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Studies on cold upsetting behaviour of AA2014-based metal matrix composites, FEM simulation, and comparison with experimental results

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Abstract Cold upsetting experiments under unlubricated conditions were carried out on as cast and homogenized AA2014/SiC/10p composite billets having dispersoids in size range of 20–40 μm. The study was aimed to evaluate the effect of homogenization on their deformation behaviour. Optical and scanning electron micrographic examination of the samples was also undertaken. Hardness measurements were carried out to observe changes, if any, before and after the forging. Ring compression tests were also carried out to determine the coefficient of friction between the platens and the work piece, which is a necessary requirement to carry out simulation studies. FEM simulation analysis of the forging of composite cylinders was then undertaken using MSC-Marc software with a specified diameter-to-height ratio. Detailed comparisons of the experimental variables with the finite element method (FEM) results were carried out to ascertain the accuracy with which the deformation process can be modelled. Predictions from the simulation results were found to be in good agreement with the actual experimentation.

Introduction

Silicon carbide reinforced aluminium matrix composites have attracted considerable attention in recent years because of their potential to exhibit enhanced mechanical and physical properties in comparison to their individual alloy components [1–3]. Although many papers in the literature focus on the mechanical behaviour of Al alloy matrix composites, few of them mention the reliability of the composites. Generally, SiCp/Al composites demonstrate various brittle fracture modes by amount of SiC particulate addition into the matrix, and the strength distribution of the composites typically exhibits scatter with the volume fraction of SiC particulate and the fabrication process and condition. Therefore, the composite materials have not been frequently used as structural materials due to their low reliability [4–6]. The secondary processing techniques such as forging, extrusion, etc., are known to refine the grain structure and improve physical properties of metals. The processing is also advantageous in context of reproducibility of finished parts and improved surface finish, as compared to its cast counterpart. The process is also known for metal saving during high-production runs [7]. This paper is an attempt to study the formability and evaluate the effect of homogenization on the workability and microstructure of AA2014-based 10 vol.% SiCp reinforced MMC. Attempts have also been made to simulate forging (upsetting) conditions by FEM methods. The simulated and experimental results have also been compared in the paper.

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Experimental procedure

Materials and methods

The composite used in this study was AA2014 Alloy reinforced with 10 vol.% SiC particles (AA2014/SiC/10p) having composition (Table 1) synthesized in house by liquid metallurgy route using vortex method [8].

There were three sets of samples, namely (1) as cast-unforged, (2) as cast-forged to different deformation ratios, and (3) billets subjected to homogenization.

Table 1 Chemical composition of the AA2014/SiCp MMC (wt%)

Cu	Mg	Mn	Si	Al	SiCp
4.4	0.5	0.8	0.8	Balance	20 μm

Homogenization

The cast composites were homogenised in a muffle furnace for 12 h at 480 °C and furnace cooled.

Forging

The as cast and homogenized bars were machined into billets of 50 mm diameter and 60 mm height and subjected to upset forging, from 10% height reduction, with successive increments of 10%, to 50% height reduction in an open die using a 400 ton (BEMCO make) hydraulic press setup in un lubricated condition. For the forging/upsetting experiments, the die is arranged on the centre of base frame of hydraulic press; the punch of length 180 mm and diameter 78 mm was fitted to the upper frame of the hydraulic press. When the upper punch, which is fixed with upper frame of hydraulic press, touches the billet, the reading of height and load was continuously measured from that point onwards till the billet is pressed to the required compression as previously calculated. The load was then released and the upper plate lifted. The billet that had been compressed was then measured for its required height and diameter. The operation was repeated on different billets for all ratios of compression. The billet that had been compressed was then measured for its height and diameter to ascertain the actual compression after spring back.

Microscopy

For microstructural studies of AA2014 based composite in as-cast and forged conditions, samples of dimensions 10 mm diameter and 10 mm thick were cut and cold mounted. The specimens were mechanically polished using standard metallographic practices and etched with Keller's reagent (1% HF, 1.5% HCl, 2.5% HNO_3, and remaining water) prior to their micro-structural examination by optical (Leitz Metalloplan) microscopy. The micrographs were also examined using scanning electron microscope (SEM model: JEOL, JSM-5600).

Hardness measurements

Micro-hardness measurements were also carried out using Leica micro-hardness tester at 100 gf load at a dwell time of 10 s to study the variation in hardness of the unforged and forged; homogenized, and un-homogenized samples. An average of results has been quoted along with the standard deviation.

Finite element simulation analysis

Finite element simulation (FEM) of the forged specimens by lagrangian finite element model of the cold upset forging process under unlubricated condition is developed (Fig. 4a) using MSC-Marc software Herein four-node quadrilateral elements with 231 nodes and 200 elements are adopted to discretise the billet. The coefficient of friction required for the simulation was obtained from the ring compression test as described further.

Ring compression test

In this test, a flat ring having geometry; outer diameter:inner diameter:height in proportions of 6:3:1; was upset plastically between two flat platens. As the height is reduced, the ring expands radially outwards. For a particular reduction in height, there is a critical friction value at which the internal diameter increases from the original, if μ is lower and decreases, if μ is higher. By measuring the change in specimen's internal diameter and using the curves (Fig. 3b) which are obtained through theoretical analysis, the coefficient of friction was determined.

Results and discussion

Forging

Examination of a forged specimen reveals that one effect of friction between work piece, and the tool is to cause the vertical profile of billet becomes barrel shaped because the central position has deformed more than the upper and lower surfaces. Deformation is, therefore, inhomogeneous. This requires a higher load and greater total energy expenditure than for homogeneous deformation. This extra energy is described as redundant work. From the physical appearance of the forged composites, it was seen that cracks initiate at 20% compression for the as cast forged samples and the damage increases with the degree of compression. At and above 40% compression, there is total break down and the samples break exhibiting the depth of the cracks; it means that the energy imparted during forging can no longer be sustained in the same, leading to cracks opening up at high-compression rates. Thus, meaningful compressions only up to 20% can be given to such composites for property enhancement purposes.

It was observed that the homogenized composite showed better forgeability as compared to its as-cast

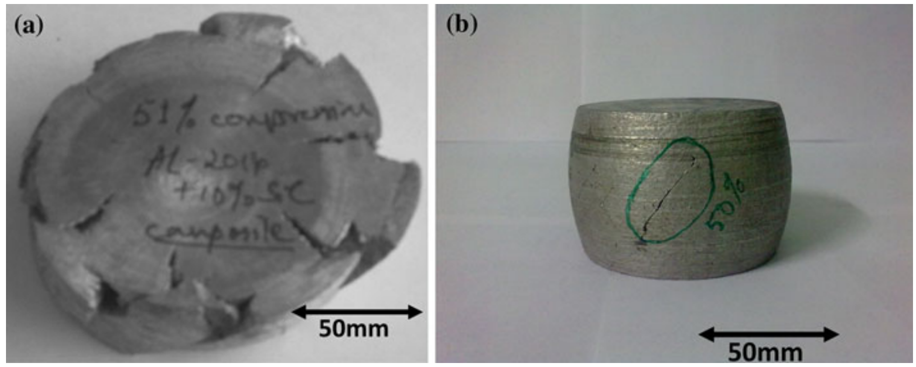

Fig. 1 Deformed billets **a** as-cast and forged and **b** homogenized and forged

counterpart when subjected to similar and higher deformation ratios (Fig. 1). It was found that after homogenisation, crack initiation starts only after forging to over 35% height reduction; and the specimen showed small cracks up at 40% height reduction through compression. The drastic failure of the as cast samples was overcome as a result of homogenization.

Generally, two types of surface cracks, speed cracks and surface tearing, are often seen in the forging of AA2014-based composite. Speed cracking is caused by the high-tensile stresses generated by the intensive friction between the forgings and the die. Surface tearing occurs when the surface temperature exceeds the temperature of the lowest melting phase. In this study, surface tearing is observed at room temperature upsetting. However, the work done during upsetting is also liberated in the form of heat which causes the local rising of temperatures and this can be accounted as the reason for the surface features observed in the forgings.

Hardness measurements

Vickers micro-hardness tests, at a load of 100 gf with a dwell time of 10 s were also carried out, in order to evaluate the matrix inter particle micro-hardness. The results obtained have been tabulated (Table 2), and it was observed that with increase in amount of deformation (forging) the hardness also increased. This can be attributed to the dislocation pileup. However, the homogenized samples showed reduction in hardness values, which are indicative of reduction in brittleness and improved workability of the material.

Microstructural studies

The forging process did not induce variations in particle size. The microstructural analysis did not show any appreciable difference in the degree of clustering of dispersoid before and after the forging. These results are probably due both to the low deformation ratios (2:1) used in this study and also to the low-strain rate adopted in the study.

The benefits of homogenization can be inferred from the micrographs (Fig. 2c, d) which show reduction of micro-segregation, thereby improving the response of composite to mechanical treatment [9]. This reduction is illustrated in the respective micrographs, which show the dissolution and re-precipitation in finer form, of the coarse $CuAl_2$ scripts at the grain boundaries.

Table 2 Hardness variation of composite

	Hardness HV	
	Longitudinal	Transverse
AA2014-based composite (as-cast)		
Unforged	103.34 ± 6.78	105.12 ± 8.13
10% compression	113.67 ± 7.95	116.72 ± 7.12
20% compression	114.53 ± 7.05	117.43 ± 6.45
40% compression	122.11 ± 5.06	123.84 ± 7.50
50% compression	124.13 ± 6.91	125.69 ± 7.88
AA2014-based composite (homogenized)		
Unforged	60.41 ± 3.1	61.53 ± 2.33
20% compression	65.50 ± 1.85	66.21 ± 1.79
50% compression	80.43 ± 4.12	81.94 ± 2.48

FEM analysis

For the FEM simulation of metal forming process, a precise knowledge of the relationship of the flow stress of the material and applied strain, strain rate, and temperature of deformation is essential [10]. In this study, FEM simulation of bulk forming of composites was undertaken; wherein the input material is in the form of billets of specified diameter-to-height ratio. The simulation of upsetting of mild steel was found to be in good agreement with the experimental data [11] which has encouraged extending the scope of study towards the particulate reinforced composites, especially the AA2014/SiCp class of composites, which are

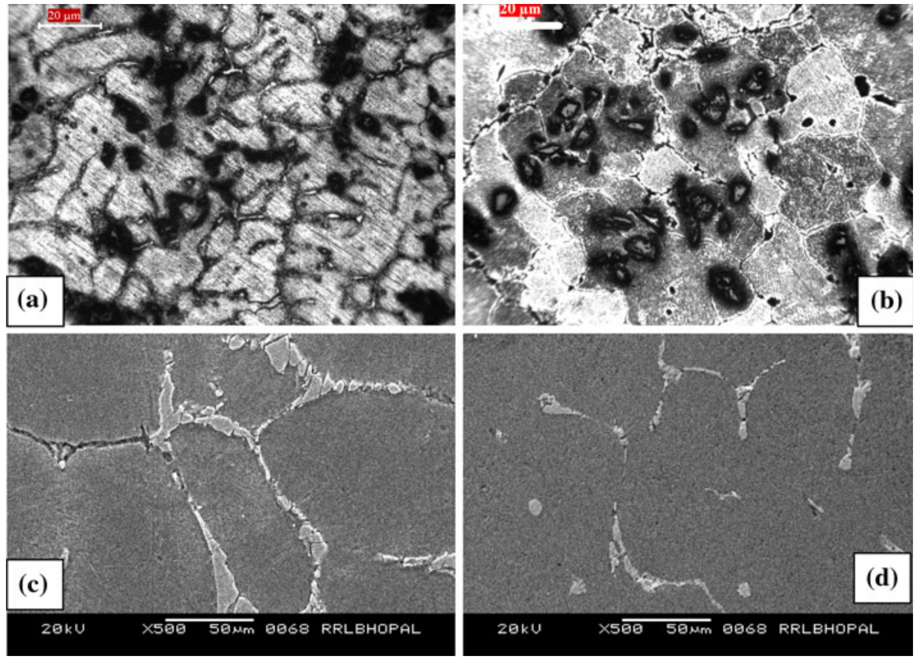

Fig. 2 Typical micrographs of AA2014/SiC/10p MMC: **a** Optical, as-cast and unforged. **b** Optical, homogenized, and unforged. **c** SEM, as-cast and unforged, network of $CuAl_2$ at boundaries of Al grains. **d** SEM, homogenized and unforged. $CuAl_2$ at the grain boundaries has been partially dissolved

being seen as the potential materials for use in different engineering components. Figure 4 provides the simulation data, and Fig. 5 compares the FEM predictions with the experimental observations in terms of deformed geometry. The final height, final diameter at bulge and load were considered as parameters for comparison of the results. Simulation was carried out to upset the billets of 50 mm in diameter and 60 mm in height. Due to the axisymetric nature of this problem as well as the existence of two axis of symmetry within each plane; a 2D model representing one quarter of the cylinder was modelled. The coefficient of friction (μ) calculated from the ring compression test was utilized.

Determining coefficient of friction

Ring compression test has gained wide acceptance in determining the friction parameters, particularly for bulk deformation processes. In this flat ring is upset plastically between two flat platens. As the height is reduced, the ring expands radially outwards. If friction at the interface is zero, both the inner and outer diameter of the ring expands as if it were a solid disk. With increasing friction, however the internal diameter becomes smaller. This is due to the fact that an incremental decrease in the internal diameter involves a smaller contact area (hence less friction energy) than an incremental increase of the same magnitude on the outer diameter. For a particular reduction in height, there is a critical friction value at which the internal diameter increases from the original if μ is lower and decreases if μ is higher. By measuring the change in the specimen's internal diameter and using the curves, which are obtained through theoretical analysis, we can determine the coefficient of friction. Each ring geometry has its own specific set of curves. The most common geometry of a specimen has outer:inner diameter:height proportions of 6:3:1. The actual size of the specimen is usually not relevant in these tests. Thus, we know the percentage of reduction in internal diameter and height; we can determine μ using the appropriate chart (Fig. 3b) The major advantage of the ring compression test is that it does not require any force measurement and that it involves large-scale deformation of the work piece material, as in case in actual practice. After the coefficient of friction is determined, its value is then incorporated in the software together with other parameters such as yield strength, Poisson's ratio, and power law as stated under.

Geometrical and material parameters

Power law, which is given by the following relationship, has been used for material modelling.

$\sigma = k\varepsilon n,$

Following are the characteristics of the material (Al 2014) taken for numerical experiments:

1. Strength coefficient $k = 690$ MPa
2. Hardening exponent $n = 0.16$
3. Young's modulus $= 2 \times 10^5$ N/mm^2
4. Poisson's ratio, $v = 0.3$

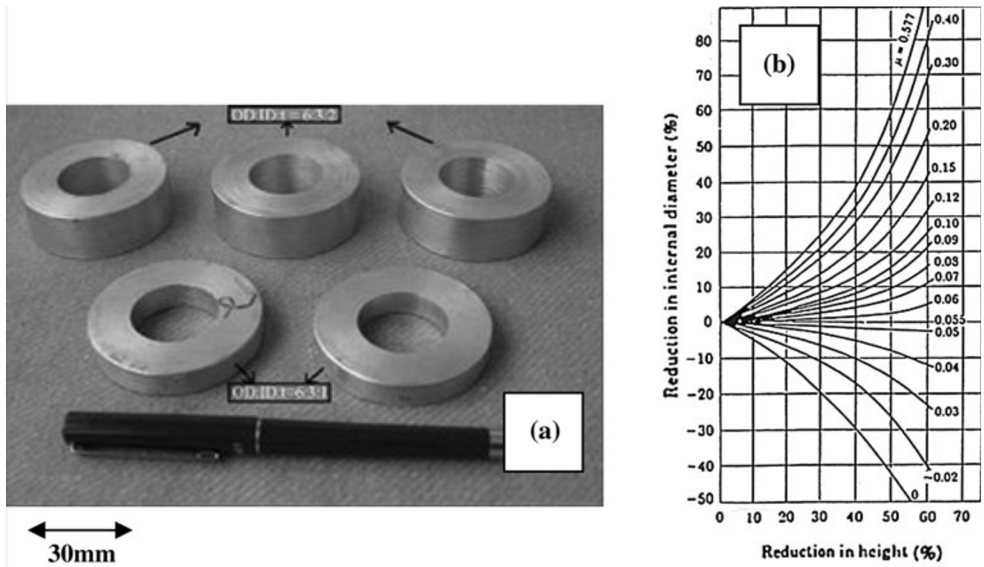

Fig. 3 **a** Composite rings for compression test. **b** Friction calibration curve in terms of μ

The coefficient of friction (coulomb) value is taken as 0.3.

Simulation results

The numerical data obtained in terms of diameter at the bulge, final height of the billets, and applied load are found to be in good agreement with the experimental data. Also the validation of these results has been presented graphically (Fig. 4) to have better understanding of the simulation studies and the simulation graphs have also been presented (Fig. 5).

Conclusions

At low-deformation ratios, the process of forging does not induce damage on composites, in terms of surface cracks or failures, in both the samples (as cast and homogenized).

However, at higher deformation ratios (30% height reduction and above); in as cast samples, hair cracks begin to appear on the surface, which are not observed in case of homogenized samples at same deformation levels. As can be observed from Fig. 1, the workability considerably improves, when the samples are homogenized.

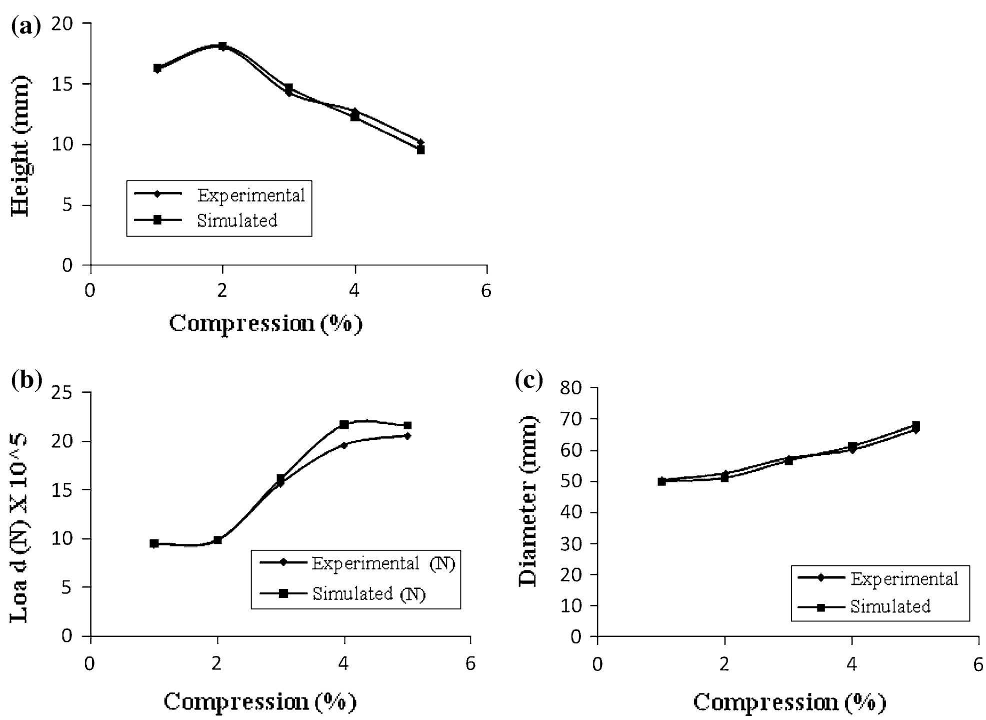

Fig. 4 Graphical comparisons between experimental and simulated results. **a** Final height versus compression. **b** Load versus compression, **c** Diameter versus compression

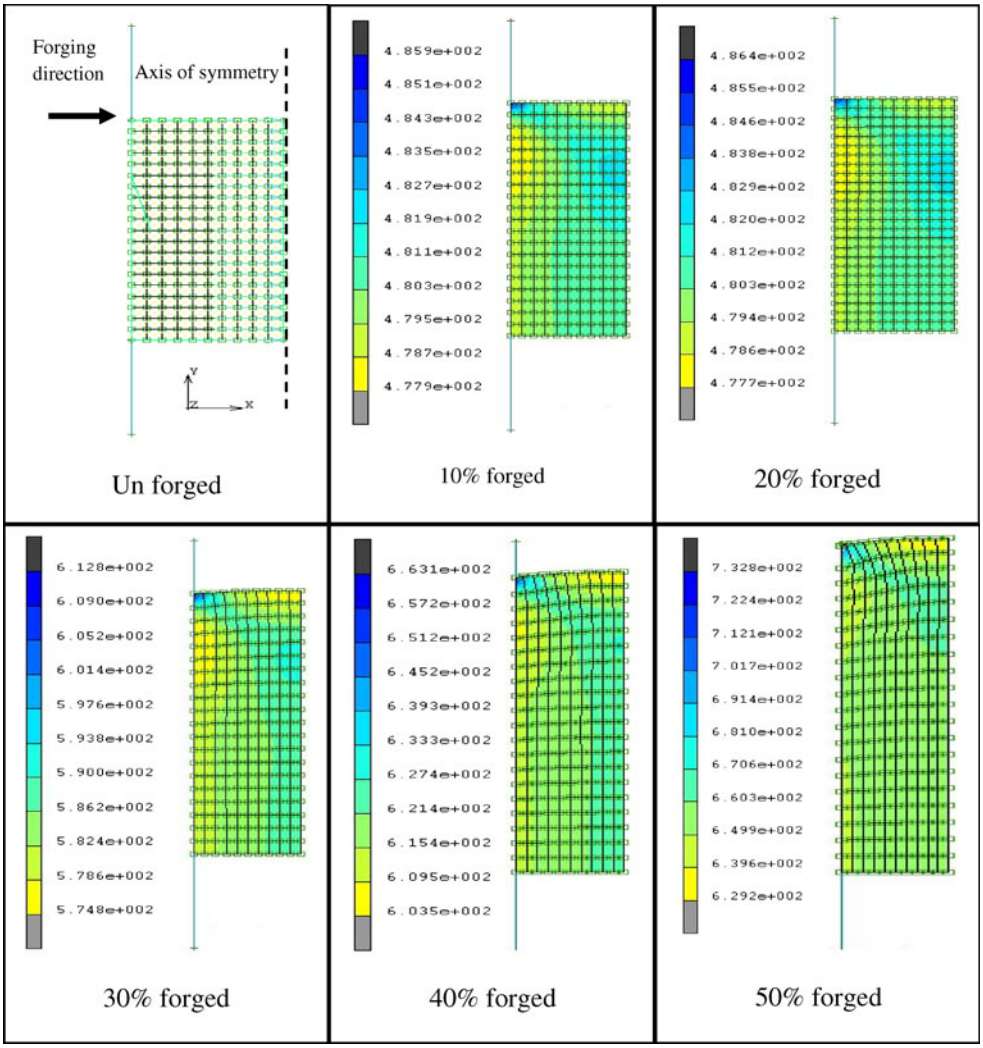

Fig. 5 Simulation results for AA2014/SiC/10p composites under as-cast and forged condition showing equivalent Von Mises stress

The software simulation studies are very useful in comparing forgeability and the effect of surface friction on forgeability of different materials, before they are put to commercial use. As the simulated and experimental results are in good agreement, further studies can be carried out only by simulation, thereby providing cost and time effective way for further experimental procedures.

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