International Journal of Impact Engineering 49 (2012) 165–178

Contents lists available at SciVerse ScienceDirect

# International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

# A parametric study on extrusion geometry and blade quantity during axial cutting deformation of circular AA6061-T6 extrusions under impact and quasi-static loading

Shun Yi Jin, William Altenhof*, Zhanbiao Li

*Department of Mechanical, Automotive and Materials Engineering, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4*

A R T I C L E   I N F O

*Article history:*
Received 28 October 2011
Received in revised form
23 February 2012
Accepted 22 March 2012
Available online 5 April 2012

*Keywords:*
Axial cutting
Circular tube
Dynamic
Cutting force
Theoretical

A B S T R A C T

A parametric study on the axial cutting deformation of circular AA6061-T6 extrusions was completed under both dynamic and quasi-static loading conditions. Parameters which would influence the response of the cutting deformation mode, including tube diameter, tube wall thickness, number of cutter blades, and loading conditions, were investigated in the experimental tests. For the impact tests completed within this research the peak cutting load and the mean cutting force ranged from 14.45 kN to 31.31 kN and from 8.28 kN to 20.56 kN, respectively. The quasi-static peak cutting load and the mean cutting force ranged from 9.07 kN to 26.93 kN and from 7.06 kN to 24.92 kN, respectively. Generally, the axial cutting force increased with the increase of the number of cutter blades, the extrusion diameter, and the extrusion wall thickness. Comparison of the experimental results to the theoretical predictions using an analytical model developed by the authors showed that the predicted steady-state axial cutting forces agreed well with the experimental results.



## 1. Introduction

As the key structures of vehicles, thin-walled structures must dissipate the kinetic impact energy in a controllable manner while maintaining the integrity of occupant compartment during a crash. The impact force transmitted to the occupant compartment has to be in compliance with defined tolerance levels to minimize the potential injury to occupants. Energy absorption devices, such as crash boxes, have been implemented into vehicle structures to absorb impact energy during a crash and to maximize the protection to occupant safety. The energy absorption structures are usually designed to absorb the impact energy through axial progressive folding deformation mode, to maximize efficiency and to avoid possible catastrophic failure of other protected structures, and avoid an undesired global bending mode. Although progressive folding mode is usually controllable under quasi-static loading conditions [1,2], it is greatly influenced by impact speed, and both geometric and material nonlinearities, which may result in a switch in deformation mode to the unwanted and typically catastrophic global bending mode [3–5].

An alternative and efficient energy absorption deformation mode is the axial cutting deformation mode. Jin et al. [6] experimentally investigated the response of AA6061-T6 circular extrusions which were exposed to cutting deformation under quasi-static axial loading conditions. This axial cutting deformation mode illustrated an extremely high crush force efficiency (*CFE*) of approximately 95%, an almost constant cutting force, and excellent energy absorption capability. The *CFE* is defined mathematically as the mean crushing/cutting force divided by the maximum crushing/cutting force and a value of unity for the *CFE* is most desirable. Jin et al. [7] further studied the axial cutting deformation mode for the AA6061-T6 circular extrusions under both dynamic and quasi-static loading conditions. It was found that the cutting deformation mode was controllable and stable under both loading conditions. A theoretical model was also developed by Jin and Altenhof [8] to predict the steady-state cutting force for circular tubes which experienced an axial cutting deformation mode.

AA6061-T6 aluminium alloy material is an attractive material due to its superior mechanical properties such as a high strength-to-weight ratio, good corrosion resistance, excellent weldability and deformability. It has been increasingly used in many applications where the structural components are subjected to dynamic

*Abbreviations:* AA, Aluminium alloy; AISI, American Iron and Steel Institute; ASTM, American Society for Testing and Materials; *CFE*, Crush force efficiency ($P_m/P_{max}$); CNC, Computer numeric control; IEPE, Integrated electronic piezoelectric; LVDT, Linear voltage differential transformer; *SEA*, Specific energy absorption; *TEA*, Total energy absorption.

* Corresponding author. Tel.: +1 519 253 3000x2619; fax: +1 519 973 7007.
*E-mail address:* altenh1@uwindsor.ca (W. Altenhof).

0734-743X/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijimpeng.2012.03.008

**Nomenclature**

| | |
|---|---|
| $B$ | One-half of the wedge/blade shoulder width |
| $D_o$ | Original tube outer diameter |
| $F$ | Total axial cutting resistance force |
| $L$ | Length of a circular tube |
| $n$ | Number of cutter blades |
| $P_{max}$ | Peak cutting force |
| $P_m$ | Mean cutting force |
| $r_m$ | Mean radius of a circular tube |
| $r_i$ | Inner radius of a circular tube |
| $r_o$ | Outer radius of a circular tube |
| $R_{axial}$ | Axial bent radius for cut petalled sidewalls |
| $R_r$ | Rolling radius of curls at the side of the wedge/blade |
| $\theta$ | Wedge/blade semi-angle |
| $t$ | Wall thickness of circular tube |
| $T$ | Blade tip with |
| $\mu$ | Coefficient of friction |
| $\sigma_\varepsilon$ | Effective material flow stress |
| $\sigma_y$ | Material yield stress |
| $\sigma_o$ | Static material flow stress |
| $\sigma'_0$ | Dynamic material flow stress |
| $\sigma_u$ | Material ultimate stress |
| $Y$ | Reduced wall thickness of extrusion |

loading [9]. In order to determine the material properties of AA6061-T6 material under dynamic loading conditions, a significant amount of work has been carried out using a variety of experimental techniques by various authors [10–14] on the strain rate dependence of this alloy's mechanical properties. The flow stress properties of AA6061-T6 obtained by the abovementioned authors is summarized and plotted as a function of strain rate in Fig. 1. It is observed from Fig. 1 that little or no significant strain rate sensitivity exhibits at strain rates in the range $10^{-4}$ $s^{-1}$–$10^3$ $s^{-1}$, however, a significant positive strain rate sensitivity of flow stress can be observed at strain rates in excess of $10^3$ $s^{-1}$. Similar observations was also found by Jones [15] and Maiden and Green [16]. Moreover, considering the Cowper–Symonds constitutive equation for AA6061-T6 material as presented in Eqn. (1),

$$\frac{\sigma_w}{\sigma_o} = 1 + \left(\frac{\dot{\varepsilon}_e}{D}\right)^{1/q} \quad (1)$$

values for $D$ and $q$ are 12,88,000 $s^{-1}$ and 4, respectively [15], with the high value of $D$ indicating a low degree of rate sensitivity for this aluminium alloy.

In the present study, a parametric investigation of the response of circular AA6061-T6 extrusions subjected to the axial cutting deformation mode were conducted under both dynamic and quasi-static loading conditions. Extrusion geometries, namely, tube diameters and wall thicknesses, as well as cutter blade quantity were considered as variables for this parametric study. Load/displacement profiles and experimental performance measures were compared for both loading conditions to better understand the performance of the extrusions as energy absorbers as well as the rate sensitivity of AA6061-T6 material. Furthermore, the experimental determined mean cutting forces were compared to the theoretical predictions using the analytical model developed by the authors [8] to further validate the theoretical model.

## 2. Experimental test

### 2.1. Test specimens and material properties

The extrusions considered in this research are commercially available circular AA6061-T6 aluminium alloy extrusions with a stock length of 6 m and a nominal wall thickness ($t$) of 3.175 mm from the supplier. The testing specimens were cut down from the stock extrusion to a tube length ($L$) of 300 mm for each extrusion as shown in Fig. 2, making sure that both end faces of the cut extrusion were perpendicular to the axial direction of the specimen. Three different external diameters ($D_o$) of 44.45 mm, 50.8 mm, and 63.5 mm were considered.

In order to accommodate the impact capacity of the droptower testing machine, wall thickness of the specimens were reduced to the thicknesses ($Y$) of 1.0 mm, 1.25 mm, and 1.5 mm spanning a length of 250 mm as illustrated in Fig. 3. Material removal of the extrusions was completed using a CNC lathe machine as illustrated in Fig. 4. A plastic insert was firstly inserted into the extrusion to ensure axial alignment of both ends of the specimen and avoid undesired deformation during the machining process. Additionally, this process was completed in an attempt to ensure a constant wall thickness throughout the reduced region of the extrusion. The machining process was computer numerical controlled with minimal material removal in the final cut of the specimen.

Material properties of the AA6061-T6 extrusions were determined through eight tensile tests which were completed in accordance to ASTM standard E8M [17] as detailed in reference [18]. Specimens were extracted from the extrusions. The engineering stress versus engineering strain curve of one representative AA6061-T6 tensile specimen is illustrated in Fig. 5. It can be seen that AA6061-T6 has a minimal level of strain hardening and an approximate mean strain to failure of 14% over the eight tensile

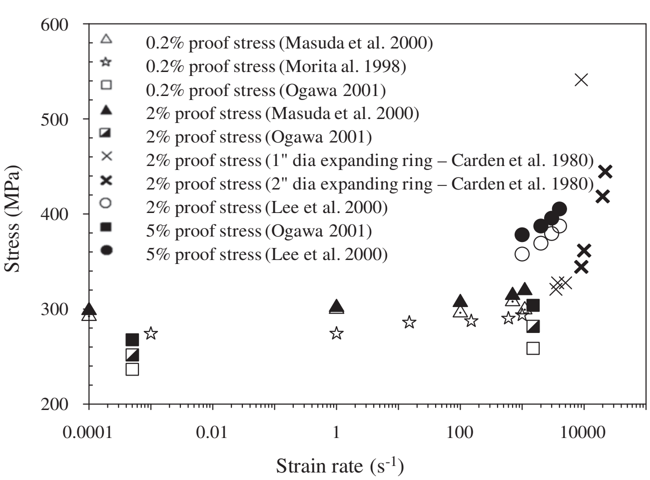


**Fig. 1.** Flow stress properties of AA6061-T6 material obtained by several authors as a function of strain rate.

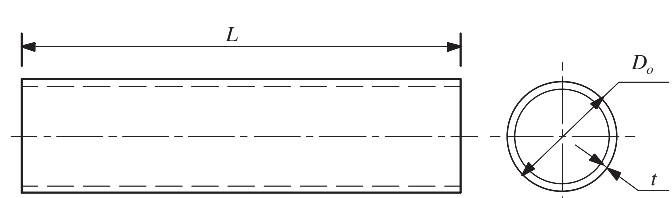


**Fig. 2.** Geometry of AA6061-T6 aluminium alloy extrusion specimens considered in present research. $L$ is the length of the extrusion specimen, $D_o$ is the nominal external diameter of the specimen and $t$ is the wall thickness of the specimen.