1-1-2013

Analysis of axisymmetric cup forming of metal foil and micro hydroforming process

Hideki Sato
Tokyo Metropolitan University

Kenichi Manabe
Tokyo Metropolitan University

Dongbin Wei
University of Technology, Sydney, dwei@uow.edu.au

Zhengyi Jiang
University of Wollongong, jiang@uow.edu.au

Recommended Citation

Sato, Hideki; Manabe, Kenichi; Wei, Dongbin; and Jiang, Zhengyi, "Analysis of axisymmetric cup forming of metal foil and micro hydroforming process" (2013). *Faculty of Engineering and Information Sciences - Papers: Part A*. 2833.
https://ro.uow.edu.au/eispapers/2833

Analysis of axisymmetric cup forming of metal foil and micro hydroforming process

Abstract

A novel forming method "micro hydromechanical deep drawing (MHDD)" is focused to improve the tribological property and forming limit. In this study, a theoretical model for MHDD is developed to investigate the size effect on deformation behavior in micro hydromechanical deep drawing. The effects of fluid pressure, the difference of friction coefficients at inner pockets and outer pockets are considered in the investigation on the size effect of tribological property. The friction force decreases as the scale factor decreases in MHDD process. It is also found that the tribological property in micro scale can be improved by applying the fluid pressure. The forming limit decreases as the relative punch diameter increases. However, it is clarified that the forming limit can be improved by decreasing the friction force in MHDD.

Keywords

process, axisymmetric, cup, metal, foil, micro, forming, hydroforming, analysis

Disciplines

Engineering | Science and Technology Studies

Publication Details

Sato, H., Manabe, K., Wei, D. & Jiang, Z. (2013). Analysis of axisymmetric cup forming of metal foil and micro hydroforming process. ASME International Mechanical Engineering Congress and Exposition (IMECE) (pp. 1-7). United States: ASME.

IMECE2013-64355

ANALYSIS OF AXISYMMETRIC CUP FORMING OF METAL FOIL AND MICRO HYDROFORMING PROCESS

Hideki SATO
Department of Mechanical Engineering, Tokyo Metropolitan University
Tokyo, Japan
sato-hideki@ed.tmu.ac.jp

Ken-ichi MANABE
Department of Mechanical Engineering, Tokyo Metropolitan University
Tokyo, Japan
manabe@tmu.ac.jp

Dongbin WEI
School of Electrical, Mechanical and Mechatronic Systems, University of Technology, Sydney
New South Wales, Australia
dongbin.wei@uts.edu.au

Zhengyi JIANG
School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong
New South Wales, Australia
jiang@uow.edu.au

ABSTRACT

A novel forming method “micro hydromechanical deep drawing (MHDD)” is focused to improve the tribological property and forming limit. In this study, a theoretical model for MHDD is developed to investigate the size effect on deformation behavior in micro hydromechanical deep drawing. The effects of fluid pressure, the difference of friction coefficients at inner pockets and outer pockets are considered in the investigation on the size effect of tribological property. The friction force decreases as the scale factor decreases in MHDD process. It is also found that the tribological property in micro scale can be improved by applying the fluid pressure. The forming limit decreases as the relative punch diameter increases. However, it is clarified that the forming limit can be improved by decreasing the friction force in MHDD.

NOMENCLATURE

p : fluid pressure
p_{d} : required fluid pressure for leakage
q : blank holder pressure
$DR = R_{\mathrm{o}}/R_{\mathrm{p}}$: drawing ratio
V_1 : volume at die shoulder radius area
V_2 : volume at side wall area
V_3 : volume at punch shoulder radius area
V_4 : volume at punch bottom area
φ : die contact angle
$\bar{\sigma}_{\mathrm{eq}}$: equivalent stress
$\bar{\varepsilon}_{\mathrm{eq}}$: mean equivalent strain rate
K : strength coefficient
n : strain hardening exponent
σ_{D} : pure drawing stress
σ_{F} : friction stress
σ_{B} : bending stress
σ_{UnB} : unbending stress
σ_{φ} : drawing stress
P : punch force
μ_{Inn} : friction coefficient at inner pockets
μ_{Out} : friction coefficient at outer pockets
μ : mean friction coefficient
w : width of blank rim area
$\lambda = R_{\mathrm{o}}/w$: scale factor

INTRODUCTION

The demand of the micro parts has been significantly increased due to product miniaturization in medical field, electronic devices and micro-mechatronics systems for automotive industry. In particular, the micro parts with high dimension accuracy, further miniaturization, and complex shapes are required to improve the performance of these devices. Micro forming becomes more and more popular to fabricate these micro parts, Geiger et al. (2001). However, the knowledge of conventional macro forming cannot be simply scaled down to micro scale due to the size effect. When the size of components is reduced from macro scale to micro scale, the formability decreases due to the tribological property and the decrease of thickness in micro forming. For the tribological properties in micro forming, theoretical analysis was performed by Engel (2006) and Putten, et al. (2007). The research showed that the friction force increases with the decrease of scale due to the decrease of the lubrication effect in micro scale. This phenomenon was experimentally verified in upsetting test by Weidel et al. (2009) and in actual forming process by Vollertsen et al. (2006). For the forming limit in micro forming, the decrease of forming limit in micro deep drawing as the thickness of the blank decreases has been clarified by Vollertsen (2012). Moreover, the manufacturing of the tiny tools becomes difficult as the size of the tools is miniaturized.

In this study, a novel forming method "micro hydromechanical deep drawing (MHDD)" is focused to solve these problems. Male die that is easy to manufacture in practice has been only adopted. Also, it can be expected to improve the drawability due to several advantages in hydromechanical deep drawing process. In macro hydromechanical deep drawing, it was reported that the decrease of friction occurred due to leakage between blank and die, Zhang (1998). Moreover, the drawing ratio in the hydromechanical deep drawing is higher than that in conventional deep drawing due to the several fracture restraint effects, Nakamura (1984). However, it is not certain that these effects in macro hydromechanical deep drawing would occur in MHDD due to the size effects. In this study, a theoretical model for MHDD has been developed to investigate the size effect on deformation behavior in micro hydromechanical deep drawing. The tribological property and forming limit in MHDD are clarified.

THEORY

In order to explain the characteristics in micro forming, the size effects should be considered in the theoretical model. In particular, the size effect of tribological property is important to describe the friction condition in MHDD and the effects of fluid pressure should be considered. Figure 1 shows the geometrical parameters in MHDD process in present work. As described in Fig.1, the curvature of the die radius area is assumed as the same with the male die radius r_d.

Geometrical description

Assuming that the volume of the blank and thickness are constant, the current rim position r_o can be obtained by

$$r_o = \sqrt{{R_o}^2 + {r_1}^2 - \frac{V_1 + V_2 + V_3 + V_4}{\pi t}} \tag{1}$$

where V_1, V_2, V_3 and V_4 are the volumes at die shoulder radius, side wall, punch shoulder radius and punch bottom areas respectively. These values can be expressed by

$$\begin{aligned} V_1 &= 2\pi t\varphi\left(r_d + \frac{t}{2}\right)\left(r_1 - \left(r_d + \frac{t}{2}\right)\sin\frac{\varphi}{2}\right) \\ V_2 &= \pi t \frac{{r_2}^2 - {r_3}^2}{\cos\varphi} \\ V_3 &= 2\pi t\varphi\left(r_p + \frac{t}{2}\right)\left(r_4 + \left(r_p + \frac{t}{2}\right)\sin\frac{\varphi}{2}\right) \\ V_4 &= \pi t {r_4}^2 \end{aligned} \tag{2}$$

Based on the theory of Manabe et al. (1992), the contact angel φ with the punch stroke s is given by

$$\varphi = \cos^{-1}\frac{-b + \sqrt{b^2 - 4a\cdot c}}{2a} \tag{3}$$

where

$$\begin{aligned} a &= \frac{\left(s - r_p - r_d\right)^2}{\left(C + r_p + r_d\right)^2} + 1 \\ b &= \frac{2\left(r_p + r_d\right)\left(s - r_p - r_d\right)}{\left(C + r_p + r_d\right)^2} \\ c &= \frac{\left(r_p + r_d\right)^2}{\left(C + r_p + r_d\right)^2} - 1 \end{aligned}$$

Basic equations

The constitutive equation of the blank material is

$$\bar{\sigma}_{\mathrm{eq}} = K{\bar{\varepsilon}_{\mathrm{eq}}}^n \tag{4}$$

Using Tresca's associated equivalent strain and a mean radius of the whole flange, Kawai (1961), the mean equivalent strain $\bar{\varepsilon}_{\mathrm{eq}}$ in the flange area can be expressed as

$$\bar{\varepsilon}_{\mathrm{eq}} = \frac{2}{3}\ln\frac{{R_\mathrm{o}}^2 - {r_\mathrm{o}}^2 + \{(r_\mathrm{o} + r_2)/2\}^2}{\{(r_\mathrm{o} + r_2)/2\}^2} \tag{5}$$

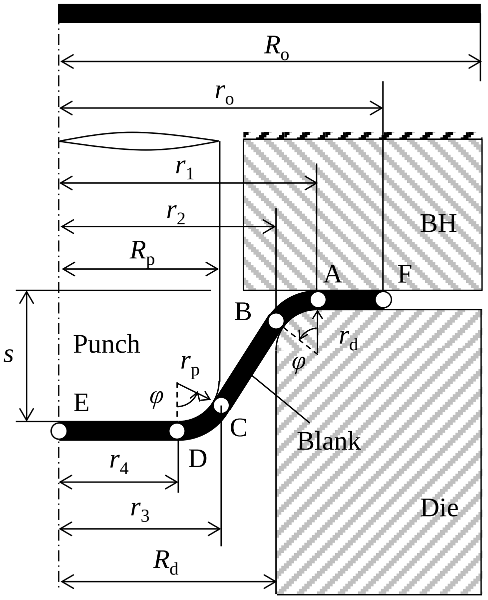


Figure 1 Geometrical parameters in MHDD process.

In deep drawing of a circular blank, the drawing stress σ_φ can be expressed by the pure drawing stress σ_D, friction stress σ_F, bending stress σ_B and unbending stress σ_UnB. The drawing stress can be obtained by

$$\begin{aligned}\sigma_\varphi &= e^{\mu\varphi}(\sigma_\mathrm{D}+\sigma_\mathrm{F}+\sigma_\mathrm{B})+\sigma_\mathrm{UnB}\\ &= e^{\mu\varphi}\left(1.1\bar{\sigma}_\mathrm{eq}\ln\frac{r_\mathrm{o}}{r_2}+\frac{2\mu q(r_\mathrm{o}-r_1)}{t}\right)\\ &\quad +1.1\bar{\sigma}_\mathrm{eq}\frac{t}{4(r_\mathrm{d}+t/2)}(1+e^{\mu\varphi})\end{aligned} \tag{6}$$

Therefore, the punch force in the conventional micro deep drawing (MDD) can be given by

$$\begin{aligned}P &= 2\pi r_2 t\sin\varphi\, e^{\mu\varphi}\left(1.1\bar{\sigma}_\mathrm{eq}\ln\frac{r_\mathrm{o}}{r_2}+\frac{2\mu q(r_\mathrm{o}-r_1)}{t}\right)\\ &\quad +1.1\bar{\sigma}_\mathrm{eq}\frac{t}{4(r_\mathrm{d}+t/2)}(1+e^{\mu\varphi})\end{aligned} \tag{7}$$

In MHDD process, it is assumed that the blank does not contact with the die due to the hydrodynamic lubrication between the blank and the die. It means that the friction coefficient between the blank and the die is assumed $\mu = 0$. Moreover, the fluid pressure plays a role in blank holder stress at flange area. From these assumptions, the punch force in MHDD process can be obtained by

$$\begin{aligned}P &= 2\pi r_2 t\sin\varphi\left(1.1\bar{\sigma}_\mathrm{eq}\ln\frac{r_\mathrm{o}}{r_2}+\frac{\mu p(r_\mathrm{o}-r_1)}{t}\right)\\ &\quad +1.1\bar{\sigma}_\mathrm{eq}\frac{t}{4(r_\mathrm{d}+t/2)}(1+e^{\mu\varphi})\end{aligned} \tag{8}$$

It is assumed that the hydrodynamic lubrication is obtained when the fluid pressure exceeds the contact pressure in die radius area. The required fluid pressure to leak between the blank and die is expressed as

$$p_\mathrm{d} = 1.1\bar{\sigma}_\mathrm{eq}\left\{\frac{t}{r_\mathrm{d}+t/2}\ln\frac{r_\mathrm{o}}{r_2}+\frac{t}{r_2}\left(1-\ln\frac{r_\mathrm{o}}{r_2}\right)\sin\varphi\right\} \tag{9}$$

Modeling of friction coefficient in MHDD

Roughness valleys should be considered when tribological property of macro forming is studied. The valleys which connect to the edge of the blank cannot keep the lubricant as shown in Fig. 2. These are named outer pockets. The pockets which can keep the lubricant are named inner pockets. With the decrease of scale, the ratio of areas of outer pockets to blank surface increases. Therefore, the lubricant cannot be kept which results in increase of friction force.

On the other hand, if the fluid medium is inserted in outer pockets in MHDD as shown in Fig. 2, the lubricant can be kept at outer pockets in MHDD. The tribological properties of the conventional MDD and MHDD will be different. To model the tribological property in MHDD, the friction coefficient in the flange area is calculated with considering the ratio of outer pockets to inner pockets. When the flange area is larger than outer pockets area ($w < r_\mathrm{o} - r_1$), using the scale factor λ, the mean friction coefficient at the flange area is obtained by

$$\mu = \frac{\left(a_\mathrm{o}-\frac{1}{\lambda}\right)^2-a_1{}^2}{a_\mathrm{o}{}^2-a_1{}^2}\mu_\mathrm{Inn}+\frac{\frac{1}{\lambda}\left(2a_\mathrm{o}-\frac{1}{\lambda}\right)}{a_\mathrm{o}{}^2-a_1{}^2}\mu_\mathrm{Out} \tag{10}$$

where

$$a_\mathrm{o} = r_\mathrm{o}/R_\mathrm{o},\ a_1 = r_1/R_\mathrm{o},\ \lambda = R_\mathrm{o}/w$$

The width of outer pockets w does not change when the scale becomes small. In the macro case, the scale factor λ is close to ∞, and in the micro case, λ is close to 0. Also, when the flange area is smaller than outer pockets area ($\mathrm{w} \geq r_\mathrm{o} - r_1$), the mean friction coefficient at the flange area is obtained by

$$\mu = \mu_\mathrm{Out} \tag{11}$$

Analytical conditions

The material used for analysis was stainless steel (SUS304-H) with the thickness of 50 μm. The mechanical properties are shown in Table 1. The tool dimensions used in MDD and MHDD are shown in Table 2. The fluid pressure and blank holder pressure were set up to $p = q = 50$MPa. It was assumed that the blank holder pressure was constant during the forming. Five types of lubrication conditions in MDD and MHDD were used for calculation as shown in Fig. 3. In MDD, dry friction and lubricant were adopted. In MHDD, no sealing, with sealing and perfect lubrication conditions are used. The hydrodynamic lubrication between the blank and the die was assumed under the conditions of no sealing condition. In the case of sealing condition, the hydrodynamic lubrication and lubrication at outer pockets were assumed. In the case of perfect lubrication condition, there was no friction. The friction coefficients in each case are shown in Table 3.

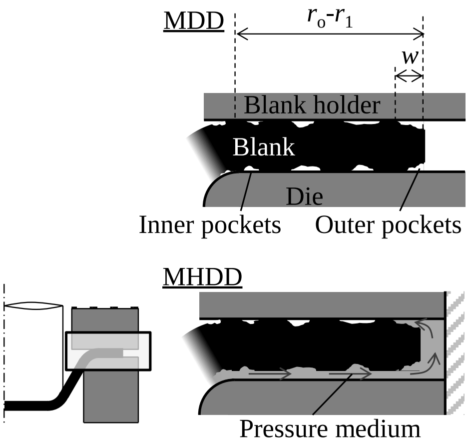


Figure 2 Difference of lubrication conditions at outer and inner pockets between MDD and MHDD.

Table 1 Mechanical properties in theoretical analysis.

Yield stress, σ_y (MPa)	1200
K-value, K (MPa)	1400
n-value, n	0.1
Tensile strength, σ_B (MPa)	1300

THEORETICAL RESULTS AND DISCUSSION

Tribological property in MHDD

Figure 4 shows size effects of tribological property under various lubrication conditions. In MDD of dry friction condition (condition a), the friction force is constant when the scale becomes small. However, in MDD of lubrication condition (condition b), the friction force increases with the decrease of scale. It is caused by the increase of the ratio of areas of outer pockets to blank surface. These phenomena are similar as that obtained by Putten, et al. (2007). On the other hand, the friction force can be significantly decreased by the hydrodynamic lubrication between the blank and the die in MHDD process (condition c). Moreover, in the case of sealing at blank rim area (condition d), the friction force decreases with the decrease of scale which is opposite to the tribological property in conventional micro forming processes. When the fluid medium leaks between the blank and the die, the space at the blank rim area is filled up with the fluid medium. Therefore, the fluid medium inserts to the outer pockets and the friction at outer pockets area decreases. This phenomenon can effectively decrease the friction force especially in micro forming where the ratio of areas of outer pockets is high. It is expected that the tribological property can be improved in MHDD process.

Forming limit in MHDD

In MDD and MHDD, the relative punch diameter D_p/t is an important parameter and ranged from 10 to 100. When the scale reduces to micro scale, D_p/t becomes small due to the limit of decreasing the thickness of metal foil. This means the thickness in MDD and MHDD is relatively thicker than that in conventional deep drawing. Figure 5 shows the effects of D_p/t and drawing ratio ($DR = R_\mathrm{o}/R_\mathrm{p}$) on the normalized maximum punch force under various lubrication conditions. When the normalized maximum punch force exceeds 1, the applied load exceeds tensile strength and fracture occurs. The normalized maximum punch force increases with an increase of D_p/t as shown in Fig. 5(a). The normalized pure drawing force is almost constant regardless of D_p/t. However, normalized friction force increases with an increase of D_p/t. This causes the increase of normalized maximum punch force and the decrease of forming limit. The same phenomenon was experimentally observed by Saotome et al. (2001). On the other hand, with an increase of the drawing ratio, the normalized maximum punch force increases rapidly as shown in Fig. 5(a). This is also mainly caused by the increase of friction force.

It is similar when lubricant is applied as shown in Fig. 5(b). In particular, when drawing ratio is low, there is no lubrication effect, and the friction force in MDD with lubrication condition is almost as same as that under dry friction condition. This is caused by low ratio of areas of inner pockets to blank surface. On the other hand, the friction can be reduced in MHDD process as shown in Fig. 5(c) and, (d). Friction force decreases significantly in MHDD with sealing no matter what drawing ratio is. The fluid medium is kept in the valleys in outer pockets area due to the sealing at the blank rim. Therefore, even if the ratio of areas of outer pockets to blank surface becomes high with the decrease of scale, the friction force keeps low in MHDD process. Furthermore, assuming the perfect lubrication condition as shown in Fig. 5(e), the normalized maximum punch force does not exceed 1 even when DR =2.5. From these results, it can be found that the high forming limit can be obtained due to the decrease of friction force in MHDD process.

Table 2 Tool dimensions used in MDD and MHDD.

Blank diameter, D_o (mm)	3.30
Punch diameter, D_p (mm)	1.90
Punch shoulder radius, r_p (mm)	0.10
Die diameter, D_d (mm)	2.04
Die shoulder radius, r_d (mm)	0.20
Clearance between punch and die, C (mm)	0.70

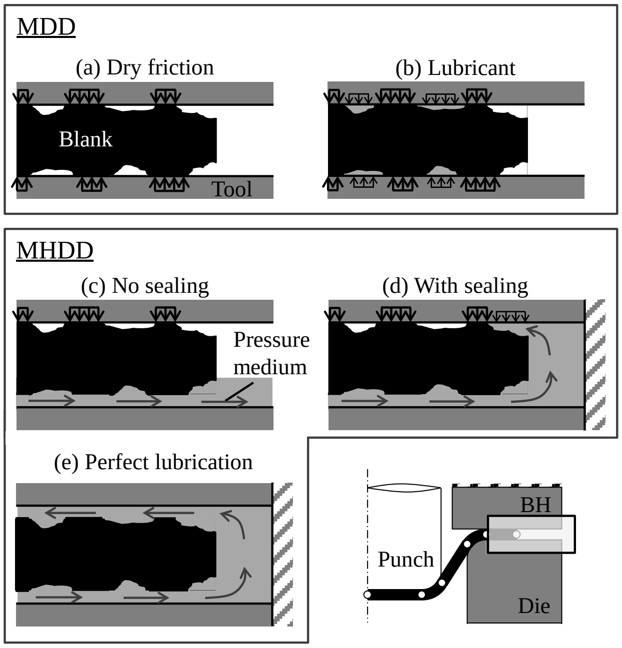


Figure 3 Schematic illustrations of lubrication conditions in MDD and MHDD.

Table 3 Friction coefficients in each lubrication condition.

Lubrication conditions	Friction coefficients
(a) MDD with dry friction	μ_Inn =0.3, μ_Out =0.3
(b) MDD with lubricant	μ_Inn =0.03, μ_Out =0.3
(c) MHDD with no sealing	μ_Inn =0.3, μ_Out =0.3
(d) MHDD with sealing	μ_Inn =0.3, μ_Out =0.03
(e) MHDD with perfect lubrication	μ_Inn =0, μ_Out =0

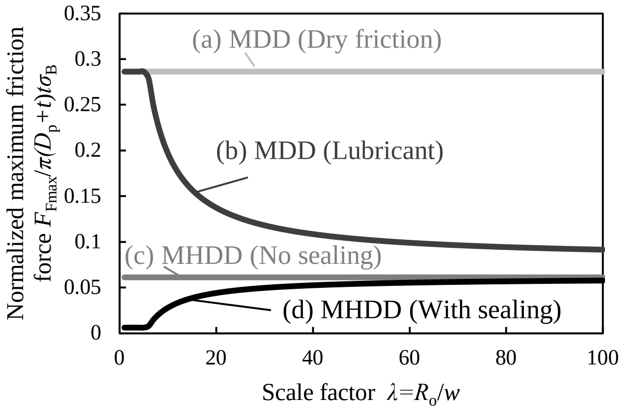
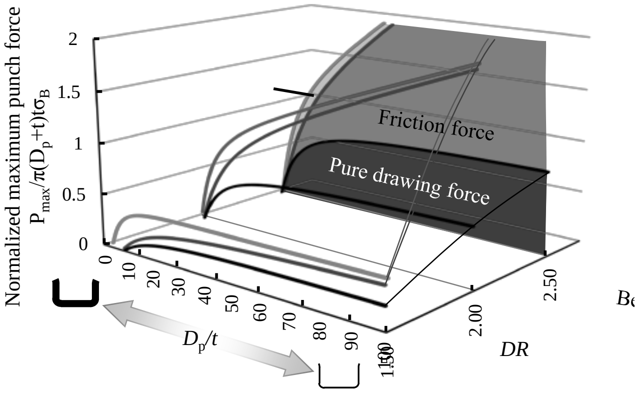
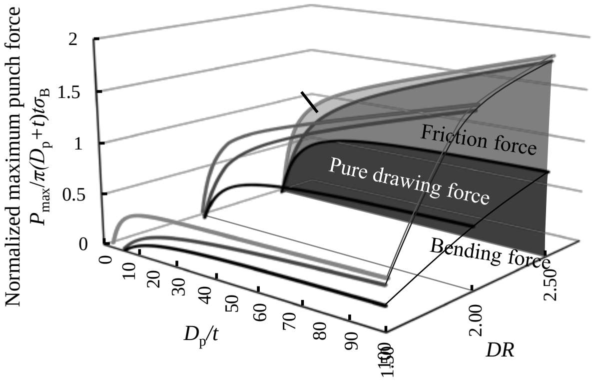


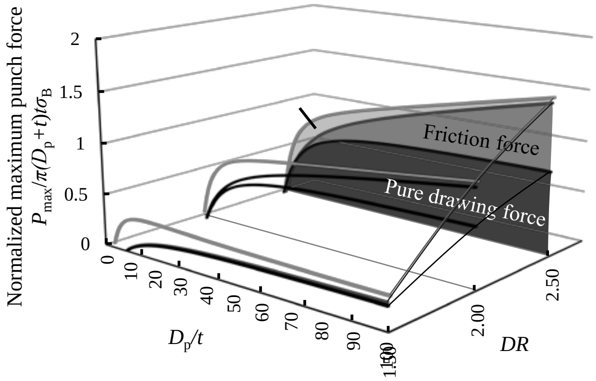
Figure 4 Effect of scale factor on maximum punch force under various lubrication conditions.



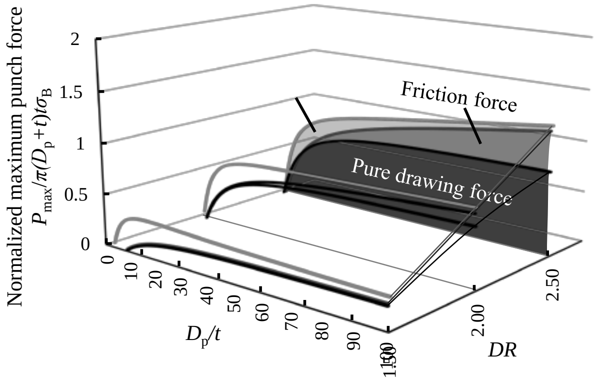
(a) MDD with dry friction



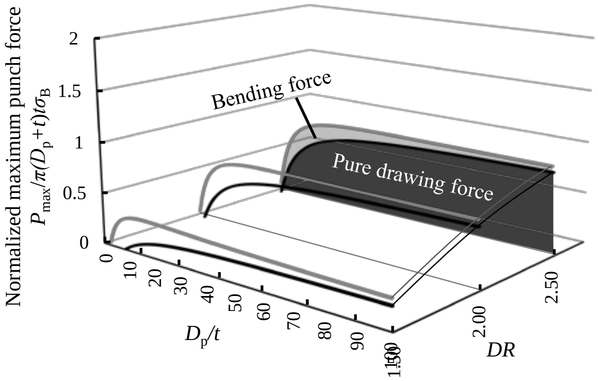
(b) MDD with lubricant



(c) MHDD without sealing



(d) MHDD with sealing



(e) MHDD with perfect lubrication

Figure 5 Effect of D_p/t and drawing ratio on normalized maximum punch force under various lubrication conditions.

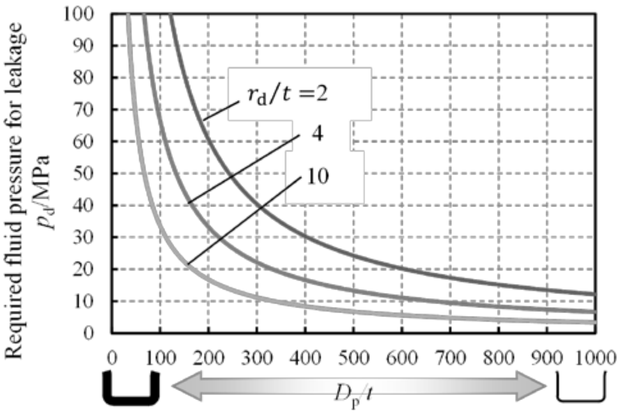


Figure 6 Effect of D_p/t and r_d/t on required fluid pressure for leakage between blank and die.

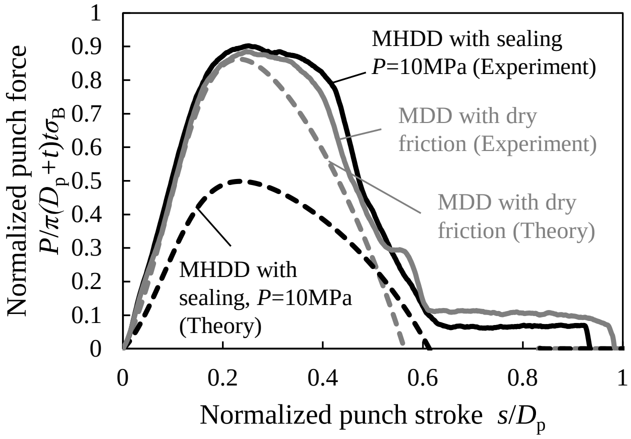


Figure 7 Comparison of normalized punch force-stroke curves between experiment and theory.

Required fluid pressure for leakage

To obtain the hydrodynamic lubrication in MHDD process, it is important to understand the required fluid pressure for the leakage between the blank and die. The required fluid pressure in MHDD is not the same as with the conventional macro hydromechanical deep drawing due to the difference of D_p/t. With a decrease of D_p/t, the thickness becomes relatively thicker and the contact pressure between the blank and the die becomes larger. This causes the required fluid pressure increases as shown in Fig. 6. Specially, the required fluid pressure becomes extremely high in the range $10 < D_p/t < 100$. However, high fluid pressure results in fracture at punch shoulder in MHDD, Manabe et al. (2012). The required fluid pressure for leakage can be reduced by increasing the die shoulder radius r_d, and the flow stress of metal foil.

Comparison of punch force-stroke curves between experiment and theory

Figure 7 shows the theoretical and experimental results of normalized punch force-stroke curves in MDD and MHDD. The theoretical and experimental results in MDD have a good agreement, but have a large difference in MHDD. The friction force in MHDD cannot be easily decreased by applying fluid pressure in experiment. It is difficult to realize the hydrodynamic lubrication due to small D_p/t in MHDD as shown in Fig. 6 although friction force decreases theoretically by the increase of outer pockets with the decrease of scale as shown in Fig. 4. Therefore, it is necessary to clarify the effects of D_p/t and outer pockets on the friction force in MHDD experiment in future.

CONCLUSIONS

The size effects of tribological property and forming limit in micro hydromechanical deep drawing have been investigated using a simple theoretical plastic model. This study can be summarized as follows:

(1) The tribological size effect in MHDD was modeled in the theoretical model, based on the assumption that the lubricant can be kept at outer pockets by applying fluid pressure.
(2) The friction force in MHDD decreases by maintaining the lubricant at outer pockets area with the decrease of scale, while it increases in conventional MDD.
(3) The forming limits in MDD and MHDD decrease with an increase of the relative punch diameter D_p/t due to the increase of the normalized friction force. To improve the forming limit, it is effective to apply fluid pressure and realize the hydrodynamic lubrication in MHDD process.
(4) The required fluid pressure for leakage becomes big with an increase of D_p/t. To reduce the required fluid pressure, the die shoulder radius and flow stress should be decreased.

REFERENCES

Engel, U., 2006, “Tribology in Microforming,” *Wear*, Vol.260, pp.265–273.

Geiger, M., Kleiner, R., Eckstein, M., Tiesler, N., Engel, U., 2001, “Microforming,” *CIRP Annals – Manufacturing highlights*, Vol.50, pp.445–462.

Kawai, N., 1961, “Critical Conditions of Wrinkling in Deep Drawing of Sheet Metals,” Reports 1, 2 and 3, *Transactions of the Japan Society of Mechanical Engineers (in Japanese)*, Vol.4, pp.169-192.

Manabe, K.., Soeda, K.., Nagashima, T,. Nishimura, H., 1992, “Adaptive Control of Deep Drawing Using the Variable Blank Holding Force Technique,” *Journal of the Japan Society for Technology of Plasticity (in Japanese)*, Vol.33, pp.423-428.

Manabe, K., Sato, H., Furushima, T., Wei, D., Mathew, N., Jiang, Z., 2012, “Deformation Behavior in Micro Sheet Hydroforming Process,” *Steel Research International,* Special Edition, pp.651-654.

Nakamura, K., Nakagawa, T., 1984, “Fracture Mechanism and Fracture Control in Deep Drawing with Hydraulic Counter Pressure – Studies on Hydraulic Counter Pressure Forming I,” *Journal of the Japan Society for Technology of Plasticity (in Japanese)*, Vol.25, pp.831-838

Putten, K.V., Franzke, M., Hirt, G., 2007, “Size Effect on Friction and Yielding in Wire Flat Rolling,” *Proceedings of the 2nd International Conference on New Forming Technology*, pp.583-592.

Saotome, Y., Yasuda, K.., Kaga, H., 2001, “Microdeep Drawability of Very Thin Sheet Steels,” *Journal of Materials Processing Technology*, Vol.113, pp.641-647.

Vollertsen, F., Hu, Z., 2006., “Tribological Size Effects in Sheet Metal Forming Measured by a Strip Drawing Test,” *CIRP Annals-manufacturing Technology*, Vol.58, pp.291-294.

Vollertsen, F., 2012, “Effects on the Deep Drawing Diagram in Micro Forming,” *Production Engineering*, Vol.6, pp.11-18.

Weidel, S., Engel, U., 2009, “Characterisation of the Flattening Behavior of Modelled Asperities,” *Wear*, Vol.266, pp.596-599.

Zhang, S. H., Danckert, J., 1998, “Development of Hydro-mechanical Deep Drawing” *Journal of Materials Processing Technology*, Vol.83, pp.14-25.