Frictional Condition Evaluation in Hot Magnesium Forming Using T-Shape and Ring Compression Tests

S.M. Pezeshki*, H. Badnava and F. Fereshteh-Saniee

Department of Mechanical Engineering, Faculty of Engineering, Bu-Ali Sina University, Hamedan, Iran

Abstract

T-shape compression test is a newly introduced friction test for evaluation of frictional condition in metal forming processes. This test includes large surface expansion and high contact pressure within the contact surfaces, similar to what is occurred during a real forming operation. Therefore the resulted friction factors are reliable and applicable. One of the friction tests which widely used for evaluation of frictional conditions in forming operations is the ring compression test. This test is very simple and does not require manufacturing a specific die. In the present research, the frictional conditions of hot magnesium forming were studied experimentally using the ring and T-shape compression tests. The tests were conducted in the same temperature and ram velocity. Three different lubrication conditions and two different die geometries of the T-shape tests were used. Finally the resulted friction factors, surface expansion ratio and maximum contact pressure in these tests were compared.

Keywords: Friction, T-shape compression test; Ring compression test; Hot magnesium forming.

1. Introduction

An obvious understanding of process parameters, material behavior, forming tools and interfacial frictional conditions are required to produce defect-free components. Frictional conditions can affect surface finish of the produced components, die wear and forming load. Therefore, a precise estimation of frictional condition is essential. In addition, finite element simulation of forming processes requires precise value of friction factor. Various friction tests are proposed for evaluating frictional conditions of forming processes such as the ring compression test, double cup and forward extrusion test, upsetting-sliding test, spike test and T-shape compression test. The T-shape compression test is a newly proposed friction test, so results of this test have not been compared with other friction tests yet.

Zhang et al. employed the T-shape friction test as a new method to determine frictional conditions in cold forging by using numerical simulation and experimental investigation [1]. Taureza et al. improved sensitivity of the T-Shape compression test by introducing the double-sloped T-Shape test [2]. They have proposed using the extruded height and load curves throughout the normalized stroke to determine the friction sensitivity of T-shape tests.

Bernd-Amo et al. investigated the effects of temperature, strain rate and scaling factor on friction factor by means of ring compression test [3]. Some efforts have been made to understand the effects of various parameters such as deformation speed, surface roughness, temperature and lubrication on the friction factor [4, 5 and 6]. Jung and Im examined the influence of deformation speed on the shear friction factor under various lubrication conditions [4]. In their research, finite element analysis was utilized to determine the shear friction factor of each lubricant at various ram velocities. Bay et al. studied the effects of the normal pressure, surface expansion, sliding length and tool-workpiece interface temperature on friction factor [7]. Their results showed that normal pressure and tool-work piece interface temperature have a significant effect on friction factor, while the other process parameters showed minor influence on friction factor.

The ring compression test is one of the most prevalent friction tests which were used for evaluation of friction in metal forming processes. Fereshteh-Saniee et al. employed the ring compression test together with various lubricants for the physical modeling of the bulk metal forming processes [8].

Due to their low density and their high specific strength and stiffness, magnesium alloys have a great potential to be used in different engineering industries such as aerospace and automotive industries. The AZ80 magnesium alloy was used on both the ring and T-shape experiments. Forming process of magnesium alloys is usually performed at elevated temperatures because of limited ductility of these alloys at the room temperature. In the present research, the ring and T-shape compression test were used for evaluating frictional conditions of hot magnesium forming. Two different die geometries are
used for the T-shape compression tests. Calibration curves for the ring and the T-shape compression test were obtained numerically by using finite element simulations. The obtained friction factors from these types of tests were compared. Moreover, the reasons why these friction factors were different were discussed.

2. The ring compression test

In this type of test, a short hollow cylinder is compressed axially between two platens. The inner radius of the test specimen is sensitive to frictional condition. In the high friction condition the inner radius of the ring decreases (See Fig. 1). In the contrary, this radius increases for low friction coefficient (good lubrication). The friction factor is usually measured using ring compression test’s calibration curves [9]. These curves could be plotted using analytical/finite element approach. A set of FE based calibration curves is illustrated in the Fig. 2. These curves were obtained using flow stress behavior of AZ80 magnesium alloy at 250°C and the deformation rate of 0.01s⁻¹. The deformed geometry of sample was utilized for obtaining friction coefficient from these curves.

The percentage reduction in height and percentage reduction in internal diameter were calculated using the (1) and (2) relations, respectively:

\[ \Delta h\% = \frac{h_0 - h}{h_0} \times 100 \]  
\[ \Delta d\% = \frac{d_i - d'_i}{d_i} \times 100 \]

where \( h_0 \) and \( d_i \) are initial height and internal diameter, respectively. The \( h \) and \( d' \) are denoting to the above-mentioned values after deformation.

3. The T-shape compression test

This test firstly was introduced by Zhang and his co-workers in 2009 [1]. A cylindrical specimen is located in a V-shape groove as is shown in the Fig. 3(a). The punch, sample and die are three parts of this test. As the punch moves downwards, the specimen is compressed between the punch and die. The deformed specimen is similar to T letter (See Fig. 3(b)). The geometry of the deformed sample and the forming load are sensitive to frictional conditions. Therefore, these two factors could be used for evaluating the friction factor.

Deformation of the sample could be divided to two different stages. In the first stage, the specimen is compressed and the material flows between the punch and the upper flat part of the die. In this stage, the slope of the force-displacement curve is linear (See Fig. 4).
In the second stage, the material of the test specimen flows in the V-groove. In this stage, both the slope and the force value in the force-displacement curve are increased sharply (See Fig. 4).

4. Experimental Procedure

Two type of experiments were employed, the ring compression tests and the T-shape compression tests. The as-cast AZ80 magnesium alloy was used as material in both types of experiments. The test specimens were manufactured by using machining process. All tests were conducted at the temperatures of 250°C using three different lubrication conditions namely lubrication with MoS₂, Copper Anti Seize Paste (CASP) and lubricant free (dry) conditions.

4.1. The ring compression experiments

The ring samples with the ratio of outer diameter/inner diameter/height equal to 6/3/2 and with 9mm outer diameter were used. This used ratio is the most prevalent geometry for ring test [10]. The tests were performed under three different deformation rates, 0.001, 0.01 and 0.1 s⁻¹. The deformed ring samples are shown in Fig. 5(a).

4.1. The T-shape compression experiments

Cylindrical test samples with height/diameter ratio of 1.5 and 6mm diameter were used. The tests were performed under the same punch velocity of the ring tests.

The employed die geometry of T-shape compression tests is shown in Fig. 5(b). Two different die corner radii, R=1 and 2 mm were used. The V-groove angle of die and its depth were 15 degree and 10 mm, respectively. The deformed test specimens are shown in Fig. 5(a). Each test was repeated at least two times.

5. Results and discussion

5.1. Calibration curves of ring tests

The ring compression tests’ calibration curves at temperature of 250°C and deformation rate of 0.01 s⁻¹ together with experimental findings related to three different frictional conditions are plotted in the Fig. 5. The highest friction factor was the friction factor of the lubricant free conditions, 0.28. The friction factors are also shown in Table 1.

Table 1 Friction factors of the ring and T-shape compression tests for AZ80 Mg alloy at temperature of 250°C, ram velocity of 1.5 mm/min and three different frictional conditions

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Geometry</th>
<th>Lubrication condition</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring compression test</td>
<td>6/3/2</td>
<td>MoS₂</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CASP</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td>0.28</td>
</tr>
<tr>
<td>T-shape compression test</td>
<td>R=1</td>
<td>MoS₂</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CASP</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>R=2</td>
<td>MoS₂</td>
<td>0.17</td>
</tr>
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</tr>
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<td></td>
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<td>Dry</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Fig. 5 (a) The deformed samples of ring and T-shape compression tests, (b) the employed die geometry of T-shape experiments.

Fig. 6 The FE based calibration curve and experimental results of ring compression test for AZ80 Mg alloy at 250°C, 1.5mm/min ram velocity and different frictional conditions.

It is worth mentioning that both temperature and deformation rate can affect the geometry of FE based calibration curves fairly. The presented results were obtained by considering the related calibration curve for the mentioned forming condition, i.e. the above-mentioned temperature and deformation rate.

5.2. Calibration curves of the T-shape compression tests

For investigating effects of friction on results of T-shape tests, a set of calibration curves is needed. The extruded height in the T-shape tests, the height of the material which is inputted to the V-groove, is sensitive to frictional conditions in the surfaces of the V-groove. Higher friction leads to smaller extruded height. The frictional condition can also affect the forming load of these tests. Therefore a plot of the extruded height versus the forming load could be used as calibration curves of the T-shape tests. This plot is illustrated in the Fig. 7.
The ratio of the extruded height to the initial diameter of the test sample ($H_e/D_b$) was used as dimensionless extruded height in this figure. Higher friction leads to smaller extruded height and larger forming load. Hence, in the lubricant free condition, as it is shown in Fig. 7, the extruded height is smaller than those of other frictional conditions. It can be seen that the required forming load in this case is higher than of two other frictional conditions.

The resulted friction factors from T-shape experiments are mentioned in Table 1. Lubrication with MoS2 led to the lowest friction factor among all lubrication conditions of T-shape tests. The friction factors related to lower die edge radius was slightly higher than the other one. The lower the die edge radius, the harder is the flow of material to the V-groove. This is the reason why friction factor for $R=1$mm is higher than the one of $R=2$mm.

FE simulations of the T-shape test were performed using the obtained friction factors. The load curve of the FE simulation for the die edge radius of $R=1$mm and three different frictional conditions was compared with experimental results in Fig. 8. The FE results were in good agreement with experimental ones. Therefore, it can be concluded that the obtained friction factors are reliable and accurate. It is worth mentioning that friction factor may vary by variation of temperature and deformation rate. It also depends on the material of the sample and the roughness of the punch and the die surfaces.

5.3 Comparison of the friction factors of ring and T-shape compression tests

The friction factors of the ring and T-shape compression tests for AZ80 Mg alloy at temperature of 250°C, ram velocity of 1.5 mm/min and three different frictional conditions are compared in the Table 1. The friction factors of the ring tests were smaller than those of T-shape tests. By considering the die edge radius of $R=1$mm for the T-shape tests, friction factors of the ring tests were 44%, 29% and 22% smaller than those of the T-shape tests for lubrication with MoS2, CASP and lubricant free condition, respectively.

This deviation between friction factors of the ring and T-shape tests were because of three major reasons. The first one was the different contact pressure in these tests. The maximum contact pressure in the mentioned forming condition for ring compression tests was about 300 Mpa whereas the maximum contact pressure of T-shape tests were about 1800 Mpa which was six times larger. This high contact pressure resulted in higher friction among contact surfaces and therefore led to higher friction factors.

The second reason of deviation between friction factors of these two tests was the complex deformation path in the T-shape test. The material had to flow through the punch and the die while in the ring test the material flowed freely without any limitation. The simpler deformation path, the smaller was the friction factor.

Finally, the third reason of different friction factors was the different surface expansion of these tests. The maximum surface expansion in the ring test was approximately about 20% while the T-shape test had a surface expansion about 40-50%. The larger surface expansion results in weaker lubrication because the lubricant cannot perform the desired lubrication for the newly produced surfaces. It is clear from Table 1 that the difference among friction factors of the ring tests and T-shape tests is larger in the case of lubrication with MoS2 while for the lubricant free condition this deviation is minimized.
5.4. Microstructure of deformed T-shape samples

The result of the microstructure analysis in the T-shape test is shown in Fig. 9. It is obvious that the friction force changed the grain boundary pattern near the die surface. In the vicinity of the edge radius of V-groove section of the die are located the more elongated grains. However, the grains located far from the die surface were less influenced by friction.

6. Conclusions

A comparative experimental study on the ring and T-shape compression test was carried out. The following concluding remarks can be summarized:
1. MoS2 provided the best lubrication among three different lubrication conditions for hot forming of AZ80 Mg alloy.
2. Higher friction in the T-shape compression test leads to smaller extruded height and larger forming load as it can be seen from lubricant free conditions.
3. For the T-shape compression tests, the smaller the die edge radius, the larger is the resulted friction factor.
4. FE simulation of the T-shape test based on determined friction factors resulted in accurate load curves in comparison with experiments.
5. The friction factors of the ring tests were lower than those of T-shape tests. The differences were greater for the lubricated conditions.
6. Higher contact pressure, larger surface expansion and complicated deformation path resulted in higher friction factors in the T-shape test in comparison with the ring compression test.

Fig. 9 Cross section of T-shape specimen showing metal flow path for AZ80

References