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Determination of friction law in metal forming under oil-lubricated condition

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ABSTRACT

Frictional behaviour under oil-lubricated conditions is studied in compression of a steel sheet by a DLC coated tool. The average frictional stress increases linearly with the average pressure first, then decreases and finally increases linearly again. This tendency is not affected by the lubricant viscosity, lubricant thickness and the stress state of the specimen. It is concluded that the decrease of the frictional stress with increasing average pressure is due to the decrease of the ratio of real contact area, which is caused by the lubricant pressure in closed pools. A new law of friction under oil-lubricated condition is proposed.

1. Introduction

Recently, process simulation by FEM analysis has become precise enough and is used commonly in metal forming factories. But the friction data used in the simulation is not as accurate as the simulating method and the material data. Thus, establishment of accurate friction law is desired in designing the processes which are affected significantly by the frictional condition, such as plate forging [1].

In the previous paper, a friction law under dry condition is proposed [2]. The main feature of this friction law is Coulomb friction up to a critical pressure p_{cr}, and a constant frictional stress for higher pressures as shown in Fig. 1. p_{cr} of this friction law can be determined by measuring the friction coefficient μ at any average pressure lower than p_{cr}, and can be included in the FEM codes easily. In this paper, the friction law with liquid lubricants is discussed.

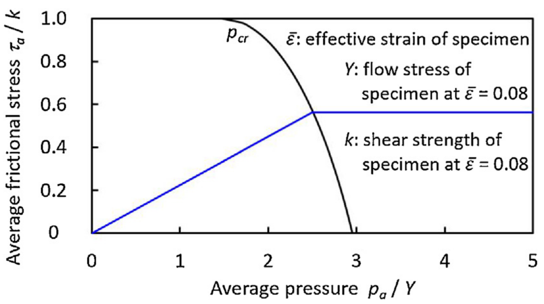

Fig. 1. Friction law under dry condition [2].

2. Friction and lubricating models for liquid lubricant

Fig. 2 shows the interface model between a flat tool and a workpiece with liquid lubricant [3]. When the frictional shear stress at the real contact area is τ_r and the shear stress of the lubricant is τ_l, the nominal frictional shear stress τ_a is given by:

$$\tau_a = \alpha\tau_r + (1-\alpha)\tau_l \tag{1}$$

where α is the ratio of real contact area.

If the pressure p_r of the real contact area and the average pressure p_l of the lubricant are known, the nominal contact pressure p_a is:

$$p_a = \alpha p_r + (1-\alpha)p_l \tag{2}$$

Then the average friction coefficient μ is given by:

$$\mu = \frac{\tau_a}{p_a} = \frac{\alpha\tau_r + (1-\alpha)\tau_l}{\alpha p_r + (1-\alpha)p_l} \tag{3}$$

As long as the liquid lubricant can flow out from the gap (open pool), the average pressure p_l of the lubricant is zero, and the shear stress τ_l of the lubricant is usually negligibly small, $\tau_l = 0$. In this case, Eq. (3) becomes:

$$\mu = \frac{\tau_r}{p_r} = \mu_r \tag{4}$$

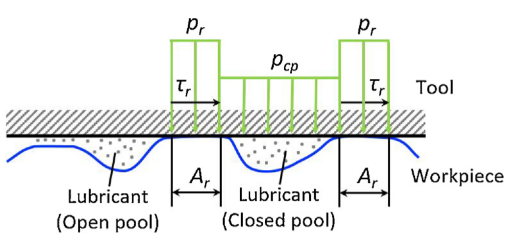

Fig. 2. Schematic illustration of contact area with liquid lubricant [3].

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This situation continues until the lubricant is trapped into independent reservoirs as is called closed pool and the average pressure p_l of the lubricant begins to increase.

Kudo [4] and Nellemann et al. [5] suggested a theory to determine the friction coefficient taking the trapped lubricant into consideration.

Azushima [6] proposed a model like that shown in Fig. 2 based on the results of in situ observation. He suggested that micro roughening takes place and the lubricant trapped in the pool is permeated into the real contact area under a nominal contact pressure close to the yield strength of the workpiece.

Bech et al. [7] calculated the hydrostatic and hydrodynamic lubricant pressure in the pool and suggested that the lubricant in the pool can be dragged out. Wang et al. [8] proposed a model on the friction reduction due to the lubricant escape from the lubricant pool.

Geiger et al. [9] studied the size effect of friction in micro forming based on the fact that the lubricant trapped in the closed pools can transmit the forming load and thus reduce friction.

Zhang et al. [10] investigated the difference of frictional behaviour between starved lubrication state and abundant lubrication state.

However, as Azushima [6] pointed out, the pressure dependence of the friction coefficient cannot be understood well by the lubricating model shown in Fig. 2.

3. Experimental methods and conditions

Since the presently used testing method has been reported in the previous paper [2], only the testing principle is shown in Fig. 3. A specimen is fixed at the left end, and stretched at the right end with a constant load. The compression tool is pushed upwards to compress the specimen with the friction tool and then the friction tool is slid on the surface of the specimen. During sliding, the compressing load and the frictional force are measured.

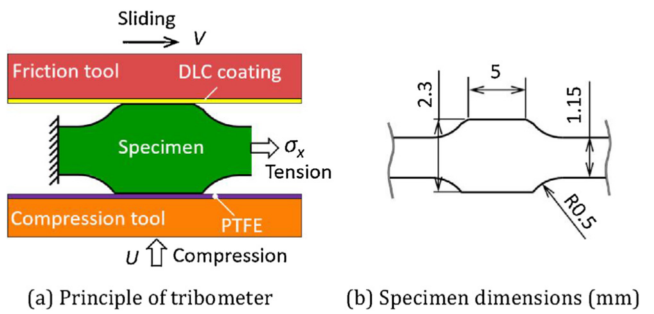

Fig. 3. Schematic illustration of testing method [2].

The specimen is cut off from a cold rolled steel sheet SPCC and the flow curve is determined by tension test to be $Y = 548(\varepsilon + 0.005)^{0.21}$ MPa. The yield strength Y_0 is 180 MPa and the flow stress to be used in the dimensionless average pressure $Y_{\varepsilon=0.08}$ is 326 MPa [11]. The surface roughness of the specimen is 10.2 μmR_z.

Two paraffinic mineral oils are used: P100 (viscosity at 313 K: 100×10^{-6} m^2/s) and P10 (viscosity at 313 K: 10×10^{-6} m^2/s).

The thickness of coated lubricant h_0 is controlled to be 0.5 and 7.0 μm by using mixtures of the lubricant and ethanol. The specimen is cleaned by acetone and then is dipped in the mixture. After vaporization of ethanol, the lubricant with the controlled thickness is left on the specimen surface. The lubricant thickness is calculated by using the difference in weight before and after lubricant coating.

4. Experimental results

4.1. Frictional behaviour

Fig. 4 shows the relationship between the average frictional stress and average pressure for the lubricant P100 under a side-stretching stress $\sigma_x = 0.8Y_0$. The round circles are obtained in high

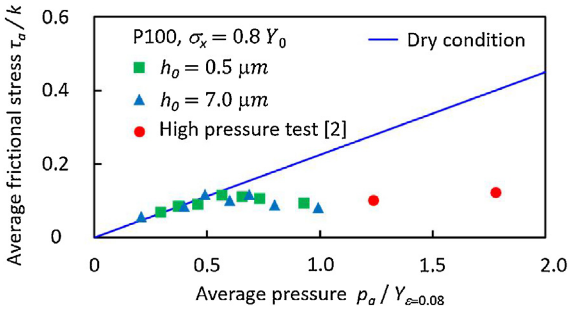

Fig. 4. Relation between average frictional stress and average pressure for P100.

pressure test [2] under lubricated condition with the lubricant P100. When the average pressure $p_a/Y_{\varepsilon=0.08}$ is lower than 0.5, the experimental points drop on the line of dry condition.

When $p_a/Y_{\varepsilon=0.08}$ becomes higher than 0.5, the average frictional stress shows a slowdown increase, then turns to decrease at around $p_a/Y_{\varepsilon=0.08} = 0.7$ and finally increases linearly again at higher pressures of $p_a/Y_{\varepsilon=0.08} > 1.0$. No large difference can be found for different thickness of the lubricant.

As shown in Fig. 5, the lubricant P10 with a lower viscosity shows the same tendency as that for the lubricant P100, but the average frictional stress is slightly higher.

In Fig. 6, the effect of the side-stretching stress on frictional behaviour is shown. It is clear that the stress state of the specimen does not give influences on the frictional behaviour.

Fig. 7 shows the variation of the average frictional stress in the friction test under stepdown average pressures. The specimen is compressed first to the average pressure $p_a/Y_{\varepsilon=0.08} = 0.4$ and the

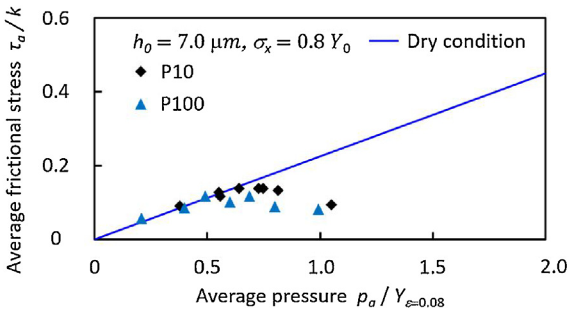

Fig. 5. Influence of lubricant on frictional behaviour.

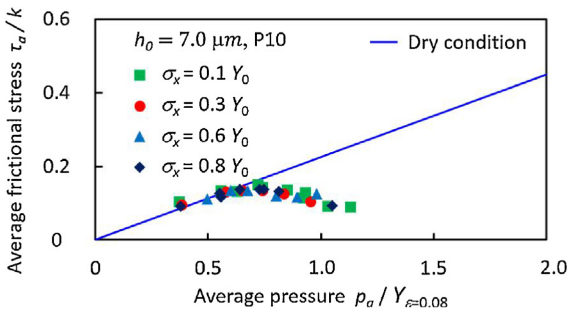

Fig. 6. Effect of side stretching stress on frictional behaviour.

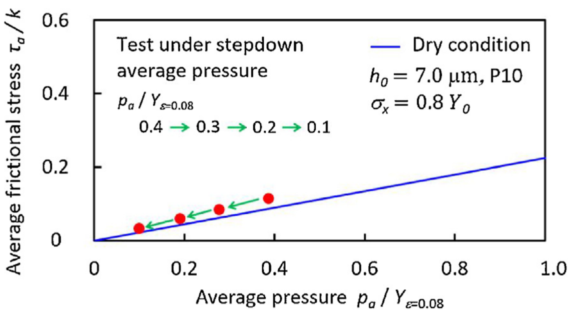

Fig. 7. Frictional behaviour under stepdown average pressure.