WORKABILITY OF AL6061 ALLOY/SiC COMPOSITES IN COLD COMPRESSION

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ABSTRACT

In the present work, a metal matrix of Al 6061 alloy is reinforced by SiC particles using a pressurized air infiltration (PAI) technique followed by the vortex method. Cold workability of the metal matrix composites (MMCs) are studied using the cold upsetting test in the axial direction of the specimens. Two different particle sizes (20, and 125 μm), volume fractions of SiC particles (5%, 10% and 15%) and test specimen aspect ratios (1, 1.5 and 2) were used in the tests. The effect of these parameters on the workability limit are presented. Failure modes of the MMC materials reinforced with different particle sizes under compression are discussed.

Keywords: Metal matrix composites (MMCs), Pressurized air infiltration (PAI) , Workability, Aspect ratio, Volume fraction of SiCp and cold compression.

INTRODUCTION

Aluminium base metal matrix composites (MMCs) have attracted considerable interest recently since they offer the opportunity to tailor a material with a combination of strength and wear properties superior to most metal alloys. Reinforcement in the form of long fibers, whiskers, and particles, typically SiC particles or Al_2O_3, can be added to various commercial aluminum alloys.

The development of particle-reinforced MMCs was based on the consideration that they can be homogeneously produced by some conventional processing, e.g., casting, spray and powder metallurgy techniques. Furthermore, the reinforcing particles are generally cheap and readily available. One of the advantages of particle-reinforced MMCs is that most existing processing techniques can be used in the fabrication and finishing of composites, including hot rolling, hot forging, hot extrusion and machining [1-2]. These MMCs have become the subject of extensive research addressing issues in processing, microstructure, physical properties, mechanical properties and technological indexes.

Workability of materials implies the extent to which materials are able to deform without formation of cracks during a mechanical working process. It is not a unique property of a material but depends on process variables such as strain rate, geometrical factor, temperature, aspect ratio and material variables such as inclusion content, volume fraction of particles and grain size [3].

The use of the compression test, its limitations, the concept of forming limits, and the practical applications of workability indexes were reviewed [4-5]. Only a few studies on the influence of microstructural parameters on the workability of particulate reinforced MMCs have been reported in the literature [6-14]. The aspect ratio remains however one of the most important parameters, as it controls to a great extent, manufacturing costs and properties. Grain size is one of the most important parameters determined in quantitative metallography, owing to the importance of this microstructural feature in influencing mechanical properties of metal [6-8].

Studies have been carried out to determine both strengthening and the failure mechanisms. Particle cracks and debonding of the particle-matrix interface in tensile tests have been reported [15-16]. It has been noticed that most of the studies were based on experiments under tensile loading, which are detrimental to defects that may be in the material. There is little information on the effects of cold compression, grain size, volume fraction and aspect ratio on MMC materials. In production, a number of products are manufactured by bulk forming in which compressive loading is mainly involved. Information about the behavior of MMCs subjected to compressive load would help understanding these materials more thoroughly.

The objective of this paper is to study the cold workability of both Al6061/SiCp composites and their matrix material and to analyze the effect of both the composite structure and the process parameters. Failure modes of the MMCs material reinforced with different particle sizes and their volume fractions under compression are discussed.

EXPERIMENTAL PROCEDURE

Materials

The material used in this study was Al 6061 alloy reinforced with SiC particles of average particle sizes 20 and 125 μm. The volume fraction of SiC particles in the composite were around 0.05, 0.10 and 0.15. The fabrication procedure for the composite is mentioned in details in Reference 17. The composite was produced in the form of cast ingots of dimensions 20x20x110 mm. The particle distribution in the matrix was examined using an optical microscope.

Test Procedure

Cylindrical test specimens of 10 mm diameter and different heights of 10, 15 and 20 mm were machined from the ingots. Cold upsetting tests were carried out using a computerized universal testing machine 200 kN capacity cross head speed of 1 mm/min was used in all tests. Variation of the frictional conditions of the contact surfaces and of the aspect ratio of the specimen, lead to a change of the barrelled curvature. Consequently, this leads to a change in the secondary tensile hoop-stress developed at the bulge surface. Two different friction conditions were used, dry and renewable paraffin grease. In the case of lubricated conditions, the lubricant was renewed at every 10% reduction in height to prevent lubrication deterioration. The parameters for the materials and upsetting tests are summarized in Table1. The values in Table 1 are the averages of measurements at several fracture sites. All experiments were carried out at room temperature. The workability of the composites was examined by observing the surface strains until the onset of crack formation of the barrelled specimens. At the limit strain, cracks were observed using naked eye with the help of 5X lens, at that moment the test was stopped.

Axial and hoop strains were calculated as follows:

Axial strains $\varepsilon_z = \ln (H_i / H_o)$,

Hoop strains $\varepsilon_\theta = \ln (D_i / D_o)$.

Where D_o and H_o are the initial diameter and the initial height of the specimen, D_i and H_i are the final diameter (at the equatorial plane of the barrelled specimen) and final height at each reduction step. These measurements were continued until visual detection of cracking.

RESULTS AND DISCUSSION

Fracture Curves

Fracture curves are determined from the results of upsetting tests for the materials under consideration. It demonstrates the relation between the axial and hoop strains at the equatorial plane of the barrelled specimen, which is the site where most fractures occur. Systematic experimental tests were carried out using the process variables of friction conditions and aspect ratios. The tests were performed and readings were taken at reduction in height of about 10% until a crack was observed.

Table1 Summary of experimental results in cold compression.

No	H_o/D_o	Interface condition	volume fraction	Particle Size	Fracture strain , ε_z	Fracture strain ε_θ	Material constant q
1	1.0	Dry	0.0	---	- 0.204	0.204	0.306
2	1.5	Dry	0.0	---	- 0.225	0.215	0.333
3	2.0	Dry	0.0	---	- 0.282	0.242	0.403
4	1.0	Lub	0.0	---	- 0.210	0.207	0.314
5	1.5	Lub	0.0	---	- 0.236	0.220	0.346
6	2.0	Lub	0.0	---	- 0.300	0.252	0.426
7	1.0	Dry	5% SiC_p	125 μm	- 0.136	0.150	0.211
8	1.5	Dry	5% SiC_p	125 μm	- 0.188	0.178	0.277
9	2.0	Dry	5% SiC_p	125 μm	- 0.203	0.185	0.296
10	1.0	Lub	5% SiC_p	125 μm	- 0.144	0.154	0.221
11	1.5	Lub	5% SiC_p	125 μm	- 0.195	0.180	0.285
12	2.0	Lub	5% SiC_p	125 μm	- 0.232	0.198	0.331
13	1.0	Dry	10% SiC_p	125 μm	- 0.113	0.133	0.180
14	1.5	Dry	10% SiC_p	125 μm	- 0.150	0.134	0.217
15	2.0	Dry	10% SiC_p	125 μm	- 0.174	0.144	0.246
16	1.0	Lub	10% SiC_p	125 μm	- 0.120	0.116	0.178
17	1.5	Lub	10% SiC_p	125 μm	- 0.160	0.137	0.229
18	2.0	Lub	10% SiC_p	125 μm	- 0.197	0.155	0.275
19	1.0	Dry	15%SiCp	125 μm	- 0.090	0.082	0.131
20	1.5	Dry	15%SiCp	125 μm	- 0.130	0.105	0.183
21	2.0	Dry	15%SiCp	125 μm	- 0.162	0.122	0.223
22	1.0	Lub	15%SiCp	125 μm	- 0.100	0.088	0.144
23	1.5	Lub	15%SiCp	125 μm	- 0.140	0.110	0.195
24	2.0	Lub	15%SiCp	125 μm	- 0.180	0.130	0.245
25	1.0	Dry	5%SiCp	20 μm	- 0.133	0.142	0.204
26	1.5	Dry	5%SiCp	20 μm	- 0.193	0.170	0.278
27	2.0	Dry	5%SiCp	20 μm	- 0.202	0.181	0.293
28	1.0	Lub	5%SiCp	20 μm	- 0.140	0.147	0.214
29	1.5	Lub	5%SiCp	20 μm	- 0.194	0.177	0.283
30	2.0	Lub	5%SiCp	20 μm	- 0.220	0.190	0.315
31	1.0	Dry	10%SiCp	20 μm	- 0.111	0.105	0.164
32	1.5	Dry	10%SiCp	20 μm	- 0.150	0.122	0.211
33	2.0	Dry	10%SiCp	20 μm	- 0.170	0.138	0.239
34	1.0	Lub	10%SiCp	20 μm	- 0.120	0.110	0.175
35	1.5	Lub	10%SiCp	20 μm	- 0.160	0.130	0.225
36	2.0	Lub	10%SiCp	20 μm	- 0.180	0.140	0.250
37	1.0	Dry	15%SiCp	20 μm	- 0.080	0.072	0.116
38	1.5	Dry	15%SiCp	20 μm	- 0.125	0.092	0.171
39	2.0	Dry	15%SiCp	20 μm	- 0.160	0.115	0.218
40	1.0	Lub	15%SiCp	20 μm	- 0.100	0.072	0.136
41	1.5	Lub	15%SiCp	20 μm	- 0.140	0.105	0.193
42	2.0	Lub	15%SiCp	20 μm	- 0.180	0.126	0.243

An example for these fracture curves is plotted in Figure 1 for the Al6061 /10% SiC composite. The figure indicates a strain ratio of one half for the case of homogeneous deformation. The slope of the fracture curve increases with decreasing friction between the flat surface of the die and the specimen. Under certain friction condition the slope of the fracture curve increases with decreasing aspect ratio.

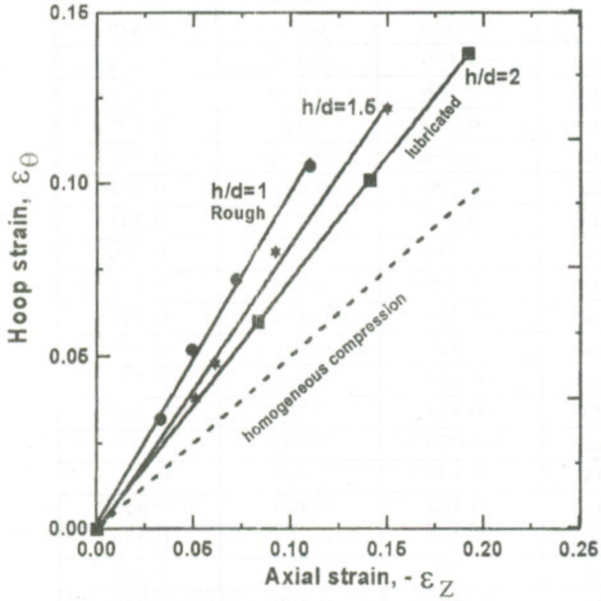


Figure 1 Strain paths in upsetting test for Al6061/10% SiCp

Forming-Limit Line

The limiting tensile, ε_θ, and compressive, ε_z, strains were plotted for the Al 6061 alloy, Al6061/SiC composites of different SiCp fractions of 5, 10 and 15%, two different particle sizes (20, and 125 μm), and different aspect ratios (1, 1.5 and 2), as shown in Figure 2. It is shown that the relations between the axial and hoop strains untile fracture are linear and parallel to the line of homogeneous deformation for specimens of different volume fractions and different particle sizes of silicon carbide.

The limiting strains were calculated when cracking was observed by the naked eye on the free surfaces of the cylindrical upset specimens. It is noted that the increase in the aspect ratio and the decrease of volume fraction of silicon carbide, leads to an increase in the limiting strains. It is observed also that the increase in the limiting strains is more remarkable when decreasing the volume fraction of silicon carbide than when increasing the aspect ratio. On the other hand, increasing the particle size of SiC, the workability limits increase. This can be attributed to the fact that, decreasing particle size and increasing the volume fraction of SiC leads to reduction in the inter-particle spacing. Consequently the barriers to deformation band (dislocation) increases.

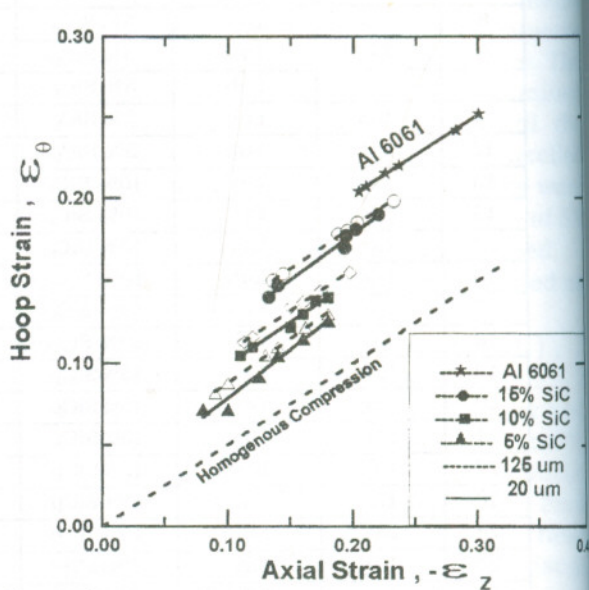


Figure 2 Fracture limit lines, corresponding to different SiCp as well as for Al 6061 alloy

This explanation depends on the assumption that the composite fracture is due to the matrix rupture or the interfacial decohesion, and is not due to particle cracking. If the fracture of the composite is due to the cracking of the particles, this observation will be completely inversed. This is confirmed by microscopic examination of the composite specimen with larger particles (125 μm) and no cracked particles are found. Moreover, Surey *et. al.* [9] reported that, in the case of the soft matrix the local stress is small even in the presence of stress concentration and the void nucleation will occur mainly in the matrix which agree with the present results.

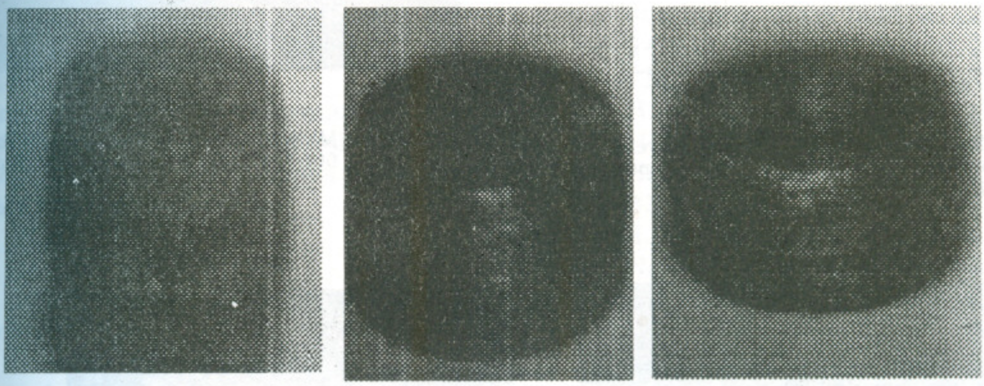
The tested materials are less ductile than conventional workable materials in terms of their tensile failure strains. However, similar linear fracture lines were obtained. Three types of surface fractures were observed in the upsetting tests on these materials as seen in Figure 3. They were longitudinal cracks, mixed cracks and oblique cracks, similar to that observed in the ductile materials described by Jiang and Dodd [10]. When the test was under well-lubricated testing conditions, the specimens usually fractured suddenly before any cracks could be seen.

Figure 2 demonstrates that for each value of volume fraction of SiC particles the points representing different friction conditions fit a straight forming-limit line. Different lines were obtained for different aspect ratios with increasing slip for the decreased aspect ratios.

The lines for different volume fractions of SiCp are parallel with a constant slope of 0.5, so that the relationship can be represented by the equation:

$$\varepsilon_\theta = q - 0.9\,\varepsilon_z \qquad (1)$$

which is in agreement with previous work on aluminum alloy [3,4 and 18] and on different types of steels.



A B C

Figure 3 Types of surface fractures observed in the upsetting tests; a) longitudinal cracks, b) mixed cracks and c) oblique cracks.

The influence of particle size, volume fraction of SiC particles and aspect ratio on the correlation constant value "q" are displayed in Table 1 and plotted in Figure 4. It is clear that increasing the aspect ratio and decreasing the particle sizes of SiC leads to an increase in the correlation constant value "q" Also, by changing from the dry condition to lubricated conditions, an increment in correlation constant values "q" are obtained.

Fracture Modes

It is generally accepted that particle cracking, matrix fracture and debonding between the reinforcement and matrix interface are the main possible sources of the failure of the particulate MMCs [19-20]. The low ductility of MMCs under tensile loading is due to the pre-existing defects of the brittle reinforcement phase and the high stress triaxiality around the hard particle, which will initiate debonding of the interface. The present and previous studies [17, 21 and 22] have found that the fracture mechanisms of these materials were different in tension from those in compression. This great difference between tensile and compression is attributed to a strong effect of the stress states on the forming processes and suggest that different failure mechanisms in tension and compression might exist.

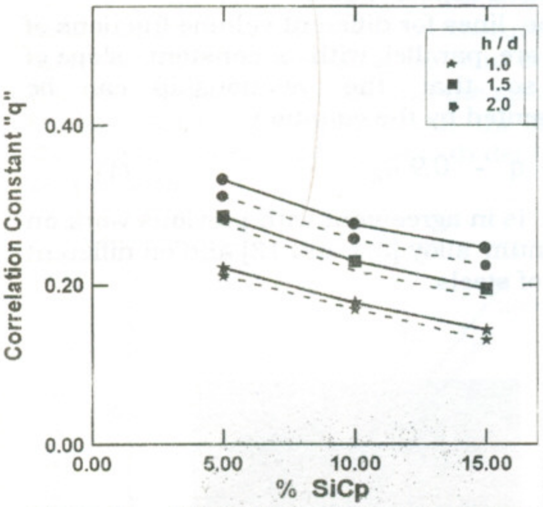


Figure 4 Effect of SiCp addition on the correlation constant value "q" (---dry,----lub, particle size = 125 μm)

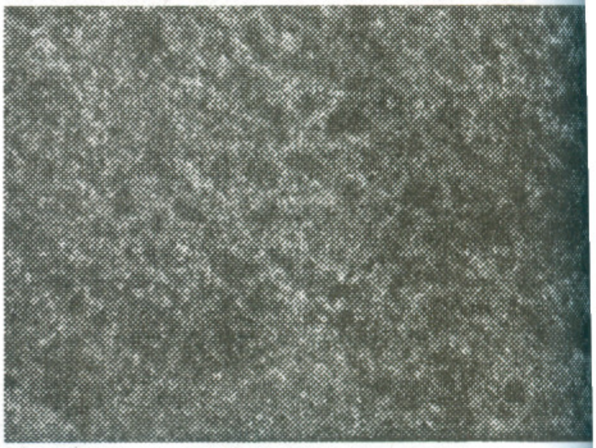


Figure 5 Microstructure of the sectioned for Al 6061/10%SiCp to fracture in compression

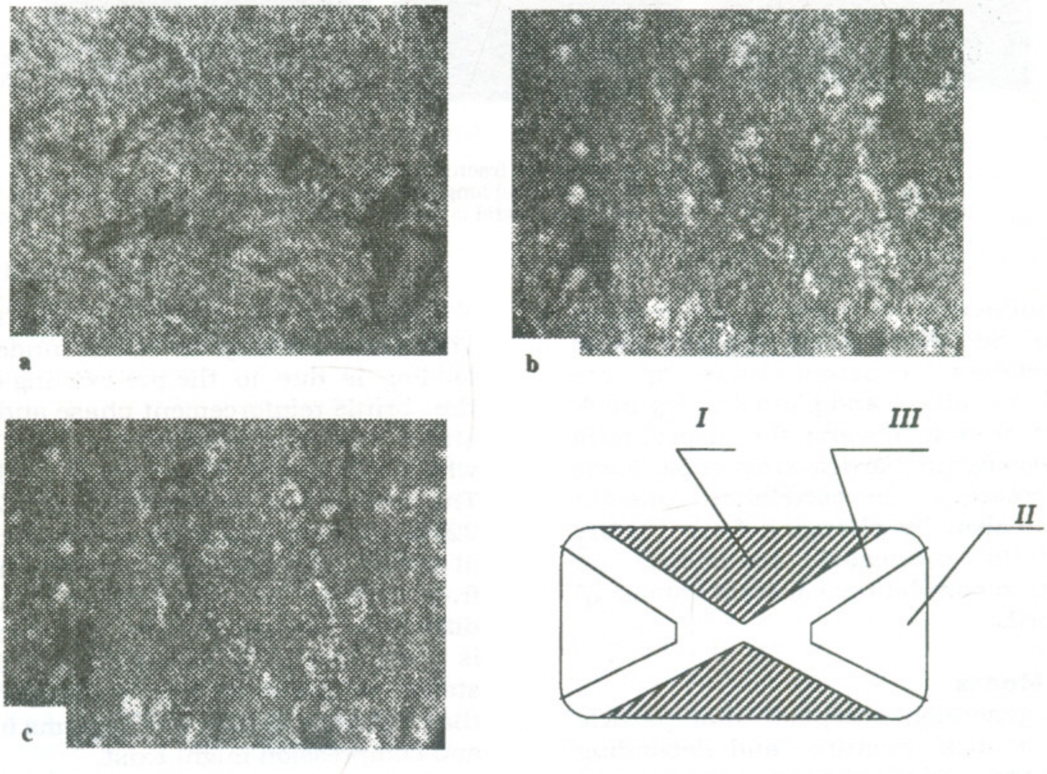


Figure 6 Micrograph for Al6061/10%SiCp, compressed under the lubricated condition with h/d=1.5

Microscopic observations have shown the different failure mechanisms of MMCs in tension (reinforcement matrix interface debonding) [17] and compression (localized shear band formation of the matrix between hard particles), as shown in Figure 5.

Microstructure of the Fractured Specimen

Using the optical microscopic examination, different deformation zones during the upsetting test can be obtained as shown in Figure 6. Three distinct zones of deformation can be identified:

(a) a dead-metal zone in contact with top and bottom surfaces (region I);

(b) a bulged zone subjected to hoop tensile stress near to the outer surfaces (region II)., and

(c) a most severe deformation is concentrated in zones of shear just outside the dead - metal zones near each contact surface (region III).

CONCLUSIONS

The results obtained from the present work can be summarized in the following points:

- The relation between the axial and hoop strains until fracture are linear for both, the matrix and composites.
- Increasing aspect ratio and decreasing the volume fraction of SiC particles lead to an increase in workability limit. Also, by decreasing the particle size of SiCp the workability limit increases.
- Increasing the aspect ratio and decreasing the particle size of SiCp lead to an increase in the correlation constant value "q".

These results will be very useful for enhancing wider use of MMCs in industrial applications.

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قابلية التشكيل لسبيكة الالومونيوم 6061 المدعمة بحبيبات كربيد السيلكون تحت الضغط علي البارد

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ملخص البحث

فى هذا البحث ، تم تدعيم سبيكة الالومونيوم 6061 بحبيبات كربيد السليكون بأستخدام اسلوب الترشيح بالهواء المضغوط (PAI) والمتبوعه بطريقة التدويم (vortex technique). تم دراسة قابلية التشكيل لهذه المؤتلفات المعدنية تحت الضغط على البارد فى الاتجاه المحورى للعينات، حيث أجريت الاختبارات لدراسة تأثيرحجم حبيبات كربيد السليكون (125,20 ميكرون) ،النسب الحجميه لكربيد السليكون (15,10,5 %) ، النسبة الباعيه Aspect ratio (2,1.5,1) على حد قابلية التشكيل .

بالاضافه إلي ذلك تم دراسة وتحليل شكل الهيارهذه المؤتلفات المعدنية تحت قوى الضغط على البارد