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Experimental and numerical investigation on cutting deformation energy absorption in circular tubes under axial impact loading by damage criterions

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ABSTRACT

In this study, cutting deformation energy absorption was experimentally performed in circular tubes under axial impact load. It was numerically simulated by various damage criterions. When applying impact load, thin-walled aluminum tubes are cut using multiple-blade cutting tools in a controlled mode from multiple points simultaneously and the petals created during processing are bent to absorb more energy. Therefore, special cutting tools with different geometric shapes were designed. The impact testing machine was equipped and experiments were conducted using the available facilities and data were also collected by a data-logger. Thereafter, numerical modeling was done in ABAQUS by utilizing damage initiation criteria. The results of the numerical solution were compared with experimental results and an acceptable agreement was observed between them. Cutting and folding deformation were compared. Energy absorption characteristics were investigated including maximum axial displacement and load, Mean Crush Load (*MCL*), Special Energy Absorption (*SEA*) and Crush Force Efficiency (*CFE*). The results reveal that the wall thickness, the number of cutting blade and the crash velocity would enrich the crashworthiness capacity of the structure. This also showed that, unlike folding deformation, the cutting deformation is predictable, controllable, stable, and continuous. Lower maximum force, less sensitivity to strain rate, and higher *CFE* are among the other significant features of cutting deformation compared to folding between two parallel plates.

1. Introduction

The rapid growth in the number of vehicles riding through the highways would lead to the countless accidents in the world. Thin-walled components are used as one of the most significant structures in the automobile, train, airplane and other means of transport. In the past years, researches have been concentrated on dissipating kinetic energy of the impact with ordered, stable and controllable way, and decreasing the damage to occupants [1]. Experimental, analytical and simulation work has been done to investigate various energy absorption of thin-walled structure, such as axial collapsing [2–4], flattening [5,6], inversion [7–9], bending [10,11], expansion [12], splitting [13]. Each energy dissipation mechanism has its own characteristic, and also has the corresponding application in practice.

Energy absorption in thin-walled structures during tearing is one of the methods that is recently applied as a method for absorbing energy during collision. According to what Altenhof [14] described and is presented in Fig. 1, in this method, the aluminum tube profile is cut by a cutting tool during the collision.

Reddy and Ride [15] investigated the cutting behavior of a circular cross section steel tube under loading using a punch to rupture the tube profile. They observed that, during plunging the punch inside the tube under axial compressive load, cracks are established on the tube surface causing the tube to be ruptured as several strips that are congregated ring-like during the immergence. This mode of deformation has showed a stroke efficiency (i.e. the maximum deformable distance of the structure along the loading direction) greater than 90%. Of course, this value is less than when the tube crushed under compressive load.

Huang et al. [16,17] investigated the axial rupturing of thin-walled structures with circular and square cross sections. They observed three different mechanisms of energy absorption during applying a conical punch caused by the action and reaction of the punch and the structure. These three mechanisms include: (1) cutting and splitting of the tube forehead, (2) creating plastic deformation and bending in a place away from the crack, and (3) twisting and extending the created strips. They concluded that the load that is required for rupturing the structure could be estimated from the balance of energy.

Cheng and Altenhof [18] examined extruded aluminum tubes with

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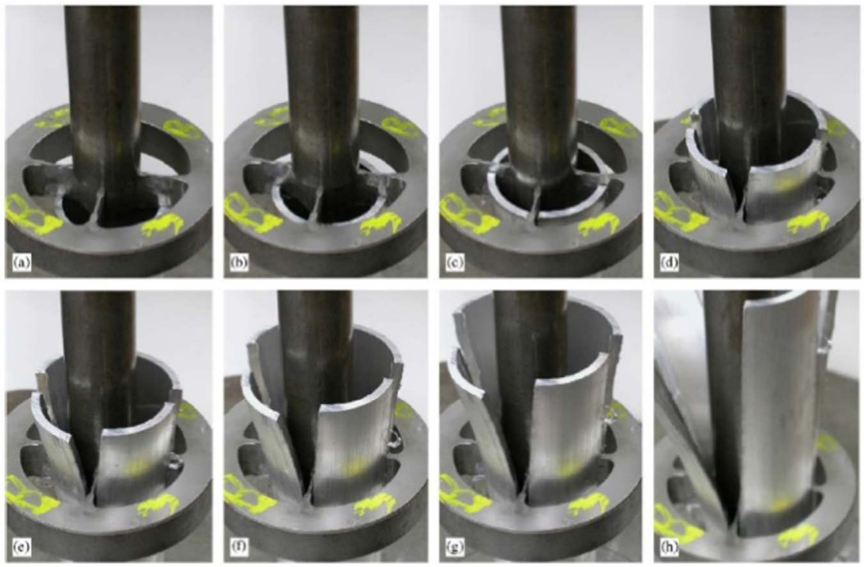

Fig. 1. The process of cutting aluminum tube with round cross section [14].

square cross section under quasi-static load by using of a special cutting tool. They found that there is a constant relation between load and displacement during the cutting process and lubrication would not influence it significantly. The crush force efficiency during the cutting process was about 80%. Whereas, in the case that without using the cutting tool, the tube was being subjected to compression and being bent, the efficiency was approximately 25%.

Ohtsubo et al. [19] evaluated the load-displacement curve and energy absorption of extruded circular tubes for cutting deformation by using a special cutting tool in the case of applying quasi-static load. They observed that after rupturing the tube in a depth of 15 mm, the load-displacement relation remains constant. They also observed that the thickness of the cutting tool edges and the aluminum tube length have no influence on the load-displacement response under axial loading. The crush force efficiency during the cutting process of the tests was approximately equal to 95%. Whilst, for the cases where there is no cutting tool and the axial load causes folding and bending, this efficiency was equal to 66% and 20%, respectively.

Majumder et al. [20] investigated axial cutting of two circular cross section tube samples from extruded aluminum alloy (AA6061 T4 and T6) with two different wall thicknesses subjected to quasi-static loading. Similar to the previous works, they found that the tube cutting process is stable, repeatable, and controllable. They realized that the tube length and the thickness of the cutting tool edges have a negligible effect on the load-displacement results. For both aluminum alloys, the tube with less thickness also had less crush force efficiency.

Jine and Altenhof [21] studied the effect of tube thickness and the number of the cutting tool blades on the load-displacement parameters and energy absorption in tubes made of AA6061-T6 subjected to axial compressive load. With the aim of creating a simpler cut, they used a conic shape tool as a deflector for created petals during cutting.

Jin et al. [22] performed a study on various factors affecting the deformation of axial cutting of tube profile with circular section made of AA6061-T6. They investigated the effect of various factors including the tube profile diameter, the tube wall thickness, the number of the cutting tool blades, and the loading conditions, on the deformation mode of cutting. Additionally, they surveyed the influence of increasing the cutting tool blades' length and observed that, if the length of the blade used in the experiment is more than 26.1 mm, there is the possibility of buckling of the blades.

Yuen et al. [23] experimentally dealt with axial tearing of three types of aluminum tubes prepared from extrusion process with the help of a cutting tool and deflector. Unlike their former research works, instead of applying axial load and displacement of the cutting tool and deflector, they took both constant and applied the force to the tube end, directly, so that it passes through the multi-blade cutting tool and tears. They observed that the cutting process is more repeatable and better controlled when the tube is of less wall thickness.

So far, few studies have been dynamically conducted concerning energy absorption during cutting and tearing of thin-walled structures under axial load. The present study investigates energy absorption by aluminum profile with circular section subjected to dynamic loading during the process of tearing due to the cutting tool. Moreover, this studied the effects of the number of blades and their angle, the impact velocity, and tubes' wall thickness. The entire process in this study has been investigated both experimentally and numerically.

2. Definition

Various parameters are affecting the passengers' safety in an automobile accident, from which the amount of energy absorption and crush force efficiency of the automotive components constituting structures could be mentioned as the most important factors. In order to evaluate a structure that is used as energy absorber, the following parameters are often recommended as energy absorbing characteristic:

2.1. Total energy absorption

The area under the load-displacement curve is equal to the amount of absorbed energy. This value is calculated by using Eq. (1) by integrating the load-displacement curve.

$$E_{ea} = \int_0^{\delta} F d\delta \tag{1}$$

2.2. Specific Energy Absorption (SEA)

The specific energy absorbed by a structure is equal to the ratio of energy absorbed to its mass as expressed in Eq. (2).

$$SEA = \frac{E_{ea}}{\mathrm{m}} = \frac{\int_0^{\delta_{max}} F d\delta}{\mathrm{m}} \tag{2}$$

2.3. Peak crush load

The force exerted in an impact is mainly containing a peak Force (F_{peak}) that is clearly specified in the load-displacement diagram.