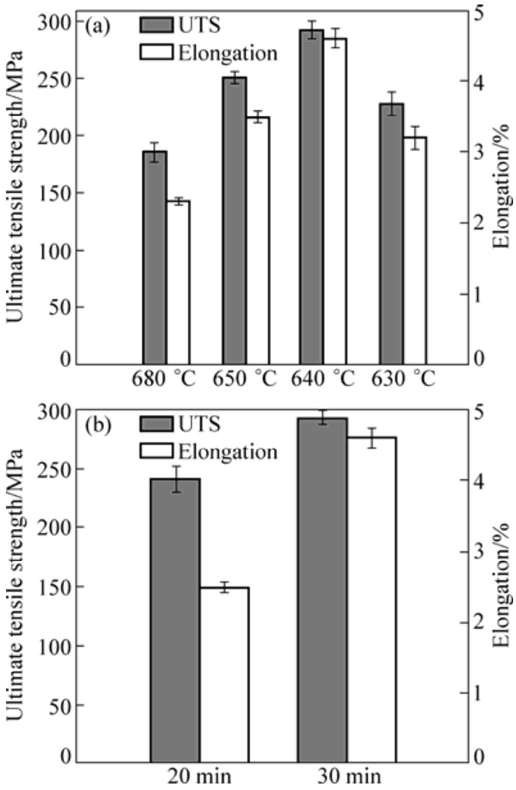

Fig. 5 Tensile properties of $(5\%ABO_w+15\%SiC_p)/6061Al$ composites fabricated with different stirring parameters: (a) Stirring temperature; (b) Stirring time

variations of the ultimate tensile strength (UTS) and elongation-to-failure (δ) of the composites with deferent stirring temperatures. It can be seen that the tensile properties of the composites initially increase and later decline with decreasing the stirring temperature. By comparison, the UTS of the composite fabricated at 640 °C is 293 MPa, which is increased by 57.5%, 16.7% and 28.5% compared with that of the composites fabricated at 680 °C (186 MPa), 650 °C (251 MPa) and 630 °C (228 MPa), respectively. The elongation of the composite fabricated at 640 °C (4.6%) is increased by 50%, 23.9% and 30.4% compared with that of the composites fabricated at 680 °C (2.3%), 650 °C (3.5%) and 630 °C (3.2%), respectively. The improved tensile properties of the composites with the decreased stirring temperature is probably attributed to the improvement of uniform whisker and particle distribution, the reduced oxidation at low temperature, and the controlled injurious interfacial reactions. However, the agglomeration formed at 630 °C is harmful to the mechanical properties of the composite.

Figure 5(b) shows the variations of UTS and δ of the composites with deferent stirring times. It can be seen that the UTS and δ of the composite increase significantly with increasing the stirring time due to the uniform distribution of whiskers and particles in the composite. By extending the stirring time from 20 min to 30 min, the UTS of the composite increases from 214 MPa to 293 MPa and δ increases from 2.5% to 4.6%, respectively. That is to say, the suitable stirring time (30 min) is necessary to fabricate the composites with a homogeneous microstructure and superior mechanical properties.

According to the above mentioned results, the superior stirring parameters to fabricate the $(5\%ABO_w+15\%SiC_p)/6061Al$ composite with superior mechanical properties are 640 °C, 30 min and 300 r/min.

3.3 SEM fractographs of composites

Figures 6(a)−(d) show the fractographs of the composites fabricated with deferent stirring temperatures and Fig. 6(e) shows the fractograph of the composite fabricated at 640 °C for 20 min. It can be seen from Fig. 6 that no interfacial debonding exists between reinforcements and matrix due to the improvement in debonding strength after ABO_w and SiC_p pretreatment. The SiC_p agglomerations can be observed in Figs. 6(a), (d) and (e). The effect of the particles on strength of the composites cannot exert sufficiently due to the fact that the particle-rich region can prevent the flaw extending effectively but the particle-poor region will offer channels for flaw extending. This is consistent with the tensile properties (as shown in Fig. 5). In addition, it can be found from Fig. 6(a) that there are many dispersed

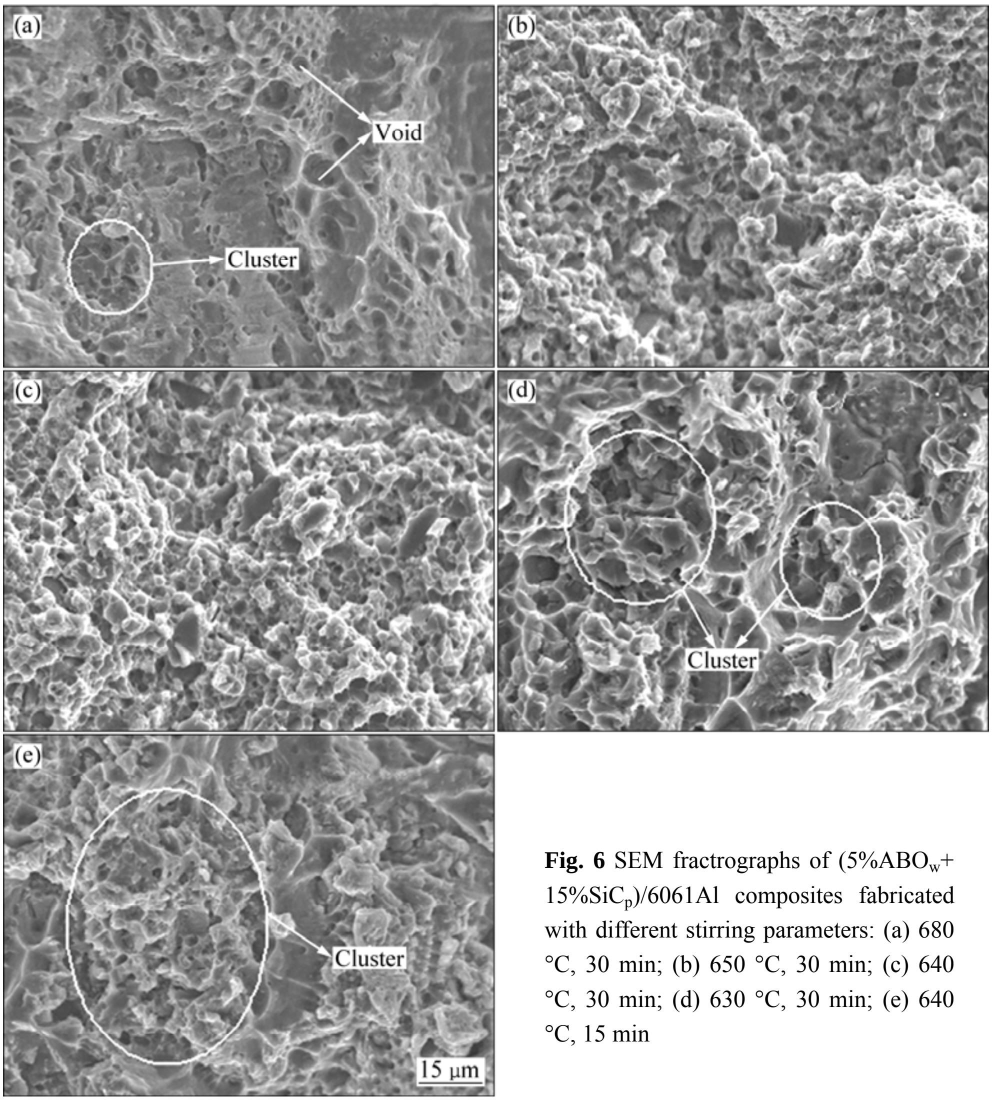

Fig. 6 SEM fractrographs of (5%ABO_w+15%SiC_p)/6061Al composites fabricated with different stirring parameters: (a) 680 °C, 30 min; (b) 650 °C, 30 min; (c) 640 °C, 30 min; (d) 630 °C, 30 min; (e) 640 °C, 15 min

micropores in the composite, caused by the gas absorption during high temperature stirring. The micropores can deteriorate the mechanical properties of the composite because they offer channel for crack propagation [14], which leads to the lowest tensile properties of the composite (in Fig. 5). Figure 6(c) shows small and uniform ductile dimples which can be attributed to the uniform distribution of reinforcements in the composite, corresponding to the best tensile properties of the composite. That is to say, the optimal stirring parameters (640 °C, 30 min) are beneficial to restrain reinforcement agglomeration and micropore formation, and accordingly to improve the tensile strength and ductility of the composites.

4 Conclusions

1) The pretreatment of ABO_w and SiC_p significantly improves the wettability and prevents the serious interfacial reaction between reinforcement and matrix alloy.

2) The reinforcement distribution state and tensile properties of (5%ABO_w+15%SiC_p)/6061Al composite are improved with decreasing the stirring temperatures and increasing stirring time when the matrix alloy is in a liquid state during stirring.

3) The (5%ABO_w+15%SiC_p)/6061Al composite with a homogeneous microstructure and superior mechanical properties can be fabricated with the optimal stirring parameters of 640 °C and 30 min.

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搅拌参数对半固态搅拌工艺制备(ABO_w+SiC_p)/6061Al 复合材料微观组织和力学性能的影响

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摘 要：采用不同半固态机械搅拌工艺(变化搅拌温度和搅拌时间)，制备硼酸铝晶须(ABO_w)和碳化硅颗粒(SiC_p)混杂增强 6061 铝基复合材料。利用扫描电镜(SEM)、X 射线衍射(XRD)、透射电镜(TEM)和拉伸试验研究搅拌工艺参数对复合材料微观组织和力学性能的影响。结果表明：在可以搅拌的情况，增强体在复合材料中分布的均匀性和复合材料的力学性能随着搅拌温度的降低和搅拌时间的延长而得到提高。基于对复合材料微观组织的观察和力学性能的测试得到最佳的搅拌工艺参数为：搅拌温度 640 °C，搅拌时间 30 min。

关键词：铝基复合材料；半固态搅拌；搅拌参数；力学性能

(Edited by YANG Bing)