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Experimental and numerical studies on the folding response of annular-rolled Al tube

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ABSTRACT

It is important to increase energy absorption of a tube under axial loading without using any reinforcement material. Also, such a process results directly in an increase of specific energy absorbing (SEA) capability of the tube. Based on this consideration, applicability of annular rolling process to thin-walled aluminium 6063-T5 tubes (D/t = 58/1.5) has been investigated experimentally and numerically. The study was conducted with two groups of tubular specimens. After determining the appropriate restricted fold length (RFL) value from short length tubes, the data were applied to long tubes. From the experimental studies of long-length annular-rolled tube, folding initiates within the RFL, and it enhances not only maximum folding, but also upper and lower force peaks in force-displacement curve. Thus, 23% improvement in SEA was obtained. Moreover, annular rolled tubes exhibited more outward folding with respect to that of the base tube, and this folding behaviour was used to explain results of the finite element (FE) analyses. It is concluded that annular rolling process is promising for thin-walled circular tubes for enhancing their energy absorption capabilities.

1. Introduction

It is known that crash box is used as passive measures to reduce the aggressiveness of the crash event. For this purpose, thin-walled metal circular tubes have been widely used due to its stability and predictable collapse type, long stroke, and low costs. In order to improve absorbed energy, tube in various shapes and with modified cross sections have been investigated: tapered tubes [1–3], multiple skin tubes [4,5], grooved tube [6,7], tubes stiffened by stringers or rings [8–10]. Hosseinipour et al. experimentally demonstrated that folding can be guided by grooves from inside and outside of metallic tubes. It is also emphasized that it is possible to minimize the oscillation of the folding force in the study [11,12]. Moreover, some studies on filling materials such as foams, wood, honeycomb have been also made to improve the energy absorbing capacity of metal tubes [13–19]. The studies revealed that the metallic foam filling offers without doubt high contribution to energy absorption capacity, however concurrently increases crushing force [20,21]. It is generally reported that especially foam plays a major role in the stability of deformation of tubes [22–24]. On the other hand, specific energy absorption (SEA) is an important factor to be considered in the development of crash box.

Therefore, any attempt aiming to increase energy absorption of tubes without getting weight improves the specific energy absorption capacity also. Recently, it is possible to find some studies in the literature regarding the effect of grooving on axial deformation [25–27]. It is deduced that the grooving process is only suitable for thick-walled tubes, accordingly advantage of the process is limited in terms of the SEA.

It has been reported that, from the studies performed on the axisymmetric folding, the fold distance primarily changes with the tube diameter and the wall thickness [22]. Fold length may be thought as buckling length of section under compressive load in mechanical aspects. Reducing the fold length on the tube will cause the required folding force to increase. Particularly, delaying of folds that occur after first folding in the tube will increase the magnitude of absorbed energy, as expected.

Although some studies have been done to improve the energy absorbing capability of the tube by several attempts, no study has been done on the annular- rolled of the thin-walled tube in the open literature. Accordingly, it is thought that it is possible to improve the energy absorbed during the axial deformation of an annular-rolled tube. In this study, the effect of annular rolling on folding behaviour of the aluminium tube subjected to quasi-static loading has been investigated experimentally and numerically. The study was conducted with two groups (short and long) of tubular specimens. Firstly, specimen group with short length were used to determine the effect of restricted fold length (RFL) on folding behaviour of the tube and the appropriate RFL in terms of maximizing the energy absorption without any usage of

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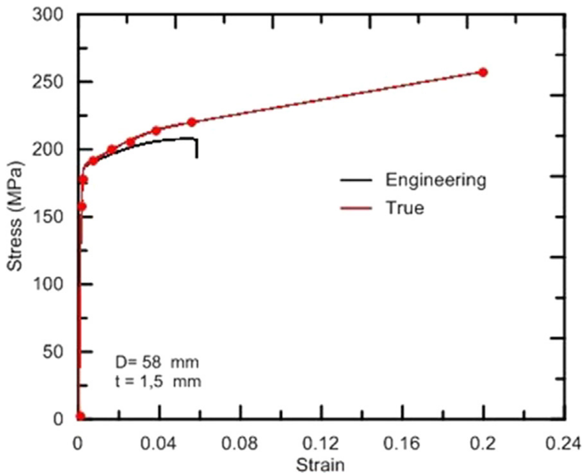

Fig. 1. Stress-strain curve of the 6063-T5 aluminium alloy.

reinforcement material. Then the data obtained from these tests were applied to long tubes. Moreover, FE analyses were conducted to examine the folding characteristic of the rolled tube in detail. After verifying the simulation results, the FE model was also implemented to axial crush loading.

2. Experimental study

2.1. Materials and specimen preparation

The material is aluminium 6063-T5 with the following properties; mass density $\rho = 2.7$ g/cm3, Young's modulus E = 69 GPa, yield strength $\sigma_y = 188$ MPa, ultimate stress $\sigma_u = 212$ MPa, Poisson's ratio $\nu = 0.33$. The engineering and true stress-strain curve of Al 6063-T5 alloy is given in Fig. 1. The tube with an outside diameter of D = 58 mm and the wall thickness of t = 1.5 mm is used, it is cut for different specimen lengths.

In the experimental studies, two groups of specimens, 34 mm and 90 mm in length, were used. It is known that the folding length is related to the diameter and the thickness of the tube ($L = (Dt)^{0.5}$), and it is approximately 18 mm for the tubes used in this study. The first group of specimens (short) was used in detailed investigation to study the effect of restricted fold length (RFL) on folding behaviour of the tube. These specimens having single RFL were subjected to rolling in such a way that $\lambda = 10$ and 20 mm. Second group specimens in long length were designed for multiple RFL.

According to schematic representation (Fig. 2b), specimens were prepared by application of annular rolling operation in a specially designed bench as shown in Fig. 2a. In order to obtain valid results from the specimens, any crack formation should be avoided not only during annular rolling of the tube but also in folding under the axial loading test. For this reason, the operation must be applied to a certain appropriate thickness. To occur strain hardening for a certain region, the tubes were rolled annularly under the compressive load by means of the disc with displacement controlling, as shown in Fig. 2 (a). From the rolling practice, the appropriate rolling depths were selected to be 0.2 mm. Hardness measurements were made to evaluate the rolled section.

2.2. Test set-up

The experimental set-up used for axial loading is shown in Fig. 3. Quasi-static testing was performed on a compressive testing machine with a capacity of 250 kN which applied the axial load through flat end plates. Crosshead speed is approximately 60 mm/min. Applied force and axial displacement were recorded automatically by a digital data acquisition system. Moreover, the deformation process during the test was recorded by a camera.

3. Experimental results

Fig. 4 shows the change of hardness throughout the width of the

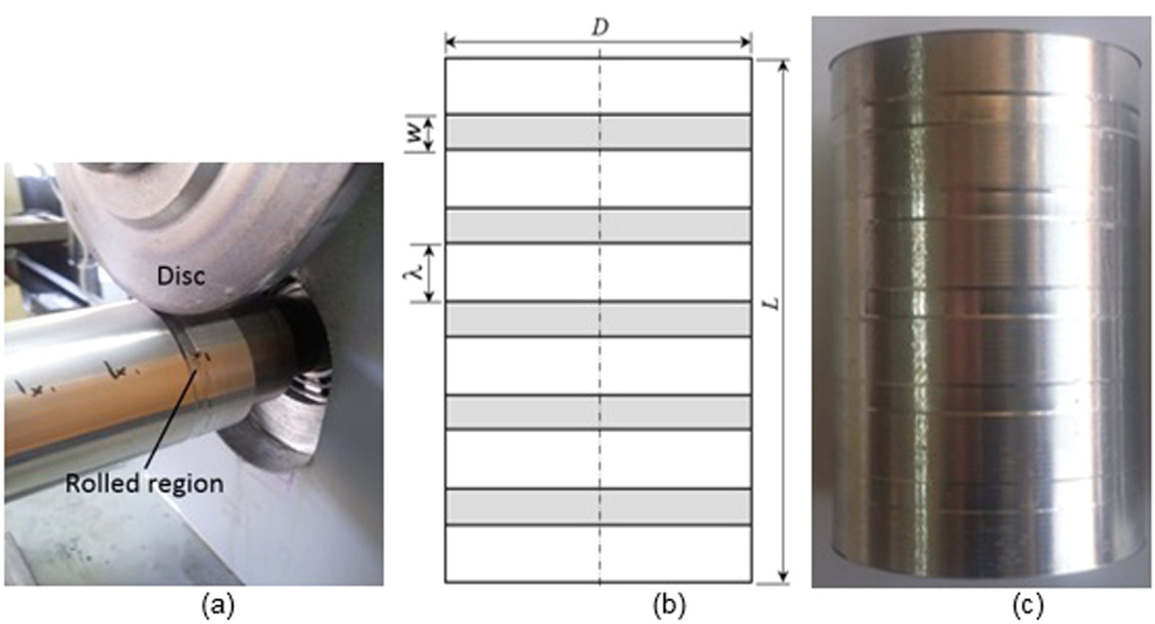

Fig. 2. (a) Application of annular rolling, (b) Schematic representation of the annular rolled region on the tube specimen, (c) annular-rolled long (second group) tube (w: rolled-region, λ: restricted fold length (RFL), L: tube length, D: tube diameter).