

Simulation of the Axial Cutting Deformation of AA6061-T6 Round Tubes Utilizing Eulerian and Mesh Free Finite Element Formulations

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ABSTRACT

Experimental and numerical studies have been completed on the deformation behaviour of round AA6061-T6 aluminum extrusions during an axial cutting deformation mode employing both curved and straight deflectors to control the bending deformation of petalled side walls. Round extrusions of length 200 mm with a nominal wall thickness of 3.175 mm and an external diameter of 50.8 mm were considered. A heat treated 4140 steel alloy cutter and deflectors, both straight and curved, were designed and manufactured for the testing considered. The four blades of the cutter had an approximate average thickness of 1.00 mm which were designed to penetrate through the round AA6061-T6 extrusions. Experimental observations illustrated high crush force efficiencies of 0.82 for the extrusions which experienced the cutting deformation mode with the deflectors. Total energy absorption during the cutting process was approximately 5.48 kJ. Further testing, considering extrusion lengths of 200 mm and 300 mm which resulted in progressive folding and global bending deformation modes were also completed which illustrated crush force efficiencies of 0.66 and 0.20 respectively. Numerical simulation of the axial cutting deformation process followed by contact between the cut petalled extrusion side walls with either the curved or straight deflector were simulated by employing Eulerian and Smoothed Particle Hydrodynamic (SPH) mesh free methods. Good predictive capabilities of the numerical model employing the Eulerian element formulation 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 with the presence of curved or straight deflectors.

INTRODUCTION

Occupant safety and meeting tough environmental regulations are the two major challenges for automotive designers. To minimize negative impact on the environment, fuel economy is critical requiring reduction of vehicle weight without compromising safety of vehicle occupants. The ability to absorb energy in a controlled

fashion is crucial for occupant safety during an accident. Thin-walled metal extrusions are extensively used in the vehicle structure due to their excellent energy absorbing capability and the ability of generating a wide range of deformation modes. The use of aluminum in a vehicle body becomes more popular as weight savings up to 25% can be achieved compared with conventional steel structures [1]. In addition, aluminum is favourable as a result of its corrosion resistance and recyclability.

A significant amount of theoretical and experimental research work has been performed on thin-walled structures under quasi-static and dynamic axial compression loading conditions. Abramowicz and Jones [2-3] investigated static and dynamic axial crushing behaviour of circular and square steel tubes with respect to deformation modes and geometry parameters both theoretically and experimentally. They found that theoretical predictions give reasonable agreement with the corresponding experimental results. In addition, the progressive folding deformation mode is far more effective in terms of energy absorption capabilities compared to the global bending deformation mode. An experimental study of critical parameters which govern the transition from global bending to progressive folding for circular and square thin-walled mild-steel columns subjected to static and dynamic axial loads was also performed [4]. Langseth and Hopperstad [5] experimentally investigated the behaviour of thin-walled square AA6060 aluminum extrusions with T6 and T4 tempered condition and variable wall thickness under static and dynamic axial loading conditions. It was observed that under quasi-static loading, the extrusions always exhibited a symmetric mode of deformation, with the lobe fold length being a function of the temper. Jensen et al [6] further experimentally investigated the transition behaviour between progressive folding and global bending of AA6060-T6 aluminum extrusions under quasi-static and dynamic axial loading condition with variable local (D/t) and global (L/D) slenderness of extruded members and impact velocity. They observed significantly higher energy absorption in the progressive folding deformation mode than in the global bending deformation mode and the difficulty to control deformation mode due to the dependence on impact velocity and extrusion geometry.

The major concerns in the design of components for crashworthiness are the ability to predict the mode of collapse, the repeatability of the mode of collapse and to dissipate kinetic energy of the impact in a controlled manner. Arnold and Altenhof [7] experimentally investigated crush characteristics of AA6061-T4 and T6 structural square tubes with and without the presence of circular discontinuities to initiate a progressive folding deformation mode. They observed repeatability of the collapse mode and higher crush force efficiency, but fluctuation of the crushing force associated with the progressive folding mode was significant and consistent with extrusions without any discontinuity. In an effort to control deformation mode under compression Cheng and Altenhof [8] conducted experimental investigations on the crush performance of AA6061-T6 tubes under an axial cutting deformation mode using a specially designed cutting tool. They reported an almost constant force during cutting and a high crush force efficiency of 0.80. Jin and Altenhof [9] further experimentally investigated cutting deformation of AA6061-T6 round extrusions and observed much higher crush force efficiencies of approximately 0.95 and total energy absorption capability of approximately 6.11 kJ for the specimens considered.

Finite Element Modeling using commercially available explicit non-linear FE packages is a very good resource to study crush behaviour of different structures. Langseth et al. [10] conducted numerical simulations using the FE code LS-DYNA to validate their numerical model based on experimental observations obtained from static and dynamic tests on square AA6060 aluminum extrusions with T4 and T6 tempered. The quasi-static simulations predicted the number of lobes as well as the profile of the force-displacement response quite well compared with experimental observations. The peak load and the mean load as a function of the axial displacement were predicted within $\pm 10\%$ compared with experimental data. Meguid et al [11] developed a finite element model for quasi-static axial collapse of foam-filled aluminum tubing using LS-DYNA. Their numerical findings predicted the experimentally observed overall deformation and number of folds, though the FE predictions slightly overestimated the initial collapse load. Arnold and Altenhof [12] developed a numerical model to simulate axial crushing of AA6061-T4 and T6 and AA6063-T5 structural square tubes with circular discontinuities. They found a good correlation between the results of the experimental quasi-static compressive tests and the results of the finite element simulations conducted using LS-DYNA when employing a damage mechanics material model for the extrusion.

In the present paper, both experimental testing and numerical modeling of AA6061-T6 extrusions with round cross-sectional geometry under an axial cutting deformation mode with and without the presence of straight and curved deflectors were performed to study the deformation behaviour. For comparison purposes, experimental crush tests of extrusions with identical

geometry and material under progressive folding and global bending were examined. Numerical models, employing an Eulerian finite element formulation and smooth particle hydrodynamic (SPH) mesh free methods, were developed to simulate the deformation behaviour of the AA6061-T6 round extrusions using explicit non-linear LS-DYNA finite element code.

As a result of the energy dissipation capacities of the proposed cutting mode of deformation, which will be presented in the manuscript, and the ability to tune the cutter for specific load and energy requirements, there exists a number of applications for such a device. In addition to automotive applications, other areas such as personal safety devices (harnesses) and blast mitigation are also possible.

EXPERIMENTAL APPROACH

Experimental testing of the circular AA6061-T6 extrusions under cutting deformation in the presence of straight and curve deflectors are discussed in this section. Furthermore, axial crush tests which generated global and progressive deformation modes are also discussed.

EXPERIMENTAL TESTING

In this research the specimens considered were aluminum alloy AA6061-T6 round cross sectional extrusions with a length (L) of 200 mm or 300 mm and nominal external diameter (D) of 50.8 mm with a wall thicknesses (t) of 3.175 mm. The geometry of these round extrusions is shown in Figure 1.

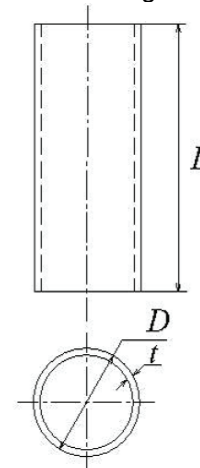


Figure 1. Geometry of AA6061-T6 aluminum alloy extrusion specimens considered in the experimental tests. L is the length of the extrusion specimen, D is the external diameter of the specimen and t is the wall thickness of the specimen.

The material properties of AA6061-T6 aluminum extrusions were obtained by performing tensile tests on specimens extracted from the stock extrusion material. Eight tensile specimens were extracted from the side walls of the tube stock in the direction of extrusion. Tensile testing was completed on an INSTRON 8562

tensile testing machine equipped with a 100 kN load cell in accordance to ASTM standard E8M [16]. The elongation of the specimen was measured using an extensometer with a gauge length of 25.4 mm. Data from the load cell and extensometer were acquired using a computer controlled data acquisition system. Load and extension measurements were recorded at a sampling rate of 5 Hz. The tests were conducted at a constant crosshead speed of 5 mm/min at room temperature. The engineering stress-strain curves of one representative AA6061-T6 tensile specimen is illustrated in Figure 2 and the material properties are summarized in Table 1. The AA6061-T6 extrusion illustrated a minimal level of strain hardening and an approximate mean strain to failure of 14%.

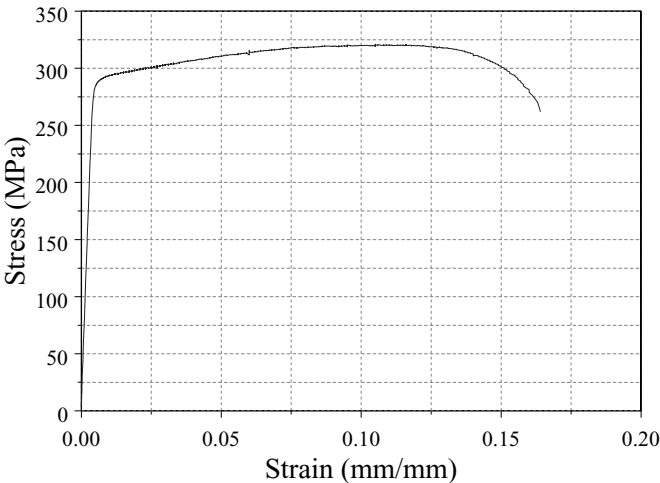


Figure 2. Engineering stress-strain curve of AA6061-T6 extrusion obtained from tensile tests [14]

Table 2. Mean values of material properties of the 6061-T6 extrusions from tensile tests [9]

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

The geometry of the cutter is presented in Figure 3. The cutters were machined from AISI 4140 round bar stock followed by a two stage heat treatment process. Hardness for the cutters was observed to be no less than approximately 52 on the Rockwell ‘C’ scale. The cutters had an outside diameter of 101.6 mm and a thickness of 20 mm. Four tapered cutting blades, 7 mm in length with a nominal blade shoulder width (W) of 6 mm were machined into the cutters. The tip widths of the cutting blades, after machining and heat treatment were measured and are listed in Table 3.

The deflectors had an outside diameter of 108 mm and a thickness of 50 mm. Two different deflector geometries, namely a straight surface profile with an angle of 41.4° to the horizontal (referred to throughout this manuscript as the straight deflector) and a curved surface profile with a radius of 50.8 mm (referred to throughout this

manuscript as the curved deflector) were considered in this research and are presented in Figure 4.

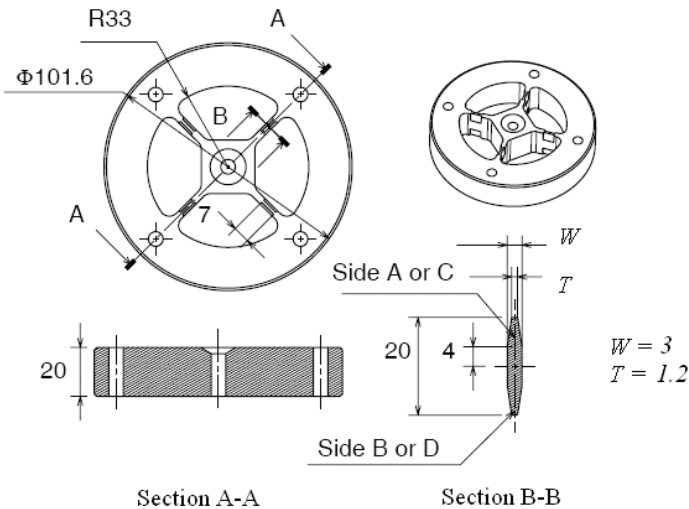


Figure 3. Geometry of the cutter used in the experimental cutting test (all dimensions in mm).

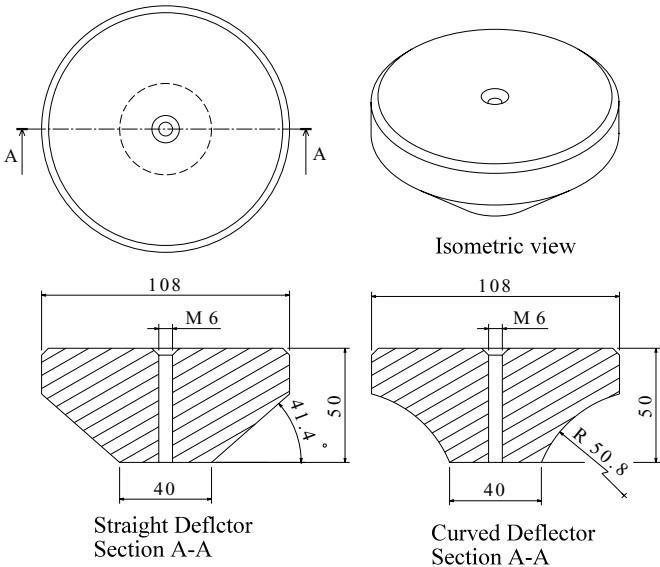


Figure 4. Geometry of the deflectors used in the experimental cutting test (all dimensions in mm).

Table 3. Cutting blade tip width dimensions of the cutters (mm).

	Blade 1	Blade 2	Blade 3	Blade 4	Avg
Side A	0.87	1.2	0.81	1.14	1.01
Side B	1.11	0.87	1.14	0.87	1.00
Side C	1.27	1.08	1.24	1.08	1.17
Side D	1.09	0.97	1.06	0.96	1.02

The quasi-static axial compressive tests of AA6061-T6 extrusions with a round cross-sectional geometry were performed using a hydraulic Tinius-Olsen tension/compression testing machine equipped with a 150 kN load cell. A linear voltage differential transformer (LVDT) with a range of 150 mm was used to measure

displacement. The measurements from the load cell and LVDT were recorded through data acquisition software at a sampling rate of 60 Hz. The compressive tests of the specimens were carried out at a constant speed of approximately 2.2 mm/s. It is generally accepted that loads applied at this velocity can be considered as quasi-static [13].

Sixty quasi-static axial cutting tests were performed on extrusions with lengths of 200 mm, utilizing the straight or curved deflector, in combination with the cutter to evaluate the energy absorption and load/displacement behaviour of the AA6061-T6 extrusions under cutting deformation mode. To compare the energy absorption capabilities and the load/displacement response between cutting deformation and progressive folding or global bending, ten quasi-static axial crush tests were also completed. Extrusions of lengths 200 mm and 300 mm were selected such that a progressive folding or global bending deformation mode resulted based upon the critical L/D and D/t ratios reported in reference [4].

FINITE ELEMENT MODELING AND SIMULATION

Two different models were developed utilizing Eulerian and Smoothed Particle Hydrodynamics (SPH) technique to predict deformation behaviour of AA6061-T6 aluminum extrusions under axial cutting mode in the presence of straight and curved deflectors. The explicit non-linear finite element code LS-DYNA [17-18] was used to simulate both models.

EULERIAN FINITE ELEMENT FORMULATION

Eulerian FE formulation is a better choice over commonly used Lagrangian FE formulation for numerical simulation of axial crushing of tubular extrusions as the massive mesh distortion of Lagrangian type elements leads to significant numerical error in large deformation processes. In the Eulerian approach, the overall mesh can be considered as two overlapping meshes, consisting of a background spatial mesh (airmesh), which is fixed in space, and material, which can flow through the fixed mesh. The purpose of airmesh is to accommodate deformed materials throughout the duration of the simulation. Special care must be taken to model the airmesh large enough to provide space around the workpiece for any possible material flow.

Model Geometry and Discretization

Finite Element Model Builder (FEMB) was used to generate the mesh for the AA6061-T6 aluminum extrusions with circular geometry, the airmesh, straight deflector, curved deflector and the cutter blade. Due to the symmetry observed in the experimental quasi-static cutting process of these specimens, only one quarter of the tubular specimen, one quarter of the deflector and one corresponding cutter blade were considered in these models. Moreover, only approximately 100 mm length of the tubular specimen was considered during modeling to minimize computational cost as it was

observed during experimental tests that a steady-state cutting process was achieved after a cutter displacement of approximately 60 mm. The geometry of the cutter and the deflectors were identical to the nominal geometry of the cutter apparatus.

The solid elements used to model the tubular extrusion, airmesh, straight deflector, curved deflector, and cutter were eight-noded solid elements. The discretization of the tubular extrusion, airmesh, deflectors, and cutter is shown in Figure 5 with the straight deflector. For the extrusion and airmesh a single point quadrature Eulerian element was utilized. As shown in Figure 5, the mesh density of the tube in the vicinity of the region of contact between the cutter and extrusion was finer than other regions in order to ensure an accurate approximation of the stress distribution and deformation near the contact region. The deflectors (either curved or straight) and the cutter utilized a constant stress (single point integration) Lagrangian element formulation.

The Eulerian mesh of the extrusion and airmesh were discretized with a smallest dimension of 0.27 mm employing an aspect ratio of 1.5 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.

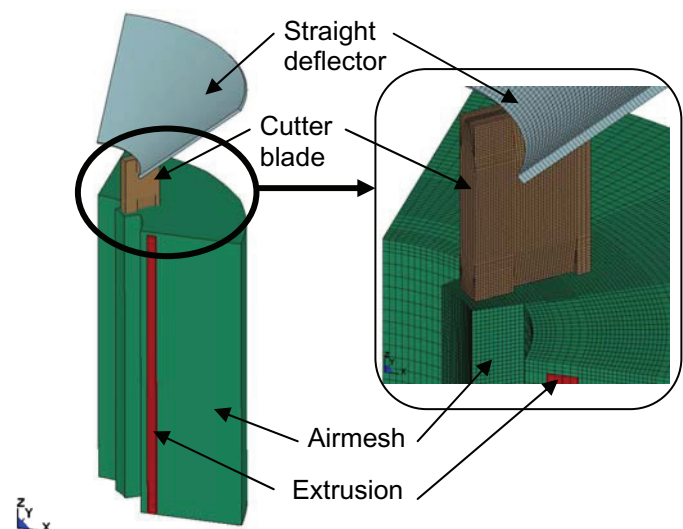


Figure 5 Discretization of the AA6061-T6 specimen, the tube airmesh, the cutter blade and the straight deflector.

Modeling Contact

Contact between the extrusion and both the cutter blade and deflector was modeled using a single constraint contact algorithm available in LS-DYNA (*CONSTRAINED_LAGRANGE_IN_SOLID). A penalty based formulation for contact was employed and nodes and a 3x3x3 point grid representing virtual nodes located at the Gauss points of the extrusion airmesh were checked for penetration in the Lagrangian surface. The