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Research Article

Effect of Green Body Formation by Single and Double Action Pressing on the Mechanical Properties of Al Foams

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ABSTRACT

In the present study, aluminum foams with a relative density of 0.38 were fabricated through powder metallurgy route by using carbamides as space holders. The effect of using double and single action die pressing methods to produce green compacts, were studied on the mechanical and energy absorption capacity of the fabricated foams. Carbamide space holders were removed by being leached in water, whereafter the samples were sintered at 640ºC for 2 hours in air. Mechanical properties and energy absorption capability of the fabricated foam samples were evaluated by the means of compression test. The results proved that double action die pressing method can significantly improve mechanical properties and energy absorption capacity of the fabricated foam by creating more uniform density distribution in foam structure. Therefore, for foams with a relative density of 0.38, using double action die pressing process caused nearly 95 % increase in plateau stress and more than 24% improvement in energy absorption ability for the fabricated foam.

1. Introduction

Metal foams are one of the most important engineering materials with porous structures. These types of engineering structures attracted many researchers because of their unique thermal, mechanical and electrical properties [1]. Metallic foams have been used in many interesting engineering applications such as; automotive, energy absorbers [2, 3], biomedical, aerospace, batteries, fuel cells [4, 5], acoustic dampers and solar power systems [6, 7].

According to the starting materials, metal foams can be fabricated by different methods including melt foaming routes [8], precursor foaming [9, 10] and power metallurgy [11, 12]. One of the well-known methods for fabrication of metal foams is the space holder technique via powder metallurgy route. This technique is relatively expensive due to the use of fine metal powders as raw material [13]. At the same time, it possesses a few parameters for microstructure control such as morphology, cell size and distribution of porosity, and therefore by using this method it would be possible to well adjust properties of the created foams [14-16]. In addition, in this method, porosities with specific shapes and sizes can be created by using abundant and unexpensive foaming agents, such as carbamide or salt particles [17, 18].

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In the past decade, researchers have paid attention to improve the production process by optimizing the fabrication parameters including sintering condition, cell structure and cell size in order to improve physical and mechanical properties of fabricated metal foams via space holder techniques [19-21]. Zhao et al. analyzed the effects of the compaction and liquid-state sintering conditions on the structure of the resultant aluminum foams fabricated by the sintering and dissolution process [22]. Surace et al. studied the influence of processing conditions, including compaction pressure and sintering time, on the properties of fabricated aluminum foams by utilizing the sintering and dissolution method [14]. Bafti and coworkers reported about the effect of cell size and shape on compressive behavior of fabricated aluminum foams [21]. Bafti et al. proved that addition of 1 wt.% Sn and Mg to aluminum powder increase strength of foams structure [20]. Recently we reported the effect of pore density and distribution on the compression behavior and energy absorption capacity of aluminum foams fabricated by space holder techniques via the powder metallurgy route [23]. Although aluminum foams have been made with double action die pressing process in our group, but no attention has been paid to the effect of applying double and single action die pressing process on mechanical properties of the fabricated foams. In order to illustrate the differences between double pressing (DP) and single die pressing (SP), it is worth mentioning that, Wei et al. investigated numerically the effect of DP and SP compaction methods on micro and macro properties of Fe-Al composite powders. They showed that the DP method can create dense compact with more uniform stress and relative density distribution [24]. Bonaccrosi et al. examined the foaming behavior of aluminum powder that included titanium hydride as its blowing agent, compacted by two different double and single cold uniaxial compressions. They proved that the best results would be obtained by double action die pressing in a lubricated die [25]. Rahmani et al. investigated the effect of double die pressing on mechanical and physical properties of Mg-WO_3 nanocomposites [26].

In the present research, powder metallurgy route using carbamide as space-holder is used to fabricate Al foams. The effect of using double and single die pressing methods in the green body formation step is investigated on the mechanical properties as well as the energy absorption capacity of the fabricated foams.

2. Experimental Procedure

In this study, the powder space holder technique was used in order to fabricate aluminum foams with relative density of 0.38. Commercially pure aluminum powder with an average particle size of 40 µm and irregular shape was used as starting material. The typical morphology of the used aluminum powder is shown in Fig. 1. The chemical composition of the aluminum powder is introduced in Table 1.

Spherical carbamides with a size range of 1.7-2 mm were used as space holder. The construction stages of the aluminum foams, used in the current research, are summarized in Fig. 2. As can be seen, the layer by layer technique, developed by Mirzaei et al. [27, 28], was employed in order to fabricate specimens. Details of the used method are explained in our recently published report [23].

Green specimens were formed by uniaxially single and double die action pressing by applying 330 MPa pressure. To carry out the single and double die action pressing, the die setup shown in Fig. 3 was used.

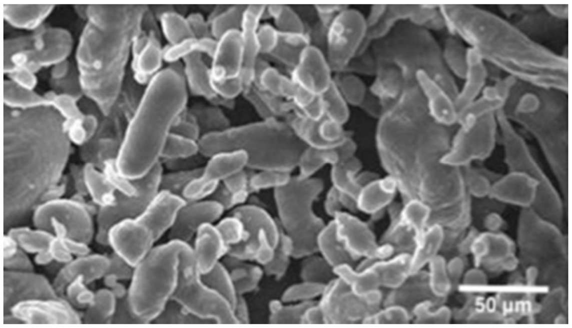

Fig. 1. SEM image of the used commercially pure aluminum powder.

Table 1. Chemical composition of the initial aluminum powder as determined by Optical Emission Spectroscopy (OES) method (in wt.%)

Al	Fe	Si	Cu	Other elements
99.5%	0.244%	0.131%	0.047%	0.078%

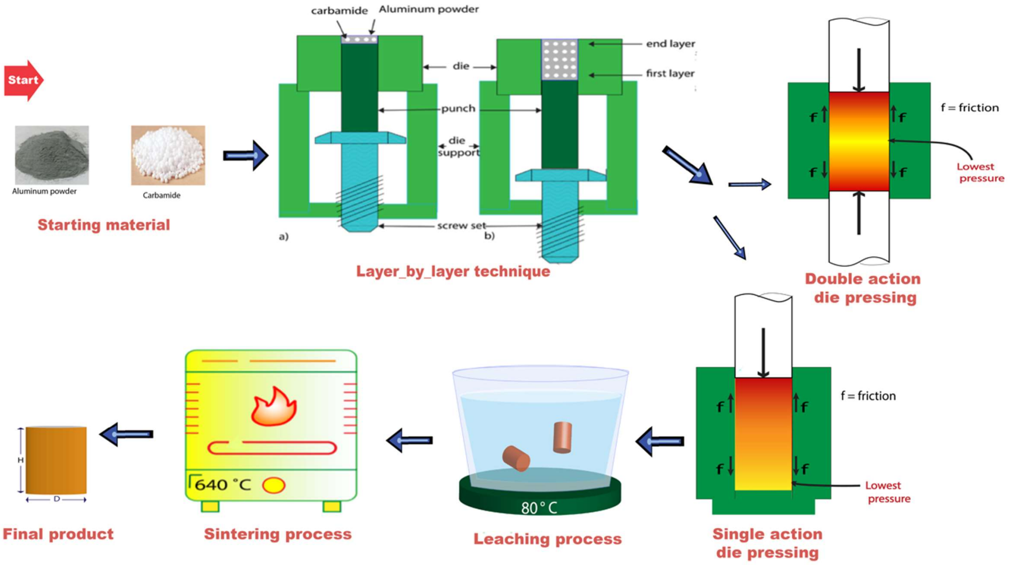

Fig. 2. Fabrication stages used in this study for producing metal foams via powder metallurgy technique.

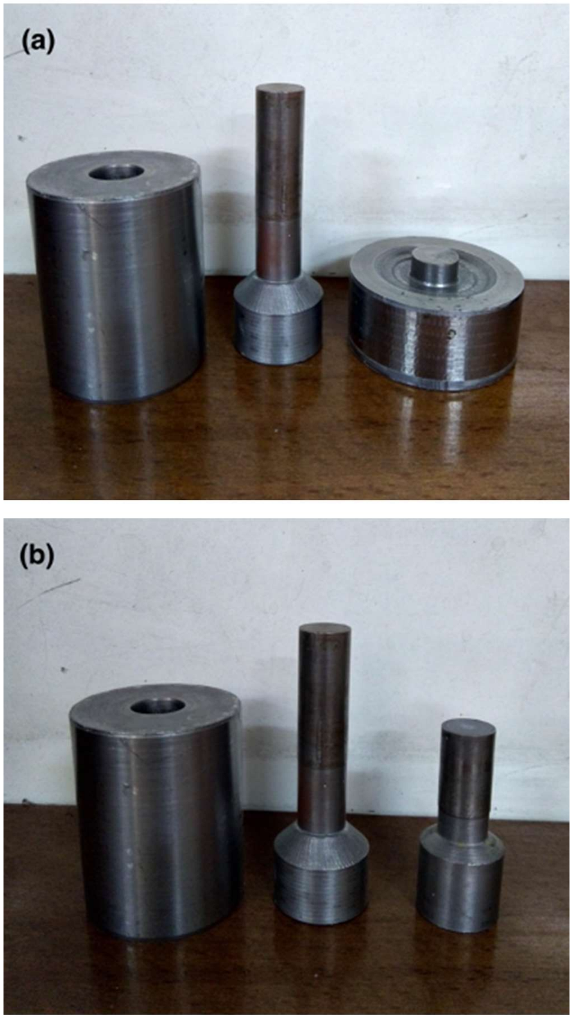

Fig. 3. Pressing die setup: (a) single die action pressing die setup. (b) double die action pressing die setup.

In the single die action pressing method, the lower punch is stationary, but in double die action pressing both punches are movable and the die is float. The height (H) and diameter of the compacted samples were 25 and 15 mm, respectively. The resulted green specimens were immersed in water at 80℃ in order to leach out the used carbamides. About 90% of the carbamide was removed after 2 h leaching process. The sintering stage of the specimens was performed for 2 h in a tube furnace at 640°C in air. In the present work, samples with relative density of 0.38 with single and double die action pressing methods were prepared. These samples were labeled as SP (0.38) and DP (0.38), respectively.

The density of the fabricated aluminum foams were calculated by measuring the weight and volume of each sample (based on geometric dimensions). The relative density of the fabricated foams was calculated by using the theoretical density of solid aluminum (2.7 g/cm^3). The compression test was performed by the Santam STM-150 machine having a constant cross-head speed of 1 mm/min, taking into account ISO standard 13314 [29].

3. Results and Discussion

Aluminum foams with relative density of 0.38 were perfectly fabricated by the powder metallurgy route. As shown in Fig. 4, most of the porosity are isolated,

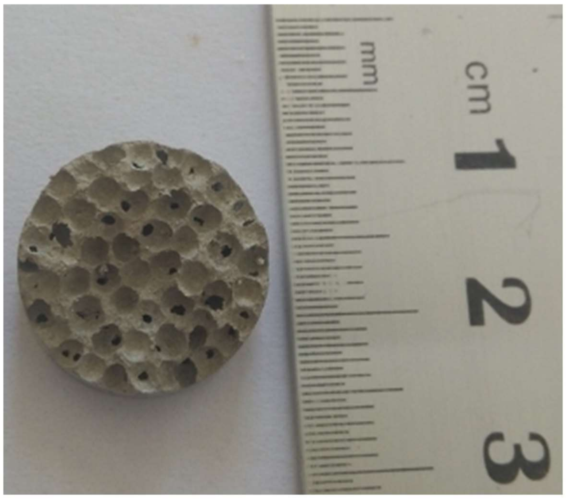

Fig. 4. Cross section image of fabricated foam with respect to compaction.

it means that fabricated foams may be considered as a close cell structure.

Fig. 5 shows the compressive stress-strain curves for the fabricated foams with the same relative densities of 0.38 (SP (0.38), DP (0.38)). Basically, the stress-strain curves are divided into three distinct zones including: (1) elastic deformation, in which stress increases linearly with strain until the first maximum compressive strength is reached, (2) plateau stress, in which the stress changes slightly and fluctuates around an average value corresponding to the type of the foams' structure, and (3) densification region, where the cell walls come in contact with each other and a sharp increase in the value of stress relative to the strain is observable. The first local peak in the stress-strain curve is considered as the maximum value of compressive stress. The plateau stress is one of the most important parts of stress-strain curves, where the average of the maximum compressive strength and the densification stress, regarded as the mean plateau stress. It has a notable effect on energy absorption ability of the foams structure. Regarding Fig. 5, it can be seen that the first maximum compressive strength for the sample DP (14.067 MPa) is higher than what obtained for SP (13.297 MPa) sample. Regarding Fig. 5, it can be seen that different plateau areas can be recognized in the second zone of stress-strain curve for the foams with different green body forming methods. It can be noticed that plateau stress for the DP sample began and continued above the plateau region for the SP (0.38) sample. Accordingly, as shown in Fig. 5, the stress in the plateau region for the SP foam sample decreases with increasing strain and shows sharp fluctuations in the plateau region, while for the DP sample the change in stress with increasing strain is relatively slow and a nearly flat plateau region is recorded. This deformation behavior causes the recording of higher values for the mean plateau stress for the DP sample. The mean plateau stress of different foam samples is reported in Table 2. The main reason for the difference in plateau stress and maximum compressive strength is related to the applied green body forming method. Regarding both applied methods (single and double pressing methods), there is a gradient in the applied compaction pressure due to the die wall friction. As shown in Fig. 6, an axial density gradient is created along the green compact, and in the case of single action die pressing method, the bottom region becomes relatively weaker. To reduce the effect of die wall friction, that cause a non-uniformity in the applied pressure and weakness in the green body formation stage, the double pressing method has been introduced. By using this method, as can be seen in Fig. 6,

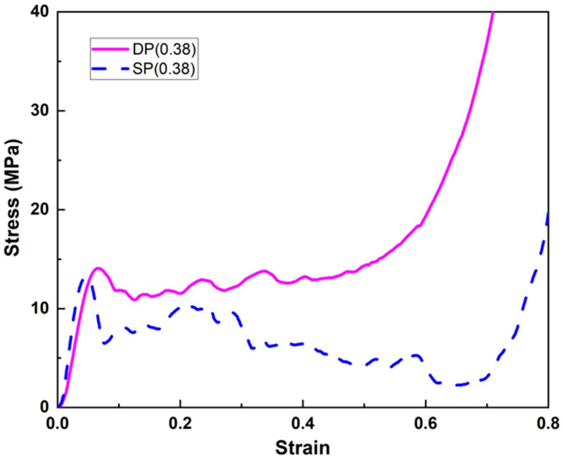

Fig. 5. Compressive stress-strain curve of fabricated foams with 0.38 relative density.

Table 2. The value of maximum compressive strength, highest energy absorption efficiency points, mean plateau stress and dentification strain of the fabricated foams.

Sample	Mean plateau stress (MPa)	Highest energy absorption efficiency point	Densification strain
SP	6.482	0.3808	0.7762
DP	12.68	0.422	0.5206

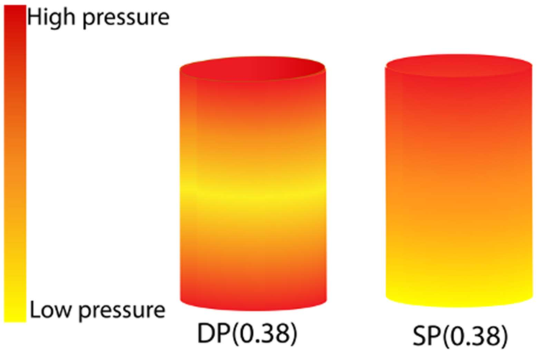

Fig. 6. Schematic of density changes along the samples produced by using two different pressing methods (single (SP) and double action (DP) die pressing).

the region with the lowest density is in the middle part of the sample and is smaller with higher density than the low-density region that is created in the single action method if the same compressing pressure is applied. In other words, green body formation by double action die pressing method results in creating green bodies with more uniformity in density and microstructure. Accordingly, as shown in Fig. 5, higher plateau stress and higher maximum compressive strength was recorded for the foam sample produced by using double action die pressing method. This is consistent with the results reported by other researchers [30- 32].

One of the valuable applications of metal foams is associated with their ability in energy absorption. Energy absorption capacity (W), ideality energy absorption efficiency (I) and energy absorption efficiency (E) are three main features that can be used for evaluation of metallic foam properties. In this research, these parameters were estimated using the following equations [28, 33];

$$W = \int_0^{\varepsilon} \sigma \, d\varepsilon \tag{1}$$

$$E = \frac{\int_0^{\varepsilon} \sigma \, d\varepsilon}{\sigma} \tag{2}$$

$$I = \frac{\int_0^{\varepsilon} \sigma \, d\varepsilon}{\sigma \ \varepsilon} \tag{3}$$

The energy absorption capacity of the fabricated foams was determined by calculating the area under stress-strain curve up to the densification strain according to Eq. (1) in which, σ and ε are the stress and strain, respectively. Densification strain (ε_d) was calculated using energy absorption efficiency-strain curve, where the maximum point is considered as the densification strain, according to Eq. (4). This method is in line with the method recommend by Miltz and Ramon [34].

$$dE/d\varepsilon = 0 \tag{4}$$

Fig. 7 shows energy absorption efficiency of the foam samples as a function of strain. Densification strain for the two different foam samples were obtained by information presented in this figure, and are illustrated in Table 2. The estimated densification strains were used for calculating the total energy absorption capacities of the foam samples according to Eq. (1). As shown in Fig. 7, in both cases, the energy absorption efficiency increases by increasing the strain, and after reaching a maximum value, it decreases. This is a usual trend that has also been reported by other researchers [35]. As can be seen in Fig. 7 and Table 2, the highest energy absorption efficiency is higher for the foam fabricated when using the double action die pressing method, the one that has lesser changes in the plateau region, and is nearly horizontal. This result is in line with the result reported by other researchers [36].

The relationship between energy absorption capacity and strain for the fabricated foams is shown in Fig. 8. As

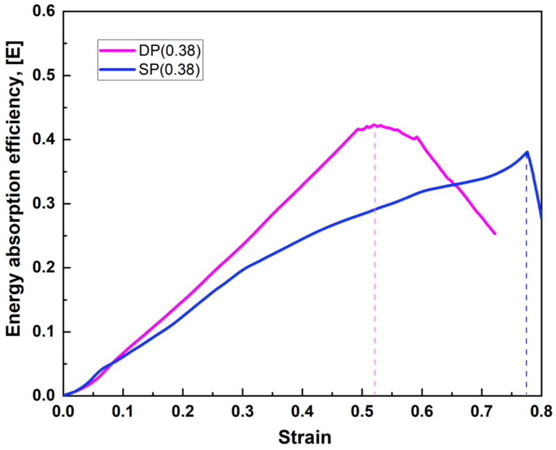

Fig. 7. Energy absorption efficiency of fabricated foams with two pressing methods and with 0.38 relative density.

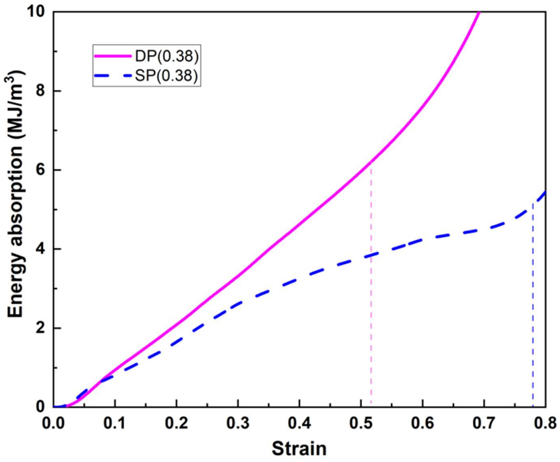

Fig. 8. Energy absorption versus strain curves for the SP and DP foams with the same relative density of 0.38.

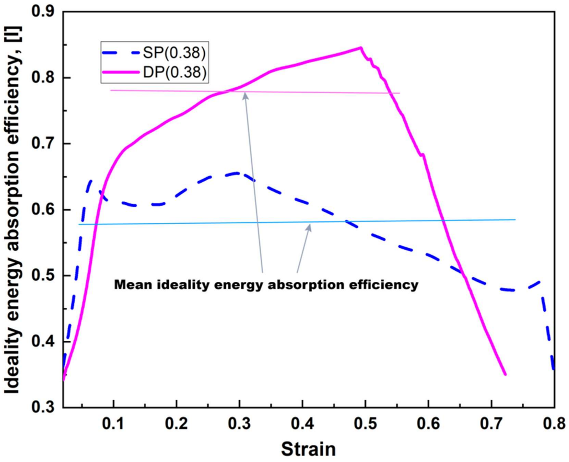

Fig. 9. Ideality energy absorption efficiency versus strain curves for the SP and DP foams with the same relative density of 0.38.

is apparent, the energy absorption capacity in both cases increases by increasing the strain. Furthermore, the total energy absorption capacity, which directly depends on plateau stress, is higher for the sample produced by double action pressing method, because of its higher plateau stress. In addition, as shown in Fig. 8, the slope of increasing in energy absorption capacity for the evaluated samples are different and is higher for the sample produced by double action method. Regarding the graphs presented in Fig. 8, it can be also seen that for the DP foam, energy absorption capacity versus strain is relatively linear causing it to become closer to the ideal foams' behavior in which the plateau area is horizontal [35]. Based on the data presented in Fig. 8, the increase in total energy absorption capacity caused by using the double action die pressing method instead of single action method in preparing green body is about 24%.

As previously mentioned, the ideality energy absorption efficiency is calculated according to Eq. (3). This parameter indicates the ratio of the absorption energy by a real metal foam to the absorption energy by an ideal metal foam when they are compressed up to a specified strain and stress. Fig. 9 shows the change in ideality energy absorption efficiency as a function of strain for both metal foams fabricated in this study. It is readily apparent that in all cases ideality energy absorption efficiency consists of three stages: (1) sharp increasing region (2) stable region, where the ideality energy absorption efficiency changes slightly and fluctuates around an average value [37, 38] and (3) attenuating region. The mean ideality energy absorption efficiency in stable region is 0.78 and 0.579 for the DP and SP foam samples, respectively. It means that, fabricated foam by double action die pressing method behaves closer to an ideal metallic foam due to its more homogenous structure.

Fig. 10 shows the energy absorption of the fabricated foams as a function of applied stress up to the densification stress. It can be recognized that, even though energy absorption capacity is defined as the area under the stress-strain curve up to densification stress, it continues after this value, although at stress levels higher than densification stress, the foam structure collapses and it begins to densify. As shown in Fig. 10, it can be

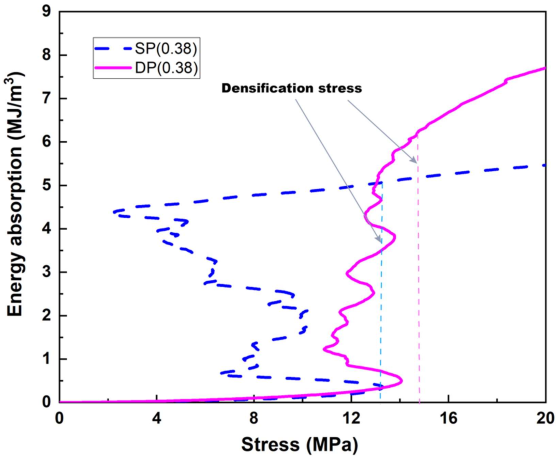

Fig. 10. Energy absorption versus applied stress of the SP and DP foams with the same relative density of 0.38.

noticed that at stress levels lower than 2.258 MPa, the energy absorption by both fabricated foams is very low and is in the same range, which can be contributed to the elastic deformation zone of stress-strain curve for these foams. However, it can be seen that, for the stress levels in the range of 2.258 to 13.059 MPa, SP sample shows higher energy absorption than the DP sample. This behavior is because of the fact that the mean plateau stress for the DP sample is extended in lower stress level in comparison with the other fabricated foam. This trend is reversed as the stress level exceeds 13.059 MPa, which is due to the wide plateau area created by the DP foam sample in this range of applied stress. Furthermore, as it is crystal clear, the DP sample absorbs energy in a wider range of stresses than the other sample, and its energy absorption is extended up to its densification stress of 14.74 MPa.

4. Conclusion

In the present study, aluminum foams were fabricated via powder metallurgy route by using carbamide, as space holder and using two different die pressing methods of single and double actions. It was shown that the pressing method used for producing green bodies has a very important effect on the compressive behavior of the fabricated foams. In this study, it was proved that by adopting double action die pressing method instead of single action die pressing method, it would be possible to nearly overcome the effect of die wall friction and creates green compacts with more uniform density. The foam fabricated by double action die pressing method shows a nearly 95% higher plateau stress and also around 24% higher ability in energy absorption than that of the foam fabricated by single action die pressing method and with the same relative density.

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