Light Metals 2015
Edited by: Margaret Hyland
TMS (The Minerals, Metals & Materials Society), 2015

Load/Displacement and Energy Dissipation Performances of Aluminum and Magnesium Extrusions Subjected to Quasi-Static and Dynamic Loading under Axial Crush and Cutting Deformation Modes

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Keywords: Magnesium, Aluminum, Axial Crushing, Axial Cutting

Abstract

Findings from quasi-static and impact loading of aluminum (AA6082-T6) and magnesium (AZ31B-F) circular extrusions when subjected to crush and cutting modes of deformation are presented. Circular cross sectional extrusion geometry with a thickness of 1.5 mm, a diameter of 62 mm, and lengths equal to 300 mm were selected. Dynamic loading resulted from impact with a dropping mass of 57 kg at a velocity of 7 m/s. Under cutting deformation, the aluminum alloy extrusions generated lengthy chips ahead of the cutter followed by stable formation of petalled cut side walls. The magnesium extrusions, illustrated the formation of small chips and sides walls which often, although not consistently, fractured. Energy dissipation was noted to be greater and the deformation more stable for the aluminum extrusions. Under a cutting deformation mode, energy dissipation of 0.621 - 0.684 kJ for the magnesium extrusions was found compared to 1.20 - 1.23 kJ for the aluminum extrusions.

Introduction

Driven by the growing demand for increased fuel economy and superior vehicle performance, it has become important for vehicle manufactures to integrate lightweight structures into vehicle production to reduce curb weight and maintain a highly competitive production line within a global economy. Owing to their favorable mechanical properties and other incentives such as minimized manufacturing cost through the reduction of tooling, materials such as aluminum and magnesium alloys have become strong contenders to replace many traditional steel components within vehicle sub systems [1]. One particular area where the implementation of alloys has generated significant interest is vehicle crash safety. Experimental research has demonstrated that many thin walled structures constructed using lightweight alloys show excellent energy absorbing potential under a variety of loading conditions and deformation modes. The use of thin walled structures also offers a great degree of control over the mechanical response of an energy absorbing structure through the use of various cross sectional geometries as well as the addition of matrix particulate materials [2].

In the work of Wagner et. al [3] AM30 magnesium extruded beams were tested under both quasi-static and dynamic axial crushing as well and four point bending loading conditions. The experimental load/displacement results were then compared to those predicted by an FEA model simulated using LS-DYNA for each respective test. The beams utilized the double top hat geometrical configuration. For both the quasi-static and dynamic axial tests a large section of the flange were removed from each tube and a "bump" was created on the top and bottom tube surface to act as a crush trigger to produce a sequential collapse. Material cracking and separation were observed under all 3 distinct loading conditions. FEA results were observed to have a tendency to over predict the energy absorbing capabilities of the specimens however experimental load/displacement data demonstrated a high degree of repeatability for all tests.

In addition to crushing, axial cutting has been investigated as a means of energy absorption under both quasi-static and dynamic loads. In the work of Majumder et. al [4] AA6061-T4 and -T6 aluminum extrusions were subjected to quasi-static axial cutting using a custom 4 blade cutting tool. Tests were completed using a Tinius Olsen compression testing machine and test specimens machined to a wall thickness of 1.587 mm or 3.175 mm were investigated. It was observed that the cutting deformation mode was stable and repeatable for all specimens considered and a crush force efficiency as high as 0.92 was achieved. Jin et. al [5] expanded upon the work of [4] through the completion of a parametric study on AA6061-T6 aluminum extrusions subjected to both quasi-static and dynamic axial cutting. Parameters examined during the study included extrusion diameter, wall thickness, number of cutting blades, and loading condition. Levels of absorbed energy for quasi-static and dynamic axial cutting modes ranged from 1.01-3.44 kJ and 1.50-2.18 kJ respectively. Additionally, the axial cutting force was noted to increase with the increase in cutting blade quantity and increased wall thickness.

To further understand the cutting deformation mode as a means of energy absorption, an experimental study has been completed investigating the mechanical responses of 6082-T6 aluminum and AZ31B magnesium circular thin walled extrusions subjected to both quasi-static and dynamic axial cutting as well as axial crushing loads. This paper presents the collected experimental load/displacement data as well as computed metrics such as crushing force efficiency (CFE) and specific energy absorption (SEA) to provide a thorough assessment of the mechanical performance of each alloy when utilized as an energy absorbing structure.

Experimental Testing Procedure

Specimen Preparation

The aluminum and magnesium extrusions considered in this research were cut from commercially available 6082-T6 and

AZ31B extrusions. The aluminum extrusions possessed an outer diameter of 60 mm and a wall thickness of 3 mm. The magnesium extrusions had an outer diameter of 65 mm and wall thickness of 3 mm.

Prior to testing, both the aluminum and magnesium extrusions required minor modifications to ensure proper fitment within the test fixture used during impact testing and to ensure the specimens were well suited to the impact energy capacity of the drop tower system. First, the outer diameter (D_o) of the magnesium extrusions was reduced from 65 mm to 63.5 mm to ensure proper fitment of a support cup utilized during impact testing. Second, a threaded section was removed from the aluminum samples to achieve a uniform surface profile along the length of the extrusion. Finally, the wall thickness of both the aluminum and magnesium extrusions was reduced to 1.5 mm over a section spanning 130 mm measured from the extrusion free end. All material modification was completed using a conventional lathe operated by a professional technician. When machining the thin walled 130 mm section, a plastic insert was placed within the extrusion to minimize the risk of extrusion bending during the material removal process and to ensure that a consistent wall thickness was retained. The shoulder created as a result of machining the thin walled section was cut with a 45° chamfer in an effort to minimize the creation of localized stress concentrations upon loading of the extrusions.

Preparation of Cutting Tool

The four blade cutting tool and deflector utilized during quasi-static and impact axial cutting tests is consistent to that used in previous experimental studies completed by [4] and [5]. The cutting tool has an outer diameter and thickness of 101.6 mm and 20 mm respectively. The cutting blades contained within the tool possess a nominal blade shoulder width (2B) of 3 mm, a nominal blade tip width (T) of 1 mm, and a nominal blade length (w) of 26.1 mm. The conical deflector possesses an upper diameter of 108 mm, a lower diameter of 23 mm, a thickness of 50 mm, and a radius of 50.8 mm. Both the cutting tool and deflector were machined from a section of AISI 4140 round bar stock using a computer numeric controlled (CNC) milling machine. Following the CNC machining process, the cutting tool and deflector were subjected to a two-stage heat treatment process which left the pieces with an experimentally determined hardness of no less than HRC 53. Readers are encourage to review [6] for a comprehensive overview of the two-stage heat treatment process utilized in the manufacturing process of the cutter and deflector.

Quasi-Static Crushing and Cutting

Quasi-static axial crushing and cutting tests were completed on a hydraulically operated Tinius-Olsen compression testing machine. Extrusions were positioned such that the centre longitudinal axis of the extrusion, consistent to that indicated in Figure 1, was parallel to the translating direction of the machine crosshead and centered within the machine platen. Prior to testing, the 4 blade cutting tool and deflector were manually coupled using a simple socket head screw. The cutter and deflector assembly was subsequently manually placed on top of the extrusion. A careful visual check was completed to ensure that the centre axis of the extrusion and cutting tool were in alignment after placement. Axial compressive forces were measured using a PCB 90 kN 1204-02A strain gauge based load cell. Vertical displacement of the compression testing machine crosshead was measured using an Acuity AR700-12 high accuracy non-contact laser displacement sensor with an operating range of 300 mm. Information from the PCB load cell and displacement transducer were recorded by a laptop computer equipped with custom programmed LabVIEW software at a sampling rate of 60 Hz. All quasi-static test trials were completed at a crosshead speed of approximately 1.3 mm/s at room temperature.

Dynamic Impact Crushing and Cutting

Dynamic axial cutting and crushing test trials were completed on a custom designed drop tower system. The drop tower system consists of a primary support frame, a pneumatic accelerator, guide posts, a vertically translating carriage/dropping entity with a mass of 53.7 kg, and a support device with an integrated 3 jaw chuck. A 6061-T6 aluminum plate, with a thickness of 25.4 mm, was secured to the translating carriage and acted as the impacting surface between the cutting tool/extrusion during test trials. An AISI 4140 steel disk was used to mount the lower load cell and also to provide a surface for the 3 jaw chuck to clamp and constrain the test apparatus without physically contacting the load cell. The lower load cell was fastened to the steel disk using a 1/4-28 copper mounting stud. A support cup was fastened to the top of the lower load cell using an identical mounting stud. Extrusions were placed within the support cup such that the centre axis of the extrusion was parallel to the translating direction of the dropping entity. No mechanical fastening was used to secure the extrusions within the support cup.

Displacement of the dropping entity was measured using an Acuity AR700-12 high accuracy non-contact laser displacement sensor with an operating range of 300 mm. Axial forces arising during the impact event were measured by PCB 200C20 and PCB 200C50 load cells. The PCB 200C50 load cell, which was designated as the upper load cell, was mounted on top of the conical deflector and was utilized to measure the forces arising during the impact occurring between the aluminum impacting plate of the dropping entity and deflector. The PCB 200C20 load cell which was designated as the lower load cell was utilized to measure the impact cutting forces. For tests investigating impact crushing only the lower load cell was utilized in the measurement of force data as impact occurred between impacting surface of the dropping entity and extrusion.

Data from the upper and lower load cells was measured using a NI 9233 24-Bit IEPE DAQ module with a maximum sampling rate of 50 kHz per channel. Analog voltage output from the laser displacement transducer was measured using a NI 9215 4 channel 16-Bit analog input DAQ module. Both the NI 9233 and 9215 were mounted within a CompactDAQ NI 9174 chassis. Measurement data from both the displacement transducer and load cells was recorded using a laptop personal computer installed with custom programmed LabVIEW data acquisition software. A data sampling rate of 50 kHz was implemented for each impact test. Visual data was collected using a Photron SA4 high speed camera. For the purposes of this study all tests were filmed at a frame rate of 5000 frames/s, a shutter speed of 1/12000 s, and at a resolution of 1024 x 800 pixels^2. Time synchronization of the measured and visual data sets was accomplished by a NI 9401 TTL input/output module also mounted within the NI 9174 chassis. A predetermined voltage was selected within the LabVIEW software corresponding to measurement data received from the laser displacement transducer. Voltage values typically corresponded to operational output voltage limit of the transducer. Once the appropriate voltage was recognized by the LabVIEW software a digital output signal was sent to both the high speed camera and DAQ system to initiate the collection of both measured and visual data from the upper and lower load cells as well as the high speed camera just prior to impact.

Consistent to the methodology described in [5] a small pre-cut was formed prior to each impact cutting test in an effort to minimize any misalignment between the cutting tool assembly and extrusion as it may lead to an undesired transition from cutting to a global buckling/bending mode of deformation. Formation of the pre-cut was completed by placing the cutter/deflector assembly on top of the extrusion. A visual check was completed to ensure that the centre axis of the cutter and extrusion were in alignment and the specimen was placed on a nearby loading frame. A conventional bottle jack was used to push the extrusion upwards and force the cutting tool into the specimen creating a pre-cut of approximately 1 mm in depth. For each test the carriage/dropping entity of the drop tower was raised to a height of 1514 mm. When required, the pneumatic accelerator was pressurized to approximately 620 kPa which accelerated the carriage of the drop tower to a velocity of roughly 7 m/s prior to impact.

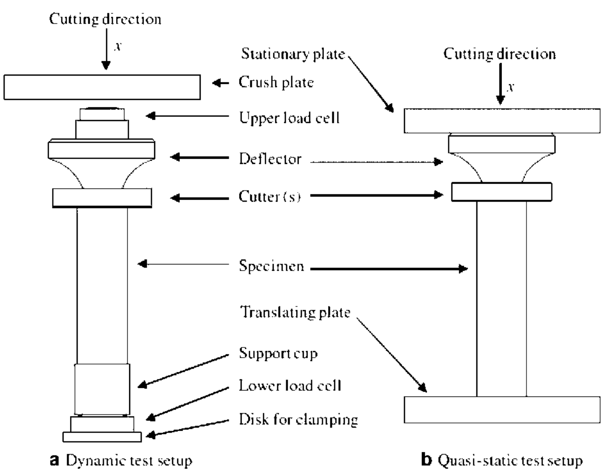


Figure 1: Schematic diagram for axial cutting tests. (a) Impact test setup. (b) Quasi-static test setup

Specimen Grouping and Performance Parameters

Test specimens were identified using the naming convention α_#_β_γ where 'α' indicates the material composition of the extrusion (Al or Mg); '#' indicates the test number for a particular testing configuration; 'β' indicates the deformation mechanism (cutting or bending); and 'γ' indicates represents the loading condition for a given test ('Dyn' for dynamic and 'QS' for quasi-static). The mechanical performance of the extrusions was assessed using a number of computed parameters which include the total energy absorbed, the mean crushing/cutting force, the crush force efficiency, and specific energy absorption. The total energy absorbed (*TEA*) is defined as the area bound by the experimentally recorded force versus axial displacement curve. Numerical integration using a rectangular rule as defined in equation (1) was utilized in computing the area.

$$TEA = \sum_{i-1}^{n-2} P_i * \left(\frac{\delta_{i+1} - \delta_{i-1}}{2} \right) \tag{1}$$

The average crushing force (P_m) is defined as the average value of the crushing or bending force calculated over the total displacement of the testing machine crosshead or drop tower carriage.

$$P_m = \frac{\sum_{i-2}^{n-1} (\delta_{i+1} - \delta_{i-1})/2}{\delta_{total}} = \frac{TEA}{\delta_{total}} \tag{2}$$

The crushing force efficiency (*CFE*) is defined as the ratio of the average crushing force (P_m) normalized with respect to the peak crushing load.

$$CFE = \frac{P_m}{P_{\max}} \tag{3}$$

The specific energy absorption (SEA) is defined at the total energy absorbed by the extrusion normalized with respect to the extrusion mass.

$$SEA = \frac{TEA}{m} \tag{4}$$

Experimental Observations and Discussion

Quasi-Static Crushing and Cutting Test Results

Axial Crushing:

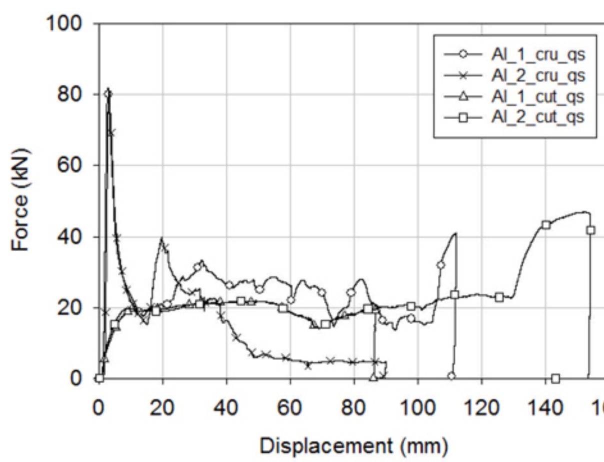


Figure 2: Force/displacement responses of aluminum extrusion specimens subjected to quasi-static axial crushing and cutting

Aluminum extrusion specimens demonstrated a uniform progressive folding deformation mode early in the loading process. Folding was observed to initiate at the end of the thin walled section consistent with the observations of Abramowicz et al. [7]. Crushing displacements beyond roughly 10-15 mm produced localized tearing within the vicinity of the folded material. Further crushing resulted in localized material fracture and separation which initiated a transition from a clean progressive fold to a combination of localized progressive folding and tearing of the fractured extrusion wall as the primary mechanisms of energy absorption. The transition from a clean progressive fold to a combination of folding and tearing resulted in a minor increase in the measured axial crushing force followed by a decreasing, oscillating crushing force throughout the remainder of the loading phase.

Figure 3: Aluminum extrusions subjected to quasi-static crushing (a) and cutting (b) post test.

Early in the loading process, magnesium extrusions exhibited deformation indicative to the generation of a progressive folding deformation mode as indicated by the formation ridges along the thin walled section depicted in Figure 5 (a). Following the formation of the ridges, significant material tearing and fracture was observed along the thin walled section which resulted in a transition from the initiation of a progressive fold to a localized and inefficient buckling deformation mode. Following the onset of buckling, the axial crushing force rapidly decreased with increasing crushing displacement as material crack and fractures continued to propagate throughout the extrusion walls.

Axial Cutting:

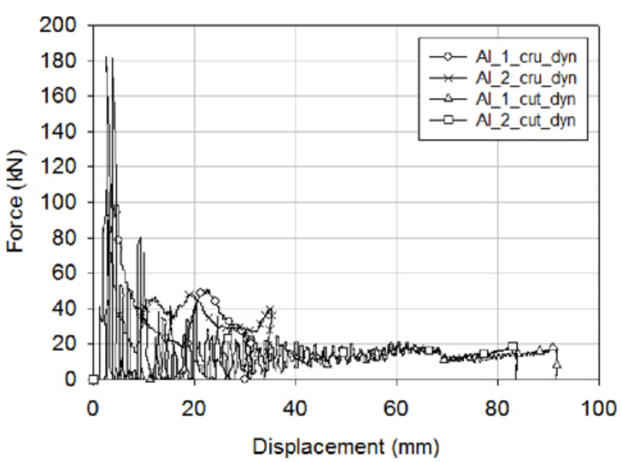
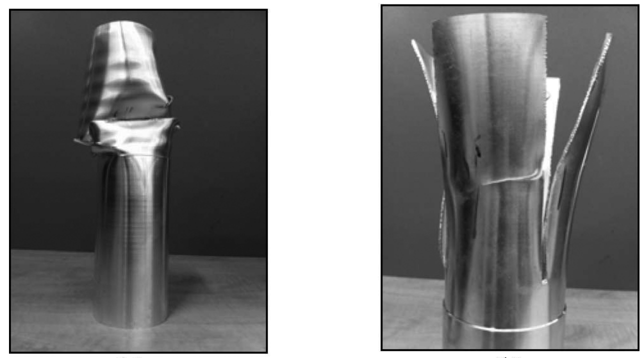


Figure 4: Force/displacement responses of aluminum extrusion specimens subjected to dynamic axial crushing and cutting

Aluminum extrusions formed long chips ahead of the cutting blades and petalled side walls indicative of the formation of a clean curling cut. No material tearing or localized folding was observed along the petalled side walls and cut surface. The presence of a relatively clean cut is expected as the T6 temper of the aluminum permits highly localized plastic deformation with relatively little strain hardening of the surrounding material.



(a) (b)

Figure 5: Magnesium extrusions subjected to quasi-static crushing (a) and cutting (b) post test.

Magnesium extrusions were observed to form short brittle chips ahead of the cutting blades and did not achieve a clean curling cut throughout the entirety of the loading process. Petalled side walls were left deformed in a folding pattern within the vicinity of the cutting surface and cut edges were left with a rough jagged surface indicative of chip fracture. Additionally, the chip fracture was reflected in the load/displacement response as the axial cutting force oscillated by approximately ± 0.5 kN throughout the cutting process. The distortion of the petals is expected as the magnesium extrusions cannot accommodate the highly localized plasticity generated by the cutting blades owing to the relatively low yield strength of the AZ31B alloy and susceptibility to strain hardening when compared to that of the aluminum samples. Upon contact with the conical deflector, petals experienced localized bending near the cutting tool as they were displaced in the radial direction and an increase in the measured axial cutting force was observed. Petals occasionally experienced material fracture/tearing as depicted in Figure 5 (b).

Extrusion Performance Parameters:

I.D	P_m (kN)	SEA (kJ/kg)	TEA (kJ)	CFE (%)
Al_1_cru_qs	25.0	13.7	2.79	30.5
Al_2_cru_qs	15.2	6.75	1.37	18.6
Mg_1_cru_qs	10.7	3.21	0.414	29.4
Mg_2_cru_qs	15.4	2.82	0.364	44.1
Al_1_cut_qs	18.7	7.94	1.61	85.7
Al_2_cut_qs	23.2	17.6	3.57	49.3
Mg_1_cut_qs	5.95	5.25	0.677	69.1
Mg_2_cut_qs	5.85	5.13	0.662	67.8

Table 1: Extrusion performance parameters computed from quasi-static test trials.

For the extrusion geometries subjected to quasi-static axial compressive loading, average crushing force values ranged from 10.7 - 25.0 kN for crushing and 5.85 - 23.2 kN for axial cutting deformation modes. The failure of both the aluminum and magnesium extrusions to achieve and maintain a progressive folding mode of deformation during axial crushing trials resulted in relatively low CFE values of 18.6 - 44.1 %. CFE values were found to be greater for the axial cutting tests with values ranging from 49.3 - 85.7 %. Folding deformation of petalled side walls resulting from localized strain hardening within the blade vicinity is believed to be attributed to the relatively low CFE values of magnesium extrusions compared to those of aluminum specimens. It is hypothesized the use of a different temper such as h24 could demonstrate improved CFE and TEA values resulting through the reduction of localized strain hardening during cutting.

Dynamic Crushing and Cutting Test Results

Axial Crushing:

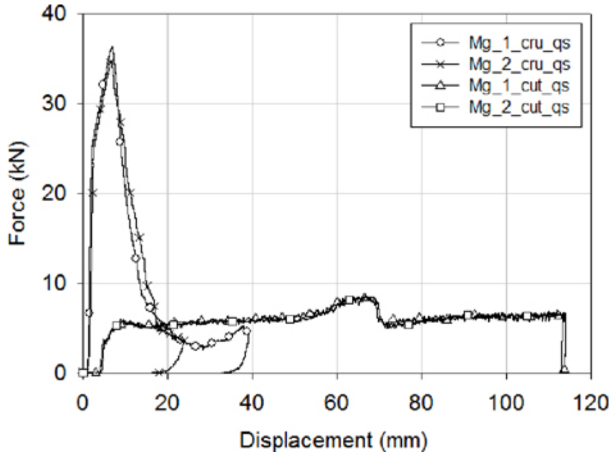


Figure 6: Force/displacement responses of magnesium extrusion specimens subjected to quasi-static axial crushing and cutting.

Aluminum specimens tested under crushing impact loads demonstrated a progressive folding mode of deformation which was initiated at the upper or lower endpoint of the thin walled section of the extrusion. This behavior is consistent to that described in [7] as the relatively small slenderness ratio of the specimens tends to minimize the influence of lateral inertia during axial loading thus reducing the probability of transitioning to a global bending mode of deformation. Material tearing within the folded portion of the extrusion was found to be consistent with that observed during quasi-static tests however complete fracture of the extrusion wall did not occur. Crushing of the aluminum extrusions occurred over a displacement of roughly 30 mm before decelerating the drop tower carriage to a complete stop. Immediately upon impact of the drop tower carriage, magnesium extrusion specimens were deformed along the length of the thin walled section in an undulating wave pattern similar to the initiation of a progressive folding mode of deformation. This behavior was unexpected as the findings from [7] predict the formation of folds at the impacted end of the extrusion early in the deformation process. Following the initial impact, magnesium extrusions experienced material fracture and tearing originating at the impacting surface or extrusion mid-span which would subsequently propagate to the surrounding areas. The fracturing behavior is consistent with the findings of Lin and Chen [8] who investigated the effect of strain rate on square AZ31B extrusion specimens where decreased ductility and a greater strain hardening rate with increasing strain rate was noted. Crushing occurred over a displacement of roughly 20 mm before decelerating the carriage to a complete stop.

Axial Cutting:

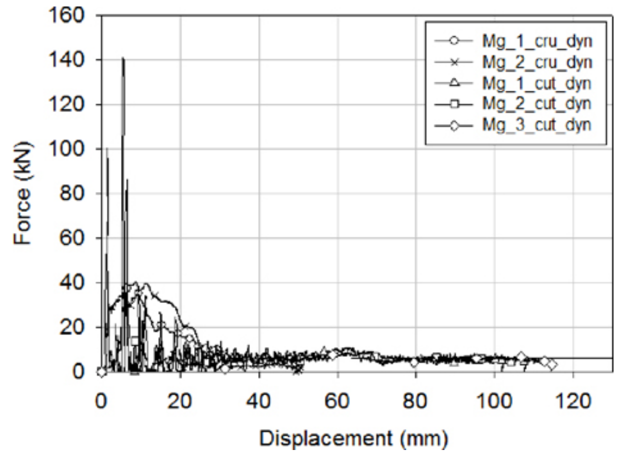


Figure 7: Force/displacement responses of magnesium extrusion specimens subjected to dynamic axial crushing and cutting.

The impact event occurred over a time span of approximately 30 ms for aluminum extrusion specimens. Throughout the cutting process long continuous chips formed ahead of the cutting blades indicating the formation of a continuous clean curling cut. Petalled side walls were observed not to experience any binding with the cutting tool during the cutting process and were left relatively undeformed prior to contacting the conical deflector at a cut depth of roughly 50 mm. Upon contact with the conical deflector, lateral shifting of the cutting tool was observed for both magnesium and aluminum extrusions which resulted in an increase in the measured axial cutting force . The direction of lateral shift appeared to be random in nature and governed by the interaction between the drop tower carriage plate and upper load cell upon impact. Forces registered by the upper load cell were considerably larger than those registered by the lower cell early in the deformation process with peak impacts load of approximately 180 kN for aluminum specimens and 85 kN for magnesium specimens.

(a) (b)

Figure 8: Magnesium extrusion specimens subjected to dynamic crushing (a) and cutting (b) post test.

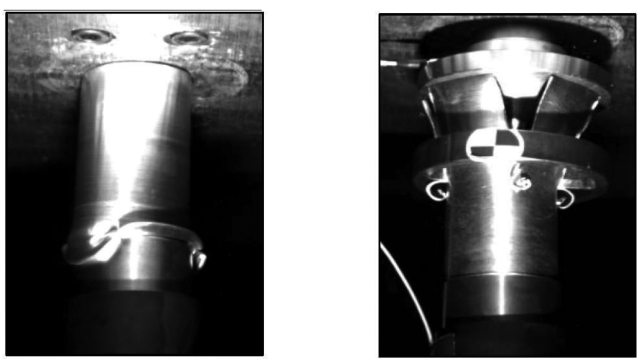
Magnesium extrusion formed small brittle chips ahead of the cutting blades and did not achieve a clean curling cut throughout the duration of the impact cutting process. The impact event occurred over a time span of approximately 50 ms. Petalled side walls were left with jagged edges within the vicinity of the cut indicative of brittle chip fracture however petals were deformed to a lesser extent when compared to quasi-static test trials. Although magnesium extrusions did not form a continuous chip associated with a clean curling cut the loads measured by the upper and lower load cells were found to oscillate to a lesser extent throughout the cutting process compared to aluminum extrusions.

Extrusion Performance Parameters:

I.D	P_m (kN)	SEA (kJ/kg)	TEA (kJ)	CFE^{upper} (%)	CFE^{lower} (%)
Al_1_cru_dyn	17.24	5.61	1.14	N/A	15.6
Al_2_cru_dyn	18.34	6.44	1.31	N/A	17.3
Al_1_cut_dyn	12.02	6.07	1.23	6.80	45.5
Al_2_cut_dyn	11.31	5.92	1.20	6.40	47.7
Mg_1_cru_dyn	13.19	4.76	0.614	N/A	32.8
Mg_2_cru_dyn	9.40	5.24	0.676	N/A	23.7
Mg_1_cut_dyn	4.97	4.81	0.621	5.80	43.6
Mg_2_cut_dyn	6.00	5.23	0.675	6.00	36.3
Mg_3_cut_dyn	6.27	5.30	0.684	4.50	46.6

Table 2: Extrusion performance parameter computed from dynamic test trials.

Average force values ranged from 9.40 - 18.34 kN and 4.97 - 12.02 kN for impact crushing and cutting tests respectively. Similar to the observations noted in [6] CFE values computed from data collected from the lower load cell were much greater than those computed from the upper cell. Levels of absorbed energy ranged from 0.614 - 1.31 kJ and 0.621 - 1.23 kJ for crushing and cutting deformation modes.



(a) (b)

Figure 9: Aluminum extrusion specimens subjected to dynamic crushing (a) and cutting (b) post test.

Conclusions

This experimental investigation examined the mechanical responses of aluminum and magnesium circular extrusion specimens subject to axial crushing and cutting loads applied both quasi-statically and dynamically. The primary findings from this investigation include the following.

1. Under both quasi-static and dynamically applied crushing loads magnesium extrusions were observed to fail in an inefficient localized buckling mode of deformation. Aluminum extrusions exhibited deformation indicative of progressive folding early in the loading process which later transitioned to a combination of material folding and tearing

2. Aluminum extrusion specimens formed a long continuous chip ahead of the cutter blades during both quasi-static and dynamic cutting. Magnesium extrusions formed short brittle chips during quasi-static and dynamic cutting however no kinking or binding or cutter blades was observed.

3. Total energy absorption for quasi-static test trials ranged from 7.94 - 13.7 kJ and 0.364 - 0.677 for aluminum and magnesium extrusions respectively.

4. Total energy absorption for dynamic test trials ranged from 1.14 - 1.31 kJ and 0.614 - 0.684 kJ for aluminum and magnesium extrusions respectively.

Acknowledgements

The authors would like to take this opportunity to thank the Natural Sciences and Engineering Research Council (NSERC) of Canada for supporting this work.

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