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ScienceDirect

Procedia Engineering 207 (2017) 848–853

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

Deformation and fracture of AMC under different heat treatment conditions and its suitability for incremental sheet forming

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Abstract

By evaluating the deformation and fracture mechanisms of a 6092Al alloy metal matrix composite reinforced with 17.5p vol. % SiC particles (6092Al/SiCp), this paper investigates the applicability of using incremental sheet forming (ISF) process to form the 6092Al/SiCp aluminium matrix composite (AMC) under different heat treatment conditions. Tensile tests were carried out at different strain rates to study the microstructure and topography of the 6092Al/SiCp sheet by scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). The tensile test results and the morphology of the fracture showed that the 6092Al/SiCp to T6 condition has low elongation to fracture (0.08), whilst much improved elongation can be achieved after annealing to O-condition. A series of ISF tests were carried out to form 6092Al/SiCp sheet into a truncated hyperbolic shape with different ISF process parameters. At T6 condition, ISF testing showed unsatisfactory results for the 6092Al/SiCp with a low wall angle (31.2°) to fracture and a significant amount of springback. After annealing to O-condition, a much increased wall angle was achieved with reduced springback due to the enhanced ductility of the 6092Al/SiCp material. Microstructural and topographic evaluation of the 6092Al/SiCp parts formed by ISF allowed a detailed characterisation of brittle and ductile fractures for different heat treatments. The obtained ISF results and evaluation enabled the recommendation of optimum ISF operational windows for 6092Al/SiCp materials.

Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.

Keywords: Al6092/SiCp composite; ISF; Heat treatment; Fracture toughness

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Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.840

1. Introduction

Having high strength to weight ratio and other preferable mechanical properties, discontinuous reinforced AMC materials are attractive for applications in including aerospace and automotive industries. ISF is a suitable process for manufacturing small batch high value AMC sheet components. However, it can be technically challenging to form a complex shape of AMC sheets due to low ductility as an inherited trade-off for the enhanced strength and toughness of AMC materials.

There is a good correlation between the fracture mechanism of cast 6061Al/SiCp composite and heat treatment. As an example after peak-aging treatment, the fracture occurs at the interface between the Al matrix/SiCp and breaks SiC particles, while an interfacial crack propagates, along the interface between the Al matrix/SiC in the fracture surface of the specimen cooled at 3°C min^{-1} from the solutionizing temperature [1]. The quasi-static and dynamic fracture behaviour of unreinforced 6061Al alloy and 6061Al alloy reinforced with 15 and 20% of SiC particles in a high temperature, overaged condition showed that the fracture toughness of 6061 Al alloy significantly decreases with the addition of SiC particles at both loading rates (quasi-static and dynamic) [2]. $MgZn_2$ phase can be dissolved using the solid solution treatment of ultra-high strength Al/SiCp composite, and a high tensile strength can be achieved when the heat treatment is changed. The tensile fracture of Al/SiCp composite can be attributed to the broken SiC particles and the debonding at the interface between the Al matrix and SiC particles [3]. The fracture elongation of 6061Al and 7108Al alloy reinforced with 10-15% SiC volume fraction is increased more than 3 times by solution heat treatment, whilst T6 treatment works to enhance the ultimate tensile strength of rolled composite for both 6061Al-7108Al/SiCp composites [4]. With high temperature heat treatment (575°C) of 2124Al/10% SiCp, finely and coarsely dispersed phases are nucleated at the grain boundary and surrounding SiC particles, and a high percentage of silicon is observed around the SiC particles [5]. Many researches have been carried out to evaluate the formability and fracture mechanism of ISF process. The membrane analysis and ductile fracture mechanism showed fracture in ISF developed under the tensile meridional stress without localized necking before the fracture [6]. The FE results proved shear and the bending of the sheet around the tool have a significant effect on the fracture propagation in ISF process [7]. It was found from the localized deformation mechanism the deformation in ISF process occurred in the tool/sheet contact region and in the neighbouring wall while the fracture occurred between the tool/sheet contact region and the wall of the part [8]. Preliminary investigation to evaluate the applicability of ISF to composite/laminate materials has achieved by Fiorotto et al. [9]. The initial results showed ISF is suited to obtained parts from composite/metal hybrid materials. Various designs of sandwich panel were used to evaluate the feasibility of ISF to form the sandwich panel. It was found the ductile and large incompressible core sandwich panel can be produced using ISF [10]. With little effort being made to use ISF to form AMC sheet materials, this work aims to characterize the mechanical properties and fracture behaviour of 6092Al/SiCp and to investigate the feasibility of using the ISF process to form 6092Al/SiCp sheet.

2. Experimental testing

The chemical composition of the 6092Al alloy sheet is listed in table 1, which are received at T6 condition.

Table 1. Chemical composition of 6092 Al alloy.

Cu	Mg	Si	Fe	Zn	Ti	O	others	Al
0.7-1.0	0.8-1.2	0.4-0.8	0.3	0.25	0.15	0.05-0.5	0.15	bal.

To enhance the ductility of the 6092Al/SiCp sheets, the O-condition annealing was conducted based on the recommendation of ASM [11]. The annealing process started with a rapid heating rate to reach 415 °C in order to avoid grain growth. Then, the 6092Al/SiCp sheet was held at this temperature for 2.5 hours (soaking stage) and this was followed by cooling at a rate of 30 °C to reach 260 °C in 5.2 hours.

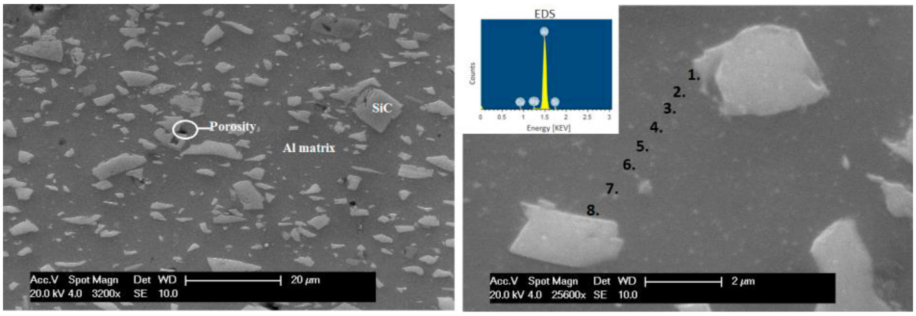
An INSTRON testing machine was employed to conduct tensile test of specimens according to ASTM-E8 at both T6 and O-conditions. A Dantec Q-4400 DIC (digital image correlation) system was used for displacement measurement.

A CNC milling machine was utilized to carry out the SPIF test based on a defined helical tool path. A hyperbolic truncated cone was employed with varying wall angles from 22.5° to 80° to evaluate the fracture position in the 6092Al/SiCp sheets. The output results from SPIF tests were related to the fracture depth, wall angle and forming load. The test was carried out with a 10 mm tool diameter and 0.2 mm step size at four feed rates (500, 1000, 2000 and 3000 mm/min). The test was repeated three times and the average values were taken.

3. Results and discussion

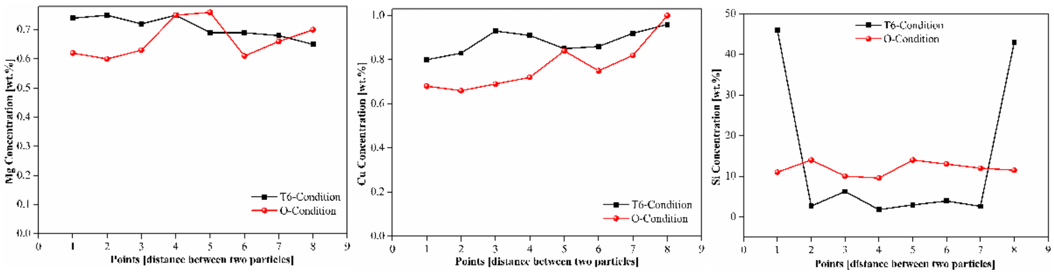
3.1. Effect of heat treatment on the microstructure of the AMC

The microstructure of the 6092Al/17.5% SiCp was analysed using XL30 SEM coupled with EDS. Fig. 1(a) illustrates the typical microstructure of 6092Al/SiCp. It is observed that the size and distribution of SiC particles are not uniform. There is some porosity around the SiC particles. SEM-EDS spot analysis was utilized to evaluate the concentrations of Mg, Cu and Si in the Al matrix after T6 and O-condition annealing. The EDS spot analyses were conducted at different positions along the distance between two SiC particles, as shown in Fig. 1(b). The EDS spot analysis was repeated three times at different points and the average value was taken. Fig. 2 shows the comparative concentrations of Mg, Cu and Si elements with T6 and O-condition annealing between the two SiC particles (see Fig. 1(b)). It is clear from the figure that there is little change in the concentrations of Mg and Cu when the heat treatment is changed, whereas significant changes in the Si concentration are observed, especially at the interface between Al/SiCp (points 1 and 8). The percentage of Si after T6 treatment is high at the interface between Al/SiCp and low in the matrix; however, this concentration becomes low after O-condition annealing at the interface and high in the matrix. A uniform distribution of Si is also observed after O-condition annealing. The high percentage of Si at the interface after T6 treatment may be due to the interaction between the Al and the SiC particles, or it could be that the SiC particles absorb the Si elements during the T6 treatment and this leads to low ductility after T6 treatment due to the lack of Si in the matrix. The O-condition annealing works to diffuse the Si elements from the interface to the matrix and achieves uniform distribution of the Si element in the matrix, leading to the enhanced ductility of the 6092Al/SiCp composite.



(a) (b)

Fig. 1. Typical microstructure of 6092Al/SiCp: (a) showing the distribution of reinforcement; (b) EDS spot analysis taken from different points between two particles.



(a) (b) (c)

Fig. 2 Elemental distribution along the distance between two particles. (a) Mg distribution; (b) Cu distribution; (c) Si distribution.

3.2. Mechanical properties and the fracture mechanism of the AMC

The tensile tests were conducted on the 6092Al/SiCp specimens at both T6 and O-conditions under three strain rates ($8x10^{-3}$, $8x10^{-4}$ and $8*10^{-5}$ S^{-1}). The tensile test results are summarized in table 2. From the table, it can be seen that there is a clear effect of strain rate on the fracture strain, the elongation at fracture at the O-condition increases by 48.46% when the strain rate is decreased from $8*10^{-3}$ S^{-1} to $8*10^{-5}$ S^{-1} as compared to 12.67% increase of elongation of the specimens at T6-condition. The strain rate has a slightly effect on ultimate tensile strength (UTS) and opposite behaviour as compared with its effect on the fracture elongation, the values of the UTS decrease with decreasing the strain rate values. With T6 treatment the UTS of composite decreases by 7.1% with decreasing of strain rate and the percentage of decreasing with O-condition annealing is 5.17. It was also observed that the annealing process enhances the ductility due to increased concentration of Si in the Al matrix in addition, the stabilising effects are present with low strain rates which delay the damage evolution as compared to the test conditions at high strain rates.

Table 2. Effect of heat treatment and strain rate on the fracture elongation of 6092Al/SiCp.

Strain Rate [S^{-1}]	Fracture Elongation		Increase of Elongation%	Ultimate tensile strength [MPa]		Decrease of UTS%
	T6-treatment	O-condition		T6-treatment	O-condition	
$8*10^{-3}$	0.071	83	83	352	232	34
$8*10^{-4}$	0.075	93.3	93.3	340	230	32.35
$8*10^{-5}$	0.08	141.25	141.25	327	220	32.72
% Increase	12.676	48.461	% Decrease	7.1	5.17	

The morphologies of the fracture surface of the tensile specimens were analysed using SEM with both heat treatment conditions (T6 and O-condition) at different strain rates. Fig. 3 depicts the effect of heat treatment and strain rate on the fracture surface. At T6-condition, the fracture surface contains shallow dimples with some broken SiC particles and debonding between the Al matrix/SiCp under high and low strain rates, although the number and depth of the dimples increase at low strain rate. In contrast, a high percentage of dimples was observed on the fracture surface of the tensile specimen after annealing treatment (O-condition) especially at low strain rate. Therefore, the annealing treatment has a significant effect to the ductility of the 6092Al/SiCp sheets. On the other hand, the deformation behavior of the material shows a degree of strain rate sensitivity in tensile testing.

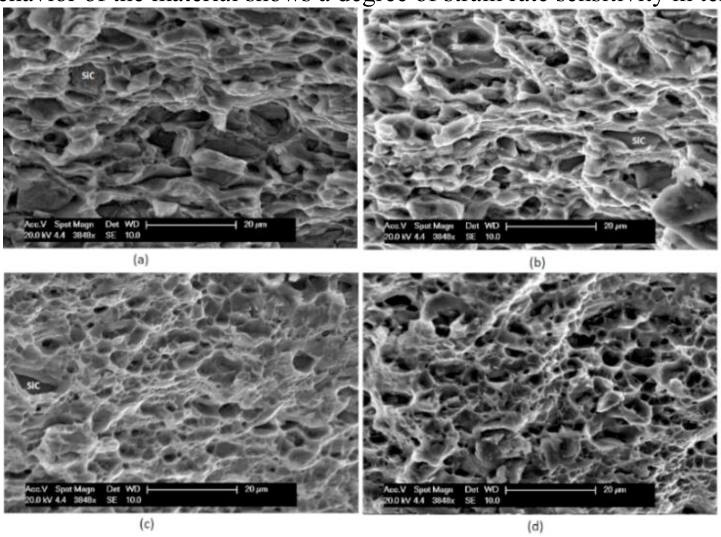


Fig. 3. Effect of heat treatment and strain rate on fractograph of 6092Al/SiCp: (a) T6-treatment with $8x10^{-3}$ S^{-1}strain rate; (b) T6-treatment with $8*10^{-5}$ S^{-1} strain rate; (c) O-condition annealing with $8*10^{-3}$ S^{-1} strain rate; (d) O-condition annealing with $8*10^{-5}$ S^{-1} strain rate.

3.3. Fracture mechanism in the SPIF

The SPIF test of a truncated hyperbolic shape with varying wall angles from 22.5° to 80° was carried out with T6 and O-condition treatments. Digital height gage was used to measure the fracture depth and this depth was unitized to determine the wall angle of SPIF parts at fracture. As shown in Fig. 4, the fracture occurs early at a wall angle equal to 31.2° with a high degree of springback and the fracture cut across the tool path for the specimen at T6 condition. After O-condition annealing, the fracture of the hyperbolic shape was propagated along the tool path at 25.5 mm depth with a wall angle 63.15°.

To study the effect of feed rate on the fracture behaviour of ISF parts, four feed rates, i.e.500, 1000, 2000, 3000 mm/min were used in forming the 6092Al/SiCp sheets at O-condition for with a non-rotating tool. The maximum wall angles with feed rates of 500, 1000, 2000 and 3000 mm/min are 63.15°, 62°, 61° and 59.63°, respectively. This is equivalent to a wall angle increase by 5.9% when the feed rate is decreased from 3000 mm/min to 500 mm/min. The clamping equipment of SPIF was mounted on a three-component dynamometer (Kistler 5073A3 Amp) in order to record the vertical forming load that obtains during the SPIF process. As shown in Fig. 5, the forming load increases with increased feed rate and the fracture occurs earlier with a higher feed rate value, a clear indication of strain rate hardening of the 6092Al/SiCp sheets at O-condition.

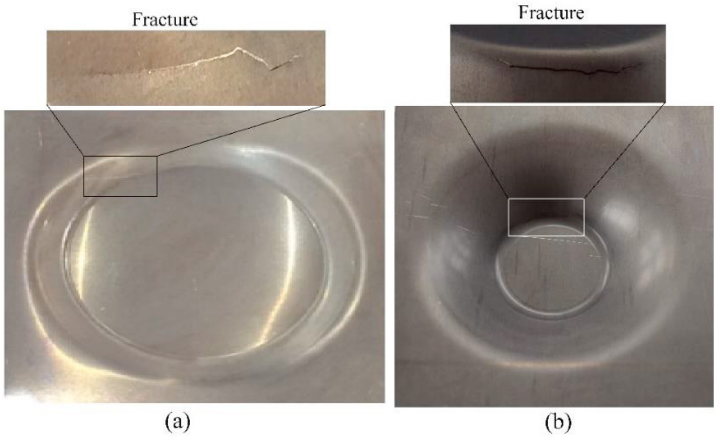


Fig. 4. Effect of heat treatment on the fracture of hyperbolic truncated: (a) after T6 treatment; (b) after O-condition annealing.

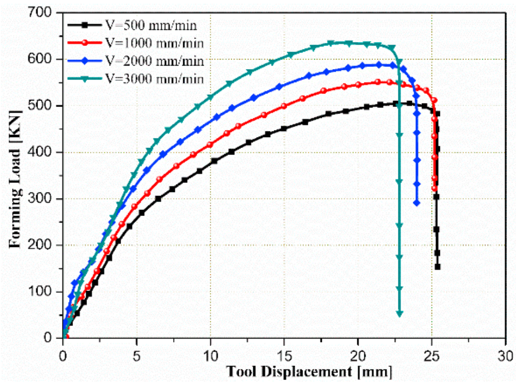
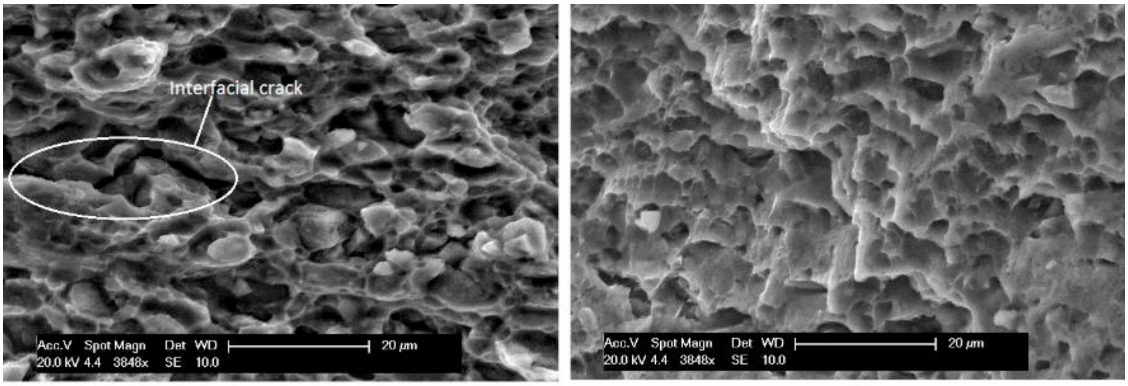


Fig. 5. Comparison of forming load at different feed rates.

The morphologies of fracture surfaces of the SPIF formed 6092Al/SiCp sheets were evaluated using SEM, as shown in Fig. 6. Brittle fracture was observed under T6 treatment with shallow dimples, broken SiC particles and debonding occurred at the interface of the Al matrix/SiCp. In addition, there was an interfacial crack in the Al matrix, while a ductile fracture with a high percentage of deep dimples was observed in the fracture surface of the SPIF part after O-condition annealing with a limited number of SiC particles. The results show a good correlation between the dimple density on the fracture surface and heat treatment type. Brittle fracture occurs with a low density of dimples under T6-treatment, while ductile fracture with a high density of dimples can be seen under O-condition annealing.



(a) (b)

Fig. 6. Effect of heat treatment on fracture surface of SPIF part: (a) T6- treatment; (b) O-condition annealing.

4. Conclusions

By investigating the feasibility of using SPIF to form 6092Al/SiCp AMC sheets for the first time, the results show that the 6092Al/SiCp sheets can be satisfactorily formed after O-condition annealing. The O-condition annealing enables diffusion of Si from the interface to the Al matrix and thus results in uniform distribution of Si in the Al matrix, which in turn leads to enhanced ductility of the 6092Al/SiCp sheets. The results also show a degree of strain rate hardening effect in incremental sheet forming of the 6092Al/SiCp AMC material. Low feed rate improves the formability and higher wall angle in the SPIF process.

Acknowledgements

The first author gratefully acknowledges the scholarship support provided by the Iraqi Ministry of Higher Education and Scientific Research (IMHESR) Ref. no. 4720. The authors would like to thank Mr Jamie Booth of Department of Mechanical Engineering, the University of Sheffield for helping preform the ISF testing. This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) of the UK (EP/L02084X/1), International Research Staff Exchange Scheme (IRSES, MatProFuture project, 318,968) within the 7th European Community Framework Programme (FP7).

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