Magnesium Alloy Applications in Automotive Structures

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The use of magnesium alloys in structural applications has great potential for the lightweighting of transportation vehicles. Research within the CAST Cooperative Research Centre has tackled some of the important issues related to the use of magnesium in structural applications. To this end, a new alloy with extrudability and properties similar to 6000 series aluminum alloys has been developed. Furthermore, a method of laser heating magnesium alloys before self-piercing riveting has enabled high-integrity joining between magnesium components or between magnesium and dissimilar metals. In this paper, new technologies and improved understanding of the deformation behavior of wrought magnesium alloys are discussed in light of key metallurgical features such as alloy composition, grain size, and work hardening rate.

INTRODUCTION

Magnesium alloys are increasingly being used for lightweighting transportation applications due to the mass reduction that can be achieved and consequent fuel reductions, which can reduce both greenhouse gas emissions and the fuel cost of transport.[1,2] Up to now, magnesium alloys have been generally high-pressure die-cast, due to the inherent advantages in this process[3,4] and because of this, a primary focus for future use has been in automotive powertrains.[5] However, magnesium alloys are being increasingly considered for higher-integrity structural applications (e.g., the USCAR front-end project),[6] where the use of wrought alloys is generally preferred due to their higher performance than cast alloys.[3] Such applications require good performance in crash situations, both in terms of energy absorption and retaining structural integrity as well as being technically and economically feasible.

Incorporating magnesium alloys into body structures is not as simple as a direct substitution for steel or aluminum alloys. Like the other metals, magnesium alloys have their own unique characteristics which allow for their substitution in some components and not in others. The uptake of magnesium alloys in applications that require wrought processing, mechanical fastening, and energy absorption during crash situations depends upon utilizing the plastic deformation characteristics of magnesium alloys.

Unlike aluminum alloys and steels, which have cubic crystal structures, magnesium alloys have a hexagonal crystal structure. This limits easy dislocation motion to the close-packed directions on the basal planes,[7] which provides only three independent deformation modes of the five required for deformation to occur without a volume change according to the Von Mises criterion. Hence twinning[7] and non-basal slip[8] are required to satisfy this criterion, and both require much higher critical resolved shear stresses than basal slip.[9] This is thought to be the reason that magnesium alloys are generally difficult to form, at or near room temperature, in comparison to aluminum alloys.[10] Furthermore, different twinning mechanisms in tension[11] and compression[12] lead to anisotropic material properties. This in turn leads to irregular-shaped yield surfaces[13] whose shape also depends upon the alloy texture and complicates the development of material models for use in simulation.

This article summarizes work that has been performed within the CAST Co-operative Research Centre on efforts to develop wrought magnesium alloys with improved processability, high-integrity mechanical joints that contain magnesium alloys, and understanding the deformation of magnesium alloys in applications that require a degree of crashworthiness.

How would you…

…describe the overall significance of this paper?

Magnesium alloys are the lightest structural alloys but they have issues that need to be overcome both in terms of processing and use. This paper highlights some approaches that have been able to provide solutions, or at least partial solutions, to these problems.

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

This paper shows how a combination of temperature, grain size, and alloy composition can improve extrudability, mechanical properties, and joining operations. Furthermore, it shows applications where the unique properties of magnesium alloys can be used to improve energy absorption during deformation.

…describe this work to a layperson?

Lighter, more fuel-efficient cars are the way of the future. Magnesium alloys are the lightest of all metals and increasing their use will assist with attaining that goal. However, they deform differently than steel and aluminum alloys so they need to be treated a bit differently and be used in the right applications. This work presents a new alloy that can be processed into shape more easily, a way of joining magnesium components without cracking, and how there are parts of a car's crash structure that will benefit from the use of magnesium, but other places where currently other metals are still better.

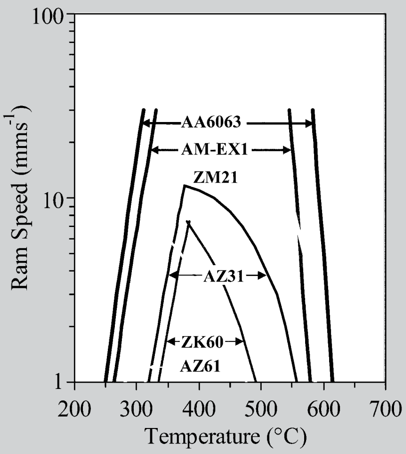

Figure 1. An extrusion limit diagram for the new magnesium alloy AM-EX1, 6063 Al alloy, and magnesium alloys (from Reference 10) AZ31 (Mg-3Al-1Zn), AZ61 (Mg-6Al-1Zn), ZM21 (Mg-2Zn-1Mn), and ZK60 (Mg-6Zn-0.5Zr).

WROUGHT MAGNESIUM ALLOYS

Currently the use of wrought magnesium alloys is very limited,[4] mainly due to slow production speeds. Consequently, the cost of extrusion for existing wrought magnesium alloys is high when compared to aluminum alloys. The main objective in developing a new magnesium extrusion alloy has been to increase the rate of extrusion while still retaining good mechanical properties, such as a high yield strength and low tension-compression anisotropy.[14] Hence there are two critical factors that need to be considered: first, what limits the extrudability of magnesium alloys and second, what are the critical factors affecting the mechanical properties.

A laboratory-scale extrusion rig was developed to assess the extrudability of various magnesium alloys.[10] The extrusion limit at low billet temperatures is related to the hot working flow stress of the alloy; the lower the flow stress, the higher the ram speed can be before the load limit of the extrusion press is reached. The extrusion limit at high billet temperatures is related to the solidus temperature of the alloy; the higher the solidus temperature, the higher the ram speed and billet temperature can be before incipient melting of the extrudate surface occurs, leading to cracking. A range of magnesium alloys was tested and it was observed that a key factor in increasing the extrudability of magnesium alloys is to reduce the alloy composition to below that found in common extrusion alloys such as AZ31 (Figure 1).

One downside of increasing extrudability through reducing the alloying content of the alloys is that certain mechanical properties, in particular yield strength, can be adversely affected. This, however, can be overcome through reducing the grain size of the extrudate. Recent studies have shown that there is a strong dependency of increasing compressive and tensile yield strength with reducing grain size.[15–17] Reducing the grain size also decreases the tension-compression yield anisotropy and improves the ductility.

Hence the most important factors in developing a fast extruding alloy with good mechanical properties is to make a leaner alloy (i.e., with lower solute additions) with a small final grain size. This has been achieved in the development of the new extrusion alloy, AM-EX1, whereby alloying elements were chosen specifically to enhance the mechanical properties. Compared to AZ31 and AA6063 (in the T6 condition), AM-EX1 has a comparable yield strength and ultimate tensile strength (Table I). AM-EX1 rivals AZ31 in specific strength and has a significantly improved elongation to fracture and reduced anisotropy of its properties.

AM-EX1 also possesses an advantage over AZ31 in its ability to maintain a fine grain size after hot deformation. In AZ31, the grain size during deformation is reduced by dynamic recrystallization (DRX); however, this rapidly coarsens due to metadynamic recrystallization (MDRX) during subsequent annealing or slow cooling.[18] The thermal stability of the deformed microstructure of AM-EX1 compared to that of AZ31 can be seen in Figure 2, which shows the evolution of grain size in both AM-EX1 and AZ31 after compression at 350ºC to a strain of 1.5 followed by annealing at the same temperature. After thousands of seconds of annealing, the grain size of AZ31 increases from 6 µm to 25 µm while the grain size of AM-EX1 remains virtually unchanged.

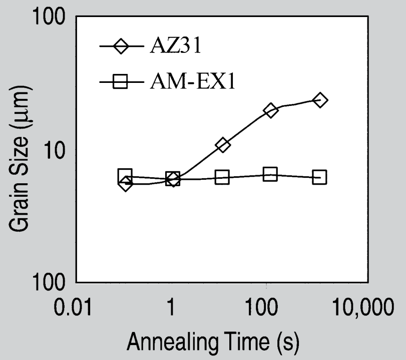

Figure 2. The evolution of the average grain size with annealing time for AZ31 and AM-EX1 samples deformed in compression to a strain of 1.5, at a temperature of 350ºC and a strain rate of 0.1 s^{-1}, and subsequently annealed at 350ºC.

The enhanced performance of AM-EX1 over that of AZ31 was demonstrated in recent industrial-scale extrusion trials. When both alloys were extruded under the same conditions, the average grain size developed in AZ31 was three times greater than that of AM-EX1 (23 µm compared to 7 µm). Also, when using a billet temperature of 370ºC, AM-EX1 was extruded at speeds more than twice that possible for AZ31.

Table I. Average Mechanical Properties* of 6063-T6 Al Alloy, Mg Alloy AZ31, and AM-EX1 in Tension Extruded and Tested under Similar Conditions

Material	0.2% YS (MPa)	Specific Strength (kN · m/kg)	TS (MPa)	YS_{comp}/YS_{tens}	ε_u (%)	ε_f (%)
AA6063-T6	195	76	258	1.0	10.3	24.6
AZ31	203	121	247	0.4	10.5	14.4
AM-EX1	184	116	259	0.7	13.7	25.2

* Including the yield strength (YS), tensile strength (TS), and the uniform (ε_u) and fracture (ε_f) elongations.

LASER-ASSISTED SELF-PIERCING RIVETING

Self-piercing riveting (SPR) is a solid-state joining process that involves the use of a die and rivet, and a large amount of plastic deformation. Cracking of magnesium alloys during SPR joining often occurs due to its poor ductility and low formability at ambient temperatures. But cracking can be prevented by thermally assisting the deformation of magnesium alloys, which in effect increases its plasticity by activating additional slip systems in the crystal structure.[19] The transition of brittle-to-ductile behavior moves to higher temperatures with increasing grain size.[20]

Thus, crack-free point joining of magnesium alloys has been reported for die-less clinching and die-less rivet clinching by using resistance heating of a flat anvil and transferring heat by contact with the magnesium,[21] and for SPR by using induction heating.[22] However, machine tools that can quickly deliver the right temperature conditions to achieve a heating and joining cycle time of less than 5 seconds need to be developed for successful industrial implementation of a thermally assisted SPR technology for magnesium alloys.[23]

A technology has been developed that not only achieves cycle times of less than 5 seconds for stacks as thick as 6.6 mm, but also involves little modification to the existing SPR tooling.[24] The magnesium alloy ply on the die side is directly preheated by a laser beam prior to the SPR operation. The laser provides non-contact, controlled, local heating of the spot to be joined as well as high flexibility in terms of the access to, size, and geometry of the spot area. When the laser is used, cracking of the bottom magnesium ply is prevented, and there is also better contact of the rivet head with the surrounding material (Figure 3).

For a given combination of ply material and thickness, the strength of the joint depends on the rivet length and hardness as well as the characteristics of the joints such as the interlock of the rivet leg into the bottom ply and thinning of the bottom ply, which can be optimized by modifying the die profile (Figure 4). Laser-assisted SPR joints can hence be produced to meet a variety of strength requirements. Maximum shear loads of more than 6 kN have been obtained for Mg+Mg and hybrid Al+Mg joints of total ply thickness ranging from 5.5 mm to 6.6 mm (Figure 5).

Whether the strength of a joint is acceptable depends on the application. Continuous development of the technology to a level of production readiness is ongoing. This involves exploiting the many technological advantages afforded by laser systems and utilizing new improvements of Henrob's patented servo-riveting process[25]—such as enhanced features in pre- and post-clamping and insertion of rivets at higher speed.

DEFORMATION OF MAGNESIUM ALLOYS

If magnesium alloys are to be used in structural applications, their crash properties need to be evaluated, particularly energy absorption during plastic deformation, and their fracture characteristics. It would be expected that the greatest benefits for magnesium alloy substitution can be achieved in situa-

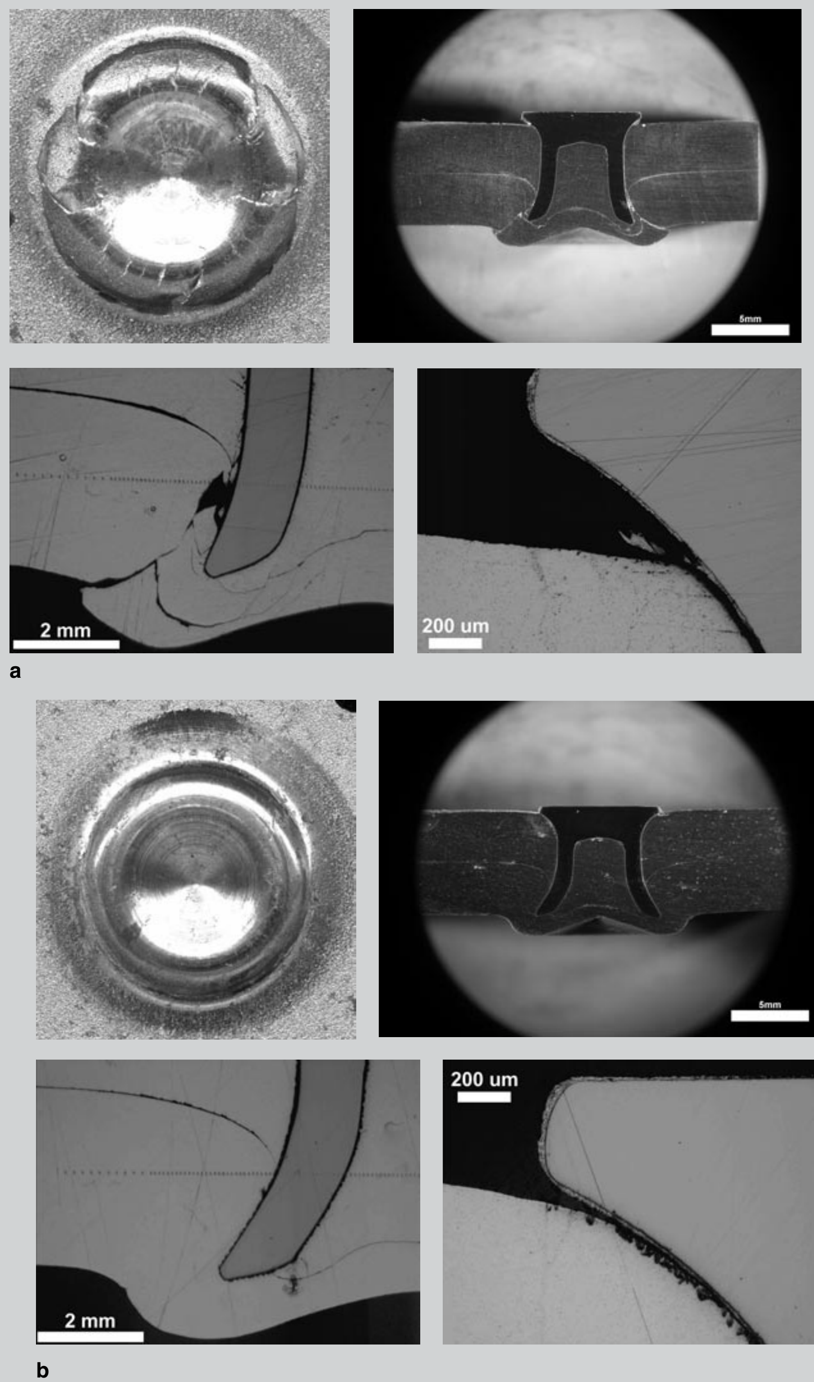

Figure 3. The SPR joint of 3.3 mm + 3.3 mm AZ31 produced (a) without laser and (b) with laser heating.

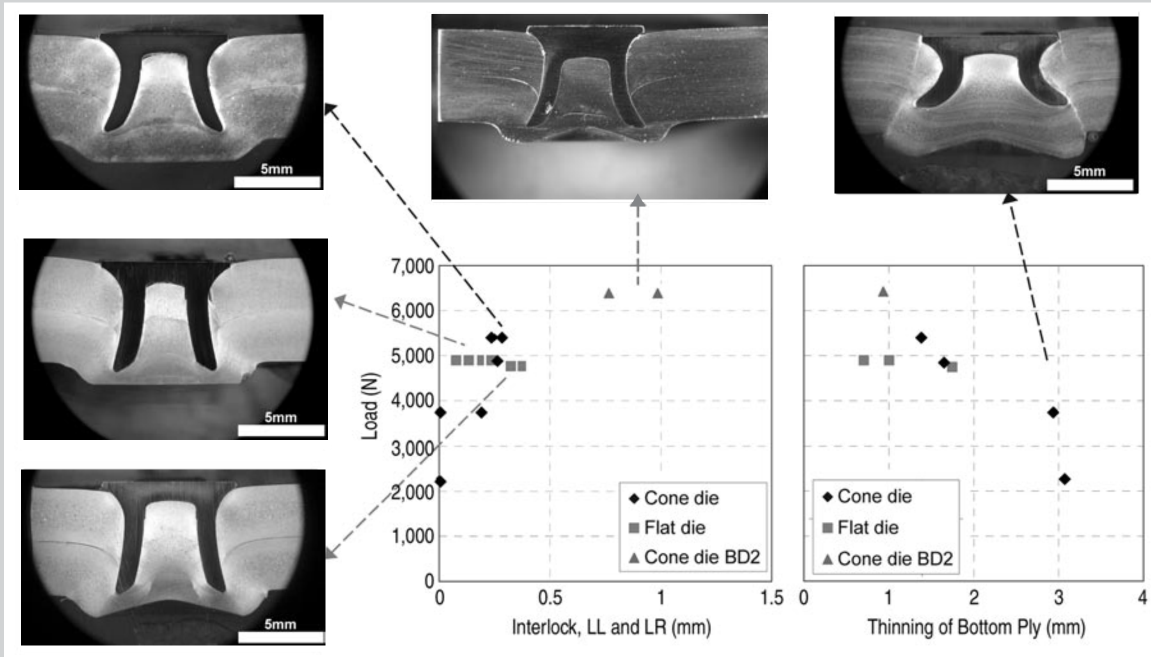

Figure 4. The related effects of die profile, rivet length, and hardness and joint characteristics on the strength of 3 mm + 3 mm AM50 joints.

tions where bending and buckling occur, where reduced mass thicker sections lead to substantial improvements in strength due to the increased moment of inertia.[26] For flat sections (e.g., sheet), the force required for deformation scales with the square of the thickness[27] and hence light alloys are likely to provide the greatest advantage in these applications. Experimental investigations have been performed into buckling of thin plates, three-point bending of tubes, and uniaxial compression of tubes.

The energy absorbed by magnesium alloys (high-pressure die-cast (HPDC) AM20, AM50, AM60, and extruded AZ31) in a buckling test was significantly greater than the aluminum alloy 6061 T6 and particularly mild steel of a similar weight, but was less than that of the aluminum alloy and steel for the same thickness (Figure 6).[26] This indicates that mass savings can be achieved by the substitution with magnesium alloys to achieve similar energy-absorbing characteristics. However, one of the greatest differences between the magnesium alloys and the other alloys was that the deformation occurred with a much greater minimum radius of curvature (Figure 7), which appears to be because of the high work hardening rates of these alloys.[26,28] Consequently, extra energy was absorbed as the deformation occurred over a greater volume. However, the plastic hinges were more likely to be crushed and fracture once a minimum bend radius was achieved. Hence it was thought to be important to consider how the deformation characteristics of magnesium alloys affect the deformation of sections that are more commonly used.

Using the laboratory-scale extrusion rig discussed previously, small thin-walled tubes (15 mm diameter and 1 mm thick) of AZ31 and aluminum alloy 6063-T6 were produced. These tubes were subjected to three-point bending with indenters of different diameters (i.e., 5 mm, 15 mm, and 25 mm). The maximum load for AZ31 occurred at a significantly larger indenter displacement than 6063-T6 using the 15 mm and 25 mm diameter indenters. This means that while 6063-T6 was initially stiffer at very small indenter displacements, the magnesium alloy absorbed

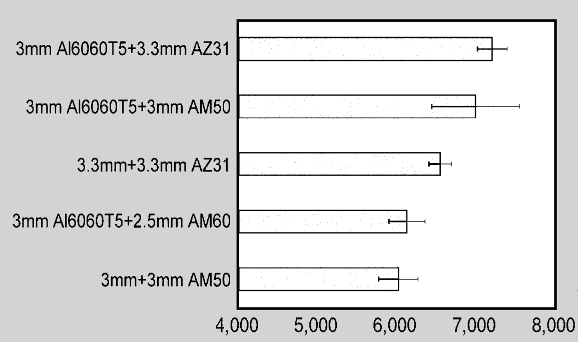

Figure 5. The strength of various thick laser-assisted SPR joints of Mg+Mg and hybrid Al+Mg.

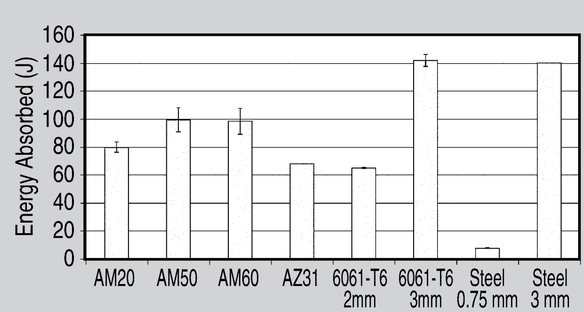

Figure 6. A comparison of the energy absorbed during buckling testing. The 0.75 mm thick mild steel and 2 mm 6061-T6 results are for comparing equal weights. All other plates were 3 mm thick.[26]

significantly more energy than the aluminum alloy as deformation progressed despite being 33% lighter (Figure 8). For the samples tested with the 5 mm indenter the AZ31 samples fractured prematurely on the compression side perpendicular to the extrusion direction, leading to a sudden load drop and reduced energy absorption compared to 6063-T6 (Figure 9).

While magnesium alloys show significant advantages in energy absorption in situations where bending and buckling occur, another possibility is to use them in crash boxes or front rails. This involves the assessment of the uniaxial compression of the sections, and the most energy is absorbed when the sections fail in a progressive folding pattern. With the appropriate folding pattern, sections absorb much more energy than in bending or buckling modes.[29] The deformation mode depends heavily upon the section parameters such as section thickness, diameter, and length.[30]

Extruded tubes of AZ31 have been deformed under uniaxial compression and compared with aluminum alloy 6061-T6 and ASTM A106 Grade B steel. Most tubes tested were 250 mm long and approximately 50 mm in diameter and a range of tube thicknesses was tested. It was found that AZ31 tubes can absorb significantly more energy than either the aluminum alloy or the steel on an equivalent mass basis (Figure 10). It should be noted that the 250 mm long 6061-T6 tube failed by global buckling. Thus, the load response for a 120 mm tube is included on Figure 10 so that the different alloys can be compared for deformation according to the failure mode that is most beneficial for energy absorption. While the steel tube failed by progressive folding, the AZ31 tube tended to fail by sharding or segment fracture (Figure 11a and b) for this thickness-diameter ratio. For the AZ31 alloy tube, most of the energy was absorbed when fine shards were produced and the fracture mechanism appeared to depend upon the prevalence of micro-cracking on the surface of the tube. When tested at a higher strain rate the alloys tended to shard and compact instead (Figure 11c) and even greater advantages in energy absorption were observed.

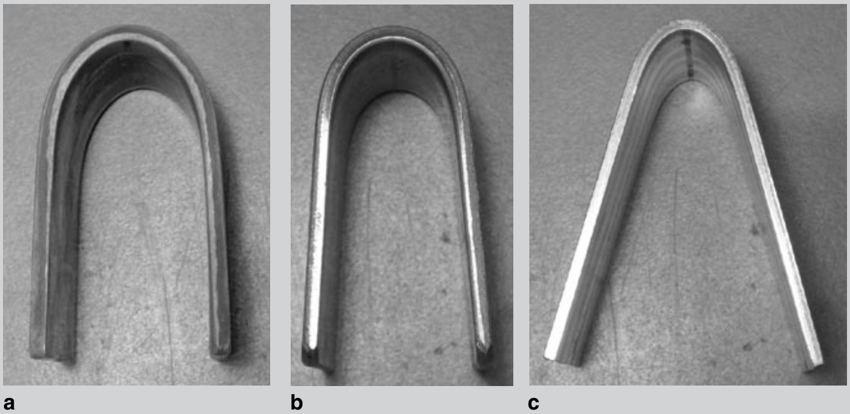

Figure 7. The deformed samples of (a) AM20, (b) mild steel, and (c) 6061-T6 after buckling testing.[26]

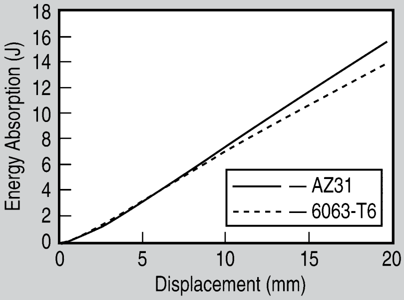

Figure 8. Energy absorption versus indenter displacement for AZ31 and 6063-T6 tubes (D/t = 15) using an indenter diameter of 15 mm. The lower support separation was 100 mm.

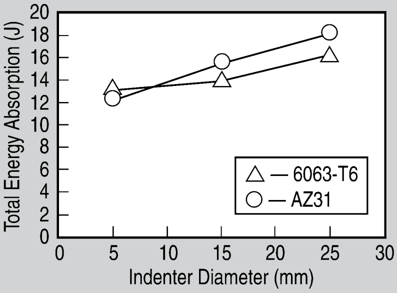

Figure 9. The total energy absorption at an indenter displacement of 20 mm for 6063-T6 and AZ31 (D/t = 15) tubes at different indenter diameters using a lower support separation of 100 mm.

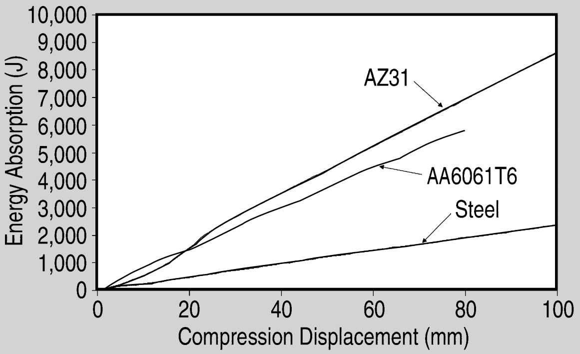

Figure 10. A quasi-static equivalent mass energy absorption comparison for higher tensile 1 mm thick ASTM A106 Grade B steel and 4 mm thick magnesium alloy AZ31 tubes 250 mm long, and 3 mm thick AA6061-T6 Al alloy 120 mm long tubes up to a displacement of 100 mm.

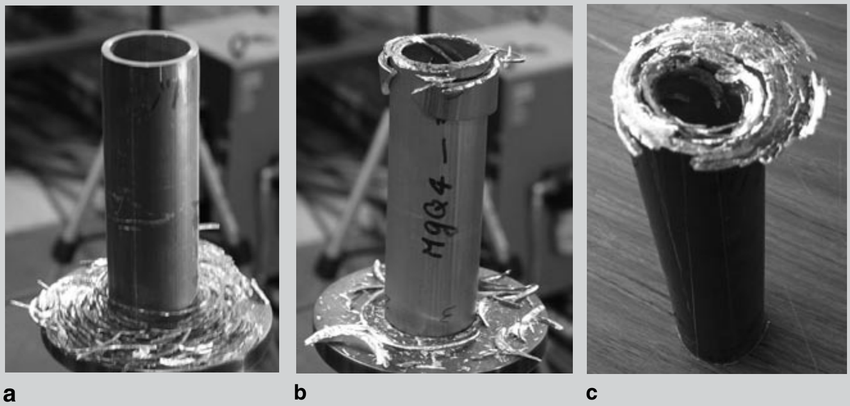

Figure 11. The fracture behavior of one of the 4 mm thick AZ31 tubes (a) dominated by sharding and (b) showing a combination of sharding and large segment fracture. (c) The compacted sharding that was observed after testing on a drop test rig.

CONCLUSION

Magnesium alloys present great potential and a number of challenges to successful use in automotive structures. The main benefits are the extra weight reduction that can be achieved, especially when thicker sections are used which increase the moment of inertia in bending, improving the rigidity, strength, and energy absorption during crash situations. Also beneficial are the high work-hardening rates in many magnesium alloys that delay plastic hinge formation, increase the size of the plastic hinges, and consequently increase energy absorption.

The research presented here suggests that a number of the identified problems related to the use of magnesium alloys in structural applications can be overcome. A new alloy, AM-EX1, is able to achieve extrusion rates and strength similar to 6000 series aluminum alloys combined with exceptional ductility. This was achieved by reducing the alloy content and carefully selecting alloying elements to restrict grain growth during recrystallization. Furthermore, its compression-tension anisotropy is reduced compared with AZ31.

In applications where current magnesium-based alloys need to be mechanically joined, the key factor was to increase the formability by increasing the temperature in an efficient manner. Laser-assisted self-piercing riveting has been successfully used to rapidly and locally heat magnesium alloys to produce crack-free joints with good mechanical properties while maintaining a high production rate.

It appears that magnesium alloys have very good energy-absorbing characteristics; however, they deform and fracture differently than aluminum alloys and steel. It appears that the greatest benefit can be obtained when magnesium alloys are used in situations where bending or buckling is the dominant failure mechanism. In these cases, the use of magnesium alloys can lead to substantial improvements in the energy absorption of the components and there is not a tendency toward premature fracture. In situations where magnesium alloy sections undergo uniaxial compression substantial increases in energy absorption during deformation can also be achieved; however, the fracture modes may be problematic. It is possible that the development of magnesium alloys with greater ductility that are less strongly textured will produce a fracture mode that will still provide some structural integrity. It should be noted, however, that composites also tend to lose structural integrity when they fail[31] albeit not as severely and these are still being promoted for use in such applications.

Given the improved understanding of the unique deformation behavior of magnesium alloys and technological advances in alloy design and joining technologies, it is anticipated that the use of magnesium alloys in structural applications will increase. A key challenge still to be overcome is the development of reliable material models for use in simulation for the range of available alloys.

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