Friction Properties of Surface with Circular Micro-patterns

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***Abstract*—From the previous study, it is found that the spring-back of plate in a press forming can be reduced by changing the friction property of the plate and die in a press process. In the present study, the friction property of the die surface is varied by machining a micro-pattern on the surface. However, it is very hard to conduct the experiment for all combinations of different shapes of pattern and the number of the pattern per area. Hence, it is desired to estimate the friction property using a numerical simulation. In the present paper, a three-dimensional contact analysis is carried out for a circular micro-pattern and various contact conditions, an apparent friction coefficient of the plate with the pattern will be estimated through the comparison of experiment and numerical simulation. It will be shown that the friction coefficient can be evaluated using the numerical simulation.**

***Index Terms*—Micro-pattern, contact simulation**

I. INTRODUCTION

Until now, a lot of experiment on friction control for improving the performance of machines and the quality of industrial products has been carried out. There is several ways for controlling the friction property of surface. One solution is to manufacture micro-patterns on a surface. Gong *et al.* [1] conducted an elasto-plastic finite element analysis of a sphere in normal and sliding contact with a layered medium possessing a patterned surface with regularly spaced rectangular pads. They investigated the effect of pattern geometry on the contact pressure distribution and subsurface stress-strain field. Tianxiang *et al.* [2] developed an element-free Galerkin-finite element (EFG-FE) coupling method, combined with the linear mathematical programming technique, to solve two-dimensional elasto-plastic contact problems. Dini *et al.* [3] investigated the contact pressure and shear traction distributions for a sphere pressed onto an elastically similar half-space whose surface is populated by a uniform array of spherical asperities. They showed that the rough contact absorbs less energy than a smooth one subject to the same loading history under light shear loads. Loan *et al.* [4] developed a simplified algorithm to predict pressure distribution in elasto–plastic contacts. Lin *et al.* [5] presented a method for solving the two-dimensional (2-D) isothermal rough surface contact problem of general anisotropic materials with friction. Furthermore, a lot of studies on contact analysis have been done until now [6]-[15].

It is known that the surfaces with regular patterns have a specified friction property and wettability. Recently, it is required that the flow of materials into a mold is managed by the suppression part of wrinkles in a press forming. Now, the flow of material during the press process may be controlled using the press die surface with a fine micro-pattern. Arbitrary shapes of micro fine patterns can be produced using a recent advanced process technology. Then, there are too many combinations of the shape, the size and the arrangement of patterns. Furthermore, experiments on the investigation of friction property for the patterned surface have been conducted. However, all combinations of the shape and the number of pattern cannot be investigated in experiment. So, in the present study, a method that the friction property of the surface with a fine pattern can be estimated from a numerical simulation of three-dimensional contact analysis will be presented, and the evaluated values of friction coefficient are compared with those obtained from experiment.

II. EXPERIMENTS

A. Experiment Setup

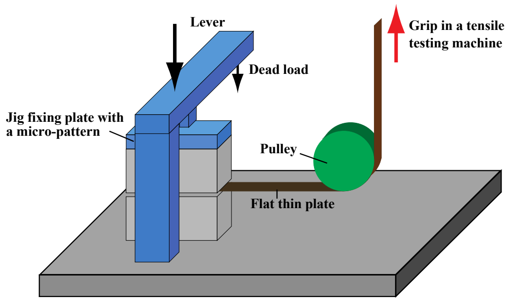

Figure 1. A schematic view of friction test apparatus.

Experimental apparatus is developed for evaluating the friction property of the plate with a pattern. A flat thin

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Manuscript received December 24, 2016; revised June 10, 2017.

doi: 10.18178/ijmerr.6.4.285-289

plate is set between two plates with the micro-pattern and is a constant load in the normal direction is applied to the flat thin plate. Fig. 1 shows a schematic view of the friction test apparatus. In this apparatus, a constant load is applied to the plate with the pattern using the principle of leverage. A flat thin plate is pressed by the patterned plates and is pulled at a constant tensile speed, 1mm/min, using a tensile testing machine as shown in Fig. 2.

Figure 2. Tensile testing machine (Tolerable load: 50kN) and friction test apparatus.

B. Experimental Condition

A precise figure for contact status is presented in Fig. 3.

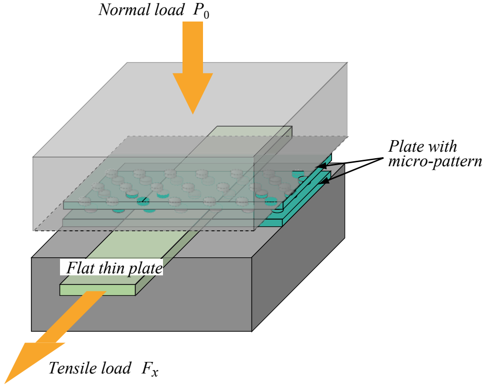


Figure 3. Precise contact status of flat thin plate with patterned surface.

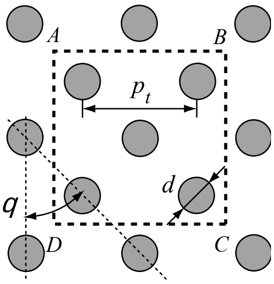


Figure 4. Configuration of micro-pattern.

In the present study, a circular pattern with sizes as shown in Table I is processed using a chemical etching technique. After the process, hard chromium electroplating or physical vapor deposition (PVD) of chromium is carried out on the patterned surface. Contact region of flat thin plate and the patterned plate is $10 \times 20 = 200\text{mm}^2$, and the number of circular pattern in the contact area is 421. The pitch and size of the circular pattern are shown in Fig. 4 and Table I. Material in the patterned plate is SKD11. For the evaluation of the friction coefficient, the normal load applied to the flat thin plate and the tensile load are recorded using computer and AD converter during the test. Experiment for several test conditions is prepared. Conditions in experiment are shown in Table II. For instance, conditions: 1) The flat thin plate are pressed by smooth flat plates, 2) The flat thin plate is pressed by the patterned plates, 3) The patterned plates processed by PVD is used, 4) and 5) One side surface in the flat thin plate is pressed by the plate with the pattern and the other is pressed by the smooth flat plate. These conditions are referred to as conditions 1, 2, 3, 4 and 5, respectively.

TABLE I. PARAMETERS IN EXPERIMENTS AND SIMULATIONS

Flat thin plate			steel	Aluminum
	Young's modulus,		210 GPa	68.3 GPa
	Poisson's ratio		0.33	0.34
Parameters	Normal load P_0		1.6kN	520N
	Tensile speed		1.0 mm/min	
Micro-patterns	Circle	Diameter d	100 mm	
		Pitch P_t	724 mm	
		Height	30.0 mm	
		Angle □	60.0°	
Plate with micro-pattern	Young's modulus,		210 GPa	
	Poisson's ratio		0.33	

TABLE II. CONDITIONS IN EXPERIMENT

	Upper surface		Lower surface	
Condition	Pattern	Coating	Pattern	Coating
1	Flat	Electroplating	Flat	Electroplating
2	Pattern	Electroplating	Pattern	Electroplating
3	Pattern	PVD	Pattern	PVD
4	Flat	Electroplating	Pattern	Electroplating
5	Flat	Electroplating	Pattern	PVD

III. NUMERICAL SIMULATION

Figure 5. Model for contact analysis using MARC.

The present study aims to investigate how to evaluate the friction coefficient between the flat thin plate and the patterned plate using a numerical simulation. In the present simulation, a general-purpose finite element program called as MARC is used for a three-dimensional contact analysis. All materials used in the simulation are isotropic and elastic. Contact status in experiment is modelled as shown in Fig. 5. The total number of element is 370,004 and total number of node is 365,019.

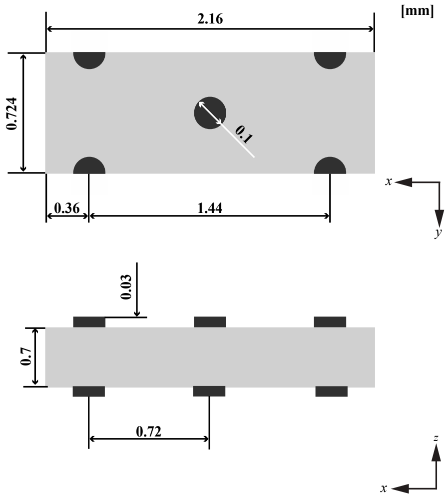
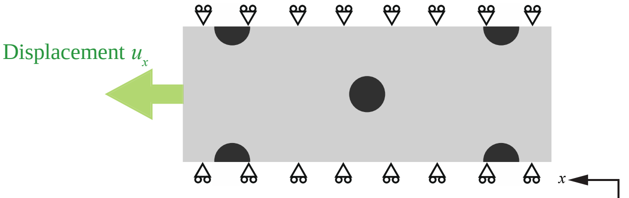
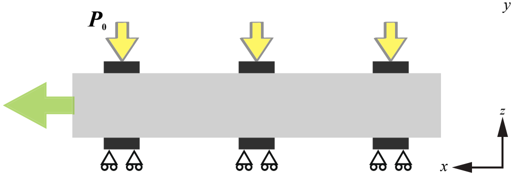


Figure 6. The size of model for analysis.



(a) *x*-*y* plane



(b) *x*-*z* cross section

Figure 7. Boundary conditions in the simulation.

The minimum size of element is 7m. The sizes of model for analysis are 2.16mm in length, 0.724mm in width and 0.7mm in thickness. Micro-pattern shape is circle in the analysis as shown in 6. The micro-pattern is 30 m in height. One circular pattern is placed at the center of the upper and lower surfaces and four one-half patterns are set on the both surfaces as shown in Fig. 5. In modeling of contact status, the symmetry of contact status with respect to the *x*-axis is considered. Boundary condition for the analysis is shown in Fig. 7. Fig. 7(a) and Fig. 7(b) represent the boundary conditions on the *x*-*y* plane and *x*-*z* cross section in the model. At the first stage, the flat thin plate is pressed by the patterned plate, at the second stage, the left side surface in the flat thin plate is pulled in the *x*-direction at a constant speed.

IV. Results in Experiment and Numerical Analysis

Fig. 8 represents a photograph of surface in the patterned surface. Very fine circular patterns are observed. Fig. 9 demonstrates a photograph of scratches formed in the flat thin plate of steel after experiment. At first, several fine traces of the circular micro-pattern remain on the flat plate, and then the plate with the micro-patterns slip on the flat thin plate. Then, several scratches of micro-pattern are observed.

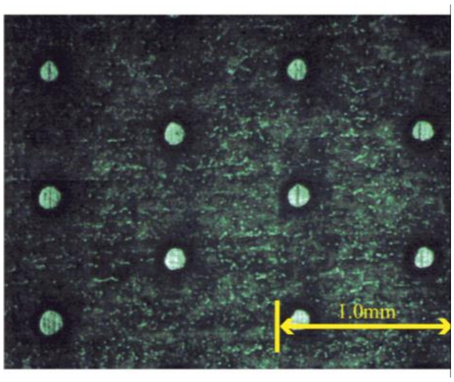


Figure 8. Photograph of surface with fine circular pattern.

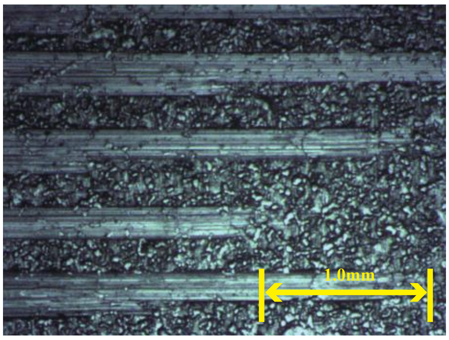
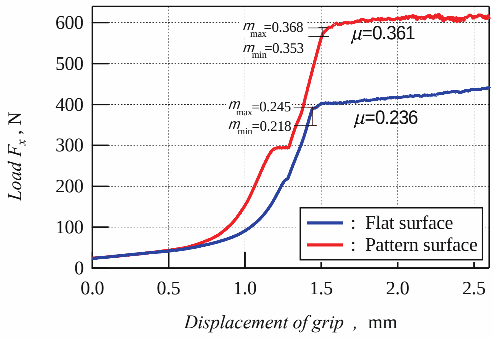
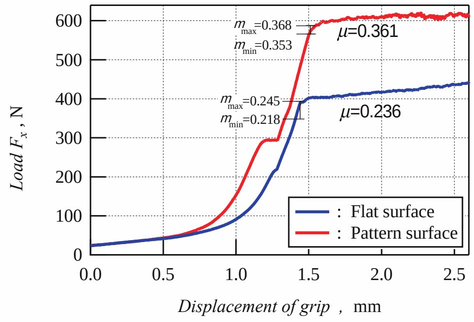


Figure 9. Photograph of scratched pattern in the steel flat plate.



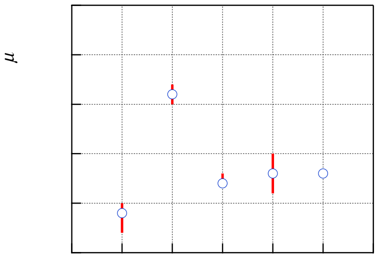
(a) Steel (Normal load: 1.6kN)



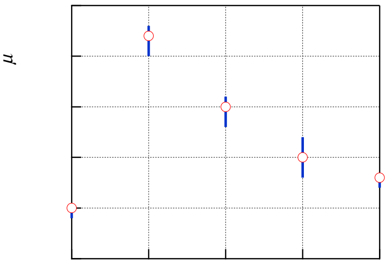
(b) Aluminum (Normal load: 520N)

Figure 10. Load against the displacement of grip.

Fig. 10 demonstrates a relationship between the tensile load and the displacement of grip in the tensile testing machine. Fig. 10(a) represents the result of steel flat plate and 10(b) that of aluminum flat plate. In the steel flat plate, the grip do not move apparently until the tensile load of 24N, after that, the load increases gradually. The steel plate without patterns slips about 400N under the condition 1 and 600N for the plate with pattern under the condition 2. In the aluminum plate, the grip does not move until 22.5N of the tensile load. The tensile load increases with the displacement of grip, the aluminum plate slips around 80N for smooth flat surface of condition 1 and 115N for the patterned plate of condition 2. Then, an apparent friction coefficient is evaluated from a ratio of the normal load to the tensile load at slip. It is found that the values of friction coefficient in the patterned surface are about 1.2-1.5 times larger than those without the pattern. The values of friction coefficient for different conditions in experiment are shown in Fig. 11. The results in the steel flat plate are shown in Fig. 11(a) and those in the aluminum flat plate are in Fig. 11(b). It is found that the value in condition 2 is the largest one than that in every other condition. The friction coefficients in condition 4 and 5, in which patterned surface is used in one side, yield the middle value of conditions 1 and 2.



(a) Steel flat plate



(b) Aluminum flat plate

Figure 11. A comparison of friction coefficients for several contact conditions.

Then, the friction coefficient will be controlled by combining these contact conditions. Next, the results in the simulation are shown.

In the simulation, the friction coefficient is set to be 0.24, which is obtained from experiment. Fig. 12 shows the deformation of the thin plate in the model for analysis. The flat thin plate firstly deforms by the normal load. The distribution map of shear stress on the upper surface indicated in Fig. 13 is shown in Fig. 14. It is found that shear stress concentrates at the edge of each micro-pattern in the tensile direction.

Next, an idea for evaluating a friction coefficient will be explained. It is very hard to integrate the shear stress for the whole contact areas due to the complexity of geometry of contact area. So, tensile stress, σ_{xx}, in the tensile direction at the side surface applying the forced displacement is integrated for the cross section of thin plate. This force balances with the total of shear stress.

The friction coefficient, μ_a, can be evaluated using Eq. (1).

$$\mu_a = \frac{1}{P_0}\int_A \sigma_{xx}\, dA \tag{1}$$

where A represents the area of cross section of the thin plate and P_0 is the normal load.

The friction coefficient of surface with circular micro-patterns in condition 2 for the steel flat plate was estimated as $\mu_a = 0.38$. This value in simulation is a little bit larger than that in experiment. In the present analysis, it is assumed that all materials are elastic and isotropic. In the next step, at least the flat thin plate should be set to be elasto-plastic materials. Though there are several issues in the present simulation, the calculated value is fairly well. So, it is supposed that the proposed method can be adequately estimated the friction coefficient.

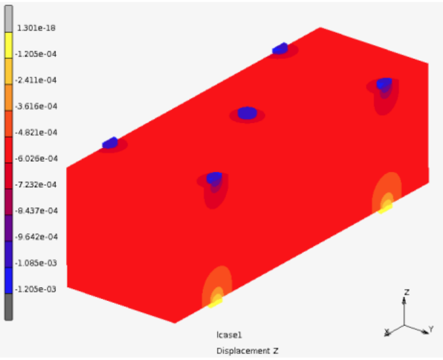


Figure 12. Deformation of whole model.

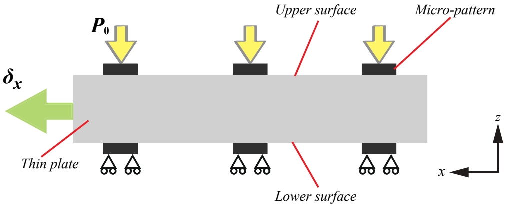


Figure 13. Mapping plane of shear stress.

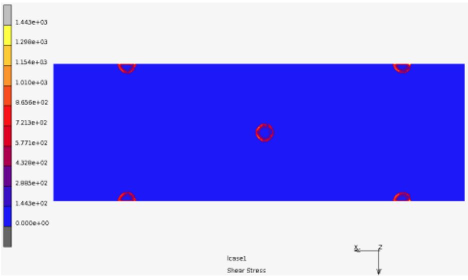


Figure 14. Contour map of shear stress, τ_{xy}

V. CONCLUSIONS

In the present paper, friction coefficients were evaluated by experiment and the numerical simulation for improving the controllability of metal forming in the press working. In particular, a method calculating the friction coefficient using the result obtained from the simulation was presented. Then, the stress distribution around the pattern was also investigated. The results in the present study are summarized as follows:

1. Newly developed friction testing machine yielded repeatedly the similar value of the friction coefficient for the same condition in experiment. The friction coefficient in the aluminum plates was larger than that in the steel plates. The friction coefficient in the patterned surface plates was larger than that in the smooth surface.

2. The distribution of shear stress on the patterned plate concentrated at the edge of the circular micro-pattern.

3. Evaluated friction coefficients were almost similar values to the values in experiment. This result indicates that the calculation method of the friction coefficient in the simulation is adequate.

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