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# FEM Simulation and Experimental Validation of Cold Forging Behavior of LM6 Base Metal Matrix Composites

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## ABSTRACT

The present paper examines the deformation behavior of solid cylinders of an aluminium alloy metal matrix composite (MMC) undergoing axial compression in a Universal Testing Machine under dry condition. The composite was prepared by the stir casting method from LM6 aluminium alloy using silicon carbide particles (SiC) as reinforcing agent. The effect of weight percentage of silicon carbide on microstructure, hardness and upsetting load is studied. The friction factor at die metal interface is evaluated by ring compression tests and its effect on non-uniform deformation is investigated. The experimental results are finally compared with those obtained by FEM simulation.

**Keywords:** LM6-SiC MMC; Hardness; Microstructure; Forging; FEM

## 1. Introduction

In recent years considerable attention has been directed to the study of aluminium metal matrix composites because of their growing applications in aerospace and automotive industries [1,2]. This is not only due to their superior mechanical and thermal properties (high specific strength, excellent wear resistance, high thermal conductivity [2,3]) but is also to a large extent due to the fact that these properties can be manipulated by careful control of the relative amounts and distribution of the ingredients and the processing conditions to suit specific requirements [2].

Metal matrix composites can be produced by the powder metallurgy method [4,5], by spray deposition technique [6] and by stir casting [7-11]. For discontinuous metal matrix composites the last method is generally accepted as a particularly promising route currently practiced commercially. Its advantages lie in its simplicity, flexibility and applicability to large quantity production at relatively low cost.

Presence of silicon carbide particles influences the mechanical properties and the deformation behavior of the aluminium metal matrix in a number of ways. The proof stress (0.2%) and ultimate tensile strength of aluminium tend to increase while its toughness and ductility decrease as the volume fraction of SiC particles in the matrix increases or when its particle size decreases [12]. The brittle fracture behavior of these composites is also found to be affected by the weight fraction of the reinforcing agent [13]. Secondary processing and heat treatment operations are seen to contribute to the performance of these materials. Thus crack formation in axial compression of Al/SiC solid cylinders made by powder metallurgy is found to be suppressed by subjecting these cylinders to an annealing or quenching treatment prior to the deformation process [14]. Parts having undergone forming operations such as forging and extrusion tend to have refine grain structure resulting in their improved performance. It must be stated, however that most of the studies on mechanical behavior and material characterization of Aluminium-SiC metal matrix composites have been limited to materials prepared by powder metallurgy. For composites prepared by ingot metallurgy similar studies are relatively less.

In the present investigation an attempt is made to evaluate the effect of SiC particles on the microstructure and mechanical behavior of an aluminium alloy composite (LM6/SiC) made by stir casting. Microstructure studies of caste samples have been carried out using an optical microscope to look into the degree of wettability and segregation of the reinforcing particles. Microhardness and compression tests were also performed to study the effect of SiC on the forgeability of caste metal matrix. The experimental results are finally compared

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with those obtained by finite element simulation.

## 2. Experimental Procedure

### 2.1. Materials and Method

The composite for the present study was prepared from LM6 aluminium alloy using silicon carbide particles (approximately 400 mesh size) as reinforcing agents. The aluminium alloy was first melted in a resistance furnace and 3 wt% of magnesium was subsequently added to the molten metal. This was because magnesium is known to favour formation of a strong bond between the matrix and the reinforcing particles by decreasing the surface energy (wetting angle). Addition of pure magnesium also enhances the fluidity of molten aluminium. Preheated SiC particles (temperature 850˚C - 900˚C) in varying weight fractions (5 wt% - 12.5 wt%) was then added to the melt and the mix was mechanically stirred at a temperature of 750˚C by an impeller at a stirring speed of about 400 rpm - 500 rpm. The melt was poured at a temperature of 745˚C into silica sand moulds for preparation of the test samples. The composition of LM6 alloy is given in "**Table 1**".

### 2.2. Microscopy

For microscopic examination specimens of cast composites of 10 mm diameter and 15 mm thickness were first ground through 320, 400, 600, 800, 1200 and 1500 grit emery papers followed by polishing by 6 μm diamond paste. The samples were then etched with Keller's reagent (2.5 ml $HNO_3$, 1.5 ml HCl, 1.0 ml HF, 95.0 ml Water) and dried by an electric drier. The microstructure was observed by a metallurgical microscope (Olympus, CK40M).

### 2.3. Hardness Measurements

Micro-hardness measurements were also carried out using a LEICA VMHT micro-hardness tester at 100 gms load with a dwell time of 10 seconds to study the variation of hardness with different wt% of SiC.

### 2.4. Compression Test

For forgeability tests, cylindrical specimens of L/D ratio equal to 1.5 (height L = 15 mm, Diameter D = 10mm) were compressed axially on a 100-ton hydraulic press at room temperature under dry condition. To plot the stress-strain diagram, the tests were interrupted at every 5 mm reduction in height and the corresponding load $P$ and the equatorial diameter $D_E$ were measured. The stress ($\sigma$) and the strain ($\varepsilon$) were then calculated from the equations:

$$\sigma = P/A_E \quad (1)$$

where, $A_E = \pi/4\, D_E^2$ was the area of the equatorial plane and

$$\varepsilon = \ln\left(L_o/L\right) \quad (2)$$

where $L_0$ was the initial height and $L$ the current height of the cylinder. The tests were continued till cracks appeared at the free surface and was stopped when these cracks grew sufficiently large leading to the collapse of the specimens. The forgeability limit was taken to be the height strain at which the cracks were first observed on the free surface of the specimen.

#### 2.5. Finite Element Simulation

Finite element simulation of the cold upsetting process under un-lubricated condition was carried out with the help of DEFORM-3D software using the Lagrangian formulation. The coefficient of friction required for the simulation was obtained from the ring compression test.

#### 2.6. Determination of Coefficient of Friction

In metal forming interface friction plays an important role. It controls the magnitude of the redundant work, the magnitude of the metal forming load and the stress and strain distribution in the deforming medium. The interface friction may be quantified either by a friction factor m ( $\tau = mk$ , $k$ = shear stress of work material) or a coefficient of friction $\mu$ (Coulomb's law, $\tau = \mu p$ ). In the present study Coulomb's law of friction was assumed at the interface between the die and the deforming billet and the coefficient of friction was determined by the ring compression test as suggested by Male & Cockcroft [14]. **Figure 1(a)** shows [15] the calibration curves for determination of coefficient of friction and the geometry of a ring before and after compression is presented in **Figure 1(b)**.

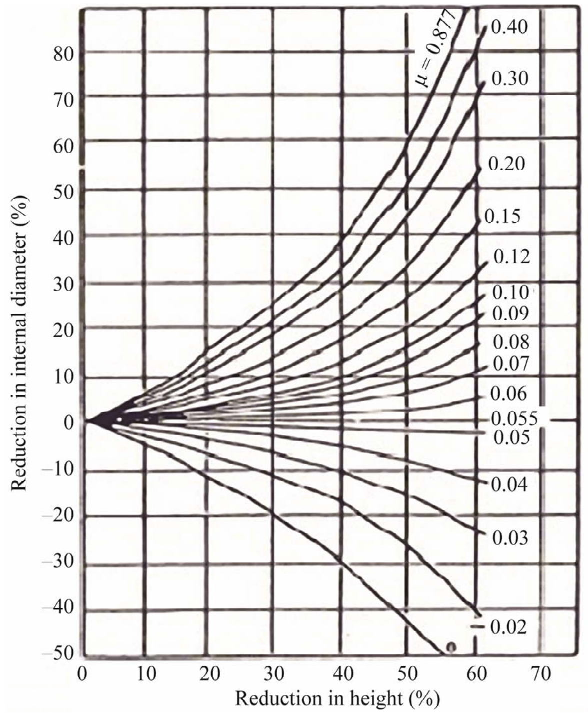
## 3. Results and Discussions

The microstructures of the caste and polished samples as revealed by a metallurgical microscope are presented in **Figure 2**. In these microstructures the dark areas represent the ceramic phase where as the metallic phase appears white. The microstructures show a reasonably uni-

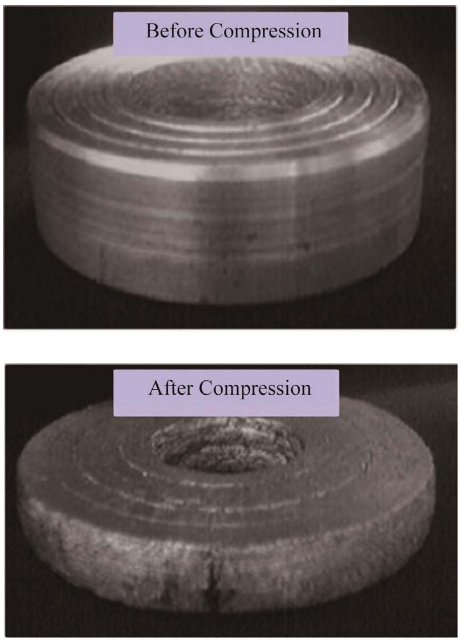
**Table 1: Chemical composition (LM6).**

| Elements | Si | Cu | Mg | Fe | Mn | Ni | Zn | Pb | Sb | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Percentage (%) | 10 - 13 | 0.1 | 0.1 | 0.6 | 0.5 | 0.1 | 0.1 | 0.1 | 0.05 | 0.2 | Remaining |

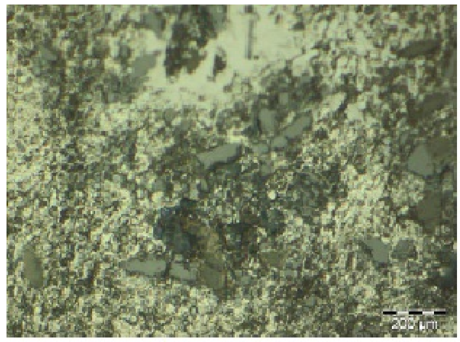



(a)

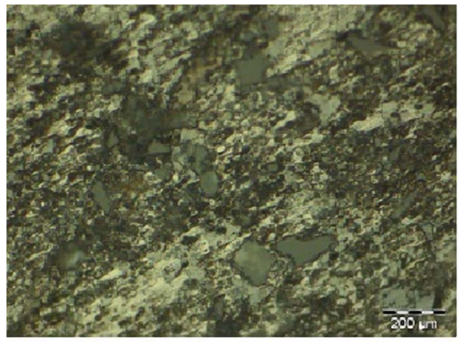



(b)

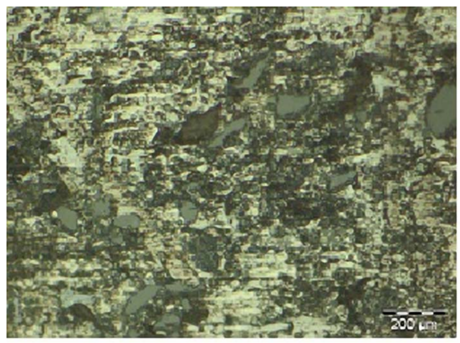
**Figure 1. (a) Friction calibration curves in terms of coefficient of friction; (b) Ring compression specimen (a) before and (b) after compression.**



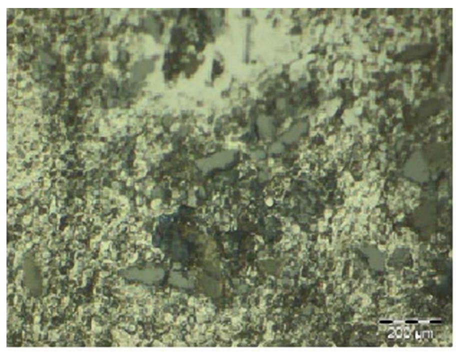

(a)




(b)




(c)




(d)

**Figure 2. Microstructures of cast LM6/SiC composites (a) SiC: 5%; (b) SiC: 7.5%; (c) SiC: 10%; (d) SiC: 12.5%.**

form distribution of SiC particles in the matrix with only slight macro-segregation in some areas. This indicates good wetting of the silicon carbide particles by the molten metal and excellent interfacial bonding between the two phases.

The hardness (**Figure 3**) and the compressive strength (**Figure 4**) of the composites are found to increase with increase in the weight fraction of the reinforcing particles. The compressive strength here refers to the average axial stress $\sigma$ (Equation (1)) over the equatorial plane. The

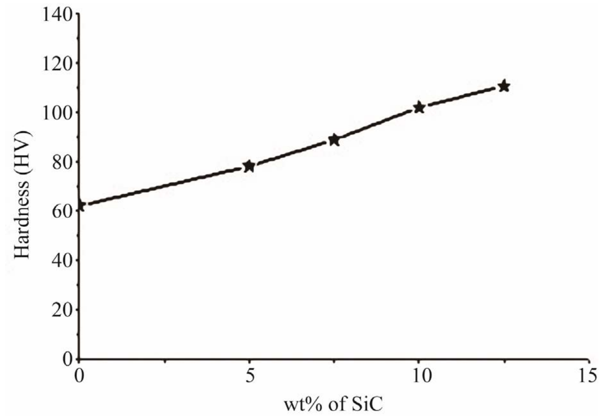



**Figure 3.Variation of hardness with weight percentage of SiC.**

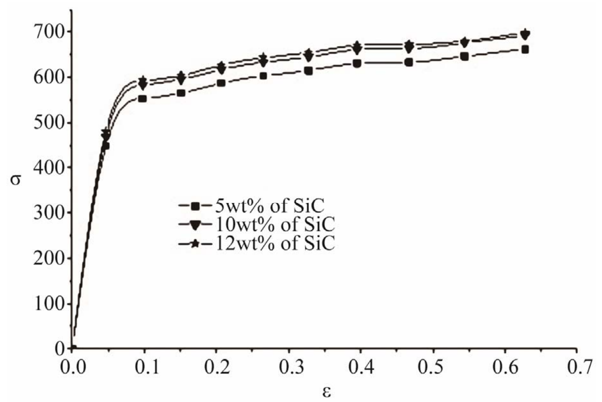



**Figure 4. Variation of equatorial stress with height strain.**

above increase may be due to the increase in dislocation density at the interfaces of the hard carbide particles and the soft metal matrix or may be the result of the income-patibility in the elastic and the plastic behavior of the two phases due to their differential thermal expansion. A reduction in the grain size of the metal matrix due to addition of silicon carbide might also have contributed to this improvement in the mechanical properties.

Two types of cracks are seen in the forging of LM6 based composites. These are the speed cracks and the surface cracks. Friction at the interface between the die and the billet during axial compression results in inhomogenity of deformation and consequent barreling of the free surface of the billet. This gives rise to high tensile stresses leading to speed cracking. Surface tearing occurs when the surface temperature exceeds the melting temperature of the phase having the lowest melting point. In the present study surface tearing was observed at room temperature. This might be due to the conversion of work of compression into thermal energy resulting in temperature rise of the billets. It was also observed that cracks were initiated only after compression of the billets by about 28% - 32% depending on the weight fraction of the SiC. The specimens collapsed completely after a reduction in height by about 34% - 38%.

## 4. FEM Simulation

As a basis for comparison finite element simulation of the upsetting process was carried out using DEFORM-3D software that uses implicit Lagrangian formulation for the analysis. For this purpose the material constitutive equation was assumed as:

$$\sigma = K\varepsilon^n \tag{3}$$

where $K$ is the stress coefficient, $n$ is the strain hardening index, $\sigma$ is the effective stress, $\varepsilon$ is the effective strain, $K$ and $n$ were both determined from compression tests and used for simulation.

The other data used for simulation were Poisson's ratio $\nu = 0.33$ and coefficient of friction $\mu = 0.34$.

The coefficient of friction was determined from the ring compression test as mentioned in 2.6.

The four-node quadrilateral elements with 3168 nodes and 3040 elements are adopted to discretise the cylinder and that of a cylinder before and after compression are shown in **Figure 5**.

In **Figures 6** and **7** the experimentally measured parameters are compared with those obtained from the finite element simulation. The increase in radius of the equatorial plane with height reduction by both the methods show excellent agreement with each other (**Figure 6**). Similar conclusion is also established when flow stress in the equatorial plane is considered (**Figure 7**). Simulated results for stress, strain and velocity at different stages of upsetting are also presented in **Figures 8-10**.

## 5. Conclusions

The significant conclusions from the present study on

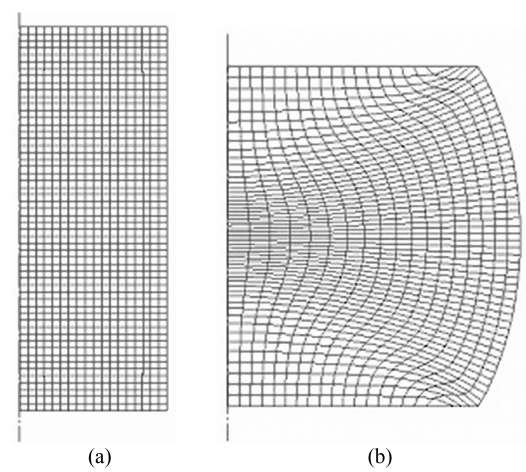



**Figure 5. FEM – model of the sample (a) before and (b) after compression.**

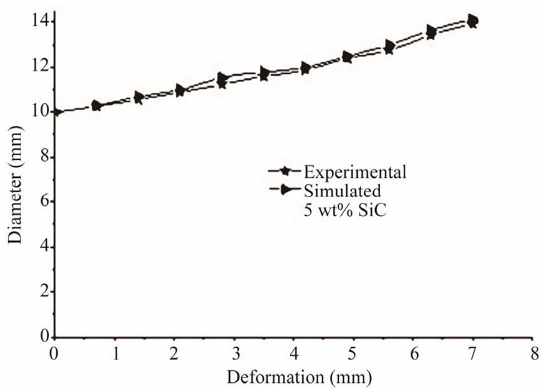



**Figure 6. Variation of equatorial diameter with height reduction. Comparison of results from experiment and simulation (5 wt% SiC).**

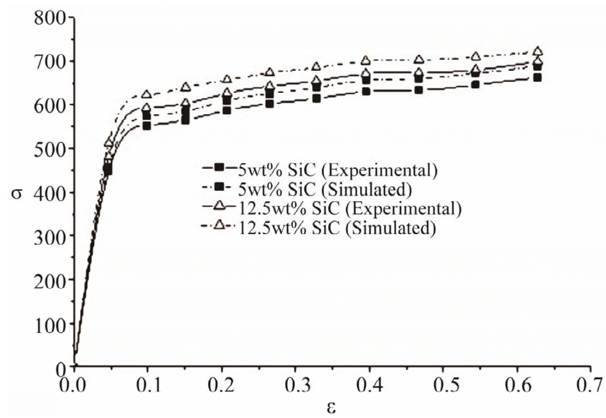



**Figure 7. Variation of σ with ε. Comparison of experimental and simulated results (5 wt% and 12.5 wt% of SiC).**

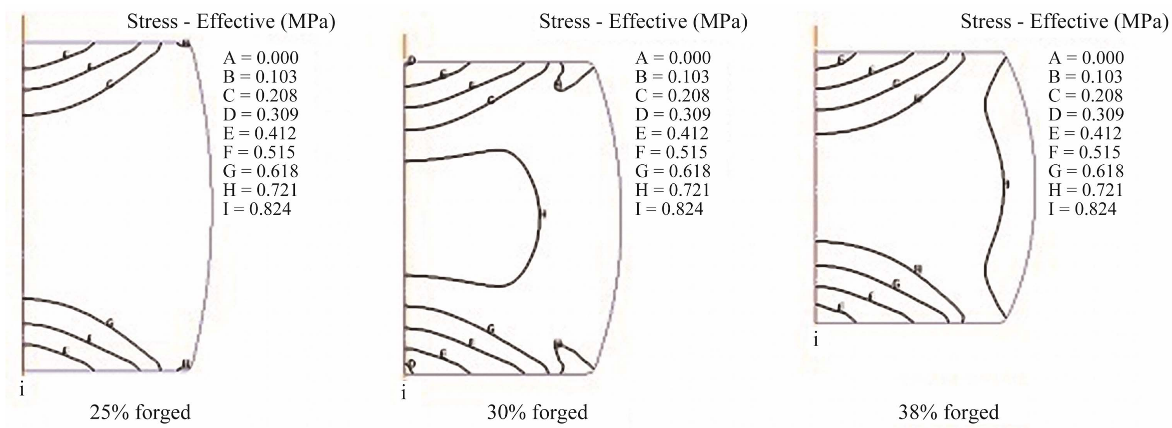



**Figure 8. Simulation results showing effective stress distribution at different stages of compression (5 wt% SiC).**

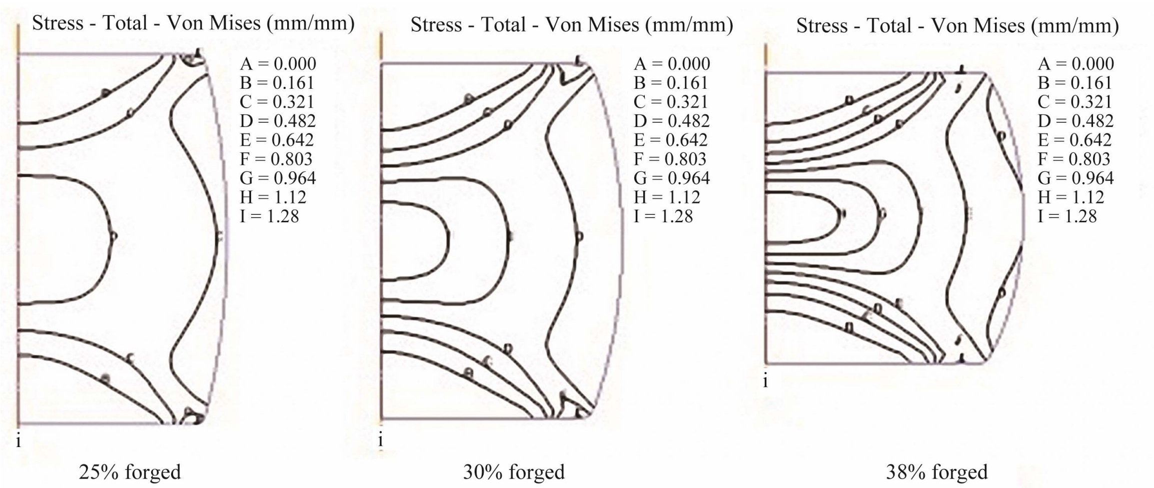



**Figure 9. Simulation results showing distribution of Von-mises strain at different stages of compression (5 wt% SiC).**

LM6/SiC aluminium alloy composites are as follows:

- Homogeneous LM6/SiC aluminium alloy composites can be successfully prepared using liquid metallurgy techniques.
- Both hardness and strength of the composites increase with increase in SiC content.
- Cylindrical preform can be successfully compressed to a height reduction by 28% - 32% without fracture.

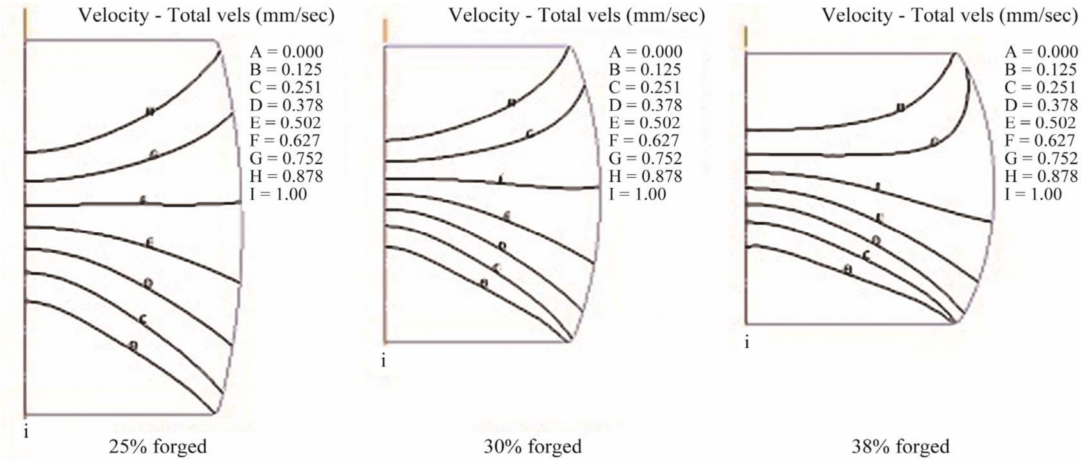



**Figure 10. Simulation results showing variation in velocity within the specimen at different stages of compression (5 wt% SiC).**

Preforms collapse only after a reduction in height by 34% - 38%.

- Finite element simulation of the deformation behavior of the composite can be carried out as that for a homogeneous material.
- There is close agreement between the simulated results with experiment.

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