1-1-2014

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Abstract
A modeling of tribological size effects in micro deep drawing (MDD) and micro hydromechanical deep drawing (MHDD) is a main focus in this study. The inner and outer pockets in which the different friction coefficients can be applied at different lubrication conditions are considered on the blank surface. The ratio of the area of outer pockets to inner pockets is changed with the decrease in the size. The low friction coefficient at the outer pockets is assumed in MHDD by considering the lubrication effect of fluid medium. The numerical analysis is performed under six lubrication conditions. The analytical results of punch force-stroke curves are in good agreement with the experimental values. The friction force decreases in MHDD with the decrease in the size although it increases in MDD. The friction coefficient at die shoulder significantly influences the friction force due to high contact pressure in MHDD.

Keywords
hydromechanical, drawing, micro, deep, effect, size, modeling, numerical

Disciplines
Engineering | Science and Technology Studies

Publication Details
H. Sato, K. Manabe, D. Wei & Z. Jiang, "Numerical modeling of size effect in micro hydromechanical deep drawing," in AIP Conference Proceedings (1567): The 9th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes, 2014, pp. 926-929.

Numerical Modeling of Size Effect in Micro Hydromechanical Deep Drawing

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Abstract. A modeling of tribological size effects in micro deep drawing (MDD) and micro hydromechanical deep drawing (MHDD) is a main focus in this study. The inner and outer pockets in which the different friction coefficients can be applied at different lubrication conditions are considered on the blank surface. The ratio of the area of outer pockets to inner pockets is changed with the decrease in the size. The low friction coefficient at the outer pockets is assumed in MHDD by considering the lubrication effect of fluid medium. The numerical analysis is performed under six lubrication conditions. The analytical results of punch force-stroke curves are in good agreement with the experimental values. The friction force decreases in MHDD with the decrease in the size although it increases in MDD. The friction coefficient at die shoulder significantly influences the friction force due to high contact pressure in MHDD.

Keywords: Modeling, Micro forming, Size effect, Tribology, Micro hydromechanical deep drawing, Fluid pressure.
PACS: 46.55.+d

INTRODUCTION

With the increase of miniaturization in products, a market demand on micro parts is significantly growing. These micro parts need further miniaturization, high accuracy and high functionality to develop the communications, electronic and medical products. However, the knowledge in macro forming cannot be simply scaled down to micro scale because the size effects occur with the decrease in the size [1]. In particular, the tribological size effect causes the low formability in micro forming due to the increase of friction force with the decrease in the size [2].

On the other hand, the hydroforming is widely used in macro scale due to several advantages, such as improvement of forming limit, improvement of shape accuracy and manufacture of complex shape. In particular, the hydrodynamic lubrication which can significantly improve the lubrication occurs in hydromechanical deep drawing [3]. From these backgrounds, a micro hydromechanical deep drawing (MHDD) is developed by the authors to improve the formability in micro forming [4]. It has been clarified that the tribological property can be improved by applying the fluid pressure in MHDD [5]. However, the mechanism of tribological property in MHDD has not been confirmed. In this study, the modeling methods of tribological size effect in micro deep drawing (MDD) and MHDD are developed, and the tribological size effects in MDD and MHDD are confirmed using the developed finite element (FE) model.

FE ANALYSIS

Modeling of Size Effect in MHDD

The tribological size effect is mainly caused by the outer pockets that contact with the edge of the blank. The outer pockets cannot keep the lubricant in MDD as shown in **Fig. 1**. Furthermore, the ratio of area of outer pockets to inner pockets increases with the decrease in the size to micro scale because the width of outer pockets *w* does not change [6]. These cause the tribological size effect in MDD. On the other hand, if the fluid medium is provided to the outer pockets in MHDD as shown in **Fig. 1**, the lubricant can be kept at the outer pockets. Based on this, it was

NUMISHEET 2014
AIP Conf. Proc. 1567, 926-929 (2013); doi: 10.1063/1.4850121

assumed that the outer pockets have a low friction coefficient in MHDD. To model these tribological size effects, the blank surface was divided to inner and outer pockets areas and the different friction coefficients were applied at each pocket. The ratio of outer pockets was expressed by the scale factor $\lambda = D_o/2w$.

FE model

The analysis was carried out with an explicit dynamic finite element code, LS-DYNA. The dimension of tools is shown in **Fig. 2**. The stainless steel (SUS304-H) foil with thickness of 50μm was used. The mechanical properties of material used are shown in **Table 1**. The isotropic elastoplastic and rigid body were used for the blank and tools, respectively. Fluid pressure was set up to P= 10 and 30MPa in MHDD. The six kinds of lubrication conditions were used in the analysis as shown in **Table 2**. The static and kinetic friction coefficients between the blank and punch were μ_s=0.35 and μ_d=0.30 at all analytical condition, respectively. In MDD, the dry friction and lubrication conditions were adopted. In MHDD, no leakage, leakage between the blank and die, radial pressure without leakage and perfect lubrication conditions were adopted. To evaluate the friction force in MHDD process, the measured punch force P_H is recalculated by the effective punch force P_E. It is expressed by

$$P_E = P_H - F_H = F_S + F_B + F_F \quad (1)$$

where F_H is the force to push the punch by fluid pressure, F_S is the pure drawing force, F_B is the bending force and F_F is the friction force at flange and die shoulder area. F_S and F_B are approximately constant in the same dimension of tools. Therefore, the effective punch force P_E can evaluate the difference of friction forces F_F in each condition.

EXPERIMENTAL

In order to verify the validity of FE analysis results, the experiments of MDD and MHDD were performed. A MHDD apparatus which can perform the pressure generation, blanking, drawing and knockout process in the same axis was used to improve the handling. A miniature load cell with rating capacity of 20KN was used in the tool.

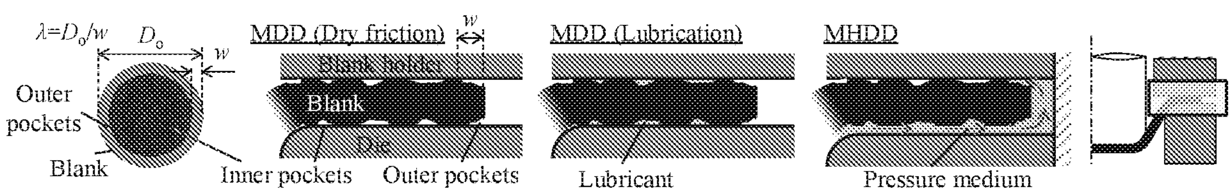


FIGURE 1. Different lubrication conditions at inner and outer pockets between MDD and MHDD.

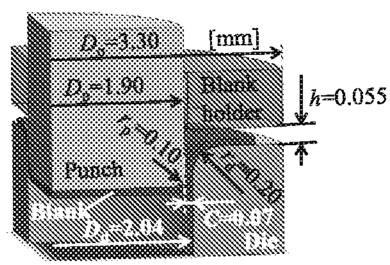


FIGURE 2. Dimension of tools

TABLE 1. Mechanical properties of material used.

Yield stress, σ_Y [MPa]	Young's modulus, E [GPa]	Tensile strength, σ_B [MPa]	Elongation, δ [%]
1217	192	1334	2.4

TABLE 2. Friction coefficients between blank and BH and die at each lubrication condition.

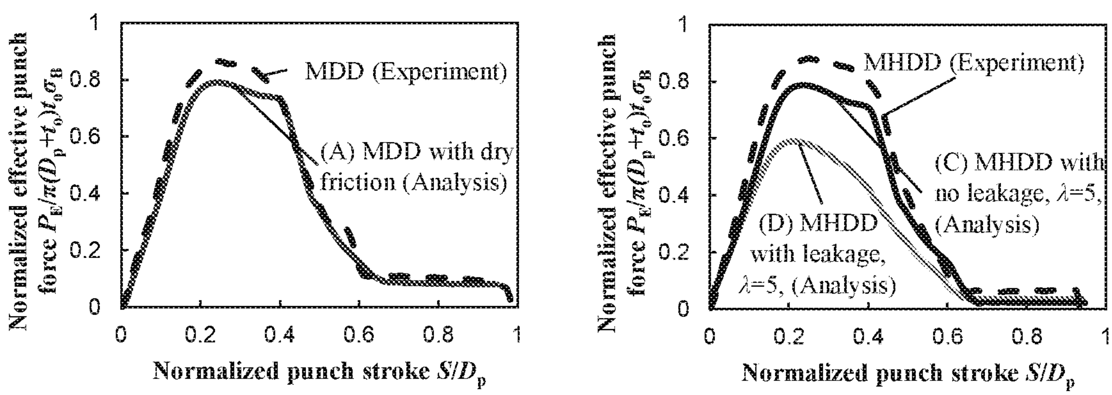
Lubrication conditions	**Inner pockets**	**Outer pockets**
(A) MDD with dry friction	μ_s=0.35, μ_d=0.30	μ_s=0.35, μ_d=0.30
(B) MDD with lubrication	μ_s=0.05, μ_d=0.03	μ_s=0.35, μ_d=0.30
(C) MHDD with no leakage (Blank-Side wall of die)	μ_s=0.05, μ_d=0.03	μ_s=0.05, μ_d=0.03
(C) MHDD with no leakage (Blank-BH, flange of die)	μ_s=0.35, μ_d=0.30	μ_s=0.35, μ_d=0.30
(D) MHDD with leakage (Blank-Die)	μ_s=0.05, μ_d=0.03	μ_s=0.05, μ_d=0.03
(D) MHDD with leakage (Blank-BH)	μ_s=0.35, μ_d=0.30	μ_s=0.05, μ_d=0.03
(E) MHDD with radial pressure	μ_s=0.35, μ_d=0.30	μ_s=0.05, μ_d=0.03
(F) MHDD with perfect lubrication	μ_s=0, μ_d=0	μ_s=0, μ_d=0

A pump which can provide a maximum pressure value of 20MPa was used in a hydraulic system. The dimension of tools used and material used in MDD and MHDD are the same as the FE analysis. The experiments of MDD were conducted under dry friction. The machine oil with the kinematic viscosity of $44 mm^2/s$ at 40°C was used for experiments of MHDD. The drawing speed was 0.4 mm/s.

RESULTS AND DISCUSSION

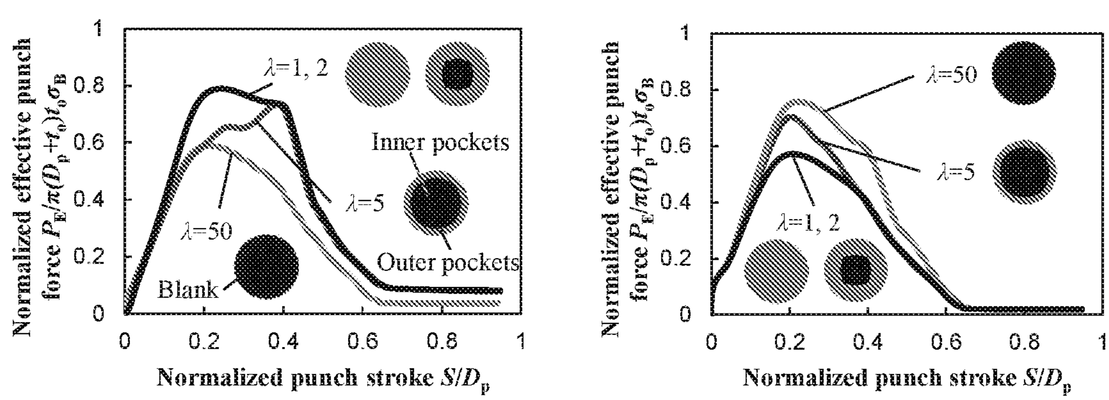
Fig. 3 shows the comparison of normalized punch force-stroke curve between experiment and analysis. The punch force-stroke curves obtained by experiment in MDD and MHDD are in good agreement with the analytical results of MDD with dry friction and MHDD with no leakage. However, the punch force-stroke curves between the MDD and MHDD are almost the same. The difference of effective punch force shows the difference of friction force. It means there is a high friction force in the experiment of MHDD due to no leakage of the fluid medium between the blank and die. Generally, the leakage makes the friction force low at die shoulder and flange area. However, the contact pressure between the blank and die becomes high at the die shoulder area due to small D_p/t in MHDD [7]. This prevented the leakage and caused the high friction force in MHDD.

Fig. 4 shows the effects of scale factor on the normalized punch force-stroke curves at MDD with lubrication and MHDD with radial pressure. The shape of punch force-stroke curves in λ=1, 2 is as similar as that with λ=50 at MDD and MHDD. In these conditions, only the inner or outer pockets exist in the flange area. Therefore, the friction coefficient in the flange area is almost uniform. On the other hand, in λ=5, the inner and outer pockets are mixed in the flange area. In the initial process, the inner pockets mainly exist at die shoulder and flange area and affect the tribological behavior significantly. Therefore, the punch force-stroke curves are as similar with that in macro scale. However, in the middle process, the ratio of outer pockets increases. Therefore the tribological behavior shifts to that in micro scale. This behavior appears at both MDD and MHDD. This causes the maximum punch force shifts as shown in **Fig. 4 (a)**. These results indicate the ratio of the outer pockets to the flange area during the forming process influences the tribological behavior.



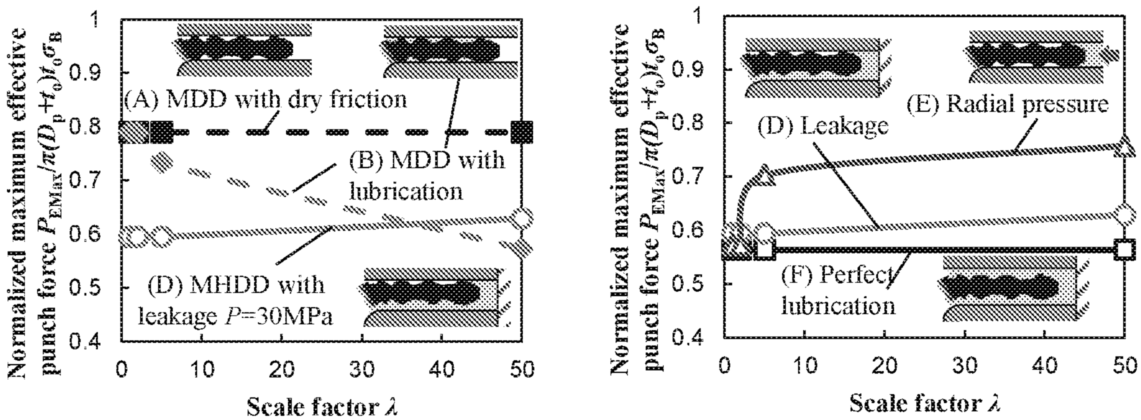
(a) MDD with dry friction (b) MHDD, P=10MPa

FIGURE 3. Comparison of normalized punch force-stroke curves between experiment and analysis.



(a) MDD with lubrication (b) MHDD with radial pressure, P=30MPa

FIGURE 4. Effects of scale factor on normalized punch force-stroke curve at different lubrication conditionss.



(a) Comparison of MDD and MHDD (b) Comparison of lubricate types in MHDD

FIGURE 5. Tribological size effects at different lubrication conditions in MDD and MHDD.

Fig. 5 (a) shows the tribological size effects in MDD and MHDD. With the decrease in the size, the friction force increases in case of MDD with lubrication because the ratio of outer pockets increase. When λ=1, 2, the maximum effective punch forces in MDD with the dry friction and lubrication become the same because only the outer pockets exist at flange area. On the other hand, with the decrease in the size, the friction force in MHDD decreases. It can be seen the tribological size effect in MHDD has an opposite behavior with MDD. In MHDD, the fluid medium is provided to the outer pockets whose ratio is high in micro scale. This caused the decrease in friction force in MHDD. This effect has been theoretically confirmed [7]. **Fig. 5 (b)** shows the effect of the lubrication type on friction force in MHDD. The decrease of friction force in radial pressure condition is much larger than that in leakage condition. Also in radial pressure condition, the friction force significant decreases from λ=5 to 1. It is because the contact pressure between the blank and die at die shoulder is higher than that between the blank and blank holder in the small D_p/t. Therefore, it can be seen that the decrease in friction coefficient at die shoulder is especially important to decrease the friction force in MHDD. According to the above results, the friction force can decrease with the decrease in size in MHDD, while it only increases in MDD. The friction force can be reduced by filling the fluid medium in the outer pockets in MHDD.

CONCLUSION

To model the tribological size effect in MDD and MHDD, the inner and outer pockets which have different friction coefficients are considered on the blank surface in FE model. Also, the low friction coefficient at the outer pockets is assumed in MHDD to consider the lubrication effect of fluid medium. The analytical results of punch force-stroke curves are in good agreement with the experimental results. The ratio of outer pockets to the flange area during forming process influences the tribological behavior. With the decrease in the size, the friction force can be reduced in MHDD because of the existence of fluid medium in outer pockets.

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