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A semi-empirical analytical model to predict the axial cutting force of AZ31B magnesium extrusions

John Magliaro[a], Peter Shery[a], Ryan Smith[a], William Altenhof[a,*], Elmar Beeh[b], Philipp Straßburger[b], Thomas Grünheid[b]

[a] Department of Mechanical, Automotive and Materials Engineering, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4
[b] Institute of Vehicle Concepts, German Aerospace Center, Pfaffenwaldring 38-40, Stuttgart, Germany

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ABSTRACT

In several industries where weight reduction is a crucial design goal, especially transportation, magnesium alloys are becoming a favourable option to further innovate since magnesium is the lightest structural metal available. Cylindrical, seamless extrusions composed of AZ31B magnesium alloy were subjected to quasi-static and dynamic axial cutting to assess the potential for magnesium alloys to be exploited for crashworthiness applications. Geometrically similar aluminum extrusions composed of AA6061-T6 and AA6082-T6 alloys, which are commonly utilised for energy absorbers, were also tested under similar loading conditions to provide data for comparison. A semi-empirical model to predict the cutting forces in magnesium extrusions was derived using the experimental findings from this study. This revised model accounts for the discontinuous chip formation mechanism and frictional effects more appropriately than previously developed models. The extrusions possessed 1.5 mm wall thicknesses, outer diameters of 57 mm or 62 mm, and free lengths of 180 mm. Quasi-static tests were conducted on a Tinius-Olsen compression machine and dynamic tests on a drop tower with a 57 kg falling mass at an impact velocity of 7 m/s. Under the observed cutting deformation mode, all specimens produced evenly sized, petalled sidewalls. However, for the aluminum extrusions long, continuous chips formed ahead of the cutter while short, discontinuous chips formed for the magnesium extrusions. The corresponding energy dissipation ranged from 1.23 kJ to 3.57 kJ for the aluminum specimens and 0.63–0.72 kJ for the magnesium specimens.

1. Introduction

There are numerous advantages to implementing lightweight materials in mechanical assemblies. Vehicle manufacturers are driven by increased consumer and legislative demand for vehicles with reduced greenhouse gas emissions. Aluminum alloys generally offer favourable mechanical properties with additional incentives such as reduced weight and machining costs compared to steel. Magnesium alloys are also an emerging alternative to steel for several vehicle subsystems [1]. A key advantage which has stimulated interest in magnesium alloys is their relatively low weight; the density of magnesium is approximately 60% that of aluminum. Thin walled, metallic extrusions can be used as effective energy absorbers because they offer a high degree of control in their force/displacement response [2]. The sacrificial nature of energy absorbers combined with their relatively large geometries are design challenges which can be offset by more lightweight, inexpensive materials.

However, no amount of weight or cost reduction can warrant a design change if crashworthiness is compromised. Therefore, extensive knowledge of the mechanical properties for any new material must be well established before implementation. While there are several manuscripts which investigate manufacturing techniques for magnesium alloys [3–10], literature related to mechanical performance is scarcer. Easton *et al.* [11] tested AZ31 magnesium extrusions under both quasi-static and dynamic axial crushing. Their work concluded rather than experiencing progressive folding, a characteristic failure mode in ductile materials, the AZ31 extrusion deformed by a mode referred to as segment fracture or "sharding".

Additionally, a novel energy dissipation system comprising a hollow metallic extrusion compressed axially through a tool with fixed blades [12] has been developed at the University of Windsor; the energy dissipation mechanism is referred to as axial cutting. Axial cutting yields a near-constant load/deflection response [13] which is advantageous to

Abbreviations: P_m, mean cut/crush load; SEA, specific energy absorbed; TEA, total energy absorbed; CFE, cut/crush force efficiency

* Corresponding author.
E-mail address: altenh1@uwindsor.ca (W. Altenhof).

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Nomenclature

$\dot{E}_{b\_far\_field}$	rate of energy dissipation for far-field bending
$\dot{E}_{b\_axial}$	rate of energy dissipation for cut petalled sidewall bending outward
$\dot{E}_{chip}$	rate of energy dissipation due to continuous chip formation
$\dot{E}_{m\_trans}$	rate of energy dissipation for membrane deformation zone between the transient and stable flaps
$\dot{E}_{tip}$	rate of energy dissipation for membrane deformation in the vicinity of the blade tip
F_p	axial cutting resistance force without effect of friction force
F_f	friction force
F	total axial cutting resistance force
F_{chip}	amplitude force to form discontinuous chip for one blade
F_{model}	total cutting resistance force predicted by physical models
F_{exp}	total cutting resistance force measured during experiments
P	axial load
δ	crosshead position
B	one- half of wedge/blade shoulder width
θ	wedge/blade semi angle
t	wall thickness of an extrusion
T	blade tip width
A_c	contact area between blade and extrusion
μ	coefficient of friction
σ_f	fracture stress of extrusion material
σ_o	flow stress of extrusion material
V	blade advancing velocity in the axial direction
r_i	inner radius of an extrusion
r_o	outer radius of an extrusion
R_{axial}	axial bent radius for cut petalled sidewalls
R_r	rolling radius of curls at the side of the wedge/blade
r_m	mean radius of an extrusion
n	number of cutter blades
ζ	angle between bent petalled sidewall and axial direction
l_t	length of tear in axial direction
d_c	crack depth normal to cutting direction
$Error$	relative difference as a percentage between experimental and theoretical cutting forces

passenger safety in a vehicular crash scenario. The goal of this study was to observe the force/displacement response of both aluminum and magnesium alloys under several different loading conditions. Thin walled, circular extrusions of AA6061-T6 aluminum, AA6082-T6 aluminum and AZ31B magnesium alloys were prepared with similar geometries and subjected to quasi-static and dynamic axial cutting. The experimental load/deflection data is presented in the following sections along with key metrics including: specific energy absorption (SEA) and cutting/crushing force efficiency (CFE).

Finally, a semi-empirical model was developed to allow for reasonable cutting force predictions of magnesium alloys. This was a major effort in this study; correspondingly, the experimental work was limited to axial cutting for validation purposes. Successful modeling efforts, both numerical and analytical, are of great interest to design engineers. No other models to predict the cutting deformation of magnesium alloys have been proposed.

2. Literature review

While a plethora of studies can be found relating to the manufacturing and machining of magnesium fewer studies investigated its mechanical performance. Wagner et al. [14] tested magnesium extruded beams under quasi-static and dynamic axial crushing. A finite element model was developed utilising the explicit finite element code LS-DYNA; the model's predictions were compared to their respective test results. The flanges were machined to tapered ends, which served as locations of high stress concentration and failure initiation. Under crush load application, the beams produced an even, sequential collapse. The FEA results tended to over predict the energy absorption capabilities of the extrusions, however, a high degree of repeatability was observed for the experimental load/displacement results. Segment fracture or “sharding” was observed by other authors [15,16] in addition to Easton studying magnesium extrusions under axial crushing. However, the onset of sharding appears to only be initiated when the wall thickness of an extrusion exceeds a critical value. Below this critical thickness AZ31B magnesium alloy extrusions have been shown to fail by global buckling [17], consistently producing a single kink, which is an ineffective use of material since the energy absorption performance is poor. By contrast, the same loading conditions on geometrically similar AA6061-T6 aluminum extrusions were observed to deform with multiple, progressive folds. However, the specific energy absorption (SEA) of the AZ31 extrusions was comparable to, or even slightly greater than similar AA6061-T6 aluminum extrusions at increased displacements [11]. Additionally, a new magnesium alloy referred to as AM-EX1 was developed with an average grain size three times smaller than that found in AZ31; this resulted in a tensile strength comparable to 6000 series aluminum with exceptional ductility. While studies of this nature offer the most direct benefits when studying mechanical performance, a comprehensive understanding of the effects of magnesium processing is also necessary to create ideal magnesium alloys.

Studying manufacturing techniques generally involves a myriad of tests with extensive data collection since there are a large number of process variables (cooling rate, ram speed, etc.) which can affect the final microstructure. However, the development of new magnesium alloys is complex and tailoring the material properties is not a straightforward process. For example, impacts on tensile strength and ductility are treated separately since the improvement of one material property will often adversely affect the other. One must also acknowledge that despite its advantages, magnesium has several disadvantages compared to more traditional materials. Compared to aluminum, magnesium alloys are more expensive, not as easily formable, and more susceptible to corrosion.

In addition to the manufacturing challenges, magnesium possesses a significantly different microstructure than aluminum; consequently, the deformation mechanisms differ greatly. Magnesium is characterized by a hexagonal close-packed crystal structure, which possesses more slip directions than the face centered cubic structure of aluminum. The deformation of magnesium was determined to be caused by a combination of basal slip and twinning [18–20]. Magnesium is also strain-rate sensitive [21]; accounting for this property increases the level of difficulty when predicting mechanical response. The tension-compression asymmetry [22] and anisotropic nature of aluminum [18,23] further complicate the development of reliable numerical models for magnesium structures. The flow stress behaviour of AZ31 alloys was found to vary with different loading directions [24]; significant strain hardening was also observed.

Given the numerous complex parameters in magnesium deformation, numerically modeling the deformation of magnesium alloys has developed into another research category in recent history. Experimental compression tests have been conducted on thin-walled aluminum extrusions to calibrate the performance of numerical models [25,26]. Steglich et al. [27] developed numerical models of thin-walled, square profile magnesium extrusions under axial crushing and compared the predictions to experimental test results. Their work focused on AZ31 and ZE10 alloys tested in three different configurations: the