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Quasi-static Axial Crushing Behavior of Thin-walled Circular Aluminum Tubes with Functionally Graded Thickness

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Abstract

In this paper, the crushing behavior of circular aluminum thin-walled tubes with functionally graded thickness (FGT) are investigated experimentally. To this aim, three different thickness grading patterns are introduced to the longitudinal direction of tubes using a grading function, and then specimens are tested by universal testing machine under quasi-static axial compression loading. In addition, to show the efficiency of FGT tubes, the quasi-static axial crushing performance of FGT tubes are compared with their uniform thickness (UT) counterparts at the same weight. The test specimens have been made of commercial quality 6060 aluminum alloy and manufactured with computerized numerical controlled (CNC) machining workbench. Initial crush force (ICF), total energy absorption (EA), specific energy absorption (SEA) and mean crush force (MCF) values are measured from the tests to infer the quasi-static axial crushing performance of the tubes. The test results showed that the energy absorption characteristics of FGT tubes are better than the UT counterparts and FGT tubes allow effective control of the energy absorption parameters when compared with the UT tubes due to their varying stiffness along their longitudinal direction.

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Keywords: thin-walled tube, functionally graded thickness, quasi-static axial crushing, energy absorption

1. Introduction

Thin-walled structures are the most conventional passive energy absorbing elements in automotive, aerospace, transportation and defense industries due to their simplicity and cost effectiveness [1-3]. Hence, extensive numerical and experimental research have been conducted to determine and improve the energy absorption capability of these structures. At this point, various types of crash absorbing structures are developed such as circular, triangular, rectangular, hexagonal, tapered, frusta, grooved, pyramidal, honeycomb, foam filled, windowed, cellular and surface patterned etc. [2-8]. Among these structures, metallic circular tubes are the most attractive type due to fabrication easiness and effectiveness. On the other hand, circular aluminum tubes are widely used as energy absorbing structures because of their low density, high specific strength and good deformability [9-15].

The energy absorption performances of thin-walled structures having uniform thickness (UT) are extensively investigated in the previous studies. On the other hand, the UT tubes may not provide the best energy absorption capabilities. Indeed, the functionally graded thickness (FGT) enables to obtain variable stiffness along the structure; thus, the energy absorption performance of tubes may be controlled and improved more efficiently. Therefore, the number of studies about energy absorption capabilities of thin-walled tubes having variable thickness has increased in recent years [15-25]. Shahi and Marzbanrad [15] analytically and experimentally investigated the quasi-static axial crush behavior of segmented circular tubes. Li et *al.* [16] presented a numerical investigation on the energy absorption capabilities of FGT and UT foam-filled quadratic thin-walled tubes under multiple load cases. In another study, Baykasoglu and Tunay Cetin [17] studied the crashing behavior of circular aluminum FGT and UT tubes under axial impact loading by using finite element (FE) method. Li et *al.* [18] compared the energy absorption characteristics of hollow and foam-filled FGT thin-walled tubes with their UT counterparts under multiple loading angles.

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Besides, Li et *al.* [19] also examined the energy absorption characteristics of FGT and UT tubes under oblique impact loading. Furthermore, Li et *al.* [20] investigated numerically the crashworthiness performances of straight UT, tapered UT and straight FGT tubes under axial impact loading. Sun et *al.* [21] examined the effect of various wall thickness grading patterns on crashworthiness of tubes under axial impact loading. Sun et *al.* [22] also studied the energy absorption performance of FGT and UT tubes under lateral impact loads by using FE method. In another study, Xu [23] investigated numerically the effects of aspect ratio and wall thickness on the crash behavior of circular FGT tubes subjected to axial loading. Zhang et *al.* [24] investigated the crash behavior of tapered circular tubes with graded thickness under axial impact loading. Furthermore, Baykasoglu and Baykasoglu [25] developed a multiple objective optimization procedure for crashworthiness optimization of circular tubes having FGT. Overall, above studies indicated that the energy absorption characteristics of FGT tubes have superiority over UT tubes with the same weight.

As also mentioned in the literature review, although there are some published works about determining the energy absorption behavior of thin-walled FGT tubes, there are limited experimental studies about crushing behavior of FGT tubes. Additionally, there are no experimental studies on the energy absorption performance of aluminum circular FGT tubes in the literature. For the absence of any experimental studies, the energy absorption characteristics of circular FGT tubes are investigated in this paper. To this aim, three different aluminum FGT tube specimens in which different thickness grading patterns are introduced to the longitudinal direction are manufactured with computerized numerical controlled (CNC) machining workbench. Then, specimens are tested by universal testing machine under quasi-static axial compression loading. To show the efficiency of FGT tubes, the crushing performance of FGT tubes is compared with UT counterparts at the same weight. The test results shows that thickness grading pattern has significant effect on the energy absorption characteristics of the thin-walled tubes and FGT tubes provide a better balance between different energy absorption performance criteria.

Nomenclature

D_i	inner diameter of energy absorber
D_o	outer diameter of energy absorber
E	elasticity (Young's) modulus
EA	total energy absorption
F	crush force
FGT	functionally graded thickness
ICF	initial crush force
i	data point
L	length of energy absorber
MCF	mean crush force
m	mass of thin-walled tube
N	number of data points
n	grading exponent
SEA	specific energy absorption
t(x)	thickness grading function
t_i	individual thickness
t_{max}	maximum thickness of energy absorber
t_{min}	minimum thickness of energy absorber
t_{UT}	equivalent thickness of UT tube
UT	uniform thickness
x	distance from the top end of tube
δ	displacement
υ	Poisson's ratio
ρ	density
σ_y	yield stress

2. Energy Absorption Parameters

In order to investigate the energy absorption performance of thin-walled structures, different performance parameters such as ICF, EA, SEA and MCF can be used [26]. The ICF indicates the force required to initiate collapse and to start the progressive deformation and energy absorption process (e.g. Fig. 1). It is important to assess the ICF for determining optimum occupant safety in a low speed impact [25]. On the other hand, EA is described as:

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

where $F(\delta)$ is the instantaneous crush force corresponding to the displacement δ. The SEA is defined as the absorbed energy per unit mass and can be given as:

$$SEA = \frac{EA}{m} \tag{2}$$

where m is total mass of the structure. The MCF for a given deformation indicates the energy absorption capability of a structure:

$$MCF = \frac{EA}{\delta} \tag{3}$$

Fig. 1 shows the typical force-displacement curves of UT and FGT tubes. As seen from Fig. 1, there is a significant difference between the two curves. Namely, the UT tubes have nearly uniform force values with increasing displacement whereas the crush force values of FGT tubes increase with increasing displacement due to their varying stiffness throughout longitudinal direction. Hence, the energy absorbing performance of FGT tubes increases with the increasing deformation.

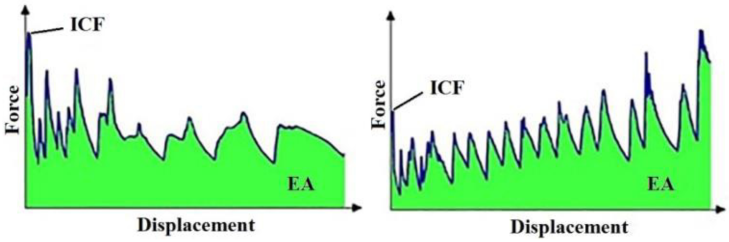

Fig. 1. Typical force-displacement curves of the UT (left) and FGT (right) tubes.

3. Experimental Tests

In this study, FGT tubes having circular cross-sections and their simple UT counterparts at the same weight are used for quasi-static axial crushing tests. Thin-walled tubes are designed to dissipate energy under dynamic loadings. However, the mechanical behaviour under quasi-static axial loading is usually studied firstly to analyse the collapse modes and relative performance of tubes due to the easiness of experimental procedure [9, 15]. Motivated by the similar facts, the quasi-static axial crushing tests of the FGT tubes and their UT counterparts are performed and the results are compared in this study. The circular FGT tube and its geometric parameters are illustrated in Fig. 2. For all thin-walled tubes, the inner diameter of tubes (D_i) is chosen as 40 mm. On the other hand, the specimens having the initial length of 120 mm are considered. For the longitudinal direction of FGT tubes, the thickness grading $t(x)$ is defined by the following power function [26]:

$$t(x) = t_{\min} + (t_{\max} - t_{\min})(\frac{x}{L})^n \tag{4}$$

where $t(x)$ is the thickness grading function, t_{min} is the minimum tube thickness (i.e. 1 mm), t_{max} is the maximum tube thickness (i.e. 2.5 mm), x is the distance from the top end of the tube (e.g. Fig. 2), L is the tube length and n is the grading exponent. To investigate the effects of grading exponent on the quasi-static axial crushing behaviour of the FGT tubes, three different grading exponent values as 0.4, 1 and 4 are considered in experimental tests (e.g. Fig. 2). The thickness grading function shows an ascending pattern and it has convex, linear and concave forms for the grading exponent values of 0.4, 1 and 4, respectively. Thus, the total weight of the tube decreases with the increasing thickness grading exponent value (e.g. Fig. 2). The ascending grading patterns are selected in order to obtain variable stiffness throughout the length of the tube and to ensure good energy absorption behaviour due to progressive folding. On the other hand, the equivalent thicknesses of UT tubes t_{UT} are calculated as follows:

$$t_{UT} = \sum_{i=1}^{N} \frac{t_i}{N} \tag{5}$$

where t_i and N represents the individual thickness of the data point i and the total number of data points which is used in manufacturing of the FGT tubes, respectively. Note that, in order to manufacture ideal functionally graded test specimens, an infinite number of data points should be used. After the tests, 120 data points are selected to manufacture the specimens.

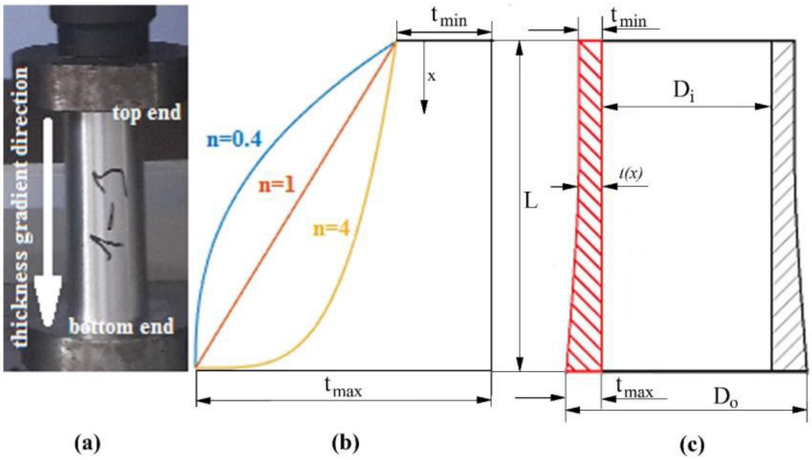

Fig. 2. (a) Testing procedure, (b) thickness grading functions and (c) thin-walled tube geometry.

Aluminium alloy based thin-walled tubes have been preferred due to their low weight combined with good energy absorption capability. Hence, the tube material is chosen as 6060 aluminium alloy. The mechanical and physical properties, and chemical composition of the testing material are given in Table 1 and Table 2, respectively.

Table 1. Mechanical and physical properties of the testing material.

HB10	σ_y [MPa]	σ_{uts} [MPa]	ρ [kg/m^3]	E [GPa]	ν
85	239.15	247.31	2700	70	0.33

Table 2. Chemical composition of the testing material.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ga	V	Zr	Al
0.5090	0.1920	0.0009	0.0240	0.4550	0.0022	0.0015	0.0100	0.0160	0.0092	0.0012	98.7800

The UT and FGT tubes are machined from the extruded thick-walled tubes. At this point, all the test specimens are manufactured via computerized numerical controlled (CNC) machining workbench having a precision of 0.01 mm. Shimadzu Autograph AG-IS universal testing machine with the capacity of 100 kN is utilized to perform the quasi-static axial compression tests at the stable speed of 5 mm/min. As shown in Fig. 2a, the tube specimens are placed between the two parallel flat platens (i.e. fixed lower and moving upper platens) and crushed under axial quasi-static compressive load. No additional fixture is used in order to hold the tube specimens in place between the fixed and moving platens.

4. Results and Discussions

In order to demonstrate the superiority of the FGT tubes, energy absorption characteristics of FGT tubes are compared with their UT counterparts at the same weight. ICF, MCF, EA and SEA parameters are considered to evaluate crushing performances of thin-walled structures. The formulations of these parameters are given in the previous section. Fig. 3 shows the crushing force-displacement curves of FGT and UT tubes for selected *n* value (i.e. *n*=1). According to Fig. 3, the force-displacement curves of FGT tube and its UT counterpart have different characteristics. Namely, distribution of the force along the crush range has nearly uniform trend in simple UT tube due to constant thickness along the tube, but in the FGT tube, the crush force increases with increasing deformation due to ascending variable stiffness throughout the longitudinal direction of the tube. As clear from Fig. 3, the peak crush force upsurges during the formation of the first fold at the beginning of the crush range in simple UT tubes, while the peak crush force occurs at the end of the crush range in the FGT tubes due to their ascending variable stiffness throughout longitudinal direction. Therefore, the FGT enables possibility for reduction of the ICF at the beginning of the crush range and in exerted deceleration at the moment of impact. Therefore, in term of ICF value, the FGT tubes allow obtaining better crashworthiness performance when compared with traditionally designed UT counterparts.

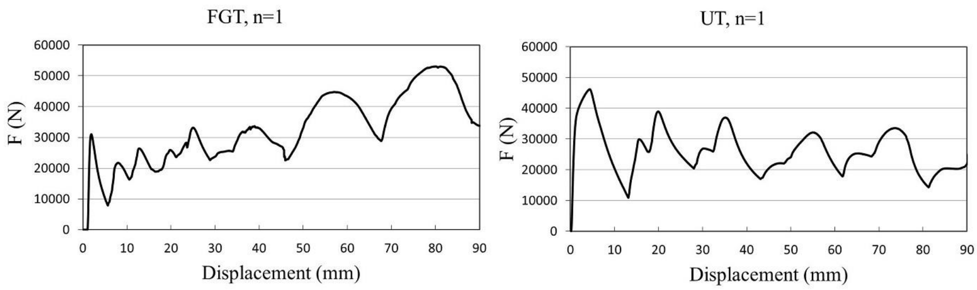

Fig. 3. The crushing force-displacement trends for FGT and UT tubes.

The EA and SEA values of FGT and UT tubes are shown in Fig. 4. It is clear from the figure that when the grading exponent value decreases, the magnitude of absorbed energy increases for both FGT and UT tubes. Furthermore, the EA values of FGT tubes are greater than UT tubes for all grading exponents. Similar to the EA trends, the SEA trends for all *n* values increase when the grading exponent value decreases. Particularly, the SEA value of FGT tube is approximately 9.26 % higher than of UT tube with grading exponent 0.4. Additionally, it is apparent from the obtained data that the SEA value of the UT tube having grading exponent 4 is close to the SEA value of the FGT tube having grading exponent 1, while the FGT tube has approximately 37 % less weight than UT tube for these grading exponents.

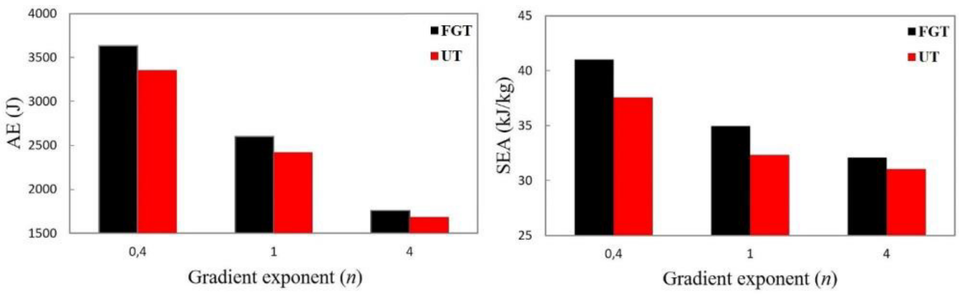

Fig. 4. The (a) EA and (b) SEA values of FGT and UT tubes.

The ICF and MCF trends of the FGT and UT tubes are presented in Fig. 5. As shown in Fig. 5, the ICF decreases with increasing grading exponent value for both FGT and UT tubes. The ICF values of FGT tubes are significantly lower when compared with the ICF values of UT tubes due to the ascending variable stiffness throughout longitudinal direction of the FGT tube. Thus, the FGT provides decrease in the ICF values and enhance the crashworthiness performance of thin-walled structures in terms of ICF value. On the other hand, the MCF values of all FGT tubes are greater than that of UT tubes and there is a significant decrease for both FGT and UT tubes with increasing grading exponent. The MCF values of FGT tubes are 8 %, 7 % and 4 % higher than that of UT tubes for grading exponent values of 0.4, 1 and 4, respectively. These results suggest that the energy absorption performances of circular FGT tubes are superior to circular UT counterparts.

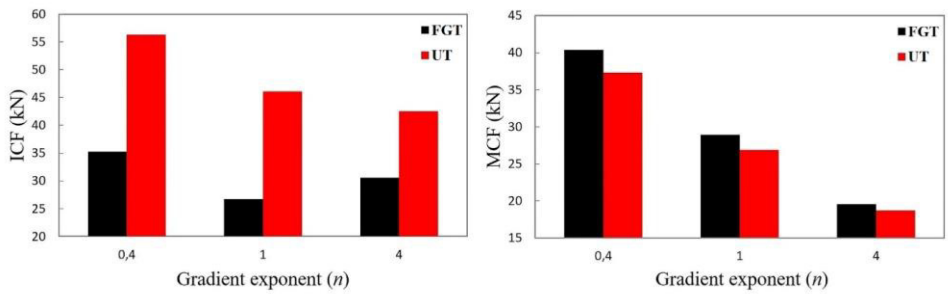

Fig. 5. The (a) ICF and (b) MCF values of FGT and UT tubes.

Fig. 6 illustrates the deformation modes of FGT and UT tubes with the same weight at the various grading exponents. It appears from Fig. 6 that, while the deformation patterns of both FGT and UT tubes having the grading exponent value of 0.4 are in concertina (axisymmetric) mode, the deformation patterns of both FGT and UT tubes having the grading exponent value of 1 are in mixed (concertina and diamond) mode. The deformation pattern of FGT tube having the grading exponent value of 4 is in diamond (nonsymmetrical) mode, while the deformation pattern of UT tube having the grading exponent value of 4 is in concertina mode. As seen in Fig. 6, total number of lobes in FGT tubes is higher than that of their UT counterparts for the specimens having similar deformation modes as in FGT and UT tubes with exponent values of 0.4 and 1 due to variable stiffness of the FGT tube. Particularly, FGT tube having the exponent value of 0.4 has six concertina lobes, while its UT counterpart has five lobes after deformation.

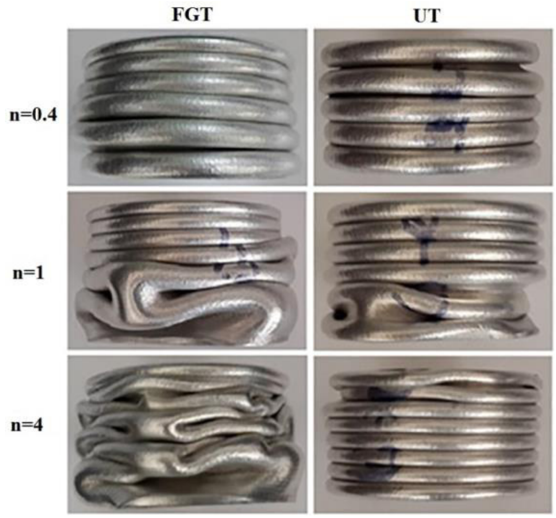

Fig. 6. Deformation modes of FGT and UT tubes.

5. Conclusions

In this study, the energy absorption capabilities of FGT tubes are experimentally compared with their UT counterparts under quasi-static axial loading. The thin-walled FGT and UT energy absorbers are manufactured from aluminum alloy 6060 using CNC machining workbench. Both FGT tubes and their UT counterparts have the same weight and are tested by universal testing machine with constant punch speed of 5 mm/min. The inner diameter of tubes are selected as 40 mm, the minimum thickness and maximum thickness are chosen as 1 mm and 2.5 mm, respectively. The ICF, MCF, EA, SEA and deformation patterns are selected as related parameters to compare the crushing performance of FGT and UT tubes. The following conclusions are obtained:

- In all cases, it is observed that the FGT and UT tubes show progressive crush behavior. On the other hand, they have different deformation patterns in terms of number of lobes and deformation modes.
- The FGT enables possibility for reduction of the ICF at the beginning of the crush range. Hence, the FGT tubes are more effective than UT counterparts to decrease the ICF and thus to protect the passenger safety and vehicle components.
- The EA, SEA and MCF values gradually decrease with increasing grading exponent value for both FGT and UT tubes. Furthermore; the EA, SEA and MCF values of FGT tubes are greater than UT counterparts for all grading exponents.
- In general, the energy absorption performance of FGT tubes has superiority over the energy absorption performance of UT tubes with the same volume and weight due to the ascending variable stiffness throughout longitudinal direction of the FGT tube.
- The test results show that the grading exponent value has significant effect on energy absorption performance of the tubes. Hence, in future, more grading exponent values will be considered to optimize the energy absorption performance of the FGT tubes.

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