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Deep drawing of square cups with magnesium alloy AZ31 sheets

Fuh-Kuo Chen *, Tyng-Bin Huang, Chih-Kun Chang

Department of Mechanical Engineering, National Taiwan University, Section 4, No. 1 Roosevelt Road, Taipei 10764, Taiwan, ROC

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Abstract

The square cup drawing of magnesium alloy AZ31 (aluminum 3%, zinc 1%) sheets was studied by both the experimental approach and the finite element analysis. The mechanical properties of AZ31 sheets at various forming temperatures were first obtained from the tensile tests and the forming limit tests. The test results indicate that AZ31 sheets exhibit poor formability at room temperature, but the formability could be improved significantly at elevated temperatures up to 200 °C. The test results were then employed in the finite element simulations to investigate the effects of process parameters, such as punch and die corner radii, and forming temperature, on the formability of square cup drawing with AZ31 sheets. In order to validate the finite element analysis, the deep drawing of square cups of AZ31 sheets at elevated temperatures was also performed. The experimental data show a good agreement with the simulation results, and the optimal forming temperature, punch radius and die corner radius were then determined for the square cup drawing of AZ31 sheets.

Keywords: Magnesium alloy AZ31 sheet; Square cup drawing; Formability; Finite element method

1. Introduction

Due to its lightweight and high specific strength, magnesium alloy has been widely used for structural components in the aerospace, electronics, and automobile industry to replace some existing materials [1,2]. Although the principal manufacturing process has been die casting, the press forming has considerable potential because of its competitive productivity and performance. As for press forming, the AZ31 (aluminum 3%, zinc 1%) sheet is considered as the suitable magnesium alloy for the stamping process at the present time. However, because of its hexagonal closed-packed (HCP) crystal structure, in which only the basal plane can move, the magnesium alloy shows low ductility at room temperature, and requires thermal activation to increase its ductility and formability [3–7]. Since most applications of magnesium alloys in the electronics industry bear rectangular shapes, such as the cases of notebook, mobile phone, and MD player, the square cup drawing of AZ31 sheets at various forming temperatures was studied in the present study. In order to perform the finite element simulations and set up the fracture criterion, tensile tests and forming limit tests of AZ31 sheets were first conducted to obtain the mechanical behavior of AZ31 sheets at various forming temperatures.

The finite element analysis was then performed to investigate the effects of the process parameters on the formability of square cup drawing. The punch radius (R_p), die corner radius (R_c), and the forming temperature are considered to be the major process parameters affecting the formability of the square cup drawing. In order to validate the finite element simulation results, the actual square cup drawings with different process parameters were also conducted and the experimental data were compared with the finite element simulation results both qualitatively and quantitatively.

2. Tensile and forming limit tests at elevated temperatures

The stress–strain relations are the basic information for the study of formability of a sheet metal. Since magnesium alloys exhibit poor formability at room tempera-

* Corresponding author. Tel.: +886-2-3621-522; fax: +886-2-3631-755.
E-mail address: fkchen@ccms.ntu.edu.tw (F.-K. Chen).

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ture, tensile tests at various temperatures ranging from room temperature to 400 °C were performed in the present study. The test specimens made of AZ31 sheets of 1.2 mm thickness were prepared according to the ASTM standards. The specimens were cut along planes coinciding with the rolling direction (0°) and at angles of 45° and 90° to the rolling direction. The cut edges were polished to avoid fracture occurring at an undesired location of the specimen.

In the tensile tests at elevated temperatures, a heating furnace was mounted on the MTS810 test machine. The specimens were heated to 100, 200, 300, and 400 °C before the tensile tests were performed. During tests, the temperature of specimen was kept constant until the specimen was stretched to failure.

The mean flow stress $\bar{\sigma}$ calculated from $\bar{\sigma} = (\sigma_0 + 2\sigma_{45} + \sigma_{90})/4$ for each measured true strain was adopted to plot the stress–strain relations, where σ_0, σ_{45}, and σ_{90} are the stresses obtained from the specimens cut in the rolling, 45° and 90° directions, respectively. Fig. 1 shows the true stress–true strain relations of the AZ31 sheet at various test temperatures. It is clearly seen in Fig. 1 that the yield stress drops significantly as the temperature increases. Also the elongation of specimen reaches to 46% at 400 °C. It is confirmed from Fig. 1 that the AZ31 sheet exhibits excellent formability at elevated temperatures. It is also noted in Fig. 1 that the work-hardening effect becomes insignificant as the test temperature increases. Since the work-hardening property is usually considered as an index whether the sheet is deformed uniformly or not, the insignificant work-hardening property indicates that the uniform deformation in the thickness direction is not easy to achieve in the forming of AZ31 sheets at higher temperatures. However, it can be inferred that forming of AZ31 sheets becomes possible as long as the sheet is heated to an elevated temperature.

In addition to the basic mechanical properties, the forming limit tests were also performed to construct the forming limit diagram (FLD) [8], which has been a widely accepted criterion for fracture prediction in the sheet-metal forming. To determine a FLD, stretching tests were performed for sheet specimens with different widths using a semi-spherical punch. The specimens were first electrochemically etched with circular grids that would be deformed into ellipses after being stretched. The engineering strains measured in the major and minor axes of the ellipse are termed the major strain and minor strain, respectively. They are also the principal strains on the planes where the strains are measured.

In the present study, rectangular specimens having the same length of 140 mm, but with different widths ranging from 20 to 140 mm in an increment of 20 mm, were tested. Similar to the tensile tests, the AZ31 sheet was cut at three orientations to the rolling direction, i.e., 0°, 45°, and 90°, for each size of specimen. During the tests, specimens clamped at the periphery were stretched to failure over a 78 mm semi-spherical punch. The major and minor strains measured in the location closest to the fracture for each specimen were recorded and then were plotted against one another with the major strain as the ordinate. The curve fitted into the strain points was defined as the forming limit curve. The diagram showing this forming limit curve is termed the FLD. The FLD is a very useful criterion for the prediction of the occurrence of fracture in a stamping process.

For the forming limit tests at elevated temperatures, the heating oven used in the tensile tests was mounted in the same test machine enclosing both die and punch, i.e., the tooling and the specimen were heated at the same time and were kept at the same temperature. The forming limit curves for specimens tested at 100, 200, and 300 °C are shown in Fig. 2. In the FLD, the higher the forming limit curve, the better is the formability. As seen in Fig. 2, the specimen tested at a higher temperature clearly possesses a higher curve. This means that the AZ31 sheet is not easy to fracture and has better

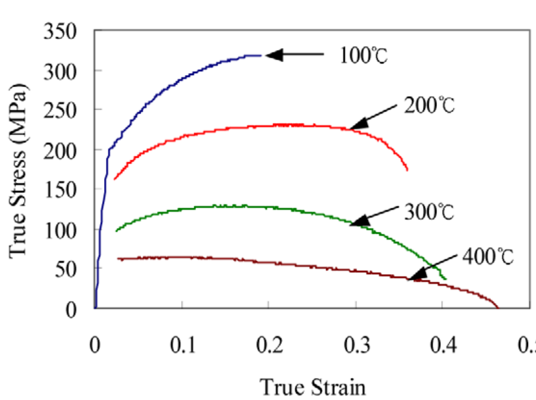

Fig. 1. Stress–strain relations at elevated temperatures (strain rate: 0.01/s).

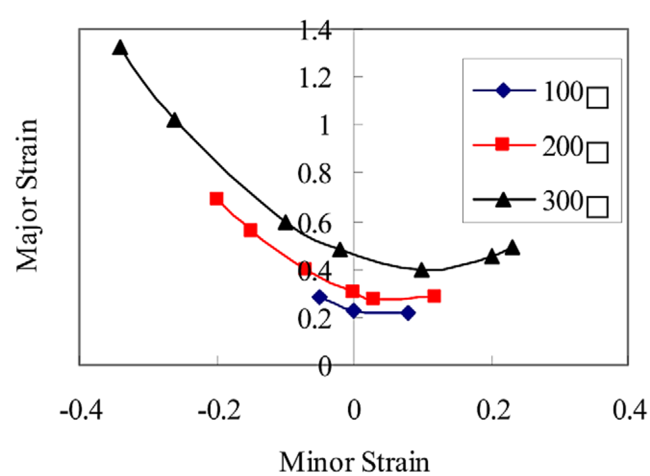

Fig. 2. The forming limit curves at elevated temperatures.

formability at elevated temperatures. This trend agrees very well with that obtained in the tensile tests.

3. Finite element model

The effects of process parameters, such as punch radius, die corner radius and forming temperature on the formability of square cup drawing were examined by the finite element analysis. The tooling geometries were constructed by the CAD program PRO/Engineer, and were then converted into the finite element mesh, as shown in Fig. 3, using the program DELTAMESH. The effect of forming temperature was studied first and the optimum forming temperature obtained from the analysis was then adopted in the subsequent simulations for the investigation of the effects of punch radius and die corner radius on the square cup drawing. The drawing of a square cup of dimensions 40 × 40 mm from a 0.5 mm thick AZ31 sheet was simulated. The material properties and FLD of the AZ31 sheet obtained from the previous tests were used in the finite element simulations. The other simulation parameters were: die clearance of 0.6 mm on each side, blank-holder force of 2.5 kN, coefficient of friction of 0.1, and punch speed of 3 mm/s. The finite element software PAM_STAMP was employed to perform the analysis and the four-node shell element was used in the simulations.

4. Experimental work of the square cup drawing

The same process parameters used in the finite element simulations were adopted to design the tooling for the actual square cup drawings. Fig. 4 shows the schematic design of the tooling. Punches and dies with different radii were manufactured to conduct the square cup drawings. In the drawing process, a sheet blank was clamped between the blank holders, which were heated

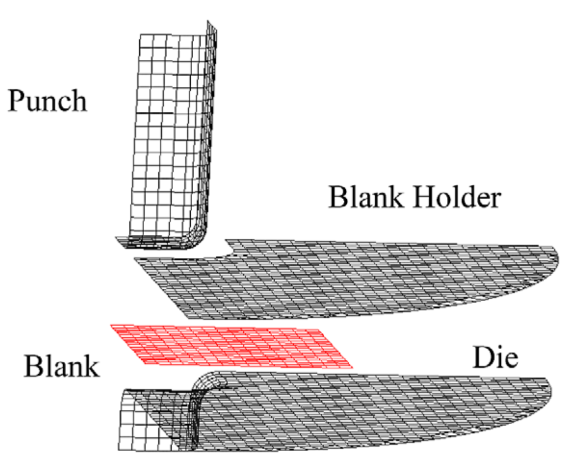

Fig. 3. FEM mesh of dies and blank.

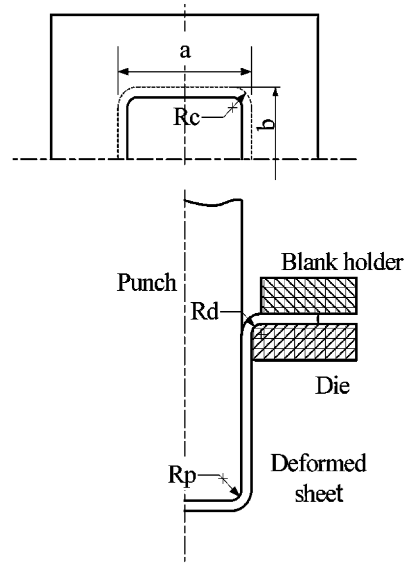

Fig. 4. Geometric parameters of square cup drawing dies.

by electric devices, and the heated punch moved down to form the square cup. The temperatures of both the sheet blank and the tooling were controlled by thermocouples and temperature controllers. The MTS 810 test equipment was used to perform the square cup drawings.

5. Results and discussions

The maximum depth of the drawn square cup without fracture was used as the index of formability. In the finite element analysis, the FLD was adopted as the fracture criterion to determine the maximum drawn depth of the square cup.

The effect of forming temperature on the formability of square cup drawing was examined first. The punch radius (R_p) of 5 mm, die radius (R_d) of 6 mm, and corner radius (R_c) of 8 mm were the tooling dimensions used in both the finite element simulations and the experiments, in addition to the other dimensions specified in Section 3. Fig. 5 displays the relations between the forming temperature and the drawn depth obtained from the finite element simulations and the experimental work. It

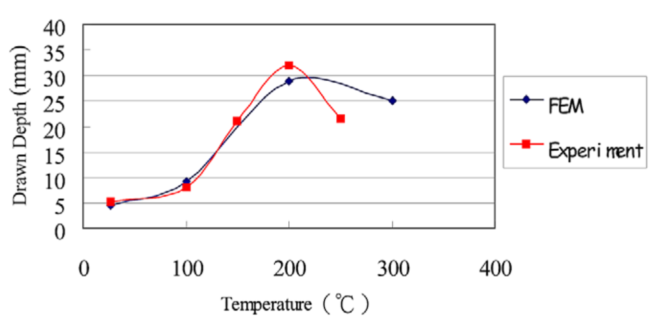

Fig. 5. Relations between forming temperatures and drawn depth.

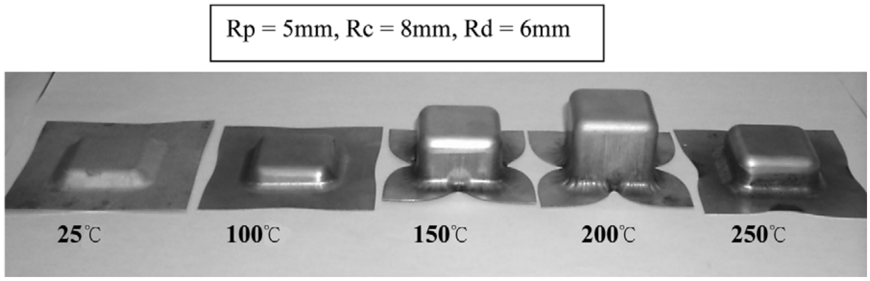

Fig. 6. Drawn cups formed at various temperatures.

is seen in Fig. 5 that both the finite element simulation results and the experimental data indicate an optimum forming temperature of 200 °C for the square cup drawing with a 0.5 mm thick AZ31 sheet. The decease of depth of the drawn cups formed at temperature higher than 200 °C is also clearly observed in Fig. 6. The decrease of drawn depth is attributed to the lower work-hardening exponent of AZ31 sheet at a higher forming temperature that induces local thinning at the draw-wall of the square cup. This result implies that there may exist an optimum forming temperature for each stamping process of AZ31 sheets, depending on the thickness of sheet and geometry of the part as well, and not the case of extremely high forming temperature adopted. It is also noted in Fig. 5 that the finite element simulation results agree well with the experimental data except at forming temperatures higher than 200 °C. This discrepancy is because a flat line was used in the finite element simulations as the stress–strain relations to replace the softening phenomenon shown in Fig. 1 for the square cups formed at temperatures higher that 200 °C. An improvement could be made if the softening effect is considered in the finite element simulations.

The effects of tooling geometries on the formability of square cup drawing of AZ31 sheets at forming temperature of 200 °C were then studied. It is known that a smaller punch radius reduces the formability of square cup drawing, as shown in Fig. 7, which was plotted according to the finite element simulation results. To examine the failure mode, the strain paths tracing the fracture points in the forming processes using punches with radii of 1.5 and 6 mm are shown in Figs. 8 and 9, respectively. It is seen in both figures that the fracture of the sheet is caused by biaxial stretch under the punch profile at the corners. However, it is noted in Fig. 8 that the smaller punch radius restrains the material from being stretched equally in both directions, resulting in a dramatic increase in major strain causing an early fracture. While the larger punch radius allows for an equal biaxial stretch, as shown in Fig. 9, under the punch profile and delays the fracture to happen.

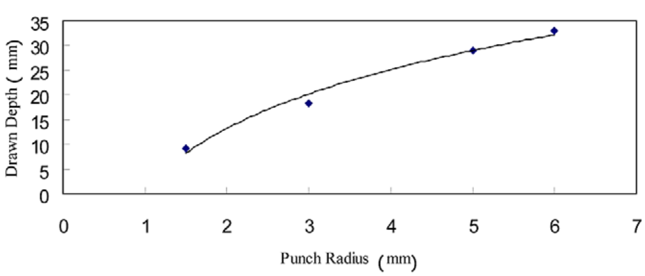

Fig. 7. Relations between punch radius and drawn depth.

The effect of die corner radius (R_c) was studied by both the finite element analysis and the experiments with punch radius of 5 mm and die radius of 6 mm. Fig. 10 shows the relations between the corner radius and the drawn depth of the square cup. As seen in Fig. 10, the finite element simulation results agree well with the experimental data in trend, but predict lower drawn depth. However, the difference is not significant. It is to be noted in Fig. 10 that there exists an optimum die corner radius for the drawing of square cups. When the die corner radius is larger than 8 mm, the drawn depth turns toward a smaller value, as shown in Fig. 10. The strain paths tracing the fracture point in the forming processes with die corner radii of 2 and 16 mm are shown in Figs. 11 and 12, respectively. It is noticed in Fig. 11 that the strains of the fracture point are in the draw mode, i.e., the left-hand side of the FLD, at the beginning of forming process and move toward the stretch mode afterwards, delaying the occurrence of fracture. While the material flow of the fracture point is limited to the major direction when the die corner radius is increased to 16 mm, as shown in Fig. 12, resulting in a smaller value of minor strain and causing an early fracture close to the plane-strain mode. For the die corner radius of 2 mm, it is seen in Fig. 11 that the fracture point is located at the corner of cup bottom where the sheet metal is under biaxial stretching. While the fracture point moves to the side of cup bottom, as shown in Fig. 12, for the die corner radius of 16 mm, and the sheet metal is subjected to the plane-strain deformation at the side of cup bottom. Figs. 11 and 12 have displayed the change of fracture mode of the drawn square cups for the die corner radius being increased from a smaller value to a larger one.

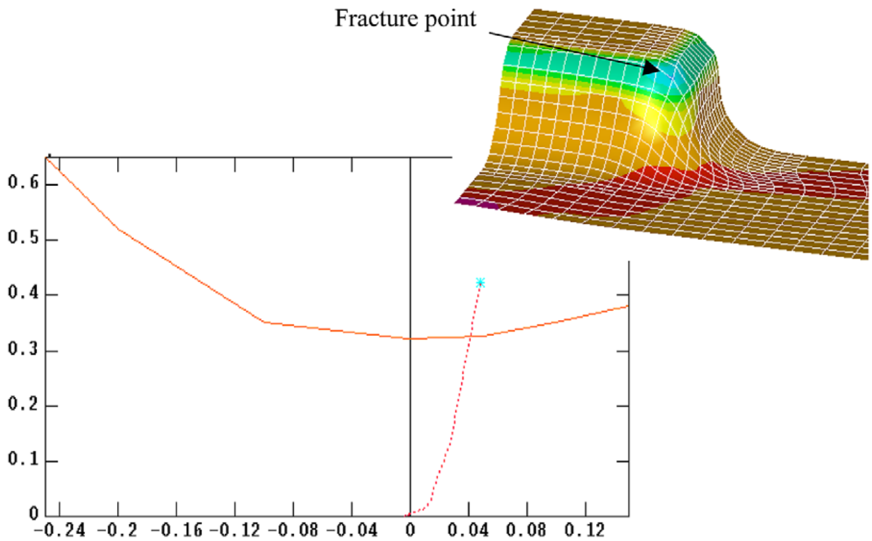

Fig. 8. Strain-path of fracture point (R_p = 1.5 mm).

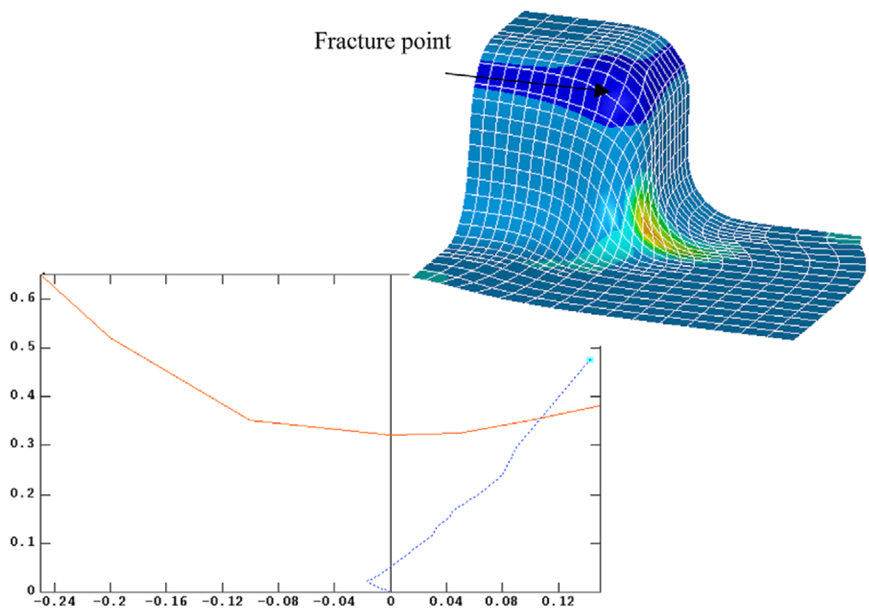

Fig. 9. Strain-path of fracture point (R_p = 6 mm).

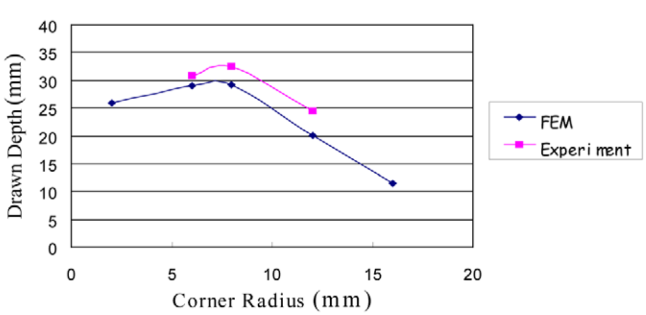

Fig. 10. Relations between die corner radius and drawn depth.

6. Concluding remarks

The formability of square cup drawing of magnesium alloy AZ31 sheets was studied in the present study using the experimental approach and the finite element analysis. Both the tensile tests and the forming limit tests indicate an inferior formability of AZ31 sheets if formed at room temperature. However, the formability could be dramatically improved when the AZ31 sheet is stamped at elevated temperatures. Both the finite element results and the experimental data reveal that an optimum forming temperature of 200 °C exists for the drawing of square cups with 0.5 mm thick AZ31 sheets. However, this optimum temperature may vary with the sheet thickness and the part geometry to be formed.

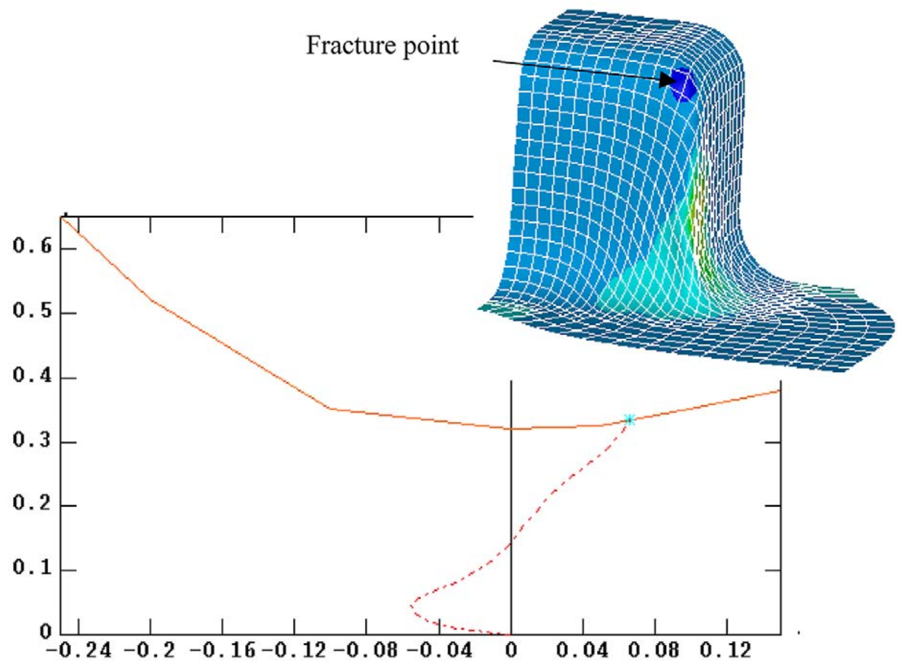

Fig. 11. Strain-path of fracture point (R_c = 2 mm).

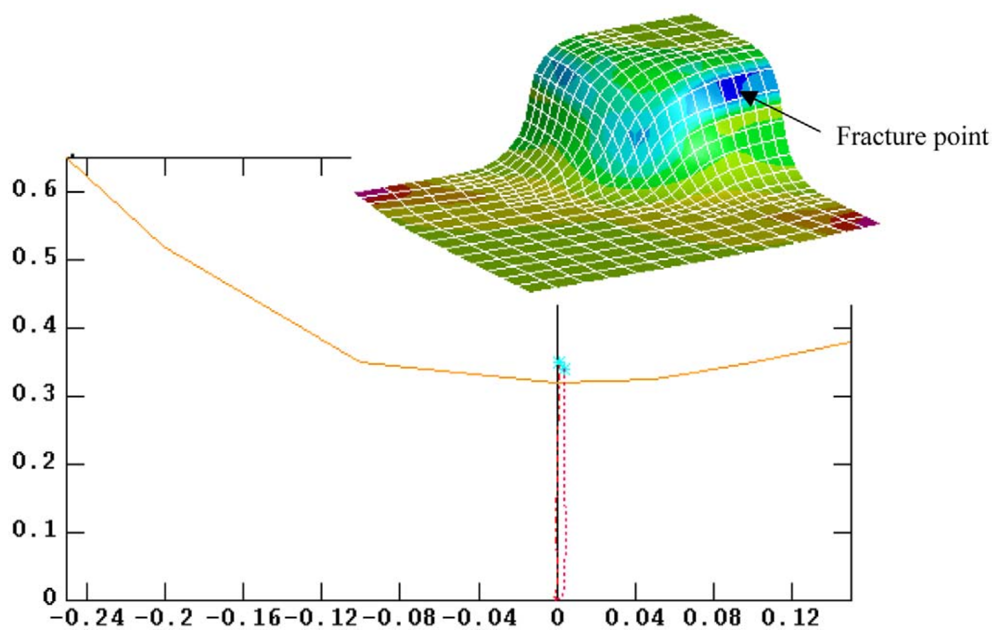

Fig. 12. Strain-path of fracture point (R_c = 16 mm).

The strain paths tracing the fracture points in the forming process were recorded in the FLD and were analyzed by the finite element method to investigate the effect of the punch radius on the formability of the drawing of square cups. The finite element simulation results indicate that a larger punch radius allows for a uniform material flow toward both of the two principal directions under the punch profile at corners and delays the occurrence of fracture. This strain-path pattern explains the reason why a larger punch radius leads to a better formability for the drawing of square cups.

An optimum die corner radius for the drawing of square cups was also determined by both the finite element analysis and the experimental work. The investigation reveals that the formability is improved as the die corner radius increased up to an optimum value, and becomes worse when the die corner radius is further increased. The strain-path analysis indicates that the deformation of the sheet at the fracture location changes into the plane-strain mode from the stretch mode as the die corner radius is further increased from the optimum value, resulting in an early fracture since the plane-strain mode has a lower forming limit as shown in the FLD of Fig. 2.

In conclusion, the magnesium alloy AZ31 sheet could be formed at elevated temperature and the optimum punch radius and die corner radius obtained in the present study could provide a design guideline for the drawing of square cups.

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