A Study on the Warm Incremental Forming Limit of AZ31B Sheet

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ABSTRACT: The author puts forward a warm incremental forming processing approach that is liquid supporting and heating in order to study forming limits of magnesium alloy sheets of different processing parameters. With ABAQUS software as the tool and mises stress and sheet thickness as research indicators, the author studies the influence of different temperatures, diameters and layer spacing on the forming limit and verifies through experiments. The result indicates that this approach is able to form AZ31B magnesium alloy sheet. In a certain temperature range, the higher the temperature, the smaller the layer spacing and the larger the forming limit angle Tool head diameter has a small impact on forming limit angle

Keywords: magnesium alloy; incremental forming; forming limit; forming angle; material forming

Featuring excellent physical and mechanical properties such as low density and high specific strength, magnesium alloy is widely used in automobile, aerospace, aviation, etc. It has a poor deformability of room-temperature ductility but a good forming property when the temperature is around 250°C [1]. Therefore, the processing technique of warm forming is mostly adopted in magnesium alloy sheet forming at present.

The single point warm incremental forming technique is a die-less warm forming technique, which realizes successive partial plastic forming of sheet metal by heating the sheet to a certain temperature with certain methods and forming a 3D envelope layer-by-layer with numerical control procedures controlling simply-shaped forming tools [2-5]. The warm incremental forming technique has been used gradually in the field of magnesium alloy sheet forming and attracted great attention of scholars at home and abroad who have carried out some studies.

G Ambrogio carried out experimental studies on warm incremental forming of magnesium alloy, finding out that the forming of magnesium alloy performs best when the temperature is 250°C [2]. Park J J carried out studies on warm incremental forming of AZ31 magnesium alloy, finding out that the forming property of magnesium alloy improves with the increase of temperature and obtaining the forming limit of magnesium alloy. Cone-shaped part of various inclination angles were successfully formed on this basis [3]. With the approach of incremental forming of frictional heating, Otsu M formed AZ31, AZ61 and AZ80 pyramid box-shaped part by adjusting the principal axis speed, the feed speed and the size of forming angle, the minimum semi-cone angles of which are respectively 25°, 30° and 40° [4]. Domestic scholars have also carried out some studies on the incremental forming of magnesium alloy. According to the requirements of the warm incremental forming technique of magnesium alloy sheet, Guoxin Zhang developed an automatic tracking unit of gas heating, realizing the heating of warm incremental forming of magnesium alloy sheet [5]. With the approach of orthogonal test, Hai Wang studied the influence of technique parameters

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on sheet forming performance during the incremental forming process of magnesium alloy sheet tools [6]. Qinglai Zhang conducted technical studies and theoretical analyses on the warm incremental forming of AZ31B magnesium alloy sheet through experiments, indicating that the quality of sheet is one of the main factors for defects of magnesium alloy incremental forming [7].

The above-mentioned scholars have made efforts on forming angles and limits of incremental forming, but they failed to combine theoretical analyses, numerical simulation and experimental research organically. In this paper, the author puts forward a warm incremental forming processing approach that is liquid supporting and heating, establishes a finite element analytical model, and carries out a theoretical analysis, a numerical analysis and an experimental verification on the influence of technique parameters (temperature, layer spacing, tool head diameter) on forming limit. The results provide a basis for the parameters optimization of warm incremental forming technique of magnesium alloy sheet, the development of warm incremental forming technique and the development of related equipment.

1 EXPERIMENTAL DEVICE AND THE ESTABLISHMENT OF THE FINITE ELEMENT MODEL

1.1 Experimental device

The experimental device is composed of a numerically-controlled machine tool, a single point incremental forming device, heating units, a relief valve, a pressure gauge, a heat insulating material, a temperature control equipment, hydraulic oil, etc. [8]. As shown in Figure 1, the processed sheet is fixed by the upper and the lower blank holders and inside hydraulic oil is heated by heating units. A pressure value is set for the relief valve at the same time so that it maintains a certain pressure inside the forming device. The hydraulic oil under high temperature not only heats the forming sheet but also plays a supporting role in the forming process. The edge of the sheet metal is fixed at this time and the forming tool head controlled by the numerically-controlled equipment is gradually formed along the inner surface of the model from the edge to the center until the forming is completed.

1.2 The establishment of the finite element model

In this paper, the author uses ABAQUS to establish a finite element model and carries out the numerical simulation of single warm incremental forming. As shown in Figure 2, an inverted cone is selected as the experimental model. The tool head is discrete and rigid, having no deformation by default. The sheet is measured 150×150mm and the thickness is 1mm. Divide the pressured region on the edge of the sheet and replace the upper and the lower pressing plates by restraining all the freedom degrees. The sheet is supported by liquid below. So, pressure intensity of 0.1MPa is distributed uniformly under the sheet, as shown in Figure 3. The surface-to-surface contact algorithm is adopted in the analysis. The tool head is the principal surface and the forming region is the subordinate surface based on nodes. The rotating speed of the tool head is 3000r/min, the feed speed is 100mm/min, and the forming angle is 45°. As present in Figure 4, the motion track is a contour line.

2 THEORETICAL ANALYSIS

2.1 Strain analysis of the single point incremental forming process

The stress-strain condition of the deformation zone when the tool head moves from the nth layer to the
n+1th layer in the process of incremental forming is shown in Figure 5. In the figure, α is the forming angle, h is the layer spacing, and r is the radius of the tool head.

\[ l_0 = ab + bc \]  
\[ l_n = ad + de \]  

In the formula, \( l_0 \) is the length of the deformation zone at \( n^{th} \) layer; \( l_n \) is the length of the deformation zone at \( n+1^{th} \) layer.

\[ ab = \pi r \alpha = de \]  
\[ bc \tan h \alpha = \frac{h}{\tan \alpha} \]  
\[ ad = \frac{h}{\sin \alpha} \]  
\[ \varepsilon_z = \ln \frac{l_n}{l_0} = \ln \frac{h}{\sin \alpha} \frac{\pi r \alpha}{180 \sin h \alpha} \]  

In the formula, \( \varepsilon_z \) is the axial strain of the deformation zone.

\[ F = \frac{h \sin \alpha + \pi r \alpha}{\tan \alpha} + \frac{h}{\tan \alpha} \frac{\pi r \alpha}{180} \]  

When other variables keep constant, formula (7) takes the derivative of \( \alpha, h \) and \( r \). Because \( 0 < \alpha < 90^\circ \), so:

\[ \frac{dF}{d\alpha} = \frac{h^2 \sin \alpha + \pi r \alpha (1 - \cos \alpha)}{180 \sin \alpha} > 0 \]  
\[ \frac{dF}{dh} = \frac{\left( \frac{1}{\sin \alpha} \right) \pi r \alpha}{180} \frac{h}{\tan \alpha} > 0 \]

It can be concluded from formula (8), (9) and (10) that strain \( \varepsilon_z \) increases if the forming angle \( \alpha \) and the layer spacing \( h \) increase and the tool head radius \( r \) decreases when other variables keep constant.

2.2 An analysis on the deformation zone’s thickness of the cone frustum

Matsubara carried out an experimental study on the incremental forming process of tapered sheet metal parts, proposing that the change of the formed sheet thickness is related to the semi-cone angle. This research finding is known as the sine law \([9]\), namely:

\[ t_p = t_0 \sin \theta = t_0 \cos \alpha \]  

In this formula, \( \theta \) is the semi-cone angle of formed parts; \( \alpha \) is the forming angle of formed parts; \( t_0 \) is the original thickness; \( t_p \) is the side wall thickness of formed parts.

Liuru Zhou verified formula (11) through experiments \([10]\). However, \( t_p \) obtained from formula (11) is the average thickness of the side wall of formed parts. According to the finite element analysis and the experimental verification, thicknesses of the side wall of formed parts are not the same. The thickness and the equivalent strain contours are presented in Figure 6 and Figure 7. Thickness values of 20 nodes selected from the sheet, as shown in Figure 8, are presented in Figure 10. It can be known from the figure that the thinnest places of the formed sheet are regions between the 4th and the 6th node and between the 15th and the 17th node, where sheet rupture is the most likely to happen.
3 THE INFLUENCE OF DIFFERENT TECHNIQUE PARAMETERS ON FORMING LIMIT

3.1 The influence of temperature on forming limit

Use a sheet metal with the tool head diameter of 10mm and the layer spacing of 1mm at the temperature of 150, 200 and 250°C for numerical simulation. Select 20 nodes of the sheet shown in Figure 8 and get the average of Mises stresses of 20 nodes, as shown in Figure 10. It can be inferred from the figure that temperature has a significant impact on Mises stress, which decreases obviously with the increase of temperature. The main reason is that magnesium alloy is featured by its close-packed hexagonal crystal structure [1]. Only 3 slip systems on the base plane {0001} can be activated at room temperature, which are much less than 5 independent slip systems required by the polycrystal uniform deformation. So, magnesium alloy has a relatively low plasticity and a poor formability at room temperature. Yet as the temperature increases, non-basic slip systems can be activated along with dynamic recrystallization that causes fundamental ductility transition of the forming property of magnesium alloy and makes the plasticity of magnesium alloy stronger.

Figure 11 is the variation curve of formed parts at different temperatures. It can be known from the figure that thickness distributions of AZ31B magnesium alloy sheet parts at different temperatures are basically the same. The minimum thickness locates in node 6 and 16. The lower the temperature is, the smaller the minimum thickness is. Ruptures are more likely to happen. Therefore, within the range of 150 to 250°C, the plasticity and the forming property of AZ31B sheet improve and the forming limit angle becomes larger as the temperature increases. Ruptures are less likely to happen. The variation with temperature of AZ31B magnesium alloy helps to improve its incremental forming property.

3.2 The influence of layer spacing on forming limit

Use a sheet metal with the tool head diameter of 10mm and the layer spacing of respectively 0.5mm, 1mm, 1.5mm and 2mm at the temperature of 200°C for numerical simulation. Select 20 nodes of the sheet shown in Figure 8 and get the average of Mises stresses of 20 nodes, as shown in Figure 12. It can be known from the figure that the larger the layer spacing h is, the greater the Mises stress is. Results of the finite element analysis and the above theoretical analysis are the same. This is because, in the forming process, the larger the layer spacing and the pressing distance are, the greater the sheet deformation per unit area and the tensile stress are.

Thickness variation curves of formed parts with different layer spacing are presented in Figure 13. It can be inferred from the figure that thickness distributions of formed parts processed with different layer spacing are basically the same. The minimum thickness locates in node 6 and 16. The larger the layer spacing is, the smaller the thickness is. Ruptures are more likely to happen. So, in the forming process, the thinning ratio decreases while the sheet thickness increases if smaller layer spacing is selected when other conditions are permitted. The possibility of a rupture can be also reduced.
3.3 The influence of tool head diameter on forming limit

Use a sheet metal with the layer spacing of 1mm and the tool head diameter of respectively 8, 10, 12 and 14mm at the temperature of 200°C for numerical simulation. Select 20 nodes of the sheet shown in Figure 8 and get the average of Mises stresses of 20 nodes, as shown in Figure 14. It can be known from the figure that Mises stress becomes greater as the tool head diameter increases. But the value has little change.

According to the analysis in 2.1, it can be known that strain $\varepsilon_z$ decreases with the increase of $r$. Yet the stress does not decrease. When other variables keep constant, the number of sheet metals of plastic deformation becomes larger as the tool head diameter and the contact range of the tool head and the sheet increase. So the stress and the thinning ratio increase while the thickness decreases as the diameter increases. However, the forming force of incremental forming is quite small, so the influence of the tool head radius on forming force would not be great [11]. This can be verified by Figure 14. It can be also known from Figure 15 that the influence of the tool head diameter has little impact on forming limit angle because wall thicknesses of formed parts processed with different tool heads are very close.

4 EXPERIMENTAL VERIFICATION

4.1 Experimental device

As shown in Figure 16, the experimental platform is established according to the scheme in 1.1. The sheet metal is clamped on the fixture of the machine tool. The tool head of the forming tool is a cylinder with a semi-spherical end and a polished surface. Tungsten carbide-cobalt hard alloy with the hardness of 65-68HRC is selected as the material. The rotating speed and the feed speed of the tool head are respectively 3000r/min and 100mm/min. The motion trail is a contour line, which is the same as the numerical simulation settings.
4.2 Experimental results

Set technique parameters respectively that are identical with those in the numerical simulation in Chapter 3 so as to get forming limit angles of different temperatures, layer spacing and tool head diameters. As shown in Figure 17-19, the warm incremental forming limit angle increases obviously with the increase of temperature while decreases with the increase of layer spacing. The change of tool head diameter has little impact on forming limit angle. The experimental result agrees with the result of the above theoretical analysis and numerical simulation.

Figure 17. Forming limit angles at different temperatures.

Figure 18. Forming limit angles of different layer spacing.

Figure 19. Forming limit angle of different tool head diameters.

Forming temperature is one of the important influencing factors of magnesium alloy’s incremental forming. When the temperature is between 150 and 200°C, the forming angle increases from 47° to 58° and the increment of limit angle is large. Yet when the temperature is above 200°C, the increment of limit angle is quite small as the temperature increases. For example, the limit angle is about 62° at 250°C. When the forming temperature is increased to more than 200°C, requirements on the performance of seal and valve of processing equipment are relatively high. Consequently, the cost as well as the processing difficulty will increase greatly. Therefore, the recommended processing temperature is around 200°C for the consideration of processing, cost and other factors.

Layer spacing refers to the feed amount of Z axis during the processing. It can be known from the above analysis that the smaller the layer spacing is, the better the surface quality is [12]. The smaller the reduction of forming parts is, the larger the forming limit angle is. But this will largely increase the processing time. So, it is necessary to take into account various processing conditions and requirements and to select suitable layer spacing.

It can be concluded from Figure 17 that it is more conducive to forming uniformity if the tool head diameter is larger. The smaller the thinning ratio is, the larger the forming limit angle is. Hence the possibility of rupture is smaller. Yet these influences are not significant from the perspective of values. If the tool head diameter is too large, the contact area increases correspondingly so that the frictional resistance increases during the forming process, causing not only forming force but also surface abrasion of the forming tool. Besides, it is hard to form small-sized parts with complex geometrical shapes [13, 14]. If the diameter of the tool head is too small, it will cause the phenomenon that the sheet metal is cut by turning tools despite the small axial force [15], making the forming quality of sheet poor. Meanwhile, the tensile stress decreases, and the forming precision becomes lower. Therefore, a moderate principle should be adopted to select the tool head diameter.

5 CONCLUSION

(1) The warm incremental forming limit angle of AZ31B magnesium alloy sheet increases obviously with the increase of forming temperature. When the temperature is between 150 and 200°C, the increment of the forming limit angle is large. When the temperature is above 200°C, the forming angle will change gently.

(2) Layer spacing has certain influence on the warm incremental forming limit angle of magnesium alloy sheet. The larger the layer spacing is, the smaller the forming limit angle is and the larger the reduction of the formed part is. And it is more likely to have rupture.

(3) Although the forming limit angle increases with
the tool head diameter, the increasing trend is not obvious. So the tool head diameter has a small impact on forming limit angle.

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