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Influence of squeeze casting pressure on nanoparticle distribution and mechanical properties of nano-SiC_p/Al−Cu composites assisted with ultrasonic vibration

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Abstract: The influence of squeeze casting pressure on nanoparticle distribution and mechanical properties of 2 wt.% nano-SiC_p/Al−Cu composites assisted with ultrasonic vibration was investigated. Results show that as the applied pressure increases from 0 to 400 MPa, the α(Al) grains are significantly refined at first and then the refinement trend slows down, and the porosity of composites is gradually reduced. When the applied pressure is 400 MPa, α(Al) grain size is reduced from 105 to 25 μm, and the nanoparticle distribution is significantly improved, resulting in the optimal mechanical properties of the composites. The ultimate tensile strength, yield strength and elongation of the composites are 290 MPa, 182 MPa and 10%, which are 52.6%, 25.5% and 400% higher than those of the nano-SiC_p/Al−Cu composites prepared by gravity casting (0 MPa). The enhancement in strength and elongation of nano-SiC_p/Al−Cu composites under high pressure is mainly attributed to grain refinement, reduction of porosity and uniform distribution of nanoparticles.

Key words: aluminum matrix composites; nano-SiC_p; squeeze casting; ultrasonic vibration; microstructure; mechanical properties

1 Introduction

In recent years, nanoparticles reinforced aluminum matrix composites (NAMCs) have attracted more and more attention, due to their high specific strength, high specific stiffness, high elastic modulus, high wear resistance and low density [1−3]. Among many ceramic nanoparticles, nano-sized SiC particles (nano-SiC_p for short) have higher thermal conductivity and smaller relative density than others, making nano-SiC_p/Al composites a research hotspot in this field. Gravity casting is one of the common and economical preparation methods for composites, but it will face problems such as poor wettability between SiC and Al, severe interfacial reaction, and difficulty in adding nano-sized particles into liquid melt [4,5]. Researchers have found that the combination of high-energy ball milling, mechanical stirring and ultrasonic vibration techniques can successfully add nanoparticles to the Al melt and make the nanoparticles uniformly dispersed in the liquid melt [6−8]. However, due to the slow solidification rate of the melt and coarse α(Al) grains during gravity casting, the dispersed nano-SiC_p may be pushed to the front of the solid/liquid interface by primary α(Al) phase due to the incoherent crystal planes and poor wettability between SiC and Al, thereby reducing the performance of composites and limiting its application [9,10]. Therefore, other manufacturing techniques, such as squeeze casting, need to be used to prepare nano-SiC_p/Al composites.

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Squeeze casting can increase the liquidus temperature of alloy, accelerate the solidification rate, refine the grain, and eliminate defects such as porosity and shrinkage in the casting, and thus, the nanoparticle distribution and the performance of composites may be better than those of ordinary gravity casting [11−13]. Among many process parameters of squeeze casting, the solidification pressure is a very important parameter. Many scholars have studied the influence of applied pressure on the microstructure and properties of the alloys [14−16]. However, the current studies on squeeze casting are mainly based on Al and Mg alloys, and the applied pressure is generally less than 200 MPa, which has a limited effect on the solidification behavior of alloys. Therefore, it is reasonable to infer that applying higher pressure can make the effective pressure (decrease with the thickness of the solidified shell) continue to exist during the solidification process. In addition to refining grains and second phases, it can also help prevent nano-SiC_p from being pushed to the grain boundary during the solidification process, improving the nanoparticles distribution in the casting, which is expected to further improve the mechanical properties of NAMCs. However, the influence of high pressure (>200 MPa) on the microstructure and properties of nano-SiC_p/Al composites is rarely reported.

In this study, 2 wt.% nano-SiC_p/Al−Cu composites slurry was prepared using ultrasonic vibration technology at first, and then the composites slurry was formed by squeeze casting at different applied pressures (0, 50, 200 and 400 MPa). The effects of applied pressure on the microstructure evolution, nanoparticles distribution and room-temperature mechanical properties of the nano-SiC_p/Al−Cu composites were investigated, and the mechanisms was discussed in depth.

2 Experimental

Firstly, according to previous studies [8], the optimal ultrasonic time is 5 min at the power of 2.8 kW, and the ultrasonic treatment temperature is selected in the range of 700−720 °C. After the raw materials were melted at 740−750 °C, the same ultrasonic vibration technology was used to prepare about 200 g of composites slurry each time. Then, the slurry was poured into permanent mold preheated at 200 °C, with pouring temperature of 680−690 °C. Finally, castings with a diameter of 30 mm and a height of 90 mm were obtained under different pressures. The pressure was set as 0 (i.e., gravity casting), 50, 200 and 400 MPa, respectively.

The samples were selected from the same position of the four castings under 0, 50, 200 and 400 MPa, respectively. Various methods were carried out to observe and reveal the microstructure evolution of samples, including optical microscope (OM, CK−DMM490C), scanning electron microscope (SEM, JSM−7600F) and electron back scattered diffraction (EBSD, Gemini SEM300). The relative density and porosity of composites were measured by the Archimedes method, and five samples of each composite casting were tested to obtain the average value. Three specimens were taken for each composite casting to obtain its room-temperature tensile properties using a Shimadzu AG−100KN universal testing machine at transverse speed of 1 mm/min, with GB/T 228.1 — 2010 Standard (Equivalent to ASTM A370—2016).

3 Experimental results

3.1 Microstructure of squeeze-cast nano-SiC_p/Al−Cu composites

When ultrasonic vibration treatment was ended, a small amount of melt was extracted with a 6 mm diameter quartz tube for water quenching. Figure 1 shows the back-scattered electron (BSE) microstructure of 2 wt.% nano-SiC_p/Al−Cu composites slurry samples obtained by water quenching, which is beneficial to indirectly reflecting the nanoparticles distribution in the liquid melt. As shown in Fig. 1, a large number of white striped Al_2Cu phases are distributed along the grain boundaries. Without ultrasonic treatment, large nanoparticles aggregates exist in the water-quenched sample of composite slurry, and their size can be as large as 200 μm (Fig. 1(a)). After ultrasonic treatment, nano-SiC_p agglomeration in the composites is eliminated, as shown in Fig. 1(b). Since the solidification rate of water-quenched sample is as fast as hundreds of degrees per second, α(Al) grains are refined to below 20 μm and the moving distance of solid/liquid solidification front is shortened, which may weak the effects of pushing by the solid α(Al) phase on the distribution of the nanoparticles. Therefore, by comparing and

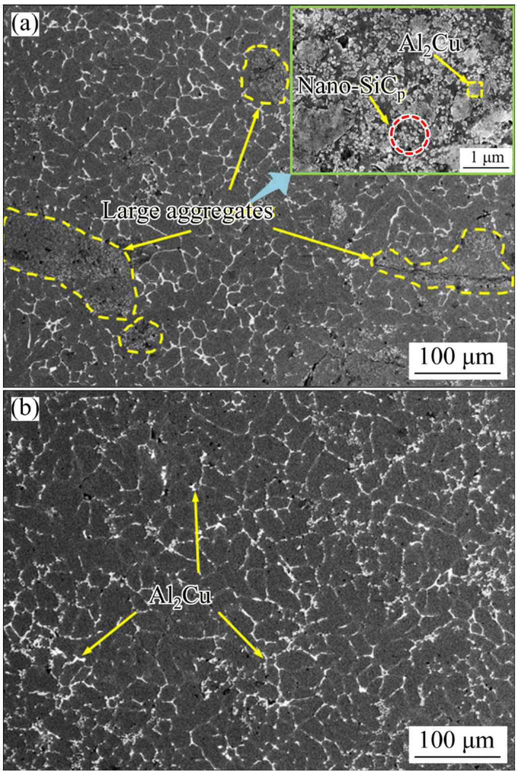


Fig. 1 BSE images of 2 wt.% nano-SiC$_p$/Al−Cu composites slurry samples obtained by water quenching: (a) Without ultrasonic treatment; (b) With ultrasonic treatment.

analyzing the nanoparticles distribution in the water-quenched samples of composite slurry before and after ultrasonic treatment, it is helpful to distinguish whether the nano-SiC$_p$ aggregates at the grain boundary in the casting are formed due to being pushed to the front of the solid/liquid interface by primary α(Al) phase during the solidification process or exist in the slurry before solidification. In the water-quenched sample of composite slurry with ultrasonic treatment, there is no nanoparticle agglomeration that exists before solidification, which indicates that applying ultrasonic treatment to the melt can effectively promote uniform distribution of nano-SiC$_p$ in the slurry.

The OM images of 2 wt.% nano-SiC$_p$/Al−Cu composites under applied pressures of 0 MPa (Sample 1), 50 MPa (Sample 2), 200 MPa (Sample 3) and 400 MPa (Sample 4) are shown in Figs. 2(a−d). As the applied pressure increases from 0 to 400 MPa, the shape and size of the α(Al) phase have undergone significant changes. For gravity casting (0 MPa), the α(Al) grains in the composites are dendritic with large sizes and large dendritic arm spacing (Fig. 2(a)). When a pressure of 50 MPa is applied, the grain size and dendritic arm spacing are significantly reduced, and the dendritic crystal changes to equiaxed crystals, as shown in Fig. 2(b). As applied pressure increases to 200 or 400 MPa, the α(Al) grains in the composites are further refined, as shown in Figs. 2(c, d). Figure 2(e) gives the quantitative statistics of the average grain size of the nano-SiC$_p$/Al−Cu composites after squeeze casting under different applied pressures. Compared with gravity casting (0 MPa), the α(Al) grains are refined from 105 to 25 μm when the pressure is 400 MPa, with a decrease of 76.2%. When the pressure increases from 0 to 50 MPa, the average grain size decreases by 61.9%, but the decreasing trend of grain size slows down with continuous increase of applied pressure. Figure 2(f) shows the inverse pole figure (IPF) of nano-SiC$_p$/Al−Cu composites with the applied pressure of 400 MPa, where the inset in the lower right corner is the pole figure. The maximum extreme value is only 1.85, which reveals that the castings formed by high pressure squeeze casting are isotropic and there is no texture inside the castings.

After the pressure is applied, there are two main reasons for the grain refinement in the composites. On the one hand, squeeze casting would change the alloy solidification process, especially under high pressure (0.1−10 GPa) conditions. As stated in the Clausius−Clapeyron theorem, the pressure could increase the liquidus temperature of the alloy, so that the nucleation of crystal grains becomes easy and the nucleation rate is increased. At the same time, under the action of pressure, the diffusion coefficient of atoms is reduced, thus inhibiting grain growth [17]. On the other hand, in the traditional die casting process, due to thermal shrinkage, an air gap is easily formed between the material and the mold. LEE et al [18] reported that continuous application of pressure can effectively eliminate the air gap between the slurry and the mold during squeeze casting. In other words, squeeze casting can make the contact between the slurry and the mold closer to increase the heat transfer coefficient between the two, thereby increasing the cooling and solidification rate of the alloy, and finally resulting in α(Al) grains with a smaller size and a more spherical shape.

Figure 3 shows the low-magnification SEM images of the nano-SiC$_p$/Al−Cu composites after squeeze casting under different pressures. Without the applied pressure (0 MPa), large nanoparticles aggregates exist at the grain boundaries, and their size can be as large as about 100 μm (Fig. 3(a)). When a pressure of 50 or 200 MPa is applied, large nanoparticles aggregates in the composites are eliminated, but there are still a few small aggregates with a size of 20 μm at the grain boundaries (Figs. 3(b, c)). When the applied pressure is increased to 400 MPa, all nanoparticles aggregates in the composites are effectively eliminated, and the nanoparticle distribution is further optimized (Fig. 3(d)). The inserted pictures in Fig. 3(d) are map scanning images of the area shown in Fig. 3(d). Obviously, the strip phase distributing at grain boundaries is Al$_2$Cu, and LI et al [19] revealed that the nanoparticles are distributed around or inside Al$_2$Cu phase at grain boundaries, where the two

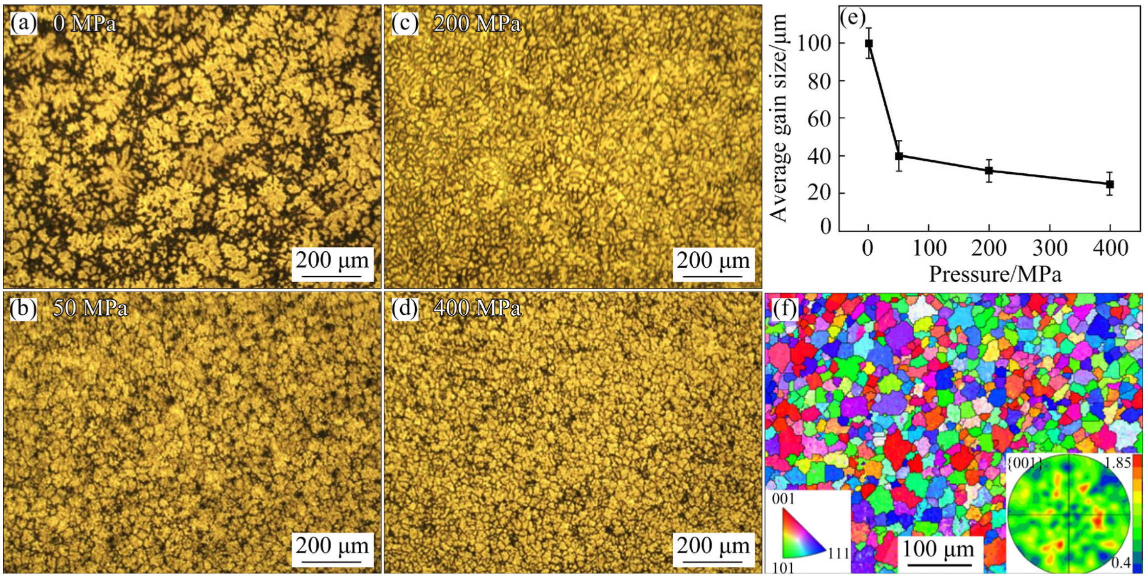


Fig. 2 OM images of 2 wt.% nano-SiC$_p$/Al−Cu composites under different applied pressures (a−d); Average grain size of four samples (e); Inverse pole figure (IPF) with pole figure (PF) of composites under 400 MPa (f)

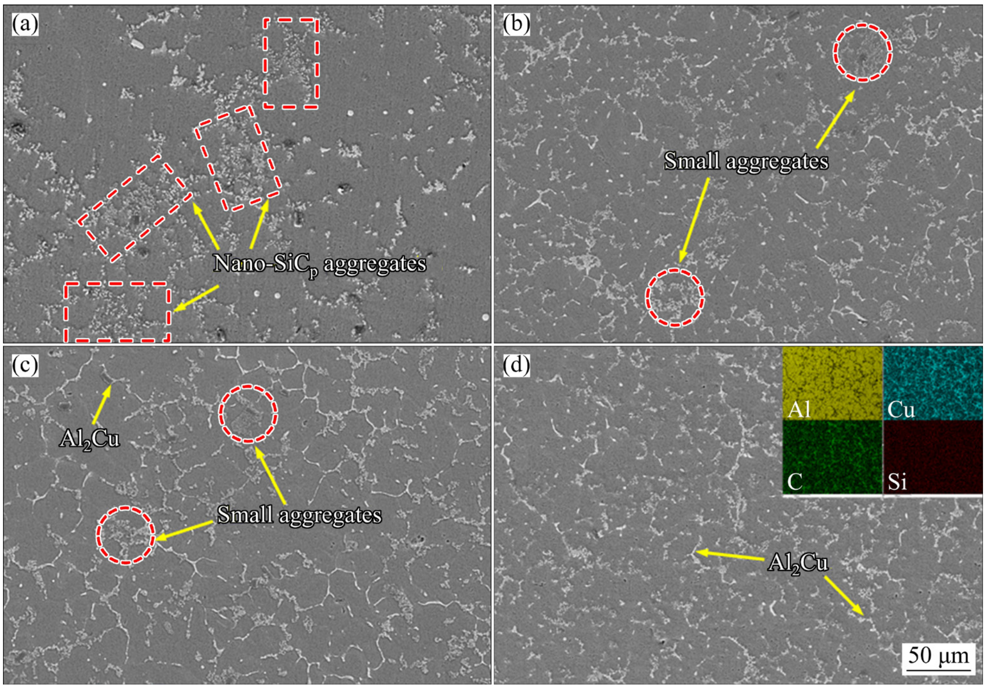


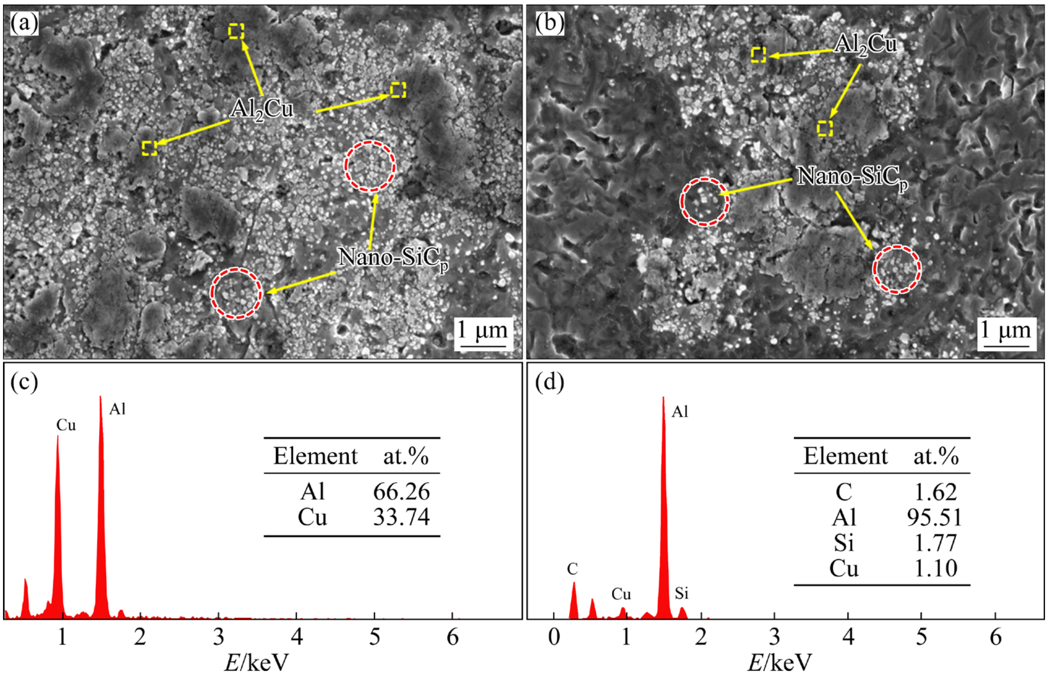
Fig. 3 Low-magnification SEM images of composites under different pressures: (a) 0 MPa; (b) 50 MPa; (c) 200 MPa; (d) 400 MPa

phases are intertwined. As mentioned above, the nanoparticles in the composite slurry after ultrasonic treatment are uniformly distributed, but there are still nanoparticles aggregates in the castings. Therefore, this confirms that the nanoparticles move to the solid/liquid front during solidification and eventually distribute at the grain boundaries. With the elimination of nanoparticle agglomeration in the slurry, the distribution of nano-SiC$_p$ in the squeeze casting ingots is more uniform than that in the gravity casting ingots. As the applied pressure increases, the solidification rate of the composites increases, and the grains become smaller, which helps prevent the nano-SiC$_p$ from being pushed to the grain boundaries and improve the distribution of nano-SiC$_p$ in the castings.

In order to better understand the effects of high pressure on the nanoparticle distribution during solidification, the nano-SiC$_p$/Al−Cu composites formed by gravity casting (0 MPa) and squeeze casting (400 MPa) are selected. Figure 4 exhibits the high-magnification SEM images of two composites. According to the EDS results of the gray bulk phase and white nanoparticles, the molar ratio of Al to Cu in the gray bulk phase is 2:1, and the molar ratio of C to Si in the white particles is close to 1:1, which indicates that they are Al$_2$Cu phase and SiC$_p$ respectively. Obviously, nano-SiC$_p$ is intertwined with Al$_2$Cu phase at the grain boundaries. This is because the Al$_2$Cu phase is a low-melting intermetallic compound that precipitates out at the end of the solidification of composites and is therefore intertwined with nanoparticles that are pushed towards the grain boundaries. Figure 4(a) shows an enlarged detail of the large nanoparticles aggregates in Fig. 3(a), and a large amount of nano-SiC$_p$ gathers at the grain boundaries. This is because the solidification rate of composites under gravity casting is relatively small, so that the α(Al) grains are coarser and solid/liquid front moves longer, which has a great effect on the movement of nanoparticles. After applying a pressure of 400 MPa, nano-SiC$_p$ aggregates at the grain boundaries are eliminated, and even a small number of nanoparticles are distributed in the α(Al) grains, as shown in Fig. 4(b). This further shows that squeeze casting is beneficial to improving the nanoparticles distribution in the castings.

3.2 Mechanical properties of squeeze-cast SiC$_p$/Al−Cu composites

Figure 5 exhibits the tensile properties of 2 wt.% nano-SiC$_p$/Al−Cu composites in as-cast state under different pressures. With the increase of applied pressure from 0 to 400 MPa, the ultimate tensile strength (UTS), yield strength (YS) and



Element	at.%
Al	66.26
Cu	33.74

Element	at.%
C	1.62
Al	95.51
Si	1.77
Cu	1.10

Fig. 4 High-magnification SEM images of two composites formed by gravity casting (0 MPa) (a) and squeeze casting (400 MPa) (b), and energy dispersive spectroscopy (EDS) results of Al$_2$Cu phase (c) and nano-SiC$_p$ (d)

elongation of composites continue to increase. Especially, from 0 to 50 MPa, the mechanical properties of composites are improved most significantly. Without applied pressure (e.g. gravity casting), the UTS, YS and elongation of composites are only 190 MPa, 145 MPa and 2%, respectively. When 50 MPa pressure is applied, the UTS, YS and elongation of the composites increase to 268 MPa, 162 MPa and 7%, which are 41.1%, 11.7% and 250% higher than those of gravity casting. However, as the applied pressure further increases, the rate of improvement in strength and elongation reduces significantly. When 400 MPa is applied, the UTS, YS and elongation of the composites are 290 MPa, 182 MPa and 10%. Compared with gravity casting, these mechanical properties of composites are increased by 52.6%, 25.5% and 400%, respectively.

Figure 6 shows the SEM images of the tensile fracture morphologies of the nano-SiC$_p$/Al−Cu composites under different pressures. When no pressure is applied, there are almost no dimples and more pores on the fracture surface, which is a typical brittle fracture, as shown in Fig. 6(a). It can be also seen that there are some nanoparticles aggregates with severe entrainment. Many studies have shown that the nanoparticles agglomeration

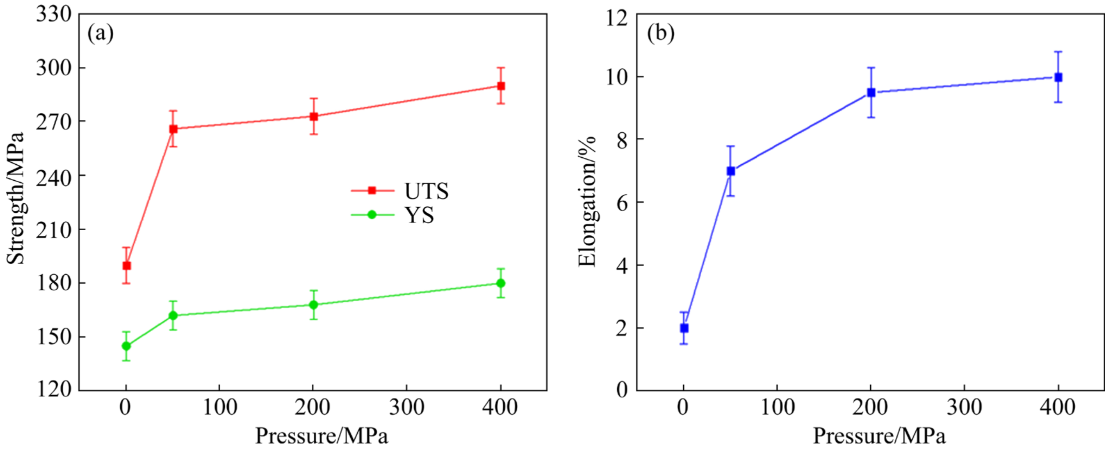


Fig. 5 Tensile properties of nano-SiC$_p$/Al−Cu composites under different pressures: (a) UTS and YS; (b) Elongation

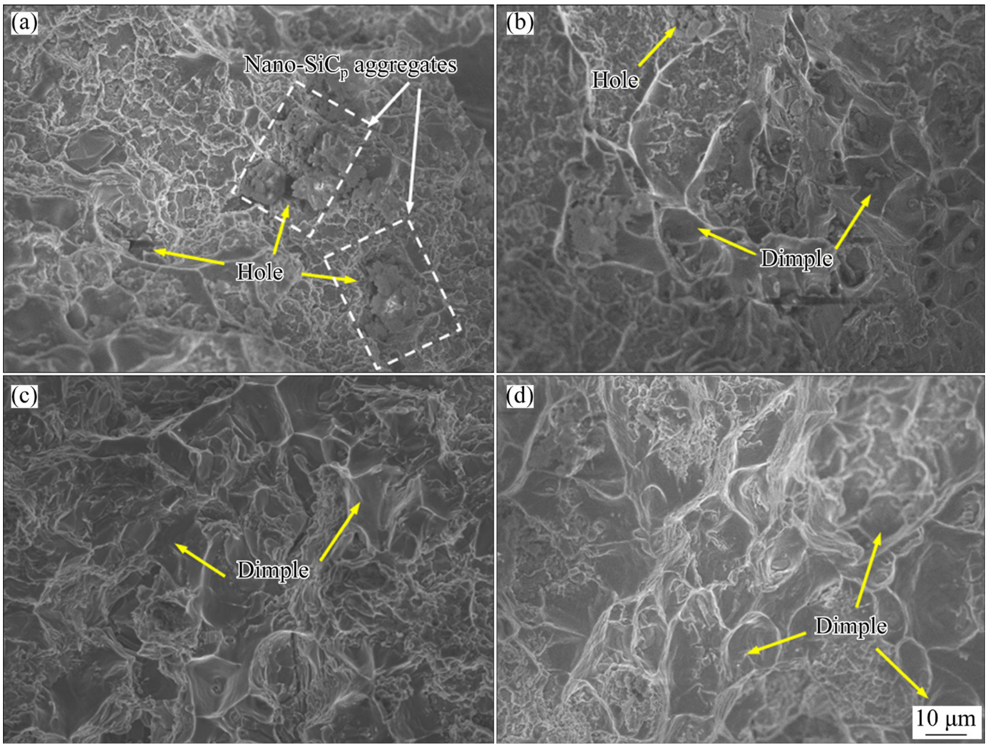


Fig. 6 Fracture surface morphologies of nano-SiC$_p$/Al−Cu composites cast under different pressures: (a) 0 MPa; (b) 50 MPa; (c) 200 MPa; (d) 400 MPa

area tends to have higher porosity. After applying a pressure of 50 MPa, the fracture morphology changes greatly, and a small number of dimples appear, as shown in Fig. 6(b). Although the number of poles is reduced, there is still smaller nanoparticles aggregate on the fracture surface. As the applied pressure further increases to 200 or 400 MPa, the number of dimples increases significantly, and the poles are eliminated, as shown in Figs. 6(c, d). As mentioned above, no matter whether 50, 200 or 400 MPa pressure is applied, the application of squeeze casting can change the fracture mechanism of the composites from brittle fracture to plastic fracture.

4 Discussion

4.1 Particle distribution under applied high pressure

According to the above research results, ultrasonic treatment and squeeze casting are two crucial factors for the uniform distribution of nanoparticles. Figure 7 shows a schematic diagram of the solidification of the nano-SiC_p/Al−Cu composites formed by gravity casting and squeeze casting after ultrasonic treatment.

Figures 7(a−c) show a schematic diagrams of ultrasonic action mechanism in the slurry preparation stage. Usually, ultrasonic vibration technology acts on the melt in the form of periodic positive and negative pressure alternatively [20−22]. On the one hand, in the lower end area of ultrasonic horn, many small cavitation bubbles are formed in the melt under tensile stress, and then the cavitation bubbles grow rapidly to absorb the heat of surrounding melt. Finally, the cavitation bubbles break up under the action of compressive stress, which will produce instantaneous high-speed jet and local high pressure, which can effectively disperse nanoparticles aggregates. Moreover, the cavitation bubbles will repeatedly undergo the processes of nucleation, growth, and collapse. On the other hand, since the ultrasonic amplitude gradually attenuates along the propagation direction from the lower end of the horn, a certain sound pressure difference will be formed in the melt, and the melt will produce a strong flow, that is, the acoustic streaming effect. Therefore, the acoustic cavitation effect is used to remove the gas and impurities adsorbed on the surface of ceramic particles to reduce the surface energy of the melt during the slurry preparation, thereby increasing the wettability of the nanoparticles and the melt. Meanwhile, nanoparticles aggregates are broken up to uniformly distribute in the melt under the combined action of acoustic cavitation and acoustic streaming [8,22].

As mentioned above, ultrasonic vibration has a significant effect on the nanoparticle distribution in

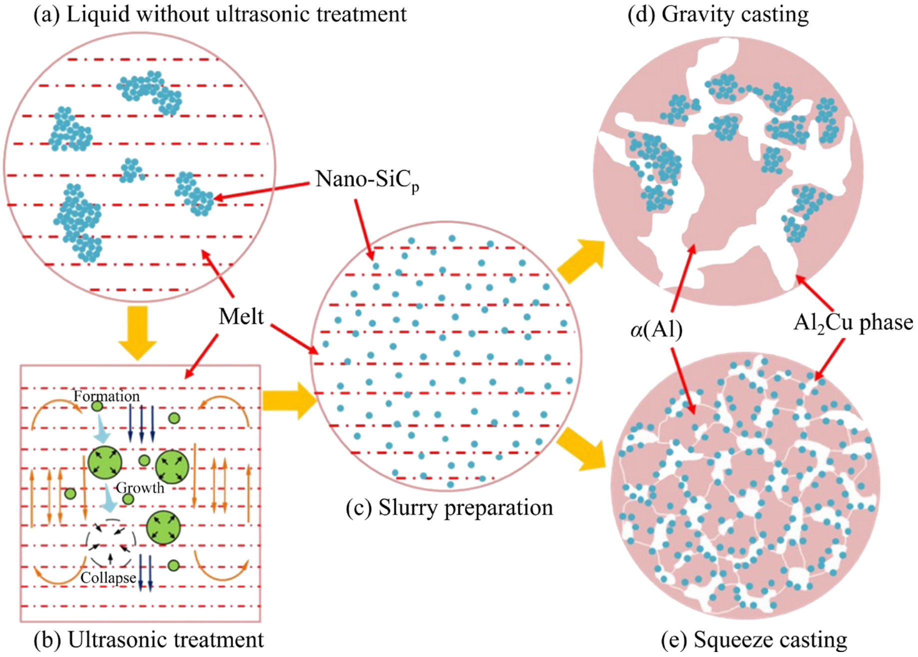

(a) Liquid without ultrasonic treatment
(b) Ultrasonic treatment
(c) Slurry preparation
(d) Gravity casting
(e) Squeeze casting

Fig. 7 Schematics of solidification process of nano-SiC_p/Al-Cu composites under gravity casting with ultrasonic treatment, and squeeze casting with ultrasonic treatment the process of slurry preparation. During the rheological process, the applied forming pressure plays an important role in the uniform distribution of nanoparticles. When the composite slurry is solidified under gravity casting, the α(Al) phase nucleates and grows, and the dispersed nano-SiC$_p$ in the melt is pushed to the solid/liquid front by the primary α(Al) phase. Owing to the small solidification rate of composites under the pressure of 0 MPa, the α(Al) grains are very coarse, and the solid/liquid solidification front moves long, which will promote the nano-SiC$_p$ to accumulate at the grain boundaries, as shown in Fig. 7(d). When the nano-SiC$_p$/Al−Cu composites slurry with ultrasonic treatment is solidified under high pressure conditions, the nanoparticles uniformly distribute in the castings, and the grain is significantly refined, as shown in Fig. 7(e). There are two main reasons for the change of nanoparticle distribution after squeeze casting. On the one hand, under the action of high pressure, the supercooling of the solid/liquid front would become larger, which could effectively increase the heterogeneous nucleation rate and reduce the grain growth rate, leading to grain refinement [14,23]. The refinement of the primary α(Al) phase increases the number of grains and grain boundaries, which helps shorten the moving distance of the solid/liquid solidification front and improve the particle distribution in the casting. On the other hand, the melt with ultrasonic treatment will complete the crystallization process in a non-equilibrium solidification manner under the high pressure and rapid cooling conditions produced by squeeze casting, which can better retain the optimization effect of ultrasonic treatment on the nanoparticle distribution in slurry. Therefore, the combination of ultrasonic treatment and squeeze casting can more amplify the advantages of ultrasonic treatment, which is expected to obtain composites with more optimized reinforcement distribution and higher mechanical properties.

4.2 Mechanism for change of mechanical properties

The improvement of the mechanical properties of the 2 wt.% nano-SiC$_p$/Al−Cu composite prepared by squeeze casting assisted with ultrasonic treatment is attributed to the refinement of grains, the reduction of porosity and the uniform distribution of nanoparticles. The change rule of the mechanical properties of composites with the applied pressure is opposite to the change rule of the average grain size, i.e., grain refinement strengthening. The refinement of the primary α(Al) phase increases the number of grain boundaries, thereby increasing the resistance to the movement of dislocations during the deformation process, which exerts a strong grain boundary strengthening effect and improves the strength of the composites. From the energy point of view, as the applied pressure increases, the grains become finer to increase their number of grain boundaries gradually, which is conducive to the storage of more interfacial energy at the grain boundaries. Then, higher energy is required to cause the composites to deform and fracture, which is manifested in the continuous improvement of the strength and elongation. The contribution of grain refinement strengthening to the strength of the composites can be explained by the following Hall−Petch formula [24,25]:

$$\Delta\sigma_s = K(d_{P2}^{-1/2} - d_{P1}^{-1/2}) \tag{1}$$

where $\Delta\sigma_s$ is the strength increase, K is the Hall−Petch constant, d_{P1} and d_{P2} are the average grain sizes of composites under different applied pressures. It is assumed that the nano-SiC$_p$/Al−Cu composites have the same K value as Al alloys, usually $K = 0.01 - 0.3\ \text{MPa}\cdot\text{m}^{1/2}$. According to Eq. (1), compared with gravity casting (0 MPa), the contribution of grain refinement to the yield strength of the composites formed at 400 MPa is less than 27 MPa. It can be seen from Fig. 5 that compared with gravity casting, the total yield strength of the composites formed at 400 MPa is 37 MPa, which is greater than the contribution of grain refinement, which indicates that the increase in strength is also related to other factors.

Through the above discussion and analysis, the increase in strength and elongation of nano-SiC$_p$/Al−Cu composites is also related to the uniform distribution of nanoparticles. Many studies showed that air entrainment was severe in the nanoparticle aggregates area, where cracks were often easy to form and grow rapidly under the application of external force, thereby reducing the mechanical properties of the composites [26,27]. The combination of ultrasonic vibration treatment and squeeze casting can effectively eliminate the agglomeration inside the casting and promote the uniform distribution of nanoparticles, as shown in Figs. 4 and 7. According to Orowan strengthening mechanism, the dispersed nanoparticles could play a pinning role to hinder the movement of dislocations effectively, thereby strengthening the composites [28]. Therefore, the uniform distribution of nanoparticles is also another important factor in improving the strength and elongation of composites.

Figure 8 shows the actual densities and porosities of 2 wt.% nano-SiC$_p$/Al−Cu composites under various applied pressures. Based on the Archimedes drainage method, the masses of the composites in air and water, namely m_1 and m_2, are measured by an electronic balance (JA2003) respectively, and then the actual density (ρ) and porosity (φ) of the composites can be obtained by the following equations [29,30]:

$$\rho = \frac{m_1}{m_2 - m_1}\rho_0 \tag{2}$$

$$\varphi = \frac{\rho_t - \rho}{\rho_t} \tag{3}$$

where ρ_0 is the density of water, and ρ_0=1 g/cm^3; the theoretical density (ρ_t) of the composites can be calculated with the rule of mixtures [31] and ρ_t=2.82 g/cm^3. It can be seen from Fig. 8 that as the applied pressure increases, the density of the composites continues to increase, while the porosity decreases accordingly. When the applied pressure increases from 0 to 50 MPa, the density of the composites increases from 2.780 to 2.803 g/cm^3, and the porosity of the casting is 0.60%, which is 57.7% lower than that of gravity casting. With further increase of applied pressure, the increase rate of density and decrease rate of porosity become smaller. The actual density of the composites under the pressure of 400 MPa reaches 2.815 g/cm^3, which is very close to the theoretical density of the composites. This indicates that the high pressure applied can greatly reduce the formation defects such as porosity and shrinkage inside the castings, and improve the density of the castings. Under the action of high pressure, the increase in density and decrease in porosity can also effectively increase the strength and elongation of the composites, which is very consistent with the tensile fracture morphology of the composites formed by squeeze casting under different pressures, as shown in Fig. 6.

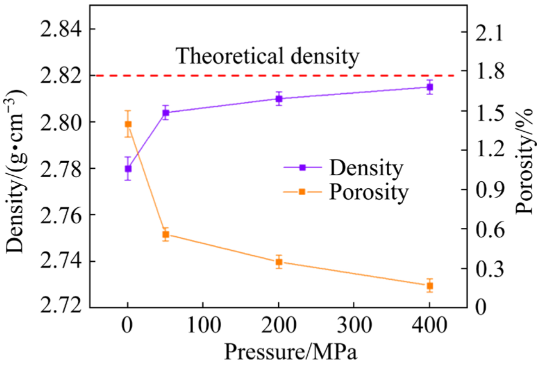


Fig. 8 Measured densities and porosities of composites under different pressures

5 Conclusions

(1) With the increase of applied pressure from 0 to 400 MPa, the average size of α(Al) grains decreases greatly at first and then the downward trend slows down. When the applied pressure is 400 MPa, α(Al) grains are refined from 105 to 25 μm, and the porosity of composites is also significantly reduced. Moreover, nano-SiC$_p$ agglomeration in the composites is eliminated, and the nanoparticle distribution is significantly improved.

(2) Compared with gravity casting with ultrasonic treatment, the combination of ultrasonic treatment and squeeze casting can more amplify the advantages of ultrasonic treatment and obtain the composites with more uniform distribution of nanoparticles, finer grains and higher mechanical properties. The ultimate tensile strength, yield strength and elongation of the nano-SiC$_p$/Al−Cu composites fabricated by the squeeze casting (400 MPa) are 290 MPa, 182 MPa and 10%, which are 52.6%, 25.5% and 400% higher than those of gravity casting (0 MPa).

(3) Under high pressure, the improvement in the strength and elongation of nano-SiC$_p$/Al−Cu composites is attributed to the grain refinement, the reduction of porosity and the uniform distribution of nanoparticles. The smaller the grain size, the more uniform distribution the nanoparticles and the lower the porosity, the higher the strength and elongation of the composites.

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挤压铸造压力对超声辅助成形纳米 SiC$_p$/Al−Cu 复合材料颗粒分布与力学性能的影响

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摘 要：采用超声振动技术制备 2%(质量分数)纳米 SiC$_p$/Al−Cu 复合材料浆料，并研究挤压铸造压力对纳米 SiC$_p$/Al−Cu 复合材料颗粒分布和力学性能的影响。研究发现，随着挤压压力从 0 增至 400 MPa，合金 α(Al)晶粒尺寸先大幅降低而后下降趋势变缓，并且铸件中孔隙率明显降低。当挤压压力为 400 MPa 时，α(Al)晶粒尺寸从 105 μm 减小到 25 μm，纳米 SiC$_p$ 分布得到明显改善，以致其力学性能最佳。复合材料的抗拉强度、屈服强度和伸长率分别为 290 MPa、182 MPa 和 10%，相比于重力铸造(0 MPa)分别提高 52.6%、25.5%和 400%。在高压作用下，纳米 SiC$_p$/Al−Cu 复合材料强度和伸长率的提高归因于晶粒细化、孔隙率降低和纳米颗粒均匀分布。

关键词：铝基复合材料；纳米 SiC$_p$；挤压铸造；超声振动；显微组织；力学性能

(Edited by Bing YANG)