Optimization of Super Plastic forming process parameters of Al 6061 alloy reinforced with SiC nano composites by Taguchi method

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Abstract. This study investigates the optimization of superplastic forming in aluminum alloy 6061 reinforced with 100 nm silicon carbide (SiC) nanoparticles, fabricated by use of the ultrasonic cavitation technique. The formed composite was subjected to superplastic forming tests, achieving a maximum dome height of 21 mm. Key parameters, including pressure 2 MPa, 4 Mpa and 6 Mpa, temperature (560°C, 580°C and 600°C), and time 15, 30, and 45 minutes, were systematically varied. To identify the optimal process parameters, a Taguchi L9 experimental design was employed, facilitating a comprehensive examination of these factors' effects on the forming performance. The findings provide valuable insights for enhancing the superplastic forming process in aluminum-SiC composite materials. Keywords: Energy transition, industrial growth, manufacturing innovation, R&D investment.

1 Introduction

The growing need for materials to enhance the overall performance of automotive and aerospace components has forced the development of composite materials, such as landing gear, airframes, etc. Aluminum Metal Matrix Composites (AMMC) are a popular composite material utilized to meet new industrial demands. The Taguchi L9 design was chosen to efficiently study the influence of multiple superplastic forming parameters with a minimal number of experiments. Compared to full factorial or response surface methods, L9 significantly reduces experimental cost, time, and material consumption while still identifying dominant factors. This approach is well suited for preliminary optimization of high-temperature forming processes with limited experimental runs. The examination of the mechanical characteristics of AMMC made using the stir casting method for different boron and silicon carbide compositions reinforced with aluminum alloy 6061. After conducting testing for tensile, flexural, hardness, and impact, it was discovered that the hybrid composites outperformed pure aluminum in terms of characteristics. The ability of a material to undergo extraordinarily high elongations of up to 1000% is known as super plasticity. Because of this high ductility, the automotive and aerospace industries have expressed interest in the possibility of creating complex shaped parts with a minimal number of mechanical steps. This allows for significant improvements in structural efficiency as well as, frequently, cost savings on both the product and operating costs [1-3]. The super plastic forming process is depicted in figure 1. Superplastic formation typically occurs at a strain rate of 10-1 to 10-5 s-1.Superplastic formation of the alloys occurs at a slow strain rate of 10-3 to 10-5 s-1. High strain rate super plastic formation occurs in aluminum metal matrix composites between 10-2 and 100 s-1 [4-7]. Aluminum Metal Matrix Composites (AMMC) are brittle by nature and cannot be created under typical circumstances, while having a low density, strong specific stiffness, and high strength.

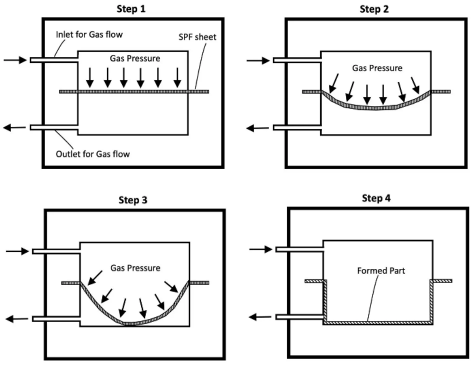

Fig.1. Superplastic forming

SPF aluminum finds widespread use in vehicles, railroads, and airplanes. More than 40 aviation manufacturing companies and 20 automotive sectors employed aluminum components made with superplastic [8-10]. The capacity to produce large components in a single process, eliminating the need for many sub-assemblies, tight dimensional precision, and good surface quality are the main benefits of SPF components.

Al 6061 was selected because it is a heat-treatable alloy that allows strength recovery after superplastic forming, unlike SPF-favourable alloys such as Al 5083. The addition of nano-SiC effectively refines grains and suppresses grain growth at elevated temperatures, enabling stable superplastic deformation. Moreover, Al 6061 offers good weldability, corrosion resistance, and industrial relevance, making it suitable for scalable applications. As a result, neither interfaces nor the flaws that often arise at interfaces exist. Saves a great deal of time and work in manufacturing. Al 6061 reinforced with SiC was selected because it combines acceptable superplastic formability with the advantage of post-forming heat-treatable strength, which is not possible in SPF-favourable alloys such as Al 5083. The addition of SiC nanoparticles effectively refines and stabilizes the grain structure during high-temperature deformation, extending the superplastic window of Al 6061. Compared to Al 7475, Al 6061 is more cost-effective, easier to process, and less sensitive to hot cracking, making it optimal for practical superplastic forming applications.

Outstanding mechanical qualities as a result of being made of equiaxed, ultra-fine grains [11-14]. A significant factor influencing the super plasticity of metals is grain size. When the tensile elongation is higher, the rate of strain sensitivity index (m) value is typically high, the flow stress is low, and the grain size is fine. Grain size characterisation is consequently crucial to the whole super plasticity characterization process. The strain rate range across which "m" is high can be controlled by a few coarse grains in a fine grain structure, and in certain situations, this can lead to the emergence of a threshold stress. In actual materials, a low grain size distribution has the significant impact of producing a comparatively large m ($m>0.5$) [15-18]. The micro-level reinforcements are frequently employed in AMCs. Technological developments in the field of Nano sciences have enabled the creation of metal matrix Nano composites, or MMNCs, as the composites that result. Reinforcement in MMNCs is expressed in nanometers. Nanoscale SiC reinforcement has a more pronounced effect on grain refinement than micro-SiC due to its higher number density and larger interfacial area, which effectively restricts grain growth through Zener pinning during superplastic forming. The refined and stable equiaxed grain structure enhances strain-rate sensitivity (m), promoting grain boundary sliding as the dominant deformation mechanism. In contrast, micro-SiC particles mainly act as load-bearing reinforcements and often introduce stress concentrations, which can reduce superplasticity and limit elongation.

The mechanical, tribological, thermal, and interfacial properties of the base material are enhanced by the nano reinforced particles in an aluminum alloy matrix. Using liquid metallurgical processes Al6061-SiC and Al7075-Al_2O_3 MMCs, which contain filler quantities up to 6% of the total weight. The microstructural analyses demonstrated the uniform dispersion of the particles within the matrix system, and the research found that the composites' densities outperform that of their underlying matrix. The hardness of Al6061-SiC and Al7075-Al_2O_3 composites was found to be 60-97VHN and 80-109VHN, respectively, and the micro hardness of the composites was observed to rise with increased filler content. It is discovered that the composites' tensile strength properties are greater than those of the basic matrix, with Al6061-SiC composites having stronger tensile properties than Al7075-Al_2O_3 composites. For the first time, the high-strain-rate superplastic gas pressure formation behaviour of an Al6061/SiCw composite sheet under constant applied flow stress conditions has been studied by Tong et al. (1997). In approximately 17.6 seconds, a hemisphere diaphragm is successfully created at a temperature of 873K and an applied flow stress of 4.0 MPa. The polar height vs. time curve revealed three different deformation regimes based on the experimental results. These deformation regimes are comparable concerns the creep behaviour of structural ceramics and the most metallic alloys when subjected to continuous loads. It is demonstrated that there is not a reasonable agreement between the experimental results and the tabulated thinning factors based on the m value found by tensile testing [19-21].

Due to the high modulus, high strength, low density, good neutron absorption, and outstanding wear resistance of silicon carbide (SiC), SiC particle reinforced aluminum (Al) matrix composites have found extensive use in the domains of aerospace, weapons, transportation, and neutron shielding [22]. There are currently many kinds of aluminum alloys on the market, each with a unique set of advantages and applications. This paper focuses on heat-curable Al-6061 Alloy (aluminum alloys) which is suitable for a variety of applications such as toughness, machinability, and resistance to corrosion [23-25]. These alloys can be considerably toughened. The novelty of this work lies in the use of nano-scale SiC reinforcement in an Al 6061 matrix to enhance superplastic forming behaviour, whereas most existing Al–SiC SPF studies focus on micro-sized reinforcements. The study systematically correlates ultrasonic-assisted nanoparticle dispersion with superplastic deformation and grain stability. In addition, the optimized SPF parameters identified using the Taguchi approach provide a practical, low-experimental-cost framework for processing nano-reinforced Al composites.

2 Material and Experiment

Because it is mostly alloyed with magnesium and is not strengthened by heat treatment but rather by strain hardening or cold working, 6061 is one of the best corrosive alloys of aluminum with great corrosion resistance. In the basic alloy, the tensile strength is 117 MPa, the hardness is 31 HRB, and the modulus of elasticity is 75 MPa. The aerospace and automotive industries are the main users of Al-6061 alloy for lightweight components. Using the Al-6061 alloy matrix, a variety of reinforcements have been employed to build the metal matrix composite (MMC) where SiC nano particles were added [6].

When creating in situ particle reinforced aluminum composites using the traditional mechanical stirring cast method, there are two primary serious problems. One is the way the created particles group together. To disperse microscopic particles less than a few micrometers in diameter, the mechanical stirring method is not the best. It has been demonstrated that a significant deterioration of the mechanical properties, such as tensile strength and fatigue resistance, occurs when the reinforced phase aggregates. The other is the excessive porosity, which deteriorates the composites mechanical qualities, particularly their resistance to corrosion. Shrinkage during solidification, hydrogen evolution, and gas trapping during mixing are the three main sources of porosity.

Gas entrapment during mixing is the main cause of pores appearing in the melt when stir casting is used to fabricate Al matrix composites. The purification, degassing, and refining of metallic melts have made substantial use of ultrasonic vibration, as the introduction of ultrasonic fields into a liquid can result in nonlinear processes such cavitation and acoustic streaming. Moreover, uniform particle distribution within the metal matrix and enhanced wettability between reinforced particles and the matrix can be achieved through ultrasonic vibration. The composition uniformity was verified by maintaining a fixed weight percentage of SiC nanoparticles during casting and confirming it through EDS elemental analysis at multiple locations. Particle distribution uniformity was quantified using SEM micrographs taken from different regions of the composite, followed by image analysis to assess dispersion and clustering. Consistent SiC area fraction and absence of large agglomerates across sections confirmed uniform reinforcement distribution.

According to some reports from this experiment, particle reinforced composites were prepared using ultrasonic vibration, and the reinforcements were injected straight into the melts. On the other hand, not much research has been published on the use of ultrasound assistance in situ approach for the in situ production of aluminum composites reinforced with particles. Following the rolling process, the finished composite material is ready (figure 2).

Fig.2. Ultra-sonic cavitation method

The thickness of the sheet was reduced from 5mm to 2mm and 1.5mm to make it suitable for blow forming. Hot rolling was carried out by heating the sheet above recrystallization temperature, followed by rolling procedure in the power roll machine as shown in the Figure 3. Until the sheet reached the desired thickness, of 2mm and 1.5mm, the rolling operation was repeated.
The rolled sheet was cut to requirement of shapes for performing hardness test and micro structural analysis, as shown the Figure 4. The blank was preparative size 80 mm Diameter and 2 mm thickness round specimen, using manual hand shearing machine.

Fig.3. Rolling Machine

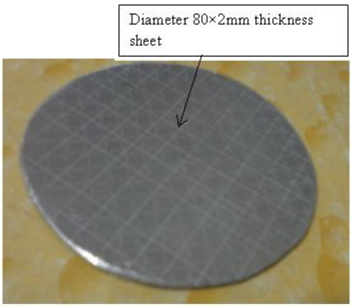

Fig.4. Al 6061 Specimen for SPF

Figure 5 shows the Microstructure of Aluminum Silicon carbide after thermo cycling process, grain size was measured using biovis software, and found as 100nm.

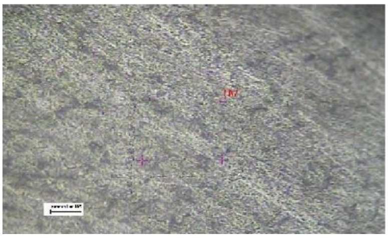

Fig.5. Microstructure of Al-SiC

A split die was designed to grease the easy making of the top and lowermost die, as shown in Figure 6. The dies were assembled inside the split furnace and maintained at a constant temperature of 530 °C. Once the set temperature was reached, a shaking time of 20 to 30 min. After that air passed into the bottom die. Gradationally the air pressure was increased and set to a particular pressure for a particular period of time. Aluminium 6061 material carried in 5 mm density standard distance, distance was cut into size of 30 × 30 mm, in power shearing machine.

Fig.6. Split die

Place the rolled component (circle in shape) into the superplastic forming apparatus with the induction coil installed and fasten it firmly. We must wait until the temperature reaches the desired level in the control monitor since the component must be formed at an initial temperature of 580 degrees Celsius. Next, apply the compressor's 4 bar of pressure via the bottom die. The component will begin to distort gradually as time goes on. For different pressures and temperatures, repeat the procedure.

Fig.7. Formed component

In the three different levels of Al/SiCp composites, Figure 4 displays the most severe arc stature shaped at a constant weight of 0.4MPa and 580˚C for 45 minutes. Initially, the arch height increased swiftly, and after 45 minutes, half of the vault's height had taken shape. The highest extreme arch height measured for 5% SiCp was 21 mm. The highest extreme arch stature obtained in 10% SiC composites was 16 mm. The height of the lump is reduced by the increase in SiCp level. Grain limit sliding is the mechanism underlying the superplastic frame. The presence of SiC in metal network composites prevents grain limit sliding from developing. When the degree of fortification is raised, it prevents the growth of the grain boundaries.

3 Analysis of process parameter

Using the statistical program Minitab 16, the findings of each experimental run were statistically analysed at a 95% confidence level using analysis of variance (ANOVA), and the effects of the chosen variable were assessed. The analysing software's input contains the process parameters, including temperature, pressure, and time (table 1).

Table 1. Process parameters of dome height experiment.

Pressure (Bar)	2	4	6
Temperature (°C)	560	580	600
Time (min)	15	30	45

The orthogonal array's degrees of freedom ought to be higher than or at least equivalent to the process parameters'. The L9 orthogonal array was employed in this work. The combinations of values for each control factor must be used in a total of nine experimental runs.

Table 2. S/N ratio and ranking.

Pressure (bar)	Temp. (°C)	Time (Min)	Obtained Dome Thk (mm)	S/N Ratio	Rank
2	560	15	12.5	22.25	9
2	580	30	13.6	24.21	7
2	600	45	12.8	23.71	8
4	560	30	19.6	25.80	2
4	580	45	21.0	24.40	1
4	600	15	18.0	24.01	3
6	560	45	17.5	24.15	4
6	580	15	16.0	23.59	5
6	600	30	15.0	24.48	6

Table 3. Signal to Noise Ratios Response.

Level	Pressure (bar)	Temperature (°C)	Time (Min)
1	22.25	24.21	23.71
2	25.80	24.40	24.01
3	24.15	23.59	24.48
Delta	3.55	0.81	0.77
Rank	1	2	3

The superplastic forming is based on dome height. The table – shows the effect of each parameter on the dome height. Data mean is used to find each process parameter effect. The effect of pressure on the dome height. When the processing pressure was less the dome height formation was also less. The higher forming pressure leads to high strain rate superplastic forming. In Al/SiCp composites good superplastic forming was obtained only in high temperature and high pressure. The only temperature at which good superplastic formation was achieved was above 580°C. Dome height creation is less than 15 mm at lower temperatures. The material was weakened at the same time the temperature rose to 600°C. At 600°C, the material cracked on the top surface in fifteen minutes. Microstructural examination of specimens formed at 600 °C for 15 minutes revealed significant grain coarsening and partial grain boundary melting, which degraded superplastic behaviour. SEM images showed cavity nucleation and growth along grain boundaries, particularly near SiC particle clusters, indicating the onset of intergranular fracture. The reduction in grain boundary stability and increased diffusion at this temperature led to localized stress concentration, ultimately causing cracking and loss of formability. The highest dome height in 580°C was created in 45 minutes at 4 bar, in table 2 and figure 8 shows, 21 mm was the highest dome height attained.

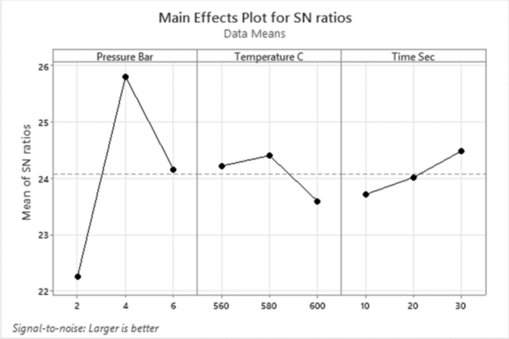

Fig.8. S/N of larger is better

The two most significant factors determining the dome height are SiC size and SiC percentage. Ultrasonic cavitation gives a very good composite for nano particles. Nanoparticle agglomeration was controlled by optimizing ultrasonic cavitation parameters such as sonication time, power, and melt temperature to generate sufficient acoustic streaming and micro-jetting. The melt was preheated and mechanically stirred prior to ultra-sonication to ensure initial dispersion of SiC nanoparticles. Continuous ultrasonic treatment during particle addition helped break soft agglomerates and promote uniform distribution within the Al 6061 matrix. The acquired findings can be used to establish the impact of a process parameter on the forming process. The S/N ratio value and ranking for the measured dome height are displayed in Table 3. A2, B2, and C3 were the ideal procedure parameters to achieve the highest dome height. ANOVA is applied to the experimental data to determine the relative contribution of hot press forming process parameters on dome height on superplastic forming of Al/SiCp composites. Table: Displays the ANOVA findings for the dome height taken into consideration in this paper shown in table 3. The processing pressure is found to have a bigger influence than the remaining parameters when comparing the percentage of contribution and ANOVA findings for dome height. Considering that the F value and contribution % are highest here. Temperature and processing pressure have a bigger impact. Time has minimal impact on the formation of superplastic. The effect of various parameters on superplastic forming using signal to noise (S/N) ratio and analysis of variance (ANOVA) will be discussed below. From the experimental results, the S/N ratio and ANOVA results were calculated through Minitab. The optimum combination of process parameters and their influence have been obtained.

4 Conclusion

An Aluminum 6061 composite reinforced with 5% SiC nano particle 100 nm is developed using stir casting with ultrasonic cavitation method and is undergoing a dome test to study the elongation of the composite. The thickness of the sheet was reduced from 5mm to 2mm and 1.5mm by rolling process. The process parameters were pressure range 2, 4 and 6 MPa, temperature 560, 580 and 600 C and time 15, 30 and 45 mins. These parameters are optimized using the L9 Taguchi algorithm. It is obtained maximum 21mm elongation at 580 °C at 4 bar pressure with 45 mins. Also it is found the rise in the proportion of SiC causes the crack to begin and propagate. A maximum elongation of 400% was achieved in uniaxial superplastic forming at a strain rate of 10-2 s-1. The reported ~400 % elongation at a strain rate of 10^{-2} s^{-1} was measured from high-temperature tensile tests conducted under superplastic forming conditions. Elongation was calculated based on the percentage increase in gauge length of standardized tensile specimens tested at 550°C and held for 15 minutes before deformation. To improve clarity, the corresponding stress–strain curves and elongation values have now been explicitly included and referenced in the results section. To get more insight into the higher strain-rate super plasticity of AMMCS in gas pressure formation, more research on the variations of m values under various stress states and conditions is therefore recommended. The maximum elongation of ~400 % achieved at a temperature of 550°C, strain rate of 10^{-2} s^{-1}, and forming time of 15 min for the Al 6061–nano SiC composite. Grain size was maintained in the ultrafine range due to effective nanoparticle pinning, resulting in enhanced strain-rate sensitivity. These quantified outcomes directly support the observed improvement in superplastic formability and process optimization.

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