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Friction effects during open-die micro-forging/extrusion processes: an upper bound approach

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Abstract

In microforming processes it is preferred to not to use lubricants, due to their complex behavior in micro-scale. Nevertheless, using lubricants could increase the life time and decrease the required forming load. Thus, it is necessary to study and develop an analytical solution for different lubrication conditions in microforming processes. A previously studied upper bound model was modified in this study for various lubrication conditions in an open-die micro-forging/extrusion process. Two approaches were chosen for identifying the friction factor in the model: (i) global friction factor, (ii) localized friction factor. Comparison of the modeling results with the experimental showed the reliability of the second approach, providing a better fit.

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Keywords: Microforming; Friction; Microstructure; Size effect.

1. Introduction

There is a large variety of tests for friction coefficient determination; although, only a few of them are applicable to scaling experiments (Taureza et al., 2012). A conventional method to study the effect of

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miniaturization on friction (friction size effect) is the ring compression test, for which an increase in friction is reported by scaling down (Chan et al., 2011). In this test, changes in the inner diameter of a ring during upsetting test is used for determination of the friction coefficient (Deng et al., 2011).

Nomenclature

a,b	constant
J_r^*	upper bound on energy consumption rate; applied power (J/sec)
m	friction factor
σ_0	effective flow stress (N/mm^2)
T	blank thickness (mm)
v_p	punch velocity (m/sec)
R_n	neutral plane radius (mm)
R_0	punch radius (mm)
$\dot{W}_i$	internal rate of power of deformation (J/sec)
$\dot{W}_f$	frictional rate of power loss (J/sec)

The friction effects at micro-scale have been explained by the lubrication pockets model (Geiger et al., 2001). Based on this model, the lubricant escapes out to the surface from those valleys which have a connection to the edge of the surface. These are so-called open lubricant pockets. In this case, the lubricant is not able to transfer loads on the surface. Therefore, the forming pressure acts only on the asperities, which flatten the contact surface and leads to higher friction (Daw-Kwei, 2009).

In comparison, closed lubricant pockets do not have any connection to the edge of the surface. Consequently, the lubricant gets trapped in these valleys, and it can transfer load on the surface. The resulting hydrostatic pressure reduces the normal pressure on the asperities, which leads to a lower friction (Engel, 2006).

Bech et al. (1998) reported that due to the size effect, there is relatively less lubricant on the surface of the micro-parts than that of macro-parts. This leads to a weaker lubrication effect, and an increase in the coefficient of friction for the micro-parts (Sørensen et al., 1999). The increase in friction stresses can result into galling, excessive pressure on tool, and reverse forming (Eriksen et al., 2010).

Thus, a few models have been developed to explain the frictional behavior via investigating the surface roughness (Weidel and Engel, 2009). However, as reported by Jeon and Bramley (2007), these models are not accurate in the case of high friction stresses (high pressures). Besides, determination of the surface roughness parameters can be difficult sometimes due to process geometries (Ghassemali et al., 2013c).

In a previous study (Ghassemali et al., 2013b), the Upper Bound Theory was used to find a universal solution for the open-die forming processes in dry condition. Developing such a model can be used as an alternative solution for evaluating different lubrication conditions. This could also help in gaining a deeper understanding of the in-process material behavior.

Therefore, the aim of this work was to study the effect of lubricants with different friction factors on the material behavior during the open-die micro-forging/extrusion process. After studying the friction effects on the final part dimension and the required forming load, the developed Upper Bound model was justified to evaluate the friction effects on the solution.

2. Materials and methods

2.1. Microforming process

As discussed in a previous study (Ghassemali et al., 2013c), a progressive microforming process was used for the manufacturing of micro-pins, which consisted of two stages: (i) Pin forming by forward extrusion, and (ii) Blanking. In the first stage, which is the main stage, the strip is deformed by a punch of a defined diameter, and specified displacement. As a result, a portion of the material is forward extruded into the die orifice. In the second stage, the formed pin is blanked out from the strip material. More details of the process can be found in (Ghassemali et al., 2013b).

Electrical Tough Pitch (ETP) C11000 copper (99.94%) strips, in the as-received cold-rolled condition, with 200 mm in length and 20 mm in width were used as the raw initial feed for the process. The thickness of the strips was determined based on the desired pin dimension.

2.2. Lubricants

Two different liquid lubricants with different viscosities were used as compared to the dry condition: (i) WISURA Z0 3373 (Oil, High viscosity 140 cSt), (ii) FUCHS Ecocool (Emulsion, 10% in water, Low viscosity 95 cSt). Teflon layers with thickness of 0.1 mm were also used as a solid lubricant. The dies were dip-drawn in the liquid lubricant using ultrasonic vibration to help the liquid to flow better inside the die orifice. In the case for solid lubricant (e.g. coating), it was extremely difficult or near impossible to coat a uniform layer of solid lubricant inside the entire micro-die orifice thoroughly.

The friction coefficient of each condition was determined by ring compression test and FE-simulation, using a ring with dimension ratios of 10:5:2.5 mm (as for outer dia., inner dia., and thickness). All the experiments were done at least three times to assure the reproducibility of the results.

2.3. Characterization methods

A programmable servo press (SCHMIDT ServoPress 420) was used for the deformation process. The load-displacement behavior of the punch was monitored by the machine precisely, with a resolution of 0.01 kN.

The final dimension of the micro-pins was measured via micrometer and confirmed with microscope, as mentioned in detail in a previous study (Ghassemali et al., 2013c).

3. Results and discussion

The result of the ring-compression test was used to determine the friction factor for different lubricants, as presented in Table 1. The Teflon film was adhered thermally to the die surface by heating the die up to 150°C.

Table 1. Shear friction factor for various lubricants determined using ring compression test.

Lubrication Condition	Non (Dry)	Wisura	Fuchs	Teflon
Shear Friction Factor	1	0.55	0.3	0.25

3.1. Friction effects on the part dimension and forming load

To ensure the accuracy of the results, the lubricant effects were investigated on different pin diameters from micrometer (0.3 mm) to millimeter range (1.2 mm). Considering the standard deviations, no significant lubricant effect on the pin dimension can be seen in Fig. 1a. This behavior is justified by the open nature of the process, which is governed by the neutral plane (Ghassemali et al., 2013a). It is worth to note that the lubricant had a negligible effect on the surface condition of the final part, as reported previously (Ghassemali et al., 2013a).

In the case of forming load, a decrease in the friction factor leads to a drop in the forming load, as shown in Fig. 1b. The difference in the forming load is relatively larger in Stage (II) of the diagram (where is responsible for the compression phenomenon, described in a previous study (Ghassemali et al., 2014)).

Indeed, it has been proven that especially in open-die forming processes, in which the lubricant could have a way to escape out, the lubricant effect is more significant at the beginning of the process (low normal pressures). In case of solid lubricants, experiments showed that the Teflon film was torn off during the process. Consequently, there was relatively much less lubricant existed at the blank-die interface during the last Stage of the process. This is shown in Fig. 1b, where the difference in curves' height is less at the end of the process.

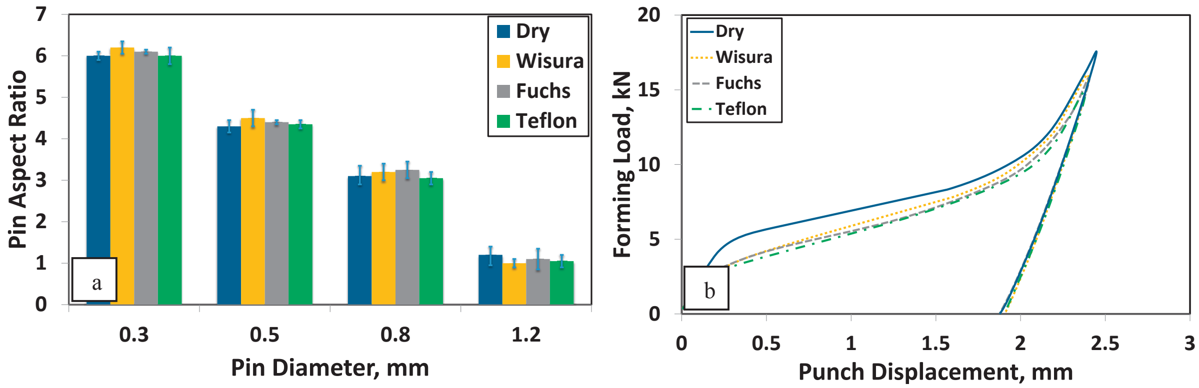

Fig. 1. Friction effects on (a) the final pin dimensions for various pin diameters manufactured by the 2.0 mm punch, and (b) the forming load behavior during production of the 0.3 mm pin using 2.0 mm punch.

It is important noting that the same behavior was seen in the case of using different punch diameters. To thermally adhere the Teflon layer on the die wall, the die diameter must be big enough to be accessible. Thus, the 1.2 mm die was selected and heated up to 150°C. After that, a 0.1 mm thick solid film of Teflon was adhered on the whole surface of the die, including inside the die orifice. This provides a well-adhered layer of Teflon on the die surface and inside the orifice.

After pin forming, although there was Teflon tear off seen on the die surface, the Teflon film inside the die orifice affected the material behavior during the process, as depicted in Fig. 2. Due to effective lubrication inside the die orifice, the pin height was increased by about three times. Indeed, Fig. 2 implies the importance of the lubricant inside the die orifice.

However, after consulting with related industries and, as mentioned above, it was found to be technically difficult to coat the Teflon inside the die orifice by any method. Especially as the die orifice gets smaller in diameter. It is worth noting that applying lubricants on the punch surface had a negligible effect on the material behavior in the process.

3.2. Upper-Bound solution in different lubrication condition

The modified Upper Bound model was justified for different lubrication conditions. To do so, the critical thickness was firstly calculated for production of the 0.3 mm micro-pin using 2.0 mm punch. Based on the previous study (Ghassemali et al., 2013b), the critical thickness was found to be roughly 0.56 mm.

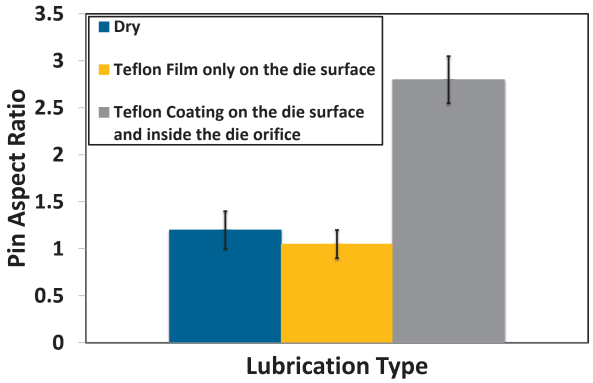

Fig. 2. Effect of solid lubricant (Teflon), coated on different part of the forming tool, on the final pin aspect ratio for the 1.2 mm pin manufacture by the 2.0 mm punch.

The next step would be changing the friction factor in the model, for which two approaches were selected as being described in the following sections.

3.2.1. Approach one: Global friction factor

One approach could be just to change the global friction factor in the model according to Table 1. Figures 3a and 3b show the result for the required forming pressure and calculated pin height, respectively. As can be seen, there is a discrepancy between experimental and modeling results for different lubricants. Thus, this approach could not be considered accurate and usable for studying the process under the mentioned circumstances.

3.2.2. Approach two: Localized friction factor

The above-mentioned miss-match could be due to the fact that the friction factor was considered globally i.e. the same throughout the process interfaces. However, as discussed in (Ghassemali et al., 2013b), the material showed different behavior during various process stages. Therefore, in another approach, two different friction factors was considered for different regions in the deforming material during the process.

Based on our observations, the lubricant effect is less during the last Stage of the process (Extrusion Stage). Thus, the hypothesis was defined as almost no lubricant effects for the Extrusion Stage. Therefore, the shear friction factor was assumed as equal to 1 for inside the die orifice in all lubrication conditions, while the friction factor for the rest of the interface was defined according to Table 1 for each lubricant. The m value in Eq. (1) was considered as m_1 equal to respective values in Table 1.

As shown in Fig. 4, there is a good fit between experimental and modeling results using the localized friction factor (approach two). Consequently, the friction behavior in modeling of the forming process must be considered based on the phenomenological studies on the material behavior during forming.

$$J_r^* = \dot{W}_i + \dot{W}_f = -\frac{\pi}{\sqrt{3}}\sigma_0 v_p R_n^{\,2}\left\{a\left(R_n\right) - 2 - ln\left[b\left(R_n\right)\right] + \frac{2mR_n}{3T}c\left(R_n\right)\right\}, \tag{1}$$

where

$$c\left(R_n\right) = 2 + \left(\frac{R_0}{R_n}\right)^3 - 3\left(\frac{R_0}{R_n}\right). \tag{2}$$

Comparison of the Fig. 3b and Fig. 4b indicates that decreasing the friction factor inside the die orifice, as well as on the die surface could lead to a relatively significant increase in the final pin height. This was experimentally shown in Fig. 2 for the 1.2 mm pin.

4. Conclusions

The lubrication effects on the material behavior were studied experimentally and analytically. It was shown that the lubrication in this manner has no significant effects on the dimension of the pins, but has marginal effects on the required forming load. This unique behavior was investigated using the developed upper bound model. It was proven that the friction factor must be considered locally rather than a global friction factor, to get a reasonable validation for the model. In fact, the liquid lubricant could not stay inside the die orifice, and it was easily squeezed out from the die wall surface. The lubrication behavior on the die surface was assumed as normal. The comparison of the experimental and modeling results proved the reliability of the mentioned hypothesis and model used. It was theoretically shown that a successful lubrication inside the die orifice could increase the final part dimension significantly. The only suggestion would be using the solid coatings. However, the challenge that we faced was the technical difficulty in coating inside the die orifice with a diameter in the micro-scale.

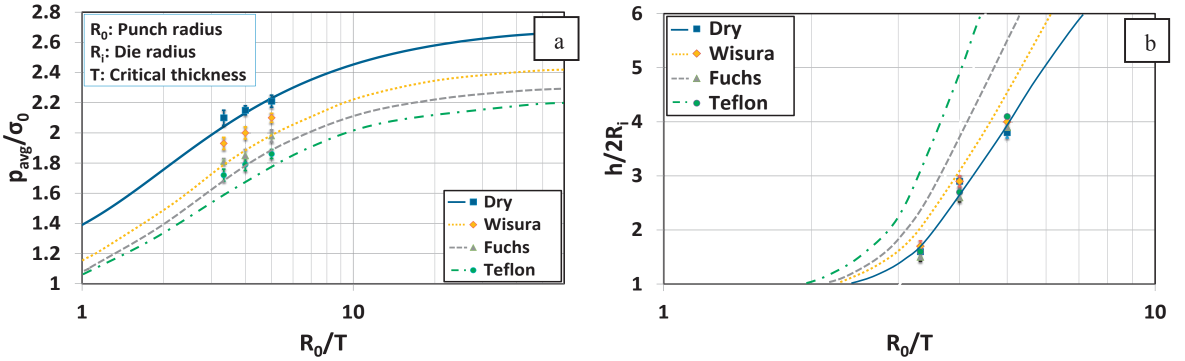

Fig. 3. "Global-Friction" Upper Bound solution for: (a) the mean forming pressure, and (b) the pin dimension; versus punch displacement for the 0.3 mm pin manufactured by the 2.0 mm punch using different lubricants.

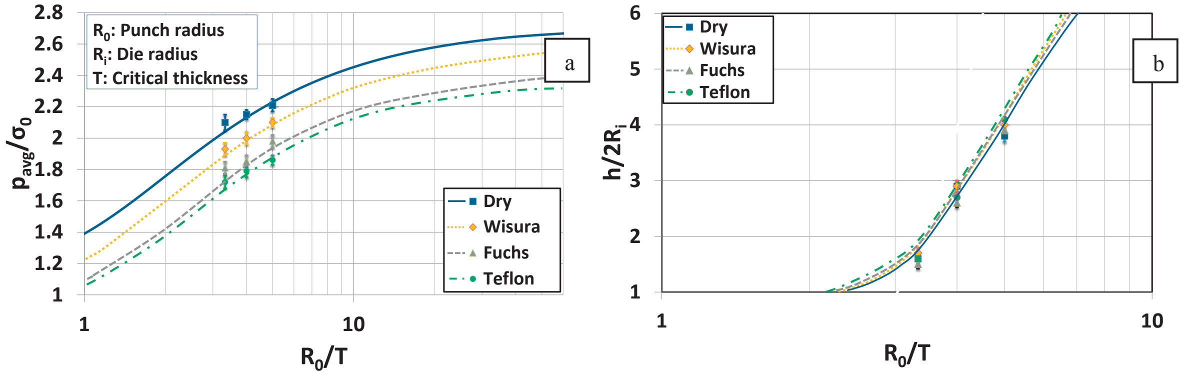

Fig. 4. "Localized-Friction" Upper Bound solution for: (a) the mean forming pressure, and (b) the pin dimension, versus punch displacement for the 0.3 mm pin manufactured by 2.0 mm punch using different lubricants.

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