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Incremental forming with local heating by laser irradiation for magnesium alloy sheet

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Abstract

An incremental sheet forming system with dynamic local heating by laser irradiation was developed to form magnesium alloy sheet which is typical lightweight hard-to-form sheet metal. In this process, tool contact area of a blank sheet is locally heated by a moving laser beam spot to increase the material ductility and decrease the material strength dynamically and partially. Incremental forming experiments of AZ31 magnesium alloy sheet was carried out under several laser irradiation conditions and forming speeds using the developed forming system. The experimental results show that the formability of AZ31 sheets increased remarkably with increasing laser power. Defocusing distance of laser beam and forming speed also affected the formability. The results also indicate that residual stress of the formed product was markedly reduced to almost zero by local heating.

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Keywords: Incremental sheet forming; Dynamic local heating; Laser irradiation; Magnesium alloy sheet; Forming limit; Residual stress

1. Introduction

Magnesium alloy is an attractive material for weight saving of metallic products since it is the lightest metallic material in practical use. Nowadays magnesium alloy sheets are increasingly used but press forming of them is not
an easy task because they are typical hard-to-form metallic sheets. Their ductility is quite limited at room temperature due to their hexagonal close-packed structure. Warm press forming would be the best technology to form such materials since their ductility becomes considerably high at elevated temperature. However, when small-batch products or single custom-made products are requested, warm press forming is not an appropriate choice since it requires specific die set with heating system, which costs a lot, for each product.

Incremental forming which can form sheet metal by relative movement of simple tools without using specific die set has been paid attention as a flexible forming method for small-batch production. A combination of warm forming and incremental forming, i.e. warm incremental forming, would be a possible attractive choice to form magnesium alloy sheet. In warm incremental forming, since plastic deformation takes place only in the tool contact area, heating of whole blank sheet is not necessary but local heating only around the tool contact point is required. Based on such idea, the authors have developed an incremental sheet forming system with local heating using a tool having a built-in heater (Hino et al., 2008, 2010) to form aluminum alloy and magnesium alloy sheets. Duflou et al. (2007, 2008), Tanaka et al. (2008) and Göttmann et al. (2011) have used laser beam for local heating in single point incremental forming (SPIF) of aluminum alloy, steel and titanium sheets.

The present study aims to develop an incremental sheet forming technology in conjunction with dynamic local heating by laser irradiation to form magnesium alloy sheet or other hard-to-form metallic sheets. As mentioned above, the blank sheet surface only around the tool contact point is heated dynamically and locally by laser irradiation. Incremental forming experiments of magnesium alloy (AZ31B-O) sheet were carried out under several laser irradiation conditions at several forming speeds in order to understand the process mechanics and examine the process capabilities. Effects of several process parameters on formability and residual stress are discussed.

2. Incremental forming with local heating by laser irradiation

Figure 1 shows schematic illustration of the incremental forming system developed in this study. The system is composed of a milling machine, a forming tool with a spherical head, a blank holder and a laser head connected to a diode laser system. A bed type NC milling machine (IB-1V made by Iwashita Industrial Co., Ltd.) is used as a base of the forming system. The blank holder is fixed vertically on the worktable of the milling machine, and the forming tool and the laser head are fixed to the spindle head using a laser-head/forming-tool holder. The forming tool is 11 mm in diameter and is made of tool steel with high carbon and high chromium (JIS SKD11). Numerically controlled motion of the spindle head allows three-dimensional positioning of the forming tool, and the blank is incrementally stretched leftward of Fig. 1.

A fiber-coupled diode laser LDF 6000-40 made by Laserline GmbH is used as a heating source. Defocusing distance of laser can be adjusted by changing the distance between the blank surface and the laser head, and, thereby, the diameter of the laser beam spot on the blank surface (i.e. heated spot size) can be adjusted. The laser head and the forming tool keep relative position constant during a forming process so that the beam spot center always coincides with the tool center. This allows dynamic local heating of the tool contact area of the blank sheet.

The tool-side surface of the blank is flushed by using water-insoluble cutting fluid (Reliacut DE-P25 by JX Nippon Oil & Energy) for not only lubrication but also cooling.

3. Experimentation

3.1. Tested material

AZ31 magnesium alloy (JIS AZ31B-O) sheet of 0.78 mm thick was used and blanks of 170 mm square were prepared for the incremental forming experiments. Warm uniaxial tension test was carried out to obtain mechanical properties of the blank at various temperatures and strain rates. Measured stress-strain curves of the AZ31 sheet are shown in Fig. 2. Temperature dependency of ductility and flow stress can be observed. The material ductility is limited at room temperature, but it is improved remarkably at elevated temperatures of 150 °C-200 °C or higher. The flow stress drastically decreases with increasing temperature. Moreover, strain rate dependency of ductility also can be observed at 300 °C or higher.
3.2. Experimental conditions and procedures

Table 1 shows experimental conditions of the incremental sheet forming with local heating by laser irradiation. Simple truncated circular cone shape is selected as a target shape of the experiments. Bottom radius and top radius of the truncated cone are 50 mm and 10 mm respectively. Tool path for truncated cone forming is shown in Fig. 3. The forming tool traces contour lines of the truncated cone, and changes its direction alternately clockwise and counterclockwise to prevent accumulation of shear strain. The contour line pitch is 1 mm in slant height direction. Tool speed is set to 480 mm·min⁻¹ and 4000 mm·min⁻¹. Local heating is performed at several laser powers ranging from 0 W (i.e. room temperature, R.T.) to 950 W, and defocusing distance of 25 and 50 mm. Direction of laser irradiation is inclined 5 degrees from the normal direction of the blank surface so that the laser beam reflected from the blank does not damage the laser head. DE-P25 cutting fluid is supplied to the tool-side surface of the blank for lubrication and cooling as mentioned before.

Formability is evaluated based on the forming limit slope angle $\alpha$ (see Fig. 3 (a)) that is the possible minimum half apex angle of the successfully formed truncated cone. Formability in incremental forming is represented by the forming limit angle $\alpha$ since the maximum major strain of the formed product increases with decreasing angle $\alpha$ as well known. Forming experiment was repeated changing angle $\alpha$ until the minimum value of $\alpha$ was found under every experimental condition.
Evaluation method of residual stress (residual bending moment, to be exact) and springback of the formed product is as follows. As shown in Fig. 3 (b), a narrow straight strip (about 2 mm in width) along the slant direction is cut from the formed truncated cone by using a wire electrical discharge machine. After the cutting, the strip curls as a result of release of the residual stress. The side-view photograph of the strip is taken, and then the curvature change ($\Delta \alpha$ in Fig. 3 (b)) due to the curl is measured and used as an index showing residual stress level.

Table 1. Experimental conditions.

<table>
<thead>
<tr>
<th>Material / Blank size (mm)</th>
<th>AZ31B-O / 170×170×0.78</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool path</td>
<td>Shown in Fig. 3 (a)</td>
</tr>
<tr>
<td>Target shape of forming</td>
<td>Truncated circular cone</td>
</tr>
<tr>
<td>Bottom radius / top radius (mm)</td>
<td>50 / 10</td>
</tr>
<tr>
<td>Pitch in slant height direction (mm)</td>
<td>1</td>
</tr>
<tr>
<td>Tool speed (mm·min$^{-1}$)</td>
<td>480, 4000</td>
</tr>
<tr>
<td>Tool diameter (mm)</td>
<td>11</td>
</tr>
<tr>
<td>Laser power (W)</td>
<td>From 0 to 950 for forming, From 40 to 1300 for temperature measurement</td>
</tr>
<tr>
<td>Defocus (mm)</td>
<td>25 and 50 for forming, 25, 40, 50 and 70 for temperature measurement</td>
</tr>
<tr>
<td>Angle of laser irradiation (degree)</td>
<td>5</td>
</tr>
<tr>
<td>Lubricant and coolant</td>
<td>Reliacut DE-P25</td>
</tr>
</tbody>
</table>

Fig. 3. Schematic illustrations of experimentation: (a) tool path for truncated cone forming and slope angle $\alpha$; (b) measurement of change in curvature of strip cut from formed truncated cone shell.

4. Results and discussions

4.1. Local heating temperature

In advance of the forming experiment, the relation between laser irradiation conditions and blank surface temperature was investigated at various laser powers ranging from 40 to 1300 W, and defocusing distance of 25, 40, 50 and 70 mm. Thermocouples and infrared thermography were used for temperature measurement. Blank surface temperature on a beam-spot path rises to its peak value quickly when the laser beam spot approaches, and, after the spot passage, falls gradually and gets close to the original temperature. Then, average value of the peak temperature is treated as local heating temperature by laser irradiation. Fig. 4 shows measured local heating temperature at various laser powers when a laser beam spot goes around on a circular path of 30 mm radius. The local heating temperature becomes high when the laser beam spot speed is slow, the defocusing distance is short and the laser power is high. Based on this result, appropriate laser irradiation conditions can be determined considering the forming conditions.
4.2. Improvement of formability

Experimental results shown in Fig. 5 demonstrate significant effect of local heating by laser irradiation on improvement of formability. Relationship between the forming limit angle $\alpha$ and the laser power is summarized in Fig. 5 (a). The same experimental results of the forming limit angle are plotted with respect to the local heating temperature, which is obtained from Fig. 4, in Fig. 5 (b). It turns out that incremental forming of AZ31 blank, which is hardly able to be formed at room temperature, becomes possible by local heating, and the formability is remarkably improved with the increase in the laser power.

The formability becomes markedly higher with the increase in the local heating temperature at blank surface. It is also found that the formability becomes higher with the increase in the defocusing distance and the decrease in the tool speed. The local heating temperature is a key factor in improvement of the formability. Effect of the local heating temperature on the formability is dominant and influence of the defocus or the tool speed is minor at the local heating temperature of 300 °C or less. However, at the local heating temperature of 400 °C, the tool speed has remarkable effect on the formability. In other words, influence of the temperature dependency of material ductility exerted on the formability is dominant at the local heating temperature of 300 °C or less, and influence of the strain rate dependence of material ductility becomes remarkable at 400 °C.
4.3. Reduction of residual stress

For evaluation of residual stress, nine truncated cones whose slope angle is 55 degrees were formed under nine conditions shown in Fig. 6. In the figure, side views of the strips cut from the formed truncated cones are shown. Curl (or springback) is hardly observed in all the strips and curvature change $\Delta \alpha$ is found to be only 0.0033 mm$^{-1}$ at the maximum. This result indicates that residual stress is reduced to almost zero by the effect of the local heating and shape fixability of the formed product is high enough.

<table>
<thead>
<tr>
<th>Tool speed (mm min$^{-1}$)</th>
<th>480</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defocus distance (mm)</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Laser power (W)</td>
<td>110, 150</td>
<td>120, 200, 340</td>
</tr>
</tbody>
</table>

Fig. 6. Side view of strips cut from truncated cone shells formed under various conditions where angle $\alpha$ is fixed to 55 degrees.

5. Concluding remarks

An incremental sheet forming system with dynamic local heating by laser irradiation was developed for the purpose of small-batch forming of lightweight hard-to-form sheet metals such as magnesium alloy sheet. Relationship between various conditions and formability was investigated by performing incremental forming experiments using AZ31 magnesium alloy sheet. Advantages of the developed incremental forming process, such as improvement of formability and reduction of residual stress, were confirmed. These characteristics are strongly related to the temperature/strain-rate dependences of mechanical properties of sheet metal.

Further study will be needed to investigate several problems such as formability in wider range of forming conditions, residual stress in the hoop direction, grain size and mechanical properties of formed material, effect of local heating on reduction of forming force and improvement of shape accuracy, design of optimum tool path to minimize shape error, application to other kind of metallic sheet, and so on.

Acknowledgements

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References