Study on cryogenic deep drawing of 2219 aluminum alloy spherical shell

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Abstract—In order to meet the urgent needs of aluminum alloy integral shell, a new forming process is required to solve the problem of splitting at room temperature. The plasticity of aluminum alloy is significantly improved at cryogenic temperature, and a novel cryogenic forming method was developed recently. In this paper, a cryogenic forming unit was established to study the cryogenic drawing behavior. The effects of sheet diameter on the wrinkling and deformation behaviors were analyzed by experiments and numerical simulations. The study showed that a spherical shell with a diameter of 200mm and a thickness-diameter-ratio of 1.0% could be formed at -160℃, which split at room temperature. The drawing depth was increased 74.3% at cryogenic temperature. The tendencies of wrinkling and splitting were controlled by the appropriate sheet diameter. It is concluded that cryogenic deep drawing has great potential for forming aluminum alloy integral shells.

1. Introduction

With high strength–to–weight ratio, excellent fracture toughness, and good corrosion resistance\textsuperscript{[1–3]}, aluminum alloys have been widely used in the manufacture of curved shell in aviation, aerospace, automotive, and marine fields, such as the bottom of launch vehicle fuel tanks, aircraft skins, body coverings of automotive, and ship–shaped deep–cavity components\textsuperscript{[4–6]}. Since the significant improvement of the new generation equipment for high reliability, long life and light weight, there is an urgent need to replace the traditional multi–piece tailor–welded structure with an integral structure \textsuperscript{[7][8]}. Such integral thin shell is a kind of large–size curved surface components. The splitting is easy to occur in the integral forming process, due to the poor formability of aluminum alloys at room temperature. Meanwhile, the methods taken to prevent wrinkling will further result in splitting. A new forming process is required to solve this problem.

In order to improve the formability, hot forming is usually used\textsuperscript{[9]}, but will cause coarse surface and microstructural damage. Recently, Prof. Yuan\textsuperscript{[10]} has developed a novel cryogenic forming method by using simultaneous increase of elongation and hardening ability of aluminum alloys at cryogenic temperature, which has great potential for forming the aluminum alloy integral thin shell made of high strength aluminum alloy.

In order to meet the current demand for large–scale integral curved shells, a sufficiently large sheet is required for cryogenic deep drawing. It is very important to choose an appropriate sheet blank by comprehensively considering the ability of a current rolling equipment, material utilization and forming defects. The smallest possible sheet should be selected under the premise that the component can be formed. However, the effect of size on the wrinkling in cryogenic forming process is still
unclear. In this paper, a cryogenic forming unit was developed to study on the cryogenic drawing deformation behavior, and the effects of sheet diameter on the wrinkling and deformation behaviors were analyzed by experiments and numerical simulations. The obtained results can provide important guidance for cryogenic deep drawing of the large-scale integral curved shell.

2. Experimental procedures

2.1. Materials and Specimens
The initial material is an annealed 2219 aluminum alloy sheet with a thickness of 2 mm, and the mechanical properties at 25°C and –160°C were measured through a uniaxial tensile test. The elongation at –160°C is increased to 32.5%, which was 51.9% higher than that at room temperature. It illustrates that the better formability can be obtained at cryogenic temperature.

A spherical specimen with a diameter of 200 mm is chose to study the cryogenic drawing behavior, whose thickness–to–diameter ratio is 1.0%. Fig. 1 shows the schematic of forming dies, including a punch, blinder and die. The specimen is shaped by the punch with a diameter of 200 mm, the gap between the punch and die is 1.1 times the thickness of the sheet, and the die radius is 15 mm.

2.2. Cryogenic deep drawing experiment
Fig. 2 is the schematic diagram of cryogenic deep drawing device. The key to cryogenic deep drawing is the die cooling, which was achieved by using liquid nitrogen. And the die temperature was precisely controlled by adjusting the liquid nitrogen flow in real time. The temperature control accuracy was ±2°C, and the lowest temperature achievable was up to –180°C. When the drawing dies reached the target temperature and were constant for 5 minutes, the experiment started.

Firstly, the cryogenic deep drawing experiment was carried out with the initial sheet diameter of 350 mm, and the room temperature drawing experiment was used to compare the deformation behaviors between the different temperatures. Then, the cryogenic deep drawing experiment with initial sheet diameter of 330 mm was used to study the wrinkling behaviors of different initial sheet diameters. The blank holder force was 5t at room temperature. Larger blank holder force (15t) was used for cryogenic deep drawing experiment because the deformation resistance of aluminum alloy is significantly improved at cryogenic temperature.
2.3. Numerical simulation

A finite element model of deep drawing process was established by using ABAQUS software, as shown in Fig. 3. The dynamic explicit algorithm and the stable time increment step method were utilized to control the integral solution speed, and the time increment step is $1.0 \times 10^{-6}$. The surface–to–surface contact was set between the sheet and the dies. Since the friction coefficient of aluminum alloy increases at cryogenic temperature$^{[11]}$, a friction coefficient of 0.6 was set between the punch and sheet, and the friction coefficient in the flange area of the sheet was set to 0.12 due to implementation of lubrication by film.

A double–curvature shell element type (S4R) was used in the model, the mesh size was 2 mm, and the reduced integration and default hourglass control strategy were adopted, with 5 Gaussian integration points in the thickness direction. The drawing dies mesh size was 3mm. In order to study the effect of sheet size on the wrinkling and deformation behavior by analyzing the circumferential stress and radial strain, numerical simulations of cryogenic deep drawing were carried out using four kinds of sheets (310, 330, 350, 370 mm), the unit blank holder force is 0.5 MPa.

3. Results and Discussions

3.1. Drawing specimens at different temperatures

Fig. 4 shows the drawing specimens formed at room temperature and $-160 \, ^\circ\text{C}$, whose initial sheet diameter is 350 mm. At room temperature, splitting occurred in the transition area between sheet and punch due to the poor plasticity of aluminum alloy, and the drawing depth was 66 mm. A defect free spherical shell was formed at $-160 \, ^\circ\text{C}$. The drawing depth was 115 mm, which was 74.3% higher than...
that at room temperature. Meanwhile, a more uniform thickness distribution was exhibited at \(-160^\circ C\), and the maximum thinning rate and the thickness deviation in the surface area is 11.7% and 0.21 mm, respectively. That is to say, the drawability of 2219 aluminum alloy at cryogenic temperature can be improved significantly, and cryogenic deep drawing have great potential for forming large-scale integral curved shells.

Absolutely, the cryogenic drawing is affected by many factors. Fig. 5 shows cryogenic drawing specimens with initial sheet diameter of 330 mm. When the sheet diameter is reduced to 330 mm, the wrinkling occurred under the same blank holder force of 15 t. The initial diameter of the sheet directly determines the area of the blanking region, the smaller initial diameter is, the smaller flow resistance of the sheet, which leads to the greater wrinkling tendency. However, the larger sheet diameter causes the less material utilization, especially for the forming of large-scale components. Therefore, an appropriate initial sheet diameter should be selected to improve material utilization while suppressing wrinkling in the novel after cryogenic deep drawing process.

3.2. Circumferential stress distribution

Fig. 6 shows the circumferential stress distribution of the drawing specimens with different initial sheet diameters. The wrinkling of spherical shell is mainly generated in the unsupported area due to the circumferential compressive stress, with an uneven distribution. It can be seen that the wrinkling occurs when the diameter of the sheet is 310 mm and 330 mm. The remaining material in flange area is insufficient when the diameter of the sheet is 310 mm, serious wrinkling is further caused by the invalid edge pressing. When the diameter of the sheet is 350 mm and 370 mm, there were no wrinkles, and the circumferential stress distribution in the suspended area is relatively uniform. However, when the diameter of the sheet is 370 mm, there was too much leftover material in flange area, resulting in material waste. It can be concluded that when the diameter of the sheet is small, the larger circumferential pressure will generate, which leads to the greater the wrinkling tendency. When the diameter of the sheet is larger, the circumferential stress is correspondingly reduced, but it causes the
less material utilization, which further indicates that the appropriate initial sheet diameter needs to be selected.

3.3. Radial strain distribution

Fig. 7 shows the radial strain distribution of the drawing specimens formed with different sheet diameters. It found that the radial strain increases gradually from the center to the fillet, and then decreases on the whole from rounded corner to edge. As the sheet diameter increases, the radial strain of the specimen also increases. When the sheet diameter is 370 mm, the maximum radial strain is up to 0.28, which are 25.6% larger than that of the condition of 310 mm sheet diameter.

To summarise, the larger sheet diameter causes the larger radial strain, which results in the greater splitting tendency and the requirement for material formability due to the poor room temperature. Therefore, the selection of sheet diameter needs to comprehensively consider drawing defects and material utilization.
4. Conclusion

(1) A cryogenic forming unit was established to study the cryogenic drawing behavior.

(2) A spherical shell with a diameter of 200 mm and a thickness diameter ratio of 1.0% is formed successfully at –160 ℃, which split at room temperature. The drawing depth is increased 74.3% at cryogenic temperature, which illustrates the cryogenic deep drawing has great potential for forming aluminum alloy integral shells.

(3) The initial sheet diameter has a significant effect on drawing behavior, the smaller initial diameter of the sheet, the greater wrinkling tendency. The larger sheet diameter, the greater flow resistance of the sheet, resulting in large radial strain. An appropriate initial sheet diameter should be selected in the cryogenic forming process.

Acknowledgments

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