

Mechanical Performance of Circular AA6061-T6 Extrusions Under Axial Cutting Deformation

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ABSTRACT

Dynamic and quasi-static axial cutting of circular AA6061-T6 extrusions with variable instantaneous wall thickness in the axial direction was completed to investigate the capability of controlling the load/displacement responses of the extrusions. Circular specimens considered for this research had an original nominal wall thickness of 3.175 mm, an external diameter of 50.8 mm, and a tube length of 300 mm. Variations of the wall thickness were completed by material removal of the extrusions using a CNC machine. Specially designed cutters having a block height of 20 mm, a blade tip width of 1.0 mm and a blade shoulder width of 3.0 mm were employed to generate the axial cutting deformation mode. Either one or two cutters were selected to initiate a single or dual cutting deformation. A curved deflector with a profile radius of 50.8 mm was used to flare the cut petalled sidewall and facilitate the cutting system. Results from the impact tests illustrated that an initial peak cutting force with a magnitude of 1.08-1.99 times higher than that for the quasi-static loading was needed to initiate the cutting deformation mode. After this transient cutting stage, the load/displacement responses were observed to be similar to that from the quasi-static tests except for some slight fluctuations resulting from material fractures which occurred on the petalled sidewalls. The mean cutting force from the dynamic tests was determined to be 0.92-1.10 times that from the quasi-static tests for both single and dual cutting deformation modes. Control of load versus displacement responses of the extrusions under both impact and quasi-static cutting conditions was accomplished through the variation of the wall thickness along the axial direction of extrusions and/or adopting the dual cutting deformation.

INTRODUCTION

Aluminium alloys have become increasingly favoured in vehicle design due to significant weight saving and their excellent mechanical characteristics. Moreover, aluminium is an environmentally friendly material and has good corrosion resistant properties. Aluminium alloy extrusions have received a great attention due to their effective energy absorption capability through a wide range of plastic deformation modes in forms of progressive folding, bending, twisting, and splitting. Particular, a circular tube of mean diameter (D) and wall thickness (t) which experiences a stable progressive folding deformation is an efficient energy absorbing member. However, when its length (L) is greater than a critical length (L_{cr}), which identifies the transition between progressive folding and global bending, the extrusion deforms in the global bending mode. Global bending is an inefficient mode of energy absorption and needs to be avoided in crashworthiness applications. Thus, investigating the collapse modes of extrusions is of great interest; similarly, controlling the energy absorption characteristics is a significant and important challenge.

Andrews *et al.* [1] experimentally investigated the modes of deformation for circular aluminium tubes with $D/t = 4-63$ and $L/D = 0.17-8.75$ under both quasi-static and dynamic loading conditions. A classification chart was also presented in reference [1] to reveal the relationship between different deformation modes and tube geometries. Guillo *et al.* [2] further studied the deformation mode transition of AA6060-T5 extrusions with geometry of $D/t = 10-450$ under quasi-statically axial loading, experimentally and numerically.

Jensen *et al.* [3, 4] numerically and experimentally investigated the transition of square AA6060 extrusions and found that the energy absorption was dependent on the collapse mode. The

total energy absorption decreased when increasing impact velocity due to inertia forces preventing direct global bending and the early transition from progressive to global bending. A direction relationship was found to occur between energy dissipation and both L/b and b/t extrusion geometry ratios in the quasi-static tests and impact tests with a velocity of less than 13 m/s, where b is the width of the extrusion. An inverse relationship was found when the impact velocity was 20 m/s. Thus, the overall response is found to be highly dependent on the location of the first lobes.

Karagiozova and Alves [5] experimentally and numerically studied circular aluminium tubes under both dynamic and quasi-static axial loading conditions. It was reported that the critical length (L_{cr}) was significantly influenced by the impact velocity.

It has been shown by references [1, 2, 5] that given a certain material and particular D/t ratio, an L_{cr} exists under quasi-static loading. However, for the dynamic loading condition, the collapse mode of the extrusions no longer depends only on material properties, boundary conditions and extrusion geometries but is also dependent on the impact velocity [3, 4, 5]. Furthermore, geometrical imperfections play a more important role in the dynamic crush conditions.

Galib and Limam [6] experimentally and numerically investigated the quasi-static and dynamic axial crushing of circular AA6061-T5 extrusions subjected to variable impact mass and impact velocity values. The progressive folding deformation modes of the specific circular extrusion under both dynamic and static loading were generally the same. The main difference is related to the first part of the impact, where the dynamic force is approximately 40-60% higher than the static one. Following this initial high peak force, the crush force oscillated significantly during the formation of the lobes in both loading conditions. The mean dynamic crush forces were about 10% higher than the corresponding values in the quasi-static tests, which indicated the strain rate insensitivity property of this type of material.

With the attempts to control and stabilize the collapse mode and improve the energy absorption capability of the extrusions under axial loading conditions, geometrical discontinuities, due to the easy implementation, are commonly used to initiate a specific collapse mode and improve energy absorption.

Abah *et al.* [7] experimentally and numerically examined the square AA6060-T5 extrusions with or without the circular cutout at the four edges of the extrusion; up to 50% reduction of the peak forces were observed depending on the size of the cutout and loading condition. However, the mean crush load remained relatively constant for both loading conditions.

Arnold and Altenhof [8] experimentally studied crush behaviour of square AA6061-T6 and T4 extrusions with centrally located

circular discontinuities under quasi-static axial loading. Cheng and Altenhof [9] further investigated square AA6061-T6 extrusions with circular, slotted and elliptical holes under quasi-static axial loading. It was shown from references [8, 9] that a great reduction of the initial peak crush load and higher crush force efficiency (CFE) were observed for extrusions containing discontinuities. Furthermore, the energy absorption capacity was greatly improved by altering the deformation mode within the extrusion through the implementation of the geometrical discontinuities within the tubular member.

While control of the collapse mode of the extrusions is reliable under the quasi-static axial loading through the implementation of initiators, the initiation of the desired deformation mode under impact loading becomes more complicated and may lead to a very poor energy absorption mode since the collapse mode greatly depends on the impact velocities [3, 4, 5, 6]. This collapse mode dependency of extrusions can be eliminated when extrusions are configured to experience a splitting or cutting deformation mode.

Reddy and Reid [10] experimentally investigated the behaviour of splitting circular mild steel and aluminium circular tubes under both quasi-static and dynamic axial loading conditions using a mandrel type of die. Crack formations were observed for all tests with or without the pre-slit on extrusions. The cracked extrusions then generated strips which curled afterwards. A peak load was observed along with the formation of the splitting mode and a steady crush force was also observed during the steady state splitting process. Such a mode of deformation illustrated stroke efficiency greater than 90%, although it is not as efficient as a tube undergoing axial crush or inversion.

Huang *et al.* [11, 12] investigated the quasi-static axial splitting behaviour of circular and square mild steel and aluminium tubes by the use of a conical die whereby three energy dissipation mechanisms were reported, namely, a 'near tip' tearing and splitting of the tube, a 'far-field' plastic bending and stretching of curls and finally a dissipation mechanism associated with friction due to the interaction of the tube with the die. The splitting deformation modes in references [10, 11, 12] were observed to be very stable.

Jin *et al.* [13] experimentally studied the cutting deformation of circular AA6061-T6 extrusions with an extrusion wall thickness (t) of 3.175 mm under a quasi-static loading condition using a specially designed cutter. The cutting deformation mode of the circular extrusion was observed to be very stable. An extremely high crush force efficiency of 95% and a constant steady-state cutting force were reported.

Jin *et al.* [14] further investigated the load/displacement characteristics of circular AA6061-T6 extrusions with an extrusion wall thickness (t) of 1.587 mm under dynamic and quasi-static loading conditions using a cutter/deflector

assembly. Cutting deformation was observed to be stable under both dynamic and quasi-static loading conditions and only a minor difference in the load/displacement and energy dissipation characteristics were found between the loading rates considered. The mean cutting force was found to be approximately 0.8 to 1.2 times that of the quasi-static cutting tests.

In the present study, dynamic and quasi-static axial cutting tests were conducted on circular AA6061-T6 extrusions with variable wall thickness in the axial direction. These tests were carried out using the same cutters and a curved deflector from reference [14] to investigate the load/displacement responses and energy absorption characteristics. Both single- and dual-cutter configurations were considered. The focus of our research was on the controllability of the load/displacement responses of the extrusions under both dynamic and quasi-static loading conditions either through the variation of instantaneous extrusion wall thickness in the axial direction or through the use of the second cutter. The AA6061-T6 material was selected due to its strain rate insensitive and least degree of strain hardening characteristics for the test velocities and/or strain rate considered. These material properties are very important to minimize the cutting force oscillations during dynamic loading and for controlling of the load/displacement of the extrusions under axial cutting deformation mode. Control of load/displacement response of an energy absorption device might be very challenging yet practical for the best protection of important structures, apparatus, or vehicular occupants. Additionally, the mechanical response of these structures allows for passive adaptive energy dissipation.

EXPERIMENTAL TESTING

TEST SPECIMENS AND MATERIAL PROPERTIES

Specimens considered in this research were AA6061-T6 circular extrusions. The original geometry of the extrusions had a nominal external diameter (D_o) of 50.8 mm, wall thickness (t) of 3.175 mm, and length (L) of 300 mm as shown in Figure 1. Variations of the wall thickness along the axial cutting direction (x direction), as illustrated in Figure 2 and Figure 3, were completed through material removal using a CNC lathe with minimal material removal in the final cut of the specimen. Various combinations of wall thickness change, in the axial direction, were considered to investigate their influence and controllability on the load/displacement responses of these extrusions. Care must be given when selecting the minimum wall thickness in order to avoid any switch to other undesired deformation modes, i.e., a local progressive folding mode.

Material properties of the AA6061-T6 extrusions were determined by averaging results from eight tensile tests

presented in reference [8]. The obtained engineering stress-strain curve of a representative tensile specimen is illustrated in Figure 4. It can be seen that the AA6061-T6 material illustrated a minimal level of strain hardening and an approximate mean strain to failure of 14% evaluated over all eight specimens. The material properties of the AA6061-T6 averaged over the eight tensile specimens are summarized in Table 1, where the yield strength is the 0.2% proof stress.

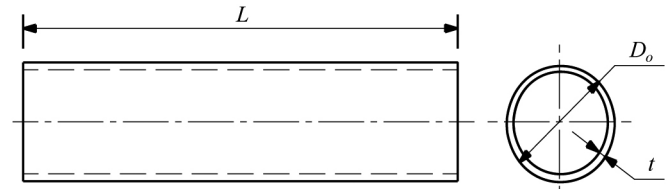


Figure 1. Extrusion original geometry considered for dynamic and quasi-static cutting testing. Where $D_o = 50.8$ mm; $t = 3.175$ mm; and $L = 300$ mm

Cutters and deflectors

A cutter or a combination of cutter(s) and curved profile deflector was used to generate a cutting deformation within the extrusions. The introduction of the deflector was to reduce the spatial requirement of the axial cutting apparatus since an additional steel rod is needed to push the cutter into the tube in the absence of the deflector. The cutters and the curved deflector are consistent with those used in previous research completed by the authors [14]. The RevI cutter was selected for the single cutter configurations and a combination of the RevI and RevII cutters was used for the dual cutters configurations. Both cutters had an outside diameter of 101.6 mm, a thickness of 20 mm, and four tapered blades with a nominal blade shoulder width ($2 \cdot B$) of 3.0 mm and a nominal blade tip width (T) of 1.0 mm. Figure 5 shows the geometries of the RevI cutter considered. The cutters were machined from AISI 4140 round bar stock followed by a two-stage heat treatment process. The hardness of the cutters after heat treatment was determined to be no less than HRC 53 thus ensuring cutting deformation within the AA6061-T6 extrusions without deformation or failure of the cutter blades.

Experimental test

Two tests were completed for each extrusion of the same geometry as shown in Figure 2(a), Figure 2(b), Figure 2(c) and Figure 3(d), Figure 3(e), Figure 3(f), Figure 3(g), Figure 3(h) in order to investigate the controllability of the load/displacement responses and energy absorption characteristics. Extrusions with geometries as illustrated in Figure 2 (a) and Figure 2(b) were cut by a single cutter/deflector assembly while the extrusions with geometries as shown in Figure 2(c) were cut by dual cutters/deflector assembly under both dynamic and quasi-static loading conditions. For the dual cutters configuration, the second cutter was rotated 45° relative

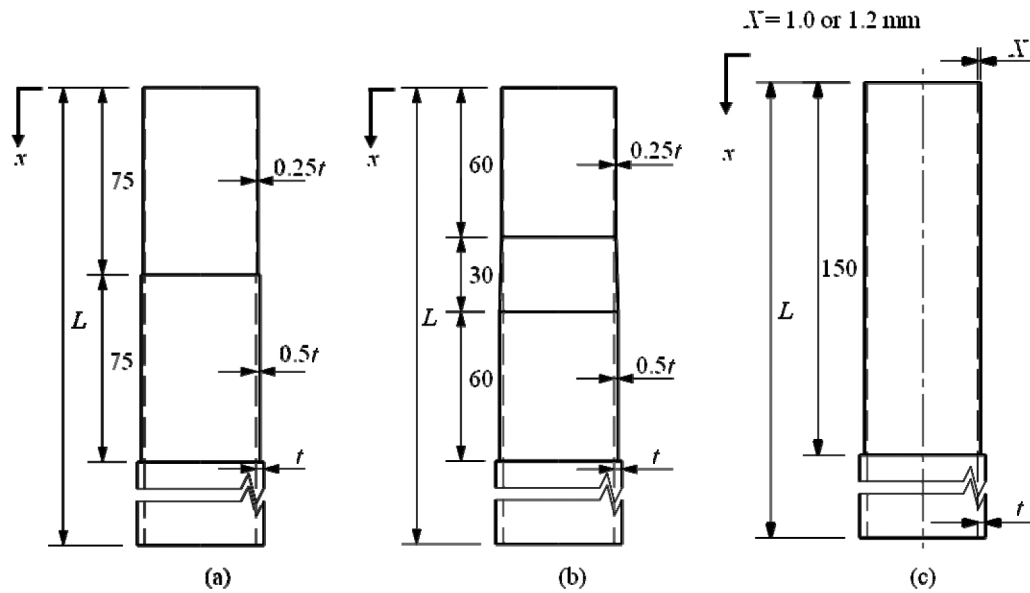


Figure 2. Extrusion geometries considered for both dynamic and quasi-static cutting testing (all dimensions in mm). (a) and (b) were considered for a single cutter/deflector assembly cutting tests; (c) was considered for the dual cutters/deflector assembly cutting tests

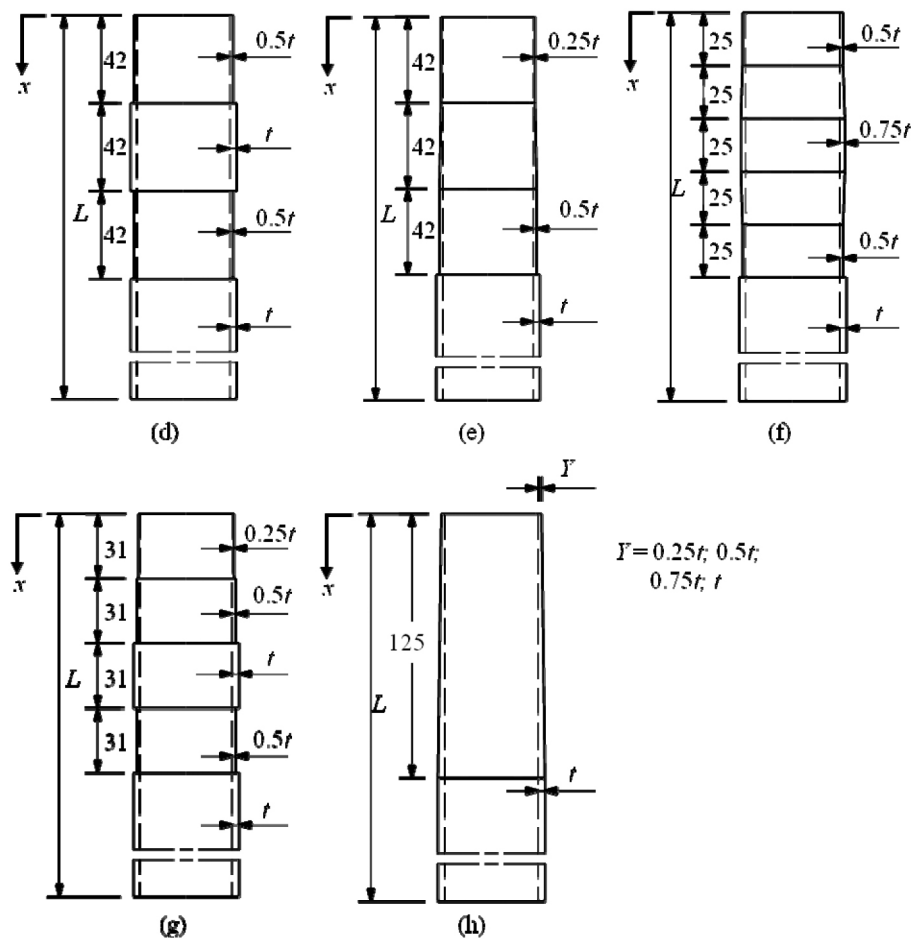


Figure 3. Extrusion geometries considered for quasi-static single cutter only cutting testing (all dimensions in mm)

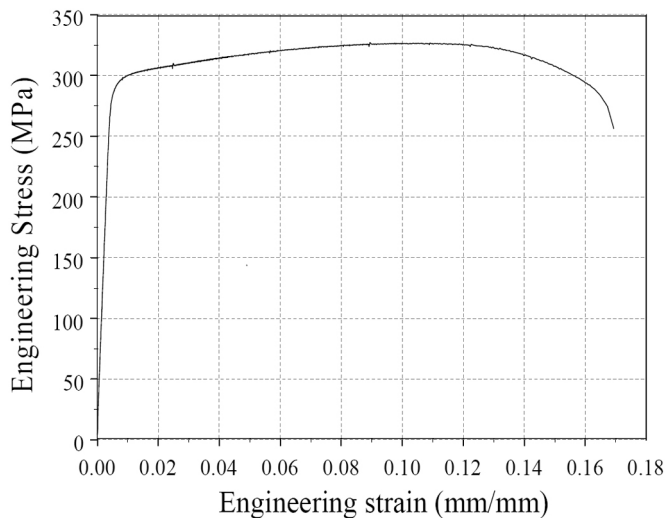


Figure 4. Engineering stress/engineering strain response of AA6061-T6 material [8]

Table 1. Material properties of the AA6061-T6 obtained from the tensile tests [8]

Properties	AA6061-T6
E (GPa)	68.1
σ_y (MPa)	277.5
σ_u (MPa)	320.2

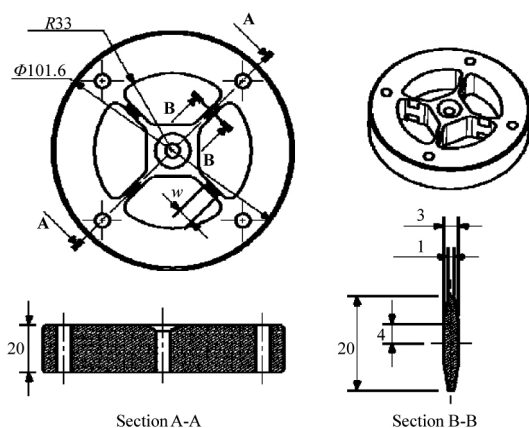


Figure 5. Geometries of the Rev1 cutter considered (all dimensions in mm)

to the first cutter so that four new cuts would be generated into the extrusion. Since the deflector had a very minor influence on the load/displacement response [14], quasistatic cutting tests using a single cutter only were carried out on the extrusions with geometries as shown in [Figure 3\(d\)](#), [Figure 3\(e\)](#), [Figure 3\(f\)](#), [Figure 3\(g\)](#), [Figure 3\(h\)](#) to further study the controllability of load/displacement responses of the extrusions.

The specimens tested dynamically and quasi-statically are listed in [Table 2](#) and [Table 3](#), respectively. The identification system of the cutting tests follows the convention $\alpha_\beta\gamma$, where ' α ' indicates either 'single' or 'dual' cutter(s) was used; ' β ' represents the geometric profile of the specimen; and ' γ ' indicates the cutting test loading condition (D for dynamic and S for quasi-static).

Dynamic cutting test

Dynamic axial cutting of the extrusions was performed using a custom built droptower system as shown in [Figure 6](#). A schematic diagram of the dynamic cutting test setup is shown in [Figure 7\(a\)](#). The droptower system consisted of a pneumatic accelerator, a dropping entity with a mass of 53.7 kg, and a support device. The dropping entity, which was comprised of steel mass blocks and a 25.4 mm thick AA6061-T6 impact plate, traveled along two guide posts. A desktop computer with custom-developed software was used to control the height of the dropping entity. The support device had a three-jaw chuck by which a hardened AISI 4140 flat disc was clamped. The flat disc, a piezoelectric impact load cell (referred to as the lower load cell), and a hardened AISI 4140 cup were fastened together using standard $\frac{1}{4}$ inch fasteners. The lower load cell (model # 200C20) had a capacity of 89 kN and was used to measure the impact cutting force. The support cup had an inside diameter of approximately 0.5 mm greater than the outer diameter of the specimens in order to ensure an appropriate hold of the extrusion during testing.

The cutter(s) and the deflector were fastened together using a standard $\frac{1}{4}$ inch fastener and manually placed at the top end of the specimen with careful alignment to ensure that the centre of the cutter was along the axial centreline of the specimen. Prior to inserting the test specimen into the support cup, a pre-cut of the extrusion was made at a nearby loading frame using a hydraulic jack by pushing the cutter(s)/deflector assembly into the extrusion approximately 1 mm. This process was completed to avoid any shifting or mis-alignment between the centerlines of the extrusion and the cutter/deflector assembly as a result of a slight shaking of the droptower system during the impact process. Another piezoelectric impact load cell (referred to as the upper load cell) was fastened to the top end of the deflector to measure the impact force between the impact plate and the deflector. This load cell (model # 200C50) had a capacity of 222 kN.