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TECHNICAL PAPER

Effect of SiC particles on hot deformation behavior of closed-cell Al/SiC_p composite foams

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Abstract
Aluminum foams are one of the best energy absorber materials for various impact protection applications; such as lightweight structural panels, packing materials, and energy-absorbing devices. In the present study, the hot deformation behavior of closed-cell Al/SiC_p composite foams was investigated at different contents of SiC particles (3, 6, and 10 vol%) and at various temperatures (100, 200, 300, and 400 °C). High-temperature uniaxial compression tests with constant 0.1 s^{-1} strain rate were carried out to get the fundamental stress–strain profiles. The results showed that the yield strength, plateau stress, and energy absorption of composite foams increase with increase in the SiC content and decrease with increase in the deformation temperature. Mechanical properties and electron microscope photographs demonstrated that increase in the SiC particle contents, as microstructural obstacles, resulted in cell's walls reinforcement against the early failure especially at the higher temperatures.

Keywords Aluminum composite foams · Closed-cell foam · SiC reinforcement particles · Hot deformation · Plateau stress and energy absorption

1 Introduction

Aluminum foams have a desirable specific strength and high energy dissipating performance and thus can be used as a perfect energy absorber material in a large number of practical applications under severe loading conditions [1, 2]. Their special cellular microstructure leads to a high degree of permanent plastic deformation at an almost constant yield strength. This ability results to absorb a large amount of kinetic energy by the structure before collapsing or fracture [3, 4]. Nowadays, metal foams are increasingly used for high-temperature applications such as heat exchanger, heat shielding for aircraft, the cooling system in the burning chamber of a gas turbine, and steam turbine [5, 6]. However, most studies on the mechanical behavior of the metal foams were carried out at the room temperature [7–9] and very few investigations were considered the influences of the higher temperatures on the mechanical properties of the metal foams [10, 11]. The mechanical properties of metal foams can be tailored by varying the parameters like properties of relative density and types of load static or dynamic, cell wall material, anisotropy of foam structure, free or constrained compression and reinforced particles [11].

Aly et al. [12] reported that the mechanical properties of the Alporas foams are directly related to the relative density and temperature. They showed that the compressive strength of the aluminum foam decreases with increase in the test temperature and increases with increase in the relative density. Sahu et al. [5] investigated the thermomechanical properties of ZA27/SiC_p zinc-based composite foams. They demonstrated that the plateau stress and energy absorption increase with increase in the relative density and strain rate and decrease with increase in the temperature and cell size. Lu et al. [13] showed that the yield strength and plateau stress of the Mg metallic foam significantly decrease with temperature. Furthermore, they demonstrated that the deformation mechanism of the metallic

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foam begins to shift from brittle fracture to the mechanism which is a combination of brittle and ductile fractures with increase in temperature. They have described that at the low-temperature range (up to 200 °C) the dislocation movement was promoted which improves the plasticity of the cell walls and consequently leads to a significant hardening. On the other hand, at high temperature, the softening mechanism took place during the testing so that the metallic foams tend to homogenize deformation under the compressive stress. Cady et al. [14] studied the dynamic and quasi-static properties of Alporas foams at the temperature range of − 196 to 21 °C. They found that the mechanical properties of these type of foams strongly depend on temperature. Temperature dependence of mechanical properties of aluminum foam under dynamic loading was investigated by Wang et al. [15]. Their results showed that the strain rate sensitivity of aluminum foams increases as temperature increases. Li et al. [16] investigated the effect of temperature on the indentation behavior of aluminum foams. According to their results, the collapse strength and energy absorption are temperature-dependent parameters. Linul et al. [17] studied the influence of temperature and anisotropy on the mechanical properties of the closed-cell aluminum foams. Their results showed a monotonic decrease in mechanical properties of the foam and lateral loading with increase in the temperature. It was observed that the main mechanical properties in the axial loading direction are more affected by temperature than the lateral one. Taherishargh et al. [18] investigated the compressive properties of expanded perlite/A356 aluminum syntactic foam and bulk matrix material at different temperatures between 25 and 500 °C. They observed that the elastic stiffness, strength, and energy absorption of foam and solid samples decrease with increase in temperature. They reported that the property reduction of the foam samples followed the trend of the solid material. However, a strong property reduction was observed for the solid samples between 250 and 375 °C which was attributed to significant work softening of the matrix material. In the foam samples, the property decrease was less pronounced which is most likely due to the transition from brittle to ductile deformation. Increasingly ductile deformation of the foam samples suppresses the formation of macroscopic shear bands and thus improves their deformation resistance.

This work was aimed to evaluate the compressive deformation behavior of Al/SiC_p composite foams with different contents of SiC particles (3, 6, and 10 vol%) and CaO_3 as the foaming agent at various temperatures of 100–400 °C.

2 Experiments

2.1 Materials

Closed-cell Al A356 with 3, 6, and 10 vol% SiC composite foams were manufactured by casting technique, with a constant density of 0.5 g/cm^3. Commercial A356 cast aluminum alloy was used as a base material. The reinforcement phase consisted of SiC particles with the purity of 98% and mean particle size of 10 µm. SiC particles were heated for 1 h at 950 °C and then for 2 h at 650 °C in a conventional air furnace to improve the wettability between SiC and Al melt by removing adsorbed gases from the surface of particles and after that, they were gradually cooled down to the room temperature. $CaCO_3$ powders with the purity of 98% and 5 µm average size were used as blowing agent. $CaCO_3$ powders were also heat-treated at 200 °C for 2 h to remove humidity and adsorbed gases from the surface and improve wetting properties and dispersion of $CaCO_3$ powders in molten metal.

The aluminum alloy was melted in a crucible at 680 °C, and then the powder of SiC particles was added into the melt as reinforcing agent with different contents of 3, 6, and 10 vol%, under the stirring condition (600 rpm) for 10 min to prepare the viscous slurry. At the final step, 3 wt% of calcium carbonate powder ($CaCO_3$) was added into the melt, and the melt was stirred at 650 rpm for 3 min. Subsequently, the melt was put into the mold (745–755 °C for 6 min) to allow $CaCO_3$ blowing agent get decomposed and CO_2 gas is released [19]. Subsequently, the melt was gradually cooled down to the room temperature within the mold just after the CO_2 gas release was completed.

Samples pieces were cut into $25 \times 25 \times 30$ mm cubic blocks for the microstructural examination and compression testing. For the metallographic investigations, the samples were polished and then examined through the scanning electron microscope (SEM) to determine SiC particles distribution and microstructure of the cell walls before and after the high-temperature compression tests.

2.2 High-temperature compression test

The test specimens were heated with a high-temperature chamber to desired temperatures for at least 15 min to ensure fully and uniformly heating of samples before compression loading. Mica sheet was used as lubricant, and it was employed only on the active end surfaces of the specimen. Compression tests were carried out via a ZWICK Z250 universal testing machine with a constant strain rate of 0.1 s^{-1} at 100, 200, 300, and 400 °C. The force–displacement data were recorded automatically by the computer connected to the machine.

3 Results and discussion

Image analysis of the composite samples was performed using Manual Microstructure Phase Fraction Measurement (Nahamin Pardazan Asia Co., Iran) to find the volume fraction

of SiC particles as shown in Fig. 1. The volumetric content of reinforcing SiC particles were measured to 3, 6, and 10 vol% as presented in Figs. 1a, b, 2c–f, respectively. The extracted data from Fig. 1 are listed in Table 1. Figure 2a, b shows the cell walls of produced foam, and Fig. 2c, d shows the EDX analysis of particles in the cell walls.

The compression stress–strain analysis of the samples, with different SiC contents at various temperatures were carried out according to ISO 13314 standard [20]. The results are shown in Fig. 3. The compressive strain was calculated by the following equation:

$$\sigma = \frac{\Delta L}{L_0} \times 100 \tag{1}$$

where ΔL and L_0 are the overall compressive displacement and initial length (gauge length) of the test specimen. Plateau stress was an arithmetical mean of the stresses at 0.1% or smaller strain intervals between 20 and 30% or 20% and 40% compressive strain. The plateau stress was calculated intervals between 20 and 40% compressive strain. The energy absorption,)W(, by the foams is calculated from the stress–strain curves using area under the stress–strain curve up to 50% strain.The energy absorption of foam is defined by the following relationship [20]:

$$W_{\mathrm{d}} \int_0^{\varepsilon} \sigma(\varepsilon) \cdot \mathrm{d}\varepsilon \tag{2}$$

where ε and σ are strain and stress, respectively.

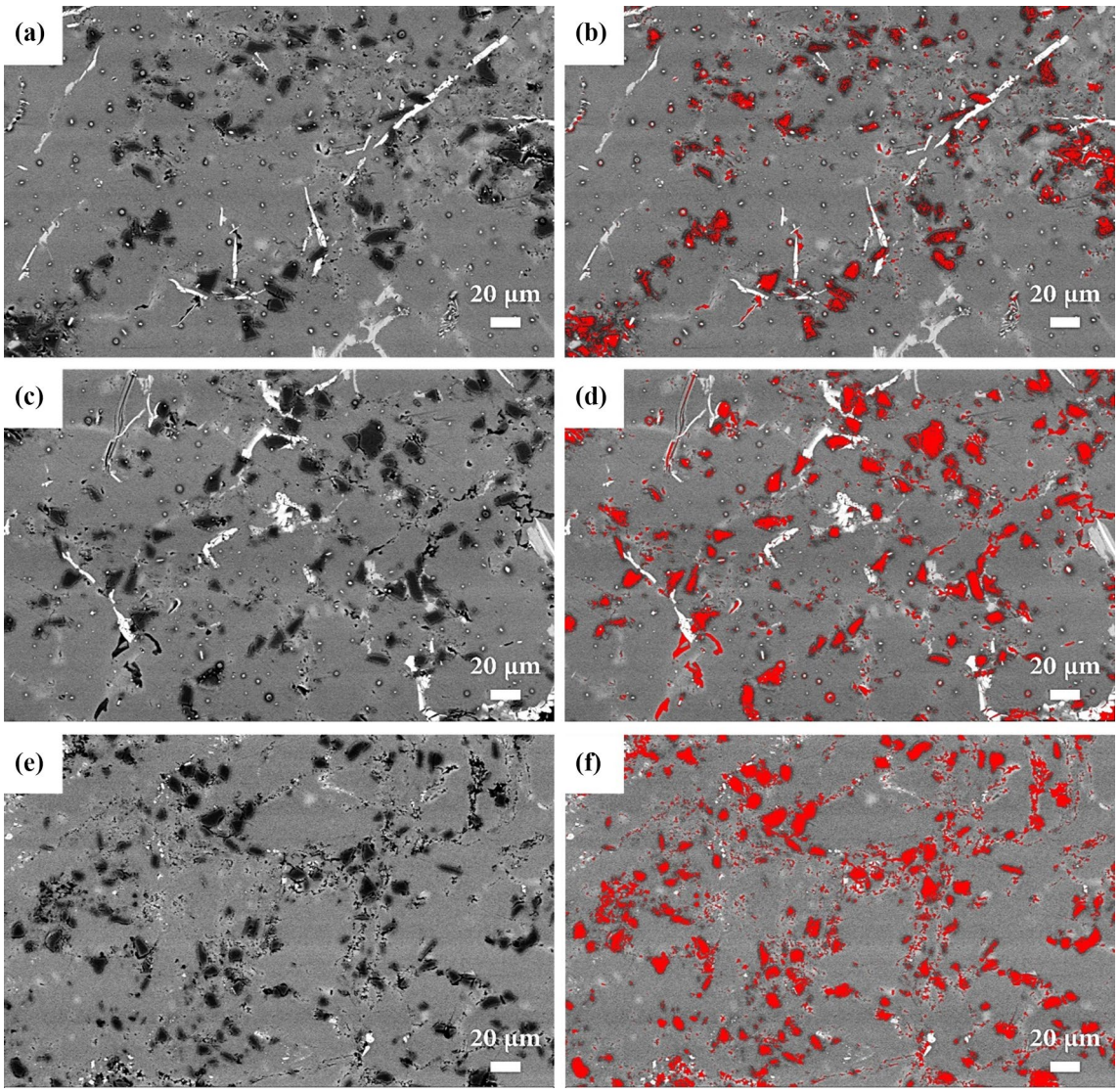

Fig. 1 Phase fraction of Al/SiC composite. **a**, **b** 3 vol%, **c**, **d** 6%, and **e**, **f** 10%

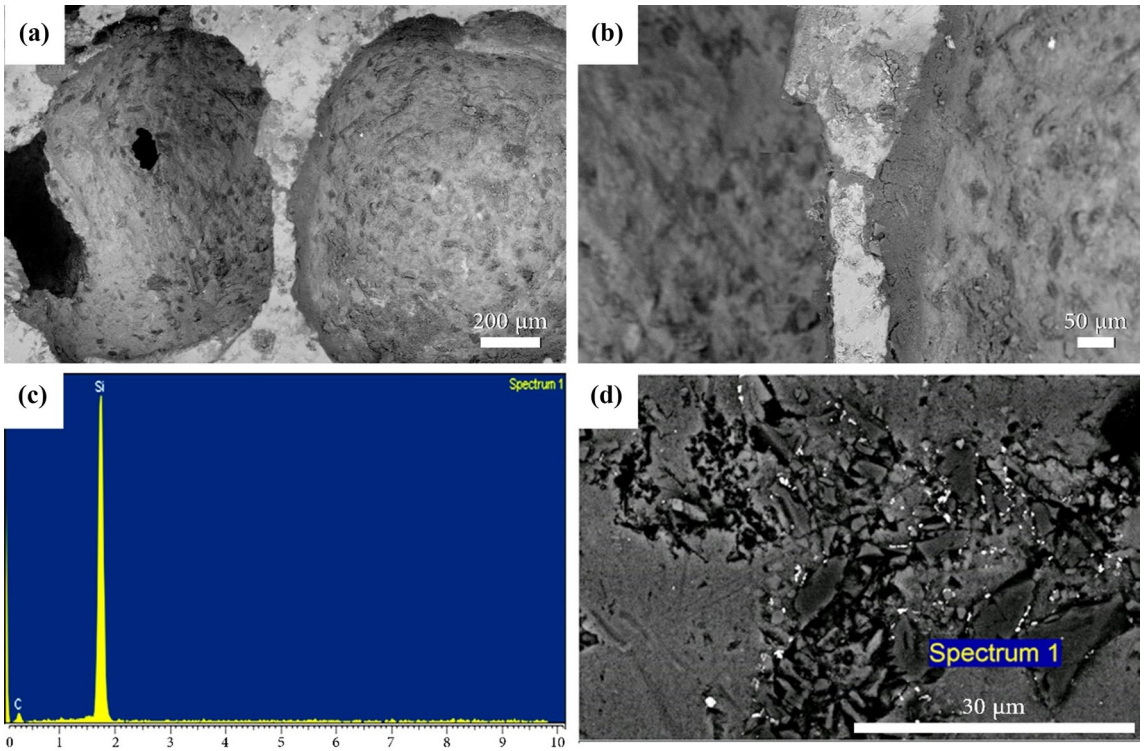

Fig. 2 **a**, **b** The cell walls of produced foam, **c**, **d** distribution of SiC particles along with the EDX analysis

Table 1 Included area and percent of reinforced SiC particle content

Phase Name	Area (μm^2)	Percentage
Figure 1a, b	2019	3.32
Figure 1c, d	43,484	6.56
Figure 1e, f	8647	9.48

Compression stress–strain curves of the samples with different SiC contents and various temperatures are shown in Fig. 3. As Fig. 3 indicates, The stress–strain profile, similar to conventional closed-cell metallic foams [21], consists of three distinct stages: linear elastic deformation region, collapse plateau region and densification region. As one can see in Fig. 3, at stress less than 0.1, a linear elastic region was observed that clearly demonstrates the elastic bending of the cell walls. As the stress increases, the first peak appears on the diagram shows the magnitude of the yield's stress of metal foam. This is called the linear elastic deformation region. By passing through the elastic region and reaching to the second region of the graph, the stress value is almost constant in a wide range of stress. The average stress in this range is equal to the collapse plateau region. Depending on the cell structure and solid properties, the plateau region may not be quite smooth and has some serrations [22]. In the composite Al/SiC foam and at low-temperatures, the plateau region is not smooth and exhibits some serrations which are mainly due to the increased brittleness in the cell walls. Note that the brittleness of Al/SiC composites is generally greater than that of Al alloy [23]. Also, non-uniformity of the structure leads to local concentrated stress which causes the plastic deformation and serrations appearance in some regions.

At strains near 0.5%, the stress increases exponentially with increase in the strain up to a maximum point where the cell's walls collapse. This behavior reflects the destruction of cellular structure in metal foam, similar to a bulk solid metal. This area in the stress–strain curve is called densification region. These three different deformation regions were observed at the whole temperature range. The extracted data from Fig. 3a–c are listed in Table 2. According to data reported in Table 2, it was understood that the stress levels strongly depend on both SiC volume fraction and temperature.

3.1 Effect of SiC content on hot deformation behavior

Figure 4 shows the effects of SiC particles contents on the mechanical properties of the composite as a function of temperature. The results show that at each testing temperature, the plateau stress values and energy absorption increase as the volume fraction of SiC increases.

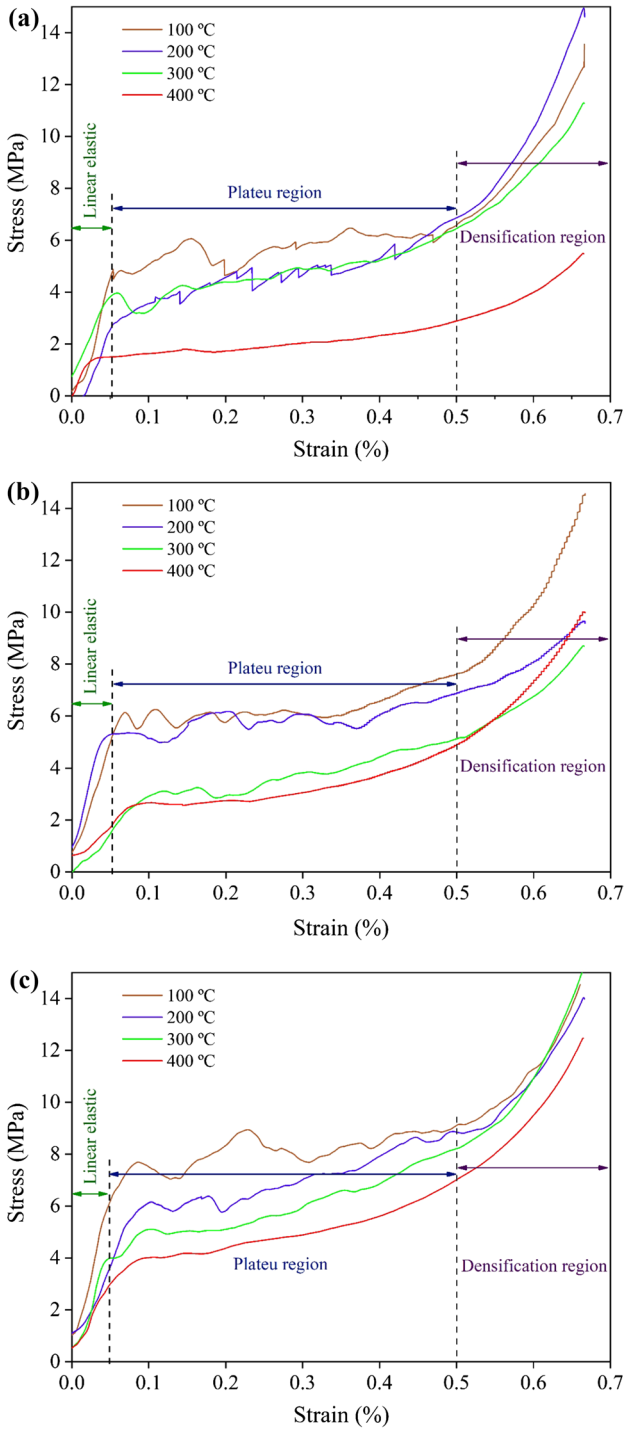

Fig. 3 Stress–strain curves of aluminum composite with **a** 3 vol% SiC, **b** 6 vol% SiC, and **c** 10 vol% SiC contents

The results at 100 °C are revealing enhancement of the yield strength from 4.7 to 6.2 and 7.8 MPa by increasing the volume fraction of SiC reinforcing particles from 3 to 6 and 10 vol%, respectively. However, at the higher temperature (400 °C), the yield strength was measured to be 1.6, 2.3, and 3.9 MPa at SiC volume fractions of 3, 6, and 10 vol%,

Table 2 The mechanical properties of investigated foams at different temperatures and SiC content

SiC contents (vol%)	Temperature (°C)	Plateau region (MPa)	Energy absorption (kJ/mm^3)
3	100	5.8	2.6
3	200	4.6	1.2
3	300	3.7	1.8
3	400	1.9	1.0
6	100	6.2	2.9
6	200	5.9	2.8
6	300	4.8	2.2
6	400	3.2	1.4
10	100	8.3	3.8
10	200	6.6	3.2
10	300	6.1	2.8
10	400	5.0	2.2

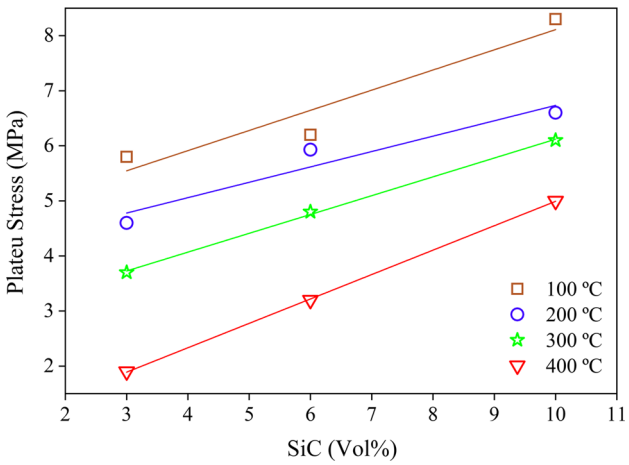

Fig. 4 Detailed plateau stress SiC vol% curves of investigated foams

respectively. These results well demonstrate the reinforcing role of the SiC particles at higher temperatures.

It should be noted that the yield strength does not change linearly with SiC contents. The reinforcing role of the SiC particles can be expressed as follows: SiC particles in the cell walls of the foam effectively withstand against applied stress and increase the strength. However, if the exerted force exceeds the tolerance of the cell walls, there would be a failure from the joint points or from inside of SiC particles [24]. confirm our results and interpretations.

Figures 4 and 5 show the effect of the volume fraction of SiC particles on the plateau stress and energy absorption of the composite foam. At constant temperature, by increasing the volume fraction of SiC particles, the plateau stress and energy absorption increases. At 100 °C, the plateau stress

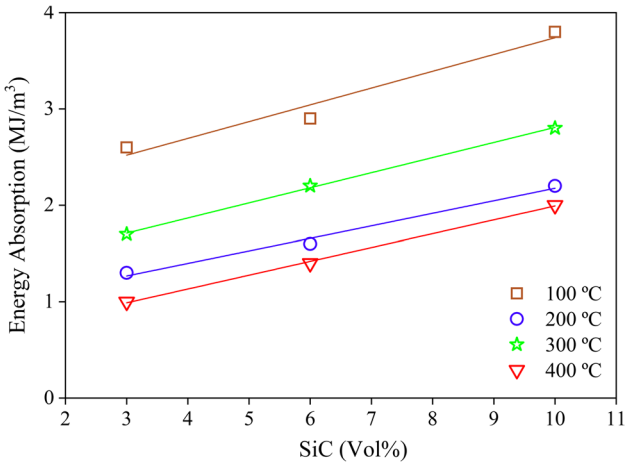

Fig. 5 Detailed and energy absorption SiC vol% curves of investigated foams

value for samples with SiC particles of 3, 6, and 10% is 5.8, 6.2, and 8.3 MPa, respectively. It can be attributed to the reinforcing role of the SiC particles. Another possible reason for the improved yield strength can be attributed to the higher rate of the composite hardness at lower tension which is due to the elastic properties of SiC particles and their inhibitive role for plastic deformation of composite foam. The non-cohesive phase between the field and SiC particles is a strong barrier for the movement of the field dislocations which increases the work hardening (strain hardening) [25].

Figure 5 shows that with increase in the volume fraction of SiC particles, the energy absorption follows the same trend as plateau stress. In the other word, the energy absorption increases as the volume fraction of the SiC particles increases. The energy absorption in the sample with 10 vol% SiC contents was improved by 46, 166, 55 and 120% at 100, 200, 300, and 400 °C, respectively compared with the sample containing 3 vol% SiC. The corresponding values are 31, 14, 27 and 57% comparing with sample containing 6 vol% SiC. The results showed that the thickness of the cell walls increases as the volume fraction of SiC particles increases [26]. Therefore, the composite foam with 10 vol% of SiC content is much stronger than those with 3 and 6 vol%. Also, the thicker cell walls affects positively on the foam resistance against bending, especially at higher temperatures.

The aggregation of SiC particles in the walls prevented the melting of the walls and made them remain stable at higher temperatures. The particles with incomplete wettability were located at the interface of gas-walls and they are more effective on the stability of the cell walls [27]. This can be explained by the fact that those particles will modify the curvatures at the interface of gas-walls which reduces the concavity of the walls and consequently enhances the cell walls stability [28].

3.2 Effect of temperature on hot deformation behavior

Figure 6 shows the variation of the plateau stress values with temperature for samples with different SiC contents. As Fig. 6 shows, the plateau stress of composite foams decreases with increase in the deformation temperature. Generally, increase in the temperature leads to a reduction in yield strength, plateau stress and energy absorption [29]. For example, in sample with 10 vol% SiC contents, increase in the temperature from 100 to 400 °C causes a reduction in yield stress by about 102%. The corresponding values for samples with 6 and 3 vol% SiC content are 221 and 177%, respectively.

The correlation of the plateau stress with temperature in a constant amount of SiC particles is shown in Fig. 6. As this figure indicates, the plateau stress reduces as temperature increases. For instance, in the composite foam with 10% of SiC content, the plateau stress values are 8.3, 6.6, 6.1, and 5 MPa at 100, 200, 300, and 400 °C, respectively. The plateau stress depends on both the strength of the field and the cell walls. Therefore, it can be concluded that the strength of the field and yield strength of the cell walls reduce at higher temperatures which consequently reduces the plateau stress.

Figure 7 represents the variation on the energy absorption by temperature. This figure shows that the energy absorption follows a similar trend as plateau stress which can be related to the reduction in the area under the graph's curve. On the other hand, increasing the temperature resulted in decreasing the stress levels and smoothing the plateau region. With increase in the testing temperature up to 400 °C, the softening occurs like ductile materials. It should be noted that as the temperature rises, the stress–strain curve falls which

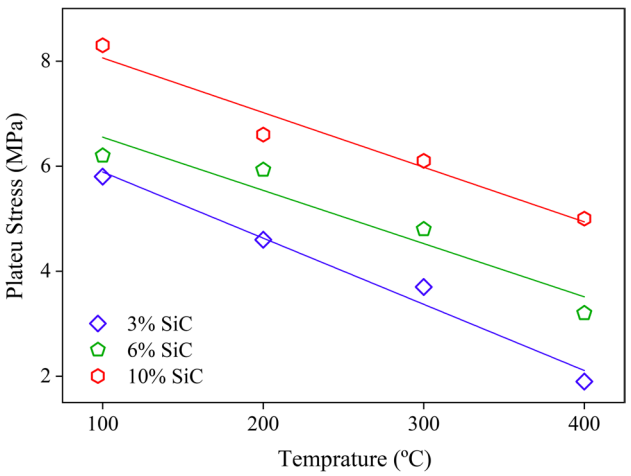

Fig. 6 Detailed plateau stress–temperature curves of investigated foams

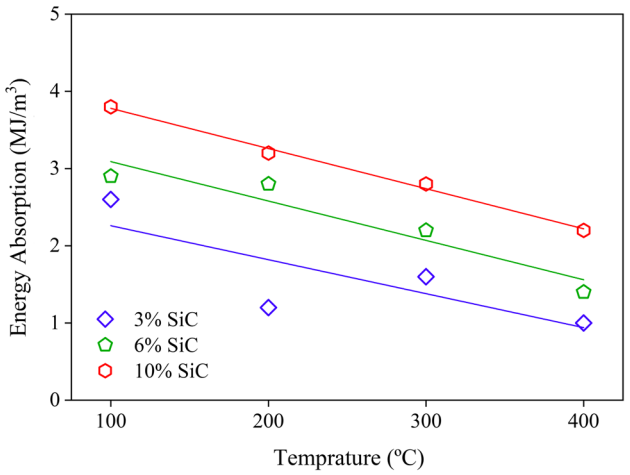

Fig. 7 Detailed and energy absorption–temperature curves of investigated foams

indicates the significant effect of the temperature on the reduction of the energy absorption capacity of the foam.

Reduction in the compressive properties of the closed-cell foam with increase in the temperature can be attributed to the change in the mechanisms of structural and walls deformations in the cells. The mechanism of the cell's walls/edges deformation could be divided to the three steps: 1—plastic bending of the cell walls/edges, 2—buckling in the form of elastic/plastic and cellular collapse, and 3—tearing due to the shear force [15]. At lower testing temperatures (100 and 200 °C), the dominant mechanism is the buckling and rupturing of the cell's walls which cause the teeth to occur in the second region of the stress–strain curve of the specimens (Fig. 7). With increase in the temperature and weakening the strength of the cell's walls, the mechanism changes from the buckling and tearing to bending. It should be mentioned that in this case, the strength of the metal foam sharply reduces and the stress–strain curve would be flat in the plateau stress region. Wang et al. [15] reported the same behavior by examining the effect of the temperature on the compressive properties of aluminum foam.

The physical appearance of the samples with 10 vol% SiC particles content after mechanical deformation at 100, 200, 300, and 400 °C is presented in Fig. 8a–d, respectively. As Fig. 8a and b indicate, after the densification of the samples and passing through the dense strain (the third region of stress–strain engineering), the cell walls have been collapsed and some of them have been isolated. The results show a severe buckling of the cell walls at the lower temperatures. However, as temperature increases, as can be seen in Fig. 8c, d, the samples show a greater potential for crushing because of higher bending capability of the cell's walls.

4 Conclusions

Herein, the hot deformation behavior of closed-cell Al/SiC composite foams was investigated as a function of the SiC particles contents (3, 6, and 10 vol%) and temperatures (100, 200, 300, and 400 °C). For the Al/SiC composite foam and at low temperatures, the plateau region at the stress–strain profile is not smooth and exhibits some serrations which is mainly due to the increased brittleness in the cell's walls. At constant temperature, by increasing the volume fraction of SiC particles, the plateau stress enhances and energy absorption increases. The plateau stress in the sample with 10 vol% SiC content was improved by 43, 43, 65 and 163% at 100, 200, 300, and 400 °C, respectively compared with that of containing 3 vol% SiC. Also, the energy absorption of the sample with 10 vol% SiC contents was improved by 46, 166, 55 and 120% at 100, 200, 300, and 400 °C, respectively compared with the sample containing 3 vol% SiC.

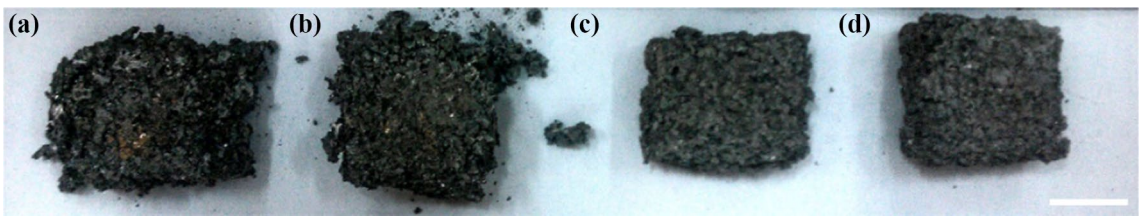

Fig. 8 Deformed specimens at different temperatures presenting: brittle **a** 100, **b** 200 °C and ductile behavior, **c** 300, **d** 400 °C. Scale bar is equal to 20 cm

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