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Experimental Comparison of the Energy Absorption Performance of Traditional Lattice and Novel Lattice Filled Tubes

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Abstract

In this study, β-Ti_3Au lattice structure was proposed for the first time in the literature as a filling material to increase the energy absorption performance of thin-walled tubes. In this context, the energy absorption performances of conventional lattice structure (i.e., body-centered cubic unit cell (BCC) and face-centered cubic unit cell (FCC)) filled thin-walled tubes and proposed novel β-Ti_3Au lattice structure filled thin-walled tubes with proposed were compared experimentally under quasi-static compression load. BCC hybrid, FCC hybrid and β-Ti_3Au hybrid structures produced by additive manufacturing technology using PA2200 powder were crushed and evaluated by considering various crashworthiness criteria such as total energy absorption (EA) and specific energy absorption (SEA). The results showed that the β-Ti_3Au hybrid structures are better crashworthiness performance than that of traditional filling BCC and FCC lattice structure filled thin-walled tubes. In particular, the β-Ti_3Au hybrid structure has 18.17% and 19.39% higher EA values than BCC hybrid and FCC hybrid, respectively. These values are 16.50% and 15.66% for SEA values, respectively. As a result, the current investigation showed that the suggested β-Ti_3Au lattice structures as a filler material can be a significant alternative for applications where energy absorption performance is critical.

Keywords: Lattice structures; Thin-walled tubes; Hybrid tubes; Energy absorption; Axial loading

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1. Introduction

Thin-walled tubes used as passive protection elements used in vehicles aim to ensure the safety of people in the vehicle in case of an accident. These tubes, also called crash boxes, are placed at strategic points of the vehicles and provide a controlled damping of a certain level of crashing energy through these elements at the time of the crash. In addition, it aims to stay as a whole in the event of an accident and exit the accident with the least loss. For these reasons, researchers try many different methods to increase the energy absorption performance of thin-walled tubes. Among these, the most commonly used methods are to cover the outer parts of the tubes with various materials [1,2] or to fill the insides of the tubes with different materials [3,4]. Composite and foam materials are generally used as coating and filling materials. The studies on the energy absorption performances of foam-filled and composite-wrapped thin-walled tubes are summarized as follows. Su et al. [5] carried out the radial and axial compression test of alumina-aluminum foam filled thin-walled tubes and individual components, and their deformation and failure mechanisms were evaluated. In the study of Rajak et al. [6], thin-walled tubes filled with foam materials having different densities were tested at different strain rates. In the study, tubes with circular, square and rectangular geometry and AlSi10Mg foam materials were used. Yao et al. [3] have proposed a new energy absorber, i.e. a bio-inspired multicellular tube containing lateral-graded multicellular configuration and axial-graded aluminum foam, by mimicking the structural features of the animal's long bone. In another study, the effect of foam fill ratio on the energy absorption capacity of axially compressed thin-walled multi-cell square and circular tubes is investigated by Altin et al. [4]. Gao et al. [7] propose and evaluate a novel foam-filled ellipse tube in comparison to hollow and foam-filled tubes with various cross-sections, including square, circle, and rectangle.

In recent years, additive manufacturing, also known as 3D printing technology, offers researchers unique opportunities to produce novel filling materials. For example, this technology makes it possible to manufacture complex shaped parts such as lattice structures, which are difficult to manufacture with conventional methods [8–13]. Micro-lattice structures produced with additive manufacturing technology; offer an outstanding combination of physical properties such as lightness, high tensile strength, impact resistance, and energy absorption [14]. At this point, in recent years, lattice structures have been proposed as filling material to further increase the energy absorption performance of thin-walled tubes [15–18]. Studies on the energy absorption performance of lattice-filled tubes are summarized as follows. Cetin and Baykasoğlu, in their pioneering works [19–23], proposed lattice structures for the first time in the literature as filling material inside thin-walled tubes. In their studies, the energy absorption performances of thin-walled tubes filled with uniform and graded lattice structures were numerically investigated under axial, oblique, and bending loads. Optimum lattice and tube structure designs were determined by considering the design parameters of body-centered cubic unit cell (BCC) and body-centered cubic unit cell with vertical struts (BCC-Z) lattice and tube structures. Similarly, Lv et al. [24] offered BCC lattice-structure filled tubes and designed via a new explainable data mining method. Five different design parameters (i.e., the height difference between tube and lattice structures, tube thickness, rod diameter, number of cells in the transverse direction, number of layers in the longitudinal direction) were selected, and energy absorption characteristics of the hybrid tube were also considered. Liu et al. [25] carried out a numerical study with the aim of improving crash endurance performances. In their study, uniform and graded BCC lattice structures were investigated by using multi-cell tubes and lattice structures. Simpson and Kazanci [26] investigated the energy absorption performance of steel tubes by placing honeycomb and re-entrant lattice structures of equal mass. In addition to the experimental studies, they examined the same models with the finite element method and showed that there was a significant increase in the performance of the models placed in the tube. Nian et al. [17] evaluated the functionally graded BCC lattice-filled composite beam composed of axial and radial graded three-dimensional lattice cores under transverse impact loading. Gunaydin et al. [18] investigated the tensile and crushing performances of composite carbon reinforced plastic tubes with hollow sections and filled with negative Poisson's ratio (auxetic) lattice structure produced by 3D printing technique. Crashworthiness indices such as the mean crush force, peak crash force, and specific energy absorption were considered for various configurations. In another study, the experimental and numeric crushing performance of empty thin-walled tubes, re-entrant and anti-tetrachiral filled AA6063 square tubes are investigated, and polyjet technique printed re-entrant and anti-tetrachiral structures were utilized as filling material [27]. Yin et al. [16], using experiment, numerical simulation and empirical formula, investigated the bending crashworthiness of the smooth-shell lattice-filled structure. Li et al. [28] two different algorithm were proposed to design and optimize the topology of octet truss lattice structures filled tubes.

In the work of Wang et al. [29], a novel non-uniform lattice-reinforced multi-cell tube based on topology optimization was proposed to investigate the crashworthy performances under axial loading and lateral bending. Wang et al. [30] proposed a new type of sandwich square tube prepared by 3D printing, and filled with a plate-lattice. A combined experimental-numerical methodology was used to examine the axial and lateral crushing performances of plate-lattice filled sandwich square tubes.

As can be seen from the above studies, the lattice structures used to increase the energy absorption performance of thin-walled tubes are generally structures such as BCC, BCC-Z and gyroid. Among these structures, BCC and FCC (face-centered cubic unit cell) are the most widely used lattice structures in the literature because they are simple and successful in terms of energy absorption capacities. With this motivation, in this study, the energy absorption characteristics of BCC and FCC lattice structures filled tubes were compared with that of a novel lattice structure filled tube. In this context, the β-Ti_3Au lattice structure was proposed for the first time in the literature as an alternative to the above lattice-filling materials, and their energy absorption performances were experimentally compared under quasi-static load.

2. Materials and Methods

2.1 Crashworthiness Parameters

EA and SEA are used to investigate and compare the energy absorption performances of proposed structures. These parameters are obtained from their force-displacement responses. The EA represents total absorbed energy during crushing, and can be calculated as

$$EA = \int_0^{\delta} F(\delta) d\delta \tag{1}$$

Where F(δ) is the instantaneous crushing force throughout the displacement (δ). The PCF indicates the highest force in the force-displacement curve. The MCF is defined as the ratio of energy to displacement and is given as follows:

$$MCF = EA / \delta \tag{2}$$

The SEA is the absorbed energy per unit mass, and is calculated as

$$SEA = EA / m \tag{3}$$

Where m is the total mass of the structure. The higher SEA values represent a higher energy absorption performance of the structures. CFE is the ratio of MCF to PCF, and is calculated as

$$CFE = MCF / PCF \tag{4}$$

In addition, the CE (crush efficiency) is described as the maximum crash length per initial tube length (L), and is given as

$$CE = \delta / L \tag{5}$$

It should be noted that above mentioned crashworthiness parameters of structures are calculated by considering the crush length immediately before densification (i.e., approximately 60 mm), and in this study, the CE value for all hybrid tubes was fixed and 0.75.

2.2 Crash boxes design and manufacture

The thin-walled tubes were filled with BCC, FCC and β-Ti_3Au lattice structures in this study. The β-Ti_3Au lattice structures (Fig. 1) were designed with reference to the work of Svanidze et al. [31] The lattice structures designed in Solidworks program were then converted to stl format and transferred to the 3D machine to be produced. The lattice structures designed are presented in Fig. 2.

The external dimensions of the FCC, BCC and β-Ti3Au lattice structures are 20x20x20 mm, wall thickness of the tube is 1 mm, and height of the tubes is 80 mm. The masses of all structures were kept equal for a logical comparison of their energy absorption performance. For this reason, the strut diameters of lattice structures vary. Considering the production time and costs, which are the disadvantages of additive manufacturing, it should be mentioned that it is more advantageous to work with relatively small sized parts, so low dimensional structures are studied in the present study.

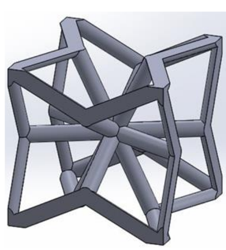

Fig. 1. Single unit cell of β-Ti_3Au structure

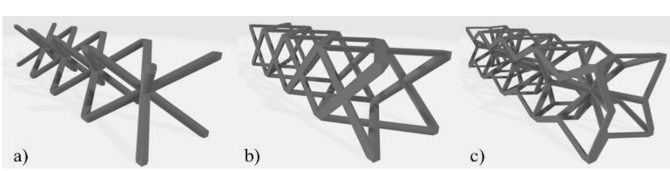

Fig. 2. a) BCC, b) FCC, and c) β-Ti_3Au lattice models

The lattice structures, tubes and tensile test samples were produced with EOS FORMIGA P110 SLS 3D printing machine. The polyamide PA2200 powders, which are extremely important in terms of lightness, strength, corrosion resistance, and availability, were used to manufacture the samples. All the samples were produced at the center of the platform bed. The manufacturing parameters were laser power of 21 W, laser scan speed of 2500 mm/s, hatch distance of 0.25 mm, layer thickness of 0.1 mm, and melting temperature of the powder of 168 ˚C. These parameters are also consisted with the literature [32]. ISO 527 standard was used to evaluate the tensile properties of SLS materials, in this study [33]. The produced lattice structures, tubes and tensile test specimens are presented in Fig. 3.

Fig. 3. The samples produced by SLS technology

Tensile tests were carried out using a Zwick Z250 machine equipped with a 30 kN load cell. Extensometers were also used for tensile strain measurements. For the crush tests, Shimadzu Autograph AG-IS universal test device with a 100 kN load cell was used. A velocity of 1 mm/min was used for both tensile and compression tests. The typical stress-strain curve of polyamide PA2200 is given in Fig. 4.

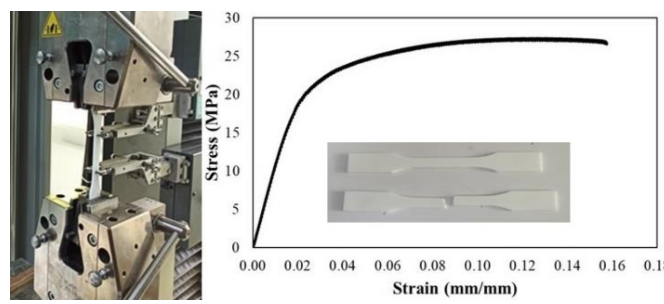

Fig. 4. Typical stress-strain curve of PA2200 tensile test sample

Six test specimens were subjected to the tensile test and their average was taken. Accordingly, the yield point of the PA2200 material used in this study was 17.8 MPa and the modulus of elasticity was 975 MPa. These values obtained in this study are in the range of values found in the literature [10,34].

The produced BCC, FCC and β-Ti3Au lattice structures are then separately placed inside of the tube to build BCC hybrid, FCC hybrid and β-Ti3Au hybrid structures (Fig. 5).

Fig. 5. Tubes, lattice and hybrid structures produced by additive manufacturing method

3. Results and Discussion

In this study, the energy absorption performance of the traditional lattice structures (i.e., BCC and FCC lattice structures) filled thin-walled tubes were compared with that of thin-walled tubes filled with the new lattice structure (i.e., β-Ti3Au lattice). The force-displacement values of the BCC hybrid, FCC hybrid and β-Ti3Au hybrid tubes are given in Fig. 6.

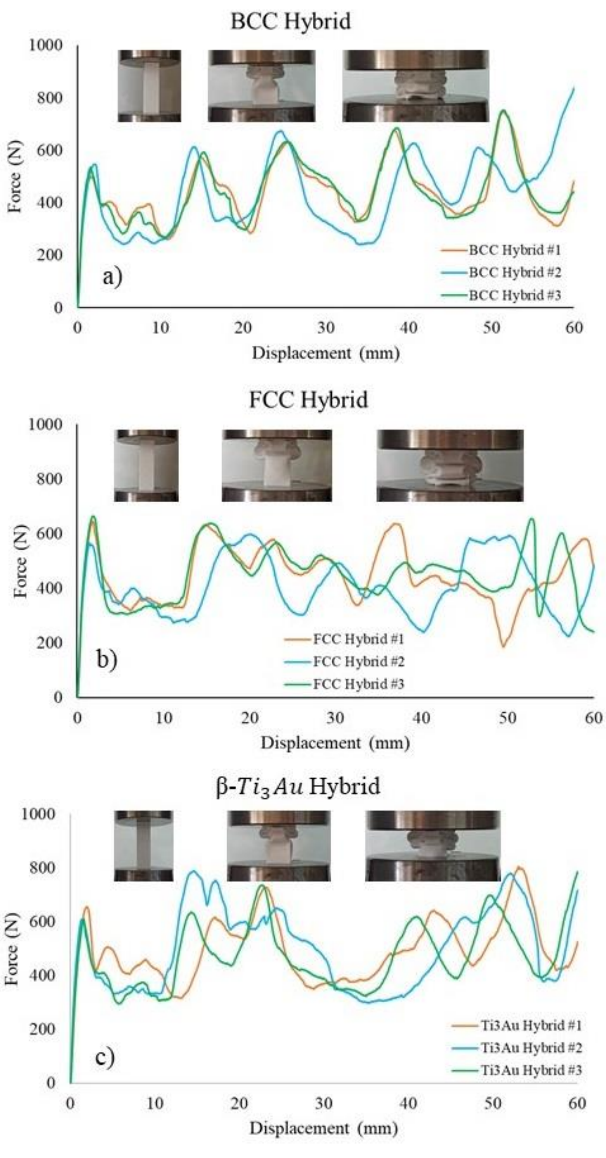

Fig. 6. Force displacement curves of different hybrid structures a) BCC Hybrid b) FCC Hybrid c) β-Ti3Au Hybrid

As seen in the figure, three crushing test were performed for each hybrid tube. Each hybrid structure shows consistent results in itself. All hybrid tubes showed a linear increase initially, followed by strength reductions with plastic deformation of the unit cell walls. In addition, all structures have same number of peaks due to the same unit cell number. Although all tubes have similar deformation views, when the three tubes are compared, it is seen that the β-Ti3Au hybrid tubes have more energy absorption capacities than the other tubes. The crashworthiness performance criteria of the hybrid structures derived from force-displacement values are shown in Fig. 7 and Table 1.

Table 1. The crashworthiness performances of the hybrid structures

Sample	EA (J)	Mass (g)	SEA (J/g)	MCF (N)	PCF (N)	CFE
BCC H. #1	26.60	6.45	4.12	443.36	750.74	0.59
BCC H. #2	26.04	6.33	4.12	433.98	838.63	0.52
BCC H. #3	26.63	6.48	4.11	443.78	754.35	0.59
BCC H. (mean)	***26.42***	***6.42***	***4.12***	***440.37***	***781.24***	***0.57***
FCC H. #1	26.84	6.37	4.22	447.37	645.64	0.69
FCC H. #2	24.54	6.13	4.00	409.03	598.53	0.68
FCC H. #3	27.06	6.40	4.23	451.02	664.27	0.68
FCC H. (mean)	***26.15***	***6.35***	***4.15***	***435.81***	***636.15***	***0.69***
β-Ti_3Au H. #1	29.63	6.35	4.66	493.83	804.88	0.61
β-Ti_3Au H. #2	35.81	6.77	5.29	596.83	911.39	0.65
β-Ti_3Au H. #3	28.21	6.34	4.45	470.17	785.03	0.60
β-Ti_3Au H. (mean)	***31.22***	***6.49***	***4.80***	***520.28***	***833.77***	***0.62***

The values of the right side of the Fig. 7 are the average values of the hybrid structures. In addition, the standard deviation values are located on the bar graphs. As shown in Fig. 7 and Table 1, the proposed β-Ti_3Au hybrid structures have the highest EA and SEA values compared to the traditional lattice structure-filled thin-walled tubes. In particular, the β-Ti_3Au hybrid structures have 18.17% and 19.39% higher EA values than BCC hybrid and FCC hybrid, respectively. In addition, the SEA values of β-Ti_3Au hybrid structures are respectively 16.50% and 15.66% higher than that of BCC hybrid and FCC hybrid structures. Unsurprisingly, the MCF values of β-Ti_3Au hybrid structures are higher than the BCC and FCC hybrid structures. On the other hand, in many cases high PCF values are encountered when high EA values are obtained. The PCF values of β-Ti_3Au hybrid structures are higher than almost all of the other hybrid structures. However, the important thing here is to obtain as much energy as possible without reducing the CFE value as much as possible. At this point, it becomes clear that the crashworthiness performance of the β-Ti_3Au hybrid structures is remarkably better than other conventional structures.

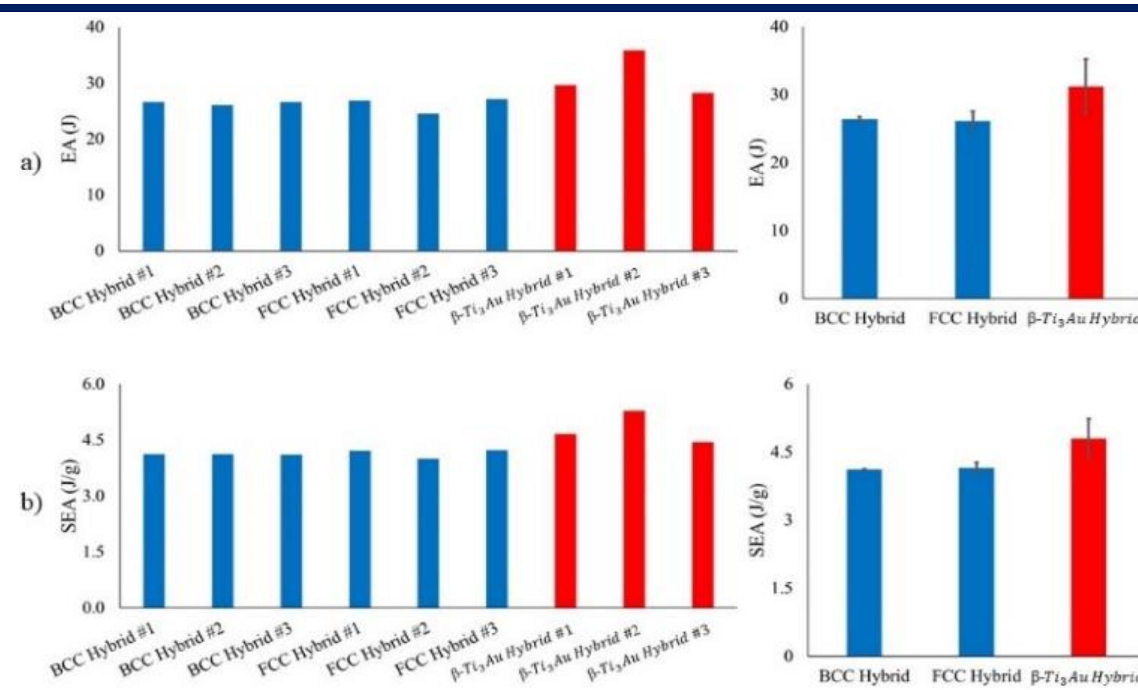

Fig. 7. a) EA, and b) SEA values for hybrid tubes having different lattice structures

4. Conclusions

In this study, a novel lattice structure called β-Ti3Au was proposed as filling materials for the thin-walled tubes for the first time in the literature. In this context, the energy absorption performance of the proposed β-Ti3Au lattice structure-filled thin-walled tubes was compared with that of traditional BCC and FCC structure filled- thin-walled tubes under quasi-static compression load. The samples produced by additive manufacturing technology were crushed and evaluated by considering various crashworthiness criteria. The proposed β-Ti3Au lattice structures significantly increased the EA, SEA, and MCF values without reducing the CFE value compared to conventional lattice structures. Thus, this study has shown that β-Ti3Au lattice structures proposed as a filling material can be a very important alternative for practical applications where energy absorption performance is crucial. With this motivation, the energy absorption performance of single and multi-cell tubes with β-Ti3Au lattice structures will be examined in detail in a future study. In this context, different strut diameters, the height of the unit cell, and tube wall thicknesses will be considered and their energy absorption performances will be examined numerically under both axial and oblique loads.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Gazi Başar Kocabaş: Conceptualization, Investigation, Methodology, Project administration, Resources, Writing-original draft, Writing-review & editing,
Erhan Cetin: Investigation, Methodology, Resources, Writing-original draft, Writing-review & editing,
Senai Yalçınkaya: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing-review & editing,
Yusuf Şahin: Supervision, Writing-review & editing.

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