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Experimental comparison of energy absorption characteristics of polyurethane foam-filled magnesium and steel beams in bending

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A B S T R A C T

Lightweight magnesium alloys and polyurethane foams have attracted much attention in the automotive industry due to their potential to reduce vehicle weight. This study conducted quasi-static/dynamic three-point bending tests to investigate the energy absorption characteristics and deformation behaviour of empty and polyurethane foam-filled magnesium alloy AZ31B thin-walled beams, and to make comparisons with mild steel DC04 beams. The results showed that both deformation/fracture modes and energy absorption capacity of the thin-walled beams subjected to bending loads depend on the strain rate and other parameters, such as the beam material's strength and ductility, foam density and wall thickness. Both the DC04 beams and AZ31B extruded beams showed a positive effect of strain rate on the energy absorption capacity. A beam filled with a higher density foam achieves higher bending resistance, but fractures at a smaller deflection. The experiments demonstrated that AZ31B significantly outperforms DC04 in terms of energy absorption and specific energy absorption for the foam-filled beams, when the beams are subjected to bending loads at a deflection of 250 mm. However, this gain could be weakened when the performance is assessed at a larger fracture deflection because the foam-filled AZ31B beams tend to fracture at smaller deflections. For applications that require limited deformation, there is a possibility to develop lightweight auto-body structures such as rocker rails by substituting foam-filled AZ31B structures for mild steel structures, while maintaining or exceeding their current crashworthiness and safety.

1. Introduction

Driven by automotive lightweighting goals through multi-material design, the wide applications of light metals (e.g. aluminium alloys, magnesium alloys and titanium alloys), advanced and ultra high-strength steels, composites (e.g. carbon and glass fibre reinforced plastics) and cellular solids (e.g. honeycombs, metallic and polymeric foams) become increasingly attractive in the automotive industry [1,2]. Magnesium alloys have always been attractive to automotive manufacturers due to their low density (≈ 1.8 g/cm^3), high strength-to-weight ratio, high damping resistance, easy recycling and so on. It is generally accepted that the expanded applications of magnesium alloy products on automotive structures should provide an effective way to reduce vehicle weight and thus improve energy efficiency and driving capability for electric vehicles. Up to now, the majority of the applications of magnesium alloys are limited to few high pressure die casting (HPDC) products, such as engine components, transmission cases, steering wheels and instrument panels, due to their inherent advantages such as excellent structural integrity and high pressure die castability [3–5]. Recently, there is a desire to employ magnesium alloys as crashworthy components in automotive body-in-white structures; therefore, more attention has been paid to wrought magnesium alloys, i.e. rolled sheets and extrusions, which generally exhibit higher strength and ductility than HPDC magnesium alloys. For instance, the European collaborative R&D project "SuperLIGHT-CAR" [6] and the Canada–China–USA collaborative R&D project "MFERD" [7] have already carried out a large amount of systematic research in this field. Generally, good crashworthiness, safety, structural integrity and corrosion resistance are required in such applications. However, overcoming wrought magnesium alloys' disadvantages, such as inferior cold formability, corrosion resistance and joinability to dissimilar materials, is still a challenging task.

Magnesium alloys show different mechanical characteristics compared with steels and aluminium alloys. Due to their hexagonal close-packed (HCP) structure, magnesium alloys can only initiate limited crystallographic slips and twinning at room temperature, resulting in low ductility [8]; whereas much higher ductility can be achieved at warm temperatures because more deformation mechanisms can be activated [9]. Moreover, during traditional rolling and extrusion processes, the normal of the basal plane of the HCP crystal generally aligns perpendicular to the rolling and extrusion direction,

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respectively. This not only forms strong texture and plastic anisotropy [10–12], but also leads to pronounced tension-compression asymmetry [9,13], which is characterised as a large strength difference between tension and compression and a very high work hardening rate in compression. Pronounced strain rate sensitivity induced by different deformation mechanisms under different load rates is another major feature of magnesium wrought alloys, thus providing an advantage in energy absorption in crash scenarios. Comprehensive studies regarding the effect of strain rate sensitivity have been covered in the literature [12–15]. Considerable effort has been devoted to improve the mechanical properties of wrought magnesium alloys through optimising forming processes or developing new alloys [16–20].

In terms of structural applications, much attention in recent ten years has been paid to the deformation mechanisms and mechanical behaviour of magnesium alloy thin-walled structures subjected to axial compressive loads. Dørum et al. [21,22] studied the force-deformation characteristics and deformation modes including the fracture modes of HPDC magnesium AM60 single and double U-shaped thin-walled sections with or without interior reinforcing ribs in axial crushing. Later, they investigated several thin-walled magnesium HPDC components as energy absorber under axial compressive loads using a shear-bolt principle and achieved good energy absorption characteristics [23,24]. In recent years, Wagner et al. [25,26] studied the deformation characteristics of magnesium AM30 extruded beams and AZ31 sheet beams in axial crushing. In such cases, magnesium beams do not produce the so-called accordion shaped deformation mode [27] like steel and aluminium beams; instead, they crack and split into large fragments. Rossiter et al. [28,29] performed finite element simulation utilising a material model considering tension-compression asymmetry and specific failure criteria. Beggs et al. [30] made a comparative study of the failure modes and energy absorption capacity of circular tubes subjected to axial compression and the experimental results demonstrated that magnesium AZ31 extruded tube with thicker wall outperforms both steel and aluminium tubes in terms of specific energy absorption because it fractures via fine sharding. Steglich et al. [49] assessed the crashworthiness of the rectangular tubes made of magnesium AZ31 and ZE10 sheet and extrusion under quasi-static axial crushing. It was observed that the higher work hardening rate in uniaxial compression tests contributes to higher energy absorption by the formation of multiple buckles.

While considerable effort has been made to understand the deformation mechanisms of generic thin-walled structural members subjected to axial crushing, a previous study [31] on 81 real world vehicle crash scenarios showed that up to 90% involved structural members fail in bending collapse mode. Previous researchers [32–36] have thoroughly investigated the bending behaviour of different types of steel and aluminium thin-walled structures and developed a series of mathematical models to accurately describe or predict the folding behaviour and bending moment-rotation characteristics. Usually, only a small portion of an empty thin-walled beam undergoes plastic deformation because the bending collapse is localised at plastic hinges with the remaining portion rotating as rigid bodies. Due to the inward fold formation at the compression wall and consequently reduced cross sectional area at plastic hinges, the load carrying capacity drops significantly after the local sectional collapse occurs at a small rotation, resulting in low energy absorption efficiency. To improve the energy absorption efficiency of thin-walled beams, the concept of filling lightweight cellular materials such as metallic or polymeric foams into empty thin-walled beams has received increasing interest. In the past two decades, a number of researchers [37–42] carried out extensive studies on the bending behaviour of steel and aluminium thin-walled beams filled with lightweight foams by using experimental, analytical and numerical methods. It was found that the internal lightweight foam filler is able to stabilise the cross section of thin-walled beam and retards the local sectional collapse at the compression wall, and therefore significantly improves the load carrying capacity and specific energy absorption. The lightweight foam filler not only absorbs kinetic energy by its own compressive plastic deformation, but also helps the surrounding metallic shell spread plastic deformation over a larger bending zone by its interaction with the beam walls.

However, little attention has been paid to the bending collapse behaviour of empty and foam-filled thin-walled beams made of magnesium alloys. Dørum et al. [21,22] studied the load carrying capacity and fracture behaviour of HPDC magnesium AM60 U-shaped thin-walled beams and found that the material's inhomogeneous micromechanical properties in uniaxial tension and initial geometric imperfections of the profiles lead to a large scatter on the mechanical response of the beams. Easton et al. [43] made a comparative study on the energy absorption capacity of several HPDC magnesium alloys, wrought magnesium alloy AZ31, mild steel HA300 and aluminium alloy 6061-T6 plates in bending and buckling. The experimental investigation performed by Hilditch et al. [44] demonstrated that the magnesium alloy AZ31 extruded circular tube in three-point bending has higher load carrying capacity and energy absorption performance than an equivalent mass tube made of aluminium alloy with similar tensile yield strength. Wagner et al. [26] and Ali [45] studied the bending collapse and its numerical simulation method of thin-walled rectangular magnesium alloy AZ31 sheet beams. Results of these investigations show that some HPDC magnesium alloys and wrought alloy AZ31 thin-walled beams in bending and buckling significantly outperform steels and aluminium alloys with respect to specific energy absorption. This performance may be due to the following two inherent features. First, magnesium thin-walled beams have a higher moment of inertia due to the thicker cross section, which is achieved by its lower density, while maintaining its mass. Second, due to the significantly higher work hardening rate in compression, a magnesium thin-walled beam shows a larger radius of curvature, and therefore more material is involved in plastic deformation. Nevertheless, a magnesium thin-walled beam is susceptible to fracture at plastic hinges at a relatively small rotation, which results in a rapid drop of load carrying capacity.

The present study develops a foam-filled hybrid structure serving as an energy absorbing component subjected to bending loads. The hybrid structure is comprised of an outer rectangular thin-walled beam made of magnesium AZ31B sheet or extrusion, and a lightweight filler made of polyurethane foam. The main objective is to investigate the energy absorption characteristics and deformation behaviour including fracture modes of empty and polyurethane foam-filled magnesium AZ31B thin-walled beams in quasi-static and dynamic three-point bending tests, and to make a comparison with mild steel DC04 beams [46]. Load carrying capacity and deformation behaviour are discussed for steel sheet, magnesium extruded and sheet beams, respectively. Different beams are examined to reveal the effect of strain rate, beam material's strength and ductility, foam filler, foam density and wall thickness on deformation mode and energy absorption performance.

2. Materials

A commercial-grade magnesium alloy AZ31B (Mg-3Al-1Zn-0.3Mn, wt.%) in two different forms was investigated in this study: extrusions with 3.0 mm nominal wall thickness and fully annealed (O-temper) sheets with 1.8 mm nominal thickness. The AZ31B sheets were produced by twin-roll cast and rolled processes in Thyssen Krupp MgF Magnesium Flachprodukte GmbH. The AZ31B seamless extrusions were fabricated by indirect extrusion process. Unfortunately, the detailed extrusion processing parameters such as extrusion speed, temperature and pressure were not provided to the authors. For