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EFFECTS OF PUNCH COOLING ON FORMABILITY OF AZ31 MAGNESIUM ALLOY SHEETS DURING HOT FORMING

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Abstract

Magnesium alloys are the lightest structural materials and have many predominant advantages. However, their industrial applications are heavily limited because of their very poor formability at room temperature. The present research was aimed to gain more insights into the formability of magnesium alloy AZ31 (aluminum 3wt.%, zinc 1wt.%) and to have first-hand knowledge of the correlations between materials properties and the process conditions. A tool system combining inverse drawing approach with local heating and cooling system was applied to investigate the formability of rectangular AZ31 cups during warm deep drawing. Conventional warm deep drawing process was also carried out to determine the proper process parameters and to investigate how

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much the formability of a magnesium alloy sheet can be enhanced by the new technique. A new optical measurement system was employed to measure the thickness distribution of the workpiece. The investigation indicated that the blank flange temperature in the range of 200-230°C was suitable for using the local punch cooling and heating technique. When setting the blank flange temperature as 230°C, rectangular cups were successfully obtained by the new technique at the maximum forming speed of 120mm/min. The effects of the process parameters on the formability of rectangular cup drawing were analyzed. A warm deep drawing process window was constructed as the forming speed and the forming temperature were taken into account.

1. Introduction

Nowadays, with the increasing demands for the weight reduction of vehicles, energy saving and environment protection, great attention has been paid to magnesium alloys because they are the lightest structural materials and can be easily recycled [5]. Although most of magnesium alloy products are fabricated by die casting, the mechanical properties of these parts often do not meet the requirements concerning the mechanical properties (e.g., endurance strength and ductility) [3]. As a promising alternative, the parts manufactured by sheet metal forming are characterized by advantageous mechanical properties. Moreover, sheet metal forming is also expected to be effective as environmentally conscious processing technology for magnesium alloys [1, 12]. However, the formed products of magnesium alloys have been limited, because magnesium alloy is hexagonal close-packed (HCP) crystal structure and shows poor formability at room temperature [9]. Therefore, how to improve the formability of magnesium alloy is in dire need of being developed and sheet forming of magnesium alloys becomes a state-of-the-art and hot issue.

In recent years, quite a few efforts have been made to improve the formability of magnesium alloys by warm deep drawing (WDD) process. Many research activities proved that magnesium alloys show excellent ductility and formability at elevated temperatures [8, 11]. In addition, Chen et al. [2] indicated that the maximum depth of drawn cup could be obtained at the forming temperature of 200°C; however the drawn depth decreased at temperature higher than 300°C. Yoshihara et al. [10]

investigated the formability of circular magnesium alloy cups at a hot forming temperature of 400°C using local heating and cooling combined with a variable blank holder (BH) pressure technique and got some good formability. The investigations about deep drawing of cylindrical AZ31 cups carried out by Huang et al. [4] and Palumbo et al. [7] also verified that a higher limit drawing ratio (LDR) could be obtained using the local heating and cooling technique when the forming temperature is around 200-250°C.

Up to now, research on warm forming of magnesium alloy sheets with this new technique is still in its infancy. Moreover, the papers published were focused on applying this technique to form the cylindrical cups and few research activities were conducted on the deep drawing of square/rectangular cups. Actually, the material flow pattern during the deep drawing of rectangular cups with magnesium alloy sheets is quite complicated and different from that of the cylindrical cup drawing process.

Furthermore, since most components of magnesium alloys used in the electronics industry bear rectangular shapes, such as the coverings of notebook computers, mobile phones and MD players, there is a great potential for the industrial applications of rectangular magnesium alloy components. In the present work, a set of inverse drawing tools was designed and manufactured. At the same time, a new optical measurement system was employed during the experiments. Warm deep drawing of AZ31 magnesium alloy sheets with punch cooling was investigated to gain more insights into the effects of punch cooling on formability of magnesium alloy AZ31 rectangular cups.

2. Experiments

2.1. Forming tools

A set of tools for performing warm deep drawing (WDD) tests on AZ31 sheets was designed and manufactured. Such tools were characterized by standard deep drawing (DD) tools with the water cooling system embedded in the punch, and electric heating system embedded in the blank holder (BH) and the die to locally heat the flange of the blank. A schematic illustration of the local heating and cooling deep drawing setup is shown in Figure 1. Table 1 shows the dimensions of the punch and the die used. A picture of the assembled tools is shown in Figure 2.

Unlike the drawing tools shown in the published papers, in this work, the punch was designed to be mounted on the lower worktable and the die on the upper crosshead of the press, as shown in Figure 2. The inverse drawing tool is expected to be useful for obtaining lower temperature in the cup bottom considering the heat transfer between the cup bottom and the environment. Moreover, this inverse structure is also necessary to employ a new optical measurement system to measure the thickness distribution and material thinning of the specimen during the forming process.

2.2. Experimental conditions

Hot-rolled and annealed commercial AZ31 sheets of 0.7mm thickness were employed in the current research. The WDD experiments were performed using the rectangular blank of $60 \times 45\,\text{mm}$ with chamfer corner $(10\,\text{mm} \times 45^{\circ})$ and the forming temperatures were in the range of 25-250°C. The initial blank holder force was 500N. The water-based lubricant PTFE was smeared uniformly on the surfaces of the blank holder and the female die in contact with the blank. There was no lubricant on the surface of the punch. The following deep drawing (DD) experiments were carried out.

(1) Local heating and cooling deep drawing experiment

During the forming process, cooling water can flow from inlet to outlet of the punch with sound circulation to keep the punch temperature between 5 and 10°C. Three thermocouples were placed in specified positions of the blank, the die and the blank holder, with the aim of collecting temperature data for evaluating the effects of the heating and cooling system. The acquisition of the temperature values coming from the thermocouples was controlled by a LabVIEW Panel. In addition, the drawing force, punch stroke values and material thinning during the WDD experiments were obtained by means of LabVIEW and the optical measurement system.

(2) Conventional warm deep drawing experiment

In this work, conventional warm deep drawing process was also carried out to be compared with the local heating and cooling deep drawing experiment. In conventional WDD, the punch initially is at room temperature and gets warmer during the process. The same data acquisition experimental procedure was applied for both strategies.

3. Results and Discussion

3.1. Effects of the process parameters on the formability of AZ31 sheets

The formability of magnesium alloy sheets is significantly affected by the forming temperature, the forming speed, the geometrical shape of the blank, the blank holder force and the lubrication. Among them the forming temperature (T) and the forming speed (V) are probably the most relevant. In order to evaluate their effects and gain more insights into the formability of magnesium alloy AZ31, conventional WDD at different forming temperatures and forming speeds was performed.

As mentioned previously, magnesium alloys exhibit poor formability at room temperature due to their hexagonal close-packed (HCP) crystal structure, in which only the basal slip systems can be activated and requires thermal activation of additional slip planes to increase its ductility [2, 6]. A sound cup could not be formed even with a low forming speed of 1.5mm/min when the forming temperature was too low to activate the slip systems, as shown in Figure 3a. In addition, the formability of magnesium alloy sheets is also strongly influenced by the forming speed due to its sensitivity to the strain rate [1, 7]. It may be noted from the tests that higher forming speed values lead to early fracture of the blank, as shown in Figure 3b. If increasing the forming temperature, the forming speed can be largely increased. When the forming temperature was increased up to 250°C, sound cups could be drawn with the highest forming speed of 120mm/min, as shown in Figure 3c, and the formed cup corner is still characterized by maximum thinning (Figure 4).

It can be seen from the above experimental results that fracture occurs in the cup wall along the diagonal of drawn cup and in the vicinity of the punch corners in deep drawing of rectangular AZ31 cups. It seems that the failure mode during rectangular cup deep drawing of AZ31 sheets is the same with that of other sheet metals. However, magnesium AZ31 exhibits obvious strain rate sensitivity. The interaction of various metal flow rates between the straight edges and the corner parts can bring about an unstable material flow and uneven material distribution around the cup wall. It is advisable to perform deep drawing of AZ31 alloy at a lower forming speed; or else, fracture occurs suddenly without any obvious necking phenomenon.

Figure 5 shows the punch stroke-load curves plotted according to the experiments. During the forming process, the force required to pull the blank into the die will decrease due to the decreasing of the flange area. It is noted that there is no remarkable difference in the punch load at a lower temperature (150°C) with different forming speeds. This result agrees well with the research results obtained by Doege and Droder [3], which implies that the influence of forming speed is less significant, if the experiment is carried out at a lower temperature. It should also be noted that the maximum punch load increased as the forming speed is increased. That is because the yield strength increases with higher forming speed. It is highlighted that the punch force needed to cause deformation is applied to the bottom of the cup. This force is transmitted through the cup wall to the flange. During the drawing process, the material at the straight edges undergoes simple bending as the blank deforms, while the material at the corner parts is compressed and the deformation resistance is increased. Since the corners of the rectangular cup bottom transmit the largest deformation forces during the forming process, the corners are characterized by maximum thinning which leads to ruptures.

3.2. Comparison between conventional WDD and deep drawing with local heating and cooling

Deep drawing (DD) with local heating and cooling technique was proposed based on the theory that with decreasing of the temperature near the punch corner, the strength of the blank here could be increased and the thinning could be decreased. However, out of expectation, when setting the BH temperature at 180°C, sound cups were obtained with the forming speed of 60mm/min by conventional WDD and on the contrary rupture occurred using the new technique. In this case, the local heating and cooling technique showed negative effect on the formability of magnesium alloy sheet. The reason can be found considering too much cooling effect of the punch when the blank holder and the die temperature were not so high; the water-cooled punch caused the excessive temperature decrease in the blank center (Figure 6) which increased the deformation resistance, even if it also means that the material strength is higher, the corresponding ductility was strongly reduced and the material was not able to experience bending and stretching in the punch radius region. In other words, it means when the blank holder and the die temperature were not so high, the water cooling effect on the deep drawing performance of the magnesium alloy sheets could not be effective, and even be negative.

It can be noted that when setting the BH temperature at 230°C, sound cups were successfully drawn with a high forming speed of 120mm/min using local heating and cooling technique. By conventional WDD process with the normal punch without water cooling, early failure occurred in the cup wall just above the punch radius, as shown in Figure 7. Thus, the effectiveness of the newly developed and designed WDD tools with local heating and cooling system was demonstrated. In addition, no rupture occurred if the temperature is increased up to 250°C when using this high forming speed (120mm/min) in conventional WDD process.

It should be highlighted that over-heating the die and blank holder is also not recommended, as it may cause excessive soft-weakening of the blank material in the flange area. In the case of present study, a temperature range of 200-230°C was found to be suitable for using the local cooling and heating technique. From Figure 6, it can be seen that a minimum temperature value about 150°C has to be ensured in the blank center to avoid the negative effect of cooling punch which leads to ruptures when using the new technique. These results indicated that establishing appropriate temperature gradient between the blank bottom and the flange area is critical to employ the local heating and cooling technique to enhance the formability of magnesium alloy AZ31 sheets.

3.3. Effects of the local heating and cooling on sheet thinning

Figure 8 shows the cups formed at the BH temperature of 180°C with a higher forming speed of 90mm/min. The punch load-stroke curves of these experiments were plotted, as shown in Figure 9. There is a peak punch force, and due to the decreasing of the flange area, the force required to pull the blank into the die will decrease. When the peak punch force is higher than the limit strength of the cup corner, the blank will fracture, and the punch force will decrease suddenly. When the peak punch force is lower than the limit strength of the cup corner, the blank will be drawn successfully, and flow into the die cavity. It can be noted from Figure 9 that the two punch load-stroke curves are very similar in both the trend and the peak value. It means that cooling effect on the punch load and its maximum value is not significant in this case.

Although the cups were all fractured, it can be easily observed from Figure 8 that the fracture in the cup formed without water cooling is worse. In order to further understand the effect of the local heating and cooling effect on the material flow, then the material thinning-punch stroke curves were plotted according to the data collected by the optical measurement system. As shown in Figure 10, two points were selected from bottom of the rectangular cup to track the thickness reduction during the forming process. One was near the corner (point A), the other one was near the center of long edge (point B). When forming without water cooling, the maximum thinning of point A and point B was 5.79% and 5.56% (Figure 10a). And with water cooling these values were reduced to 3.28% and 3.46%, respectively (Figure 10b). It can be seen that the uniformity of thickness was increased by means of local cooling and heating technique. Therefore, the possibility of material thinning could be reduced.

3.4. Construction of a process window

The formability of magnesium alloy sheets at elevated temperature is significantly affected by the forming temperature and the forming speed. It is of great significance to know the deformation characteristics of magnesium alloys under various conditions of temperature and the forming speeds. Based on the heat-gradient deep drawing experiment, a process window (Figure 11) was constructed as the temperature and forming speed taken into account. The process window presented corresponds to the lower limit, which can provide a design guideline to determine the appropriate forming conditions for the deep drawing process.

As shown in Figure 11, the magnesium alloy shows good formability at elevated temperature in a range of 150-250°C. If increasing the blank holder (BH) temperature, the forming speed can be largely increased. It is noted that sound cups could be formed at 150°C with the highest forming speed of 6mm/min, while when the forming temperature was increased up to 250°C, sound cups could be drawn with the highest forming speed of 120mm/min by conventional WDD. With this high forming speed (120mm/min), sound cups could be obtained at 230°C by DD with local heating and cooling technique.

Considering the productivity and costs of the manufacturing process, the process techniques and innovations proposed in the present study will potentially contribute to increased production efficiency and improved component performance in manufacturing rectangular components from magnesium alloys.

4. Conclusions

The formability and the heat-gradient deep drawing of magnesium alloy AZ31 sheets were systematically investigated by experimental method using the newly developed inverse drawing tools. The major conclusions are as follows.

(1) The inverse drawing approach with the local heating and cooling technique has been proved to be effective to reduce the material thinning during WDD of rectangular AZ31 cups. Establishing appropriate temperature gradient between blank bottom and flange area is critical to improve the formability of AZ31 sheets.

(2) Magnesium alloy AZ31 sheet is sensitive to the forming temperatures and strain rates; it shows good formability at elevated temperature in a range of 150-250°C. The blank flange temperature in the range of 200-230°C was suitable for using the local cooling and heating technique to enhance the formability of magnesium alloys.

(3) A process window of heat-gradient deep drawing rectangular AZ31 cups was established as the most important process parameters like the temperature and forming speed taken into account. It could provide a design guideline to determine the appropriate forming conditions of drawing process.

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Table 1. Dimensions of punch and die used in the experiment

Die radius	Rd (mm)	4
Die corner radius	Rc (mm)	4
Punch radius	Rp (mm)	3
Punch corner radius	Rc' (mm)	3
Length	a (mm)	40
Width	b (mm)	20

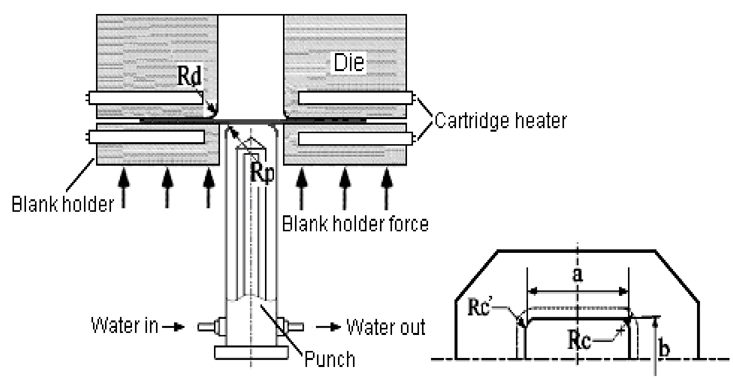


Figure 1. Schematic of rectangular cup deep drawing system with local heating and cooling.

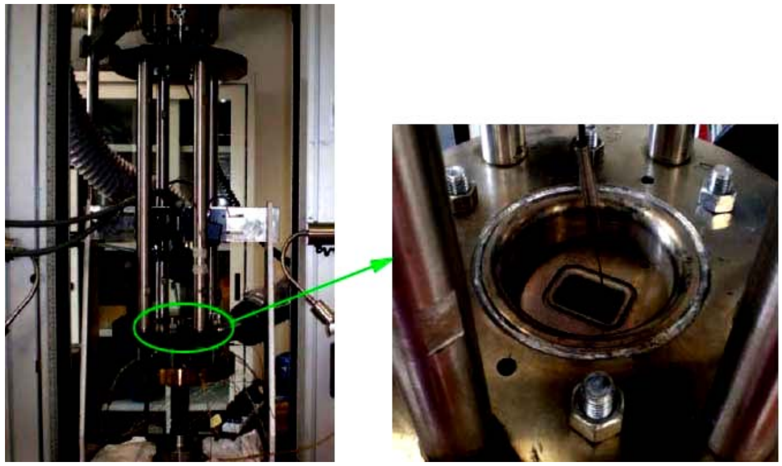


Figure 2. Final assembly of the WDD tools.

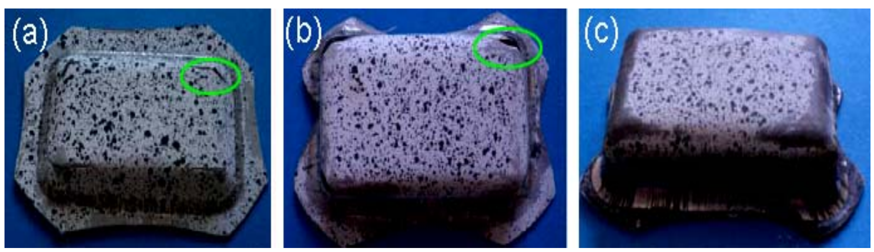


Figure 3. Drawn cups with various process parameters: (a) Room temperature, $V = 1.5\,\text{mm/min}$ (b) $T = 180^{\circ}\text{C}$, $V = 90\,\text{mm/min}$ (c) $T = 250^{\circ}\text{C}$, $V = 120\,\text{mm/min}$.

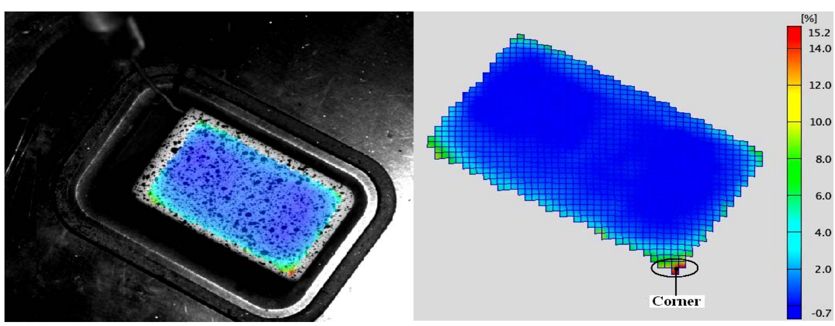


Figure 4. Thinning of the bottom of the drawn rectangular cup ($T = 250^{\circ}\text{C}$, $V = 120\,\text{mm/min}$).

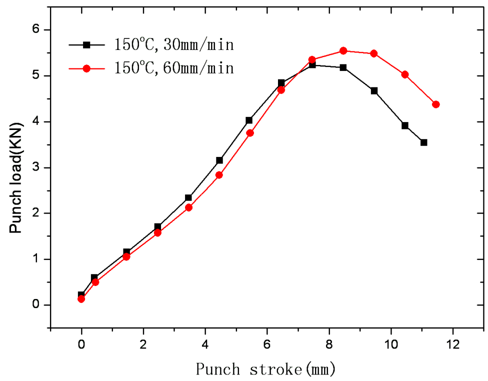


Figure 5. Punch load-stroke curves from experiments with various process parameters.

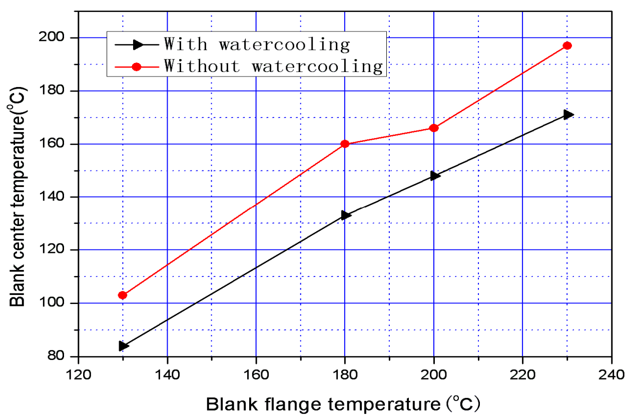


Figure 6. Comparison of the temperature data measured during each forming process.

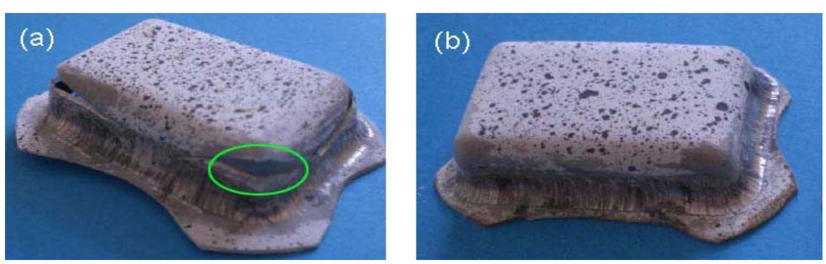


Figure 7. Drawn rectangular cups (T = 230°C, V = 120 mm/min): (a) Formed by conventional WDD (b) Formed by DD with local heating and cooling technique.

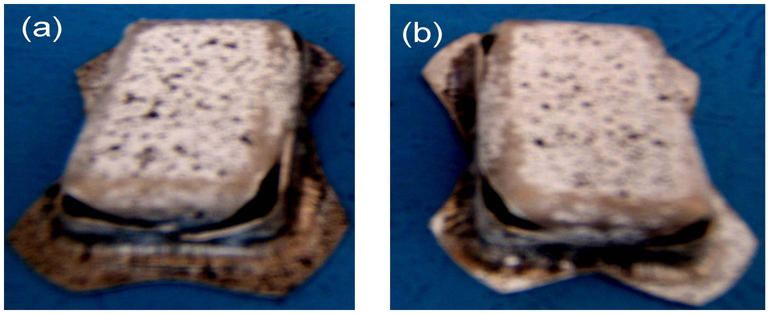


Figure 8. Drawn rectangular cups (T = 180°C, V = 90 mm/min): (a) Formed by conventional WDD (b) Formed by DD with local heating and cooling technique.

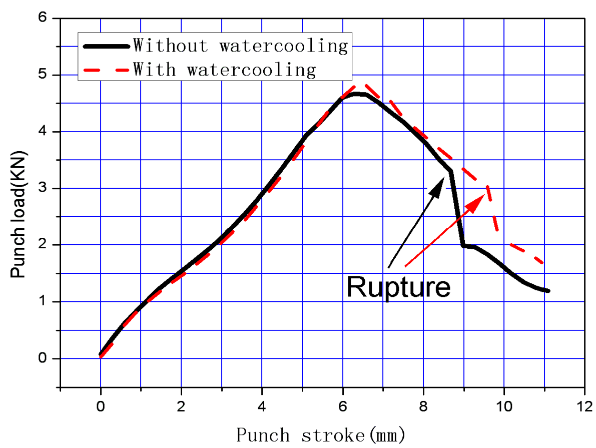
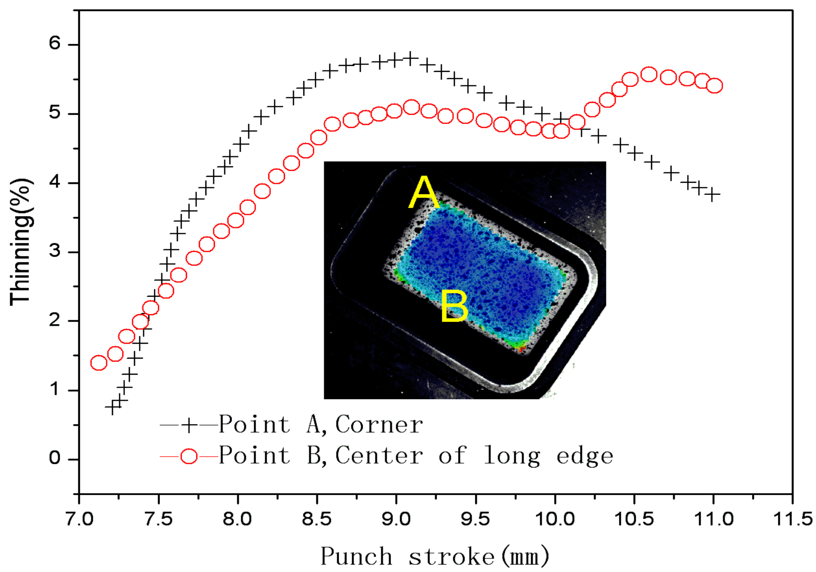
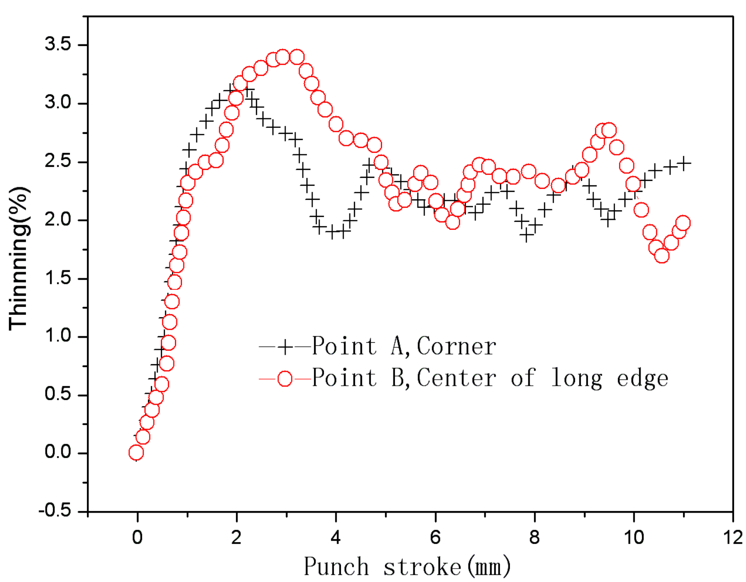


Figure 9. Punch load-stroke curves (T = 180°C, V = 90 mm/min).



(a) Without water cooling



(b) With water cooling

Figure 10. Thinning-punch stroke curves during deep drawing.

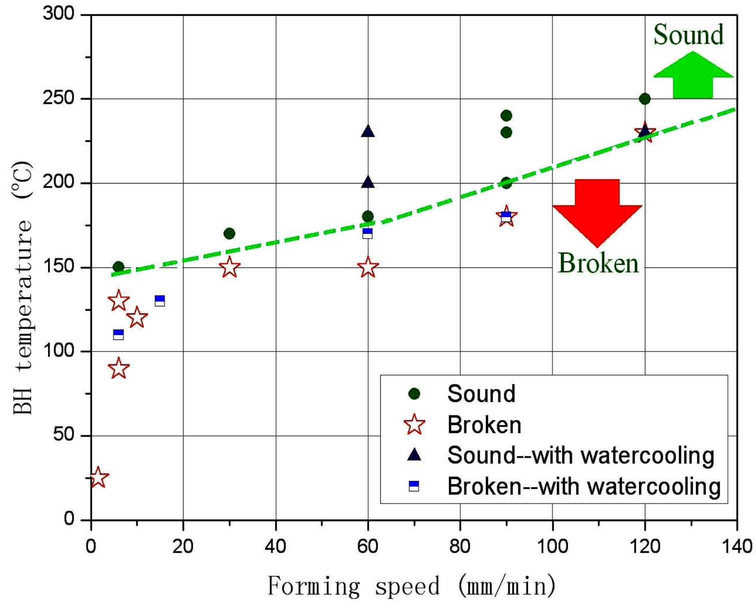


Figure 11. Process windows of non-isothermal deep drawing rectangular AZ31 cups.