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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THE MECHANICAL BEHAVIOR OF THE MODIFIED METAL AUXETIC STRUCTURE

Erkan ÖZKAN[1], Farshid KHOSRAVİ [2*]

[1]*School of Graduate Studies, Bartın University, Bartın, Türkiye*
[2]*Department of Mechanical Engineering, Faculty of Engineering, Architecture and Design, Bartın University, Bartın, Türkiye*

Abstract

Humans have always sought the optimal use of materials around them and, in this field, inspired by nature, have succeeded in inventing various structures. As one example, lattice structures, which are lightweight, strong, and stiff, are used widely in various applications, including energy absorbers. Lattice structures with a negative Poisson's ratio have been developed as a new type of lattice structure. As a result of this feature, auxetic structures have unique properties like shear strength, penetration resistance, fracture toughness, crack resistance, and high energy absorbability. In this paper, the mechanical behavior of the auxetic panels made using the 3D metal printer method is investigated by experimental tests and finite element methods. Experiments are used to verify the accuracy of the numerical model. Using the DMLS method, samples were prepared from metal based AlS10Mg Aluminum composition. The 3D printing method was used to fabricate samples. Afterwards, experimental tests were made, and the mechanical properties of these materials were determined by tensile test and used in finite element simulations. Following the confirmation of the model's accuracy, the finite element simulation results are used to perform a parametric study and determine the appropriate geometry. The numerical analysis is conducted using ABAQUS software, which uses the nonlinear finite element method.

Key Words: Auxetic Structures, Tensile Test, 3D Printer.

Sorumlu Yazar: Farshid KHOSRAVİ, fmaleki@bartin.edu.tr; farshid.khosravi09@gmail.com

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MODİFİYE EDİLMIŞ METAL AUXETIC YAPININ MEKANİK DAVRANIŞININ DENEYSEL VE SAYISAL OLARAK İNCELENMESİ

Öz

İnsanlar geçmişten günümüze etraflarındaki malzemeleri en iyi şekilde kullanmak için yollar aramışlar ve bu alanda doğadan esinlenerek çeşitli yapılar ortaya çıkarmışlardır. Bunlardan birisi, ağırlıkları düşük, basınç dayanımı yüksek ve sert olmaları nedeniyle enerji emiciler dâhil olmak üzere çeşitli uygulamalarda yaygın olarak kullanılan kafes yapılardır. Yeni bir kafes yapı tipi olan auxetic yapılar, geometrik yapılarından dolayı negatif Poisson oranına sahiptirler ve bu özelliği nedeniyle, kayma mukavemeti, penetrasyon direnci, artan kırılma tokluğu ve çatlama ve yüksek enerjiye karşı direnç gibi özelliklere sahiptir. Bu makalede, 3B metal yazıcı yöntemi kullanılarak yapılan auxetic panellerin mekanik davranışı, sonlu elemanlar yöntemi ile ve deneysel olarak incelenmiştir. Nümerik modelin sonuçlarının doğruluğu, deneysel testlerin sonuçları kullanılarak kontrol edilmiştir. Bu amaçla DMLS yöntemi ile metal esaslı AlS10Mg Alüminyum bileşiminden numuneler yapılmıştır. Numuneleri üretmek için 3B baskı yöntemi kullanılmıştır. Daha sonra deneysel testler yapılarak bu malzemelerin mekanik özellikleri çekme testi ile belirlenmiş ve sonlu eleman simülasyonlarında kullanılmıştır. Modelin uygunluğu belirlendikten sonra, parametrik bir çalışma ile uygun geometriyi belirlemek için sonlu elemanlar simülasyon sonuçları kullanılmıştır. Sayısal çalışma için, ABAQUS yazılımı kullanılmış olup modellemede doğrusal olmayan sonlu elemanlar yöntemi kullanılmıştır.

Anahtar Kelimeler: Auxetic Yapılar, Çekme Testi, 3B Yazıcı

1. INTRODUCTION

Auxetic is derived from the Greek word auxetikos. Auxetic cellular structure has a negative Poisson's ratio. So, it elongates when exposed to tension and shortens in compression. Auxetic materials take interests due to their potential applications in various fields such as prostheses [1], piezoelectric sensors [2], energy absorption, indentation, and fatigue resistance [3-5], magnetic auxetic system [6], molecular sieves [7], seat cushions [8], superior vibration dampers [9] and acoustic insulators [10].

In the 1900s, Voigt et al. [11] discovered the properties of auxetic or negative Poisson's ratio in some materials. In 1987, Lakes [12] first introduced a foam structure with auxetic properties that

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could be easily fabricated using the triaxial compression and heating process. His study showed that human-made auxetic materials are available, so after that, more scientists began to study auxetic materials. With the development of auxetic materials, these materials have gone beyond the range of isotropic materials and macro scales. They have spread to both isotropic and anisotropic materials and from macro to nanoscales. The growth and development of auxetic materials have been very rapid in recent years and many auxetic materials have been suggested. The unique properties of auxetic materials make them suitable for use in various fields, including personal protection, military applications, medicine, and applications in the textile and aerospace industries. Although many applications for these materials have been recommended, the actual applications of auxetic materials are still in the early stages of development, so efforts should be made to improve and develop functional auxetic materials. Auxetic materials have unique properties compared to conventional materials, such as decreasing.

Young's modulus, increasing shear modulus, increasing impact resistance, increasing fracture toughness and crack resistance, and increasing energy absorption. Zhang et al. [13], in a review study, examined studies of large deformations and energy absorption of auxetic materials. Meena and Singamneni [14] proposed a new auxetic structure to reduce the effects of stress concentration. Considering the production constraints, they proposed structures with S-shaped geometry and studied the performance of the proposed structure using the finite element method and experimental tests. Ren et al. [15] studied the behavior of cylindrical auxetic structures under tensile loading. Their study shows that if the structure's geometric parameters are appropriately selected, the mechanical properties can be significantly improved. Hassanin et al. [16] investigated the penetration resistance of auxetic structures made of shape memory materials. Guo et al. [17] numerically studied the mechanical behavior of auxetic cylindrical structures under axial loading. Their study shows that the energy absorption capacity of these structures is mainly dependent on the deformation modes and relative density, and the performance of auxetic cylinders against axial loading has been significantly improved compared to conventional cylinders. Nedoushan [18] studied the effect of size and cross-section of metal-shaped cylindrical structures with negative Poisson's ratio on their energy absorption characteristics experimentally and numerically. His study showed that the use of structures with negative Poisson's ratio with

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small cell size has more axial stability. Peixinho et al. [19] studied the compressive and energy absorption properties of metal-polymer hybrid cellular structures. Their study shows that the mechanical behavior of metal cell structures is highly dependent on the characteristics of the base material, the size and shape of the cells, and their structure. Lee et al. [20] investigated the effects of the auxetic structure on the crash performances in terms of the axial crash force, specific energy absorption, and deceleration. The re-entrant units were manufactured with SUS316L metal powder.

A review of research shows that although many models have been proposed for structures with a negative Poisson coefficient, studies are still ongoing to provide optimal and new geometries. Also, no study has been done to investigate the mechanical behavior of auxetic metal structures made using the 3D printer method. In this study, the mechanical properties of auxetic metal geometry, which was made using a 3D printer, were investigated. For this purpose, a tensile test was performed on standard samples. In the following, the finite element model was presented to investigate the mechanical behavior of these structures and after verifying it with experimental results, the effect of different geometric parameters was investigated.

2. MATERIAL AND METHOD

2.1. Experimental Test

To experimentally investigate the tension behavior, a new geometry has been presented for the cells of the auxetic structure, whose geometrical characteristics are given in Figure 1. Because the mechanical characteristics of the materials are needed to carry out finite element simulation, it is necessary to determine the stress-strain curve by performing tensile tests. For this purpose, AlSi10Mg coupons are made using DMLS method according to ASTM E8 standard. Also, in order to verify the results of the finite element model and perform tensile tests, the auxetic samples produced from AlSi10Mg material were made using the DMLS method, which is shown in Figure 2. According to Figure 3, in order to check the tensile behavior of these samples, SHUMADZU universal tensile machine with a capacity of 100 kN was used. The application of force was in the form of displacement control and the loading speed was chosen to be 0.2 mm/min. The force-displacement curve was derived and used to evaluate the accuracy of the

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numerical results. The chemical composition of the powder is given in table 1 according to the DIN EN 1706 standard.

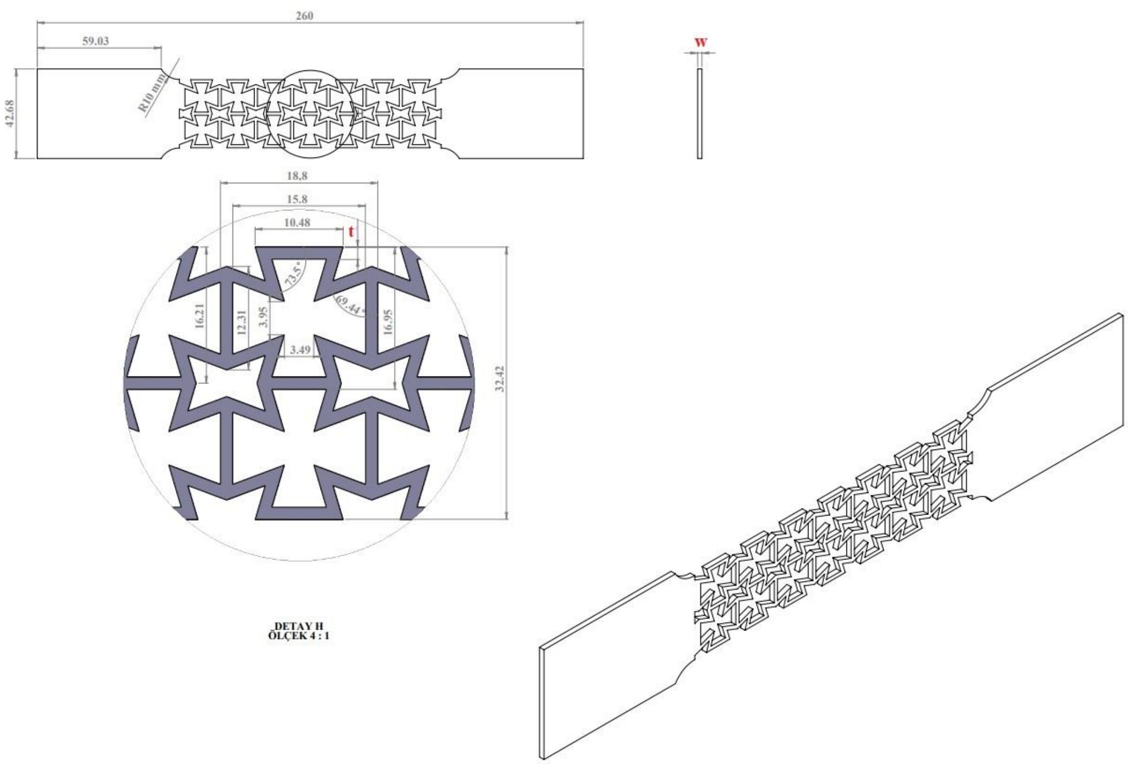

Figure 1. Auxetic structure for the tensile test (Dimensions are in mm).

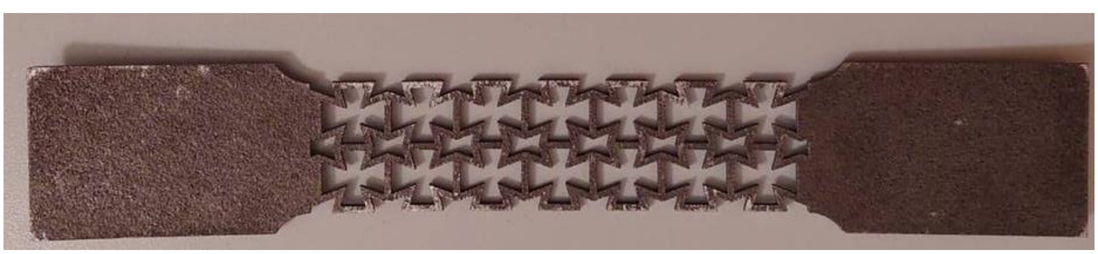

Figure 2. Tensile auxetic sample produced from AlSi10Mg by DMLS method

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Figure 3. Tensile test setup

2.2 Finite Element Modeling

The results of the finite element model were compared by the results of the experimental test of tensile test carried out on auxetic structures. Therefore, the simulations of the finite element were performed based on the geometric dimensions of the experimental tests. The geometric characteristics of tensile samples were shown in Figure 4. At this stage, the models of structures were created in Abaqus software. The next step was to apply loading and boundary conditions. Each component has then meshed separately in Abaqus.

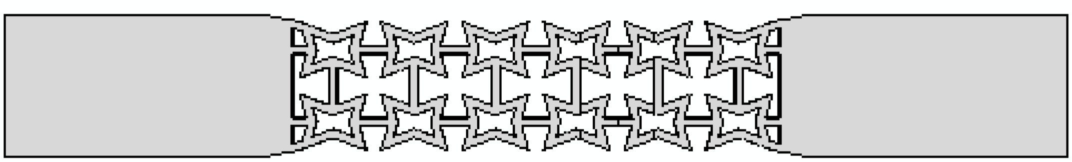

Figure 4. Geometry of auxetic structure to investigate the tensile behavior of samples made by DMLS method

In the finite element analysis, the created samples were loaded according to the laboratory conditions. In the tensile test samples, one side of the sample was fully constrained, and

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displacement was applied to the other side at a rate of 0.2 mm/min [21-23]. Ten-node tetrahedral pyramidal elements with second-order shape functions (C3D10M) were used to divide the geometry into finite elements. This element had three degrees of freedom in each node including displacement in the direction of coordinate axes. The elements in the important areas were considered smaller and denser to increase the accuracy of the stress distribution. In general, for a complex model with the same number of elements, second-order elements achieve better results than first-order elements. Because they cover curved boundaries better and create a better mathematical approximation. In all analyses, the meshing of the model in sensitive areas was controlled so that the interfaces meshed with smaller sizes. In order to check the independence of the solution from the mesh density, different element density was used, and after checking the independence of the mesh size, the appropriate size of the elements was selected for each geometry.

2.3 Mechanical Properties of Materials

The models prepared were made of AlSi10Mg alloy. These components had their mechanical characteristics, which were entered into the ABAQUS software by conducting experimental tests on standard samples and at different temperatures and were applied separately to the geometry of each part.

To model the AlSi10Mg alloy, the classical plasticity model of metals in Abaqus was used. This model uses a von Mises yield surface with the associated plastic flow that enables isotropic yielding. By using this model, it is possible to define complete plastic behavior or isotropic or kinematic hardening behavior, which is a combination of isotropic and kinematic properties.

The stress-strain curves obtained from the tensile test of standard samples was shown in Figure 5. According to the stress-strain results, the mechanical characteristics of AlSi10Mg alloy including yield stress, fracture strength, fracture strain, and Young's modulus at three temperatures were summarized in Table 1. Constants of the ductile fracture criterion of AlSi10Mg alloy were given in Table 2.

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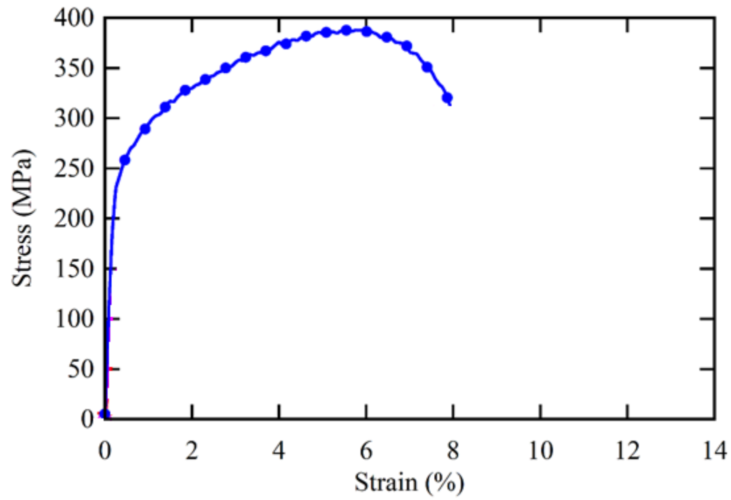

Figure 5. Stress-strain curves of AlSi10Mg alloy obtained from the tensile test

Table 1. Mechanical characteristics of AlSi10Mg alloy

Elastic modulus, (GPa)	Yield stress, (MPa)	Ultimate tensile stress, MPa	Elongation at fracture, (%)
76.7±8	187±12	387±25	5.7

Table 2. Constants of the ductile fracture criterion of AlSi10Mg alloy

ε_0^{pl}	stress triaxiality	strain rate
5.87	1/3	0

3. RESULTS and DISCUSSION

In this part, finite element results were analyzed. For this purpose, first, the independence of the results from the mesh was checked. The validation of the results for the tensile test was given, and then after choosing the appropriate model, a parametric study was done on the model, and the geometrical specifications were determined to achieve the maximum yield strength and energy absorption.

Figure 6 showed the convergence analysis process for the tensile sample. As can be seen, by increasing the number of elements from about 0.8 million elements, the results of the maximum

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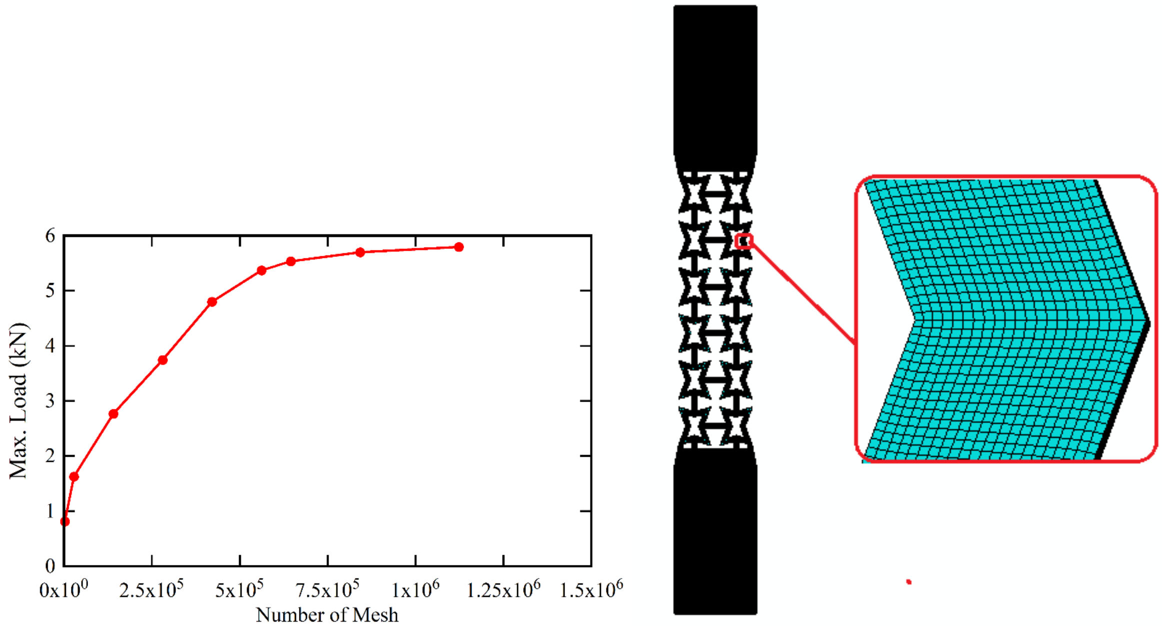
force converged to 5.6 kN, and accordingly, this number of elements was used in the analysis of the current research.



(a) (b)

Figure 6. (a) Mesh convergence analysis process for standard tensile test,
(b) optimal mesh of the structure

Figure 7 showed the force-displacement curves for four auxetic samples obtained from the finite element method and the experimental results. As can be seen, for these samples, the finite element model predicted the tensile failure behavior with good accuracy. To compare the failure mechanism, figure 8 showed the predicted failure mode with numerical results obtained from experimental results. The results showed the optimal accuracy of the used damage criterion.

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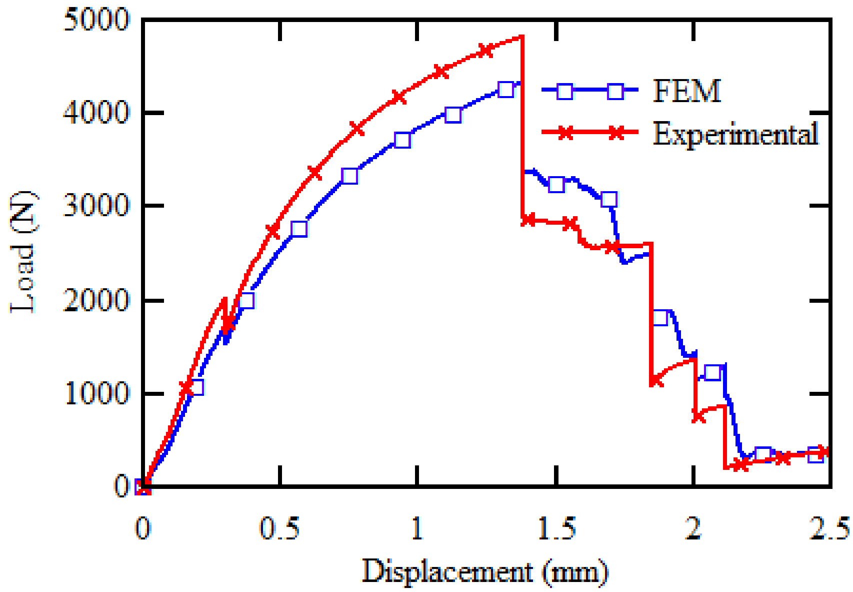

Figure 7. Force-displacement curves of the auxetic sample obtained from the finite element method and experimental results

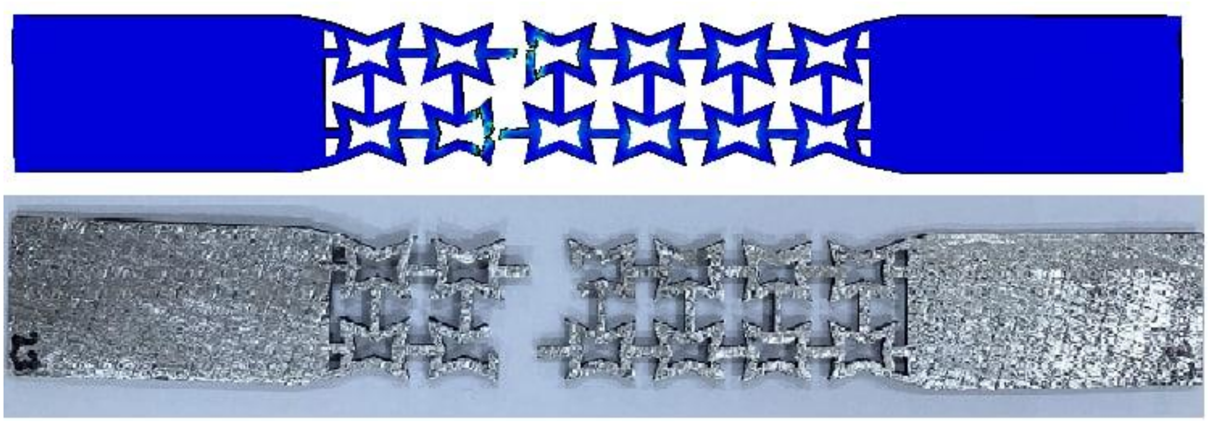

Figure 8. Comparison of the tensile failure mode of the auxetic structure obtained from the results of the finite element model and the experimental results

The effect of different geometrical parameters on the performance of this sample was investigated in the following. For this purpose, the geometric specifications that have changed in the original design were according to Table 3. For these samples, the force-displacement curve was extracted and the results were presented in Figure 9. According to the results, the maximum

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breaking force for sample B and base sample (i.e. sample A) is 5 kN and 4.2 kN, respectively. Therefore, the maximum braking force of modified sample B has increased by 17% compared to the base sample and this sample has the best tensile performance. Figure 10 shows the failure mechanism in these six samples under investigation.

Table 3. Geometry thickness (t) and material thickness (w) variation and naming of the samples

Number of third design sample	w (mm)	t (mm)
A	2	1.5
A1	3	1.5
A2	4	1.5
A3	5	1.5
B	2	1.75
C	2	2
D	2	2.2

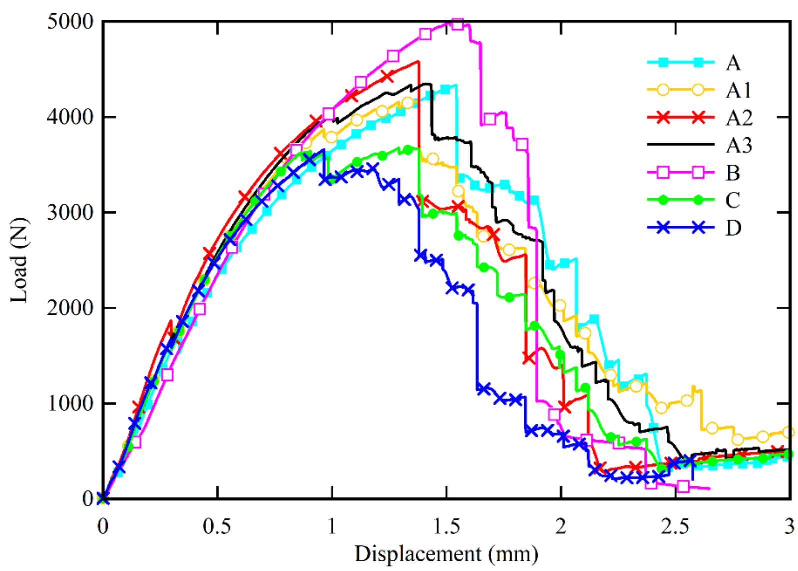

Figure 9. The force-displacement curve in different samples

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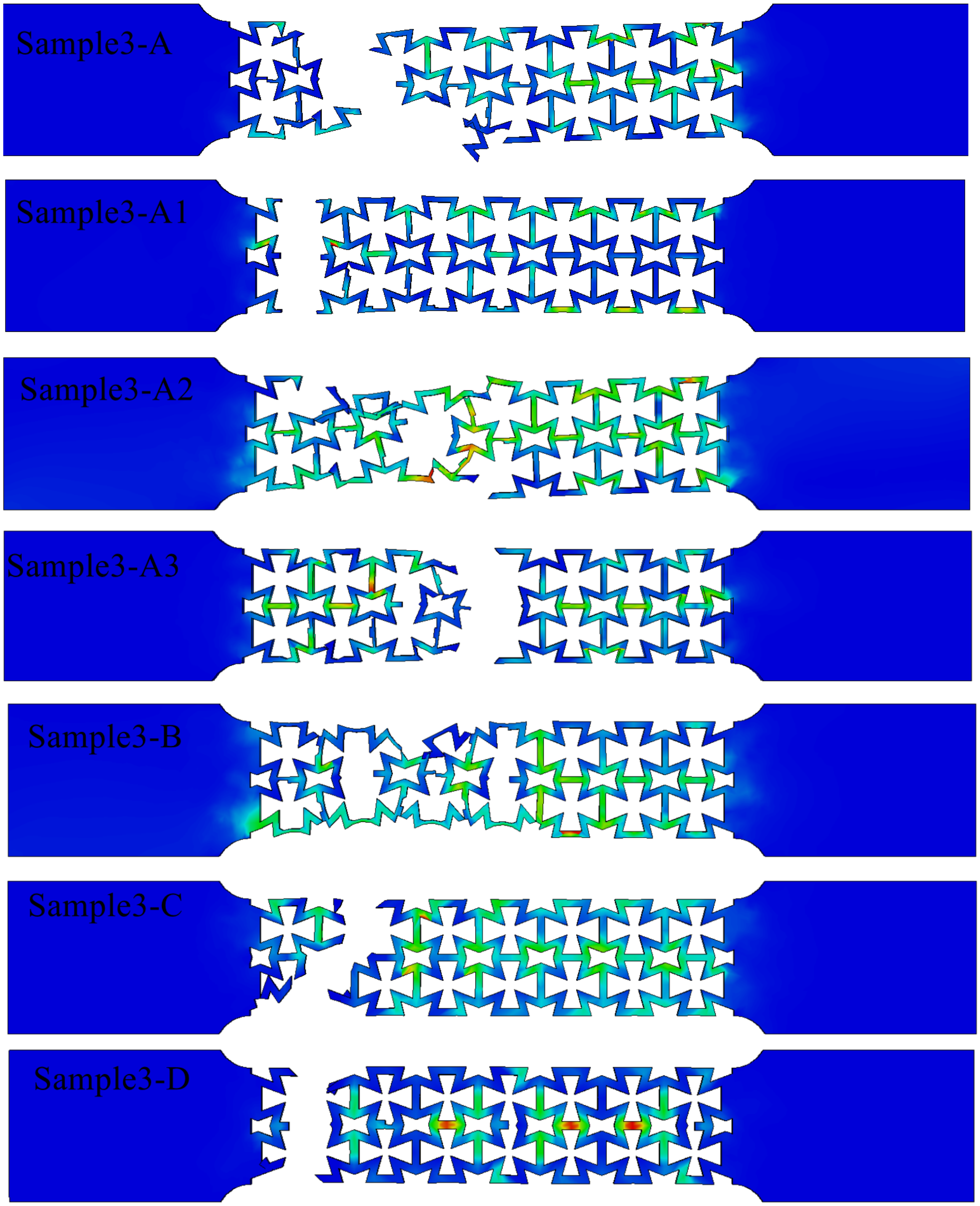

Figure 10. Failure mechanism in six improved samples under investigation

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4. CONCLUSION

Additive manufacturing, also known as 3D printing, is a method that, unlike traditional manufacturing methods, shapes the desired piece layer by layer from powder. With the help of this method, it is possible to make parts with complex geometries. Considering the development of the use of this construction method, it is very important to investigate the mechanical behavior of different types of structures produced by this method. The main aim of the current research was to investigate the mechanical behavior of 3D-printed AlSi10Mg auxetic panels using finite element and experimental methods. By simulating the finite element of the auxetic structure in ABAQUS software, the effect of geometric parameters on the tensile behavior of different samples was discussed. The accuracy of the results of the numerical model was checked using the result of the experimental test. Finally, after confirming the accuracy of the model, in order to perform a parametric study and determine the appropriate geometry, the finite element simulation results were used. The force-displacement curves for the auxetic structure presented and obtained from the finite element method and the experimental test showed that the finite element model predicted the tensile failure behavior with good accuracy. The maximum prediction error of the maximum failure force between the finite element model and experimental results was less than 3%.

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