

## **A Study in Superplastic Forming in Aluminium Metal Matrix Composites**

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### **Abstract**

This paper presents a review of Superplastic forming process in Aluminium Metal Matrix Composites. The advantage of superplastic forming is to develop the complex shapes which is mainly used in Aerospace applications. The metal matrix composites are brittle in nature because of the reinforcements present in the matrix. The normal metal forming process cannot be adopted for metal matrix composites due to the brittle property. Superplastic forming the metals were heated one half of the melting temperature of the metal, due to that the composites have advantage in superplastic forming over other forming methods. Superplastic forming was formed through grain boundary sliding mechanism. For the grain boundary sliding need optimum temperature and method to be followed. This paper broadly discuss about the methods followed in the superplastic forming for

composites.

## 1. Introduction

Discontinuously reinforced metal matrix composites are attractive for many structural applications because the materials exhibit unusual combinations of mechanical, physical and thermal properties. These properties include high modulus and strength, good wear resistance, good dimensional stability, low density and low thermal expansion. Although MMCs possess these good properties, the materials also have certain draw backs in particular they generally have low room temperature tensile ductility and poor toughness. Even at elevated temperatures, the materials normally show only limited tensile ductility. This poor ductility prevents MMCs from being considered for many potential applications. The exact causes leading to the low tensile ductility and toughness in MMCs remain sources of controversy. The microstructure inhomogeneities, such as the agglomeration of reinforcements and the presence of coarse inclusions and the mechanical constraints exerted on the matrix by the reinforcements are primarily responsible for the brittle behavior observed in MMCs.

The studies have demonstrated that certain discontinuously reinforced aluminium MMCs can behave Superplasticity. Superplasticity has now been demonstrated in aluminium composites with reinforced SiC particulates ( $\text{SiC}_p$ ), SiC whiskers ( $\text{SiC}_w$ ),  $\text{Si}_3\text{N}_4$  whiskers ( $\text{Si}_3\text{N}_{4w}$ ). From the studies  $\text{SiC}_w$  reinforced with 2124 Al and  $\text{Si}_3\text{N}_{4w}$  reinforced with 2124 Al,  $\text{Si}_3\text{N}_{4w}$  reinforced with 7064,  $\text{SiC}_w$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Si}_3\text{N}_{4w}$  reinforced with 6061 Al composites exhibited Superplastic properties at extremely high strain rates between ( $10^{-3} \text{ s}^{-1}$  and  $1 \text{ s}^{-1}$ ).

Table 1: The experimental data in high strain rate superplastic aluminium and magnesium matrix composites

Materials	Max. Elongation	Strain rate	Flow stress	Grain size	Particle Size	Vol. of Particle	Temperature
Si <sub>3</sub> N <sub>4p</sub> /Al-Cu-Mg	840	4x10 <sup>-2</sup>	2	2.3	1.0	20	788
Si <sub>3</sub> N <sub>4p</sub> / Al-Cu-Mg	280	3x10 <sup>-1</sup>	8	1.1	0.2	20	773
SiC <sub>p</sub> / Al-Cu-Mg-C-O	610	5	15	.5	2.0	17	823
SiC <sub>p</sub> / Mg-Zn-Zr	450	10 <sup>-1</sup>	15	1.7	2.0	17	623
Al6061/SiC	342	.02-0.3x10 <sup>-1</sup>	-		1.0	10	573
Al <sub>2</sub> O <sub>3</sub> /Al6061	300	0.4x 10 <sup>-3</sup>	-	2	1.0	10	573

## 2. Fabrication and Thermomechanical Treatment

Primary fabrication processes for metal matrix composites include powder metallurgical processing, casting processing such as a vortex method, compocasting processing squeeze casting. In-situ process, vortex and a compocasting process are cost effective and practical for fabrication processing of automobile components, satellite structure and so on.

Takeo Hilosaka and Tsunemichi Imai, Thermo-mechanical processing could produce HSRS and improve the reliability for metal matrix composites. Hot rolling and extrusion process give fine grain structure in the Al6061/SiC composites. The hot rolling was carried out at 523, 573, 623, 673, 723 and 873K. Rolling strains strains per pass used are 0.05, 0.1, 0.2 and 0.3 and the reheating time between each rolling passes was about 5 minutes. Al Composite exhibit more than 200% elongation in the wide strain rate region from 0.02-0.3 s

1. Al composite hot rolled at 573K observed maximum elongation 342%, under 0.1 rolling strain per pass has a better effect on building finer grain size and on making fine SiC particle dispersed homogeneously. Lower  $m$  value 0.2 obtained at the temperature between 573-623K. Optimum rolling temperatures achieve large total elongation at strain rate of about  $0.1 \text{ s}^{-1}$  were 573, 673 and 723K.

### **3. Thermal cycling process in MMCs**

Internal stress superplasticity is the extensive elongation that occurs in some material under conditions where internal stress exists concurrently with deformation, which enhances plastic flow in the direction of the applied stress and can result in high ductility during deformation. Generally two methods by means of which to induce internal stresses (i) thermal cycling of material through a phase change with concurrent application of a small external stress and (ii) thermal cycling of a material with anisotropic coefficients of thermal expansion whilst simultaneously applying a load. Temperature cycling process on the 10%  $\text{Al}_2\text{O}_3$  reinforced Al6061 matrix. Each of the parameters were changed for each test and compared with the standard. i.e. : temperature range of  $150^\circ \text{C}$  a heating up time 90s, a cooling down time of 60 s and strain rate of  $0.4 \times 10^{-3} \text{ s}^{-1}$  Due to thermal cycling process % of elongation increases up to 36%. By increasing the strain rate from  $0.4 \times 10^{-3}$  to  $40 \times 10^{-3} \text{ s}^{-1}$  the specimen increases overall elongation to 64%. Thermal cycled material  $m=0.3$ , isothermal process  $m=0.17$ . Thermal cycling process increases the strainrate sensitivity index.

T. G.Langdon et al. In addition to fine structure superplasticity there is also internal superplasticity. When internal stresses are developed, considerable tensile plasticity can take place (by a slip

creep mechanism) under the application of a low external stress. Internal stresses can be generated by thermal cycling of composite material in which the constituents have different thermal expansion coefficients, thermal cycling of polycrystalline pure metals or single phase alloys that have anisotropic thermal expansion coefficients, and by thermal cycling through a phase change. Experiments show that internal stress superplasticity be utilized to enhance the ductility of metal matrix composites. I.Ozdemir, k.Onel, Thermal cycling between 100 and 430 °C under applied stresses in the range 3-5MPa increases the ductility of the matrix alloy and the composite samples. The ductility values obtained in thermally cycled specimens are above 70% elongation much higher than those obtained in isothermally tested specimens. The maximum ductility level of thermally cycled specimens at the applied stress was 5 Mpa. During the thermal cycling tests the achieved strain rates ranged between  $4.8 \times 10^{-6}$  and  $1.6 \times 10^{-4} \text{ s}^{-1}$  for the matrix alloy and the composites.

#### **4. Superplastic forming Temperature**

W.J.Kim et al.: High strainrate superplastic behavior of powder-metallurgy processed 0%, 10%, 20% and 30% SiC particulate reinforced 6061 Al composites was studied over a range of temperatures from 430-610 °C . Elongation to failure data in the temperature (520 – 610 °C ) and strain rate region ( $10^{-2}\text{s}^{-1}$  - $10^{-1}\text{s}^{-1}$ ) where high m values (0.25-0.3 ) are obtained. For the composites high ductility was not observed unless temperature is higher than 590 °C and only obtainable within a narrow temperature range (590-600 °C). The m value was determined to be 0.2 in the lower temperatures (430-490 °C) and 0.4 in the higher temperatures (520 – 610 °C). 10% SiC/6061 al composite deformed to failure (450% at 600 °C and at

$1 \times 10^{-2} \text{s}^{-1}$ ). Particle weakening was observed in 6061 Al composites at high temperatures where GBS controls the plastic flow. The  $\text{SiC}_p/6061$  al composites become weaker than the 6061 Al matrix alloy as temperature is higher and the volume fraction of reinforcement is higher.

## 5. Superplastic Gas Pressure Forming

G.Q. Tong and K.C.Chan : Superplastic gas pressure forming tests were conducted in the pressures 1Mpa, 2Mpa, 3Mpa and 4 Mpa at the temperature of 873K. The deformed Al6061/SiC<sub>w</sub> composite diaphragms shown in Fig below. It is worth to mention that the required time for forming a hemisphere is just about 17.6 sec at applied flow stress of 4 Mpa and the temperature 873K . From the experimental findings, 4Mpa stress applied while forming has higher dome height and the forming timing also very less. Three distinct deformation regimes were observed from the polar height Vs Time curve, which is similar to the creep behavior of most metallic alloys and structural ceramics at a condition of constant stress.

## 6. Effect of Strain Rate in Suerplastic Forming

K.C.Chan and G.Q.Tong : Al 6061/20% SiC composites tested in uniaxial tensile test with different strain rates. A maximum elongation of 505% was obtained at strain rate =  $6.56 \times 10^{-2} \text{s}^{-1}$ . In low strain rates ( $10^{-2} \text{s}^{-1}$  or below) m value of less than 0.1 is obtained. A maximum m value of about 0.41 is obtained at strain rate =  $6.56 \times 10^{-2} \text{s}^{-1}$  while m value 0.35 was obtained at the strain rate of  $1.31 \times 10^{-1} \text{s}^{-1}$ . A high m value results in high tensile elongation.

Table 2: Testing conditions of Composites with various Reinforcement

Materials	Temperature (K)	Strain Rate( $s^{-1}$ )	Stress MPa	Strain rate sensitivity Index m
Al4.4Cu.5Mg/21SiC <sub>w</sub>	793	0.17	3	.34
Al6061/20Si <sub>3</sub> N <sub>4</sub> p	833	2.0	8	.50
Al6061/20SiC <sub>w</sub>	873	.017	-	0.34
Al2009/20SiC <sub>w</sub>	808	.21	-	0.35
PM-64/10SiC <sub>p</sub>	773	$2 \times 10^{-4}$	1.0	0.40

### 7. Cavitation behavior in superplastic forming

K.C.Chan and G.Q.Tong reveals the cavitation volume fraction with true strain of the au-1.5Mg/21%SiC<sub>w</sub> deformed under bothe uniaxial and equibiaxial tension. It is obvious that the amount of cavities increases with increasing strain in all testing conditions. Similar phenomenon has been reported for some conventional superplastic metals and HSRS Al-MMCs. The amount of cavitation resulting from equibiaxial tension is slightly greater than that from uniaxial one and slightly larger parameter of cavity growth rate is also observed under equibiaxial tension. The analytical model to predict the volume of cavities  $C_v = C_{v_0} \exp(\epsilon \eta)$  Where  $C_v$  is the volume of cavities at zero strain,  $\eta$  is the cavitation growth rate parameter, which varies according to material, grain size strain rate and temperature.  $C_{v_0}$  and  $\eta$  values for the composite summarized in Table

The deformation and cavitation behavior of a high strain rate superplastic Al2009/20%SiC<sub>w</sub> composite examined at temperatures ranging from 753-823K, and at the initial strain rates form  $1.67 \times 10^{-3}$  to  $1.67 \times 10^0 s^{-1}$ . A maximum elongation of 250% was obtained at an optimum initial strain rate of  $3.33 \times 10^{-1} s^{-1}$  and a temperature of 808 K. The value of volume fraction of cavities for Al2009/20%SiC<sub>w</sub>,

Al6061/20Si<sub>3</sub>N<sub>4p</sub> and Al7475 are found to be 2.5, 0.5, and 3.6 respectively. Al6061/20Si<sub>3</sub>N<sub>4p</sub> illustrating that a smaller value is obtained at a temperature slightly above its solidus temperature than that below, due to the liquid phase. The results confirmed that higher strain rate level contain larger cavities.

Table 3: Cavitation volume and Cavitation factor

Materials	Temperature (K)	Strain Rate (s <sup>-1</sup> )	Stress MPa	Strain rate sensitivity Index m	Cv <sub>o</sub> (%)	H
Al4.4Cu.5Mg/21SiC <sub>w</sub>	793	0.17	3	.34	1.9	1.9
Al6061/20Si <sub>3</sub> N <sub>4p</sub>	833	2.0	8	.50	0.5	0.5
Al6061/20SiC <sub>w</sub>	873	.017	-	0.34	1.2	1.2
Al2009/20SiC <sub>w</sub>	808	.21	-	0.35	2.5	2.5
PM-64/10SiC <sub>p</sub>	773	2x10 <sup>-4</sup>	1.0	0.40	3.2	3.2

## 8. Friction Stir Processing in Superplastic Forming in MMCs

The main applications of FSP are to refine the microstructure, produce fine-grain microstructure which exhibits superplasticity. In FSP the combination of large plastic strain and temperature results in recrystallized smaller grains and break-up of constituent particles, it is likely to generate more nucleation sites. FSP creates microstructure containing fine grains with large grain boundary misorientation. FSP constituent particles lead to lower cavitations, thus increasing superplastic elongation. A.H.Feng et al: AA2009/15%SiC<sub>p</sub> composite plates were friction stir welded along the extrusion direction at a tool rotation rate of 600 rpm and a transverse speed of 50mm/min. After FSW, the distribution of SiC particles was significantly improved and the micro structure was characterized by homogenously distributed SiC particles and fine equiaxed recrystallized grains of 5µm. Compared to the sharp SiC particles in the extruded composite the edges and corners of the SiC particles

blunted and micro cracks were detected in some large SiC particles. Further more the size and aspect ratio of the SiC particles were obviously decreased after FSW. The tensile and yield strengths of the as FSW composite welds in both longitudinal and transverse directions were superior to those of the as extruded base metal.

## **9. Conclusion**

In this paper, the fundamentals and superplastic deformation behaviors of several series of Al alloys are described and it can be seen that currently the main different kinds of Al alloys all have exhibited outstanding superplasticity. Furthermore, the mechanisms of superplastic deformation are discussed and various theories regarding superplastic mechanism are summarized and analyzed, including theory of grain boundary sliding with accommodation mechanism and deformation-induced continuous recrystallisation. Meanwhile, factors that affect superplastic deformation process of Al alloys are explained in detail, including temperatures, stain rates, and thermal-mechanical process. Subsequently, two significant superplastic deformation parameters of different Al alloys, strain rate sensitivity ( $m$ ) and deformation activation energy ( $Q$ ), are compared to help understand the relationship within these two parameters and superplastic deformation mechanisms. Finally, the existing challenges and limitations of current sup.

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