Engineering Structures 164 (2018) 1–13

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental study on the crush behavior and energy-absorption ability of circular magnesium thin-walled tubes and the comparison with aluminum tubes

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ARTICLE INFO

Keywords:
Magnesium tube
Crashworthiness
Deformation/failure mode
Length/diameter ratio
Compression speed
Induced feature

ABSTRACT

In this study, a series of axial crush tests were performed on AZ31B magnesium and A6063 aluminum thin-walled circular tubes to investigate the influence law of the failure mode and energy absorption capacity dictated by length/diameter (L/D) ratio, compression speed, and induced features as well as their difference. In general, the magnesium tubes absorbed energy mainly by fracture while the aluminum tubes absorbed energy by plastic yielding with folding generated. With increasing L/D, the failure mode of magnesium tube generally tended to change from a splitting mode with relative good crashworthiness to a bi-tube slicing mode with inferior crashworthiness and, finally to an Euler mode that nearly lost its crashworthiness, whereas, for the aluminum tubes, the ring or diamond or ring & diamond mixed mode was observed, with crashworthiness parameters changing very slightly. The compression speed has more obvious effect on the energy-absorption increment of magnesium tube than that of the aluminum tube. The SEA (specific energy absorption, which is defined as the energy absorbed per unit mass of the crushed tubes) of the magnesium tube was lower than that of the aluminum tubes at quasi-static condition regardless of the failure modes; however, it outperformed the aluminum tube at the compression speed equal or greater than 0.1 m/s. The induced features characterized in this study exhibited an alternating trend between the original deformation/failure mode and an inferior mode, which did not facilitate the load-carrying and energy absorption of both the magnesium and aluminum tubes.

1. Introduction

Lightweight alloys such as those of magnesium and aluminum are becoming increasingly attractive for use in the automobile, rail, aerospace and construction industries and are being explored as replacements for conventional steel alloys [1–3]. Thin-walled structures have been widely used as primary energy absorption structures in the design of crash safety systems. Considering the novelty of lightweight magnesium alloys, as energy absorption structures, it is therefore necessary to evaluate the deformation/failure mode and the energy absorption ability of tubular form alloys to better design the specific structures.

Much work has been done to explore the deformation mode and crashworthiness of steel and aluminum alloy tubes subjected to compressive loads. Early studies tended to develop an analytical theory model to reveal the crush behavior and loading prediction of the tubes, thereby providing a reasonable agreement with the test results of the crush loads to a certain degree [4–7]. At present, a series of static and dynamic compressive and bending tests have been conducted on steel and aluminum tubes, of which the effect of the geometric parameters on the crushing modes and crashworthiness were analyzed [8–18]. Furthermore, numerical methods were proposed to run parametric simulations. These models were combined with the tests or theoretical models to investigate the crush behavior and loading responses of the aluminum tubes [19,20].

In comparison, little work has been conducted on the crush behavior and energy absorption assessment of magnesium, as well as comparison between magnesium and aluminum. Beggs et al. [21] conducted axial compression tests on AZ31B circular magnesium tubes to compare the energy absorption performance of steel and aluminum tubes. The results indicated that the specific energy absorption ability mainly depended on the failure mode of the tube's structure. Wu et al. [22] conducted tests on AZ31B rectangular tubes of three different lengths, the results of which indicated that the tube length presented no obvious effect on the load-carrying ability in the absence of buckling failure.

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https://doi.org/10.1016/j.engstruct.2018.02.083
Received 27 September 2017; Received in revised form 26 February 2018; Accepted 26 February 2018
Available online 06 March 2018
0141-0296/

Yoon et al. [23] compared the load-displacement curves of AZ61 circular magnesium tubes at two speeds. The results indicated that higher initial peak load at high speed as compared to that at low speed. Dorum et al. [24] proposed a shear-bolt principle for the magnesium component, in which a bolt was forced to shear through the thin-walled component. The test results suggested that the appropriateness of the deformation principle in providing a relatively good energy absorption capacity.

In addition to the above-mentioned experimental studies, certain simulations have been conducted. Wagner [25] conducted simulations on double-top-hat AZ31B magnesium tubes under axial compression to evaluate their crashworthiness. Dorum et al. [26] and Rossiter et al. [27] proposed a new numerical simulation method using a user-defined material model to try to simulate the fracture process and to reproduce the test data of magnesium thin-wall components under axial crushing. Samer et al. [28] conducted simulations on a magnesium hexagonal tube with trigger features and discovered that the effect of the trigger on the crush behavior mainly depended on its position. In addition, the deformation behavior of a magnesium tube under bending conditions was also investigated [26,29].

The above studies presented promising results that reveal the crashworthiness of circular magnesium alloy tubes. However, (1) crush tests on circular magnesium tubes with different L/D ratios at varied strain rate are very scarce; (2) the range of the strain-rate was quite narrow and dynamic tests were generally performed through a drop tower apparatus which cannot provide constant strain-rate in compression; (3) the deformation mode and the energy-absorption features of the tubes with imperfections of hole or crack were not investigated. Therefore, the present study focused on the above problems to evaluate the potential of thin-walled circular magnesium tubes AZ31B as crashworthy structures.

2. Experimental methods

2.1. Specimen details

Extruded circular AZ31B magnesium tubes and A6063 aluminum tubes, with outer diameters of 45 and 40 mm and thicknesses of 1.5 and 2 mm respectively, as well as lengths of 1D–4D (D represents the tube diameter), were employed in the axial crush tests (Fig. 1(a)). The machining center was used to cut the tubes in preparing the end surface, in which the positioning and repeatability accuracy of the machining center is 0.01 mm and 0.005 mm respectively. Apart from the intact tubes, four kinds of induced features and symmetrically/asymmetrically distributed holes and cracks, were introduced on the intact magnesium and aluminum tube walls as presented in Fig. 1(b)–(e). The hole had a diameter of 5 mm and the crack size was 15 mm in length and 1 mm in width. These cracks or holes were located at L/4, L/2, and 3L/4 along the tube length, and distributed at 90° intervals around the circumferential direction of the tube. The chemical compositions for the magnesium and aluminum tubes are listed in Table 1.

The mechanical properties of the AZ31B magnesium and A6063 aluminum tubes were tested through uni-axial tensile tests. The specimens were cut from the circular tube walls along the axial direction as presented in Fig. 2(a). To clamp the specimen, a pair of fixtures with a concave part (Part I) and a convex part (Part II) was designed to fit with the specimen as shown in Fig. 2(b). To make sure the fixture fit closely with the specimen and the axial tension force passed through the geometrical centroid of the curved specimens, (1) part I was machined into the same curvature with the specimen's concave surface and Part II was machined into the same curvature with specimen's convex surface; (2) the length of Part I (A1) at central location equals to the length of the Part II (A2). Fine threads were added to the surface of the fixture to increase contact.

2.2. Quasi-static test method

Quasi-static axial crushing tests were conducted using a WDW-100 universal test machine with a loading capacity of 100 kN, as shown in Fig. 3(a). The tube specimen was axially placed on the base plate. The measured load-displacement curve was recorded and an industrial camera was used to monitor the deformation process and fracture pattern during compression. In addition, tensile tests were also performed on the specimens being cut from the tubes using the tension module of the same test machine that was quipped for the compression tests on tubes (Fig. 3(b)). An extensometer with gauge length of 50 mm was employed for strain measurement.

The test matrix of the quasi-static compression test is presented in Table 2. To investigate the effect of the length/diameter (L/D) ratio on the crashworthiness of the tubes, several L/D ratios were included in the matrix. The aforementioned induced features were introduced on the tube with an L/D ratio of 4. The quasi-static test had a speed of 3 mm/min (5×10^{-5} m/s) and the tests were performed in triplicate for each configuration. Additional tests were conducted in cases that

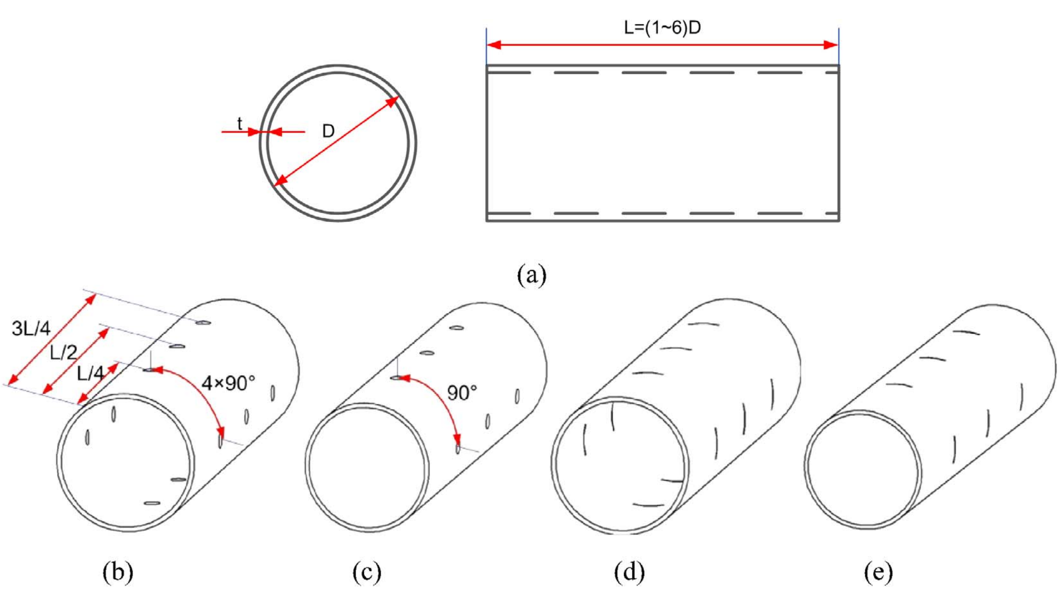

Fig. 1. (a) Shape of intact magnesium and aluminum tube; (b) symmetric distribution of the holes on the tube wall; (c) asymmetric distribution of the holes on the tube wall; (d) symmetric distribution of the cracks on the tube wall; (e) asymmetric distribution of the cracks on the tube wall.