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Finite Element Investigation of Mechanical Behavior of Rhombic Dodecahedron Micro-structures under Static Loading

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Abstract
In this paper, the structures constructed and tested by Yavari et al [8] was investigated numerically using ANSYS (for the elastic properties), and LS-DYNA (for the yielding behavior) finite element codes. In their work, rhombic dodecahedron interconnected cells were created using SLM method. The results showed that considering irregularity in cross-section of the structure struts decreases both the yielding stress and densification strain. Also, both the values obtained for the irregular structure are closer to the experimental results. Another conclusion was that the both the plateau stress and densification strain of the FEM solution are higher than the experimental values. This can be attributed to lower amount of damage considered in the modeled struts. The results also showed that the plateau stress decreases by increasing the porosity. By increasing the porosity of the structure, the densification strain first increases but then decreases.

Keywords: Rhombic dodecahedron, Micro-structure, Selective Laser Melting, Implant

Introduction

Currently pure Ti and Ti6Al4V alloys are widely used for loadbearing metal implants because of their exceptionally good corrosion resistance and excellent biocompatibility. However, these materials have significantly higher stiffness than natural cortical bone. Although the durability of Ti-based total hip replacement (THR) is quite good, some implants still fail as a result of instability and aseptic loosening of the implant, which arises due to: (i) weak interfacial bond between implant surface and living tissue, (ii) stress-shielding and (iii) wear-induced osteolysis [1].

Several manufacturing techniques exist for production of porous metals [2] including the space holder technology [3] and additive manufacturing techniques [4]. The main advantage of additive manufacturing techniques as compared to other techniques is their ability to manufacture interconnected porous biomaterials with predictable and pre-determined unit cells. Selective laser melting [5] and selective electron beam melting [4] are among the methods that are used for production of porous metallic biomaterials [6].

Different designs have been proposed and investigated for being used in construction of SLM made bio-structures. Parthasarathy et al [7] produced seven cubic samples of porous titanium using selective electron beam melting. The materials were produced using cube unit cells. The cross-section of struts was square. They showed that strength of the lattice structure depend on the geometrical dimensions of the solid struts apart from the overall porosity values. Their mechanical strength studies indicated the fabricated structures with porosities as high as 50% to 70% satisfy the mechanical strength requirements needed for craniofacial applications.

Campoli [6] presented finite element (FE) models that could predict the mechanical properties of porous titanium produced using selective laser melting or selective electron beam melting. The irregularities caused by the manufacturing process including structural variations of the architecture were implemented in the FE models. The predictions of FE models were compared with those of analytical models and are tested against experimental data. It is shown that, as opposed to analytical models, the predictions of FE models are in agreement with experimental observations.

Yavari et al [8] studied the cyclic behavior of porous structures made of Ti6Al4V ELI powder using selective laser melting. Four different porous structures were manufactured with porosities between 68 and 84 % and the fatigue S-N curves of these four porous structures were determined. The normalized fatigue S-N curves of these four structures were found to be very similar.

In this paper, the structures constructed and tested by Yavari et al [8] will be investigated numerically using ANSYS (for the elastic properties), and LS-DYNA (for the yielding behavior) finite element codes. The manufactured structures were regular and in accordance with the designed microarchitecture. In their work, rhombic dodecahedron interconnected cells were created using SLM method. Micro images of the created microstructure are shown in Fig. 1. The manufacturing technique was not perfect and there were some imperfections in the micro-architecture of the structures

(Fig. 1). In particular, it was noted that some struts were significantly weaker than others [8].

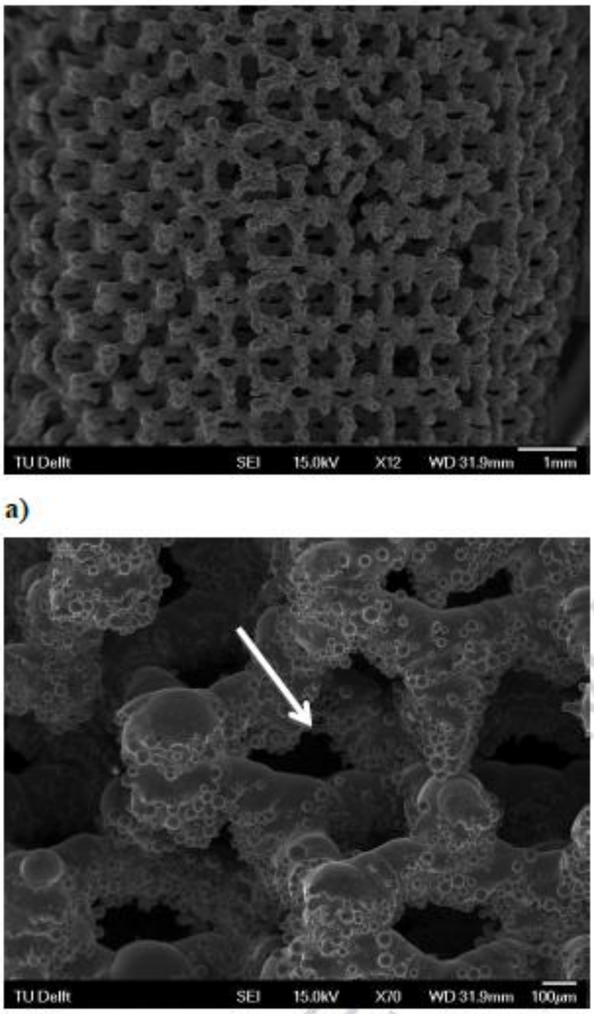


Fig. 1 Micro images of the created microstructure studied [8]

Finite Element Modeling

As already stated, the material considered for the structure was Ti6Al4V ELI. The mechanical properties of this material are listed in Table 1. The geometrical specifications of different sample types are given in Table 2.

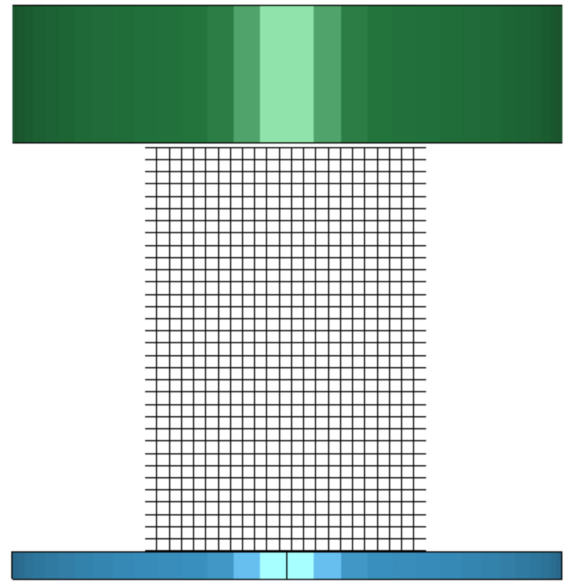
Table 1 Mechanical Properties of Ti6Al4V

Property	Value
Elastic modulus	113.8GPa
Poisson's ratio	0.342
Tangent Modulus	1.25 GPa
Yield stress	1000 MPa
Ultimate tensile strength	1200 MPa

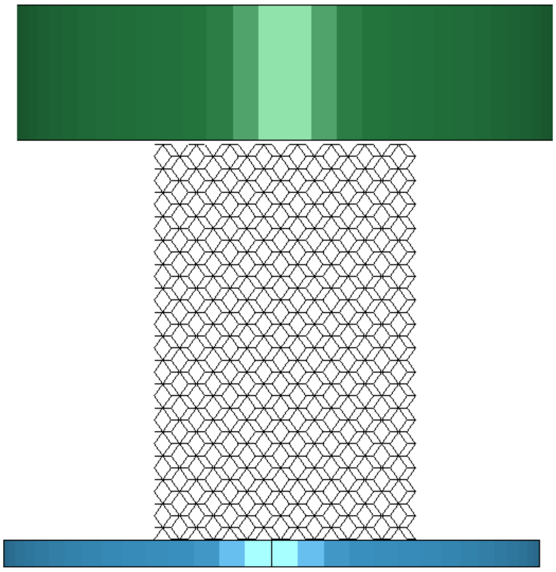
Table 2 Geometrical specifications of the four different samples investigated [8]

	Sample 1 Ti 120-500	**Sample 2 Ti 170-450**	**Sample 3 Ti 170-500**	**Sample 4 Ti 230-500**
Dimension (D×L)	10×15	10×15	10×15	10×15
Pore size (μm)	560±173	486±162	608±182	560±186
Strut size (μm)	140±38	216±64	218±62	251±76
Porosity (%)	84.22	71.2	77.68	68.45

For modeling the elastic model, implicit finite element code ANSYS was used. The finite element model is shown in Fig. 2 from two views. As the actual struts have variations in their diameters, this can be applied to the FE models too by defining several beam elements with different diameters in a strut. Generally, increasing the number of elements along a strut decreases its mechanical properties. Increasing the number of beam elements per strut decreases the overall structure elastic modulus. Anyway it was seen that more than two beam elements per each strut can lead to instabilities in the model under fatigue and yielding loadings. It is because increasing the number of beam elements per strut increases the number of struts having very small cross-sections which will lead to the failure of a large group of struts (catastrophic failure). A simple probability calculation shows that the number of weak struts in a three-element-per-strut structure is much higher than a one-element-per-strut structure. To explain this better, consider the struts having a diameter lower than d_{cr} in a FE lattice structure as weak struts and assume that they constitute 25 percent of a FE structure having one element per strut. Then 75 percent of the struts of this structure are strong. Now a structure with 3 elements per unit has (0.75)*(0.75)*(0.75)=42 % strong elements because all the elements constituting a so-called strong strut must be strong. Anyway this calcultions are not true in a real lattice structure because in real SLM made structure, not "the majority" of the struts have very small cross-sections. In fact, if it is necessary to use more than 1 element per strut, more data than just standard deviation of strut diameter is needed to be known. Therefore in all the models, one beam element will be used per each strut. Anyway different struts of the FE model are considered to have different cross-sections. For the FE structure, 21 different strut diameters was considered and applied.



Front View



Side View

Fig. 2 Finite element model of the Rhombic Dodecahedron micro structure

For modeling yielding of the structure, explicit finite element code LS-DYNA was used. Plastic kinematic material model was used for modeling the mechanical behavior of the metal. Automatic node to surface contact algorithm was used for modeling the interaction between the structure and the grips, while Automatic single surface contact algorithm was used for modeling the contact between the strut elements.

In dynamic problems, the density of the material is of importance. A density of 4420 kg/m3 was considered for Ti6Al4V. The lower grip was fixed and the upper grip was moved with a constant speed of 3 mm/min.

Results

Effect of Irregularity

The deformation of the lattices structure having regular and irregular struts are shown in Figs. 3 and 4. The 45 degree failure pattern can be seen in both structures but more obvious in the regular structure. The stress-strain curves of sample 1 modeled considering regularity and irregularity has been plotted and compared to each other in Fig. 5. Irregularity in cross-section of the struts has decreased both the yielding stressand densification strain. Both the values obtained for the irregular structure are closer to the experimental results (Tables 3 and 4)

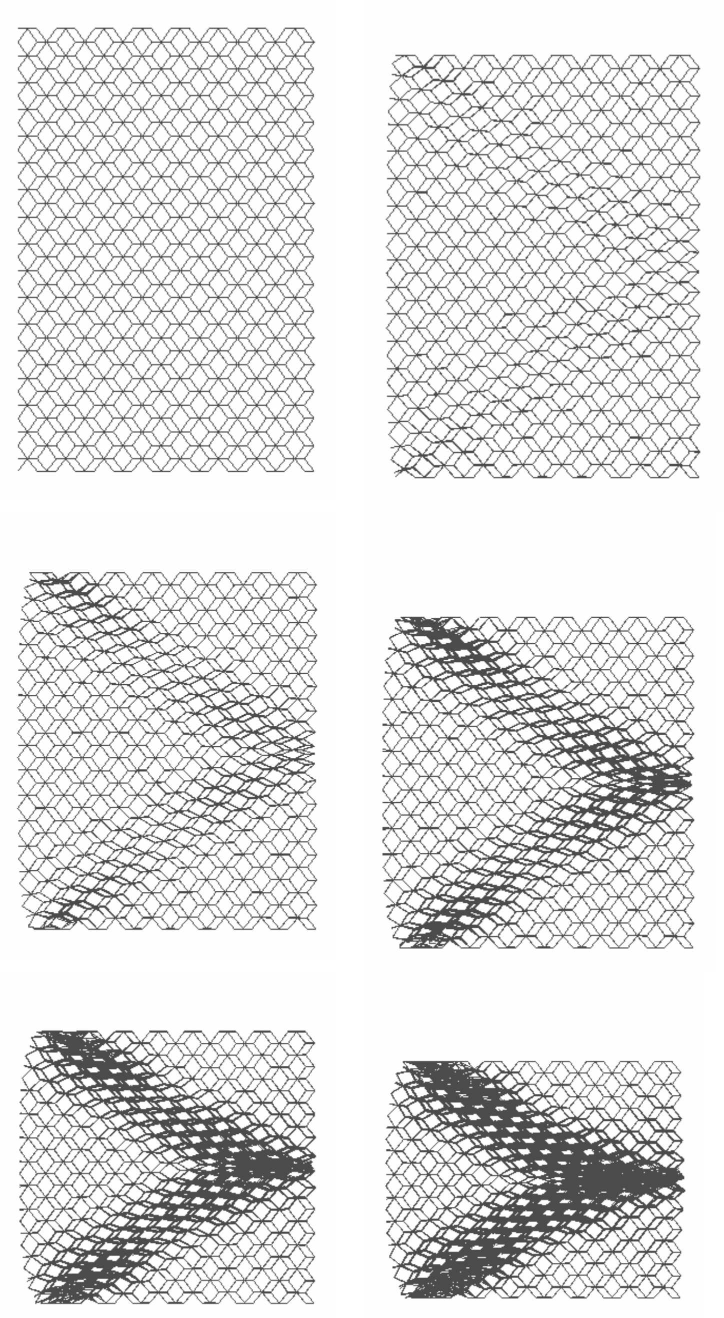


Fig. 3 Deformation of the regular structure

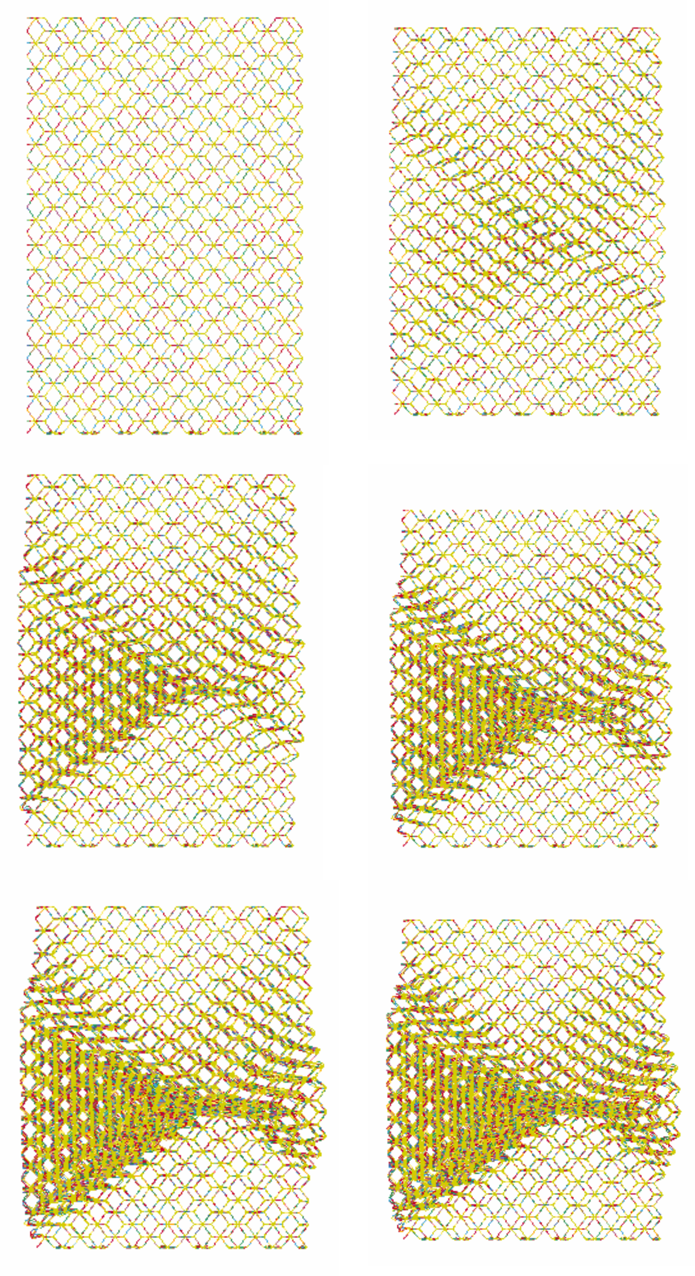


Fig. 4 Deformation of the irregular structure

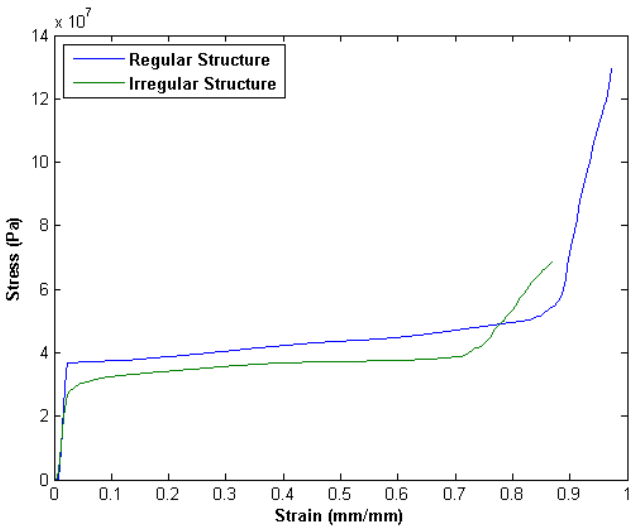


Fig. 5 Comparison of stress-strain curve of the regular and irregular structures

Effect of dimensions of the microstructures

The elastic modulii obtained from theory, our FEM code and experimental tests [8] are listed in Table 3 and compared in Fig. 6. As it can be seen the numerical values obtained are lower than theoretical values due to different cross-section in different struts. Also, the numerical Young modulus is higher than experimental values. This is because the irregularities in each strut have not been considered.

Table 3 Comparison of theoretical, numerical and experimental Young modulii

	Sample 1 Ti 120-500	**Sample 2 Ti 170-450**	**Sample 3 Ti 170-500**	**Sample 4 Ti 230-500**
Theory	621	5241	2412	5324
FEM	584	3155	2195	4598
Experiment [8]	550	2620	1400	3490

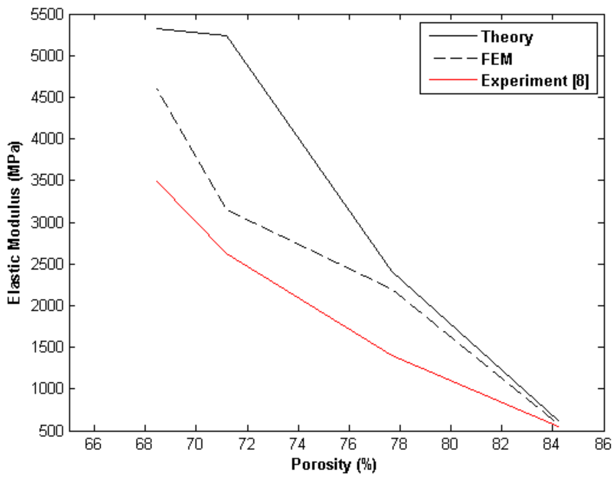


Fig. 6 Comparison of elastic modulii obtained from theory, our FEM code and experimental tests [8]

The stress-strain curves of the four samples are shown in Fig. 7. The plateau stress and densification strain of the numerical model and the experimental tests are compared in Table 4 and Figs. 8 (a-b). As it can be seen in Fig. 8 (a-b), the experimental and numerical results are relatively in good accordance. Both the plateau stress and densification strain of the FEM solution are higher than the experimental values. This can be attributed to lower amount of damage considered in the modeled struts. Both the numerical end experimental results show that the plateau stress decreases by increasing the porosity (Fig 8(b)). By increasing the porosity of the structure, the densification strain first increases but then decreases.

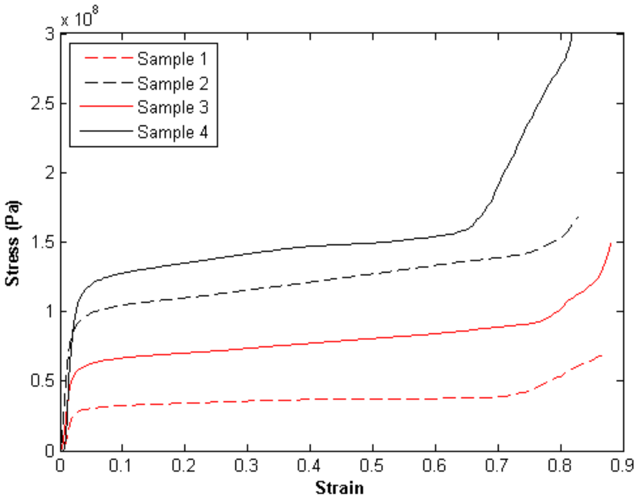
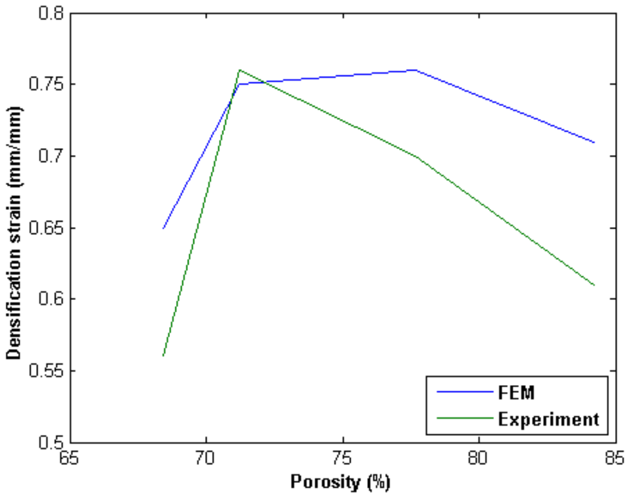
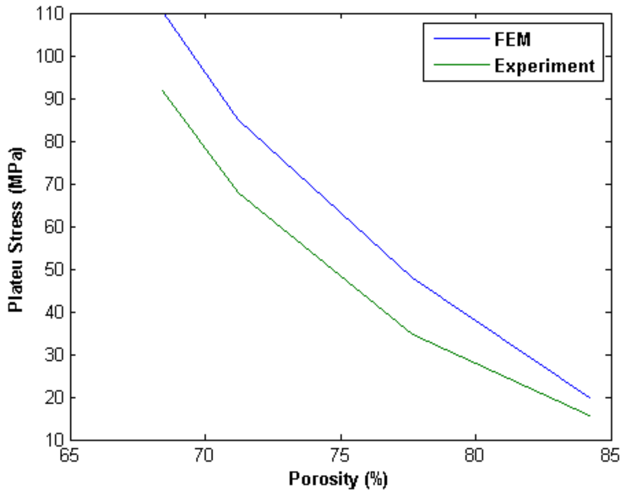


Fig. 7 Stress-strain curves for the four samples



(a)



(b)

Fig. 8 Variation of (a) densification strain, and (b) plateau stress with respect to porosity

Table 4: Comparison of plateau stress and densification strain of the numerical model and the experimental tests

	Sample 1 **Ti 120-500**	**Sample 2** **Ti 170-450**	**Sample 3** **Ti 170-500**	**Sample 4** **Ti 230-500**
ε_d **(FEM)**	0.71	0.75	0.76	0.65
ε_d **(Experiment)**	0.61	0.76	0.7	0.56
σ_p **(FEM)**	20 MPa	85 MPa	48 MPa	110 MPa
σ_p **(Experiment)**	15.8 MPa	67.8 MPa	34.8 MPa	91.8 MPa

Conclusions

In this paper, the structures constructed and tested by Yavari et al [8] was investigated numerically using ANSYS (for the elastic properties), and LS-DYNA (for the yielding behavior) finite element codes. In their work, rhombic dodecahedron interconnected cells were created using SLM method. The results showed that considering irregularity in cross-section of the structure struts decreases both the yielding stress and densification strain. Also, both the values obtained for the irregular structure are closer to the experimental results. Another conclusion was that the both the plateau stress and densification strain of the FEM solution are higher than the experimental values. This can be attributed to lower amount of damage considered in the modeled struts. The results also showed that the plateau stress decreases by increasing the porosity. By increasing the porosity of the structure, the densification strain first increases but then decreases.

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