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ORIGINAL ARTICLE

Drawability and frictional behavior of pure molybdenum sheet in deep-drawing process at elevated temperature

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Abstract Forming of pure molybdenum crucible is greatly demanded for its broad application in production of single crystal sapphire. To fabricate molybdenum crucible and other sheet metal products of molybdenum, it is necessary to determine the limiting draw ratio and frictional data with the aid of finite element analysis to reduce the massive experiments. To ensure the accuracy of finite element analysis, it is crucial to determine the reproducible frictional data. In this study, an evaluation methodology combined hot deep-drawing test with numerical simulation used to investigate the formability and tribological behavior of pure molybdenum at elevated temperature. For calculation of friction coefficient, the isothermal deep-drawing tests were carried out at the temperature ranging from 993 to 1143 K under lubricated and dry conditions. According to the predicted relation between frictional coefficient and forming temperature, the influences of forming temperature, lubrication, and blank diameter on friction are discussed, and the limiting draw ratios of molybdenum sheet at various temperatures are obtained. It is found that there is a significant improvement in drawability of pure molybdenum from 1.2 at room temperature to 1.98 at 1143 K by using boron nitride lubricant. However, the effect of forming temperature on the formability of molybdenum sheet is not significant under dry friction condition. Compared with the experimental results, the method used for evaluation of the formability and friction characteristic in hot deep drawing of molybdenum sheet is verified efficiently.

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1 Introduction

Molybdenum (Mo) has been widely used in many high-temperature engineering scenarios. However, its poor formability and weak oxidation resistance greatly limit its application [1–3]. Fortunately, the formability of Mo sheet can be improved by the increase of forming temperature before or during forming process. Hot deep drawing is an effective technology for manufacture of Mo thin-wall components, which involves a great deal of sliding between sheet metal and forming tooling. Limiting draw ratio (LDR), as an effective indicator of sheet metal formability, is defined as the ratio of the maximum blank diameter, which can be safely drawn into the die without flange, to the punch diameter. The value of LDR is a fundamental for process determination and die design. Nevertheless, the determination of LDR of Mo sheet at elevated temperature is a very costly and nontrivial issue, which heavily relies on experiments and has to be performed in vacuum or inert gas protection environment. In addition, the value of LDR is affected by frictional condition between the workpiece and forming tooling at different forming temperatures. Accurate analysis thus needs to be done to determine the optimal combination of lubricant and temperature conditions. Meanwhile, the sliding in deep-drawing process results in the friction between the tools and sheet metal material, and this friction in turn influences the forming process behavior as performed. During the deep-drawing operation, the magnitude and distribution of friction affect material flow, dimension accuracy, product quality, tool wear, and production cost. In finite element (FE) analysis, it is very important to determine the reliable friction data for a specific lubrication system. The drawability of pure molybdenum is closely related to frictional characteristic, and the evolution of tribological condition in the contact zones between the sheet metal surface and tooling is significant for understanding of the friction phenomenon and accurate simulation to predict the formability of Mo sheet at high temperature.

The deep-drawing process involves various types of contacts between sheet metal and tools, and various testing models for evaluation of friction behavior are developed, including flat-drawing test [4], strip deep-drawing test [5], radial strip-drawing test [6], and strip stretching test [7], as illustrated in Fig. 1. It is noticed that the frictions in deep-drawing operation consist of the sliding along flat surface and the radius of die. Different simulation tests correspond to various contact types, and all the tests shown can be simply categorized to two types, namely a radial strip drawing with different boundary conditions and a flat-drawing simulator. However, when the deep-drawing process is conducted at high temperature and vacuum environment, the prediction of friction gets complicated due to the change of coefficient of friction with temperature. The tests mentioned above cannot be easily transferred to high-temperature circumstance, especially for vacuum environment prepared for oxidizable materials.

For hot forming of sheet metals, two methods are usually used to evaluate tribological phenomena, viz., hot flat-drawing test and cup-drawing test. In this respect, Yanagida et al. [8–10] developed a new hot flat strip-drawing test machine for measurement of the friction coefficient and obtained the friction coefficient continuously to examine the functions of the proposed test machine at elevated temperature. Then, they conducted a series of research on the measurement of friction coefficient of aluminum-coated high-strength steel in hot stamping process under dry as well as lubricated conditions for various surface roughness of the die. Kondratiuk and Kuhn [11] gained the coefficients of friction under the realistic conditions using the hot strip-drawing experiment. Due to the poor temperature control in hot strip-drawing test, the hot deep-drawing test was proposed to simulate the types of contacts between the steel sheet and tooling. Geiger et al. [12] presented a combined

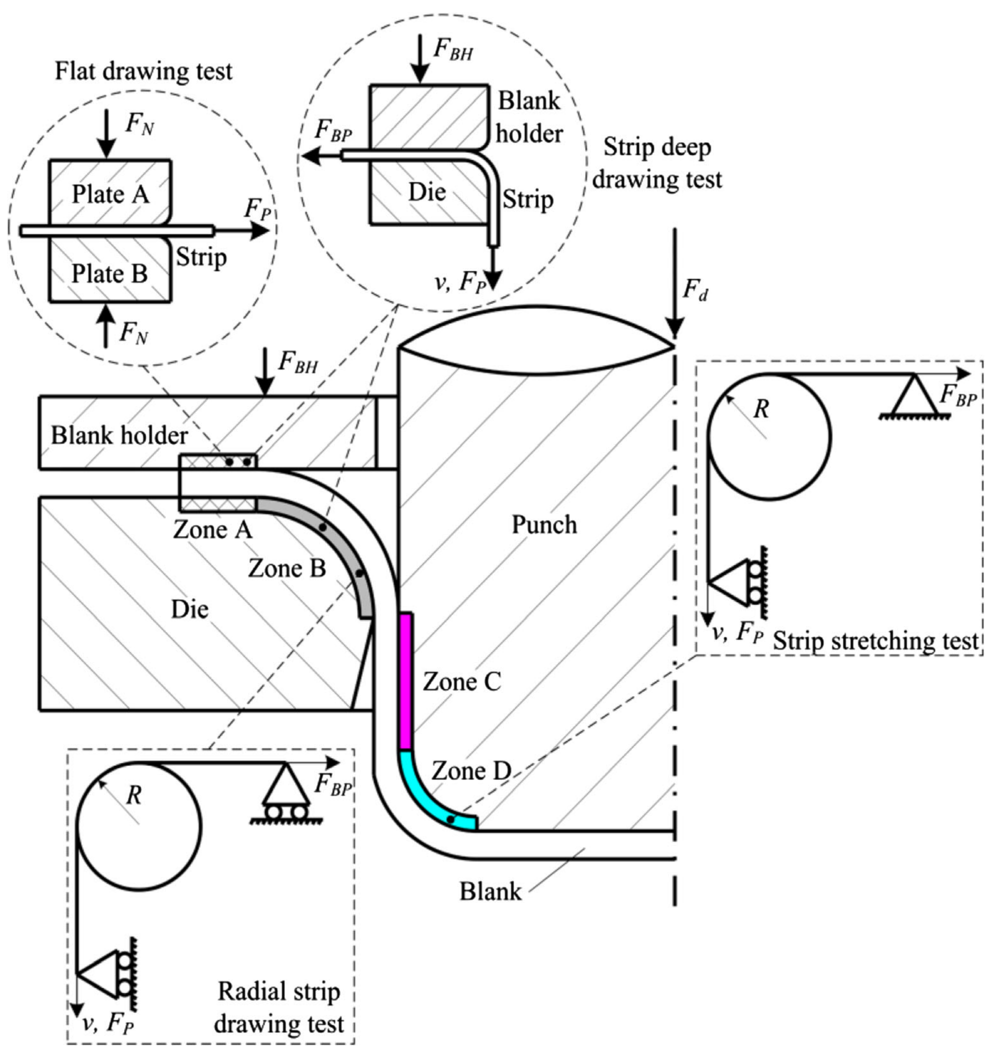

Fig. 1 Friction zones and corresponding tribological models in deep-drawing process

experimental-analytical-numerical evaluation method for determination of the friction coefficient by using a modified cup deep-drawing test and the modeling of the maximum drawing force of Siebel. In addition, Grüner et al. [13] introduced the geometrical conditions into the Siebel's formula for special cases of deep-drawing process to improve the prediction accuracy in determination of friction coefficients.

Due to the great difficulty in direct determination of friction, the method of using inverse calculation approach combined with numerical analysis had been widely used. Lin et al. [14, 15] employed the thermo-elastic-plastic FE method and the Levenberg-Marguardt approach to determine the friction coefficient in warm upsetting process of Mo under a known loading history. They compared the result with the other studies to confirm the feasibility of the proposed inverse calculation method. In addition, Ramezani et al. [16] investigated the friction behavior of tool/workpiece contact in metal forming processes based on the newly developed dry friction model, which was compared with the Coulomb friction law in simulation of V-bending process.

Currently, different methods for evaluation of friction coefficient had been proposed based on hot strip-drawing test [8–11], modified cup-drawing test [12, 13], and theoretical estimation [14–16] in hot stamping process, and the frictional behavior and formability during the isothermal forming of materials with poor antioxidant properties have not been extensively studied. Regarding the drawability and friction in the isothermal forming of pure Mo sheet, extensive research needs to be done. This paper presents an inverse comparison approach for evaluation of friction between the molybdenum workpiece and the tool at the elevated temperature. Meanwhile, the LDRs of the sheet metal under lubricated and dry friction conditions are determined at different forming temperatures varying from 993 to 1143 K. Experimental and simulation results are presented with respect to the relation between the friction at die/workpiece interface and the drawing force, as well as the influences of temperature and lubrication on the formability of the Mo sheet.

2 Material and research methodology

2.1 Experimental material

The pure molybdenum (Mo1) with the thickness of 2.0 mm was used in this study, which has poor anti-oxidation at high temperature and low plasticity at room temperature. The used molybdenum sheet metal was annealed after hot rolling to reduce residual stress. According to the previous literature [17], the plastic deformation behavior of the molybdenum plate is presented in Fig. 2 under five different forming temperatures (293, 993, 1043, 1093, and 1143 K) and the constant strain rate (0.02 s^{-1}). It can be observed that the elongation of pure molybdenum sheet at room temperature is only 6 %, and the plasticity increases with the forming temperature.

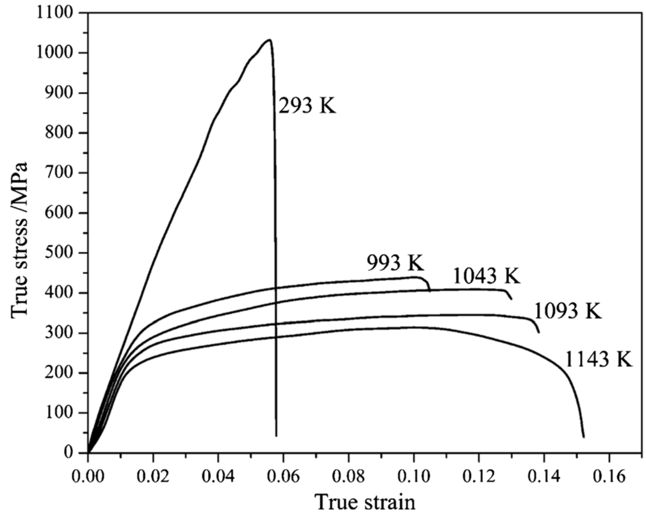

Fig. 2 True stress-strain curves of pure molybdenum under different temperatures

2.2 Research methodology

Figure 3 shows the vacuum hot deep-drawing operation for molybdenum sheet. In the figure, μ is the friction coefficient in the area between the die rounding and the sheet metal. d_p is the punch diameter. α is the wrap angle between the blank and die radius. r_d is the die corner radius. δ is the defined gap between the blank holder and the die. F_{BH} is the blank holding force (BHF). F_d is the drawing force. In deep-drawing process, the metal flow and the total deformation load are affected by the frictional condition at the interface between the die and the workpiece. According to the analytical model developed by Siebel et al. [18], the

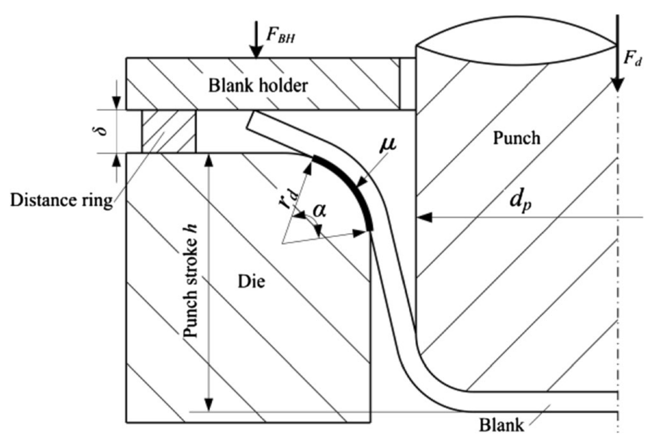

Fig. 3 Schematic illustration of hot deep-drawing process

maximum drawing force ($F_{d,\max}$) in deep-drawing process can be represented as follows:

$$F_{d,\max} = \pi d_m t_0 \left[e^{\mu\alpha} \left(1.1\sigma_{fm1} \ln\frac{d_{F,\max}}{d_m} + \frac{(\mu_1+\mu_2)F_{BH}}{\pi d_{F,\max} t_0} \right) + \sigma_{fm2}\frac{t_0}{2r_d} \right] \quad (1)$$

where t_0 is the initial blank thickness, d_m is the mean diameter of the cup wall and equals to (d_p+t_0), $d_{F,\max}$ is the outer diameter of the flange at the maximum drawing force $F_{d,\max}$, σ_{fm1} and σ_{fm2} are the mean flow stresses at the flange and die corner regions, respectively. μ_1 and μ_2 are the friction coefficients at the flange between the blank and die/blank holder, which can be determined by hot flat-drawing test. In hot-forming process, a distance ring with the thickness δ is often utilized to omit the BHF, which can avoid the issues including the high friction and low limit of BHF at elevated temperature. In this case, the friction coefficients including μ_1 and μ_2 are considered negligible. Meanwhile, the wrinkling of the part flange can be avoided by the defined gap. It is observed from Eq. (1) that the maximum drawing force gives a particular knowledge about the coefficient of friction. Generally, the drawing force is influenced solely by the tribological condition when the material, tooling, and process parameter configuration are fixed. According to this relationship, the friction coefficient of pure molybdenum sheet at high temperature can be calculated via selection of the appropriate graph obtained by FE simulation that fits well with the experimental force stroke data.

Figure 4 illustrates the methodology to evaluate the frictional condition for pure molybdenum sheet at the elevated temperature. In the figure, the flow stress-strain relations are obtained via the uniaxial hot tensile tests. To achieve the actual drawing force curves in dependence of punch stroke, the modified cup-drawing tests are implemented in vacuum environment. Secondly, it goes to FE simulation stage. In this stage, the meshing of the tooling and blank is conducted, and the boundary condition is established. Then, the coefficient of friction can be extracted from the comparison of drawing force curves generated by FE simulation and actual experiment under the same forming condition. The initial value and the increment of friction coefficient in FE simulation can be adjusted according to the previous calculated results, which determine the computation precision and the total computing time. Finally, the values of LDR at various forming temperatures can be determined by FE simulation using the relationship between friction coefficients and forming temperatures under different lubricated conditions.

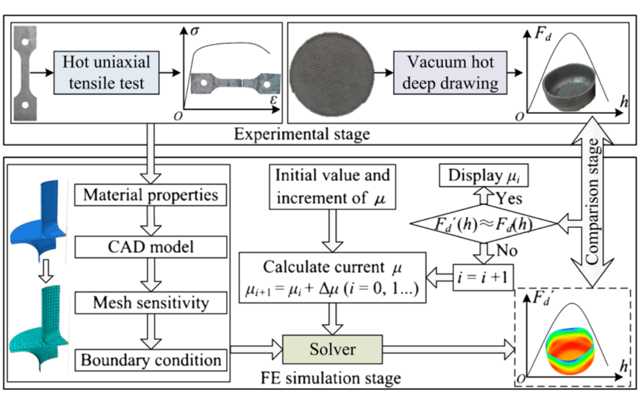

Fig. 4 Computation flow chart for determining friction coefficient

3 Experiment and numerical simulation

3.1 Hot deep-drawing test in vacuum environment

To simulate the frictional behavior in the hot deep drawing of Mo sheet, the hot deep drawing of the sheet was conducted on a special hot-drawing press type BCS-50AR equipped with vacuum environment [19]. The test machine offers three thermocouples to measure the temperatures of blank, die, and blank holder, respectively, to ensure the temperature control precision with ±5 K. Prior to the hot drawing, the air was pumped out to make a perfect vacuum of 10^{-2} Pa. Then, the specimen and tools were heated to the forming temperature and maintained for 15 min to ensure the homogeneity of temperature distribution. For precise measurement of the temperature of the blank, the retractable temperature measuring device was utilized, which dropped to contact the blank during heating process and returned back automatically when the blank and tools were heated to the forming temperature.

The die set and experimental samples are shown in Fig. 5. The punch and die diameters are 50 and 55.2 mm, and the radii of punch and die corner are 8 and 18.6 mm, respectively.

Fig. 5 Test device for vacuum hot deep drawing of pure molybdenum sheet

The die was fabricated with the high-temperature stainless steel of Cr25Ni20. The gap between blank holder and die is maintained at 2.5 mm. In addition, the punch stroke and drawing force were continuously recorded during the cup-drawing test. In particular, all the tests were performed with a constant punch velocity of 30 mm/min, corresponding to the strain rate of 0.02 s^{-1} during the uniaxial tensile test. The experimental parameters including blank diameter (d_0), drawing speed (v), forming temperature (T), vacuum degree, and lubrication are listed in Table 1. In the table, experiments from nos. 1 to 6 were performed to study the influences of temperature and lubricant on frictional behavior. The high-temperature lubricant employed in this study is hexagonal boron nitride (HBN) aerosol characterized with the low coefficient of friction and oxidation resistance at high forming temperature (up to approximate 1173 K). The lubricant is naturally white, which consists of HBN and refractory binders, and exhibits an excellent adhesive property. After the solvent evaporates, the lubricant cures at room temperature to form a solid film coating. When the lubricant coating with the thickness between 15 and 30 μm is subjected to pressure, the texture of this coating becomes compressed and creates an extremely shiny and smooth film surface. In addition, the lubricant generates an effective separating layer between the tool and the surface of sheet metal and thus acts against the adhesion forces to prevent the bonding between the sheet metal and tooling. Because of the serious wear of tools induced by the permeation as the blank sliding through the die surface under dry condition, the experiments without lubricant were conducted only at the temperature of 1043 and 1093 K, and the blank diameter was designed with 91 mm to reduce the wear. The tests of nos. 4, 7, and 8 were employed to analyze the effect of initial blank diameter d_0 on friction behavior. During the process, when the temperature and vacuum condition reached the experimental requirements and remained for a soaking time, the blank holder and punch started to move sequentially until the full cup was drawn or the fracture appeared. Simultaneously, the relations of drawing force with respect to punch stroke were recorded automatically, as shown in Fig. 6. It can be observed that the drawing force curves exhibit two states. First, the drawing force increases to the maximum value with punch stroke and then decreases smoothly until the force decreases to zero, which indicates that the full cup is drawn without rupture. Secondly, the drawing force represents a sharp decline before the occurrence of the peak force, demonstrating that the fracture occurs.

Table 1 Experimental conditions for hot deep drawing of the molybdenum sheet

Number	d_0 (mm)	v (mm/min)	T (K)	Vacuum (Pa)	Lubrication
1	95.0	30.0	993	10^{-2}	HBN lubricant
2	95.0	30.0	1043	10^{-2}	HBN lubricant
3	95.0	30.0	1093	10^{-2}	HBN lubricant
4	95.0	30.0	1143	10^{-2}	HBN lubricant
5	91.0	30.0	1043	10^{-2}	Dry lubricant
6	91.0	30.0	1093	10^{-2}	Dry lubricant
7	97.0	30.0	1143	10^{-2}	HBN lubricant
8	100.0	30.0	1143	10^{-2}	HBN lubricant

3.2 Numerical implementation

In this research, FE simulation was conducted using software ABAQUS. The die geometry was created based on the actual testing conditions. A quarter model was established to enhance the computation efficiency based on the symmetrical characteristic of the forming system. The four-node linear quadrilateral element S4R mesh was employed. In addition, the true stress-strain relation was generated and input into the system according to the measured data shown in Fig. 2. The yield criterion Hill 48 material law was applied with the isotropic hardening definition. The standard Coulomb's law states that the shear stress due to friction is proportional to the normal stress. However, this model results in a discontinuous shear stress and deflection relationship, which would result in nonconvergence in numerical simulation. Instead, the modified Coulomb friction model with a constant coefficient was used to describe the frictional condition at the tool/workpiece interface, where the friction is induced by the mechanical interaction between the asperities of contacting surfaces. In the modified Coulomb model, the transition from a shear stress of $-\mu p$ to $+\mu p$ takes place as a linear variation over the deflection range $-\Delta c$ to $+\Delta c$, as illustrated in Fig. 7. τ is

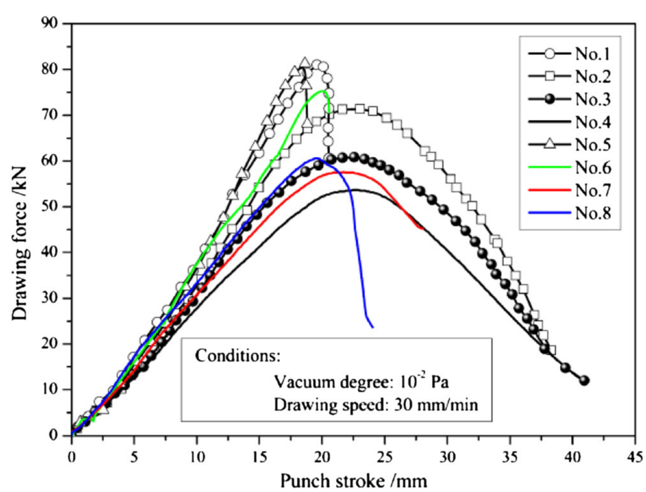

Fig. 6 Experimental curves of drawing force in dependence of punch stroke

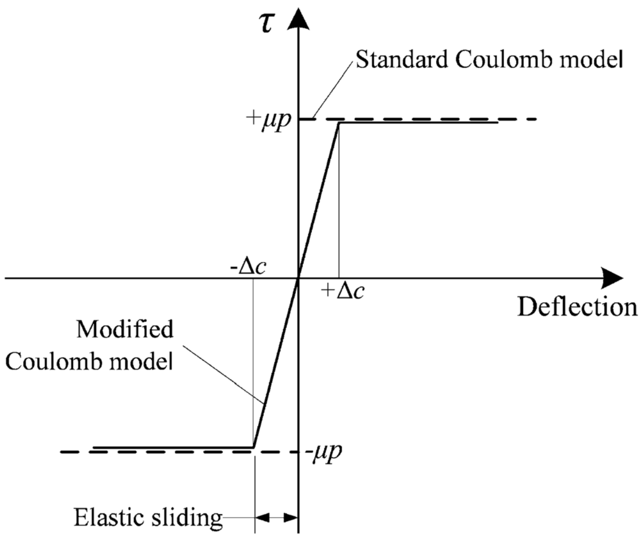

Fig. 7 Difference between the standard Coulomb and the modified Coulomb friction models

the shear stress induced by friction, μ is the friction coefficient, p is the contact pressure, and Δc is the permissible elastic sliding given by

$$\Delta c = \frac{\mu p}{K_s} \quad (2)$$

where K_s is the shear stiffness and a high value of K_s leads to the ramping taking place over a short distance. Since the crystal lattice of HBN lubricant possesses a layered structure consisting of thin parallel planes, which allows the sliding movement of the parallel planes, and results in a low shear stress despite of applying a high contact pressure, however, according to the Coulomb's friction law, the shear stress caused by friction is proportional to the normal stress. When the friction behavior between the solid lubricant surface and the die is simulated, the relationship between the normal stress and frictional stress is not linear, and the Coulomb friction may show a poor approximation. In order to avoid the effect of this nonlinearity, the lubricant coating is not modeled in numerical simulation. Instead, a low friction coefficient is

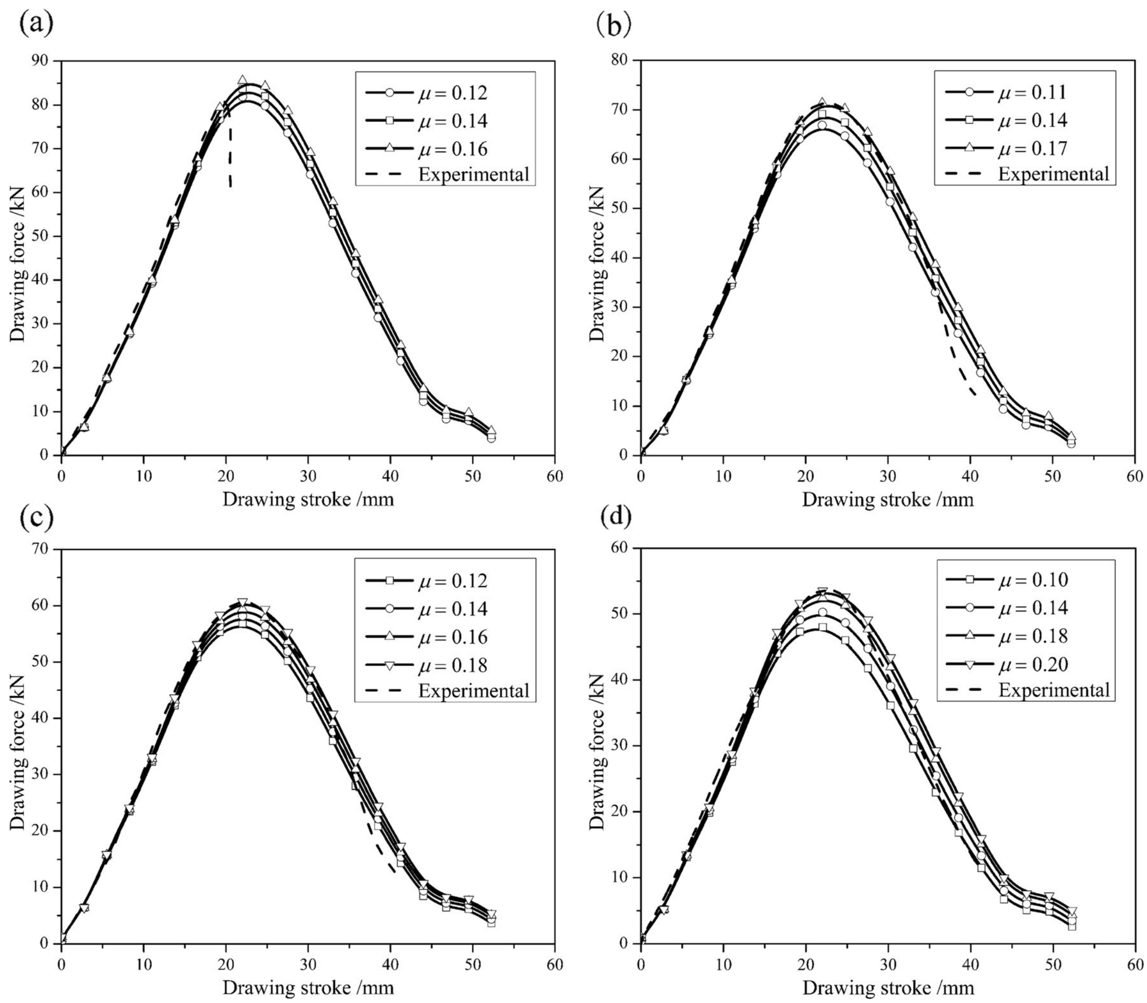

Fig. 8 Comparisons of drawing force curves between simulations and experiments under lubricated condition at temperatures of **a** 993, **b** 1043, **c** 1093, and **d** 1143 K

assumed to characterize the influence of the lubricant. In simulation, Coulomb's law is admissible to simulate the hot deep-drawing process. In order to compare the experimental results with FE simulation, the die parameters and process variables were set to be the same as the experiments except the friction coefficient, which is assumed to have different values. The actual friction coefficient at different temperatures could be confirmed by the simulation result agreeing well with the measured data.

4 Results and discussion

Figure 8 shows the comparison of the drawing force curves generated by simulation and experiment under the boron nitride lubricated condition. It can be seen that the drawing force is controlled by the friction at the die/workpiece interface, and the magnitude and shape of drawing force curve provide a quantitative information about the coefficient of friction at a certain forming temperature. Using the inverse comparison approach, the coefficient of friction at a certain temperature was calculated via matching the force stroke curve measured by experiment with the simulation results. However, there is a divergence with respect to the force stroke curve when the fracture appeared during deep-drawing process at the temperature of 993 K. Different from the experimental curves characterized by a significant drop with fracture, the simulation curves keep on growing and then decrease smoothly. This is because the FE simulation conducted in this research could not determine the occurrence of fracture, and the drawing process continued until the given stroke. Under this kind of situation, the friction coefficient was determined by the drawing force before the occurrence of the rupture.

4.1 Effect of temperature and lubrication on friction

Figure 9 presents the determined friction coefficients under lubricated as well as dry conditions at the temperature ranging from 993 to 1043 K. As expected, the coefficient of friction of pure molybdenum sheet increases with temperature. This well-known relation is attributed to the decrease of yield strength of Mo plate and the increase of surface contact between Mo sheet and tooling at elevated temperature [20]. Further, the coefficient of friction at 1043 K increases from 0.17 under HBN lubricated condition to 0.55 under dry condition. It can be seen that the forming temperature and lubricant are the two major factors affecting the coefficient of friction, and the effect of the latter is more significant. On the other hand, the lubricant is effective

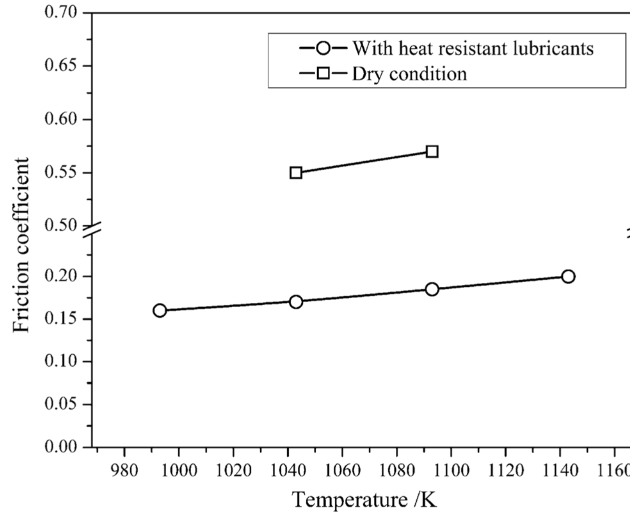

Fig. 9 Relation of friction coefficient in dependence of temperature

for improving formability and decreasing drawing force and tool wear in hot deep-drawing process.

4.2 Effect of initial blank diameter on friction

In order to study the effect of d_0 on the friction coefficient, the hot deep-drawing tests were conducted at the temperature of 1143 K with three different blank diameters. It can be seen from Fig. 6 (Nos. 4, 7 and 8) that the drawing force increases with d_0. The drawing force is characterized by a sharp decline when d_0 equals to 100 mm, which represents the fracture of the drawn cup. According to the abovementioned method, the friction coefficients for different values of d_0 were calculated at the temperature of 1143 K using HBN lubricant, as shown in Fig. 10. It is noticed that friction coefficient increases slightly with the initial blank diameter, demonstrating that the value of d_0 does not have a significant impact on friction. This is because the

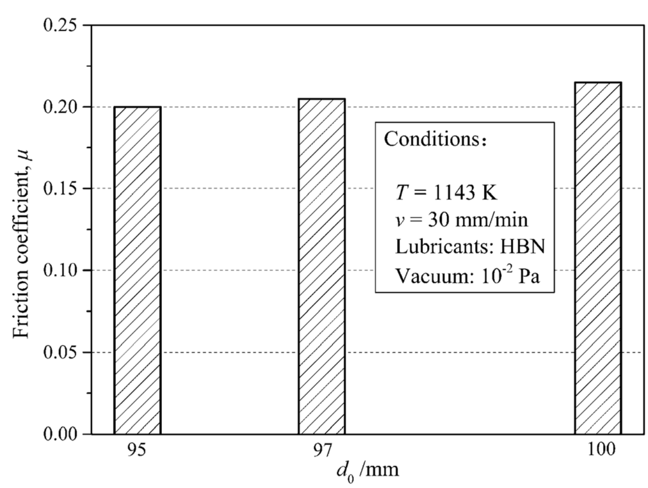

Fig. 10 Effect of initial blank diameter on the friction coefficient

constant clearance between blank holder and die, and the friction mainly occurs in zone B shown in Fig. 1 without considering the effect of BHF. Despite of different blank diameters, the actual contact regions are the same, resulting in the insignificant influence of blank diameter on friction condition. That is why the LDR at a certain temperature can be determined by employing the same frictional coefficient without considering the change of initial blank diameter.

4.3 Drawability at different temperatures

As discussed previously, with the precise frictional data for premise, the values of LDR at different temperatures can be determined by FE analysis. Forming limit curve (FLC) is utilized to detect the plastic instability and forming limit in deep-drawing process, which is the most commonly used failure limit criterion in sheet metal forming. Since FLC determined by experiment is time consuming and costly, the used FLCs at different temperatures in this research are determined by material tensile properties combined with the ductile damage criterion based on the phenomenological model in Paul et al. [21]. The model is constructed with damage accumulation related to the nucleation and growth of microvoids and expressed in the following:

$$\begin{cases} \left[\left(\dfrac{1+\beta+\sqrt{1-\beta+\beta^2}}{2\sqrt{1-\beta+\beta^2}}\right)f(\beta)^8+\left(\dfrac{1+\beta}{2\sqrt{1-\beta+\beta^2}}\right)^{\frac{1}{3n}}\right]C=\overline{\varepsilon}_n \\ f(\beta)=\begin{cases} \dfrac{1-\beta}{\sqrt{1-\beta+\beta^2}} & 0\le\beta\le0.5 \\ \dfrac{\beta}{\sqrt{1-\beta+\beta^2}} & 0.5\le\beta\le1.0 \end{cases} \\ C=\dfrac{\overline{\eta}\,(1+n)}{\left(\dfrac{1+\sqrt{3}}{2}\right)\left(\frac{2}{\sqrt{3}}\right)^8+\left(\frac{\sqrt{3}}{2}\right)^{\frac{1}{3n}}} \\ \beta=\dfrac{1+2\alpha}{2+\alpha} \\ \alpha=\dfrac{d\varepsilon_2}{d\varepsilon_1} \\ d\,\overline{\varepsilon}_n=\dfrac{2}{\sqrt{3}}d\varepsilon_1\sqrt{1+\alpha+\alpha^2} \end{cases} \quad (3)$$

where α is the strain ratio, β is the stress ratio, n is the strain hardening exponent, C is the material constant, $\overline{\varepsilon}_n$ is the equivalent plastic strain at necking, and $\overline{\eta}$ is the uniform elongation. It can be found from Eq. (3) that the major and minor strains at the time of necking can be calculated by substituting the values of n and $\overline{\eta}$, which have been determined from the uniaxial tensile test. According to Eq. (3), the FLCs under different temperatures can be obtained via plotting the major and minor strains at the onset of local necking.

According to the obtained friction coefficients and FLCs under different temperatures, the LDRs at different temperatures were determined, as shown in Fig. 10. The friction coefficient at room temperature (293 K) used in FE analysis was set to 0.08, which was calculated from the frictional fitted curve in Fig. 9. Generally, the LDR increases with temperature under lubricated condition. Pure molybdenum sheet exhibits poor formability at room temperature, and only the blank with the diameter of 60.0 mm can be drawn successfully (LDR=1.2). However, the LDR is increased to 1.98 at the temperature of 1143 K using lubricant, which indicates that sheet metal with poor formability and high strength can be manufactured at the elevated temperature via controlling process parameters and selecting appropriate lubricants. On the other hand, the LDR decreases slightly under dry condition with the temperature varying from 1043 to 1093 K. This is because the negative effect of increasing friction on formability outstrips the positive impact of increasing ductility with the increase of temperature. This indicates that the influence of lubrication on formability is more remarkable than temperature. Therefore, the evaluation of friction under different lubricated systems is critical in hot-forming process of Mo sheet.

4.4 Comparison

The comparison between FE simulation and experiment was conducted to verify the validity of the obtained results. According to the prior art [19], the experimental LDR of pure molybdenum at 1143 K with lubricant is 1.94, which agrees well with the result shown in Fig. 11. Furthermore, the forming results of FE simulation were compared with the experimental ones at the temperature of 1143 K when the initial blank diameter is 95 mm with HBN lubricant, as shown in Fig. 12. It can be observed that the outcome of the experimental

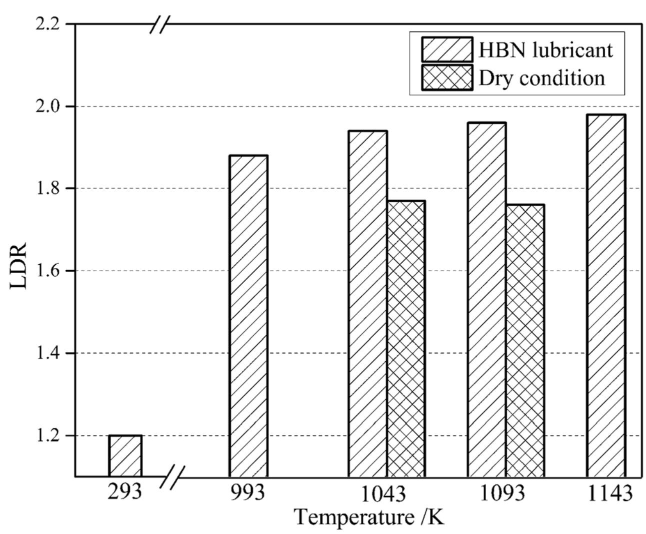

Fig. 11 LDR of pure molybdenum at various temperatures

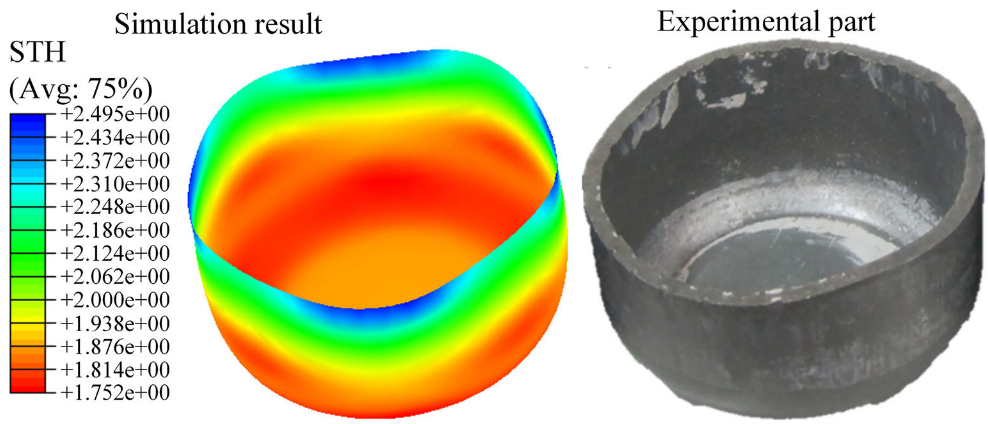

Fig. 12 Results of FE simulation and experimental part

geometry has a good agreement with the numerical prediction.

The details of the thickness measured at ten locations are shown in Fig. 13 for both the experiment and simulation studies. The Mo sheet with the original thickness of 2.0 mm changes from 1.74 to 2.53 mm in deep drawing at the temperature of 1143 K with heat-resistant lubricant. The increase in thickness is observed in the straight wall regions close to the cup edge, while the maximum reduction of thickness locates at the corner of punch. It is noted that the wall thickness of the formed cup edge is greater than the defined clearance of 2.5 mm. However, the increase of wall thickness is mainly induced by the large deformation as the sheet metal flows through the die entrance. At this point, the blank edge has already entered into the die orifice due to the large die corner radius of 18.6 mm, which is unlikely to lead to the friction between the blank and the blank holder. In FE simulation, the predicted variation of thickness is between 1.76 and 2.5 mm with the confirmed friction coefficient of 0.2, which agrees well with the experimental results. It is found that the percentage of difference in wall thickness distribution between numerical simulations and experiment is less than 6 %, which indicates that the FE simulation can be used as an efficient method to evaluate the formability and frictional condition in hot deep drawing of Mo sheet.

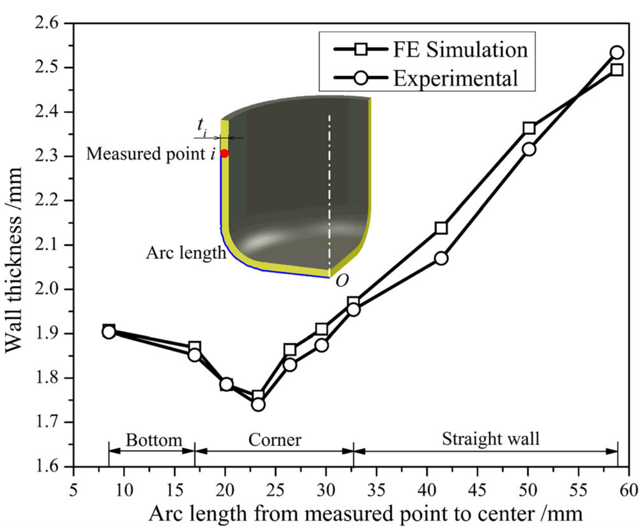

Fig. 13 Comparisons of wall thickness distributions between FE simulation and experiment

5 Conclusions

In this research, the drawability and frictional characteristic of pure molybdenum sheet at elevated temperature were investigated, and the inverse comparison method was utilized to evaluate the frictional conditions. A series of hot deep-drawing tests and FE simulations were carried out to study the friction behavior at the die/workpiece interface and the formability at different temperatures. The following conclusions are drawn from the present investigation.

1. The increasing forming temperature of Mo sheet leads to reduced drawing force and increased friction coefficient. Without considering the effect of BHF, the initial blank diameter does not have a significant influence on the friction coefficient, and the FE method can be employed to determine the LDR based on the reliable frictional data.
2. The LDR of pure molybdenum sheet increases from 1.2 at room temperature to 1.98 at 1143 K by using HBN lubricant. However, the effect of temperature on LDR under dry condition is insignificant, indicating that the lubricant is effective for improving the formability of Mo sheet.
3. The results of FE simulations were compared with those of experiments, and the percentage of difference between FE simulation and the experimental results is less than 6 %, revealing that the method combining FE analysis with experiment can be effectively used for evaluation of the formability and friction characteristic of pure molybdenum sheet in high-temperature forming process.

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