Extrusion and heat treatment characteristics of 35% SiCp/6061Al composites

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Silicon carbide particle (SiCp)-reinforced 6061 aluminum (SiCp/6061Al) composites were produced by vacuum hot-press sintering technology and were subjected to hot extrusion and T6 treatment. The microstructures of the composite materials were characterized by scanning electron microscopy and transmission electron microscopy. The density, tensile strength, hardness and conductivity of the composite materials were determined. The effects of hot extrusion and solution temperature on the microstructures and properties of SiCp/6061Al composites were investigated. The results show that hot extrusion can improve the microstructures and properties of the composite materials. After hot extrusion, the compact density improved from 98.09 to 99.10%, while the tensile strength was enhanced from 270 to 301 MPa. The properties of the composite materials can be further improved after T6 treatment. With increase in solution temperature, the dissolvable phases gradually mix and dissolve completely, with only a small quantity of insoluble phase remaining in the matrix, the hardness and tensile strength of composites first increase and then decrease, and the electrical conductivity decreases initially and attains stability after some time. After the solid is dissolved at 530°C and subjected to aging, the comprehensive property of SiCp/6061Al composite improves significantly. The tensile strength reaches 336 MPa, and the hardness is 101 HB.

1. Introduction

Silicon carbide particle (SiCp)-reinforced aluminum (Al) matrix composites have become attractive candidates as advanced structural materials for applications in the aerospace and military industries due to their desirable properties, including high specific stiffness, high specific strength, good fatigue and wear resistance.^{1–3} There are various factors that affect the microstructure and mechanical properties of particle-reinforced aluminum matrix composites, such as the size, shape and volume fraction of the reinforced particle, the composition and grain size of matrix alloy and the preparation technology.⁴ Defects such as cavity and porosity easily appear in the matrix and the interface between the matrix and reinforcement during the process of vacuum hot-press sintering. Thus, secondary extrusion is usually used to reduce the porosity of the composite material. For SiCp/aluminum 6061 (6061Al) composites, heat treatment is an effective method for enhancing the tensile strength and hardness, eliminate the residual stress of the interface, and can significantly improve the physical and mechanical properties of the composites. The research of Bo⁵ showed that the addition of SiCp cannot change the solid solution and the aging process of heat-treatable aluminum alloy matrix, but can change the technological parameters of the solid solution and the aging process of the composite. In this study, 35 vol.% SiCp/6061Al composites were prepared by the vacuum hot-press sintering process and subjected to hot extrusion

and T6 treatment, the effects of hot extrusion and heat treatment on the microstructure, mechanical properties and electrical conductivity of the composites were investigated.

2. Experimental process

In this research, the aluminum matrix composite was manufactured by the powder metallurgy technique. Commercial SiCp with a mean particle size of 10 µm and gas-atomized 6061Al powders with an average particle size of 30 µm were used as reinforcement and base alloy, respectively. The powders (35 vol.% SiCp) and beads were blended in a ratio of 2:1 in a high-energy ball-milling machine for 5 h, the mixed powders were put into the mold and hot-pressed up to 560°C at 20°C/min in an VDBF-250 experiment machine at a pressure of 2.3×10^{-3} Pa. A pressure of 70 MPa was applied on the powders for 3 h at 560°C, and then the sample was cooled to room temperature in a furnace under vacuum. Hot extrusion was performed using a YB32-100A-type hydraulic press machine, both the hot-pressed sample and hot extrusion mold were heated to 480°C and held for 30 min, then, the hot-pressed sample was hot extruded to form a hot extrusion sample at an extrusion speed of 3×10^{-5} m/s and an extrusion ratio of 6:1. Then, the hot extrusion samples were solution treated at 470, 490, 510, 530 and 550°C for 1 h, water quenched and then aged at 170°C for 4 h under air-cooled conditions.

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The microstructure of the composites was observed by using a JSW-5600 scanning electron microscope and a JEM-2100 transmission electron microscope. The tensile strength was tested by using a Shimadzu AG-1250 KN precision universal testing machine at a constant cross-head speed of 0.5 mm/min. The hardness of the composite was measured by using an HB-3000 Brinell's machine, with five measurements per condition to ensure the accuracy of the results. The electrical conductivity was measured by utilizing a 7501-type eddy-current device.

3. Results and analysis

3.1 Effect of hot extrusion on microstructure and properties of SiCp/6061Al composites

The microstructures of SiCp/6061Al composites before and after hot extrusion are shown in Figure 1. It can be seen from Figure 1(a) that the SiCp before extrusion were non-uniform in distribution, disorganized and inconsistent in orientation, and a small percentage of SiCp were adjacent to and overlapped with each other. Figure 1(b) shows that the SiCp in the SiCp/6061Al composites after hot extrusion were uniform in distribution and had a 'flow direction' parallel to the direction of extrusion.

This is because in the process of hot extrusion, under the action of compressive stress from three directions, the composites exhibited a strong plastic deformation. The matrix parallel to the extrusion direction was elongated, while that perpendicular to the extrusion direction was extruded. With the plastic deformation of the matrix, the location of the SiCp also had a significant change, and under the action of the flow stress parallel to the direction of extrusion, SiCp were subjected to intense shearing and rotation, thereby presenting a significant flow direction distribution. The transmission electron microscopy microstructure analysis showed that the grains of the matrix in the composite material were coarse before hot extrusion (Figure 1(c)) and were significantly refined after hot extrusion (Figure 1(d)). SiCp had high hardness, and the matrix had good plasticity. During the process of hot extrusion, the aluminum matrix was subjected to cleavage from SiCp under external forces, and aluminum matrix grain fragmentation occurred, so that the size of the grain was greatly reduced.⁶ Meanwhile, in the hot extrusion process, the matrix grain slipped and fractured under an external force, resulting in grain refinement and formation of large-angle grain boundaries (Figure 1(d)). The stresses in different parts of the matrix differed during the extrusion process, thus, the dislocation density of the local area became higher,

Figure 1. Microstructures of SiCp/6061Al composites: (a) scanning electron microscopy microstructure before extrusion, (b) scanning electron microscopy microstructure after extrusion (parallel to extrusion direction), (c) transmission electron microscopy microstructure before extrusion, (d) transmission electron microscopy microstructure after extrusion, (e) dislocation cell after extrusion and (f) fault after extrusion

forming dislocation cells (Figure 1(e)). With increase in dislocation density, the force of certain surface dislocations superimposed to form a stacking fault, as shown in Figure 1(f).

The properties of composites before and after hot extrusion are summarized in Table 1. It could be seen that the compactness, density and tensile strength of composites after hot extrusion increased significantly. The composite matrix before hot extrusion has defects such as pores and interface gap, particle adhesion or aggregation due to SiCp, which resulted in the low density of the matrix.⁷ In the process of hot extrusion, porosity and interface gap decreased under the effect of triaxial stress and particle aggregation due to SiCp disappeared, thus, the density and compactness of composite material increased significantly with the compactness up to 99·10%.

The tensile strength of the composite was significantly higher than that before hot extrusion. Because the composite had a certain amount of SiCp, these particles in the composites, before hot extrusion, were not very uniformly distributed. It was easy to form cracks, and the tensile strength of the composite material was low. After hot extrusion, the density of the composite material increased, the pores and other defects in the matrix were reduced. The distribution of SiCp in the composite material was significantly uniform. The bonding strength between SiCp and the matrix was enhanced, and the bearing capacity of the matrix increased. Furthermore, a large number of dislocations and stacking faults were formed in the matrix after hot extrusion, so that the tensile strength of the composites increased. In addition, the hot extrusion refined the grains in the matrix and increased the number of grain boundaries. The ability of the matrix to resist sliding deformation was improved, and the tensile strength of the composite material was enhanced. The tensile strength of the composite increased from 270 to 301 MPa.

3.2 Effect of heat treatment on microstructure and mechanical properties of composites

The scanning electron microscopy images of hot-extruded SiCp/6061Al composites, which was solution treated at various temperatures, are shown in Figure 2. There are a considerable number of intermetallic compounds present in the matrix of the composites after hot extrusion. When the composite was solution treated at 470°C, it can be seen from Figure 2(a) that there were still significant white second-phase particles existing in the matrix. Due to the low solid solution temperature, the intermetallic compounds could not be completely dissolved in the aluminum matrix. As the solution temperature increased from 490 to 510°C, as shown in Figures 2(b) and 2(c), the intermetallic compounds dissolved in the aluminum matrix gradually, the number of white second-phase particles became less. When the solution temperature was increased

to 530°C, one could hardly observe the white second-phase particles in the matrix except in very small amounts of undissolved phase existing in the matrix. With increase in solution temperature from 530 to 550°C, as shown in Figure 2(e), there is no change in the undissolved phase. This indicates that the vast majority of white second-phase particles were dissolved in the matrix after solution treatment at 530°C. The energy-dispersive spectroscopy analysis results in Figure 2(f), of the white bulky phase in Figure 2(d), indicate that this kind of undissolved phase is mainly aluminum–silicon (Si)–iron (Fe) compounds.

The tensile strength and hardness of the composite solution, treated at different temperatures, are shown in Figure 3. When the solution temperature is 470°C, because the temperature is lower than the hot extrusion temperature, the tensile strength of the SiCp/6061Al composite is almost unchanged compared with that of the non-dissolved composite. With increase in solid solution temperature, the tensile strength increases. The tensile strength of the SiCp/6061Al composite reaches a maximum (336 MPa) when the solution is treated at 530°C. The tensile strength decreases with continual increase in the solid solution temperature. The effect of the solution treatment on the hardness of the composite is similar to that of the tensile strength, after solid solution aged at 530°C, the hardness of the SiCp/6061Al composites is 101 HB. The main factors that determine the hardness of the composite are the number and morphology of the precipitates in the matrix. Below 530°C, with increasing solution temperature, more intermetallic compounds would be dissolved in the matrix and the number of precipitates would thus increase during the process of aging treatment. Above 530°C, a fraction of intermetallic compounds melts into a liquid phase and is precipitated in the grain boundary during the cooling process,⁸ which decreases the component of the aging-precipitated phase and thus reduces the hardness of the composite.

The conductivity change curve of the composite solution, treated at different temperatures, is shown in Figure 4. It can be seen that the conductivity reduces with increase solid solution temperature. The conductivity tends to be stable after the solid solution temperature exceeds 530°C. The electrical resistivity of the metal is associated with the electronic mean free path, the conductivity of the metal–matrix composites is most affected by the solid solubility of the alloy matrix. With increase in solid solution temperature, the supersaturated solid solubility of solute atoms increases, the lattice distortion degree in the matrix of the composite also increases accordingly, which leads to increase in the number and density of electron-scattering sources in the matrix lattice and thus increases the resistivity and decreases the conductivity. On the other hand, with increase in solid solution temperature, original defects in the matrix such as dislocations decrease, and the number and density of matrix electron-scattering

Table 1. Properties of SiCp/6061Al composites

	True density: g/cm ³	Theoretical density: g/cm ³	Compact density: %	Tensile strength: MPa
Before extrusion	2·83	2·885	98·09	270
After extrusion	2·86	2·885	99·10	301

Figure 2. The intermetallic compounds of composites at different solution temperatures: (a) 470, (b) 490, (c) 510, (d) 530 and (e) 550°C, (f) the energy-dispersive spectroscopy spectra obtained from the image in (d)

Figure 3. Mechanical properties of the composite at different solution temperatures: (a) tensile strength and (b) hardness

sources decrease,^{9,10} therefore, the conductivity increases. The electrical conductivity decreases with increase in solid solution temperature. When the solid solution process is completed, the conductivity of the composite tends to be stable.

In the process of solid solution treatment, the intermetallic compounds in the matrix can be dissolved into the matrix, resulting in grain lattice distortion, which would enhance the mechanical properties of the composites. At low temperature of the

Figure 4. Electrical conductivity of composite after solution was treated at different temperatures

solid solution, the second phase fails to dissolve fully in the matrix; the fewer number of ball-shaped and needle-shaped β'' phases, after aging treatment, weakens the precipitation strengthening effect.¹¹ With increasing solution temperature, the supersaturated solid solubility of the alloy elements in the aluminum matrix is enhanced and the number of precipitated phases, after aging, correspondingly increases; therefore, the mechanical properties of the composites are improved. When the temperature of the solid solution is 530°C, the intermetallic compounds can be almost dissolved completely in the matrix, and the effect of solid solution strengthening is the best and the tensile strength attains maxima. When the temperature of the solid solution is 550°C, a fraction of intermetallic compounds melts into the liquid phase and precipitates in the grain boundary during the cooling process, which decreases the quantity of the aging-precipitated phase and thus reduces the hardness of the composite. At the same time, the matrix alloy grain grows, resulting in a decrease in the strength of the composites.¹² Therefore, the comprehensive mechanical properties of the composite are best in the solution processed at 530°C.

4. Conclusion

- Hot extrusion could significantly improve the microstructure of hot-press sintered composites, refine the grain in the matrix and increase the distribution uniformity of SiCp. After hot extrusion, the compact density improves from 98.09 to 99.10%, while the tensile strength is enhanced from 270 to 301 MPa.
- With increase in solid solution temperature, the solid solubility of the intermetallic compounds in the composites is enhanced, the tensile strength and hardness of the composites initially increase and then decrease, and the conductivity is reduced and then tends to be stable after 530°C. The comprehensive mechanical properties of the composite are best at 530°C.

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