Research on the active pressurized forced lubrication deep drawing process and evaluation of the lubrication effect

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Abstract
Friction and lubrication are important parameters that affect the quality of sheet metal forming; excellent lubrication conditions and less harmful friction can reduce local thinning, delay fracture, and improve surface quality. Aiming at the poor friction conditions and difficult lubrication in the flange area during deep drawing, an active pressurized forced lubrication deep drawing (FLDD) process was proposed in this paper. A hydraulic system was employed to flush high-pressure lubricating oil into the contact gap between the die and sheet in the flange area. The high-pressure hydrostatic oil film in the contact gap can reduce the real contact area and effectively improve the lubrication conditions. The equipment is simple, the cost is low, and the lubricating oil pressure can be measured and controlled. Under the conditions of 20-kN, 35-kN, and 50-kN blank holder force (BHF), FLDD testing of box parts was carried out with 5-MPa and 9-MPa pressure using water-based lubricating oil. The horizontal comparison experiment was conducted with vegetable oil and water-based lubricating oil under the same process conditions. The test results illustrated that the lubrication effect of vegetable oil was the worst, whereas the lubrication effect of water-based mineral lubricant was significantly improved after pressurization. The maximum forming height was increased by 17.97%, the maximum forming force was reduced by 8.9%, the maximum wall thickness thinning rate was decreased by 7%, and the lubrication effect at 9-MPa pressure was superior to that of 5 MPa. The FLDD process has definite application value in improving the production environment, pollution control, and automatic production.

Keywords Forced lubrication · Hydraulic · Deep drawing · Friction · Comparative test

1 Introduction
Friction and lubrication are unavoidable topics in sheet metal forming. Good lubrication conditions have the advantages of reducing the forming force, improving the forming limit, reducing the wall thickness thinning rate, improving the surface quality of the formed parts, reducing mold wear, etc. Improving lubrication conditions to reduce the friction coefficient is of great importance to the forming process [1–3]. In recent years, scholars at home and abroad have conducted much theoretical research and practical exploration on antifriction measures and lubrication technology in sheet metal forming. Most of these studies are mainly focused on the development of new lubricating media, self-lubricating material molds, coatings or textures, and hydrodynamic lubrication processes.

Several scholars have found that the addition of solid particles to oil-based lubricants could significantly improve the extreme pressure performance of lubricants, reduce the contact effect between metals, and improve the lubrication conditions. Uda et al. [4] developed lubricants with different solid ingredients and found that the lubricant with mica powder had better friction performance through friction tests, and its lubrication superiority was verified in hot stamping of 22MnB5 steel. Tan et al. [5, 6] investigated the extreme pressure performance of lubricants with different mass fractions of SiO2 nanoparticles by utilizing a deep drawing process with increased BHF; the authors observed that the surface quality of the formed parts was smoother when the mass fraction of nanoparticles was 2%, and the drawing ratio was also improved. Moreover, it was discovered that the addition of SiO2 nanoparticles was beneficial in
delaying fracture during the deep drawing of SUS304 cylinder parts. Diabb et al. [7] added a 0.0125–0.1% mass fraction of SiO2 nanoparticles into sunflower seed oil and corn oil as a mixed lubricant and applied it to single-point progressive forming. The effects of enhanced lubricants on friction and roughness during single-point forming of aluminum alloys were analyzed using the Striebeck curve, while the interaction between nanoparticles and vegetable oils was investigated using Fourier transform infrared spectroscopy. Kamali et al. [8] performed a comparative test using three lubrication conditions of dry friction, mineral oil lubrication, and addition of a TiO2 nanoparticle lubricant in micro-drawing deep forming of magnesium-lithium alloy; the results indicated that forming force was reduced by 14.14% and the surface roughness Ra of the formed part was reduced by 18.18% after the addition of TiO2 nanoparticles.

Regarding the sheet drawing process itself, research scholars and engineers have also explored a number of lubrication options. During hydrodynamic deep drawing, as the punch descends, the liquid in the cavity of the die is pressurized, and the pressure increases continuously. When the pressure reaches a certain value, it will overflow from the gap between the sheet metal and die, and then, hydrodynamic lubrication appears [9]. Hama et al. [10] investigated the liquid outflow characteristics in the forming process by directly measuring the overflow liquid pressure distribution in the flange area and integrating it, explaining that the influence of fluid lubrication on sheet metal varies with different deformation stages during deep drawing. Abbadeni et al. [11] illustrated the lubrication mechanism of the contact zone at the flange area during the hydrodynamic drawing process, proposed an analytical model of the non-uniform fluid pressure distribution and the flow characteristics of the overflow lubricant film in the die cavity by means of the Reynolds equation, and investigated the effects of BHF and fluid pressure on formability through AA5086 aluminum alloy drawing tests. Horikoshi et al. [12] presented a scheme for the deep drawing process utilizing localized high-pressure water lubrication, and a high-pressure water stream that was ejected through small holes machined on the die to lubricate the frictional interface. The flow characteristic parameters of the liquid were calculated by the Reynolds equation, and the interaction between the nozzle position, nozzle number, and plate deformation were analyzed by combining computational fluid dynamics and the finite element method. Finally, the superiority of this scheme was verified by a series of tests. Yang [13, 14] proposed a lubrication scheme employing the relative motion of die to generate hydrodynamic pressure and used the mean Reynolds equation to propose a friction model related to the oil film thickness, surface roughness, oil viscosity, interfacial pressure, sliding velocity, and strain rate. The contact area ratio, friction coefficient, and strain distribution were predicted in combination with finite element simulation during deep drawing.

In sheet metal deep drawing, due to the large contact stress and wrinkles caused by deformation, the lubricating medium applied on the sheet surface is easily squeezed away, and the lubricating oil film is likely to be cut off, resulting in lubrication failure. The FLDD process proposed in this paper is an active lubrication process with controllable pressure, which promotes the integrity of the lubricating oil film by actively pressurizing the lubricating oil. Under complex and changeable contact conditions in sheet forming, a high-pressure lubricant with controlled pressure was utilized to improve the friction conditions and increase the effective lubrication area. Under the same process parameters and blank size, horizontal comparison tests were conducted between the FLDD process and common deep drawing process using vegetable oil and water-based lubricating oil. The feasibility and superiority of the FLDD process were verified by exploring the forming height, forming force, and wall thickness distribution.

2 Technology principle

According to the principle of plasticity mechanics, tangential compressive stress of flange area sheet increases as that continuously flows into the die fillet during deep drawing, and when the BHF provided by blank holder is not enough to resist the bending deformation of the sheet caused by tangential compressive stress, wrinkling occurs. The hydrodynamic lubricating oil film produced by plate flow is easily crushed by the folds caused by plate instability, resulting in lubrication failure. Increased BHF is usually adopted to prevent wrinkling, but a larger BHF tends to make the lubricating oil difficult to save in the contact gap, lubricating oil is squeezed away, and a lubricating oil film cannot be formed. Poor lubrication conditions increase the forming force, resulting in the fracture of sheets, which has a greatly adverse impact on plate forming.

Figure 1 illustrates the schematic diagram of the contact relationship after wrinkling in the flange area during deep drawing. Assuming that the friction coefficient between the sheet and die is µr and that the friction coefficient between the sheet and lubricant is µl, the friction coefficient in the flange area can be expressed by Eq. (1).

\[ \mu = \alpha \mu_r + (1 - \alpha) \mu_l \]  \hspace{1cm} (1)

where \( \alpha \) is the true contact area ratio, \( \alpha = L_r/(L_r + L_l) \).

In the traditional deep drawing process, due to large contact stress and constant changes in the contact surface, hydrodynamic lubrication generated by the relative motion is easily destroyed. In particular, with the increase in the
In the PLDD process mentioned in this article, a hydraulic oil source is employed to actively inject high-pressure lubricant into the contact gap between the sheet metal and die. The lubricating oil film fills the contact gap under controllable pressure to form a stable hydrostatic oil film under high contact pressure. After the lubricating oil film reaches a certain pressure, it invades the contact gap between the wrinkle peak and die and bears part of the BHF, which has an obvious effect on relieving the cutting and crushing of lubricating oil by a large BHF and deformation, reducing the value of $\alpha$ and increasing the effective lubrication area of the friction surface. Ideally, the value of $\alpha$ can be infinitely close to 0, and BHF will be borne entirely by the oil pressure, but this is difficult to achieve in practice. The oil supply system has complete oil inlet and return piping, valve control, and an oil pressure monitoring system, and the oil pressure can be measured and controlled in real time, which can realize the working conditions of circulating oil supply, holding pressure oil supply, and variable pressure oil supply with the plastic deformation process. The process principle is shown in Fig. 2.

An oil cavity is formed at the contact gap between the mold and sheet, and O-ring seals are employed on the mating surface of the mold to ensure that the oil cavity is closed. During the whole drawing process, parameters such as the oil pressure, forming force, and punch stroke can be displayed in real time through data acquisition card and can be adjusted online. Compared with hydrodynamic deep drawing process mentioned in the references [11–14] in the previous
section, the process equipment proposed in this paper is simple, easy to operate, and inexpensive.

### 3 Process test

#### 3.1 Material

An SPCC cold-rolled steel plate with a thickness of 0.8 mm was selected for the deep drawing test. SPCC is a kind of carbon steel cold-rolled sheet that is widely used in automobile manufacturing, household appliances, instruments, food packaging, and other fields, and its chemical composition is shown in Table 1. The uniaxial tensile specimens shown in Fig. 3b were designed, and an Inspekt Table 100-kN electronic universal material testing machine was adopted to test the uniaxial tensile specimens at a strain rate of 0.004 s⁻¹ for three directions of 0°, 45°, and 90° from the rolling direction. The real stress and strain curves of the material were calculated by Eq. (2) and Eq. (3), as shown in Fig. 1c. The elastic modulus $E$ was obtained by fitting the elastic section of the stress–strain curve using Eq. (4), and mechanical parameters such as the strength coefficient $K$ and hardening index $n$ were obtained by fitting the plastic phase of the real stress–strain curve utilizing the Swift model (Eq. (5)), whose basic mechanical properties are shown in Table 2.

$$
s = F \cdot \frac{L}{A_0} \cdot L_0
$$

$$
\varepsilon = \ln\left(1 + \frac{\Delta L}{L_0}\right)
$$

where $\sigma$ and $\varepsilon$ are true stress and strain; $F$ is tensile force; $L$ is the gauge length; $L_0$ is the initial gauge length (initial length $L_0=50$ mm); and $\Delta L$ is the gauge elongation.

$$
\sigma = E \varepsilon_f
$$

$$
\sigma = K(\varepsilon_f + \varepsilon_0^n)
$$

#### Table 1 Chemical composition of SPCC (wt.%)

|   | C   | Mn | P   | S   | AL | Fe |
|---|-----|----|-----|-----|----|----|
| SPCC | 0.12 | 0.6 | 0.04 | 0.04 | 0.02 | Rem |

#### Table 2 Mechanical property parameters of SPCC

|                  | Elastic modulus | Yield stress | $K$   | $n$  |
|------------------|-----------------|--------------|-------|-----|
|                  | 219000 MPa      | 152 MPa      | 495.7 MPa | 0.2444 |
where $E$ is the elastic modulus (MPa); $\varepsilon_e$ is elastic strain; $\varepsilon_p$ is plastic strain; $\varepsilon_0$ is strain value of the material at yield; $K$ is strength coefficient (MPa); $n$ is hardening index.

### 3.2 Die design

According to the process requirements, the FLDD process experiment die for box-shaped parts was designed. The three-dimensional schematic diagram and detailed dimensions of the die are shown in Fig. 4. The set of dies is mainly composed of punch, blank holder, concave die, sealing device, and assembly bases. Compared with the traditional deep drawing process, an oil supply pipeline and sealing device were added. BHF control was adopted in the deep drawing process, equipped with displacement sensor, punch pressure sensor, and oil pressure sensor. Process parameters such as the punch displacement, forming force, and oil cavity pressure were monitored in real time.

During the drawing process, the plate was lubricated on both sides, and the die and blank holder were opened with oil holes in the flange area, which were symmetrically distributed. As shown in Fig. 5, in order to distribute the

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**Fig. 4** Test die and size

**Fig. 5** Schematic diagram of working surface of die
lubricating fluid quickly and evenly on the surface of the die and improve the lubrication effect, several oil holes were manufactured at the straight edge area and rounded corner area of the die flange zone, while hydraulic valves were utilized to control the synchronized oil supply. At the same time, the oil film pressure on the contact surface could be monitored in real time through the pressure sensor.

3.3 Experimental process

The test material of a 0.8-mm SPCC cold-rolled sheet was selected for the deep drawing test which was carried out on a 500-T hydraulic press in the laboratory, and the drawing speed was set to 30 mm/min. The experimental equipment is shown in Fig. 6. Forming force, displacement, and oil pressure were transmitted from the data acquisition card to the computer for real-time acquisition during the forming process. BHF was provided by butterfly springs, which were calibrated for spring stiffness by a compression test and deformed at 75% of the maximum compression to prevent spring damage. Accurate BHF was obtained by accurately measuring the spring compression. Water-based mineral lubricating oil was chosen as the lubricating medium. A small hydraulic station with a maximum output pressure of 20-MPa oil supply was adopted as the supply system, along with a hydraulic station integrated reversing valve, relief valve, pressure gauge, and other components to control the flow of oil, and the maximum flow rate was 4.7 L/min.

The shape of test blank is shown in Fig. 7. The value range of BHF was taken according to Eq. (6) proposed by Fukui and Yoshida [15] to calculate the minimum unit BHF. However, Yoshida’s formula to calculate the unit BHF was based on cylindrical parts, and box-shaped parts were used in this paper, so $R_0$ and $r_2$ in Eq. (6) were estimated by adopting the equivalence radius $R_{equ}$ and $r_{equ}$, respectively, of Eqs. (7–8) [16].
\[
p = \frac{(\sigma_s + \sigma_b)R_0}{90\pi} \left[ \frac{2(R_0 - r_2)}{t} - \frac{8}{(R_0^2 - (r_2 + r_d)^2)} \right] \text{MPa} \tag{6}
\]

where \( p \) is the unit BHF; \( \sigma_s \) is the yield stress; \( \sigma_b \) is the tensile strength; \( R_0 \) is the blank radius; \( r_2 \) is the radius of the drawing cylinder; \( t \) is the sheet thickness; and \( r_d \) is the fillet radius of die.

\[
R_{equ} = \sqrt{S/\pi} \tag{7}
\]

where \( R_{equ} \) is the equivalence radius of blank and \( S \) is the blank area.

\[
r_{equ} = \sqrt{AB/\pi} \tag{8}
\]

where \( r_{equ} \) is the equivalence radius of formed parts; \( A \) is the long side of box; and \( B \) is the short side of box.

In the traditional deep drawing process, the pressure of the butterfly spring is the corresponding BHF. In the process of FLDD, the high-pressure lubricating oil will give an upwards reaction force to the blank holder, so the actual BHF can be expressed by Eq. (9).

\[
Q = F_s - p_lS_Q \tag{9}
\]

where \( Q \) is the actual BHF; \( F_s \) is butterfly spring pressure; \( p_l \) is lubricating oil pressure; and \( S_Q \) is the effective area of blank holder.

To qualitatively and quantitatively evaluate the FLDD process, vegetable oil and water-based mineral lubricating oil were adopted for the horizontal comparison test with the FLDD process under pressures of 5 MPa and 9 MPa (5 MPa-FLDD and 9 MPa-FLDD, respectively). All lubricating media were evenly applied on the upper and lower surfaces of the plate.

### 3.4 Evaluation index of the lubrication effect

A large contact pressure increases the friction in the flange area and the material flow resistance, resulting in increased tensile stress, sheet thinning, and fracture. At the bottom of the formed parts, the friction between the punch and sheet

![Fig. 8 Forming height under different process parameters](image_url)
metal leads to an increase in the material flow resistance, but the effect can delay thinning and fracture, which represents beneficial friction. Therefore, harmful friction in the process of sheet metal deep drawing is mainly concentrated in the flange area, which was researched in [17]. Furthermore, some research studies on friction and lubrication in sheet metal deep drawing were also mainly concentrated in the flange area as described in [18–20]. The improvement of flange lubrication is of great significance to the formability and quality. In this paper, to qualitatively and quantitatively evaluate the lubrication effect under different lubrication conditions, box-shaped drawing tests of 0.8-mm-thick SPCC plate were carried out, and the evaluation was implemented through the following indices:

1. Maximum drawing height: under the same BHF conditions, the height of the formed parts under different lubrication conditions was measured. Taking no fracture as the standard, the greater the height is, the better the lubrication effect.
2. Forming force: under the same BHF condition, the forming force curves under different lubrication conditions were compared and analyzed. The smaller the forming force is, the better the lubrication effect.
3. Maximum thinning rate: under the same BHF, the formed parts with the same forming depth under different lubrication conditions were selected and cut by spark-erosion wire cutting, and the thinning was measured. The smaller the maximum thinning rate is, the better the lubrication effect.

4 Results and discussion

4.1 Effect of lubrication conditions on the sheet metal forming limit

In the deep drawing of axisymmetric parts, the sheet forming ability is usually indicated by the limit ratio of drawing (LRD), whose value is the ratio of the blank diameter to the formed cylinder diameter. For the forming of box parts, due to its nonaxisymmetry, a unified standard for calculating the forming limit has not been established, and an equivalent radius was used to calculate the equivalent drawing ratio of box parts by a number of scholars [21–23]. In this paper, the most intuitive forming height was utilized to compare the forming capacity of sheet metal under different lubrication conditions.

Under 20-kN, 35-kN, and 50-kN BHF, a deep drawing test was conducted under four lubrication conditions. The forming height of the box part at the moment of fracture is shown in Fig. 8. As seen in the figure, the best forming performance was achieved when the BHF was 35 kN, because a small crimping force causes wrinkling in the flange area and prevents the plastic flow of metal, while a large BHF will cause the metal in the flange area to be unable to flow to the center of the die. Figure 8 shows that the water-based mineral lubricating oil improved the forming height of the metal sheet after pressurization, because pressurized lubricating oil was more likely to retain and invade the contact gap between the sheet and die under high contact pressure, increasing the proportion of fluid lubrication area and promoting metal flow. Under three BHF conditions, the forming height increased by 9.93%, 10.92%, and 13.73% at a lubricant pressure of 5 MPa and by 14.73%, 15.85%, and 17.97% at a lubricant pressure of 9 MPa, respectively. It is evident that the forming height is higher than that of 5 MPa at 9 MPa, which indicates that the increase in oil pressure is more conducive to the transformation from boundary lubrication to fluid lubrication at the contact surface. It was also discovered that the higher the lubricant pressure was, the greater the improvement in forming performance under relatively high BHF conditions, demonstrating that it was more difficult to form and maintain the lubricant film under high BHF conditions, while higher oil pressure promoted the formation of a lubricant film.

4.2 Effect of lubrication conditions on forming force

In the process of sheet metal forming, the forming force is mainly composed of the force required for sheet metal plastic deformation and that required to overcome friction loss. Friction loss in deep drawing is mainly concentrated in the flange area; therefore, it is significant to decrease the friction coefficient in the flange area and improve its lubrication conditions to reduce the forming load and energy consumption. It is well known that good lubrication conditions can reduce the forming load under the same process conditions. Figure 9 demonstrates the influence of different lubrication conditions on the trend of the forming force at 20-kN, 35-kN, and 50-kN BHF.

In the case of the same process parameters such as the BHF and shape of the mold and blank, when the punch displacement is consistent, a smaller forming force indicates better lubrication conditions, while in contrast, poor friction conditions generally lead to a larger forming force. From the curve in Fig. 9, it can be observed that in the initial stage of deep drawing, the plate deformation in the flange area was small and the difference of different lubrication conditions on the forming force was not obvious. When vegetable oil lubrication was selected, the forming force quickly reached the peak value, and then, fracture occurred under the three BHF conditions, which indicates that vegetable oil performed the worst. Moreover, the maximum force
under various lubricant conditions was approximately 90 kN, because this was the bearing limit of the selected material under this geometric parameter, fracture occurred when the load limit was exceeded. Therefore, it was unscientific to judge the lubrication performance from only the maximum force value. Pressurized lubricating oil played a positive role in reducing the forming force, which was reflected by the force value at the same punch stroke moment. When the punch stroke was unified at 30 mm, forming force after forced lubrication was significantly lower than that before pressurization under the three BHF conditions. When the BHF was 20 kN, the force after forced lubrication of 5 MPa and 9 MPa was reduced by 8.0% and 8.6%, respectively; when the BHF was 35 kN, the force after forced lubrication of 5 MPa and 9 MPa was reduced by 2.4% and 3.5%, respectively; and when the BHF was 50 kN, the force after forced lubrication of 5 MPa and 9 MPa was reduced by 3.4% and 8.9%, respectively. After forced lubrication under 20-kN and 50-kN BHF, the forming load decreased greatly, up to 8.9%, which verified that the worse the friction conditions were, the more effective the forced lubrication process was.

4.3 Effect of lubrication conditions on the wall thickness

During sheet forming, the most direct impact of harmful friction in the flange area is to impede the flow of material to the center of the die, increasing radial tensile stress, thus increasing the forming load and leading to thickness thinning or even fracture. Hence, it is meaningful to improve the lubrication condition of die and sheet to delay fracture and inhibit thinning. From the analysis in the above section, too little BHF easily caused wrinkling, and material flow was difficult under too large BHF, which caused the sheet metal to break prematurely. The most direct reason for fracture of sheet metal is excessive thinning, and the moment

![Force-displacement curves](image)
of the forming limit is the time when the material bears the maximum thinning rate. Therefore, it is not appropriate to evaluate the lubrication effect by adopting the wall thickness distribution at the maximum forming height of the part. It is more objective to evaluate the lubrication effect by considering the wall thickness distribution of formed parts under the same BHF, the same forming height, and different lubrication conditions. In this chapter, the thickness distribution of the part at a forming height of 35 mm under 35-kN BHF was discussed. To explore the influence of different lubrication conditions on the variation trend of wall thickness of formed parts, the formed parts were cut along the centerline of the fillet area and straight edge area of the box parts by wire cutting, and the wall thickness was measured an interval of approximately 3–5 mm along the cross section. The results are presented in Fig. 10.

Fig. 10 Thickness distribution under different lubrication conditions
During the sheet deep drawing process, the material in the flange area is subjected to radial tensile stress and tangential compressive stress, which produce elongated and compressed deformation in the radial and tangential directions, respectively. The thickness of the box part flange area near the die fillet area increases greatly, differing from the axially symmetrical parts in the outermost edge of the maximum thickness. According to Fig. 10, the degree of thickening in the flange area under the lubrication conditions of vegetable oil and mineral oil was not obvious, which indicated that there was less material flow in the flange area and that a large part of the box-shaped part forming was completed by sheet thinning and stretching. The greater the thickening degree of the flange area was, the more sufficient the plastic deformation was, reflecting the superior lubrication conditions. The maximum degree of thickening at 5-MPa and 9-MPa forced lubrication increased by 9.4% and 10.9%, respectively, compared with that without pressure. In the fillet area of the die, the sheet was still thickened under tangential compressive stress in the fillet area of the corner area of the box part, while the thickness of the sheet was thinned by tensile deformation and plastic bending in the fillet area of the straight edge area. The straight wall area of the formed part is the force transmission area, which is subject to axial tension. A greater material flow resistance in the flange area increases the tensile stress and causes a thinner thickness in the force transmission area. The worse the lubrication effect is, the more serious the thinning. Figure 10 shows that the wall thickness in the straight wall area after pressure lubrication was greater than that after ordinary lubricant lubrication. In addition, the thickness variation at each part of the cylinder wall area was uneven, and the thinning of the plate material became more serious closer to the bottom. The fillet area of the punch at the box bottom was the most dangerous area of the whole formed part, presenting the most serious thinning. The maximum thinning rates of 5-MPa FLDD and 9-MPa FLDD were 18.2% and 14.2%, respectively. Obviously, forced lubrication played a suppressive role in thinning, and the maximum thinning rate was reduced by a maximum of 7%. The material at the bottom of the box part had a very slow growth of radial tensile stress due to the friction between the punch and sheet, so the thickness of the bottom center area changed less.

5 Conclusion

In the sheet forming process, to reduce the adverse effect of friction in the flange area on material forming and die wear, liquid or solid lubricating media are usually applied to the sheet surface before forming. Nevertheless, traditional liquid lubricants are difficult to form and maintain under high contact pressure, while solid lubricants bring inconvenience to the forming accuracy, production environment, and automatic production. To address this problem, a forced lubrication process employing an external pressure oil source for sheet metal forming was proposed in this paper. A series of experimental explorations were conducted, leading to the following conclusions.

1. A forced lubrication drawing process was proposed for the lubrication problem in the flange area during deep drawing, the process principle was elaborated, die structure and hydraulic system were designed, and the feasibility of scheme was verified by deep drawing test.
2. Vegetable oil and water-based mineral oil were selected for the horizontal comparison drawing test compared with forced lubrication to evaluate the lubrication effect based on the indices of forming height, forming force, and wall thickness distribution of the parts. The experimental results demonstrated that the lubrication effect of water-based mineral lubricating oil was significantly improved after pressurization to 5 MPa and 9 MPa, the maximum forming height was increased by 17.97%, the maximum forming force was reduced by 8.9%, the maximum wall thickness thinning rate was reduced by 7%, and the lubrication effect was better at 9 MPa pressure than at 5 MPa.
3. Non-polluting vegetable oil and water can be selected for lubrication purposes in this process, which can be controlled qualitatively and quantitatively by adjusting the pressure and flow rate. The PLDD process has definite advantages in improving the production environment, pollution control, and automated production.

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Data availability All data calculated or analyzed during this research are included in this article.

Declarations

Competing interests The authors declare no competing interests.
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