

An Experimental Study Investigating the Influence of the Number of Blades in a Cutter Used in Axial Cutting of AA6061-T6 and T4 Round Tubes

2010-01-0380

Published
04/12/2010

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ABSTRACT

Quasi-static axial cutting of AA6061-T6 and T4 round extrusions were completed using a specially designed cutter with multiple blades. The round specimens had a length of 200 mm, a nominal outer diameter of 50.8 mm, and a wall thickness of 3.175 mm or 1.587 mm. Four different cutters, constructed from heat treated 4140 steel, having 3, 4, 5 and 6 blades on each cutter with a nominal tip width of 1.0 mm were used to penetrate through the round extrusions. A clean cutting mode was observed for the AA6061-T6 and T4 extrusions with wall thickness of 3.175 mm with an almost constant steady state cutting force. A braided cutting mode was observed for extrusions with both tempers with wall thickness of 1.587 mm, which resulted in a slightly oscillating steady state cutting force. For all extrusions with a wall thickness of 3.175 mm, the steady state cutting force increased with an increase in the number of cutter blades. To better understand the influence of the number of cutter blades on the steady state cutting force and energy absorption characteristics of extrusions, a numerical model was developed and simulated using LS-DYNA® employing an Eulerian finite element formulation to overcome numerical instabilities associated with massive mesh distortion. Good predictive capabilities of the developed numerical model were observed and were important towards the understanding of the contribution of deformation mechanisms and friction towards the force/displacement response of the extrusions in the cutting deformation mode.

INTRODUCTION

Thin-walled metallic members have been extensively applied in structural engineering due to their low cost, high stiffness and strength to density ratio, and excellent energy absorption capabilities when subjected to axial loading. In particular,

extensive work has been performed on the study of plastic deformation of axially loaded circular and square tubes owing to their wide range of deformations that can be generated, such as progressive folding, global bending, splitting and curling, inversion, and so on [1,2]. Amongst these deformation modes, progressive folding displayed notable specific energy absorption (SEA) combined with good stroke efficiency. However, this deformation mode is highly dependent on the tube geometry and loading conditions [3,4,5,6]. Moreover, an extremely high initial peak buckling force is necessary in order to initiate such deformation mode, which may cause severe injury or damage to vehicle occupants or structures being protected.

In order to reduce the initial peak buckling force as well as to control the progressive folding deformation mode, geometrical imperfections were introduced to the tubes. Abah *et al.* [7] introduced circular cutouts at the four edges of the square AA6060-T5 extrusion, resulting in an approximate 50% reduction of the peak forces which depended on the size of the cutout and loading conditions. However, the fluctuation of buckling force after the initiation of progressive deformation mode is still unfavorable for energy absorbers. An ideal energy absorber should behave with a constant buckling force throughout the entire deformation of the extrusion.

Jin *et al.* [8] experimentally studied the cutting deformation of circular AA6061-T6 extrusions with wall thickness (t) of 3.175 mm under a quasi-static axial loading condition using a specially designed cutter. No initial peak force was observed to initiate the cutting deformation. Furthermore, extremely high crush force efficiency (CFE) of 95% and a constant steady-state cutting force were reported, which led to an ideal energy absorber. This cutting process was identified as clean cut due to the observed load/displacement response and

similar energy dissipating mechanisms as reported in references [9,10] except for the far-field petalled sidewall outward bending. Although the specific energy absorption (SEA) of the AA6061-T6 extrusion experienced a cutting deformation mode it was not as effective as the specimens which underwent progressive folding; the total energy absorption (TEA) of the extrusion experienced the cutting deformation was limited by the maximum displacement of testing machine as reported in reference [8].

Jin and Altenhof [11] further carried out numerical parametric study on the steady-state cutting force and energy absorption performance of the AA6061-T6 circular extrusions with respect to the tip width of the cutter blades. An increasing, almost linear, relationship was observed to exist between cutter blade tip width and both steady-state cutting force and energy absorption. Jin *et al.* [12] extended their experimental study on the influence of wall thickness of AA6061-T6 circular extrusion on the steady-state cutting force. An almost linear relationship between them was also observed. It is obvious from reference [11-12] that the total energy absorption of an AA6061-T6 circular extrusion can be almost linearly increased by increasing either the cutter blade tip width or the wall thickness of the extrusion.

The present research focuses on the study of energy absorption characteristics of AA6061-T6 and T4 circular extrusions subject to a cutting deformation mode generated by a multiple blade cutter. A cutter having 3, 4, 5, or 6 blades was considered to investigate its relationship to the steady-state cutting force and total energy absorption.

EXPERIMENTAL APPROACH

Quasi-static axial cutting of circular cross sectional AA6061-T6 and T4 extrusions using a multi-bladed cutter is presented in this section. Furthermore, axial crush testing without the presence of a cutter is also discussed in order to compare different deformation modes that were generated from the extrusion geometries considered.

EXPERIMENTAL TESTING

Specimens for quasi-static axial cutting or crush tests were AA6061-T6 and T4 circular cross sectional extrusions. The AA6061-T6 specimens were directly cut from commercially available extrusions. The AA6061-T4 specimens were obtained through a two-stage solution heat treating of AA6061-T6 extrusions following ASTM standard B918 [14]. To obtain the T4 temper, the AA6061-T6 extrusions were firstly placed in an oven at a temperature of 530 °C for one hour and removed from the oven using steel tongs at the end of the heating period; and immediately quenched in water at room temperature.

Both temper extrusions had a length (L) of 200 mm and a nominal outer diameter (D) of 50.8 mm with a nominal wall thickness (t) of 3.175 mm or 1.587 mm, as shown in Figure 1. Extrusions with a wall thickness of 3.175 mm are referred as a thicker wall thickness (THK) extrusion throughout this paper. Extrusions with a wall thickness of 1.587 mm are referred as a thinner wall thickness (THN) extrusion.

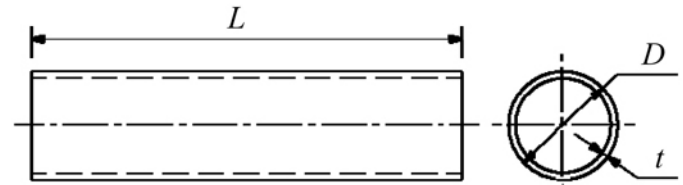


Figure 1. Extrusion geometry considered for experimental testing. Where $D = 50.8$ mm; $t = 3.175$ mm or 1.587 mm; $L = 200$ mm.

Material properties of AA6061-T6 and T4 extrusions were determined by averaging eight tensile tests presented in reference [13]. The obtained engineering stress-strain curves of a representative AA6061-T6 and T4 tensile specimen are illustrated in Figure 2. The averaged material properties are summarized in Table 1, where the yield strength is the 0.2% proof stress. It was observed that the AA6061-T6 and T4 materials had significant differences in the yield point and hardening properties. The AA6061-T6 temper material illustrated a minimal level of strain hardening while the AA6061-T4 temper material illustrated a greater amount of strain hardening.

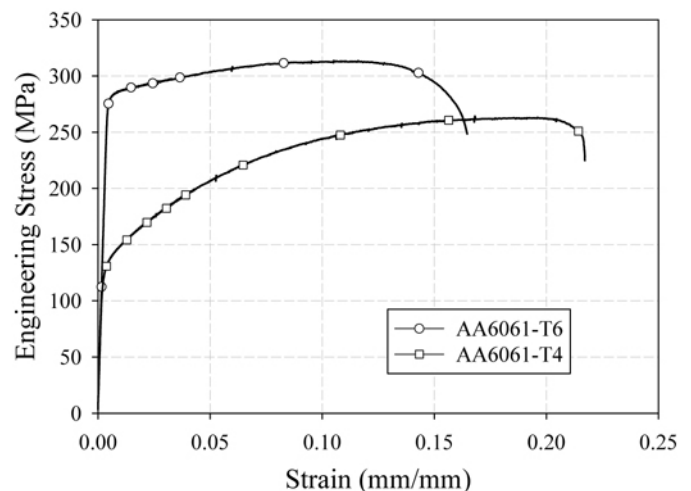


Figure 2. Engineering stress-strain curves of AA6061-T6 and T4 materials obtained from tensile testing [16]

A cutter with multiple blades of 3, 4, 5 or 6 was employed in the axial cutting tests. The cutters had an outer diameter of 101.6 mm, a block height of 20 mm, and tapered blades with a nominal blade shoulder width of 3 mm and a nominal blade

tip width of 1.0 mm, as illustrated in Figure 3. These cutters were machined from AISI 4140 round bar stock followed by a two-state heat treatment process, which was identical to the heat treatment process in reference [8]. The hardness of the cutters after heat treatment was determined to be no less than HRC 53, thus ensuring the penetration of cutter blades into the extrusion specimens without deformation or failure of the cutter blades.

Table 1. Material properties of the AA6061-T6 and T4 from tensile tests [16]

Properties	AA6061-T6	AA6061-T4
E (GPa)	68.1	65.3
σ_y (MPa)	277.5	116.2
σ_u (MPa)	320.2	258.3

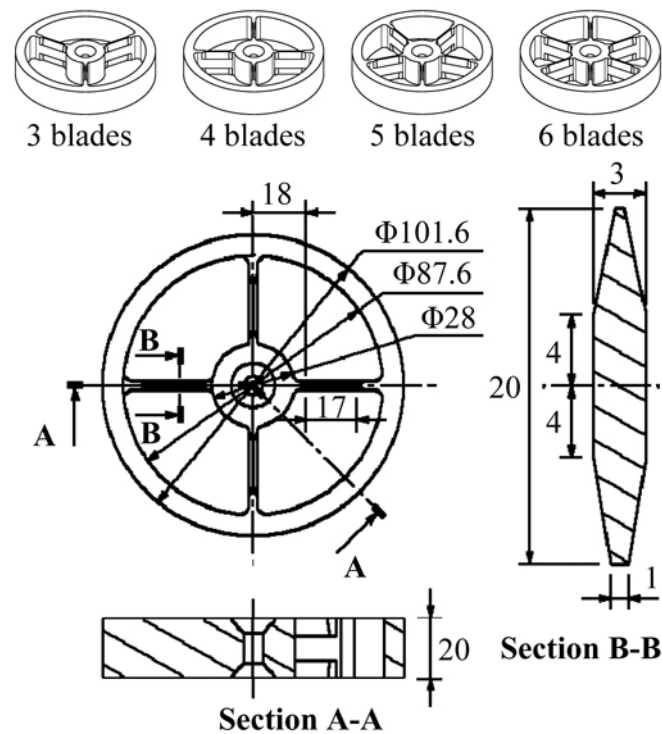


Figure 3. Geometry of cutters under consideration. (All dimensions in mm)

Quasi-static cutting or crush testing of AA6061-T6 and T4 extrusions were carried out on a Tinius-Olsen hydraulic tension/compression testing machine with a load capacity of 150 kN. The machine has a stationary upper platen and a movable lower platen. A linear voltage differential transformer (LVDT) with a range of 150 mm was used to measure the displacement of lower platen. The quasi-static compressive testing of the specimens was performed at a constant platen speed of approximately 2.2 mm/s. An approximately 140 mm platen displacement was applied to all cutting and crushing tests.

Forty-eight quasi-static axial cutting tests were completed for the AA6061-T6 and T4 specimens using the multi-bladed cutters. Furthermore, twelve quasi-static axial crush tests were also completed in order to compare the energy absorption and load/displacement response of the extrusion that generated without the presence of a cutter. The specimens tested are listed in Table 2. The identification system of the cutting tests follows the convention $\alpha_\beta\gamma$, where ‘ α ’ represents the specimen temper condition; ‘ β ’ indicates the wall thickness of extrusion (THK or THN); and ‘ γ ’ indicates the number of blades for the cutter used in the cutting tests. For tests without the presence of a cutter, no indication of ‘ γ ’ is applied.

Table 2. Cutting/crush measures of the specimens from experimental and numerical testing. The prefix ‘Sim’ in front of the name of specimen indicates the cutting measures are from numerical testing.

Specimens	P_m (kN)	P_{max} (kN)	CFE (%)	TEA (kJ)
T6_THK_3blades	39.30	42.36	92.80	5.45
T6_THK_4blades	45.16	48.52	93.05	6.19
T6_THK_5blades	50.37	54.61	92.27	6.92
T6_THK_6blades	54.30	59.64	91.03	7.53
T6_THN_3blades	15.44	18.00	85.97	2.06
T6_THN_4blades	18.44	21.73	84.77	2.47
T6_THN_5blades	22.25	26.14	85.13	3.05
T6_THN_6blades	22.41	27.34	81.97	3.09
T4_THK_3blades	28.78	31.09	92.57	3.94
T4_THK_4blades	32.85	35.30	93.07	4.54
T4_THK_5blades	38.80	41.79	92.83	5.34
T4_THK_6blades	39.57	42.63	92.80	5.43
T4_THN_3blades	10.09	11.84	85.27	1.38
T4_THN_4blades	12.72	15.08	84.33	1.74
T4_THN_5blades	17.29	18.97	91.17	2.37
T4_THN_6blades	15.81	19.07	82.90	2.17
T6_THK	98.70	145.74	67.70	14.00
T6_THN	26.48	67.55	39.23	3.70
T4_THK	68.76	98.12	70.07	9.46
T4_THN	22.35	32.99	67.73	3.15
Sim_T6_THK_3blades	35.69	41.07	86.90	1.25
Sim_T6_THK_4blades	44.69	51.48	86.80	1.57
Sim_T6_THK_5blades	51.47	58.54	88.79	1.80
Sim_T6_THK_6blades	58.35	64.16	90.90	2.04
Sim_T4_THK_3blades	25.07	28.64	87.60	0.88
Sim_T4_THK_4blades	31.35	35.75	87.70	1.10
Sim_T4_THK_5blades	36.91	40.64	90.80	1.29
Sim_T4_THK_6blades	42.08	46.54	90.40	1.47

FINITE ELEMENT MODELING AND SIMULATION

A finite element (FE) model was developed to simulate the axial cutting of AA6061-T6 and T4 THK extrusions in order

to better understand the deformation mechanisms associating to energy absorption. The explicit non-linear FE code LS-DYNA [14-15] was used to predict the response of the extrusions by employing an Eulerian FE formulation. Eight axial cutting simulations were completed for the AA6061-T6 and T4 THK extrusions cut by multiple blades.

EULERIAN FINITE ELEMENT FORMULATION

Lagrangian FE formulations are the most common in the majority of structural numerical simulations employing the FE method. However, in large deformation processes the massive mesh distortion of Lagrangian type elements will lead to significant numerical error. An alternative element selection for large deformation processes is the Eulerian or Arbitrary Lagrangian/Eulerian (ALE) FE formulations.

In the Eulerian element formulation the material coordinates and spatial coordinates of the FE mesh are dissociated and the material moves through the FE mesh. In the explicit time integration scheme, a Lagrangian formulation is first used to determine material and mesh deformation; afterwards the spatial coordinates of the FE mesh are remapped to their original position, in a process referred to as advection, and material transport to the remapped mesh occurs. In this investigation a second order accurate advection method was applied for material transport and advection was completed every five cycles in the explicit time integration scheme. As previously indicated, the FE mesh is remapped to its original position while the material coordinates are not and will move through the fixed mesh. Therefore, in this research, an airmesh must surround the original location of the extrusion material for evaluation of the deformed material as it is transported from its original configuration to its deformed state. At the start of the simulation, the airmesh contains no material and its only purpose is to accommodate deformed material during the deformation process. Care must be taken to model the airmesh large enough to account for any possible material deformation during the simulation, and yet to allow a fine enough mesh to appropriately predict deformation.

Although most research involving FE analysis of axial crushing of tubular extrusions has been conducted using a Lagrangian FE formulation, an Eulerian element was employed in the present research in order to simulate the cutter blade penetration process accurately. One of the most important aspects of the Eulerian element formulation is the capability of generating new free surfaces as a result of material transport [16,17,18,19]. Benson and Okazawa [16] studied machining of AISI 4340 steel using the Eulerian finite element formulation and successfully simulated the formation of discontinuous chips. Additionally, Raczy et al. [17] and Akarca *et al.* [18] have successfully utilized Eulerian element formulations in the study of the continuous chip

formation associated with machining of C11000 copper and 1100 aluminum, respectively. These efforts illustrated that an Eulerian element formulation was capable of simulating large material deformations and predicting chip formation which is also the case in the present study. An overview of the applicability of the Eulerian element formulation for solid mechanics problems was presented by Benson [19].

Disadvantages which may arise through use of an Eulerian FE formulation include larger CPU costs and a greater degree of mesh discretization. However this FE formulation is beneficial in dealing with the large plastic deformation processes and numerical instabilities associated with severe mesh distortion.

MODEL DEVELOPMENT

Discretization

Generation of the FE mesh for the AA6061-T6 and T4 round tubular extrusions, the tube airmesh, and the cutter blade was completed using LS-PrePost.

Due to the symmetry observed in the experimental quasi-static cutting process of the extrusions, only a portion of the tubular specimen and one corresponding cutter blade were considered in the FE model. In order to further save computational costs, only a 56 mm length of the tubular specimen was modeled since it was observed in the experimental tests that a steady-state cutting process was achieved after a cutter displacement of approximately 10 mm.

Eight-noded solid elements were utilized for the tubular extrusion, the airmesh, and the cutter blade, as shown in [Figure 4](#). A single point quadrature Eulerian element was selected for the extrusion and the airmesh. The mesh density of the tube in the vicinity of the region of contact between the cutter and extrusion was finer than all other regions. Higher discretization was completed to ensure an accurate approximation of the stress distribution and deformation near the contact region. Chip formation of the extrusion material was observed in all experimental tests with an approximate thickness of 1 mm. In an attempt to appropriately predict the deformation behaviour and chip formation, the Eulerian mesh of the extrusion and airmesh were discretized with a smallest dimension of 0.27 mm employing an aspect ratio of 1.6 in the region of contact between the extrusion and cutter. Twelve Eulerian elements through the thickness of the tube near the contact region were utilized. Transition elements were introduced between the finer mesh and coarser mesh in three directions. The airmesh was modeled with an 8 mm and 12 mm radial offset from the inner and outer surfaces of sidewall of the tube in the contact region, respectively. In all other regions, a 2.2 mm radial offset from the inner and outer surfaces of the tube sidewalls was employed. The airmesh in the axial direction was offset 1.3 mm from the top surface of