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ABSTRACT

With the development of numerical simulation of the forming processes, there is an increasing importance for developing a more suitable friction description to be used in the numerical simulation codes. In this paper, a plane strain compression tribometer is developed which can measure the vertical force, friction force and vertical displacement simultaneously and accurately. Three different friction models are evaluated by the experimental results. A modified friction model is proposed and some directories are given for future research of friction in metal forming processes.

1. INTRODUCTION

With the advances in computer technology, numerical simulation of forming processes is of increasing importance. Numerical simulation can give valuable insight into the effects of various process parameters on the product quality and tool design[1]. The material behaviour and frictional characteristics are very important inputs in numerical simulation. The friction distribution is crucial when the evolution of microstructure and prediction of forming defects (like crack initiation etc.) are included in the numerical simulation. Therefore frictional characteristics is a main concern in the research of tribology in metal forming.

Friction is most commonly introduced in the analysis of forming process by the Coulomb model and the von Mises model. The Coulomb friction model is only valid under condition of relatively low contact pressure which is rarely found in bulk metal forming processes. The von Mises model is valid only when the contact pressure is relatively high. The Coulomb model and the von Mises model are usually used in a combined way in the analysis of forming processes.

Wanheim and Bay[3] have developed a generalized friction model by analysing the asperity deformation using the slipline field theory. The physical background of this model is that with the increase of the contact pressure, the plastic deformation fields around individual asperities will interfere. This model allows for a gentle transition from the Coulomb model towards the von Mises...
model. This model only concerns the asperity deformation of the surface layer. In metal forming the local asperity deformation interacts with the bulk deformation field, so that the friction is not only determined by the interface boundary layer but also strongly influenced by the bulk deformation of the substrate material.

Ramaekers and Kals (R-K)[4] proposed a friction model based on the experimental observations: \( \tau_r = qu/A_o \). Here \( p \): normal pressure; \( u \): relative displacement between tool and workpiece; \( A/A_o \): the surface strain. This model comprises the substrate deformation by introducing relative displacement \( u \) and surface strain \( A/A_o \).

This paper presents a newly developed tribometer based on plane strain compression and the preliminary experimental results obtained from it. The experimental results are compared with theoretical results derived from slab method. Different friction models are evaluated and it is found that the R--K model best fits the experiment. However, the coefficient in the R--K model is found to be varying during the forming process. In order to improve the model, a modification of the R--K model is proposed. Finally discussion on the present work and proposition for future work are made.

2. DESIGN OF THE TRIBOMETER

To get the friction coefficients in various friction models, it is necessary to measure the friction force, contact pressure, relative slip velocity, interface temperature etc. simultaneously, simply and accurately. There is no universal test procedure in metal forming tribology. Most bulk forming processes are compressive processes. This is a reason for choosing plane strain compression as the prototype of bulk forming processes.

\[ F_{fr2} \text{ in total friction } F_r \text{ is reduced by using Teflon foil as lubricant in the side surface and by choosing the workpiece dimension } L_0/H_0 = 2.5, \text{ leading to } F_r \approx 2F_{fr1}. \]

Fig. 2 is the schematic drawing of the tribometer. A high stiffness die base is used to assure the plane strain condition. Also changeable upper and lower platens are used for evaluating different tool surface finish or tool coatings. The
Fig. 2 Schematic drawing of the tribometer
1. die base  2. steel blocks  3. upper tool
4. workpiece  5. lower tool  7. Kistler load cell
8. adjustable side platens  9. side platen
10. pre-stress screw  11. position fix screw

Fig. 3 Experimental arrangement
platens are used for evaluating different tool surface finish or tool coatings. The center line of the Kistler load cell is set to the average height of the workpiece with the consideration that relative reduction is 40% (see Fig. 2).

In Fig. 3, the experimental arrangement is schematically drawn. Besides friction force, the vertical force and vertical displacement signals are also recorded during the forming process. The three analog output signals are first converted by a PCL718 data acquisition Labcard (A/D conversion), the digitalized signals are collected and stored in a computer by using a special made software triggered program.

3. EXPERIMENTAL RESULTS

Using the newly developed apparatus, the mean values of friction coefficient $\mu$, friction factor $m$ and friction constant $q$ during the forming process can be derived (see Appendix B). Using the different friction models in the slab method analysis of plane strain compression[7] (see Appendix A), the theoretical load-displacement relation are derived which are used as a comparison with the experimental data.

3.1 Experimental material and procedure

The material used in experiment is soft aluminum. The workpiece dimensions are $W_0 \times B_0 \times H_0 = 50.02 \times 25.00 \times 19.84 \text{mm}^3$. For the uniformity of the surface finish quality, all the workpieces are processed by means of abrasive powder. The Rastagaev test at average strain rate $\dot{\varepsilon} = 8 \times 10^{-4} \text{ s}^{-1}$ showed the flow stress is: $\sigma_f = 120 \times \dot{\varepsilon}^{0.24}$.

The tool material is high speed steel. The surfaces are polished to have roughness values $R_a = 1.25 \sim 2.5 \mu m$.

3.2 Experimental results

Two sets of experiments are carried out at room temperature with average strain rate of $\dot{\varepsilon} = 8 \times 10^{-4} \text{ s}^{-1}$. One set (a) uses Tallow as lubricant, another set (b) uses no lubricant. Fig. 4, 5 and 6 show the results.
From Fig. 4, it can be seen that the reproducibility is very good. This shows that the new apparatus works well and the experiments are controlled well.

From Fig. 5, it can be seen that the coefficients in all the three friction models are not constant during the forming process. \( \mu \) and \( m \) increase with the punch travel, \( q \) first increases rapidly then decreases dramatically with the punch travel. So all three friction models find difficulty to be used in forming processes, the search for a true friction constants has to be continued.

In Fig. 6, the comparison of the load--displacement curves is given. Using the experimental results of \( \mu, m \) and \( q \) and the theoretical derivation by means of the slab method, three load curves corresponding different friction models are obtained. Firstly, it can be seen that the slab method analysis is strongly influenced by the friction distribution at the interface introduced by different friction models. Secondly, the load predicted by the slab method is lower than the experimental results. Both the load curves by the Coulomb model and the von Mises model underestimate the load. The load curve by the Coulomb model has the largest discrepancy from the experimental results. The load curve by the R--K model agrees very well with the experimental results. This implies that the R--K model predicts a more reasonable friction distribution.
3.3 Modification of the R–K model

The proposition of the R–K model is based on assuming the friction mechanism is mixed film lubrication (Fig. 7). When the shear stress of the lubricant \( \tau_l \) can be neglected compared with that of the boundary film \( \tau_b \), then the friction stress is expressed as:

\[
\tau_{fr} = \frac{A_r}{A \tau_b}
\]

In the R–K model, it is assumed that real contact area increases with normal pressure, relative displacement between tool and workpiece and nominal surface strain, the expression is: \( \tau_{fr} = q \mu A / A_0 \). From the experimental results, the R–K model can predict load very well but the coefficient \( q \) in the R–K model is not a constant during the forming process. Here a modification on the R–K model is made: assume the real contact area \( A_r / A \) increases with normal pressure and relative slip velocity \( U_s \) between tool and workpiece: \( \tau_{fr} = q' \mu U_s \). The physical meaning is that real contact area is influenced both by normal pressure and the flow of the substrate material.

The coefficient \( q' \) in the modified R–K model is calculated from the experimental results (Fig. 8). It can be seen that coefficient \( q' \) first increases very quickly and when reduction is \( \Delta H / H_0 > 0.05 \), \( q' \) is oscillating around a constant value.

![Diagram of mixed film lubrication](image)

Fig. 7 Mixed film lubrication

(a). Tallow lubricant
Here is an explanation of the oscillation of q'. In this experimental set-up, the vertical displacement is detected by an inductive sensor which gives integer pitches of the inductive coil (0.01 mm). The average strain rate is $\dot{\varepsilon} = 8 \times 10^{-4}$ s$^{-1}$. When calculating q', the differentiation of the vertical displacement in every 5 s (about 0.07 mm) is used. So the discontinuous vertical displacement signal is an important cause of the oscillation of the q' curve.

When the relative slip velocity is constant (no bulk deformation of the substrate material), the modified R--K model turns back to the Coulomb model.

The nearly constant coefficient in the modified R--K model allows it to be easily implemented in forming analysis. When the relative reduction rate $\Delta H/H_0 < 5\%$, assume that the q' increases linearly with the reduction rate, when reduction rate $\Delta H/H_0 > 5\%$, assumes that the q' is taken as a constant.

More experiments will be necessary to see the influence of the punch travel velocity on the coefficient q'.

4. DISCUSSION AND CONCLUSIONS

The friction in metal forming processes has a unique feature: it is influenced by both the deformation of the surface layer asperity and the deformation of substrate material. Therefore, it is necessary to combine the analysis of the deformation of surface asperity and the deformation of substrate material. Due to the complexity of the process models, even with many simplifications, the pure theoretical and numerical analysis is difficult. The combination of physical simulation with theoretical and numerical simulation is a promising way in the analysis of friction in metal forming. The Moiré method[8] is an effective way for analysis of plastic deformation, so that the future work will be conducted using Moiré method to verify the modified R--K model and to explore new models by taking into account both the deformation of surface layer asperity and the deformation of substrate material.

Some special points can be concluded from the present work: The newly developed tribometer works well and can get the coefficients in various friction
models reliably. The slab method results are strongly influenced by the friction distribution due to the introduction of a certain friction models. The R--K friction model predicts forming load best. A modified R--K friction model is proposed and can be easily used in forming analysis with improved accuracy. A more general friction model should be developed by taking into account both the deformation of surface layer asperity and the deformation of substrate material.

5. REFERENCE

[7]. S.L. Wang, unpublished work, 1993
[8]. Q.X. Cao, S.Y. Ye, B. Xie and X.T. Ma, Principle and Applications of Moiré Method, Tsinghua University Press, 1983

APPENDIX A

Slab method analysis

\[ d\sigma_x = 2\tau_{fr} \frac{dx}{H} \]  
(A1)

\[ \sigma_x - \sigma_z = \frac{2}{\sqrt{3}}\sigma_f \]  
(A2)

\[ \sigma_z = \frac{2}{H} \int_0^B \tau_{fr} dx + c \]  
(A3)

Introducing different friction models into (A3), the theoretical load equations can be obtained:

The Coulomb model: \( \tau_{fr} = \mu p \)
The von Mises model: 
\[ r_{fr} = mK = m\sigma_f/\sqrt{3} \]

\[ P_{vm} = \frac{WB\sigma_f(2+mB)}{\sqrt{3}} \]  

The R-K model: 
\[ r_{fr} = qpuA/A_0, \] the friction stress \( r_{fr} \) and contact stress \( \sigma_z \) are obtained, then the vertical force \( P_{rk} \) and total friction force \( F_{fr} \) are obtained by the numerical integration of \( \sigma_z \) and \( r_{fr} \).

\[ \sigma_z = -\frac{2}{\sqrt{3}}\sigma_f \exp\left[\frac{q\Delta H}{H^2}(B^2-x^2)\right] \]  

\[ r_{fr} = -\frac{2\sigma_f q x \Delta H}{\sqrt{3}H} \exp\left[\frac{q\Delta H}{H^2}(B^2-x^2)\right] \]  

**APPENDIX B**

Derivation of \( \mu, m \) and \( q \)

\[ \mu = \frac{F_{fr}}{2*F_{ver}} \]  

\[ m = \frac{\sqrt{3}F_{fr}}{2*B*W*\sigma_f} \]  

Integration of (A7) and (A8) give the total vertical force and friction force, and \( q \) is obtained as:

\[ q = 1.334 \frac{F_{fr}H}{\Delta HBF_{ver}} \]  

**NOMENCLATURE**

- \( p \): normal pressure
- \( K \): shear strength of the specimen
- \( u \): relative displacement between tool and specimen
- \( u_s \): relative slip velocity between tool and specimen
- \( W_0, B_0, H_0 \): initial length, width and height of the specimen
- \( W, B, H \): current length, width and height of the specimen
- \( \Delta H \): punch travel
- \( P_{cl}, P_{vm}, P_{rk} \): load by slab method corresponding to the Coulomb, von Mises and R-K model respectively
- \( F_{fr} \): measured friction force
- \( F_{ver} \): measured vertical force