A Friction Model for Microforming

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Abstract

For the simulation of metal forming processes, input data relating to the tool-workpiece interface is necessary. For microforming applications the tool/workpiece interface conditions tend to dominate the process and it has been found that traditional methods of modeling the interface are not realistic. This paper describes an approach that seeks to describe friction by modelling the geometric surface roughness of the tool as opposed to the use of the traditional empirical friction coefficient or factor. This finite element based model has been validated experimentally in terms of loads and metal flow using the ring test and actual surface measurements. It enables more accurate and also more flexible modeling of friction. As such it will be very suitable for microforming applications.

Keywords: Friction, FEM, Ring test.

1. Introduction

Metal forming is a very suitable manufacturing technology for micro-scale products because of high production rates, minimized material loss and the excellent mechanical properties of the manufactured parts. The problem in adapting forming modelling tools to this field of application is that the die-workpiece interface effects become very significant. Geiger [1] has shown that the use of the traditional friction coefficient of friction factor can lead to significantly erroneous results. Furthermore a drawback with most numerical simulation tools for forming processes is that it is only possible to give a global friction factor to the die-workpiece of the interface. The idea of modelling friction on tool-workpiece surface has attracted the attention of many researchers. Previous workers such as Edwards and Halling [2], Wanheim and Abildgaard [3] and Avitzur et al [4] have used physical modelling, slip line field, and upper bound techniques but the approaches are difficult to incorpoprate into an integrated numerical model. This paper describes some further development of geometric approach originally reported by Becker et al [5] where both forming loads and metal flow predictions are validated for an interface that is modelled geometrically. This leads to a situation where actual surface profile measurements can be used within the analysis of a particular forming operation and will therefore be particularly useful at the scale of microforming.

2. Definition of the geometric model

The ring compression test, established experimentally by Male and Cockcroft [6], is a common method to analyze the friction between die and workpiece. It is used in this work as a means of calibration and validation. The initial dimensions of the ring used in this case were:

$$d_o = 6mm,\ d_i = 3mm,\ h = 2mm$$

The numerical simulation of the ring compression was performed under two different die surface conditions; one with a flat profile on the tool surface as shown in Fig 1. This then uses the conventional measure of friction. In the other case the tool surface is modelled with an elliptical curve and zero friction as shown in Fig 2.

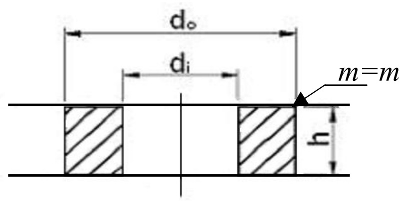

Fig 1. Geometric model of the tool surface using a flat profile

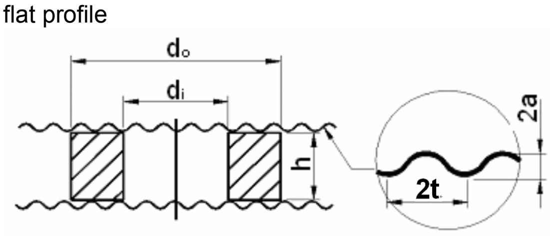

Fig 2. Geometric model of the tool surface using an elliptical or sinusoidal profile

The tool is modelled as rigid and the workpiece material as an aluminum alloy (BS 6063F). The mesh of workpiece is created by Forge2 [7]. In the ring compression test, the same change of inner radius as reduction in height between conventional friction factor with flat profile and given geometric model under conditions of zero friction can be used to determine the equivalent roughness geometry for a particular friction factor. This can then be extended to correlate with the real surface of a tool by measuring the actual roughness profile on the die surface. The conventional use of a friction factor is an empirical approach allowing for traction constraint at the tool surface and is used extensively in mechanical analysis. The approach adopted here recognizes the mechanical interference caused by the asperities on a tool surface and simply related this to the frictional constraint without further using a friction factor.

3. The relation between friction and tool surface geometry

3.1 Modelling the surface with a sine-curve [5]

Each relation $r = f(m)$, $r = f(a)$ and $r = f(t)$ has been established by the unique values of the inner radius of the ring [5]. Using these three relations, a calibration curve was determined and hence the relation $m = f(a,t)$ as given by Eqn 1. The important parameter describing the surface texture is R_a that is the arithmetic average of the nominal profile from average profile. Combining *a* and *t*, the average roughness (arithmetical average height) R_a was derived as shown in Eq. 2 [5].

$$m = -2.19\ln(0.0977\ln(t) - 0.07\ln(a) + 0.8068) \quad (1)$$

$$R_a = \frac{\pi a}{t^2}\left(1 - \cos\frac{\pi}{t}\right) \quad (2)$$

Using the Eqns 1 & 2, a comparison was made between experimental and computational results [5]. The results were very encouraging [5]. However for high values of the friction the agreement was not so good. An elliptical die profile was therefore considered. Fig 3 shows the profiles used for a friction factor of m = 0.9 for both the sinusoidal and elliptical profiles. Clearly the elliptical die profile is more sensible.

(a)

(b)

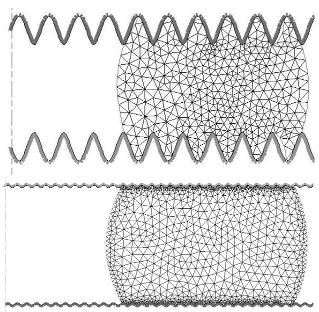

Fig 3. Comparison between sinusoidal profile (a) and elliptical profile (b) for a high friction factor $m = 0.9$

3.2 Modelling the surface with an elliptical curve.

The tool surface was modelled as an ellipse curve with zero friction. Then, *a* and *t* for ellipse curve were used same *a* and *t* for sine curve. The calibration curves between an elliptical profile with zero friction and a flat profile with various friction vectors were compared as shown in Fig 4. The correlation between inner radius and height ratio is good.

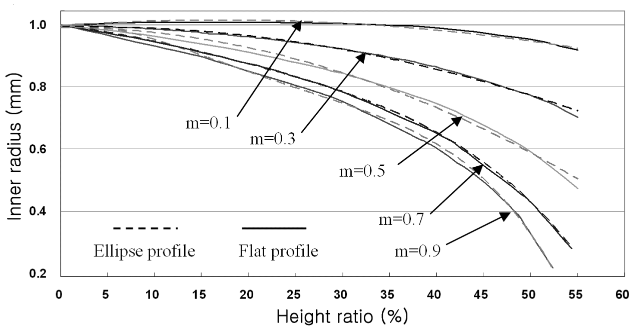

Fig 4: Comparison of the calibration curve between elliptical profile and flat profile

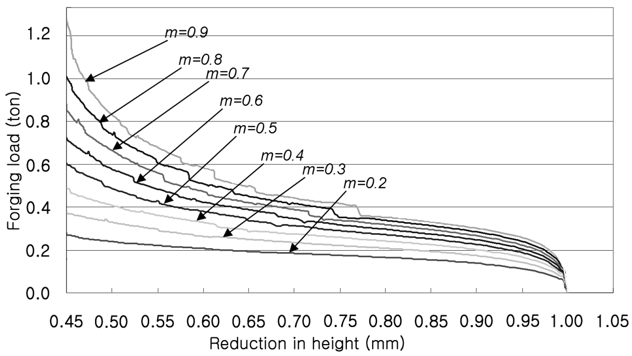

Fig 5: Forging load with conventional friction factor with a flat die profile

In Fig 5, the calibration curves are showing forging load by conventional friction factor with a flat die profile. Calibration curves of forging load with an elliptical die profile using same values of *a* and *t* from Fig 4, and the resultant calibration curve was compared with conventional friction factor with flat die profile as shown in Fig 6.

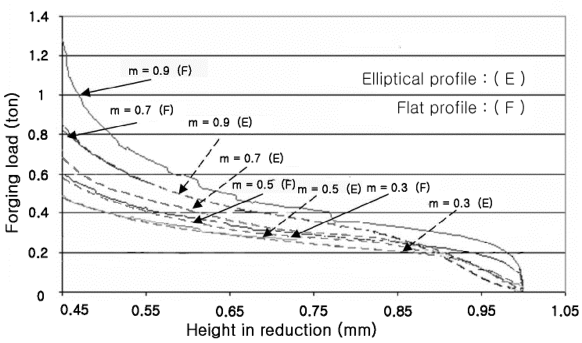

Fig 6. The calibration curves for forging load using an elliptical die profile and various values of *a* and t.

In Fig 6, some of the calibration curve are very similar such as *m = 0.3* and *m = 0.5*. However, the other calibration curves such as *m = 0.5 – m = 0.9* are different. This is because the forging load depends on metal flow that in turn is related to the ratio of amplitude *a* and period *t*. An iterative procedure was therefore invoked matching the *a* and *t* values until a satisfactory correlation was obtained. By the satisfactory calibration curves in inner radius and reduction in height & forging load and reduction in height, the following empirical equation was derived:

$$m = 90.439\left(\frac{a}{t}\right)^3 - 59.321\left(\frac{a}{t}\right)^2 + 14.642\left(\frac{a}{t}\right) - 0.4921 \quad (3)$$

Alternatively this can be expressed as:

$$\frac{a}{t} = 1.6193m^5 - 4.3152m^4 + 4.7504m^3 - 2.3098m^2 + 0.6075m + 0.0028 \quad (4)$$

These equations represented the best compromise for predicting the correct loads and metal flow. The forging load by conventional friction factor with flat profile and ellipse profile by the Eqn (3) are compared as shown in Fig 7.

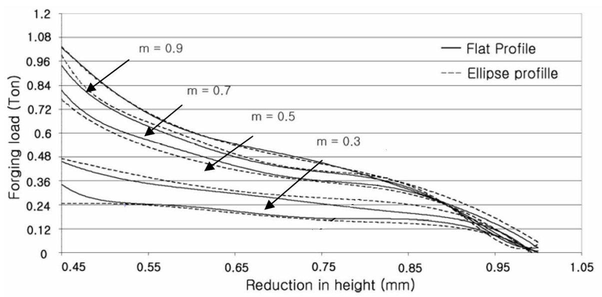

Fig 7. Forging load curves flat profile and friction factor compared with elliptical profile and zero friction.

4 Comparisons with experiment

For the ring compression test, twenty die surface variously produced by milling, turning and grinding were prepared. Combining the twenty different die surfaces, nine different sets of die with which each pair of die having the same roughness value and four different sets of die where each pair of die have a different roughness value are prepared as shown in Table 1 and Table 2. The roughness value R_a of each die was measured by a non-contacting surface profile meter, ProScan 2000.

Table 1. Die roughness value measured by a non-contacting surface profile meter

Die No.	1	2	3	4	5
R_a (μm)	1.98	3.11	7.05	16.13	24.06
Die No.	6	7	8	9	10
R_a (μm)	30.14	39.03	45.56	50.31	55.42
Die No.	11	12	13	14	15
R_a (μm)	1.94	3.08	6.97	16.11	24.12
Die No	16	17	18	19	20
R_a (μm)	30.17	38.87	45.70	50.28	55.61

Table 2: The combined sets of die with a same roughness values (S1-S9) and a different roughness value (S10-S13)

Die set No	S1	S2	S3	S4	S5
Die No.	1,11	2,12	3,13	4,14	5,15
Die set No.	S6	S7	S8	S9	
Die No.	6,16	7,17	8,18	9,19	
Die set No.	S10	S11	S12	S13	
Die No.	1,4	7,9	2,8	3,9	

The ratio of a and t was calculated from Eqn 4 using the experimental surface profile and the friction m was also determined from Eqn 3 using the ratio of amplitude a and period t from experimental result as shown in Fig 8 and Table 3.

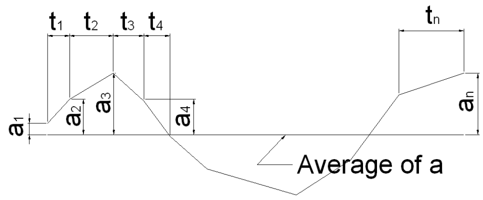

Fig 8: Determination of the average ratio of a and t using experimental surface profile

$$a_{averange} = \frac{\sum_{n=1}^{n} a_n}{n} \qquad \therefore Average\ ratio = \frac{a_{average}}{t_{average}} \quad (5)$$
$$t_{averange} = \frac{\sum_{n=1}^{n} t_n}{n}$$

The calibration curves of inner radius and reduction in height from experiment and from simulation results using the ellipse profile from the Eqn (5) with average ratio in Table 3 is compared in Fig 9. For comparing calibration curves of forging load, the ellipse profile by the average ratio of experimental data and the flat profile with conventional friction factor from Table 3 were compared in Fig 10. In Fig 9 and Fig 10, the compared calibration curves are very encouraging.

Table 3: Average ratio of *a* and *t*, and the friction factor using experimental data for some of the die sets used

Die Set No	*2*	*3*	*4*	*5*
Average ratio	*0.030*	*0.035*	*0.042*	*0.049*
Friction, m.	*0.222*	*0.310*	*0.423*	*0.498*

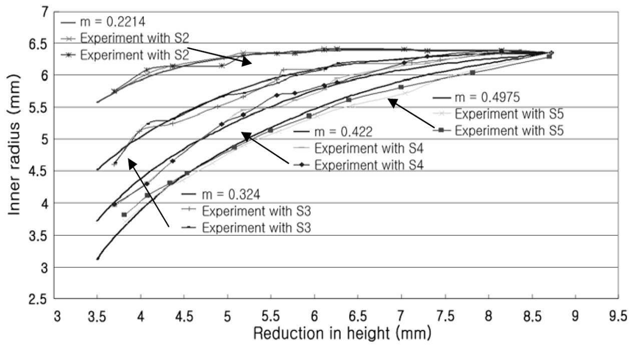

Fig 9.Comparison between experiment and elliptical profile by average ratio a/t in Table 2 for m=0.1 to m=0.5

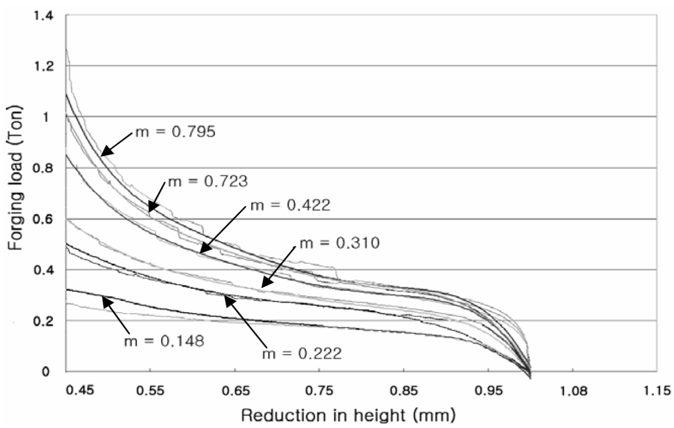

Fig 10: Comparison of forging load using the experimental data in Table 3

5 Conclusion

This paper presents a new way to create the modelling friction in forming processes by introducing a relation $f(m) = f(a,t)$ where amplitude *a* and period *t* describe an equivalent ellipse profile which in turn can be related to the average ratio of *a* and *t* determined by a surface profile meter. This now enables a new type of model to be incorporated into simulation software to give a more realistic interpretation of friction effect. The relation $f(m) = f(a,t)$ has been determined only for dry condition but can be lead way to incorporating the presence of a lubricant. This approach will enable the dominating influence of friction in microforming to be modeled more realistically.

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