Energy absorption study of warm-rolled dual-phase LZ71 magnesium alloy hollow tube using ANN

Mostafa Pahlavani, Javad Marzbanrad

1 School of Automotive Engineering, Iran University of Science and Technology, Tehran, Iran.

1. Introduction

Recently, many researchers are concentrated on control of collision kinetic energy [1-5]. Generally, there are various applications of energy absorption such as civil engineering [6], vehicle design [7-9], aerospace engineering [10, 11], etc. Basically, energy absorber converts kinetic energy into some other form of energy. Approximately, principles of all kinds of structural energy absorbers performance are based on its collapse. In the field of automotive engineering, because of the effective role on the safety of passenger cars, research on crash energy absorbers is considerably important [12]. Vehicle crash boxes are the most common structural energy absorbers which are used in various shape, namely cylindrical, tapered, polygonal etc. [13-16].

There are various experimental, analytical and simulation surveys on thin-walled structures energy absorption in several categories such as collapsing [17-19], flattening [20, 21], inversion [22, 23], bending [24-26], rupture [27-30], etc. Each mechanism has some special characteristics and also has specific applications.

Alavi Nia and Khodabakhsh [31] worked on concentric thin-walled tubes energy absorption. Their study includes simulations and experiments...
of quasi-static and dynamic loading. They conclude that comparing concentric tubes and a single tube system with an equal mass of structures absorbed the energy of the two-tube system is more than the single-tube system.

Tubular structures have considerable importance in the field of crashworthiness, due to its effect on occupant injury reduction in a crash [32]. Low cost, high strength and stiffness, excellent load efficiency and energy absorption capacity are the main reasons to make tubular crash absorbers pervasive applicable in engineering. [33]. Hence, it seems to be obligatory to study on crash behavior aiming to increase the energy absorbing capability of tubular structures [34]. Marzbanrad and Ebrahimi [12] used the explicit finite element method to simulate the crushing behavior of tubular energy absorber. They presented a method using the genetic algorithm (GA) and artificial neural network (ANN) to determine the best geometrical conditions of crash absorber based on optimizing the CFE and SEA of the structure.

Meanwhile, the geometry of crash absorbers has been the subject of various researches [35]. For instance, tapered crash absorbers have been considered due to their absorption performances [36]. Hou et al. [37] had a numerical study on tapered circular tubes. They used Multi Objective Optimization (MOO) and Design of Experiment (DoE) to achieve an optimized geometry of hollow single, foam-field single and collinear double tubes tapered crash absorber. Taştan et al. [38] researched on the crashworthiness of tapered thin-walled tubes with lateral circular cutouts. In their work, the performance of tapered crash absorbers including lateral circular cutouts has been surveyed numerically. Crush Force Efficiency (CFE) and the Specific Energy Absorption (SEA) have been considered as the main parameters of the absorbers crashworthiness performance, which computed using the finite element analysis.

Study on the effects of different types of metal forming and work hardening on mechanical properties and formability of materials is interesting for researchers [39-42]. The constituent material of the crash absorbers is also an interesting area which attracted numerous researchers [43-46]. In addition, magnesium alloys applications are experiencing a sharp rise in various industries such as Automotive, Aerospace, and Electronics due to its proper mechanical behavior [46-49]. Moreover, these alloys are well known as the lightest structural alloys having considered the density of 1.8 gr/cm³ or even less [50, 51]. Pure magnesium is one of the most abundant metals and has considerable properties, namely high durability, very high strength to weight ratio, high recyclability, desirable heat loss and electromagnetic shielding [52, 53]. Magnesium-Lithium alloys are one of the most favorable engineering metal due to its incredible properties, such as high formability and ultralow density [48]. Kiani et al. [54] had research on the design of lightweight magnesium vehicle structure. They used Dodge Neon impact data to compare their simulation performance. Some steel structural components have been replaced by AZ31 magnesium alloy to study crashworthiness effects of this lightweight alloy.

Mg-Li alloys are obviously attractive due to its elongation beside the distinct low density [55]. To achieve more proper mechanical properties, adding rare earth elements to the compound will be an effective solution. However, Mg-Li alloys containing 5 to 12 lithium weight proportion have the best structural behavior due to the fact that this portion of lithium will cause dual phase microstructure of the alloy with α-Mg (Mg solid solution, hcp structure) and β-Li (Li solid solution, body centered cubic (bcc) structure) [56].

In the present study, mechanical properties of LZ71 magnesium alloy are carried out and crashworthiness characterizations of LZ71 are studied numerically. Also, the Taguchi method is used to identify the dimensional parameters of the tubes to reduce simulation number. Moreover, crashworthiness sensitivity of LZ71 hollow tube regarding dimensional parameters is observed using the Artificial Neural Network (ANN).

2. Experimental Procedure

2.1. Alloy Preparation

In the present study, LZ71 alloy (Mg-7(Wt%) Li-1(Wt%) Zn) is cast using high-frequency Induction furnace at almost 770°C under argon protective atmosphere. Then the melt was cast into a preheated steel mold (Figure 1). The initial ingot has been warm-rolled from initial thickness of 10mm to final thickness of 2mm (total reduction of around 80% in 8 passes by 10% reduction) at a rolling temperature of 350°C (Figure 2). The sheet was then annealed at 200°C and 350°C for 3 hours.
Energy absorption study of warm-rolled dual-phase LZ71 magnesium alloy hollow tube using ANN

2.2. Metallography

To study the microstructure of the prepared alloy HUVITS HR3-TRF-P Optical Microscope (OM) is used. The specimens were ground, polished and corroded in the etchant solution of water (150 ml), HNO₃ (1 ml), CH₃COOH (1 ml) and H₂C₂O₄ (1 gr). Then, specimens were rinsed by alcohol and dried. After this, the micrographs of specimens have been taken on image analyzer and optical microscope.

2.3. Mechanical Properties

Mechanical properties of as-cast Mg LZ71, as rolled and full annealed are studied by uniaxial tensile tests. The test samples were prepared oriented along the rolling direction according to the ASTM E08 standard. Figure 3:a shows the tensile tests specimens which are cut in three directions, namely rolling direction (RD), 45° and transverse direction (TD) as illustrated in Figure 3:b. Uniaxial tensile tests were done at an initial strain rate of 1 mm/min at room temperature using SANTAM STM-50 tensile testing machine.

3. Energy absorption

3.1. Design parameters

Plastic deformability of an energy absorber before the fracture is known as its crashworthiness capability. There are several criteria to determine the crashworthiness capacity of crash absorbers, which are based on the force-displacement curve [57]. The most common crashworthiness criteria are described below.

1) Total energy absorption (TEA): defined as external work of the tube which can be calculated as:

\[ TEA = \int F(\delta) d\delta = \sum_{i=2}^{N-1} F_i \times \left( \frac{\delta_{i+1} - \delta_{i-1}}{2} \right) \]  

Figure 1: As cast ingots.

Figure 2: Warm rolled sheet.

(a)

(b)

Figure 3: Tensile tests specimens: a) Dimensions, b) Cutting directions.
where $F(\delta)$ is a function of the crash load based on the tube deformation ($\delta$). Indeed, TEA could be considered as the area under the force-displacement diagram.

2) **Peak crush force** ($F_{\text{Max}}$): the maximum axial force on the part.

3) **Mean crush force** ($F_{\text{Mean}}$): the result of division of TEA to total crush displacement ($\delta_i$).

$$F_{\text{mean}} = \sum_{i=2}^{N-1} \frac{P_i \times (\delta_{i+1} - \delta_{i-1})}{2 \delta_i}$$  \hspace{1cm} (2)

4) **Crush force efficiency** (CFE): the result of division of mean crush force to peak crush force:

$$CFE = \frac{F_{\text{Mean}}}{F_{\text{Max}}}$$  \hspace{1cm} (3)

5) **Specific energy absorption** (SEA): the ratio of total absorbed energy to part mass:

$$SEA = \frac{\text{TEA}}{m}$$  \hspace{1cm} (4)

where $m$ is the tube mass which absorbs energy during impact.

6) **Total Efficiency** (TE): the ratio of total absorbed energy to the products of $F_{\text{Max}}$ and total length of structure:

$$TE = \frac{F_{\text{mean}} \times \delta}{F_{\text{Max}} \times L}$$  \hspace{1cm} (5)

### 3.2. Finite Element Modelling

In the present study, the commercially available explicit dynamic nonlinear FE analysis code ABAQUS/Explicit software has been used to carry out the crush numerical simulations. Also, commercial mesh generation software HYPERMESH is used to mesh the models. Four-node shell elements with reduced integration are selected to simulate the circular tube crashes. The crash simulation model is shown in Figure 4: which is included the bottom and top rigid walls and circular tube as a crash absorber. Quasi-static simulation is performed to study the crashworthiness of the structure. Also, friction coefficients between tubes and rigid walls have been considered 0.2. To investigate mesh convergence, various element sizes were studied to discretize the circular structure. The effect of mesh size on mean crush force and total energy absorption is observed to study the accuracy of the model. This should be noticed, crash energy absorption parameters are calculated for the first 70% of tube length.

Figure 5: and Table 1: present $F_{\text{Mean}}$ and $F_{\text{Max}}$ from the FE models of two circular tubes (A1 and A4) regarding element size 1.5 to 5 mm. Length, thickness and the outer diameter of the A1 model are 101.6, 1.6 and 50.8 respectively and also the mentioned geometrical parameters of the A4 model are 152.4, 1.6, and 76.2 respectively. Dimensions and samples names are similar to [58] which its experimental results are used in the present work. It could be seen that the convergence has been attained at the element size of 2 mm.

![Figure 4: Crash model schematic.](image1)

![Figure 5: $F_{\text{Mean}}$ and $F_{\text{Max}}$ against mesh size: (a) and (b) A1 model, (c) and (d) A4 model.](image2)
Table 1: Convergence of mean crush force versus mesh size

<table>
<thead>
<tr>
<th>Mesh Size (mm)</th>
<th>Number of Elements</th>
<th>F_{mean} (KN)</th>
<th>F_{max} (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
<td>A4</td>
<td>A1</td>
</tr>
<tr>
<td>5</td>
<td>648</td>
<td>1458</td>
<td>24.561</td>
</tr>
<tr>
<td>4.5</td>
<td>800</td>
<td>1801</td>
<td>23.672</td>
</tr>
<tr>
<td>4</td>
<td>1013</td>
<td>2279</td>
<td>23.028</td>
</tr>
<tr>
<td>3.5</td>
<td>1323</td>
<td>2977</td>
<td>23.495</td>
</tr>
<tr>
<td>3</td>
<td>1801</td>
<td>4052</td>
<td>22.863</td>
</tr>
<tr>
<td>2.5</td>
<td>2593</td>
<td>5834</td>
<td>22.019</td>
</tr>
<tr>
<td>2</td>
<td>4052</td>
<td>9116</td>
<td>21.45</td>
</tr>
<tr>
<td>1.5</td>
<td>7203</td>
<td>16206</td>
<td>21.399</td>
</tr>
</tbody>
</table>

3.3. Validation of the FEA

To validate the FE simulations, in the present study, the results presented by Lu [58] have been used. Energy absorption parameters of the simulations of the present study, having considered Aluminum AA6082 tubes mechanical properties, as compared to the experimental results carried out by Lu [58]. Figure 6: shows the stress-strain curve of annealed Aluminum AA6082.

![Stress-Strain curve of annealed Aluminum AA6082. [58]](image)

Also, the parameters of crash absorption of experiments and simulations are compared in Table 3: The maximum difference of $F_{\text{mean}}$ is regard to A1 sample by -4.684% and overall absolute division of all samples is 2.97%. Maximum and average absolute deviations of $F_{\text{max}}$ between experiments and simulations are 9.846% and 3.859% respectively. Maximum differences of TCA, CFE, and SEA are -4.684%, -6.515% and -4.684%, respectively, while overall absolute divisions of the mentioned parameters between simulations and experiments are 2.907%, 4.288%, and 2.907%, respectively. As can be seen, maximum and average of differences are less than 10% for each case and parameter, which depict proper simulations results.

Table 2: Dimensions and mass of A1, A2, A4, A5, and A7 samples.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>L (mm)</th>
<th>t (mm)</th>
<th>D (mm)</th>
<th>D/t</th>
<th>L/D</th>
<th>M (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA6082</td>
<td>LZ71</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>101.6</td>
<td>1.6</td>
<td>50.8</td>
<td>31.75</td>
<td>2</td>
<td>0.07</td>
</tr>
<tr>
<td>A2</td>
<td>101.6</td>
<td>3.25</td>
<td>50.8</td>
<td>15.63</td>
<td>2</td>
<td>0.14</td>
</tr>
<tr>
<td>A4</td>
<td>152.4</td>
<td>1.6</td>
<td>76.2</td>
<td>47.63</td>
<td>2</td>
<td>0.16</td>
</tr>
<tr>
<td>A5</td>
<td>152.4</td>
<td>3.25</td>
<td>76.2</td>
<td>23.45</td>
<td>2</td>
<td>0.32</td>
</tr>
<tr>
<td>A7</td>
<td>203.2</td>
<td>1.6</td>
<td>101.6</td>
<td>63.5</td>
<td>2</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Figure 7: Crush mode comparison of experiments [58] versus simulations: a) A1, b) A2, c) A4, d) A5, e) A7.

Figure 8: Force-Displacement results of experiments [58] versus simulations: a) A1, b) A2, c) A4, d) A5, e) A7.
3.4. Sensitivity of Crash Absorption Parameters to Dimensions

3.4.1. Model Fitness

To study the trends of crash absorption parameters versus diameter, length and thickness, the Taguchi method is applied to determine the geometry of tubes which are needed. Taguchi method is introduced by Taguchi and Konishi, has been vastly utilized in engineering to optimize performance, quality, cost etc. according to the design parameters [59]. This method is known as one of the most important tools for a powerful and robust design of experiments [60]. In the present study, Diameter, Thickness, and Length of the tube are considered as design parameters which are set in 5 levels as can be seen in Table 4: The main reason for using the Taguchi method is to reduce the number of simulations which are required to study the effect of design variables on crash absorption indexes.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>A1</th>
<th>A2</th>
<th>A4</th>
<th>A5</th>
<th>A7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiments (KN)</td>
<td>22.504</td>
<td>50.476</td>
<td>23.841</td>
<td>81.330</td>
<td>26.122</td>
</tr>
<tr>
<td>FE Simulations (KN)</td>
<td>21.450</td>
<td>49.008</td>
<td>24.149</td>
<td>84.310</td>
<td>26.725</td>
</tr>
<tr>
<td>Differences (%)</td>
<td>-4.684</td>
<td>-2.907</td>
<td>1.295</td>
<td>3.664</td>
<td>2.307</td>
</tr>
</tbody>
</table>

3.4.2. Artificial Neural Network

Artificial Neural Network (ANN) is known as one of the most useful methods to model intricate input-output systems [61]. Design of an accurate and efficient ANN requires four steps [29, 62]:

- The suitable architecture of the ANN selection which includes the number and size of the hidden layers.
Training parameters selection, e.g. the weight adjusting.

- Selection and preparation of the proper set of data which will be used in training and testing of the ANN.
- Defining of iteration number.

In the present study, six ANN models are fitted using three input elements, namely diameter, length and thickness which are corresponded to $F_{\text{mean}}$, $F_{\text{Max}}$, TEA, CFE, SEA and TE as target elements, separately. Error! Reference source not found. illustrates the schematic of fitted ANN model.

![Schematic of ANN fitted models](image)

**Figure 9:** Schematic of ANN fitted models.

In the present study, train, validation and test ratio are set to 0.7, 0.15 and 0.15 respectively. Furthermore, a suitable number and size of hidden layers of the mentioned models are determined by try and error as shown in Figure 9:. Accordingly, the fitted models contain two hidden layers which the first one has tangent sigmoid and the second one has a logarithmic sigmoid transfer function. Moreover, the linear transfer function is appeared to be the best choice for output layers for both models.

4. Results and Discussion

4.1. Micro-structures and Mechanical Properties

In the present study, to achieve an isotropic mechanical property of Mg-Li LZ71, the effect of different annealing temperatures on mechanical properties and microstructure of warm-rolled mentioned alloy are studied. As can be seen from Figure 10: HCP and BCC phases of LZ71 are illustrated which HCP phase is speared in BCC one without specified orientation. Moreover, Figure 11: depicts RD-ND section OM images of as rolled and annealed samples at 200° C and 350° C. From this figure, dynamic recrystallization (DRX) has accrued during the rolling process which caused fined grain production besides a considerable high level of energy in the grains boundaries as depicted in Figure 11:.a and b. Also, Figure 11:.c and d illustrate a recovery in the specimen grains which has been annealed at 200° C. This is obvious that the grains have not been shaped homogeneously at the mentioned heat treatment process. On the other hand, at the 350° C annealing temperature, the grains have grown completely homogeneous as shown in Figure 12:.e and f.
Energy absorption study of warm-rolled dual-phase LZ71 magnesium alloy hollow tube using ANN

**Figure 10:** As cast LZ71 alloy OM images.

**Figure 11:** OM images of specimens: (a) and (b) as rolled, (c) and (d) annealed at 200°C, (e) and (f) annealed at 350°C.
Tensile tests results are presented in Figure 12. Although yield and tensile strength of as rolled (Figure 12: a) and annealed at 200° C (Figure 12: b) samples are more than the samples which are annealed at 350° C (Figure 12: c), mechanical properties of RD, 45° and TD samples which experienced 350° C heat treatment are considerably similar to each other. This similarity of mechanical properties shows that the plate which has been annealed at 350° C reached to isotropic properties.

This is concluded from the tensile tests results that the values of ultimate stress, yield stress, and elastic modulus of RD, 45° and TD samples are similar to each other in each heat treatment temperature but there is an obvious variation in their elongation at break point. The RD samples are shown the maximum elongation while TD sample had the minimum one. Also, the value of this parameter converges in different directions by increasing the temperature of the annealing process. On the other hand, increasing the annealing temperature causes the homogeneity of the mechanical properties of the rolled sheet in different directions. Therefore, it can be stated that the warm-rolled LZ71 sheet has become completely isotropic at the annealing temperature of 350° C. However, it is observed that the ultimate stress decreases by increasing the temperature.

In the present work stress-strain curve of warm-rolled LZ71 which has been annealed at 350° C, is used to simulate quasi-static crash behavior of circular tube. This is due to the isotropic
mechanical properties which are suitable for high deformation structural applications.

4.2. Energy absorption

4.2.1. Comparison of LZ71 and AA6082 in Energy Absorption Parameters

To compare the parameters of energy absorption of LZ71 and AA6082, results of tube crash simulation with A1, A2, A4, A5, and A7 dimensions are studied. Crush mode of the samples are illustrated in Figure 14: which indicates A2, A4 and A5 models of LZ71 and AA6082 have been collapsed pretty similarly (Figure 14: b, c, d). By contrast, A1 LZ71 is crushed reversely (the first fold is started from the bottom of the tube) (Figure 14:. a) and A7 LZ71 crushing mode shape is mixed of symmetric and diamond (Figure 14:. e). Figure 15: compares force-displacement curves of the models which shows mean and maximum crush force of LZ71 tubs are considerably lower than AA6082 ones.

![Crush mode comparison of LZ71 versus AA6082: a) A1, b) A2, c) A4, d) A5, e) A7.](image)

To study more comprehensively, the crash energy absorption parameters, videlicet $F_{\text{mean}}$, $F_{\text{max}}$, TEA, CFE, and SEA are presented in Table 5:. Although $F_{\text{mean}}$, $F_{\text{max}}$, and TEA have reduced by changing the material from AA6082 to LZ71, CFE, and SEA have seen an obvious increase. $F_{\text{Mean}}$ of A2 and A5 experienced more reduction than the other three samples by 33.648% and 36.601% respectively. Moreover, the maximum changes in $F_{\text{Max}}$ and TEA are related to A5 sample by -42.982% and -36.601, respectively.

By changing material, both CFE and SEA have risen for all samples which amongst them CFE of A4 sample and SEA of A1 sample have increased more than others by 19.838% and 28.104% respectively. The results presented in Table 5: depicts that LZ71 alloy has obviously better crash energy absorption performance compared to AA6082.
Figure 15: Force-Displacement results of LZ71 versus AA6082: a) A1, b) A2, c) A4, d) A5 and e) A7.
4.2.2. Sensitivity of Energy Absorption Parameters of LZ71 Tubes to Dimensional Parameters

Using the Taguchi method, the numbers of simulations are reduced from 125 to 25 which are shown in Table 6. Also, results of simulations have been presented in this table. As mentioned before, to study the crushing behavior of LZ71 tubes, six models are fitted. In all models, dimensional parameters, namely diameter, length, and thickness were input parameters. Also, for each model, F\text{Mean}, F\text{Max}, TAE, CFE, SEA, and TE were introduced as output parameters, separately.

4.2.3. Approximation Results

According to the available inputs and outputs variables presented in Table 6: and using ANN, the fitted models between input and output data is made for tube diameter of 50 to 150 mm, a tube length of 100 to 300 mm, and tube thicknesses of 1 to 3 mm. The calculated error for the ANN fitted model is under 5% which is proper for such problems. To comparison and analysis the present case properly, surfaces of the output parameters in terms of tube length and diameter are plotted. Moreover, the surface plots of these parameters in terms of tube thickness and diameter are presented as well.

Figure 16: to Error! Reference source not found. illustrate the surface plots of F\text{Mean}, F\text{Max}, TAE CFE, SEA, and TE respectively in terms of dimensional parameters. These surface plots have been created using the correlation equations of the mentioned crash parameters in terms of the dimensional parameters, presented in equations (6) to (11). These equations have been derived using the trained ANN models.

From the Figure 16.a, F\text{Mean} approximately remains steady against the rise of the tube length and rises when the diameter increases. In the other words, the effect of diameter changes is considerable more than tube length on F\text{Mean}. Figure 16.b illustrates the growth of thickness will cause the rise of F\text{Mean}. Moreover, the surface plots depict that the influence of thickness changes on the F\text{Mean} is larger as compared to the effect of the specimen diameter.
Table 6: Results of selected model using Taguchi Method.

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Dm (mm)</th>
<th>L (mm)</th>
<th>t (mm)</th>
<th>M (Kg)</th>
<th>Fmean (KN)</th>
<th>Fmax (KN)</th>
<th>δ (mm)</th>
<th>TEA (J)</th>
<th>CFE</th>
<th>SEA (J/Kg)</th>
<th>TE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>100</td>
<td>1</td>
<td>0.025</td>
<td>8.63</td>
<td>15.26</td>
<td>70</td>
<td>604.39</td>
<td>0.57</td>
<td>24507.41</td>
<td>0.40</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>150</td>
<td>1.5</td>
<td>0.056</td>
<td>14.99</td>
<td>28.71</td>
<td>105</td>
<td>1574.27</td>
<td>0.52</td>
<td>28371.11</td>
<td>0.37</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>200</td>
<td>2</td>
<td>0.099</td>
<td>20.76</td>
<td>35.92</td>
<td>140</td>
<td>2906.69</td>
<td>0.58</td>
<td>29465.82</td>
<td>0.40</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>250</td>
<td>2.5</td>
<td>0.154</td>
<td>26.35</td>
<td>41.25</td>
<td>175</td>
<td>4611.01</td>
<td>0.64</td>
<td>29915.52</td>
<td>0.45</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>300</td>
<td>3</td>
<td>0.222</td>
<td>29.94</td>
<td>43.65</td>
<td>210</td>
<td>6286.97</td>
<td>0.69</td>
<td>28325.63</td>
<td>0.48</td>
</tr>
<tr>
<td>6</td>
<td>75</td>
<td>100</td>
<td>1.5</td>
<td>0.056</td>
<td>16.73</td>
<td>34.82</td>
<td>70</td>
<td>1171.34</td>
<td>0.48</td>
<td>21109.60</td>
<td>0.34</td>
</tr>
<tr>
<td>7</td>
<td>75</td>
<td>150</td>
<td>2</td>
<td>0.111</td>
<td>25.73</td>
<td>51.00</td>
<td>105</td>
<td>2702.00</td>
<td>0.51</td>
<td>24347.47</td>
<td>0.35</td>
</tr>
<tr>
<td>8</td>
<td>75</td>
<td>200</td>
<td>2.5</td>
<td>0.185</td>
<td>36.78</td>
<td>64.18</td>
<td>140</td>
<td>5148.75</td>
<td>0.57</td>
<td>27836.91</td>
<td>0.40</td>
</tr>
<tr>
<td>9</td>
<td>75</td>
<td>250</td>
<td>3</td>
<td>0.277</td>
<td>47.14</td>
<td>80.87</td>
<td>175</td>
<td>8249.35</td>
<td>0.60</td>
<td>29733.59</td>
<td>0.42</td>
</tr>
<tr>
<td>10</td>
<td>75</td>
<td>300</td>
<td>1</td>
<td>0.111</td>
<td>9.69</td>
<td>23.22</td>
<td>210</td>
<td>2035.82</td>
<td>0.42</td>
<td>18344.55</td>
<td>0.29</td>
</tr>
<tr>
<td>11</td>
<td>100</td>
<td>100</td>
<td>2</td>
<td>0.099</td>
<td>33.83</td>
<td>65.50</td>
<td>70</td>
<td>2368.41</td>
<td>0.52</td>
<td>24009.15</td>
<td>0.36</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
<td>150</td>
<td>2.5</td>
<td>0.185</td>
<td>47.45</td>
<td>80.87</td>
<td>105</td>
<td>4982.52</td>
<td>0.59</td>
<td>26938.16</td>
<td>0.41</td>
</tr>
<tr>
<td>13</td>
<td>100</td>
<td>200</td>
<td>3</td>
<td>0.296</td>
<td>63.64</td>
<td>110.19</td>
<td>140</td>
<td>8909.03</td>
<td>0.58</td>
<td>30104.38</td>
<td>0.40</td>
</tr>
<tr>
<td>14</td>
<td>100</td>
<td>250</td>
<td>1</td>
<td>0.123</td>
<td>10.67</td>
<td>29.48</td>
<td>175</td>
<td>1866.55</td>
<td>0.36</td>
<td>15137.34</td>
<td>0.25</td>
</tr>
<tr>
<td>15</td>
<td>100</td>
<td>300</td>
<td>1.5</td>
<td>0.222</td>
<td>18.52</td>
<td>38.07</td>
<td>210</td>
<td>3889.70</td>
<td>0.49</td>
<td>17524.83</td>
<td>0.34</td>
</tr>
<tr>
<td>16</td>
<td>125</td>
<td>100</td>
<td>2.5</td>
<td>0.154</td>
<td>55.22</td>
<td>93.50</td>
<td>70</td>
<td>3865.46</td>
<td>0.59</td>
<td>25078.51</td>
<td>0.41</td>
</tr>
<tr>
<td>17</td>
<td>125</td>
<td>150</td>
<td>3</td>
<td>0.277</td>
<td>75.12</td>
<td>125.11</td>
<td>105</td>
<td>7887.19</td>
<td>0.60</td>
<td>28428.24</td>
<td>0.42</td>
</tr>
<tr>
<td>18</td>
<td>125</td>
<td>200</td>
<td>1</td>
<td>0.123</td>
<td>12.77</td>
<td>34.20</td>
<td>140</td>
<td>1787.34</td>
<td>0.37</td>
<td>14494.99</td>
<td>0.26</td>
</tr>
<tr>
<td>19</td>
<td>125</td>
<td>250</td>
<td>1.5</td>
<td>0.231</td>
<td>24.36</td>
<td>46.18</td>
<td>175</td>
<td>4262.22</td>
<td>0.53</td>
<td>18435.08</td>
<td>0.37</td>
</tr>
<tr>
<td>20</td>
<td>125</td>
<td>300</td>
<td>2</td>
<td>0.370</td>
<td>40.31</td>
<td>73.50</td>
<td>210</td>
<td>8464.64</td>
<td>0.55</td>
<td>22882.18</td>
<td>0.38</td>
</tr>
<tr>
<td>21</td>
<td>150</td>
<td>100</td>
<td>3</td>
<td>0.222</td>
<td>85.08</td>
<td>145.58</td>
<td>70</td>
<td>5955.22</td>
<td>0.58</td>
<td>26830.92</td>
<td>0.41</td>
</tr>
<tr>
<td>22</td>
<td>150</td>
<td>150</td>
<td>1</td>
<td>0.111</td>
<td>15.96</td>
<td>38.31</td>
<td>105</td>
<td>1676.06</td>
<td>0.42</td>
<td>15102.75</td>
<td>0.29</td>
</tr>
<tr>
<td>23</td>
<td>150</td>
<td>200</td>
<td>1.5</td>
<td>0.222</td>
<td>30.25</td>
<td>59.55</td>
<td>140</td>
<td>4234.48</td>
<td>0.51</td>
<td>19078.24</td>
<td>0.36</td>
</tr>
<tr>
<td>24</td>
<td>150</td>
<td>250</td>
<td>2</td>
<td>0.370</td>
<td>45.32</td>
<td>81.94</td>
<td>175</td>
<td>7931.35</td>
<td>0.55</td>
<td>21440.57</td>
<td>0.39</td>
</tr>
<tr>
<td>25</td>
<td>150</td>
<td>300</td>
<td>2.5</td>
<td>0.555</td>
<td>59.64</td>
<td>103.29</td>
<td>210</td>
<td>12523.91</td>
<td>0.58</td>
<td>22570.33</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Energy absorption study of warm-rolled dual-phase LZ71 magnesium alloy hollow tube using ANN

\[
Y_i = -15.6921 + 0.7398D + 0.0250L - 4.1666 \times 10^{-4}D^2 + 3.0703 \times 10^{-4}L^2 - 1.9110 \times 10^{-3}DL,
Y_j = 11.6469 - 0.1031D - 11.3395L - 4.1666c - 4D^2 + 3.1456L^2 + 0.2303Dt,
\]

\[
Y_i = 4.8663 - 0.4244Y_i + 1.1128Y_j + 7.4117 \times 10^{-1}Y_i^2 - 1.9467 \times 10^{-1}Y_j^2 - 2.9323 \times 10^{-1}Y_iY_j,
Y_j = -7.6953 + 1.0307Y_i + 0.0999L - 1.3751 \times 10^{-1}Y_i^2 - 2.7146 \times 10^{-1}L^2 - 1.6358 \times 10^{-2}Y_iL,
F_{\text{max}} = -0.0909 + 0.9823Y_i + 0.0325Y_j - 0.1083Y_j^2 - 0.0884Y_j^3 + 0.1966Y_jY_i,
\]

\[
Y_i = 11.5210 + 0.1631D - 19.8513 - 1.9573 \times 10^{-4}D^2 + 4.6346L^2 + 0.3736Dlt,
Y_j = -14.5533 + 0.2172L + 0.9486Y_i - 6.0040 \times 10^{-1}L^2 + 4.5021e - 4Y_i^3 - 7.407 \times 10^{-1}L^3Y_i,
F_{\text{max}} = -2.6563 + 0.8334Y_i + 7.6418L - 9.8598 \times 10^{-1}Y_i^2 - 3.3611L^2 + 0.1245L^3Y_i,
\]

\[
Y_i = -3957.7395 + 0.7663D + 3989.3844 + 0.1601D^2 - 256.8008L^2 + 0.3231Dt,
Y_j = -4673.6945 + 8.8352L + 3631.3678t + 0.0510L^2 - 256.8008L^2 + 1.9061Lt,
Y_k = 987.6994 + 13.5478D + 6.0246L + 0.1601D^2 + 0.0150L^2 + 0.0662DL,
Y_i = 1.5478 \times 10^{-1} + 0.2004Y_i + 0.5386Y_j - 1.8371 \times 10^{-1}Y_j^2 - 2.1368 \times 10^{-1}Y_j^3 + 4.6461 \times 10^{-1}Y_iY_j,
Y_j = -5.2499 \times 10^{-3} + 0.4657Y_i + 0.0643Y_j + 4.3528 \times 10^{-1}Y_i^2 + 4.2644 \times 10^{-1}Y_j^2 - 4.5007 \times 10^{-1}Y_jY_i,
\]

\[
Y_i = 0.7629 - 4.0679 \times 10^{-1}D + 3.8170L + 2.2548 \times 10^{-1}D^2 + 2.1501 \times 10^{-1}L^2 - 4.7593 \times 10^{-2}DL,
Y_j = 0.5215 - 5.2701 \times 10^{-1}D + 0.1987t - 2.2548 \times 10^{-1}D^2 - 0.0301t^2 + 1.2516 \times 10^{-1}Dt,
Y_k = 4.0927 - 20.5623Y_i + 6.6029Y_j + 0.21161Y_j^3 - 3.3644Y_j^2 - 4.1391Y_jY_i,
Y_j = 0.3857 + 5.9301Y_i - 0.3671Y_j + 8.9837Y_j^2 + 19.043Y_j^3 - 26.7242Y_j,
\]

\[
Y_i = 28375.5445 - 282.7104D + 6708.8609t + 0.7565D^2 - 1093.0900D^2 + 32.4318Dt,
Y_j = 15428.7095 - 11.6388L + 6092.9677L - 0.0997L^2 - 1093.0900D^2 + 19.2954Lt,
Y_k = 30054.4174 - 158.6945D + 56.5281L + 0.7565L^2 - 0.0997L^2 - 0.2958DL,
Y_i = 2.9896 \times 10^{-1} + 1.0064Y_i - 0.1628Y_j + 5.7990 \times 10^{-1}Y_j^2 + 7.1886 \times 10^{-1}Y_j^3 - 1.2413 \times 10^{-1}Y_jY_i,
Y_j = 5.5811 \times 10^{-1} + 6.5598 \times 10^{-1}t + 0.6584L + 6.1451 \times 10^{-1}t^2 - 3.4550 \times 10^{-1}Y_j^2 + 0.2110Y_j,
SEA = 1.0300 \times 10^{-1} + 2.8158Y_i + 3.7292Y_j - 1.2734 \times 10^{-1}Y_j^2 - 3.2507 \times 10^{-1}Y_jY_i + 4.5660 \times 10^{-1}Y_jY_i,
\]

\[
Y_i = 0.3650 - 3.6891 \times 10^{-1}D + 0.1391t + 1.5784 \times 10^{-1}D^2 - 0.0211t^2 + 8.7612 \times 10^{-1}Dt,
Y_j = 0.5340 - 2.8475 \times 10^{-1}D - 2.6719 \times 10^{-1}D^2 + 1.5784 \times 10^{-1}D^2 + 1.5051 \times 10^{-1}L^2 - 3.3315 \times 10^{-1}DL,
Y_k = 2.8649 + 6.6029Y_i - 20.5623Y_j - 4.8062Y_j^2 + 30.2301Y_j^3 - 5.9130Y_jY_i,
Y_j = 0.3650 - 3.6891 \times 10^{-1}D + 0.1391t + 1.5784 \times 10^{-1}D^2 - 0.0211t^2 + 8.7612 \times 10^{-1}Dt,
TE = 0.2700 + 5.9301Y_i - 6.3671Y_j + 12.8334Y_j^2 + 27.2061Y_j^3 - 38.1775Y_jY_i,
\]

3528 Automotive Science and Engineering
Figure 17: 

Surface plot of \( F_{\text{mean}} \) as a function of: a) \( L \) and \( D \), b) \( D \) and \( t \).

Figure 17:a shows that \( F_{\text{Max}} \) increases considerably against the growth of diameter while the gain of the length make it experience a mild increase. From Figure 17:b \( F_{\text{Max}} \) has risen obviously due to the increase of thickness and also the effect of thickness changes on the \( F_{\text{Max}} \) is almost more than that of the diameter.

Figure 18: 

Surface plot of TEA as a function of: a) \( L \) and \( D \), b) \( D \) and \( t \).

As can be seen from Figure 19: to Figure 21:, CFE, SEA, and TE have been influenced slightly by conversions of the length of specimens while the effects of changes of model thickness and diameter are considerable on the mentioned parameters.

TEA experienced a mild increase against rise of diameter while the effect of length changes had considerable effect (Figure 18:a). Also similar to \( F_{\text{mean}} \), the influence of thickness value is obviously more than that of diameter (Figure 18:b).
5. Conclusion

In this paper, crashworthiness of LZ71 magnesium alloy hollow tube has been surveyed numerically. To achieve mechanical properties of LZ71 sheet, the uniaxial tensile test has been applied to drive stress-strain curves. Since isotropic materials show proper crushing behavior in high deformation situations, rolled specimen annealed at 200° C and 350° C.

- Isotropic mechanical behavior has been observed in specimens which had annealed at 350° C. Therefore, results of tensile tests of the samples annealed at 350° C is used to simulate crush behavior of LZ71 hollow tube.
- FE models have been validated by the experimental results of aluminum AA6082 tube crash which showed excellent performances regarding the crush mode shape and force-displacement graphs.
- The crash energy absorption parameters including peak crush force ($F_{\text{Max}}$), mean crush force ($F_{\text{Mean}}$), total energy absorption (TAE), crush force efficiency (CFE), specific energy absorption (SEA) and total efficiency (TE), are compared between experiments and simulations which indicate that the simulations results were completely close to the experimental outcomes.
- The energy absorption performance of LZ71 and AA6082 have been compared to each other which concluded that LZ71 crashworthiness characterizations are much better than AA6082 particularly in thinner samples that this is due to LZ71 extremely low density.
- The sensitivity of energy absorption parameters of LZ71 has been studied with the help of Taguchi method (to select dimensional parameters of simulation models) and Artificial Neural Network (to fit the approximation model).
- The results of sensitivity analysis illustrate that the influences of thickness variations on $F_{\text{Mean}}$ and TAE are much more considerable with compared to length and diameter.
- The influences of the model length changes on the CFE, SEA, and TE were obviously lower than that of the thickness and diameter.

References


Energy absorption study of warm-rolled dual-phase LZ71 magnesium alloy hollow tube using ANN


[49] K. Sahoo and P. Poddar, "Studies on magnesium alloys-properties and potential for automotive and


[58] S. Lu, "Impact energy absorption analysis of different thin-walled tubes with and without reinforcement," Doctor of Philosophy, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, 2014.


