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Original scientific paper

# Forced Lubrication Method and the Quantitative Evaluation of Friction Coefficient during Deep Drawing

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**Abstract:** The friction in the sheet forming process is characterized by high contact pressure, large actual contact area and constantly changing friction surface, and the lubrication condition is very severe. In this paper, a forced lubrication process that relies on pressure from external power is proposed and applied to sheet forming. The process has the technical advantages of high efficiency, low cost, controllable and adjustable lubrication conditions. Deep drawing tests were conducted at 35 kN blank holder force (BHF) and 0-12 MPa lubricant pressure. The experimental results demonstrate that the increase of lubricant pressure significantly reduces the forming force, improves the forming performance and reduces the coefficient of friction (CoF). At a lubricant pressure of 12 MPa, the forming height of the box-shaped part is increased by 16.3%. In order to quantitatively evaluate the effect of forced lubrication, the average CoFs under different process conditions were obtained by using the finite element (FE) inverse method. The results show that the CoF tends to decrease as the lubricant pressure increases. The CoF is reduced by 30.6% at a lubricant pressure of 12 MPa. The superiority of forced lubrication is verified through experiments and simulations, which provides a certain reference for practical production.

**Keywords:** deep drawing; forced lubrication; forming performance; friction coefficient

## 1 INTRODUCTION

Facing the severe situation of the greenhouse effect, reducing global greenhouse gas emissions will remain one of the most important projects for cooperation among governments in the coming decades [1]. Manufacturing is an energy-intensive industry, driven by energy-saving and emission reduction policies and the background of green manufacturing industry, there is huge room for improvement in energy consumption and material utilization [2]. In sheet metal forming, energy consumption is mainly to resist plastic deformation resistance, but friction consumption is also a part that cannot be ignored. In addition, friction and lubrication are extremely critical process parameters in the forming process, which affect strain distribution, forming load and die life [3].

In the traditional sheet metal forming process, lubricants are often applied to reduce die wear and avoid part damage, including mineral oil, lubricating oil or solid lubricants [4-7]. With the innovation of product design concept and environmental awareness, the development of high-performance and environmentally friendly lubricating media has become a trend [8]. Environmentally friendly lubricants generally replace mineral oil with water or vegetable oil, and additives are added to make up for the lack of lubricating performance, including corrosion inhibitors, antioxidants, dispersing viscosity modifiers, extreme pressure agents, extreme pressure agents or viscosity modifiers [9]. Graphite, chalk, talc, molybdenum disulfide and nonferrous metal powder are the most commonly used additives [11-12]. In addition, the influence of the type and concentration of additives on the lubrication performance has also been widely quantitatively evaluated, which provides an important reference value for practical production [13-15].

In the past decade, with the advancement of processing technology and a number of innovative results on the friction mechanism, improving the lubricity of the lubricating medium was not the only way to improve the lubrication effect. Non-lubricating friction has become a new research hotspot [16]. Dong et al. [17] applied novel complex-structured composite coatings, NC/NiBN and NC/WC:C to the hot forming die to reduce the use of lubricant. The experimental results showed that the CoF was significantly reduced at high temperatures. Through experimental and numerical analysis, Sulaiman et al. [18] demonstrated that DLC/TiAlN coatings had high wear resistance under dry friction and film lubrication conditions, thus reducing friction and forming load. However, these process methods are limited by processing cost and processing technology, and are rarely reported in large-scale industrial production, while they are widely used in the field of microforming [19, 20].

In the process of sheet metal deep drawing, the metal in the flange area shrinks circumferentially under the action of compressive stress, which is prone to wrinkling and instability, and the lubrication conditions are very complex and difficult. This paper proposes a forced lubrication process for deep drawing, using an external hydraulic station to inject high-pressure lubricant into the flange area to improve the lubrication performance of the friction surfaces. The superiority of this process was verified by forced lubrication deep drawing tests. Finally, the CoFs under the forced lubrication condition were evaluated quantitatively by the FE inverse method.

## 2 THE PRINCIPLE OF FORCED LUBRICATION DEEP DRAWING PROCESS

During deep drawing, the metal in the flange area flows to the center of the female die with the movement of the punch, and the sheet metal shrinks circumferentially under the action of compressive stress. When the BHF is not able to resist the bending deformation caused by circumferential shrinkage, or there is a gap between the blank holder and female die, the metal in the flange area will become unstable and wrinkled.

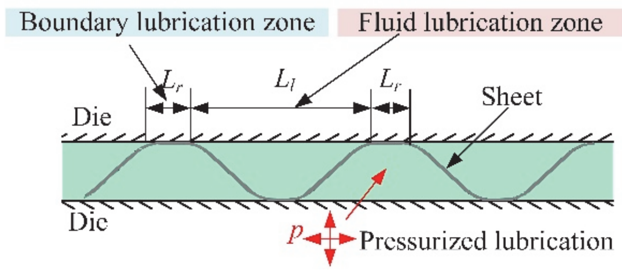



**Figure 1** Lubrication of sheet after wrinkling

As shown in Fig. 1, the lubricant film is easily cut off by folds and squeezed away, resulting in lubrication failure. The excessive BHF is also easy to squeeze the lubricant out of the contact gap, causing rigid friction between the sheet and the mold, affecting the forming quality and the life of the mold. The friction in the flange area is the most serious in the whole forming process.

A forced lubrication process proposed in this paper is to inject high-pressure lubricant into the contact gap employing an external hydraulic pump and maintain a stable pressure. After pressurization, it can effectively reduce the potential adverse factors of the lubricant being squeezed out by wrinkles or excessive BHF, invade the "lubrication dead zone" and reduce the real contact area. As shown in Fig. 1, the percentage of fluid lubrication area is increased by applying forced lubrication. Under the control of the hydraulic valves, a hydrostatic oil film with stable pressure is formed in the contact gap. The oil supply system is composed of hydraulic pump, check valve, reversing valve, relief valve and pressure gauge; the pressure can be measured, controlled and adjusted in real time according to the process demand during deep drawing. The process principle is shown in Fig. 2.

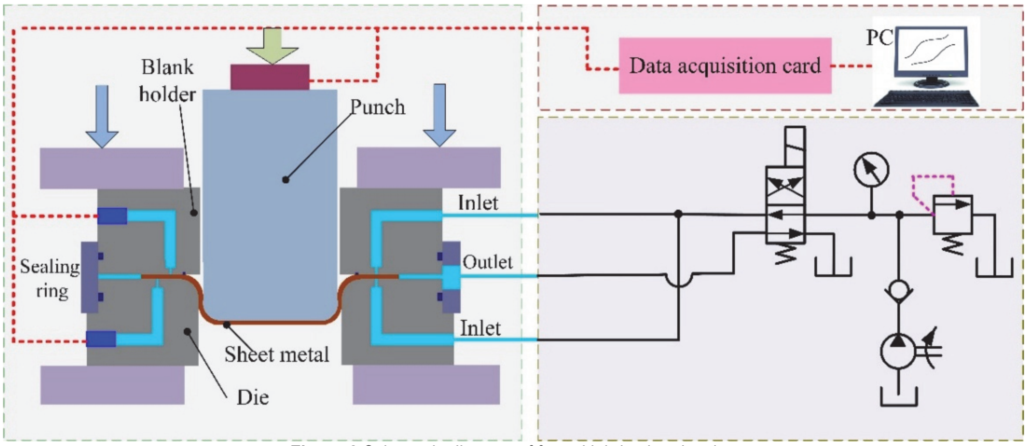



**Figure 2** Schematic diagram of forced lubrication drawing

Under the action of the sealing ring and O-rings, a closed oil cavity is formed in the gap between the blank holder and female die to establish a hydrostatic oil film. In the process of deep drawing, the hydraulic valves and hydraulic press can be coordinated and controlled according to the process requirements. The press stroke, forming force and oil pressure can be monitored in real time and output through the acquisition system. The lubrication scheme has the advantages of low cost, simple operation and easy automatic control.

## 3 FORCED LUBRICATION DEEP DRAWING EXPERIMENTS

### 3.1 Material

The 0.8 mm thick SPCC (Japanese Standard (JIS) steel name for "General Purpose Cold Rolled Carbon Steel Sheet and Strip") cold rolled sheet produced in China is selected for the tests, and its chemical composition is shown in Tab. 1. SPCC has good stamping and welding performance, widely used in automotive manufacturing, electrical instruments, household appliances.

As shown in Fig. 3, the true stress-strain curves of the specimens at 0°, 45° and 90° to the rolling direction at a strain rate of 0.004 $s^{-1}$ were obtained employing an Inspekt Table 100 kN electronic universal material testing machine. The length of the tensile specimen is 180 mm, the gauge length is 50 mm, and the width of the deformation zone is 20 mm. Through the tests, it is found that the anisotropy of the material in three directions is not obvious. Therefore, the isotropy is assumed in the later numerical simulation.

**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 |

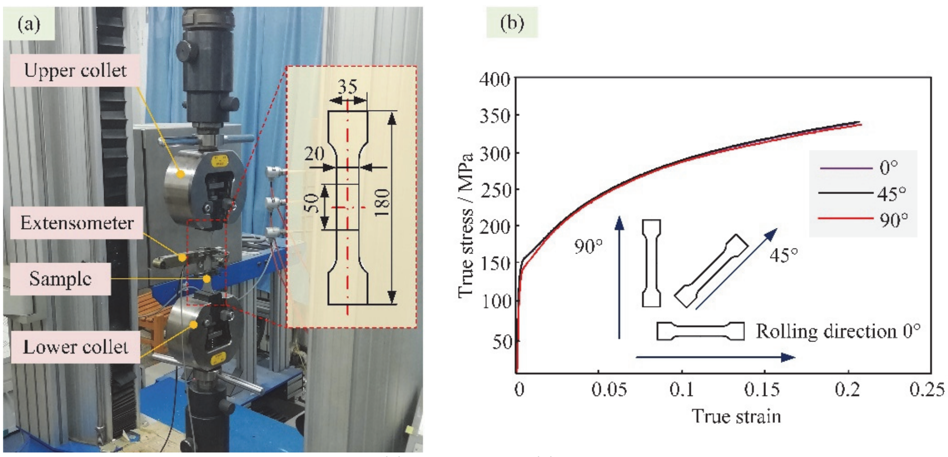


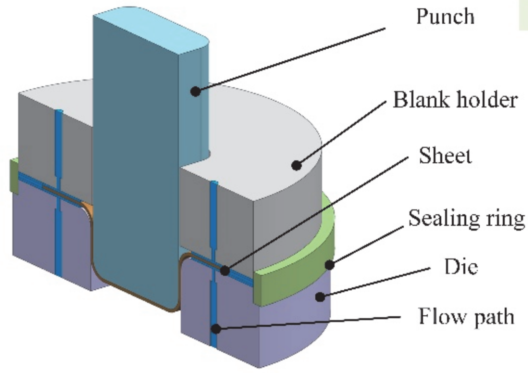

**Figure 3** Tensile tests (a) Test equipment (b) True stress-strain curves

### 3.2 Experimental Procedures

According to the concept of forced lubrication drawing process, the forced lubrication drawing dies for box-shaped parts were designed as shown in Fig. 4, and the specific dimensions are shown in Fig. 4b. The dies for forced lubrication deep drawing can be modified from the dies for the traditional process, and the sealing device is added compared with the traditional process. There are multiple sets of O-rings on the mating surface of the sealing ring and the dies to ensure the tightness. In the process of metal flow, severe friction occurs between the metal, blank holder and the female die. Hence, double-sided lubrication was adopted in this paper, the runners with the same size were machined at the corresponding positions of the blank holder and the female die in the flange area to ensure consistent lubrication conditions above and below the sheet.

As shown in Fig. 5, multiple oil inlet holes were machined in the circumferential direction of the dies to ensure sufficient lubricant on the entire contact surface and fast response time. All oil inlet holes were synchronously controlled by hydraulic valves. Moreover, oil pressure monitoring holes were machined to monitor the pressure inside the die in real time through sensors, forming a closed-loop control system with the hydraulic control valves.

(a)




(b)

| Project | Size (mm) |
|---|---|
| Punch(Length × Width × Height) | 80×60×200 |
| Fillet radius of punch | 10 |
| Corner radius of punch | 13 |
| Die (Length × Width) | 82.6×62.6 |
| Fillet radius of die | 10 |
| Corner radius of die | 14.5 |

**Figure 4** The dies for forced lubrication drawing (a) Schematic diagram of dies (b) Sizes

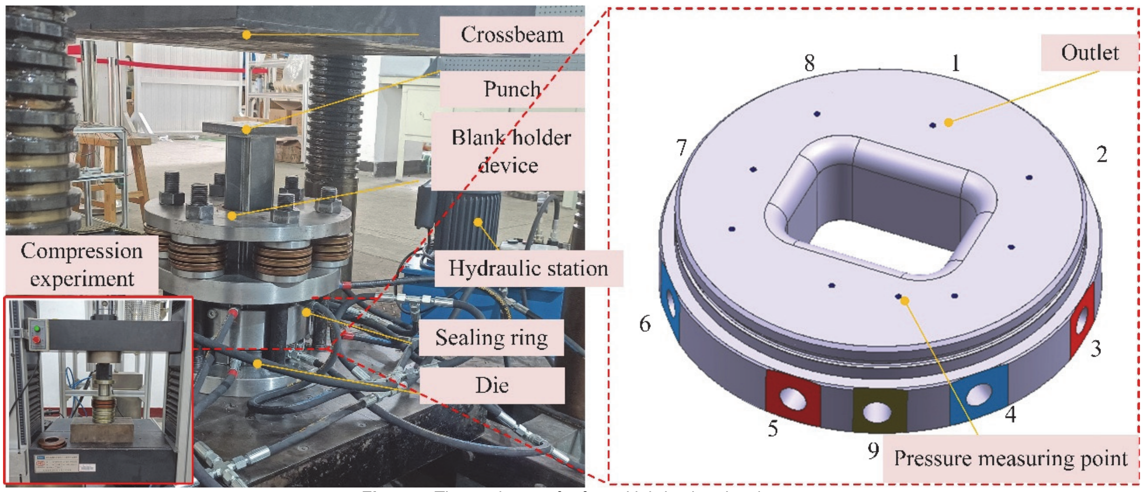



**Figure 5** The equipment for forced lubrication drawing

The drawing experiments were carried out on a 500 T hydraulic press with a drawing speed of 30 mm/min, the test equipment is shown in Fig. 5. A kind of water-based mineral oil produced in China was selected as the lubricant, with a dynamic viscosity of 112 $m^2/s$. The oil supply power system is a small hydraulic station with a maximum output pressure of 20 MPa. The hydraulic station is equipped with an integrated valve group, including check valves, reversing valves, and relief valves. During the forming process, the force, displacement and oil pressure were collected by the data collector, and displayed on the control software interface. During the tests, the BHF was provided by three sets of standard butterfly springs, and the required BHF was obtained based on precise measurement of the spring compression. Before the drawing experiment, a stiffness test experiment was conducted on each spring utilizing a compression testing machine. As shown in Fig. 5, several repetitive compression experiments were carried out on the selected disc springs within the range of 75% of the nominal compression. The test results show that the force range curve obeys a linear relationship within 75% of the nominal compression of the spring, which is considered to have been deformed within the range of elastic deformation. The spring stiffness coefficients when used in pairs and stacked combinations were calibrated, respectively. However, the force provided by the spring is not the BHF that the sheet actually bears, and the reaction force of oil needs to be subtracted. According to the formula for calculating the minimum unit BHF proposed by Fukui and Yoshida [21], the BHF was set to 35 kN for the blank shown in Fig. 6. In order to evaluate the effectiveness and superiority of the forced lubrication process, forced lubrication drawing tests were conducted at no-pressure, 3 MPa, 5 MPa, 9 MPa and 12 MPa, respectively.

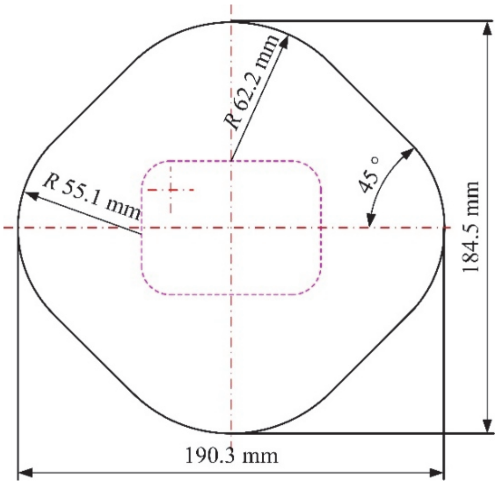



**Figure 6** Blank shape

## 4 REVERSE CALCULATION OF COFS

The value of CoF is the most intuitive criterion for evaluating the lubrication performance. In the sheet forming process, the contact relationship between the sheet and die is very complex, and the CoF is difficult to determine directly, so the utilization of FE inverse method to obtain the average CoF has become one of the common research means in the industry [22]. FE simulation analysis saves a great deal of financial and material resources and time costs for industrial production, and provides an important reference value for actual production. The change of forming force is one of the most significant signs to reflect the lubrication state. In the present paper, the average CoFs in the flange area under different lubrication conditions were estimated by adjusting the values of CoFs to match the force curve by using the FE inverse method. The solution flow chart is shown in Fig. 7.

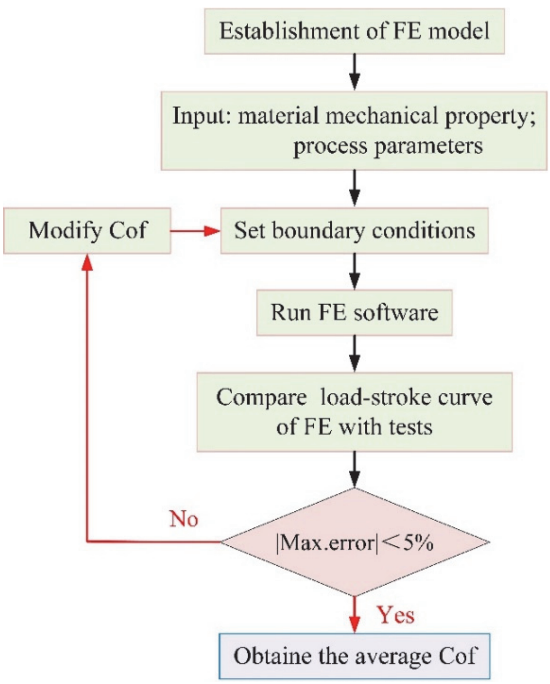



**Figure 7** The solution flow chart of CoF

In this paper, ABAQUS FE simulation software was used for the numerical simulation of the process. In order to save calculation time, the dies were set as discrete rigid bodies, the sheet was set up as a deformer. The sheet cell S4R element was employed for the sheet. To save computational time, the finite element model was set as a quarter model. The contact relationship between the mold and the plate adopted surface to surface contact, and the contact rule followed the penalty function principle. The friction model was set to Coulomb's law of friction. The mechanical index of the material required for the numerical simulation was obtained though tests and the Miss isotropic yield criterion was adopted. The geometry of the dies and the shape of the blank were consistent with the experiment.

## 5 RESULTS AND DISCUSSION

### 5.1 Effect of Forced Lubrication on Forming Force

The forming force in deep drawing is mainly composed of deformation resistance and friction resistance. The smaller the forming force under the same degree of deformation means less friction resistance and better lubrication. Fig. 8 shows the forming force-stroke curves at different lubricant pressure conditions during forced lubrication deep drawing tests.

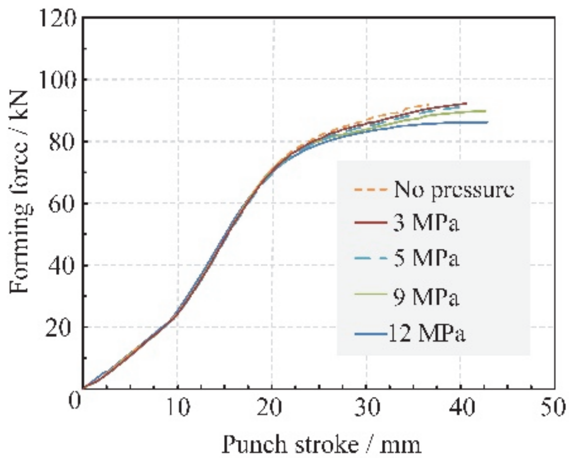



**Figure 8** The forming force-stroke curves at different lubricant pressures

As can be seen from Fig. 8, the pressurized lubricant significantly improves the lubrication effect, especially in the second half of the deep drawing process where the forming force decreases significantly. In the initial stage of deep drawing, the deformation is small, wrinkling is not obvious, and the influence of different lubrication conditions on the forming force is not significant. With the process of deep drawing, wrinkling becomes more serious and friction become more severe, highlighting that better lubrication conditions can reduce forming forces. When the punch stroke is greater than 20 mm, the forming force tends to decrease as the lubricant pressure increases, demonstrating the technical advantages of forced lubrication.

### 5.2 Effect of Forced Lubrication on Forming Height

The drawing performance of box-shaped parts cannot be evaluated by the drawing ratio, and the forming height is adopted in this paper to compare and analyze. The larger the forming height, the better the lubrication effect.

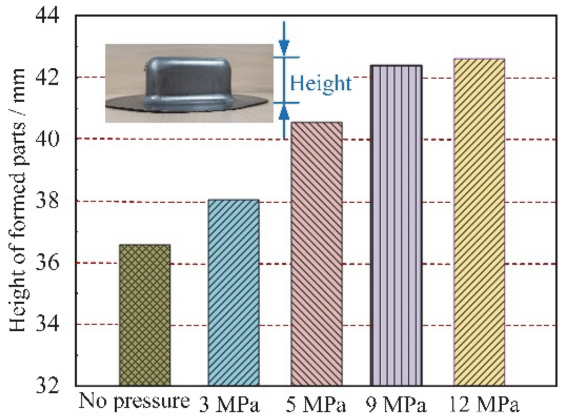



**Figure 9** The forming height of at different lubricant pressures

Fig. 9 shows the forming height of the formed parts at different pressurization pressures, indicating that the forming limit of the sheet is significantly improved when the lubricating oil is pressurized. When the pressure is 3 MPa, the increase of the forming height is not obvious, which is 3.8%. while the pressure is 9 MPa, the forming height increases by 15.8%. Continue to increase the pressure, the molding height growth rate decreases, which demonstrates that when the pressure increases to a certain value, and then continues to increase the pressure, the improvement degree of lubrication effect is no longer obvious.

### 5.3 Effect of Forced Lubrication on CoF

The CoF during sheet forming is affected by various factors such as the mechanical properties of the material and the parameters of the drawing process, and it is difficult to accurately measure the value of the CoF. The present paper adopted the method of combining FE simulations and tests, comparing the force-stroke curves obtained by FE calculations with the curves obtained by tests. The average Coulomb's CoFs under different process conditions were determined by continuously correcting the CoFs in FE simulations until the errors between the simulation results and the test results were less than 5%. The lubrication effect of forced lubrication was analyzed qualitatively and quantitatively by FE inverse method. According to the calculation flow chart in Fig. 7, the CoFs under different process conditions are fitted, as shown in Fig. 10.

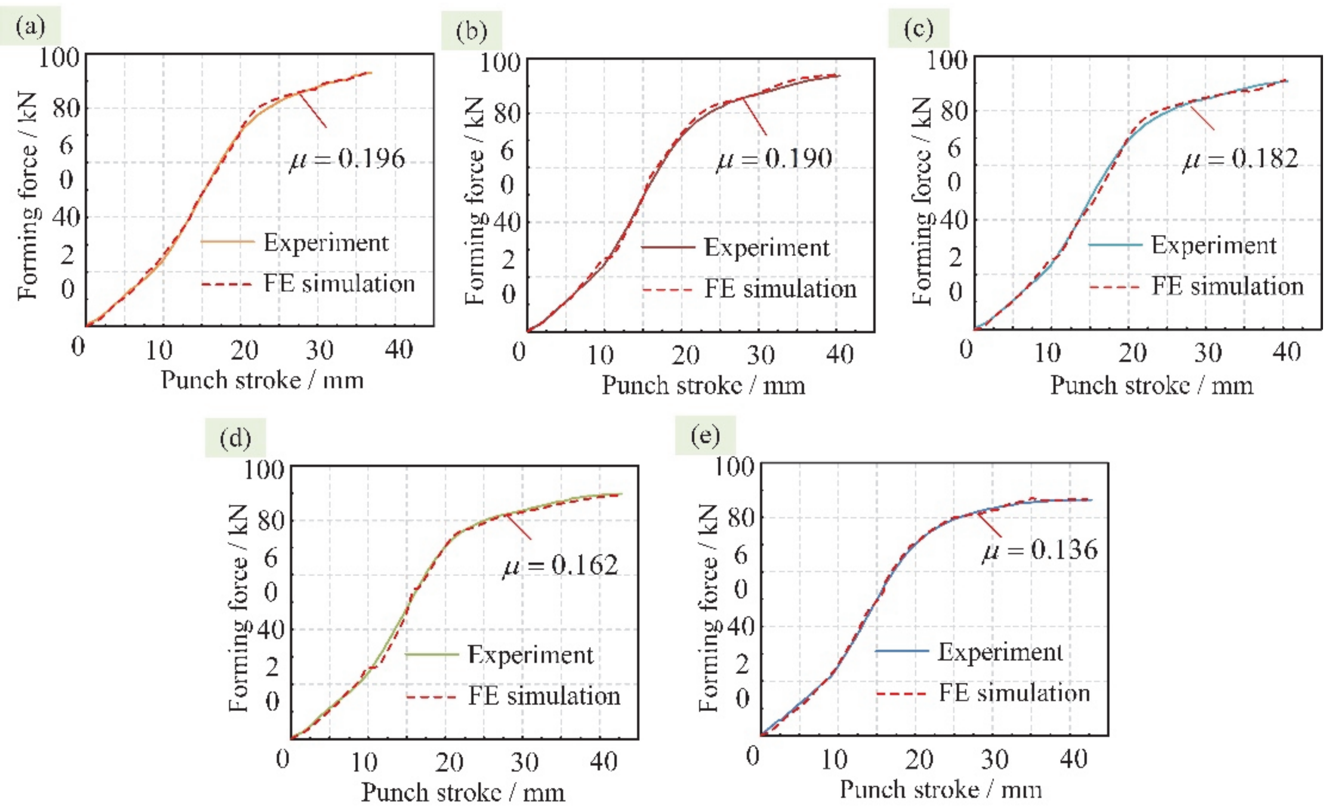



**Figure 10** The CoFs at different lubricant pressures (a) No pressure (b) 3 MPa (c) 5 MPa (d) 9 MPa (e) 12 MPa

It can be seen from Fig. 10 that the CoFs tend to decrease after the lubricant is pressurized. In particular, when the lubricant is pressurized to 9 MPa and 12 MPa, the CoFs decrease to a greater extent, which are 17.3%, 30.6% lower than those without pressurization respectively. The positive effect of forced lubrication on reducing the friction coefficient is verified by quantitatively estimating the CoFs under different pressure conditions.

## 6 CONCLUSION

(1) In order to improve the poor friction conditions in the flange area during deep drawing, a forced lubrication process utilizing an external oil source to pressurize is proposed. The structure of the dies is simple, only need to machine the flow channel and add the sealing device on the traditional dies. The lubrication pressurization system can

be interconnected and controlled with the hydraulic press to facilitate automatic control.

(2) The effect of forced lubrication was evaluated by forced lubrication deep drawing tests. The results show that the lubrication effect is significantly improved by the pressurized lubricant, the forming force decreases with the increase of pressure, and the height of the formed parts can increase with the increase of pressure. The average CoFs under different lubrication conditions were determined by the FE inverse method, and the CoF is reduced by 30.6% at a lubricant pressure of 12 MPa.

## Acknowledgment

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