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Investigation of deformation and collapse mechanism for magnesium tube in axial crushing test †

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Abstract

This paper demonstrates the quasi-static axial compression and high-speed axial compression tests of extruded magnesium alloy circular tubes for evaluating the crash and fracture behavior of mg parts. To capture the buckling and fracture behavior of Mg tube during the axial compression tests, FE simulation adopts different types of flow curves depending on the deformation mode such as tension and compression with LS-DYNA software. The Mg tube undergoes compressive plastic strain prior to buckling while according to the model based on Hill yield criterion only bulging along the radial direction is predicted. Due to the tension-compression asymmetry of Mg alloys, diameter of Mg tube expands largely at the initial plastic strain before having bulging or folding while only a bulging mode typical for materials with cubic crystal structure can be predicted. Simulation results such as punch load and deformation mode are compared with experimental results in the axial crushing test with AZ61 alloy.

Keywords: Magnesium alloy; Circular tube; Axial crushing; Tension-compression asymmetry; Buckling

1. Introduction

Increasing demands for fuel economy and vehicle performance have induced light-weight design of automobile and trains by applying the light-weight materials including magnesium (Mg) alloy. Since Mg alloys have the high strength to weight ratio compared with the other steel and aluminum alloys, there have been massive efforts to substitute for structural applications in vehicle weight reduction [1, 2]. However, a wide application of Mg alloys in various fields of industry has been limited by a lack of formability at the room temperature and suitable computer-aided engineering tools for simulation. Especially, Mg alloys show the tension-compression asymmetry in plastic flow since it has the strong basal texture according to pre-deformation process such as the rolling and extrusion.

Wagner et al. [2] conducted a finite element analysis prediction with the LS-DYNA software to capture the general initial deformation of magnesium AM30 extrude beam in four-point bending, which was compared with experimental results. Rossiter et al. [3] have derived a failure criterion for axial crush loading of tubes incorporating material hardening and tension-compression asymmetry to reproduce experimental failure structures. Chung et al. [4] have tested a new three-dimensional total shock physics code; ExLO in which it solved highly transient problems involving large deformations associated with high speed impact/penetration and explosion events. Moon et al. [5] examined the process design for an automobile crumple zone for pedestrian protection. The impact analysis was conducted to design a plastic structure which able to help reducing pedestrian injuries to the thigh area in which the fracture effect was incorporated into the model by calculating the damage to the plastic material during impact. Kim et al. [6] described a basic step for modeling the fatigue behavior of an extruded Al alloy cylinder where the microstructural analysis revealed that the material had recrystallized grains and clusters of constituent particles aligned in the direction of extrusion and fatigue life of the samples showed a shorter fatigue life representing a higher fatigue crack growth rate in the transverse direction. Langseth et al. [7] studied aluminum extrusion behavior under axial loading condition and carried out FE simulation with LS-DYNA to validate the experimental data. Karagiozova and Norman [8] have predicted the initiation of buckling based on a numerical simulation of the axial impact of strain rate insensitive square tubes using the FE code ABAQUS, which shows a good agreement with the results from experiments on aluminum alloy tubes impacted at various initial velocities. They con-

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cluded that a comparison between the buckling initiation in square tubes and geometrically equivalent circular tubes shows differences in the response, which are attributed to the stress wave propagation phenomena and to the structural differences between the two structures. Galib and Limam [9] have conducted a comprehensive experimental and numerical study of the crash behavior of circular aluminum tubes undergoing axial compressive loading. Yoon et al. [1] have modeled plastic flow of AZ31 Mg sheet in terms of anisotropy and tension-compression asymmetry using CPB06 yield criterion, which are applied to the axial crushing simulation. Nia et al. [10] studied energy absorption capacity and collapse of cylindrical and square thin-walled aluminum tubes with a crack shaped trigger under axial compression in which the cracks tends to change the collapse processes and folding modes severely.

This paper mainly concerns deformation and collapse mechanism for a magnesium tube in axial crushing tests to evaluate the crashworthiness of Mg part built in automobile. A finite element analysis for the axial crushing with extruded AZ61 is conducted with LS-DYNA software incorporating with the material card (MAT_124) considering tension-compression asymmetry in which the reaction force and deformed shape during the axial crushing are compared with each other.

2. AZ61 alloy

In order to perform the axial crushing test with AZ61 Mg tube, the initial extruded billet with the diameter of 91 mm is machined into the Mg tube with the external diameter of 90 mm, thickness of 4mm, and height of 180 mm as shown in Fig. 1. The final Mg tube weighs about 0.346 kg, which reduces the total weight of Al and Steel tubes to 34% and 78%, respectively as depicted in Table 1. The chemical composition of the initial extruded billet is described in Table 2.

A quasi-static tensile test at the strain rate of 0.001/sec is carried out to evaluate the mechanical properties of the as-received AZ61 alloy with ASTM E8/E8M specimen which is fabricated along the axial direction of the initial billet. Additionally, a compression test is conducted to compare the flow curves according to the deformation modes using a cylindrical specimen with the diameter of 10mm and height of 15 mm. Fig. 2 shows the comparison result of flow curves in tension and compression at the room temperature where the flow curve in compressive deformation shows a concave shape (i.e. hardening rate increases with increase of plastic strain) due to the occurrence of twins while it shows convex shape (i.e. hardening rate decreases with increase of plastic strain) commonly observed in tensile deformation of steel or aluminum alloys due to the slip. A compressive deformation mode along the axial direction of the extruded billet induces increase of the diameter, which generates the tensile twins since the basal plane of HCP lattice lying parallel to the extrusion direction of as-received AZ61 billet. The occurrence of the tensile twins does not only induce texture evolution about 86.5 degree but also influence the texture hardening as shown in Fig. 2 [11, 12].

Table 1. Comparison of Mg, Al alloy and steel tube weights at equivalent dimension.

Alloy	Mg alloy tube	Al alloy tube	Steel tube
Weight(kg)	0.346	0.525	1.527

Table 2. Chemical composition of AZ61.

Alloy	Al	Zn	Mn	Fe	Ni	Mg
(wt%)	6.1	0.46	0.22	0.002	0.0006	Bal

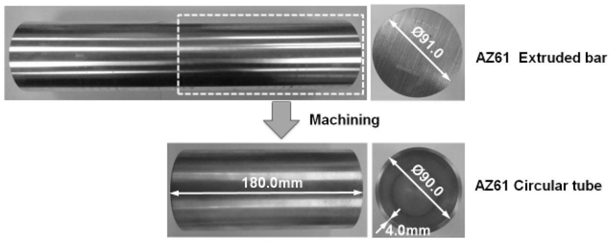


Fig. 1. Preparation of AZ61 circular tube.

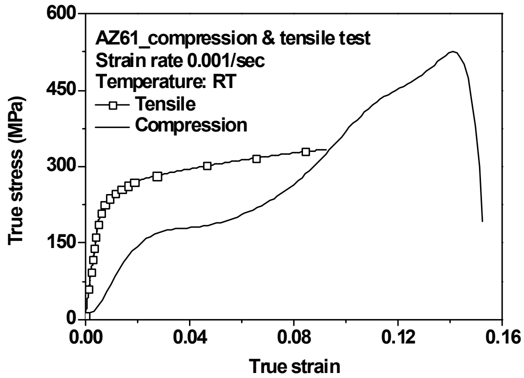


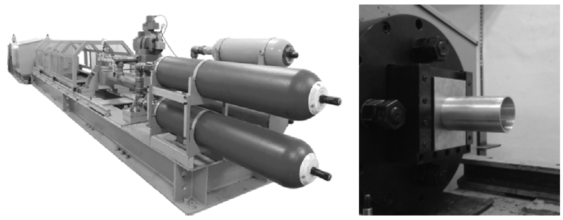
Fig. 2. Compressive and tensile flow curves for AZ61 at room temperature.

3. Axial crushing with Mg tube

3.1 Axial crushing test

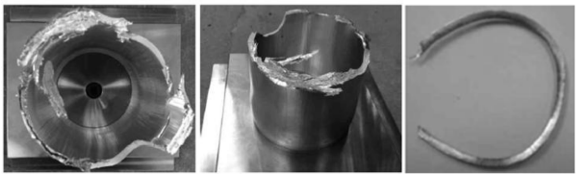
A quasi-static and high speed axial crushing tests with AZ61 Mg tubes are conducted to evaluate the deformation behavior and crashworthiness of Mg alloys at the various strain rates.

The high speed axial crushing test is carried out in the high speed crash tester (HSCT) as shown in Fig. 3(a). The HSTC operates the high speed crashing by launching the barrier with mass of 250 kg in the horizontal direction to the fixed plate where the test specimen is bolted as shown in Fig. 3(b). The maximum speed of the HSTC is 17 m/sec and the maximum crash energy becomes 78,000 Joule. In this research, the initial velocity of 7.5 m/sec to the carrier is imposed, which induces

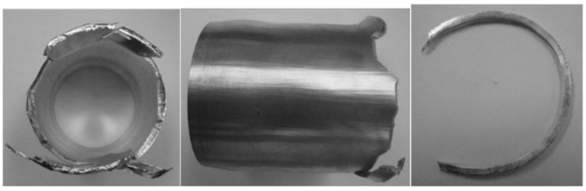


(a) (b)

Fig. 3. Axial crushing test in high speed crash tester: (a) tester; (b) initial set-up for Mg tube [13].



(a)



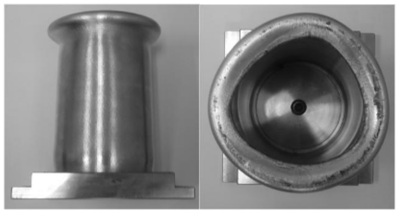
(b)

Fig. 4. Comparison of AZ61 tube compression test: (a) strain rate of 40.0/sec; (b) strain rate of 0.001/sec.

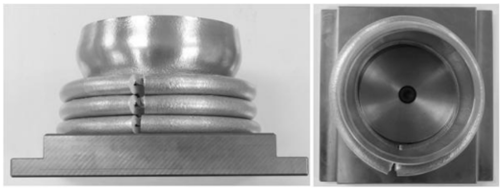
the strain rate of 40/sec in the Mg tube specimen, locally. The reaction force in the Mg tube during the axial crushing test is directly measured from the load cells built in the fixed plate while deformed shapes and strains of Mg tube are continuously taken and calibrated by high speed camera with 7000 frames/sec.

The quasi-static axial crushing test is also carried out in the 100-ton universal compression machine with the crosshead speed of 0.18 mm/sec which becomes the strain rate of 0.001/sec in the designed Mg tube.

As the carrier bumps into the Mg tube, the tube undergoes considerable compressive plastic strain along the axial direction and the diameter expands rapidly prior to buckling since the compressive flow stress is much smaller than the tensile one at the small plastic strain region as depicted in Fig. 2. Due to the low formability of AZ61 Mg alloy at the room temperature, initial fracture is investigated at the small amount of plastic strain right before the bulging along the radial direction as shown in Fig. 4. It is interesting to note that fracture fragments with a shape of circular ring have been investigated in the axial crushing tests at the quasi-static and high speed with the increase of the axial strain as shown in Fig. 4. This is because the Mg tube has the limited fracture elongation to sustain the progressive folding which occurs when the rate of bulging deformation is much faster than the expansion rate of tube diameter in the axial crushing.



(a)



(b)

Fig. 5. Deformed shape of Al6062 tube in axial crushing test: (a) strain rate of 56/sec; (b) strain rate of 0.001/sec.

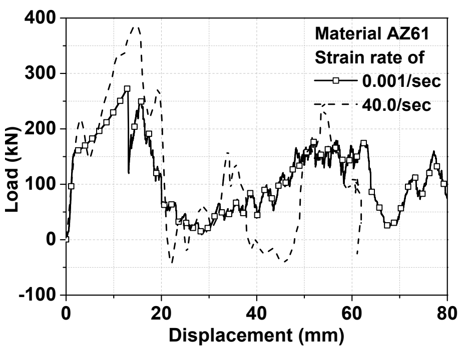


Fig. 6. Comparison of reaction forces with respect to strain rates of 40.0/sec and 0.001/sec during axial crushing tests.

In order to compare the deformation mode in axial crushing with the other materials, we have conducted the axial crushing test with Al6062 tube as shown in Fig. 5. In this test, we increased the carrier speed to 10 m/sec because the initial tube has the outer diameter of 120 mm, wall thickness of 5.3 mm, and height of 240 mm. It is noted that the progressive folding is investigated during the axial crushing as shown in Fig. 5. The final fracture only occurs along the circumferential direction due to the large expansion in diameter after three foldings occur as depicted in Fig. 5(b).

Fig. 6 shows the reaction forces in the quasi-static and high speed axial crushing tests. After it reaches the first peak, rapid drop in the reaction force occurs by the local fracture of the Mg tube. Then, it increases to the second peak with having progressive fractures, which induces many fragments of AZ61 alloy during the axial crushing test as shown in Fig. 4.

3.2 FE analysis of axial crushing

This section represents FE simulation with the LS-DYNA commercial software to take into consideration of the tension-

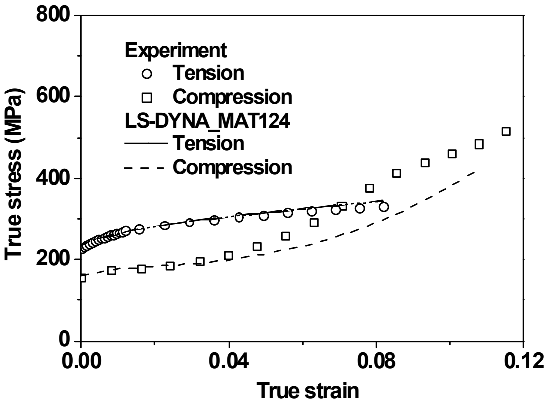


Fig. 7. Comparison results of experimental and simulation results in simple tension and compression tests.

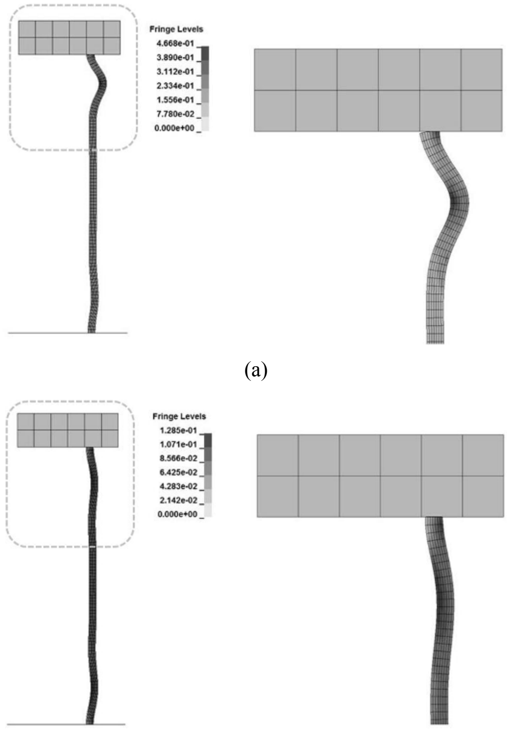
compression asymmetry in yielding and hardening rate of AZ61 Mg alloy on its response in the axial crushing at the quasi-static state. The tube is modeled with an outer radius of 90 mm, wall thickness of 4 mm, and a total length of 180 mm. The mesh used in the FE analysis consists of 630 axi-symmetric elements, totally, with 7 elements along the thickness direction.

The LS-DYNA provides a material model, MAT_124, which is able to accommodate different tension and compression material response curves. The input flow curves are scaled with respect to the strain rates based on the Cowper and Symonds model [2, 3]. To verify the material model, MAT_124, a simple tension and compression tests are conducted with 27 brick elements with the LS-DYNA.

Fig. 7 demonstrates the comparison results of experimental and simulation results in the simple tension and compression test, which shows the good agreement between experiment and simulation in flow curves, respectively.

It has been investigated for deformation mode in the axial crushing with respect to the tension-compression asymmetry of the tube material. Fig. 8 compares the deformation mode at the same punch stroke of 15 mm in which Fig. 8(a) represents the deformed shape in Al6062 tube while Fig. 8(b) shows the one in AZ61 tube. It is noted that the tube wall of AZ61 alloy sustains external load longer as compressed along the axial direction than the Al6062 since the compressive flow stress is lower than the tensile flow stress while the tube wall of Al6062 collapse with folding as shown in Fig. 8(b).

In this simulation, material fracture is described by incorporating the element deletion technique in terms of fracture plastic strain since it is essential to predict the first peak in the reaction force with AZ61 Mg tube. When it reaches fracture strain, failure criterion is triggered to delete the FE meshes within the model. Fig. 9 shows the comparison results of the reaction forces between experimental and simulation results adopting the fracture strain of 0.1. It is concluded that it is required to take into consideration of the tension-compression asymmetry in plastic flow as well as the texture evolution as



(a)

(b)

Fig. 8. Comparison of deformed shapes in axial crushing: (a) Al6062; (b) AZ61.

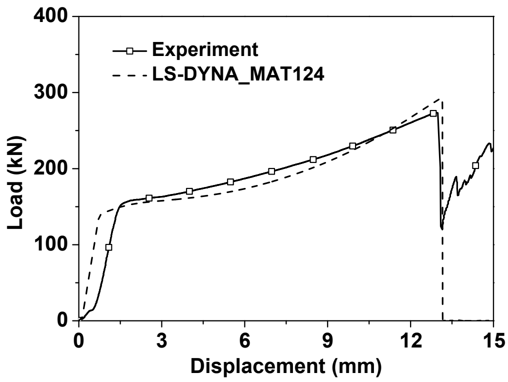


Fig. 9. Comparison of experiment and simulation compression deformation load curve.

the plastic deformation increases to evaluate the material fracture and propagation, especially, in Mg alloys.

4. Conclusions

Deformation mode and collapse mechanism in the axial crushing tests with the AZ61 Mg tube has been investigated in this paper to evaluate the crashworthiness of Mg part. In order to compare the collapse mode according to the tube materials, Al6061 and AZ61 tubes are applied in the quasi-static and high speed axial crushing tests.

The AZ61 Mg tube undergoes considerable compressive plastic strain at the small plastic strain along the axial direction and the diameter expands rapidly prior to buckling since the compressive flow stress is much smaller than the tensile flow stress while the Al6062 tube shows the progressive folding during the axial crushing. The collapse mode in the axial crushing with AZ61 Mg tube is simulated with LS-DYNA software incorporating with the material card (MAT_124) considering tension-compression asymmetry, which demonstrates the good agreement with the experimental deformed shape and reaction force.

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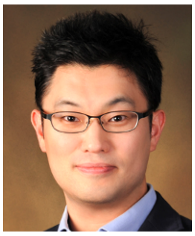

Jonghun Yoon received his Ph.D. degrees from the School of Mechanical, Aerospace and Systems Engineering at KAIST in 2008. His research interests include plasticity in Mg alloy, computational mechanics in metal forming, and mechanical properties at high strain rate.