Kovove Mater. 60 2022 411–420
DOI: 10.31577/km.2022.6.411

The influence of the casting method on mechanical properties of A356-Al_2O_3 nanocomposite

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Received 2 June 2021, received in revised form 28 April 2022, accepted 27 October 2022

Abstract

This study investigates the effect of casting methods, content and size of reinforcing particles and heat treatment on the mechanical properties of A356-Al_2O_3 composite. First, composite samples were made by three methods: gravity sand casting, squeeze casting, and semi-solid compo casting, and then some of them were subjected to the T6 heat treatment. Test specimens were extracted from the samples, and their tensile and yield strength, elongation, and porosity were measured, analyzed, and compared. In addition, the microstructures of composites made by nano and micro scale reinforcing particles were studied and compared. It was concluded that the superior mechanical properties were obtained in samples made by semi-solid compo casting using nanoscale reinforcing secondary phase and subjected to the T6 heat treatment.

Key words: gravity casting, squeeze casting, semi-solid, compo-casting, nano, aluminum

1. Introduction

Aluminum alloys have been widely used in various aerospace, automotive, and marine industries due to their light weight [1–5]. However, the application of aluminum alloys is restricted to situations where high strength and modulus of elasticity are required [6, 7]. Significant efforts have been made to overcome this problem to increase the strength of aluminum alloys [8–11].

One way to increase the strength of aluminum alloy is to reinforce it with ceramic particles and upgrade it to a composite material. Composite properties are influenced by the type, size, shape, and distribution of these reinforcing particles [12–14]. These secondary phase particles increase the strength of the soft aluminum matrix and impact its physical properties [15, 16]. In metal matrix composites, reinforcing particles are ceramic material with a higher modulus of elasticity than the soft metal matrix, enabling them to carry on mechanical load [17]. Because of this, forces are transferred and distributed to the reinforcing particles at the metal-particle interface, and consequently, the composite fails at higher strength [18–21]. The interfacial ability of a liquid metal to adhere to a solid ceramic particle is known as wettability [22]. A superior wettability is required to ensure proper bonding between the reinforcing particles and the aluminum matrix during the solidification. This adequate wetting is crucial to effectively transfer the load from the metal matrix to the ceramic particles without any failure occurring at the interface [23, 24].

Casting is a well-known method used economically among available production methods for metal matrix composites. The advantages of this method are its simplicity, low cost, flexibility in size and production, and applicability for mass production [25–27]. The cost of production of these composites by casting method is about one-third to half of other methods, which this number can reduce to one-tenth for mass production. The following items are essential for making metal matrix composites using the vortex casting method [28, 29]:

– Uniform distribution of reinforcing particles.

– Good wettability between the matrix and the secondary phase.

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T a b l e 1. Chemical composition of A356 Al alloy

Sn	Pb	Ni	Cr	Ti	Zn	Mg	Mn	Cu	Fe	Si
< 0.01	0.10	0.05	0.01	0.02	0.31	0.33	0.20	0.25	0.3	7.10

T a b l e 2. Cast samples for composite in this research

	Al_2O_3 (vol.%)	0	1	2	3	5	10
100 nano	Sand	×	×	×	×	×	×
	Compo	×	×	×	×	×	×
	Squeeze	×	×	×	×	×	×
5 μm	Sand	×	×	×	×	×	×
	Compo	×	×	×	×	×	×
	Squeeze	×	×	×	×	×	×

– Reduction of the porosity of the cast composite.
– Chemical reactions between the matrix and the second phase.
– Reduction of production time and temperature.

The main mechanisms to increase the strength of composites include [30–32]:
– Orowan mechanism for precipitation hardening.
– Strengthening due to fineness.
– Solid solution hardening.
– Strengthening dislocations.

Yield strength is dependent on all these mechanisms and can be expressed as follows:

$$\sigma_{\text{composite}} = \Delta\sigma_{\text{Orowan}} + \Delta\sigma_{\text{grain}} + \Delta\sigma_{\text{solution}} + \Delta\sigma_{\text{dislocation}}. \quad (1)$$

The reinforcing particles must be uniformly distributed in the matrix to obtain good mechanical properties with perfect wetting and bonding [33–35].

Another requirement is that the porosity and chemical reactions between the reinforcing particles and the metal matrix should be minimized [36–38]. During the solidification of the matrix alloy, the particles in the melt can move towards or away from the solidification front. This means that the grain size, due to the freezing rate, affects the distribution of reinforcing particles in the final structure [39–41]. Having microstructure with smaller dendrite arms spacing results in a more uniform distribution of particles, while the larger ones lead to particle clustering [42, 43]. Therefore, structures that solidify quickly provide a better distribution of particles due to the smaller size of dendrites. On the other hand, once an alloy has a long solidification range and can form non-dendritic cells, advanced casting methods such as compo casting can be used [44–46].

In this type of alloy, the viscosity of the solid-liquid mixture decreases sharply by applying shear stress in the semi-solid state [47–49]. In other words, a solid dendritic structure suspended in the liquid keeps the mixture viscosity high, which can be decreased by converting this dendritic structure into a globular one. Reducing mixture viscosity and consequently increasing the mixture fluidity is one of the most significant advantages of the compo casting process [50–55]. It has been proven that the injection of the second phase into the semi-solid mixture entraps reinforcing materials in the solidifying metal matrix and prevents algorithmization and settlement [56–58]. In this research, the effect of the casting method on the mechanical properties of A356-Al_2O_3 composite with different content of reinforcements is investigated. The samples were produced using three casting methods: sand casting, squeeze casting, and compo casting, and then subjected to the T6 heat treatment. Later, their mechanical properties, such as tensile strength, yield strength, elongation, and porosity percentage, were analyzed and compared. Finally, the effect of nano/micro scale reinforcing materials on the microstructure and mechanical properties of this type of composite was analyzed.

2. Experimental

Table 1 shows the alloy composition used in this study. In addition, different alumina powder sizes and content were used to produce this composite, as shown in Table 2. First, samples were made using traditional gravity sand casting, squeeze casting, and compo casting. In the traditional sand casting method, the composite melt was poured into a sand mold made using a step-like pattern, as shown in Fig. 1a. According to the calculations, the gross weight required for each sample was about 4.5 kg, including the weight of the casting, riser and gating system. Charge materials were melted

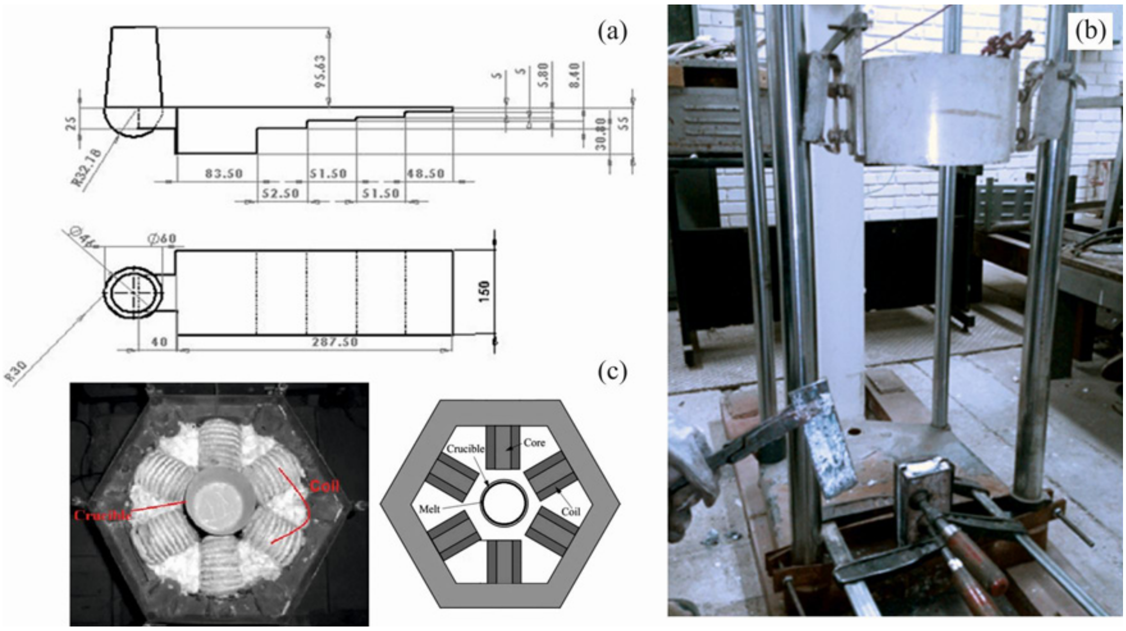

Fig. 1. Casting samples: (a) sand, (b) squeeze, and (c) compo-cast method.

in a resistance furnace with a graphite crucible to tap the melt at 720 ℃. After degassing using flux and slag, reinforcing particles were added to the melt at 720 ℃, stirred and the slurry was poured into the sand mold. In the end, the casting was shaken out, and the riser was cut out. Then each step was removed, and the center of each part was examined.

To produce the composite using the squeeze casting technique, the composite was poured into a rectangular cubic mold, shown in Fig. 1b, and pressed by weight to squeeze the composite solid-liquid mixture. About one kilogram of melt was required to make each sample to accomplish this test. The same melt preparation method used for the gravity casting previous experiment was also used for the squeeze casting method. Once the mixture reached the desired temperature of 720 ℃, it was poured into a stainless steel metal mold and immediately pressed with a 50 kg weight, then, the cubic test sample was taken out of the mold, and its center was examined.

In this study, an alternating three-phase electromagnetic agitator (Fig. 1c) was used to investigate the effect of applied shear force on the composition of the composite that tends to grow dendritically. The melt preparation method was the same as two previously explained methods. The temperature of the resistance furnace was set at 720 ℃ and after reaching this temperature and about half an hour elapsed, the crucible was taken out of the furnace, a small amount of coating flux was poured on the melt, and the melt was stirred with a spoon. The slurry was poured into a cylindrical stainless steel mold in the middle of an electromagnetic stirrer. At the same time, the pre-set electromagnetic stirrer was turned on. During the stirring process, a thermocouple was placed at the center of the sample. The semi-solid mixture was then transferred into a rectangular stainless steel mold shown in Fig. 1b and pressed with a 50 kg weight. Finally, the specimens were prepared according to Fig. 2 for the tensile test. The samples were also subjected to T6 heat treatment, and their microstructure was examined after metallography and etching with Keller solution using optical and electron microscopy.

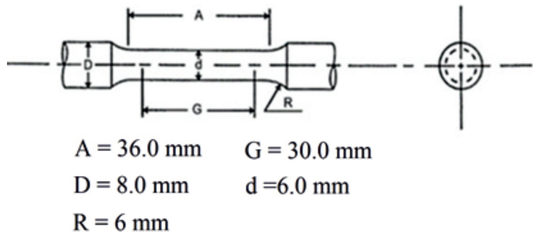

Fig. 2. Tensile test sample.

3. Results and discussion

Figure 3a shows the tensile strength of composites produced using different casting methods in heat treated and in situ conditions. As shown in this figure, the amount of tensile strength in the heat-treated samples is much higher than the one for in situ method, which can be attributed to the spheroidizing of the silicones, reduction in residual stresses and removing artificial aging. Also, samples produced using the semi-solid compo casting method presented higher tensile

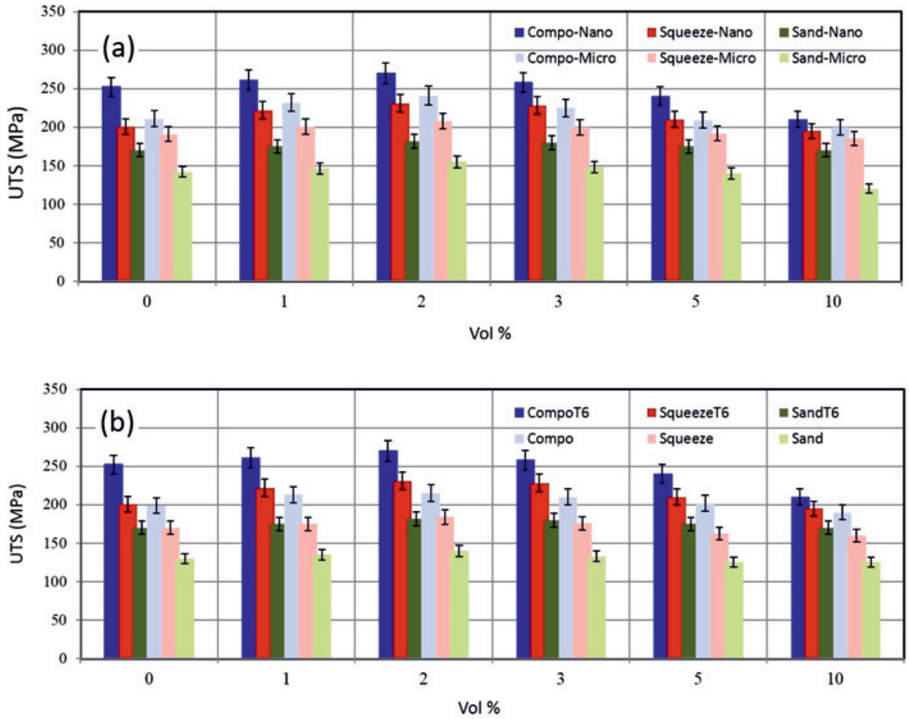

Fig. 3. Effect of heat treatment (a) and effect of particle size (b) on tensile strength in different casting methods.

strength than other methods due to a better distribution of reinforcing particles in the aluminum matrix, smaller dendrite arm spacing and distance between globular dendrite.

Figure 3b shows the tensile strength of composites made in different casting conditions using two different reinforcement particle sizes (nano/microparticles). As seen in this figure, the samples with 100 nm reinforced particles have a higher tensile strength than those with 5 µm reinforced particles. This reduction in tensile strength of composites with the micro-sized particle is attributed to the higher density of accumulated dislocations behind the larger particles, which increases the stress concentration at the particle-matrix interface. Eventually, cracks nucleate and grow at these interfaces leading to composite failure at lower stresses and, consequently, a reduction in elongation and ductility, as shown in the figure.

Increasing the solid nucleation in the liquid, which can occur by several methods and mechanisms, reduces the dendrite arm spacing, which leads to a finer microstructure accordingly. This finer microstructure is responsible for increasing the tensile strength, ductility and toughness. Higher cooling rates, adding more grain refiner, and mechanical refining of solid particles suspended in the liquid are the most applicable mechanisms that reduce the dendrite arm spacing. It should be noted that the aluminum 356A alloy has a long freezing range, making grain refining possible.

In this study, the following methods were employed to increase the nucleation and growth: Addition of a secondary phase (which also acts as a primary nucleation site), high cooling rate (which at the same time increases the number of nuclei and decreases the critical diameter of the nuclei) and breaking down the dendrite tips by shear forces (which turn them into new nuclei). As shown in Fig. 4, squeeze and compo casting samples present finer microstructure and smaller dendrite arm spacing related to the higher cooling rate and more applied pressure during the solidification. In the squeeze and compo casting method, samples were made in a metallic mold under the 50 kg weight, which both parameters increase the heat transfer coefficient (HTC) between the cast and mold and increase the cooling rate. In addition to higher cooling rates, samples made using squeeze casting and compo casting methods were under mechanical pressure and electromagnetic stirring, which break down the growing dendrite in the mushy zone.

Figure 5 shows the SEM image of the composite samples in the semi-solid state. As can be seen, the particle distribution in the matrix is relatively uniform. Also, in samples using nano-sized reinforcing particles, the stress concentration is lower due to the higher number of particles in the same volume percentage. Therefore, mechanical properties are predicted to be higher, confirmed in tensile diagrams.

Figure 6 shows the yield strength of composites made with different casting methods using two particle sizes. As can be seen in this figure, samples made with compo casting in the semi-solid state present higher yield strength compared to other methods due

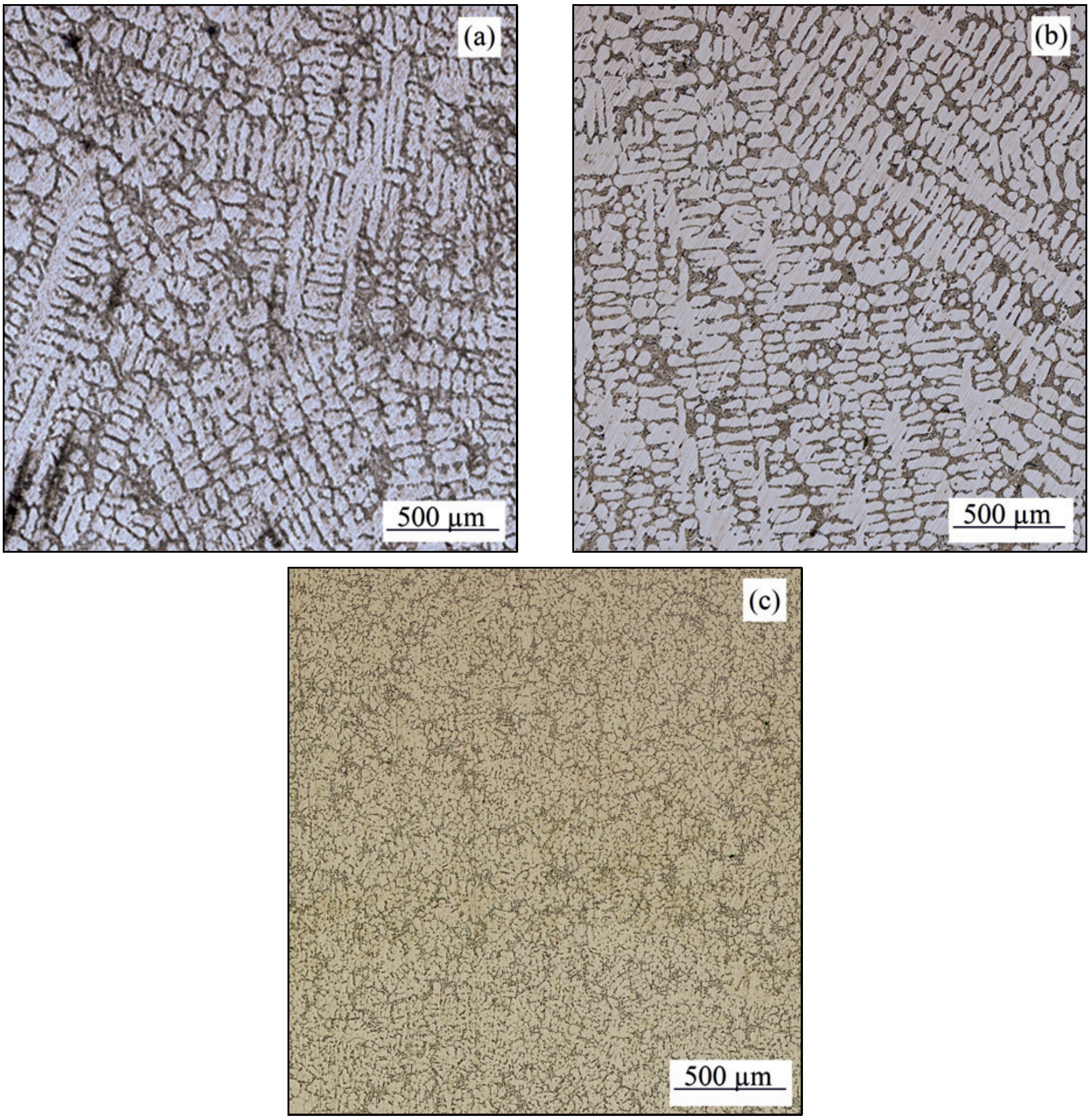

Fig. 4. Optical microscope image: (a) sand, (b) squeeze, and (c) compo-casting method of the percentages of 5 % reinforcing particles.

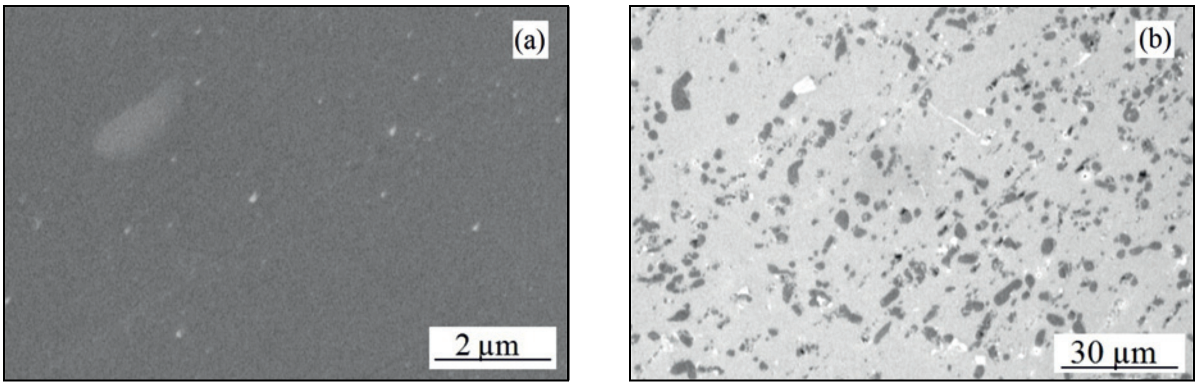

Fig. 5. SEM image of the percentages of 5 % reinforcing particles: (a) 100 nano and (b) 5 μm.

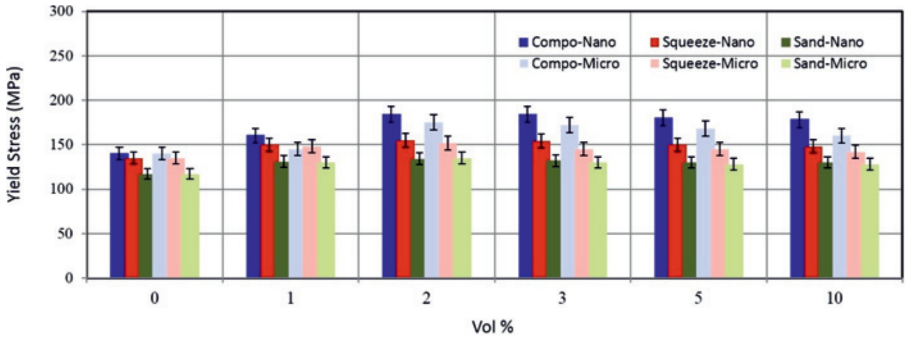

Fig. 6. Yield stress in different casting conditions.

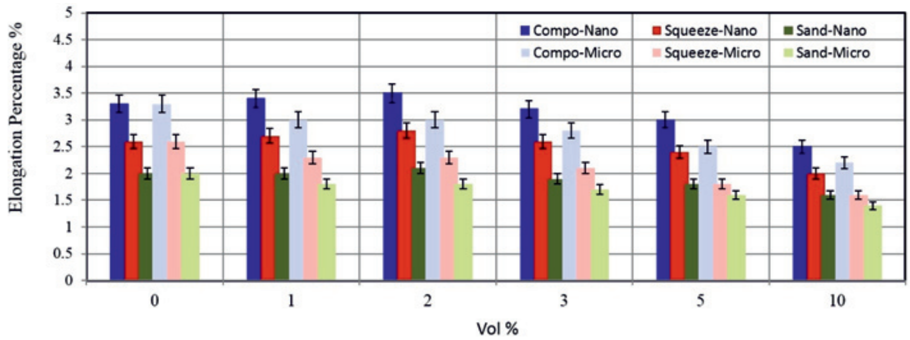

Fig. 7. Elongation percentage chart in different casting conditions.

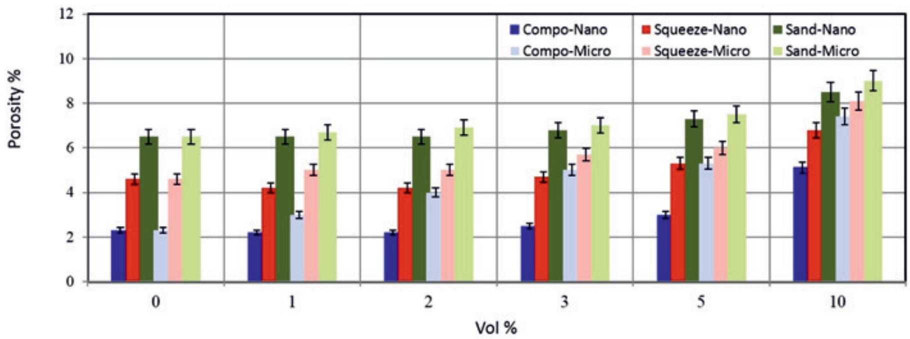

Fig. 8. Changes in porosity percentage according to the type of casting.

to the finer microstructure and more uniform distribution of reinforcing particles. In sand and squeeze casting methods, in the absence of electromagnetic forces and shear forces required for breaking dendrites, the reinforcing particles accumulate in locations where solidified last and show tendencies to absorb each other and form larger agglomerated particles. Also, according to the optical microscope images, the dendrites in these two methods are more significant than the semi-solid method.

Elongation of composites made with different casting methods using two different particle sizes is seen in Fig. 7. As expected, semi-solid compo casting samples show higher elongation due to the fineness of the microstructure. In the sand casting sample, the porosity percentage is relatively high due to the absence of external pressure during freezing. In this sample, porosity intensifies due to dendritic growth and air trapping between the dendrites.

In the case of squeeze casting, external pressure is applied to reduce porosity. However, in the semi-solid composite samples, where the microstructure has changed from dendritic to globular, external pressure and stirring forces help the dissolved gas to escape from the castings easily. Because of this, as shown in Fig. 8, the percentage of porosity has reduced. Reducing the mixture viscosity and easier removal of gas bubbles are other causes of reducing porosity in the composite samples produced by the compo casting method in the semi-solid state.

4. Conclusions

In this study, the effect of casting methods on the mechanical properties of A356-Al_2O_3 composites has been investigated in different percentages of reinforcement particles. In heat-treated samples, the tensile strength is much higher, which can be attributed to the round silicones, removal of residual stresses, and artificial aging. In addition, the samples made using the semi-solid compo casting method had higher tensile strength than those made using the sand casting and squeeze casting methods due to the better distribution of reinforcing particles in the aluminum matrix. Moreover, smaller dendritic arm spacings and solid globular structure, which clearly can be observed in the microstructure, are other parameters highly influencing increasing the tensile strength in the samples made using the semi-solid compo casting method.

Another finding was that samples with 100 nm reinforcing particles showed higher tensile strength than samples with 5 μm reinforced particles. This can be explained by increasing dislocation densities around the larger particles, which introduces higher stress concentration around them with a higher probability of cracking. Also, in samples with nano-sized reinforced particles, the stress concentration is lower due to the higher number of particles in the same volume percentage. Therefore, the tensile and yield strengths are higher. In samples made by the semi-solid compo casting method, yield strength is higher than in samples made by other casting methods due to the finer dendritic microstructure and uniform distribution of reinforcing particles. This uniform fine dendritic structure found in samples made by the semi-solid method increases the elongation compared to other methods. Samples made with the traditional gravity sand casting method, due to the lack of external pressure during freezing and lower cooling rates, the amount of porosity is relatively higher compared to the other methods. In addition, in these samples, due to the coarse dendritic structure and higher melt viscosity, there is more potential for gas entrapment, resulting in larger porosities.

On the other hand, in the squeezed cast samples, the applied external pressure reduced the porosity. In the semi-solid compo cast composites, the amount of entrapped gas between the refined dendrites is reduced because the microstructure has changed from the dendritic to the globular one. Finally, the external pressure, along with this phenomenon, makes it easier for gas to escape, which leads to a reduction in the size of porosity.

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