

Evaluation of Friction in Ultrasonic Vibration-assisted Press Forging Using Double Cup Extrusion Tests

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Ultrasonic energy is applied to a die in an ultrasonic vibration-assisted metal forming process, and the die is used to deform the workpiece. The friction between die and workpiece decreases when ultrasonic vibration is applied in metal forming process. The friction plays a crucial role in metal forming; therefore, the friction force must be evaluated and quantified to obtain the optimal forming process. The ring compression test is widely used to evaluate the friction factor or coefficient of friction. However, the ring compression test is unsuitable to determine the friction condition in forging and extrusion processes. Therefore, this study evaluated the effect of ultrasonic vibration on the friction factor using double cup extrusion tests (DCET). The apparatus design for ultrasonic vibration-assisted DCET and experiments were conducted, and the commercial finite element software Marc was used to simulate the DCET to obtain the friction calibration curves. The results demonstrated that the evaluation of the interface friction factor using DCET is sensitive. Under no lubricant condition, the friction factors of traditional and ultrasonic vibration-assisted DCET were approximately 0.1 and 0.3, respectively. Under Blue Moly lubricant condition, the friction factors of traditional and ultrasonic vibration-assisted DCET were approximately 0.05 and 0.1, respectively.

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1. Introduction

In recent years, ultrasonic vibration has been widely applied to assist conventional metal forming processes, such as wire drawing, extrusion, deep drawing, bending, and forging. The vibration-assisted techniques are also applied to microforming process.¹ The difference between conventional metal forming and ultrasonic vibration-assisted metal forming is that ultrasonic energy is applied to a die, and the die is used to deform the workpiece in ultrasonic vibration-assisted metal forming. A number of effects occur when ultrasonic vibration is applied in metal forming processes, such as a decrease in friction between die and workpiece, a decrease in forming force, and a decrease in spring-back angle during sheet metal forming. These effects increase the formability of materials. Blaha and Langenecke were the first to study the effect of ultrasonic-vibration on the plasticity of metals.^{2,3} A substantial reduction in the yield stress and the flow stress was observed in the experiment. Pohlman et al.⁴ were the first to study the influence of ultrasonic vibration on friction by placing a ball on a revolving plate and exciting it by ultrasonic vibration. The frictional force was minimized at the contact surface when the direction of vibration was parallel to the direction of motion. Siegert et al. examined

the influence of friction in strip-drawing processes by superimposing ultrasonic waves.⁵ The results demonstrated that the reduction of the friction force and the improvement of surface quality by superimposing ultrasonic waves are dependent on the amount of ultrasonic amplitude and drawing velocity.

The friction between dies and workpieces plays a vital in metal forming processes. The friction conditions at the die-workpiece interface affect the forming force, the mode of deformation, the quality of the finished products, and the resulting surface roughness. The friction force must be evaluated and quantified to obtain an optimal forming process. The ring compression test has been widely accepted among the various methods for measuring the coefficient of friction or friction factor.⁶⁻⁸ Hung et al.⁹ performed a ring compression test with ultrasonic vibration on aluminum alloy to explore the frictional effect of ultrasonic vibration on upsetting. Finite element analysis was conducted to derive the friction calibration curves and to evaluate the friction factor. The results showed that increasing temperature by ultrasonic vibration may reduce the flow stress and increase the interfacial friction. However, deformation of workpiece, contact area of die and workpiece, and normal pressure on the interface of die and workpiece are relatively small in the ring compression test. Therefore, the ring compression test

is unsuitable to determine the friction condition in a number of metal forming processes that are characterized by severe deformation, large contact area, and high pressure on the interface, such as forging and extrusion processes.

Buschhausen et al.¹⁰ developed a new method called double backward-extrusion process or “double cup extrusion test (DCET)” to determine the friction factor on the interface of die and workpiece. They used the experimental results to verify the finite element simulation, and discussed the influences of cup height ratio and diameter reduction ratio on the friction factor. Schrader et al.¹¹ evaluated the DCET by studying the influence of various geometrical and process parameters on the cup height ratio and contact pressure at the tool-workpiece interface. Based on their evaluation, recommendations were offered to redesign the DCET and increase its sensitivity to changes in interface friction.

In summary, the friction condition can be changed by superimposing ultrasonic vibration; therefore, it is crucial to determine the effect of ultrasonic vibration on friction condition. Moreover, the double cup extrusion test is considered to have more advantages over the ring compression test, and seldom research have investigated the influence of ultrasonic vibration on the friction condition using double cup extrusion tests. Therefore, this study evaluated the effect of ultrasonic vibration on the friction factor using double cup extrusion tests.

2. The Experiment of Double Cup Extrusion Tests

In double cup extrusion tests, a cylindrical workpiece is placed between two identical punches and die (as shown in Fig. 1). During the test, the upper punch moves down while the lower punch and die are stationary; consequently, the workpiece is deformed into two cups. Theoretically, the height of two cups would be the same if the interface is frictionless. As the friction increases, the height of the lower cup decreases. This occurs because the relative velocity between the lower punch and lower part of the workpiece is smaller than that between the upper punch and upper part of the workpiece while the upper punch moves down. The restriction of material deformation on the lower part of the workpiece is higher; therefore, the height of the lower cup is shorter. Therefore, this phenomenon can be used to determine the friction factor on the interface of die and workpiece. The cup height ratio (R) is defined as

$$R = h_u/h_l$$

where h_u and h_l are the height of the upper cup and lower cup, respectively.

If the friction factor is zero, R would be equal to 1; by contrast, R increases in conjunction with the friction factor.

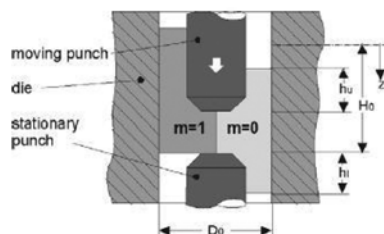


Fig. 1 Double cup extrusion test¹²

2.1 Experimental apparatus

A homemade apparatus, the maximal loading of which was 5000 kgw with a resolution of 1/20000 and displacement resolution of 0.005 mm, was constructed for the experiment. For devices of ultrasonic vibration, the frequency generator (KWS2020), produced by King Ultrasonic Co., was set to operate at an automatic frequency tracking within the range of $20 \text{ k} \pm 500 \text{ Hz}$. The ultrasonic horns must be designed for the appropriate tracking range to avoid a frequency generator overload caused by the substantial difference between the generated and resonant frequencies.

Figs. 2 and 3 show the double cup extrusion tooling. To easily release the workpiece from dies after the experiment, the dies were designed to separate into two parts and have a drafting angle on the outer surface. The diameters of punches were 2 mm, 3 mm, and 4 mm. Fig. 4 displays the photo of upper and lower punches with various diameters. During the DCET, ultrasonic vibration was applied on the upper punches so the upper punches were fixed in the ultrasonic horn.

The design procedures for the vibration tool were as follows: first, the preliminary length of the ultrasonic horn was designed as half wavelength (λ). The simplified theoretical equation of wavelength in

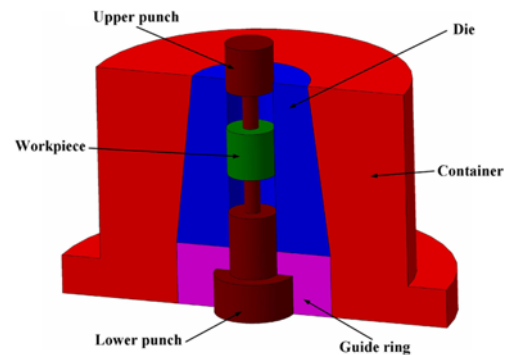


Fig. 2 Double cup extrusion tooling (cross-sectional view)

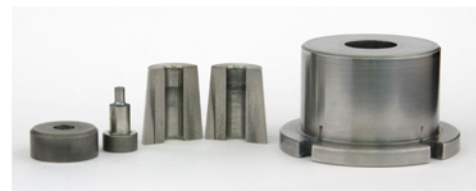


Fig. 3 Photo of double cup extrusion tooling

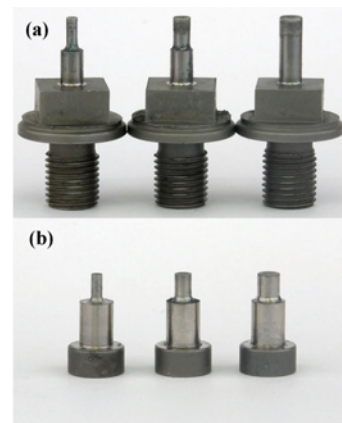


Fig. 4 (a) Upper punches (b) lower punches

one-dimensional medium is:

$$\lambda = 1/f \sqrt{\frac{E}{\rho}}$$

where E and ρ are the Young's modulus and density of the medium, and f is the resonance frequency of ultrasonic horn. Secondly, the commercial finite element software, Abaqus, was used to determine the precise dimension of this horn. Fig. 5 shows the simulation result of modal analysis of horn and punch, and the frequency was 19837 Hz, which was within the tracking range of the frequency generator. The amplitude of the punch was measured using laser displacement sensor (KEYENCE LK-H020), and the measured amplitude was approximately 5 μ m.

2.2 Experimental conditions and procedure

Table 1 lists the material of the workpiece and the conditions of DCET. The workpieces used in this research were aluminum alloy (A6061). The diameter and height of the workpieces were 6 mm. The extrusion displacement was set to 1 mm, 2 mm, 3 mm, and 4 mm (equivalent to compression ratios of 16.7%, 33.3%, 50%, and 66.7%), and the extrusion velocity was fixed at 0.033 mm/s. The diameters of the punches were 2 mm, 3 mm, and 4 mm (equivalent to area reduction ratios of extrusion of 11.1%, 25%, and 44.4%). The tests were performed with and without lubricant. The lubricant used in this research was Blue Moly, which is suited to a high pressure and temperature condition.

The procedures for DCET were as follows: first, the ultrasonic vibration system, punches, and dies were established on the homemade apparatus, as shown in Fig. 6. Second, the workpiece was lubricated and placed between two punches and die. A 20 kgw preload was applied to the workpiece, and the experiment was subsequently performed. When the loading reached 70 kgw during an experiment, ultrasonic vibration was applied on the upper punch until the end of the experiment.

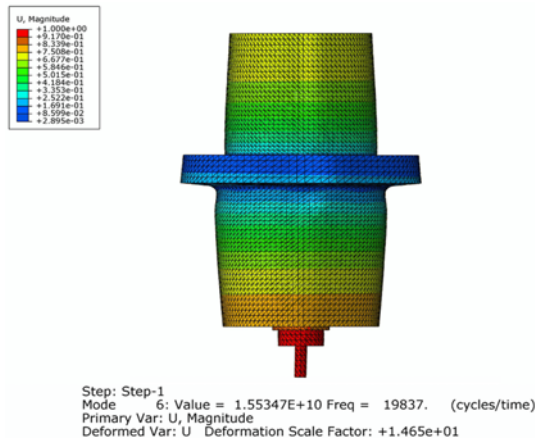


Fig. 5 Simulation result of modal analysis of horn and punch

Table 1 Material and DCE experiment condition

Specimen material	Aluminum Alloy (A 6061)
Tooling material	Stainless steel (SUS304)
Size of specimen	$\phi 6.0 \times 6.0$ mm
Lubricant	Blue Moly
Reduction (R)	11.1%, 25%, 44.4%
Extrusion speed	0.033 mm/s
Temperature of specimen	25°C

3. The Simulation of Double Cup Extrusion Tests

Finite element simulation was used to obtain friction calibration curves. During the simulation of DECT, the solution did not converge because of the considerably distorted meshes; therefore, remeshing was required in the simulation. Therefore, the commercial finite element software Marc was used to simulate the DECT to overcome the negative Jacobian problem when the meshes distorted considerably, because Marc provides functions of "Global Remeshing."

A two-dimensional axisymmetric model was chosen to simplify the simulation of DCET. Fig. 7 shows the finite element model. During the simulation of DCET, the material model of the workpiece was isotropic and homogenous with a rigid-plastic response, and the punches and die were regarded as rigid bodies. A total of 7381 nodes and 7200 elements were constructed in the FEA model. The material properties used in the simulation were derived from previous extrapolated compression tests, as shown in Fig. 8.⁹ The friction condition of the interface between

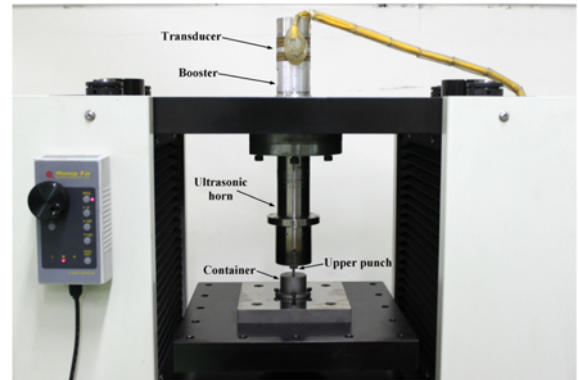


Fig. 6 Apparatus for double cup extrusion tests

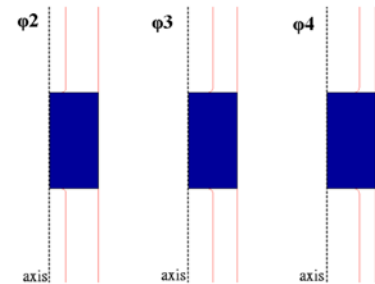


Fig. 7 Finite element model of double cup extrusion tests

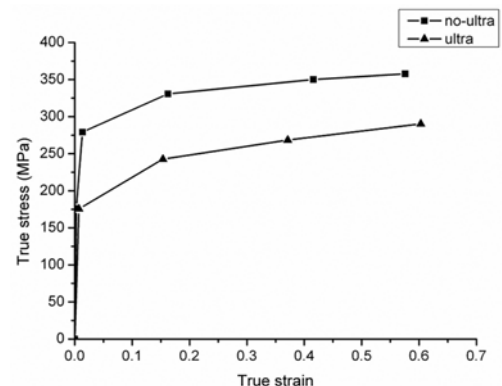


Fig. 8 The true stress-strain curves in frictionless condition⁹

punches, die, and workpiece was determined by friction factor (m). The compressive velocity was 0.033 mm/s. The total height reduction in simulation was 83.33%.

4. Results and Discussion

4.1 The influence of the diameter of punches on DCET

Fig. 9 shows the results of traditional DCET without lubricant by using various diameters of punches after various extrusion displacements. Fig. 10 shows the experimental friction calibration curves of traditional

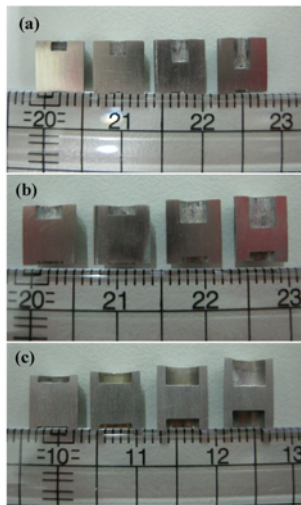


Fig. 9 The results of traditional DCET without lubricant after various extrusion displacements, punch diameter: (a) $\phi = 2$ mm, (b) $\phi = 3$ mm, (c) $\phi = 4$ mm

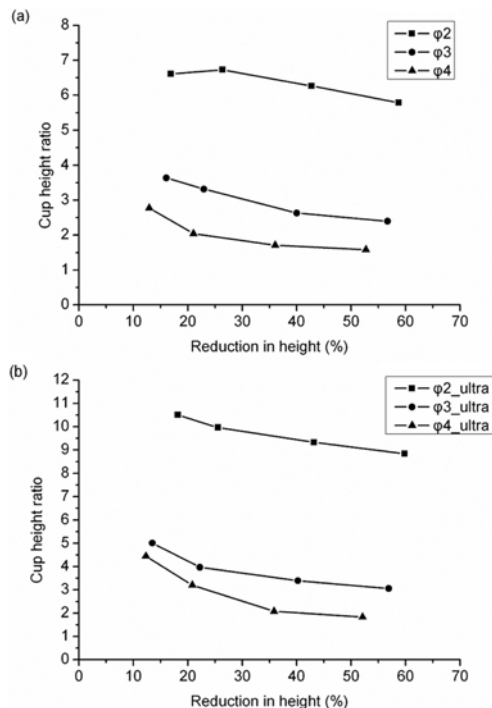


Fig. 10 Experimental friction calibration curves without lubricant by using various diameters of punches (a) traditional DCET, (b) ultrasonic vibration-assisted DCET

and ultrasonic vibration-assisted DCET without lubricant by using various diameters of punches. Under the same friction condition, the cup height ratio increased as the diameter of the punches decreased in both traditional and ultrasonic vibration-assisted DCET. This occurred because the restriction of deformation of the specimen was smaller when the diameter of the punches was smaller. Therefore, the height of

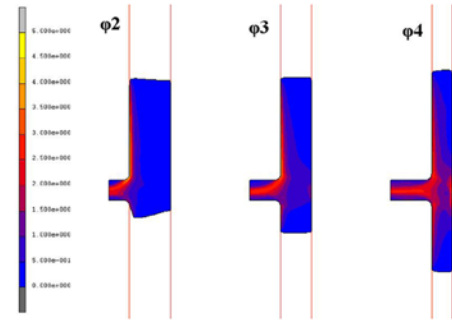


Fig. 11 Simulation results of equivalent plastic strain of traditional DCET by using various diameters of punches ($m = 0.5$)

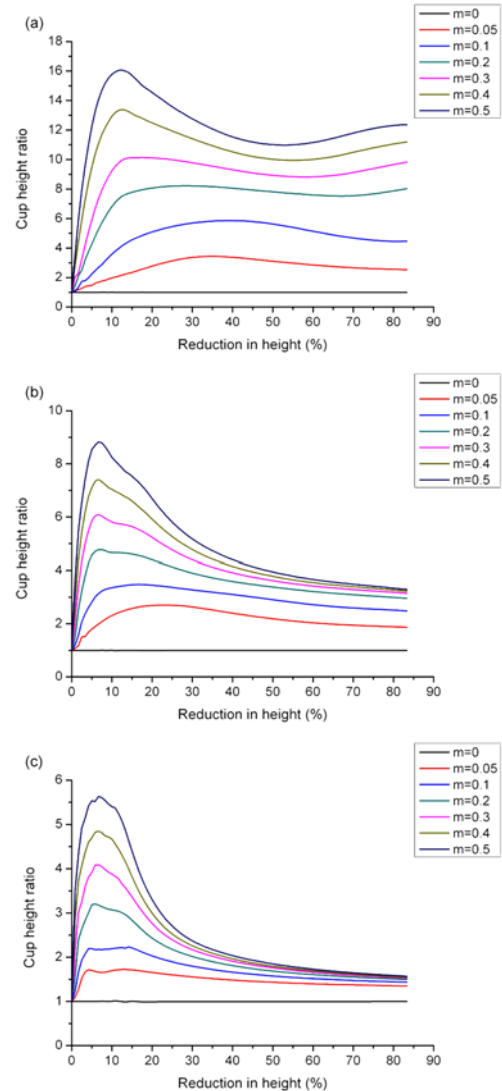


Fig. 12 Simulated friction calibration curves of traditional DCET by using various diameters of punches (a) $\phi = 2$ mm, (b) $\phi = 3$ mm, (c) $\phi = 4$ mm

the upper cup increased, and the height of the lower cup decreased.

The simulations were conducted using seven different friction factors (0, 0.05, 0.1, 0.2, 0.3, 0.4, and 0.5), and two material properties were used to simulate the traditional and ultrasonic vibration-assisted DCET. Fig. 11 shows the simulation results of distribution of equivalent plastic strain of traditional DCET using various diameters of punches when the friction factor was equal to 0.5. Fig. 12 and 13 shows the simulated friction calibration curves of traditional and ultrasonic vibration-assisted DCET by using various diameters of punches. As shown in Fig. 12 and 13, the cup height ratio increased as the area reduction ratio decreased; the simulation results correspond with those derived in the experiment. Therefore, the sensitivity of friction calibration curves is higher when the diameter of the punch used in DECT is smaller.

4.2 Friction calibration curves of DECT

Fig. 14 shows the comparison between cup height ratios of the traditional and ultrasonic vibration-assisted DCET without lubricant. Regardless of the diameter of punches used in the experiments, the cup

height ratios of the ultrasonic vibration-assisted DCET were larger than those of the traditional DCET. In other words, ultrasonic vibration applied in the experiment increased the friction factor of the interface between punches, die, and workpiece. This may occur because ultrasonic vibration increases the temperature of the material;⁹ therefore, the friction factor increases. The results obtained in previous studies^{4,5} showed that the friction decreased with the application of ultrasonic vibration on the tool because the interfacial pressures in the ball-revolving plate test⁴ and strip-drawing test⁵ were relatively smaller than that in this paper. Therefore, less frictional heat was generated during these tests. Furthermore, the material passed through the tool instantly; thus, the increase in temperature was not significant. Therefore, the interfacial friction obtained for this paper was contrary to previous results.^{4,5} However, these results are consistent with those of the ring compression test in a previous study;⁹ i.e., ultrasonic vibration increases interfacial friction.

The simulation and experimental results using 2 mm diameter

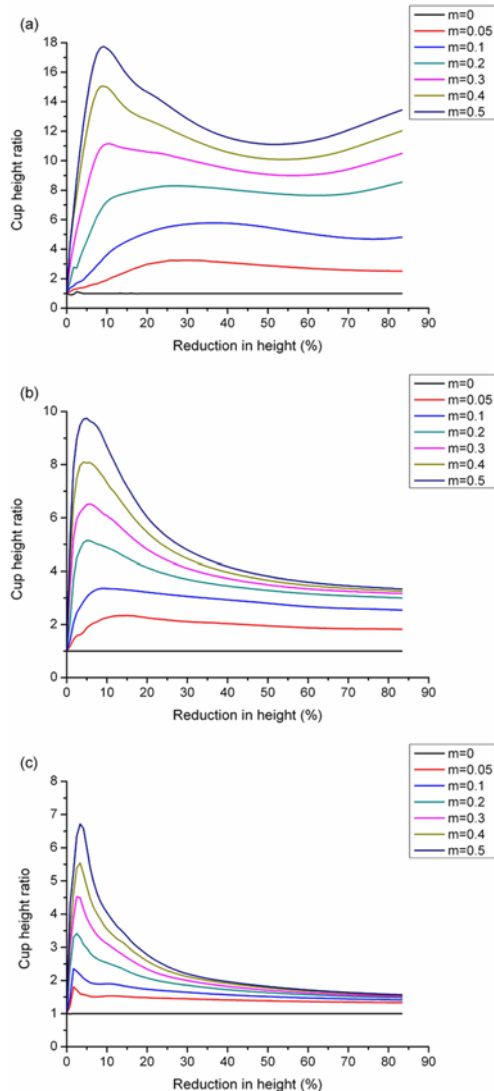


Fig. 13 Simulated friction calibration curves of ultrasonic vibration-assisted DCET by using various diameters of punches (a) $\phi = 2$ mm, (b) $\phi = 3$ mm, (c) $\phi = 4$ mm

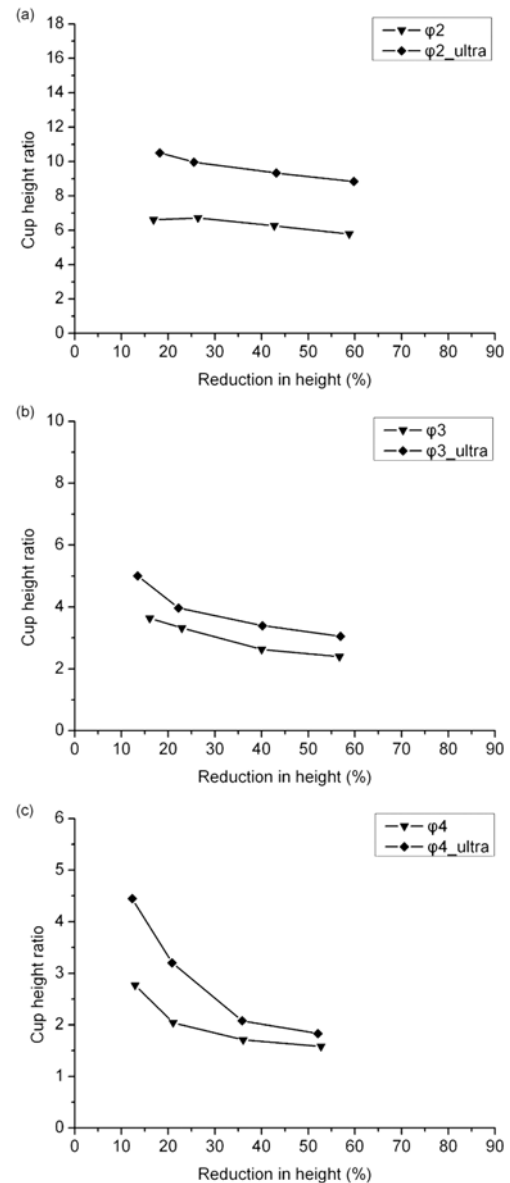


Fig. 14 Comparison between cup height ratios of the traditional and ultrasonic vibration-assisted DCET without lubricant (a) $\phi = 2$ mm, (b) $\phi = 3$ mm, (c) $\phi = 4$ mm

punches were employed to evaluate the friction factor. Fig. 15 shows the friction calibration curve of traditional DCET for FEM analysis and experimental result. As shown in Fig. 15, the friction factor of traditional DCET with lubricant was approximately 0.05. The friction factor of traditional DCET without lubricant was a few larger than 0.1.

Fig. 16 shows the friction calibration curve of ultrasonic vibration-assisted DCET for FEM analysis and experimental result. As shown in Fig. 16, the friction factor of ultrasonic vibration-assisted DCET with lubricant was between 0.1 and 0.2 at the region of lower reduction in height; however, the friction factor was nearly 0.1 at the region of higher reduction in height. The friction factor of ultrasonic vibration-assisted DCET without lubricant was approximately 0.3.

5. Conclusion

The apparatus design for ultrasonic vibration-assisted DCET and experiments were conducted, and the commercial finite element software Marc was used to simulate the DECT to obtain the friction calibration curves. The results of this research support the following conclusions:

1. The evaluation of the interface friction factor using DCET is sensitive, and the sensitivity of the friction factor is higher when area reduction ratio of extrusion is small.
2. The results of the ultrasonic vibration-assisted DECT indicate that ultrasonic vibration increases the interfacial friction.
3. Under no lubricant condition, the friction factors of traditional and ultrasonic vibration-assisted DCET were approximately 0.1 and 0.3, respectively.

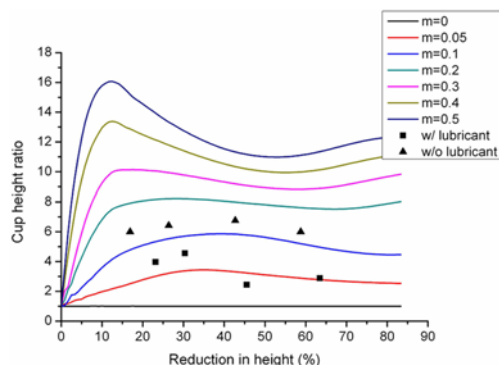


Fig. 15 Friction calibration curve of traditional DCET for FEM analysis and experimental results

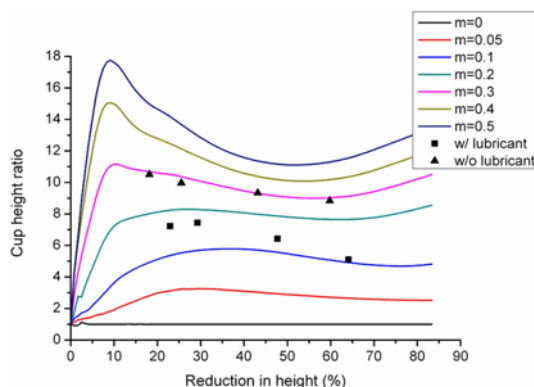


Fig. 16 Friction calibration curve of ultrasonic vibration-assisted DCET for FEM analysis and experimental results

4. Under Blue Moly lubricant condition, the friction factors of traditional and ultrasonic vibration-assisted DCET were approximately 0.05 and 0.1, respectively.

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