International Journal of Impact Engineering 37 (2010) 735–753

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Axial cutting of AA6061-T6 circular extrusions under impact using single- and dual-cutter configurations

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ARTICLE INFO

Article history:
Received 26 November 2008
Received in revised form
23 January 2009
Accepted 25 January 2009
Available online 6 February 2009

Keywords:
AA6061
Cutting deformation mode
Dynamic
Energy absorption

ABSTRACT

Experimental and numerical axial cutting of AA6061-T6 circular extrusions under both dynamic and quasi-static loading conditions were completed using single- and dual-cutter configurations to investigate load/displacement and collapse behaviour of the extrusions. Circular specimens with various wall thicknesses were considered for impact and quasi-static testing in this research. A steel cutter (AISI 4140) with four blades, having blade tip widths of 1.0 mm or 0.75 mm and blade lengths of 7 mm or 26.1 mm were used to cut through the extrusions. Straight and curved deflector profiles were used to flare the cut petalled sidewalls and facilitate the cutting system. Further quasi-static cutting tests using dual cutters were completed with or without the presence of a spacer to examine the load/displacement response as an adaptive energy absorption system. Results from the experimental impact tests illustrated that a higher peak cutting force, with a magnitude of approximately 1.09–1.98 times that of the force necessary under quasi-static testing conditions, was needed to initiate the cutting deformation mode. After this initial high force, the load/displacement responses were observed to be similar to those from the quasi-static tests with the exception of minor variations which resulted from material fracture that occurred on the petalled sidewalls during dynamic testing. Larger lengths of cutter blades and the curved deflector eased the flaring of the petalled sidewalls and reduced the occurrence of material fracture. The blade tip width had minor effects on the initial peak cutting force and mean cutting forces for extrusions under impact loading. The mean cutting force from the dynamic tests was determined to be 0.82–1.2 times that from the quasi-static experimental tests. Finally, quasi-static axial crushing of extrusions was completed to compare crashworthiness measures with the adaptive energy absorption system under the cutting deformation mode. A finite element model incorporating an Eulerian formulation was selected for the numerical model to simulate the cutting process. Simulation results generally agreed well with the experimental tests with a maximum over prediction of approximately 33% and 18% for the cutting force under impact and quasi-static loading, respectively.

1. Introduction

Vehicular passive safety requires energy dissipation devices to effectively absorb the kinetic energy at impact through plastic deformation (bending, folding, twisting or other) while maintaining the integrity of the occupant compartment. Moreover, the impact force transmitted to the occupant compartment has to be in compliance with defined tolerance levels. Hence, the ability to absorb impact energy in a stable and controlled manner is crucial for occupant safety.

Thin-walled tubes, particularly those of square or circular cross-section, are a common type of energy absorber owning to the wide range of deformations that can be generated and their effectiveness to absorb energy.

Abramowicz and Jones [1,2] experimentally investigated the crush behaviour of mild steel tubes with circular and square cross-sections under quasi-static and dynamic axial loading conditions. Langseth and Hopperstad [3] experimentally studied the crush behaviour of square AA6060-T4, T4* and T6 extrusions under quasi-static and dynamic axial loadings. It was observed in references [1–3] that significantly higher energy absorption was observed for

Abbreviations: AA, aluminium alloy; AISI, American Iron and Steel Institute; ALE, arbitrary Lagrangian/Eulerian; ASTM, American Society for Testing and Materials; CD, curved deflector; *CFE*, crush force efficiency; CNC, computer numeric control; CPU, central processing unit; FE, finite element; IEPE, integrated electronic piezo-electric; LVDT, linear voltage differential transformer; SD, straight deflector; *SEA*, specific energy absorption; *TEA*, total energy absorption.

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doi:10.1016/j.ijimpeng.2009.01.003

Nomenclature

B	half of the nominal blade shoulder width
D	material constant in the Cowper–Symonds constitutive equation
D_{ij}^p	the plastic component of the rate of deformation tensor
$\bar{\varepsilon}^p$	effective plastic strain
$\dot{\varepsilon}_e$	rate of effective plastic strain
E	Young's modulus
L	length of an extrusion
P_m	mean axial crushing force
$P_{\max}$	maximum axial crushing force
q	material constant in the Cowper–Symonds constitutive equation
R	rolling radius
R_m	extrusion mean radius
S_{ij}	deviatoric stress tensor
SEP_m	standard error for mean cutting force
t	wall thickness of the extrusion
T	cutter nominal blade tip width
σ_e	material flow stress under an elevated strain rate
σ_o	material flow stress under a quasi-static strain rate
σ_y	material yield stress
σ_u	material ultimate stress
$\bar{\sigma}$	equivalent von Mises stress
v_o	impact velocity
Φ	external diameter of a circular extrusion
W	cutter nominal blade length
Y	reduced wall thickness of the extrusion

tubes that underwent progressive folding compared to tubes that experienced global bending. A high peak force was observed to initiate the progressive folding deformation within the tubes and the crush force oscillated significantly during the formation of the lobes. This peak force was observed to be approximately 50% higher for dynamic tests compared to quasi-static tests.

Abramowicz and Jones [4] further studied the influence of tube geometrical parameters on the collapse behaviour of circular and square cross-sectional steel tubes under quasi-static and dynamic axial loading conditions. It was observed that tubes that experienced progressive folding under quasi-static axial loading might collapse with a different deformation mode under dynamic conditions.

Jensen et al. [5] experimentally studied the transition between collapse modes of square cross-sectional AA6060-T6 extrusions under quasi-static and dynamic axial loading conditions with respect to the extrusion geometries. Guillow et al. [6] experimentally studied the transition behaviour of AA6060-T5 circular cross-sectional extrusions under quasi-static axial loading. Experimental observations from references [4–6] indicated a critical tube length for buckling transition exists under static loading, for a given extrusion material and cross-sectional geometry. Extrusions shorter than this critical length collapsed progressively, while longer extrusions developed a global bending mode. However, for dynamic loading conditions, the collapse mode of the extrusion was no longer dependent only on material properties, boundary conditions and extrusion geometries but also depended on the impact velocity. Furthermore, extrusion imperfections played an important role in dynamic crush conditions [5]. Thus, the collapse behaviour of an extrusion under dynamic loading conditions is very unstable and difficult to control.

In order to control and stabilize the collapse mode of extrusions under axial loading conditions, crush initiators are introduced. Two categories of initiators, namely, material property variations and geometrical discontinuities exist. Geometrical discontinuities, due to their easy implementation, are commonly used to initiate a specific collapse mode and improve the stability of deformation.

Abah et al. [7] experimentally and numerically examined square AA6060-T5 extrusions with or without a circular cut-out at the four edges of the extrusion: a reduction of the peak forces of approximately 26–50% was observed for both quasi-static and dynamic loading conditions, depending on the size of the cut-out. However, the mean crush load was observed to remain relatively constant for both loading conditions.

Arnold and Altenhof [8] experimentally studied the crush behaviour of square AA6061-T4 and T6 extrusions with and without centrally located circular discontinuities under quasi-static axial loading. A reduction of the peak crush load and a higher crush force efficiency (*CFE*) were observed for extrusions with discontinuities. Furthermore, the energy absorption capacity was greatly improved by altering the deformation mode within the extrusion through the implementation of discontinuities.

The control of the collapse mode of the extrusion is reliable under quasi-static axial loading through the implementation of initiators. However, the initiation of the desired deformation mode is more complicated under dynamic loading since the collapse mode is very dependent on the impact velocity [5]. An undesirable collapse mode may have very poor energy dissipation.

In order to overcome the dependence of extrusion geometry on the generation of progressive folding deformation mode, reduce the high peak load, and improve the *CFE*, Cheng and Altenhof [9] experimentally investigated square AA6061-T6 extrusions under cutting deformation mode by using a specially designed cutter. A high *CFE* of approximately 80% and an almost constant load/displacement response were observed after a transient cutting stage and prior to contact between the cutter hub and the petalled sidewall.

The cutting deformation mode of thin-walled plates, as an important energy absorbing mechanism, has received considerable attention and a thorough literature review dealing with experimental and theoretical analyses of the cutting force generated by the penetration and cutting of a wedge through a steel thin-walled plate has been presented by Lu and Calladine [10], and Simonsen and Wierzbicki [11]. Depending on the deformation behaviour, three categories of the cutting process were identified in references [11,12], namely a stable (or clean) cut, braided cut, and concertina tearing. The mechanics of the cutting process are complicated because they involve plastic flow, fracture of the plate in the vicinity of the wedge tip, membrane deformation of the plate, and friction between the wedge and plate. The analysis of the cutting deformation involves two stages: the initial wedge penetration (transient) stage and the steady-state cutting stage. Analytical models were developed by Simonsen and Wierzbicki [11], and Zheng and Wierzbicki [12] to predict the cutting resistance force considering the contribution of a finite shoulder width ($2 \cdot B$) of the wedge for the steady-state cutting process under a stable cut. Three major energy dissipation mechanisms [11,12] were considered in the development of the analytical models, namely, crack tip zone in front of the wedge (ductile fracture and moving hinge line), membrane deformation, and friction.

Jin et al. [13] conducted experimental studies on the cutting deformation of circular AA6061-T6 tubes utilizing the cutter