Effects of surface finish and die temperature on friction and lubrication in forging

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Abstract

In this study, ring compression test was conducted to investigate i) effects of surface topography on friction and lubrication at room temperature with both dry and lubricated conditions, and ii) the effect of die temperature on friction and lubrication by differentiating temperatures of die and ring samples. Findings from experiments and FE results lead to develop a pressure-dependent variable friction model that concurrently changes friction factor during the forming stroke and different contact surface areas. The constant frictional model and this variable friction model were used in FE simulations of ring compression. The prediction results were compared with experimental results in details. The use of variable friction model gave very good correlations of the final ring geometry than other constant friction models in comparison to experiments. This implies that the pressure-dependent variable friction model can better characterize the interfacial friction condition in cold forging applications. In the ring compression with heated dies, the temperature rise was found to degrade the performance of lubricant, which resulted in the tapered shape ring. Therefore, the effect of surface topography and die temperature on interfacial friction condition with lubricant viscosity should be considered for the improved friction model for FE simulations of forging processes with high stroking rates.

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1. Introduction

The ring compression test was extensively used to evaluate friction and lubrication (Male et al., 1970; Altan et al., 1983). This test has an advantage when applied to the study of friction under cold forming conditions. In order

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to measure friction with this test, the force necessary to deform the ring and the flow stress of the specimen are not necessary to know. Thus, evaluation of test results is greatly simplified (Altan et al., 2005).

In the ring compression test, a flat ring-shaped specimen is compressed to a known height reduction. The change in internal and external diameters of the compressed ring is significantly sensitive to friction condition at the die-ring interface, as shown in Fig. 1. With increasing deformation, if friction is high, the internal diameter is reduced, while if friction is low, the internal diameter increases. Thus, the change in the internal diameter is used as a friction indicator. The friction condition is expressed as the shear friction factor (m), which can be quantified by comparing the internal diameter of the compressed ring to the values predicted by using various constant shear friction factors in a theoretical analysis (Altan, 1983). Today, these values are most often predicted by the Finite Element Method (Altan et al., 2005).

![Compressed Ring and Original Ring with Neutral Plane](image)

**Fig. 1. Principle of the ring compression test [Altan, 1983].**

2. **Objectives**

   The objectives of this study are to:
   - Find the effect of surface topography (i.e. surface roughness and real area of contact) on friction and lubrication
   - Develop a pressure-dependent friction model for cold forging process simulations
   - Verify the developed friction model with the FE simulation of ring compression

3. **Approach**

   The ring compression test was conducted with the compression test tooling (Fig. 2) installed in a 160-ton hydraulic press. The upper and lower die plates of tooling are made of AISI 4340 steel, while the die insert used for the test was made of D2 tool steel (hardness of HRC 60). A 200-ton load cell was mounted at the top of the tooling to measure the load during the test.

   Two sets of aluminium 6061-T6 ring specimen were prepared to have specific dimensional ratios (OD: ID: H = 2: 1: 1 as shown in Fig. 2) for the test. One set has nominally flat surface, referred as “normal ring”, while the other set has semi-micro-scale machined grooves on top and bottom ring surfaces, referred as “grooved ring” as shown in Fig. 3. The purpose of these grooves is to measure the change of surface topography (i.e. real contact area ratio and surface roughness) in semi-micro scale. The geometry of groove was selected from literature (Wanheim et al, 1973; Bay et al., 1975). It is known that the groove angle (γ) is not sensitive to the change of the real area of contact ratio (Wanheim et al, 1973). In this study, to exclude the effects of temperature on friction and lubrication, experiments were conducted at room temperature under dry and lubricated conditions. A commercial cold forging lubricant, MEC HOMAT, was used in ring compression tests for lubricated condition.
Surface profiles of ring and die surfaces were measured by using the mechanical stylus profiler. The average surface roughness, $R_a$, of die inserts was measured as 0.02 $\mu$m and this value was negligible in comparison to the grooved ring surface measured as 300 $\mu$m, which is about 15,000 times bigger than the surface roughness values of a normal ring (0.1 ~ 0.2 $\mu$m). The surface profile of the grooved ring specimen was also measured and confirmed to have consistent grooves by the optical microscope. Experiments were conducted with both grooved rings and normal rings at up to eight different reductions in height (4.5/10/15/19/30/38/48/50%) at both dry and lubricated conditions. To precisely compress the ring sample up to the specific reduction in height, different sets of stoppers made of tool steel were used at different compression levels.

Ring compression tests were also conducted at elevated temperatures. Ring specimens were made from AISI 1018 HR steel. Same dimensions of the ring were used as described in Figure 2. Extrudoil-51-DO was used to lubricate the ring specimen. Different combinations of upper and lower dies, and ring temperatures were prepared before upsetting the ring sample. In case of elevated temperature tests, the ring specimens were placed in an oven at 150°C for 3 hours and the die surfaces were heated to 150°C using band heaters. Temperature of the ring was measured using a J-type thermocouple at a drilled hole of the ring specimen to ensure the testing temperature as 150°C. The final OD and ID of the compressed ring are measured and indicate the performance of the lubricants at the elevated die/workpiece temperatures.

4. Results

4.1 Effects of surface topography on friction and lubrication at room temperature

The load-stroke curves were measured during the upsetting tests with grooved and normal ring samples under dry and lubricated conditions at 47% reduction in height. As shown in Fig. 4, dry ring samples gave higher load
than lubricated ring samples, regardless of surface finish (flat or grooved). In dry condition, the load stroke curves for grooved and normal ring samples are almost identical. However, in lubricated condition, grooved ring samples showed higher load than normal samples as the stroke increased. The local contact pressure at the summits of grooved ring is much higher than the normal ring. The reason may be that lubricant film on the summits of grooved ring can be easily “depleted” while this is not the case in using the normal ring. As a result, in lubricated conditions, the metal-to-metal contacts between die and grooved ring can be higher than those between die and normal ring. Thus, the lubricant film can easily break down while compressing the grooved ring. This implies that, in lubricated mating surfaces, the surface topography significantly influences the lubrication, which determines the interface friction.

Fig. 4. Load stroke curves measured in experiments (left), and the measured inner diameter of the ring sample (right).

As shown in Fig. 4, the ID (inner diameter) was measured in grooved and normal rings tested at different reductions in height under dry and lubricated conditions. As expected, the inner diameters of lubricated ring samples are larger than those of dry ring samples, regardless of surface finish. In comparison to lubricated groove sample, the lubricated normal sample showed slightly larger inner diameter, which indicates a lower friction. From Figure 4, it was found that surface topography significantly affects the friction condition at the die-ring interface. The rougher the surface (i.e. grooved ring), the larger the friction value regardless of reduction in height.

4.2 Developing the pressured-dependent friction model

A friction model function of the contact pressure was developed based on both experimental and FE simulation results for ring compression [Kim and Altan, 2006]. The material properties (i.e. flow stress) of the ring specimens (Al 6061-T6) for FE simulation were obtained using the standard cylindrical compression test. The strength coefficient, K, and the strain-hardening exponent, n, were determined as K = 412-MPa and n = 0.019 by the curve fitting method. The coefficients of the friction models were determined through FE simulations and experimental results. To determine the pressure-dependent friction model, the experimental load-stroke curve and the measured ring geometry were used to calculate the average (nominal) contact pressure-stroke curve. This curve was used with time-dependent friction data, which is obtained from the friction calibration chart, as inputs of modeling procedure. By analyzing the tendencies of a) avg. contact pressure vs. stroke and b) friction vs. stroke, the relationship between friction and pressure were determined. However, this pressure is an average value of contact pressure at the die-ring interface. Therefore, it should be compensated by the local contact pressure predicted by FE simulation with the time-dependent friction model.

Finally, the pressure dependent friction model was determined for both dry and lubricated conditions as shown in Fig. 5 by comparing the FEM prediction with experimental results. As shown in Figure 6, the final ring
geometry measured in experiment showed good correlation with FE predictions with the pressure-dependent friction model compared to other friction models.

Fig. 5. Pressure-dependent friction models used in FE simulations ($m_{p1}$: friction model for dry condition, $m_{p2}$: friction model for lubricated condition, and $P$: the die-workpiece contact pressure).

Fig. 6. Comparison of final ring geometry between developed friction models and experiments with dry condition at 48% reduction in height.

5. Effects of die temperature on friction and lubrication

To investigate the effects of temperature on flow stress and lubrication condition, ring compression tests were conducted by using differential heating of the dies. Table 1 gives the experimental results at various heating and lubrication conditions. Note that TD and BD mean the top and bottom dies, respectively.

The final geometry was most likely a result of differential heating of the upper and lower dies (RC1 in Table 1). The differential heating may have resulted in different lubrication conditions at the top and bottom of the ring surfaces or different flow stress conditions at the top and bottom of the ring surfaces. Similar taper shape of the ring was observed in differential lubrication of the top and bottom rings (RC3 in Table 1), while the uniform ring diameters (ID) were obtained from the uniform lubrication and heating conditions at the top and bottom of the ring.
surface (RC2 in Table 1). Inverse analysis technique based on finite element code (DEFORM-2D) was conducted to identify the flow stress of ring and the shear friction value, m, at the tool-workpiece interface by comparing with experimental data of inner diameter, ID. Table 1 gives the friction factor, m, identified from the inverse analysis. Non-isothermal condition in FE simulation enables to predict the temperature distribution on the ring surfaces.

Table 1. Experimental results.

| Test Conditions | Final Ring Geometries | Friction Factor (m) |
|-----------------|-----------------------|---------------------|
|                 |                       | Top | Bottom |
| **RC1**         |                       |     |        |
| Lubricated (top & bottom) | ID: 19.78 mm (top), 20.56 mm (bottom) | 0.14 | 0.11 |
| TD: 150 °C      |                       |     |        |
| BD, Ring: 5°C   |                       |     |        |
| Speed: 65mm/sec |                       |     |        |
| **RC2**         |                       |     |        |
| Lubricated (top & bottom) | ID: 19.81 mm (top & bottom) | 0.14 | 0.14 |
| TD,BD,Ring: 150 °C |                    |     |        |
| Speed: 65mm/sec |                       |     |        |
| **RC3**         |                       |     |        |
| Dry (top)       |                       |     |        |
| Lubricated (bottom) |                    |     |        |
| TD,BD,Ring: 150 °C | ID: 18.71 mm (top), 19.98 mm (bottom) | 0.3  | 0.14 |
| Speed: 65mm/sec |                       |     |        |

6. Conclusions

The following major conclusions were drawn in this study.

1. The effect of surface topography (i.e. surface roughness and the real area of contact) on friction increases and the constant friction factor may be limited to predict the complex part geometry in cold forging simulations.

2. The constant friction model shows limited accuracy to predict the detailed geometries (ID and OD) of the compressed ring. A pressure-dependent friction model showed consistently good correlations with experiments in both dry and lubricated conditions.

3. The performance of the lubricant at the die-workpiece interface is affected by temperature as shown in the tapered ring geometry, obtained in the experiments and simulations.

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