INSTRUMENTED SPHERICAL INDENTATION BEHAVIOR OF MECHANICAL PROPERTIES OF METALLIC FOAMS: CHARACTERIZATION

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Abstract

Instrumented indentation test have been widely used to characterize inelastic and elastic properties of metals. In this study the spherical indentation tests with a spherical indenter of 5 mm radius were used. The inelastic behaviour of metallic foam was considered as an isotropic crushable foam constitutive model of Deshpande and Fleck which has been shown experimentally that their model can be applied to aluminum foams. The spherical indentation test was modeled by finite element method. A 2D axisymmetric model was developed. Practically, the size of the indenter tip should be reasonably large compared to the size of the cells/pores in the specimen and the indentation depth should also be reasonably large so that the indentation response does reflect the averaged material behaviours, which are described by the aforementioned constitutive model. The applied load on the indenter versus its displacement was obtained under different metallic foam mechanical properties. Numerical results from the finite element simulations are used to obtain the dependence of the indentation response on the metallic foam material parameters which characterizes the plastic deformation of metallic foams. The stress – strain curves and the Elastic modulus of different foams are obtained by the indentation curve, which is obtained by FEM.

1. Introduction

Metallic foams of different alloys of aluminum, zinc, Nickel and iron are through a number of processing techniques. Their properties such as high heat resistance, good sound and energy absorption capacity, high strength-to-weight ratios and low production cost relative to other lightweight foams, as well, through brazing or adhesive bonding, thin face sheets of dense material can be applied to foamed metal cores, making them a viable candidate for sandwich panel construction [1]. Inelastic deformation of metallic foams has been investigated by some of researchers and different pressure sensitive yield surface were proposed. One of the first studies about the strength of the isotropic foams was carried out by Gibson and Ashby [2]. They proposed that hydrostatic strength is related to the relative density of the metallic foams. Since the metallic foams plastic flow is pressure dependent, Fleck et al. [3] presented a yield surface metallic powders which is a combination von-Mises criteria and hydrostatic stress. In 2000, Miller [4] modified the Prager-Drucker pressure dependent based on plastic compressibility parameter of υ_{pl}. Deshpande and Fleck [5] gave two models to describe the yield surface of the metallic foams. The 1st model is a self-similar model which defines an elliptic surface in von-Mises equivalent – mean stress space. The 2nd model is not a self-similar model and is based on the deviatoric and hydrostatic stresses. Other researchers developed new models by using the Deshpande and Fleck model such as Badiche et al. [6]. Work hardening is also modeled by different isotropic hardening models such as the models of Deshpande and Fleck [5],

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Badiche et al. [6] and Dillard et al. [7]. Isotropic hardening model will be explained in the next section.
Mechanical properties characterization of these metallic foams is an essential point in their design. One of the nondestructive tests, which have been shown its capability to deduce the mechanical properties of the solid materials, is the instrumented indentation test. Indentation has been widely used to study the mechanical behaviour of different metals, polymers and composites. Mechanical properties such as hardness, yield strength, stress-strain curve, fracture properties etc. were characterized by the indentation method. For the first time, Tabor [8] showed a direct relation between indentation diameter and average applied strain, average pressure and corresponding stress. A great number of papers concern the determination of mechanical properties of homogeneous materials. In this case, the determination of the stress - strain curve from the indentation curve can be done by using the minimization between indentation experiments and models of instrumented indentation obtained by numerical simulations [9-15]. The main advantages of this approach are the simplicity of implementation and the instant results.
In this study, the metallic foam is considered under spherical indentation test. The yield surface and the isotropic hardening models of Deshpande and Fleck [5] are used to model the inelastic behaviour of the studied metallic foams. Load – displacement curves of the indentation tests are obtained by finite element modeling under different plastic properties. Elastic modulus and the stress- plastic strain are characterized by simple proposed relations.

2. Material Model and Parameters

Metallic foams have elastic and inelastic behaviour. In elastic domain, they have a linear elastic behaviour and it can be modeled by the Hooke law as:

$$\boldsymbol{\sigma}=\boldsymbol{C}:\boldsymbol{\varepsilon}^{el} \tag{1}$$

where $\boldsymbol{C}$ represents the elastic constants tensor. $\boldsymbol{\varepsilon}^{el}$ is the elastic strain tensor. **:** represents the tensor product as: $\boldsymbol{A}:\boldsymbol{B}=A_{ij}B_{ij}$. In order to model the plastic flow of metallic foams, the model of Deshpande and Fleck [2] is considered.
Isotropic hardening is considered for the crushable foam which uses a yield surface with an elliptical dependence of the equivalent stress and the hydrostatic stress.

$$\left\{\frac{1}{1+\left(\alpha/3\right)^2}\left(\sigma_e^2+\alpha^2\sigma_m^2\right)^{1/2}\right\}^{1/2}-\sigma_y=0 \tag{2}$$

where $\sigma_e=\sqrt{\frac{3}{2}\left(\sigma':\sigma'\right)}$, $\sigma_m=p=\frac{1}{3}tr(\boldsymbol{\sigma})$ and $\sigma'=\sigma-\frac{1}{3}tr\left(\sigma\right)\mathrm{I}=\sigma-\sigma_m\mathrm{I}$ are the equivalent von-Mises stress, the hydrostatic stress and the deviatoric stress, respectively. α is the shape factor and is defined as:

$$\alpha=\frac{3k}{\sqrt{9-k^2}} \tag{3}$$

where $k=\frac{\sigma_c^0}{p_c^0}$. σ_c^0 and p_c^0 are the compression uniaxial yield stress and hydrostatic yield stress, respectively. As the non-associated flow rule is considered here. Deshpande and Fleck [2] defined a potential function as:

$$G=\sqrt{\left(\sigma_e^2+\beta^2\sigma_m^2\right)} \tag{4}$$

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and

$$\beta = \frac{3}{\sqrt{2}}\sqrt{\frac{1-2\upsilon_p}{1+\upsilon_p}} \tag{5}$$

β is defined as a shape function. υ_p is the plastic Poisson's ratio. It is considered constant and depends on the used metallic foam.

3. Finite Element Modeling

The axisymmetric nature of the problem is considered in the FEM simulation. Modeling of the indentation of a half-space using a spherical indenter with a high elastic modulus is performed. The force–displacement relation for the indentation is obtained by using the axisymmetric and large strain elastoplastic feature with the model Deshpande and Fleck [5]. Materials with various yield and hardening parameters are studied. The quasi-static nature of the process allows using the static analysis performed by the program. The boundary conditions are given as follows:

$$\sigma_z = 0 \text{ and } \tau_{rz} = 0 \rightarrow r > a \tag{6}$$

where a is the contact radius. The displacements are cancelled far from the indentation zone:

$$u_r = u_z = 0 \text{ where } r, z \rightarrow \infty \tag{7}$$

(6)

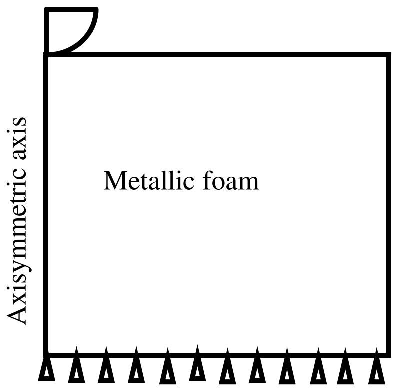

Figure 1. Used boundary conditions in the modeling of the indentation.

The bottom of the model is constrained in the axial directions. A finite element mesh of the half-space is given in Fig. 1. The program was used with 14160 linear quadrilateral elements and 14399 nodes. Other smoothness meshes were tested. The conclusion was that the results were identical.

4. Elastic Modulus Characterization of Metallic Foams

The load – displacement curve (F-δ) of indentation tests consists of two parts: Loading and Unloading (Fig. 2). It was shown that the slope of the first one-third of the unloading curve of the indentation tests, S, is related to Young modulus for solid metals as [16]:

$$S = \frac{dF}{d\delta} = C_1 E_r \sqrt{A} \tag{8}$$

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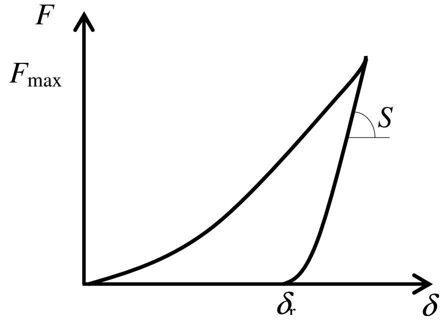

Figure 2. Schematic load – displacement curve of an instrumented indentation test.

where E_r is the reduced modulus and A is the projected contact area. C_1 is a constant which depends on the indenter geometry. In order to investigate this phenomenon for the metallic foams, the indentation of different metallic foams with different Young modulus is modeled by Finite element method. It was shown by Gibson and Ashby [17, 18] that the Young modulus of the metallic foams is related to the Young modulus of solid materials by the density ratio of solid and foam materials as:

$$E_f = E_s\left[1-\left(1-\left(\frac{\rho_f}{\rho_s}\right)^2\right)\right] \tag{9}$$

E_f and E_s are the Young modulus of the metallic foam and the solid materials, respectively. Density of the metallic foam and the solid material are represented by ρ_f and ρ_s, respectively. Density ratio is varied between 0.05 to 0.2 and the Young modulus is determined by Eq. 9. Finite element simulations are carried out and the slope of the unloading curve is determined. Young modulus is characterized by using Eq. 8 while C_1=645. Fig. 3 gives the determined Young modulus of metallic materials characterized by indentation compared by the known elastic modulus. As it can be seen a good correlation is obtained for a wide range of the density ratio.

Fig. 3 shows the capability of the indentation method to characterize Elastic modulus of metallic foams. Since the indentation is a non-destructive test, these results are promising to use this method for metallic foams.

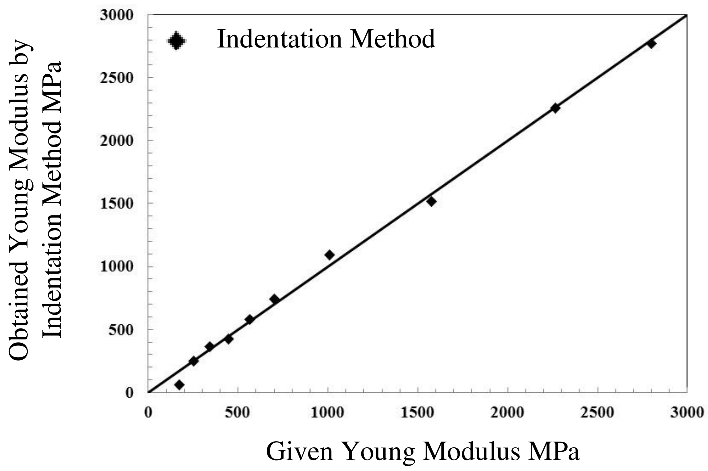

Figure 3. Comparison of the Young modulus obtained by the Indentation method and the given value in finite element simulations.

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5. Stress – Strain Characterization of Metallic Foams

Stress – strain behaviour of the metallic foams under compression test has been represented in Fig. 4, schematically. After elastic deformation till the yield stress, σ^f_y, there is a plateau for stress, which continues till ε_1. Then the stress increases rapidly.

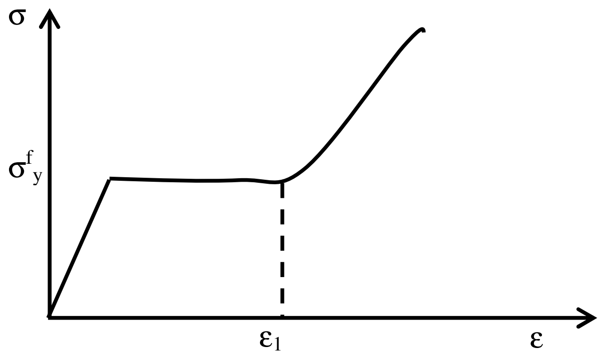

Figure 4. Schematic stress – strain evolution of metallic foams under compression test.

It was shown that the yield stress of the metallic foams, σ^f_y, is dependent on the density ratio and the solid material yield stress σ^s_y. Its relation with respect to the yield stress of solid metal is given by [2]:

$$\frac{\sigma^f_y}{\sigma^s_y} = A_2\left(\frac{\rho_f}{\rho_s}\right)^n + A_3\left(\frac{\rho_f}{\rho_s}\right) \quad (10)$$

The constants of A_2 and A_3 are 0.33 and 0.44, respectively. The end of stress plateau, ε_1, can be determined as [18]:

$$\varepsilon_1 = A_4 - A_5\left(\frac{\rho_f}{\rho_s}\right) \quad (11)$$

where A_4 and A_5 are material constants. They are 0.5 and 1.8 for ALPORAS and 0.407 and 1.44 for ALULIGHT, respectively.

Different density ratio for ALPORAS and ALULIGHT metallic foams are considered and their stress – strain curves are determined by Eqs. (10) and (11). FEM simulations are carried out by using the stress-strain curves. The used material properties are given in Tables 1 and 2.

Table 1. ALPORAS material properties.

ρ_f/ρ_s	E	σ_y	ε_y	A_4	A_5	n
0.1	700 MPa	1.844189 MPa	0.002634	0.495	1.8	6.95/2
0.0926	600.233 MPa	1.7053584 MPa	0.00284	0.495	1.8	6.95/2
0.0814	463.81 MPa	1.491918 MPa	0.00321	0.495	1.8	6.95/2
0.074	383.32 MPa	1.36559 MPa	0.00356	0.495	1.8	6.95/2

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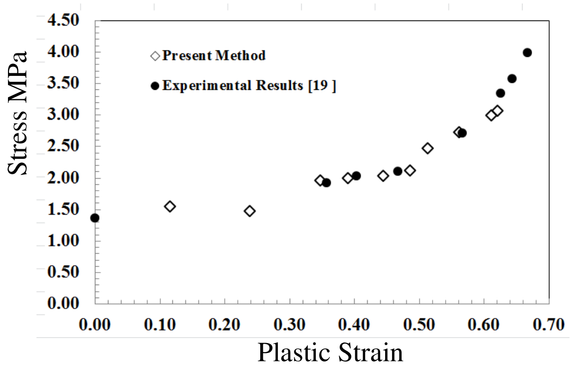
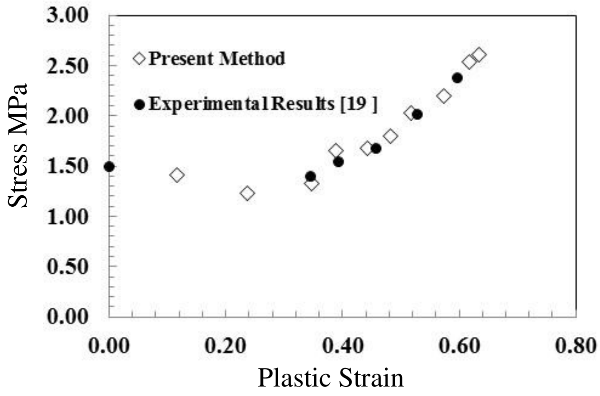
Table 2. ALULIGHT material properties.

ρ_f/ρ_s	E	σ_y	ε_y	A_4	A_5	n
0.1259	1110 MPa	2.23074 MPa	0.002	0.407	1.44	4
0.2111	3120 MPa	3.74336 MPa	0.0012	0.407	1.44	4

It was shown by Tabor [8] that the ratio δ/D is proportional to the strain induced by the indentation. And. F/A is proportional to the stress. δ is the indenter displacement, D is indenter diameter. F and A are the applied load and the projected area of the contact, respectively. In the present research, $\varepsilon_r=A_6\,\delta/D$ is considered as the representative strain and the $\sigma_r=A_7F/A$ is the corresponding stress. The variation of ε_r versus σ_r is traced for different ALPORAS and ALULIGHT with different density ratio. The comparison between the experimental stress – strain curves obtained by the compression test and the indentation test are given in Figs. 5a to 5d for ALPORAS metallic foam and Figs. 6a and b for ALULIGHTS foams. The constants A_6 and A_7 are 1.5 and 0.85, respectively. As it can be seen the plateau and the densification parts of the stress – strain curves of the metallic foams are well compared by the new present method.



(a)



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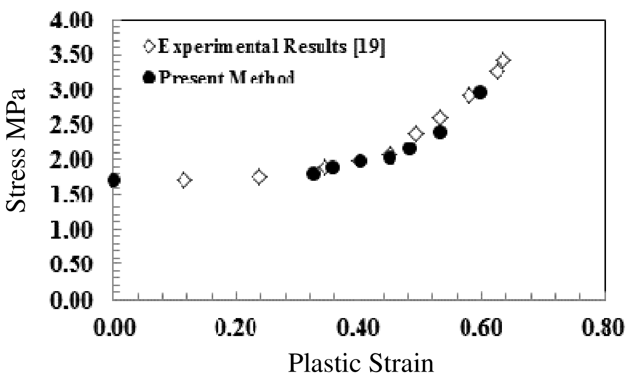

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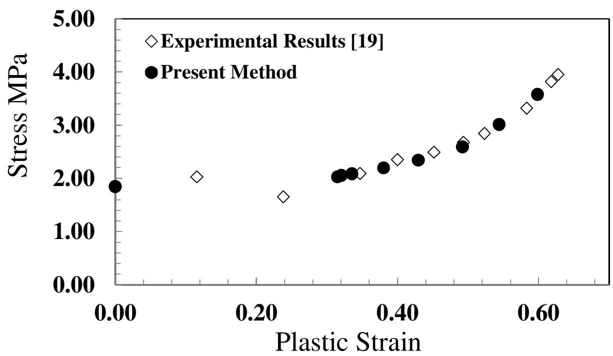

(d)

Figure 5. Comparison of the stress – strain curve of the ALPORAS metallic foam for the density ration of a) 0.074, b) 0.0814, c) 0.0926 and d) 0.1.

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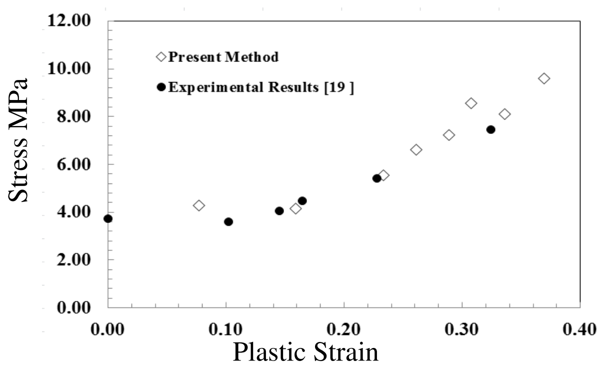
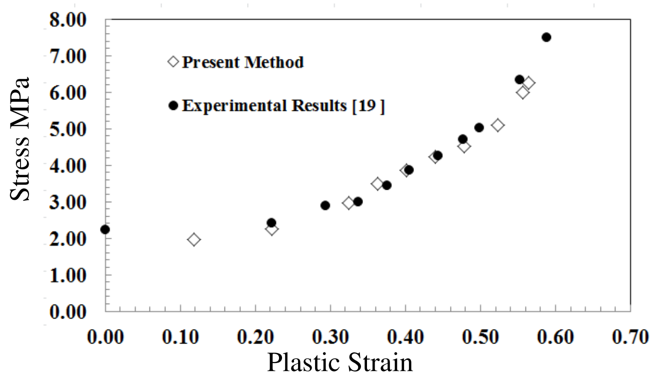


(a)



(b)

Figure 6. Comparison of the stress – strain curve of the ALULIGHT metallic foam for the density ration of a) 0.1259, b) 0.211.

6. Conclusion

Instrumented indentation test is widely used to characterize different mechanical properties of solid metals. Hardness, elastic modulus and stress-strain curve of metals were determined by indentation. This method is rarely used to characterize metallic foams. In this study, the indentation of metallic foams with different density ratio is modeled by finite element method. Simple relations are proposed to characterize the elastic modulus and the stress – plastic strain curve of aluminum foams of ALPORAS and ALULIGHT. The obtained results are compared with given elastic modulus and the stress – plastic strain curves and good comparison is obtained.

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