



## Microarticle

# Experimental investigation on bi-axial superplastic forming characteristics of AA6063/SiCp with various percentages of SiCp under various temperatures and pressures

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## ABSTRACT

In the superplastic forming process (SFP), exceptional formability can be achieved. The formability in SFP is far superior when compared to traditional methods. Through SFP, the most complex shapes with high dimensional tolerance were formed. In this article, bi-axial superplastic forming was conducted after the rolling process on various percentages of silicon carbide composite (SiCp) particles in the gas pressure forming tester. Results of this study are mainly focused on finding favorable forming parameters (temperature, pressure, and time) for the superplastic formability of various Al/SiCp prepared by the stir casting process.

## Introduction

Aluminum matrix composites (AMCs) refers to the class of light-weight, high-performance Aluminum centric material systems [1]. The research progress seen in the three decades greatly improved the physical, mechanical, thermo-mechanical, and tribological properties of AMCs [2]. However, this research progress is mostly limited to typical applications. In the last few years, the use of AMCs in high-tech structural and functional applications including aerospace, automobile, marine, transportation, mineral, defence, automotive and thermal management areas, as well as in sports and recreation became widely accepted. In most of the applications, the need for complex shapes with excellent dimensional tolerance is very high. Superplastic forming process (SFP) is one of the cheapest forming techniques that is widely used to form these types of complex shapes. Through the SFP, high dimensional tolerance and exceptional forming were obtained. Proper grain refinement will give good formability in the materials. Thermo-mechanical treatment and grain refinement technique will improve the properties of superplastic forming. Through proper grain refinement in Aluminum-based alloy, the maximum elongation of more than 700% can be obtained. Formability in superplastic forming was obtained through mechanisms like grain boundary sliding (GBS), diffusion.

Maximum 60–70% of superplastic forming was obtained through GBS mechanism [3–7]. However, achieving formability is challenging, and at room temperatures, the formability of composite is difficult due to its brittle nature. For avoiding the difficulties, a proper selection of SFP parameters such as pressure, temperature, and time is needed. Many have studied on such conditions, especially to achieve good formability in the Aluminum silicon carbide composites (Al/SiCp) [5,6,8,18]. The objective of this work is to find the favorable forming parameters such as temperature, pressure, and time in the superplastic forming of various percentage Al/SiCp composites.

## Experimental details

A stir casting process (SCP) was used for preparing the composites. Fig. 1 (a) shows a schematic diagram of the SCP. An electric motor is fixed at the top of the furnace to provide stirring motion to the stirrer, and by using the speed controller setup, different stirring speeds were obtained. The SiCp preheated to a temperature of 1000 °C by Resistance furnace before it is mixed with the molten Aluminum alloy, which is done using an electric furnace [9]. The heat treatment on SiCp was done to form a layer of SiO<sub>2</sub> on the SiCp, which improves the incorporation of the SiCp into the hot molten metal. The material is

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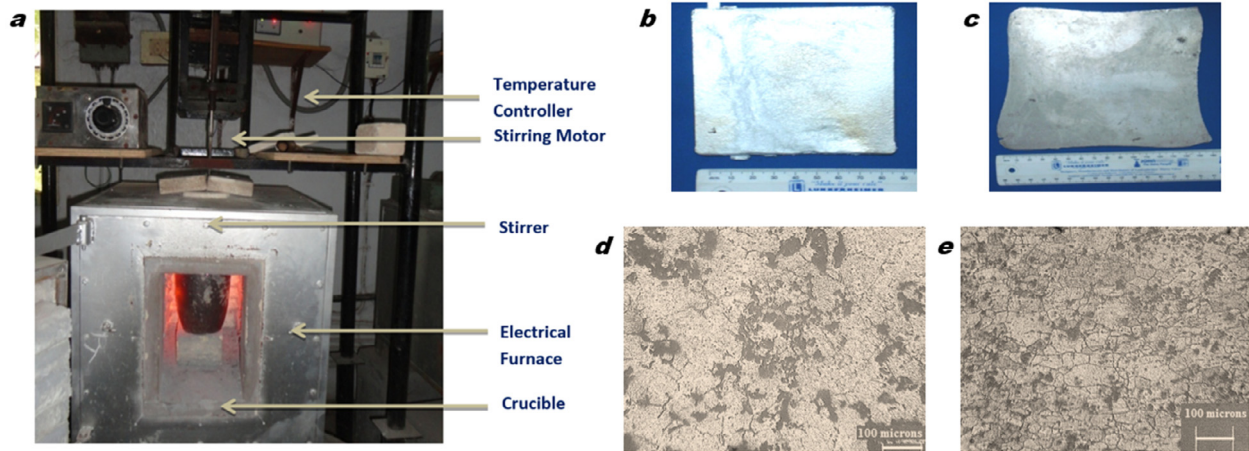


Fig. 1. (a). Stir casting unit and its components; (b). Cast specimen of Al6063/SiC<sub>p</sub> composite; (c). Rolled component; (d). The microstructure of cast specimen; (e). The microstructure of rolled specimen.

stirred with a speed of 300 rpm for a few minutes. The stirred metal is then slowly poured into the die, which is preheated to a temperature of 973 °C. The die is then allowed to cool in the air for a few hours, and then the specimen is removed [10,11]. Fig. 1 (b) shows the required cast component of Al/SiC<sub>p</sub> composite. Now the rolling process is considered, and during the rolling process, the geometric shape of the work is changed, but its volume remains constant. By the hot rolling process, the cast component thickness was reduced until 5 mm to 2 mm to make it suitable for blow forming. A hot rolling breaks up inclusions and distributes the material throughout, that means the SiC<sub>p</sub> particles are uniformly distributed all over the material. The rolled component is shown in Fig. 1 (c).

The Fig. 1 (d) Shows the microstructure of the cast specimen, the average grain size of 75 μm and more agglomeration of SiC<sub>p</sub> were seen over there. The average grain size of the rolled sheet was 30 μm, and the SiC<sub>p</sub> were distributed all over the surface of the matrix alloy, as shown in Fig. 1 (e). Bi-axial superplastic forming was conducted in the gas pressure forming tester, where constant gas pressure was applied on SiC<sub>p</sub> composites sheets. These composites sheets are prepared with varying percentages of SiC<sub>p</sub> (5%, 8%, and 10%). By the trial and run method, bi-axial superplastic forming tests were conducted at various temperatures from 520 °C to 600 °C and pressures from 0.2 MPa to 0.7 MPa. Due to the specified pressure of air, the sheets were formed into the hemispherical dome. The dome heights were measured accurately by Linear Variable Differential Transformer (LVDT) with respect to time. The experimental setup consists of a die which is placed between the split type furnace, as shown in Fig. 2 (a). The rolled composite blank of diameter 70 mm was placed between the top and bottom of the die. The furnace has a temperature controller to maintain a constant temperature, and the compressor is used to supply pressurized air into the die. A pressure gauge is used to regulate the pressure of air

supplied to the die, and LVDT was fixed on top of the blank to measure the instantaneous height.

Thickness variation is an inherent characteristic of the components formed using SFP. The commonly used thickness variation parameters are Thinning Factor, Thickness Strain, and Fractional Height. Thinning Factor is defined as the ratio of measured thickness at any point at the dome to the average thickness. The logarithmic value of thickness can determine the thickness stain at any height to the initial thickness. The fractional height is the ratio between the dome height and blank diameter and represented as dome height/blank diameter (H/D). Thickness at three equidistant points along the diametric section of the formed spherical cup was measured using a digital micrometer of ± 1.0 μm accuracy and setup, as shown in Fig. 3 (a-b). The dial gauge was mounted vertically on a stand just touching a pointed anvil with a spherical end, thus making only a point contact. In this position, the dial gauge was zero. The dial gauge stands as well as the anvil stand was placed over a flat granite surface plate. Therefore, there was no chance of error due to lateral slipping of the two measuring ends. The dial reading when a component was introduced in between the two spherical ends gave the thickness of the component at that point. While measuring the thickness on the profile, the surface should be horizontal. The thickness of the profile was measured at various positions, as shown in Fig. 3 (c), the thickness was measured at the angular positions of 30°, 60°, 90°, 120°, and 150°. At the positions of 90° is the pole thickness.

The commonly used thickness variation parameters and their equations are given below:

$$\text{Thinning Factor (TF)} = \frac{T}{T_{\text{Avg}}} \quad (1)$$

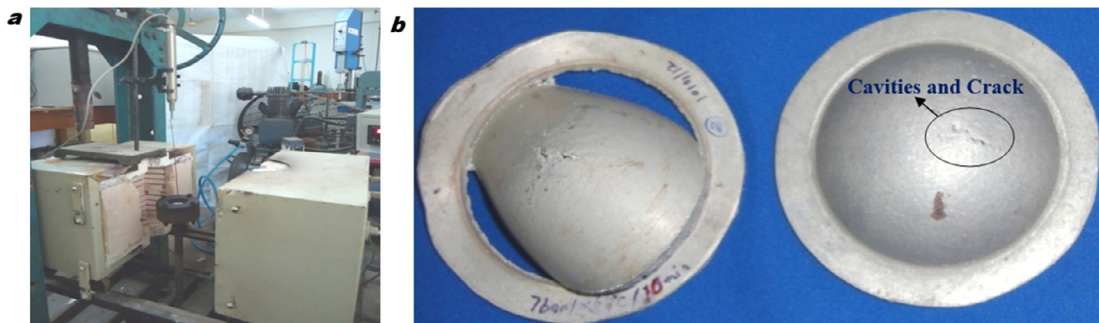


Fig. 2. (a). Superplastic forming setup; (b). Deformed specimens at pressures of 0.7 MPa and 0.6 MPa under 600 °C temperature.

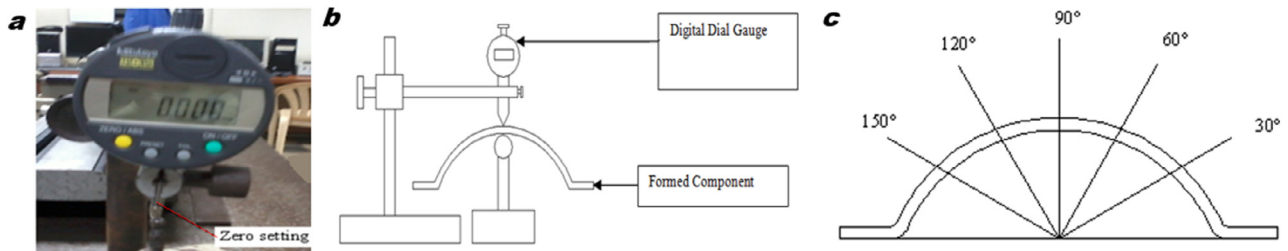


Fig. 3. (a). Digital dial gauge; (b). Digital dial gauge and measuring setup; (c). Angular positions of thickness measurement.

$$\text{Thickness Strain (TS)} = \ln\left(\frac{T}{T_0}\right) \quad (2)$$

$$\text{Fractional Height (FH)} = \frac{H}{D} \quad (3)$$

where,  $T_0$  is the original thickness;  $T$  is the thickness at any height;  $T_{Avg}$  is the average thickness of the profile;  $H$  is the height at which thickness measurement is taken;  $D$  is the blank diameter.

## Results and discussion

At the low temperature of 520 °C, the minimum amount of deformation was obtained, and the pressure was increased up to 6 bar till hemispherical shape formation takes place in the sheet. At this low temperature, there is no sign of grain moment or sliding takes place. As well as the composite sheets were tested in the higher temperature of 600 °C, the bulging takes place very quickly, and the component was failed because of the rapid movement of the liquid phase grain boundary. Due to the higher pressure, controlled deformation was not obtained, controlled grain boundary sliding with diffusion leads to superplastic forming. Fig. 2 (b) shows the deformed specimens at 600 °C with a pressure of 0.7 MPa and 0.6 MPa. At the temperature of 600 °C and 0.7 MPa, the components failed within ten minutes. The higher pressure and temperature lead to component failure; the maximum pressure was taken as 0.6 MPa. During this experiment, 8% and 10% of SiCp composites were failed at the pressure of 0.4 MPa and 0.6 MPa respectively at the same temperature of 600 °C. Fig. 4 (a) shows the maximum bulge height formed in 5%, 8% and 10% Al/SiCp composites at a constant pressure of 0.4 MPa and 580 °C for 30 min. Maximum dome height obtained was 16 mm, 12.5 mm and 11 mm for 5%, 8% and 10% SiCp respectively. The increase in the percentage of SiCp reduces the dome height due to the mechanism behind the grain boundary sliding in superplastic forming. In metal matrix composites the presence of SiCp resists the movement of grain boundary sliding. The superplastic elongations are enhanced by the presence of liquid phase in metal matrix composites, by the relaxation of stress concentration at the triple points and the edges of grain boundaries which enhance the formability. The movement of the grain boundaries is blocked by reinforcements when the percentage of reinforcements was increased [3–5]. The thinning factor is 0.86, and 0.85 was obtained for 5% and

both 8% and 10% of SiCp composites respectively. Fig. 4 (b) shows the thickness reduction along with the profile for a various percentage of SiCp composites at a constant temperature and pressure of 580 °C and 0.4 MPa, respectively. When there is an increase in the percentage of SiC particles decreases thickness reduction, and dome height was also very less (9.2 mm) due to the restriction of grain boundary sliding. The H/D ratio was calculated for different percentages of SiCp composites at constant temperature and different pressures, as shown in Fig. 4 (c). The maximum H/D ratio was obtained in 5% SiCp composites for the pressure of 0.4 MPa and 0.6 MPa to have an excellent superplastic forming behavior because the H/D ratio of Aluminum is 0.35. At 5% SiCp composite has a good formability character compared to the other two composites. Hence, 5% SiCp is taken for further study [12–17].

The superplastic forming behavior for Al6063/SiCp composites are summarized in dome height vs. time plotted, as shown in Fig. 5 (a-c). The superplastic forming was conducted for 45 min, and the instantaneous dome heights were measured with LVDT. Initially, the height of the dome increases very rapidly, and this phenomenon is similar to the creep behavior of most metallic alloys and structural ceramics at constant pressure [15]. Fig. 5 (a) shows the dome height vs. time curve at a constant pressure of 0.6 MPa and temperatures of 560 °C, 580 °C, and 600 °C, respectively. At 600 °C temperature and 0.6 MPa pressure, the dome height reached to 21 mm, but the component failed within 500 s at the pole region. Fig. 5 (b) shows the dome height vs. time curve at a constant pressure of 0.4 MPa and 560 °C, 580 °C, and 600 °C temperature, respectively. At 600 °C temperature and 0.4 MPa pressure, the dome height reached to 18 mm, and the component failed within 1800 s at the pole region, but the maximum dome height of 19 mm was obtained at 580 °C. Fig. 5 (c) shows the dome height vs. time at 0.2 MPa pressure and 560 °C, 580 °C, and 600 °C temperature. Maximum of 11 mm dome height was obtained at 600 °C temperature and for the corresponding pressure. It is inferred that the maximum dome height for 5% SiCp of 19 mm was obtained at 580 °C temperature and 0.4 MPa pressure.

## Conclusions

From this experimental work, the following conclusions were drawn. Bi-axial superplastic forming was conducted with different pressures and temperatures for rolled Al/SiCp composites. It is observed

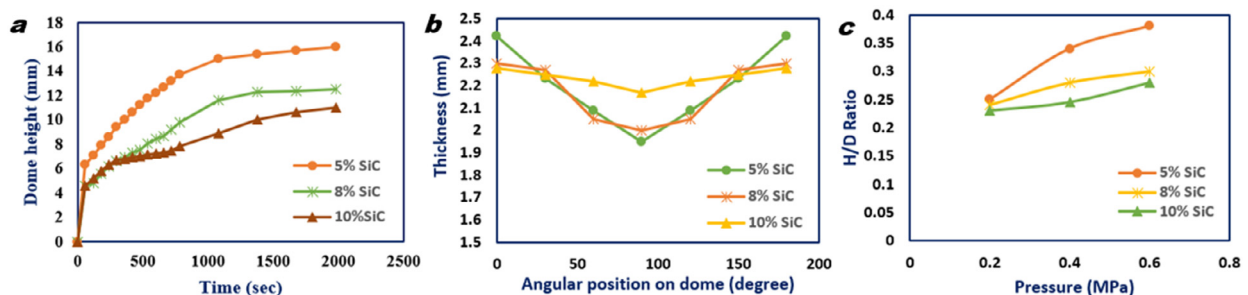


Fig. 4. (a). Dome height vs. time; (b). The thickness, along with the profile vs. angular position on the dome; (c). H/D ratio vs. pressure.



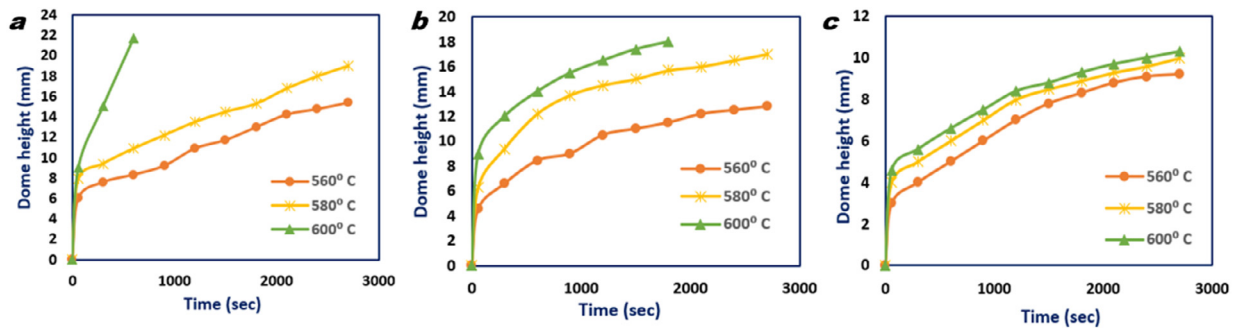


Fig. 5. Variation in dome height with respect to pressure at different temperatures (a). At a constant pressure of 0.6 MPa; (b). At a constant pressure of 0.4 MPa; (c). At a constant pressure of 0.2 MPa.

that the average grain size of the rolled sheet was 30  $\mu\text{m}$ , and the SiCp were distributed all over the surface of the matrix alloy. Dome heights are formed at a constant temperature of 600  $^{\circ}\text{C}$ , 580  $^{\circ}\text{C}$ , and 560  $^{\circ}\text{C}$  and a constant pressure of 0.2 MPa, 0.4 MPa and 0.6 MPa respectively. Maximum dome height of 19 mm was formed without failure for 5% SiCp composites at 580  $^{\circ}\text{C}$  temperature and 0.4 MPa pressure. This is because of the liquid phase formed in the grain boundaries, which leads to maximum elongation and thus increases the dome height, and the thinning factor is 0.86 was obtained for 5% of SiCp composites. The maximum H/D ratio was obtained in 5% SiCp composites for the pressure of 0.4 MPa.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rinp.2019.102624>.

#### References

- [1] Cappetti N, Garofalo L, Naddeo A, Nastasia M, Pellegrino A. A method for setting variables in Super Plastic Forming process. *J Achiev Mater Manuf Eng* 2010;38(2):187–94.
- [2] Tosun Gul. Statistical analysis of process parameters in drilling of Al/SiCp metal matrix composite. *Int J Adv Manuf Technol* 2011;55:477–85.
- [3] Chan KC, Tong GQ. High strain rate superplastic gas pressure forming of an Al-4.4 Cu-1.5Mg/21SiCw composite under variable strain rate paths. *Mater Sci Eng A* 2004;374:285–91.
- [4] Barnes AJ. Superplastic forming 40 years and still growing. *J Mater Eng Perform* 2007;16(4):440–54.
- [5] Chan KC, Tong GQ. High strain rate superplastic gas pressure forming of an Al-4.4 Cu-1.5Mg/21SiCw composite under variable strain rate paths. *Mater Sci Eng* 2002;374:285–91.
- [6] Ambrogio G, Palumbo G, Sgambitterra E, Guglielmi P, Piccininni A, De Napoli L, et al. Experimental investigation of the mechanical performances of titanium cranial prostheses manufactured by superplastic forming and single-point incremental forming. *Int J Adv Manuf Technol* 2018;98:1489–503.
- [7] Fathy A, Sadoun A, Abdelhameed M. Effect of matrix/reinforcement particle size ratio (PSR) on the mechanical properties of extruded Al-SiC composites. *Int J Adv Manuf Technol* 2014;73:1049–56.
- [8] El-Morsy Abdel-Wahab, Manabe Ken-ichi, Nishimura Hisashi. Superplastic forming of AZ31 magnesium alloy sheet into a rectangular pan. *Mater Trans* 2002;43(10):2443–8.
- [9] Balasivandha Prabu S, Karunamoorthy L, Kathiresan S, Mohan B. Influence of stirring speed and stirring time on distribution of particles in cast metal matrix composite. *J Mater Process Technol* 2005;171:268–73.
- [10] Sijo MT, Jayadevan KR. Analysis of stir cast aluminium silicon carbide metal matrix composite: a comprehensive review. *Proc Technol* 2016;24:379–85.
- [11] Hashim J, Looney L, Hashmi MSJ. Metal matrix composites, production by the stir casting method. *J Mater Process Technol* 1999;92(93):1–7.
- [12] Horita Z, Furukawa M, Nemoto M, Barnes AJ, Langdon TG. Superplastic forming at high strain rates after severe plastic deformation. *Acta Mater* 2000;48:3633–40.
- [13] Mabuchi M, Higashi K. On accommodation helper mechanism for superplasticity in metal matrix composites. *Acta Mater* 1999;47(6):1915–92.
- [14] Chan KC, Tong GQ, Gao L. Hot formability of an Al2009/20 SiCw composite sheet. *J Mater Process Technol* 1998;74:142–8.
- [15] Chan KC, Tong GQ. Formability of a high strain rate superplasticity Al-0.4Cu-1.5 Mg/21SiCw composite under biaxial tension. *Mater Sci Eng* 2003;340:49–57.
- [16] Sagar R, Purohit R. Fabrication and testing of Al-SiCp composite valve seat inserts. *Int J Adv Manuf Technol* 2006;29:922–8.
- [17] Karakizis PN, Pantelis DI, Fourlaris G, Tsakiridis P. Effect of SiC and TiC nanoparticle reinforcement on the microstructure, microhardness, and tensile performance of AA6082-T6 friction stir welds. *Int J Adv Manuf Technol* 2018;95:3823–37.
- [18] S V, et al. High temperature superplasticity and its deformation mechanism of AA6063/SiCp. *Case Stud Therm Eng* 2019;14:100479 <https://doi.org/10.1016/j.csite.2019.100479>.