DEVELOPMENT OF A PLANE STRAIN COMPRESSION TRIBOMETER

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Feb. 1994        WPA nr 120005
SUMMARY

With the development of computer technology, many metal-forming processes have been investigated by numerical analysis. The knowledge of friction and material flow stress is extremely important for performing this analysis. The interfacial friction condition and material flow stress are among the main concerns in metal-forming process design and analysis.

Until now, there is no universal test method for friction and material flow stress in bulk metal-forming processes. Based on the analysis of plane strain compression, an easy-to-handle, low cost, accurate tribometer has been developed. This tribometer can reproduce many characteristics of bulk forming processes. The evaluation tests (reproducibility tests and Moiré experiments) show that the new apparatus works well. The data acquisition is realized with a PCL 718 card. Menu controlled data processing software has been developed which can obtain the friction coefficients $\mu$, $m$ and $q$ and the material flow curve $\sigma_f = f(\epsilon_f)$ by processing the same experimental data. Compared with the ring compression test, the new method can obtain friction coefficients $\mu$, $m$, $q$ continuously without interrupting the experiment, which changes the interfacial conditions uncontrollably. Compared with the Rastegaev test, the material flow stress can be obtained up to a fairly large strain with good accuracy. The newly developed tribometer can be used to evaluate the tribological properties of lubricants, tool materials, tool surface finishes and tool coatings. It can also be further developed to be used in elevated temperature measurements.

Experimental results have been analyzed which show that the friction coefficients in the models commonly used (Coulomb, Von Mises, R--K) are not constant during the forming process. The R--K model can forecast the deformation load best among the three models. A modification on the R--K model has been made and a nearly constant coefficient $q_1$ has been obtained.

Using the newly developed tribometer, Moiré experiments have been carried out in order to verify the modified friction model.

The new developed apparatus together with the data acquisition and data processing shows good reproducible and reliable results. Friction and strain hardening parameters can be measured in a simple test.
1. INTRODUCTION

1.1. Introduction

With the advancement of computer technology, CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) has proved to be of great importance in the manufacturing industry. The trend in forming technology is characterized by increasing demands for complex shapes, close tolerances (near-net shapes) and new materials such as PM or refractory metals which have low ductility and demand a high forming load. Systematic numerical simulation of the forming process can provide valuable insight into the effects of various process parameters on the product quality and tool design[1]. Thus, the material utilization rate can be increased, production costs can be reduced and the product quality can be improved.

The accuracy of numerical simulation is strongly influenced by the tool/workpiece interface frictional conditions and the accurate expression of the material properties. So the interfacial friction condition and the material flow stress are still the main concerns in the areas of forming, material science and tribology.

In the present project, an easy-to-handle, low cost and accurate plane strain compression tribometer was to be developed. This tribometer can reproduce many characteristics of forming processes. Using the new apparatus, the friction coefficients and material flow stress are obtained in the same experiment. Various widely-used friction models are also evaluated by the experimental results. Some modification to an existing friction model has been done.

1.2. Friction in metal-forming processes

Friction exists at the interface of tool and workpiece (Fig. 1.1). The friction in metal-forming processes is very important because friction leads to an increase in the consumption of the forming force/energy; the deduction of tool life; to influence the product quality (surface finish, internal structure, product Fig. 1.1 Friction during metal-forming life etc.). The friction phenomena comprise a very complex situation during forming
processes, which demand accurate models and experiments to verify the models.

1.2.1 Friction models

1.2.1.1 Coulomb friction model[2]

The Coulomb friction model[2] (also referred to as Amonton’s model) is widely used. This model deals with sliding situation; the mathematical formulation is:

\[ T_{fr} = \mu p \]

- \( T_{fr} \): the friction shear stress
- \( \mu \): the friction coefficient
- \( p \): the normal pressure

It is shown, theoretically and experimentally[3], that the Coulomb model does not apply when the contact pressure is higher than approximately the yield stress of the specimen. In bulk forming processes, where the contact pressure usually reaches a multiple of the yield stress of the specimen, Coulomb friction model finds little validity.

1.2.1.2. Von Mises friction model[2]

The inoperability of the Coulomb friction model in bulk forming processes leads to the proposal of Von Mises friction model (also referred to as constant friction model). The mathematical formulation is:

\[ T_{fr} = mK \]

- \( m \): friction factor
- \( K \): shear yield stress of workpiece

From the Von Mises yield criterion, the friction force cannot exceed the shear yield stress \( K \) of the deforming object, so the range of \( m \) is from 0 to 1.

This model has great mathematical convenience in calculations, because \( T_{fr} \) is a constant.

1.2.1.3. Wanheim friction model[3]

Using the slipline field analysis, the plastic behaviour of surface asperities under combined load have been extensively analyzed by Wanheim, Bay et al. The mathematical formulation is:

\[ T_{fr} = maK \]

- \( a \): real contact area

This model is based on theoretical analysis, it avoids the abrupt change from...
the Coulomb friction model to the Von Mises friction model, and the parameter $a$ has a clear physical meaning. The problem is that in deriving $a$, $p$ relations, the influence of plastic deformation of substrate material on the asperity deformation have to be considered, which is a difficult task.

1.2.1.4 Kobayashi friction model[1]

For problems such as ring compression and rolling, the unknown direction of the relative velocity at the interface, all the previous three friction models (Coulomb, Von Mises, Wanheim) have difficulty in handling the boundary conditions. In this type of problem, there is a neutral point (or region). The location of this point (or region) depends on the magnitude of the frictional stress itself. To overcome this, Kobayashi et al. modified the Von Mises friction model with the inclusion of a velocity vector.

$$\tau_f = mK \tan^{-1}\left(\frac{|u_s|}{u_0}\right)$$

- $T$ : the unit vector in the opposite direction of the relative sliding
- $u_s$ : the relative sliding velocity
- $u_0$ : a small positive number compared to $u_s$

Kobayashi et al. have successfully used this friction model in the Finite Element Method analysis. This model is just a modification of the Von Mises friction model; it is too simple to represent the actual interface friction, but it provides a reasonable way to incorporate the direction of the friction force.

1.2.1.5 Ramaekers-Kals (R-K) friction model[4]

Based on the physical observations of friction phenomena, Ramaekers and Kals proposed a friction model. The mathematical formulation of R-K model is:

$$\tau_f = q p u \frac{A}{A_0}$$

- $q$ : friction constant
- $p$ : normal pressure
- $u$ : relative displacement between die and workpiece
- $A/A_0$ : surface strain

This model takes into account the relative displacement between die and workpiece. It can easily be used in dealing with problems including a neutral region. The problem is that only the mean displacement and mean surface strain were used to verify this model[4]. More experiments are needed to verify the R-K model.
1.2.2. Measurement of friction

In order to quantify the friction force, a great variety of measurements have to be made. All of the coefficients in the above-mentioned friction models have to be determined carefully by various measurement techniques. The quantity measurement of friction is also necessary for the construction of appropriate friction models. So, much work [6--9] has been done in dealing with the measurement of friction. The friction phenomenon is very complex; many parameters interact in it. The normal pressure, relative displacement (velocity), surfaces roughness, surface strain, lubricant, temperature, material (tool and workpiece) properties, work hardening and surface coatings, etc. all play a part. Until now, it has been impossible to construct a suitable formula to include all these parameters. So, different measurement is normally focused on several important aspects. The main measurement techniques and investigations can be categorized into three levels: global analysis, local analysis, micro-analysis.

1.2.2.1 Global analysis

The difficulty in measuring the friction distribution leads to the global measurement of friction. The total load and total friction force are recorded (or calibrated by calculation) and the average friction coefficient (or friction factor) is derived. This is very useful in understanding and evaluating the friction and lubricant.

In bulk metal-forming processes, it is usually very difficult, not to say impossible and also highly uneconomical to conduct full-scale experiments on production equipment in plant operations. Therefore various simulative tests have been suggested[2] to focus on some special aspects of friction phenomena. In simulating metal-forming processes, it is necessary that the test should be performed at high contact pressure and should include large plastic deformation. The simulative tests have to be designed to carefully duplicate actual operation conditions as much as possible.

Schey[2] summarized the global level simulation test for bulk forming processes and divided them into several groups (Fig. 1.2--1.6): the pin-on-disk tests which are for the most basic tribometer; the twist compression test which combines the normal pressure with continued sliding over the same surface area; the scratch test which involves localized deformation; the ring compression and plane strain compression test where friction can be evaluated by geometric measurement.
Fig. 1.2 Pin-on-disk tests

Fig. 1.3 Twist compression tests

Fig. 1.4 Scratch test

Fig. 1.5 The real plane strain compression

Fig. 1.6 Compression tests
(a. ring compression, b. plane strain compression)
The ring compression test (Fig. 1.6a) is widely used in bulk forming processes. With a calibration chart, the average friction coefficient or friction factor can be determined. The calibration chart is based on the Upper Bound Analysis proposed by Avitzur[19]. Its advantage is that the friction can be determined by geometrical measurements only, an easy to use calibration chart is available. But there are some weak points: the most valid theoretical analysis (including F.E.M analysis) for the construction of the calibration chart is not available, due to the inaccurate description of friction, the derived average $\mu$ and $m$ values can easily vary by $\pm 50\%$ in response to the choice of theory in itself[2]; the interruptions during the experiment change the boundary condition (such as the lubricant regime) and influence the $\mu$, $m$ values remarkably; the ring very often becomes oval making the measurement difficult and affecting the accuracy.

The plane strain compression test (Fig. 1.6b) is an approximating method, the average $\mu$, $m$ are back-calculated from the measured average pressure. There are many restrictions in doing this experiment which makes it less promising. The global analysis needs to be developed to represent the actual forming processes well. More improvement on the measurement technique is necessary. The material flow and stress state of the real plane strain compression test (Fig. 1.5) can represent a group of forming processes, such as rolling, free forging, coining, backward extrusion, upsetting etc. very well. It is a promising method for evaluating friction, lubrication and for obtaining the flow curves of the material.

1.2.2.2 Local analysis

The average $\mu$ and $m$ are usually not sufficient in understanding the forming processes. So some special techniques were developed to obtain the interfacial normal pressure and shear stress distribution simultaneously. The main techniques are: pin transducer, photoelastic and photoplastic, Moiré method and grid method.

The pin transducer[2] is widely used and still improving. The advantage is that it gives a direct solution and can be used in actual processes. The disadvantages are: the lubricant and material may extrude into the space between pin and die; the difference in stiffness between tool and pin may give error readings. Thus, the accuracy of the experiment strongly depends on the experience of the researcher and is not high enough.

The photoelastic and photoplastic technique[4] give the distribution of the boundary stress, but they need special model material which is difficult to simulate the actual metal-forming processes well, especially in the boundary conditions.

The Moiré method[17] and grid method can be used for actual material. It
can obtain the whole displacement field of the deforming body. After that, the relative velocity, the strain distribution and the stress distribution can be derived. The boundary information can be processed easily and accurately. They can be used in elastic-plastic, creep and high-temperature processes.

Based on the local analysis, the important factors of influence can be detected directly and the useful friction model can be discussed. Until now this is the most practical way for verifying useful friction model for forming processes.

1.2.2.3 Micro-analysis

The micro-analysis is based on the assumption of the friction mechanism and the implements the most advanced technology and measuring techniques. The friction mechanism such as: molecular theory, adhesion theory and chemical reaction theory are all needed for a clear understanding through micro-analysis.

1.3. Material flow stress

Material flow stress is a very important input parameter in the numerical simulation of the forming processes. The accuracy of it has strong influence on the results of calculation. The material flow stress is a very complex phenomenon, the strain, strain rate, temperature, microstructure, stress state, etc. all influence it. The construction of constitute equations has a long way to go before all factors of influence all be described accurately.

Various standard tests are used: tensile test, compression test(Rastegaev test, ring compression, approximate plane strain test), torsion test. The tensile test is limited by the necking of the material, which is not suitable for large deformation. The phenomenon that stress state has some influence on the material flow stress[11] makes the compression test the most suitable method to obtain the material flow stress in bulk forming processes. The difficulty of totally eliminating the influence of friction in the Rastegaev test means there is some inaccuracy in deriving the true stress. The low accuracy of the derived flow stress by means of the ring test makes it less suitable too. The approximate plane strain test also has many assumptions which lead to some inaccuracy.

The constrained plane strain test (1.9c), including the accurate measurement of the friction force, seems to be a promising method. The stress state can be controlled to accurate plane strain and the friction influence can be evaluated; the flow stress can be obtained together with the friction coefficients in one experiment.
1.4. The present work

In the present work, the following topics will be discussed:
1). analysis of the plane strain compression process;
2). design of the structure of the plane strain compression tribometer;
3). development of the data acquisition system and software;
4). development of the data processing software;
5). analysis of the experimental results;
6). modification of the friction model;
7). Moiré analysis and comparison with the experimental data.
2. DEVELOPMENT OF A PLANE STRAIN COMPRESSION TRIBOMETER

2.1. Introduction

The most reliable study on friction and lubricants during metal-forming processes can only be gained in actual production situation. However, full-scale trials are usually expensive and difficult to control and analyze. A simulative laboratory test set-up has to be developed to obtain the friction property and material property accurately, easily and less expensively.

It is a long search for measuring the friction and deformation force simultaneously, simply and accurately. The strain gauge pin sensors[2] are widely used to get the friction force and friction distribution, but their accuracy is doubted. The design and adjustment of the sensors is difficult, takes time and very much depends on experience. The determination of the average friction coefficient $\mu$ or friction factor $m$ by ring compression also has some drawbacks. There is a need to develop a simple test which can provide the friction coefficients $\mu$, $m$ and material flow stress $\sigma_f$ easily and directly.

There is no universal test in metal-forming tribology. Most bulk forming processes are under compressive stress state. The plane strain compression process has the advantages in: easy to solve with the plasticity theory, easy to realize accurately, easy to design and adjust the test set-up. The stress state, flow behaviour of the plane strain compression process are similar to axisymmetric upsetting, rolling, coining, die forging, free forging, backward extrusion etc. So the plane strain compression process is chosen as the prototype for the bulk forming processes. The plane strain compression tribometer has been analyzed and developed.

2.2. Plasticity analysis of the plane strain compression process

2.2.1. Introduction

The closed form solution of the plane strain compression process can be obtained by the slip line field theory[13]. But to construct the slip line field is not an easy job and the correctness of it depends on the given boundary conditions.
The difficulty in obtaining an accurate solution for the forming process leads to several approximate methods. The slab method is a very useful approximate way in getting a closed formula to evaluate the influence of friction and tool deflection on the deformation load. Using the slab method with different friction models, equations concerning the deformation force, normal pressure distribution, friction distribution have been derived which can be used to evaluate the experimental results.

2.2.2. Ideal plane strain compression

The ideal condition means that rigid tools are in parallel and no deformation in y direction \((\varepsilon_y = 0)\) (Fig. 2.1) takes place.

Due to the symmetry of the workpiece, only half of the workpiece is analyzed. The following definitions are made:

- \(L_0, H_0, W_0\): initial length, height, width of the specimen;
- \(L, H, W\): current length, height, width of the specimen;
- \(L'\): average contact width at interface
- \(a\): barrelling parameter
- \(\sigma_t\): flow stress including the strain hardening;
- \(P_d\): total deformation force;
- \(F_{fr}\): total friction force in the x direction.

![Fig. 2.1 The ideal plane strain compression](image)

First, let us consider the equilibrium of the small element in x direction:

\[
(\sigma_x + d\sigma_x)H - \sigma_x H - 2T_{fr} dx = 0
\]

\[
\frac{d\sigma_x}{dx} \frac{2T_{fr}}{H} = 0
\]  

(2.1)

For plane strain compression, the Von Mises yield criterion is:
\[ \sigma_x - \sigma_z = \frac{2}{\sqrt{3}} \sigma_t \]  

(2.2)

Introducing (2.2) into (2.1), the \( \sigma_z \) can be integrated (2.3).

\[ \sigma_z = -\frac{2}{H} \int r_t dx + c \]  

(2.3)

Once the friction model is given, using the boundary conditions, at \( x = L \), \( \sigma_z = -2N/3 \sigma_t \), the normal pressure \( \sigma_z \) can be determined.

The total deformation force can be obtained by the integration of \( \sigma_z \):

\[ P_d = \int_0^L -\sigma_z W dx \]  

(2.4)

The total friction force in \( x \) direction:

\[ F_r = 2W \int_0^L r_{t,x} dx \]  

(2.5)

Using the slab method with different friction models, the normal pressure distribution, the friction distribution and the load versus displacement curves can be predicted. These curves can be compared with the experimental results to work out the validity of the friction models and the validity of the slab method. For plane strain deformation, two basic assumptions are used in deriving the load versus displacement curves:

a. the existence of friction causes the barrelling of the free surface. In this slab method analysis, the average length is calculated first, \( L' = L_0 \cdot H_0 / H \), and then, a barrelling parameter \( \alpha \) obtained from the experiment is used \( L = \alpha \cdot L' \);

b. the average effective strain is used to include the strain hardening effect, \( \sigma_t = C \bar{\varepsilon}^n, \quad \bar{\varepsilon} = 2N/3 \ln(H_0 / H) \).

In this analysis, three friction models are discussed: Coulomb, Von Mises, Ramaekers-Kals.

1). the Coulomb model, \( \tau_r = \mu \rho \):

Using equation (2.3), (2.4), the following formulas can be obtained:

\[ \sigma_z = -\frac{2}{\sqrt{3}} \sigma_t \exp \left( \frac{2\mu L - x}{H} \right) \]  

(2.6)

\[ P_d = \frac{WH\sigma_t}{\sqrt{3} \mu} \left[ \exp \left( \frac{2\mu L}{H} \right) - 1 \right] \]  

(2.7)

2). the Von Mises friction model \( \tau_r = mK \):

\[ \sigma_z = -\frac{2}{\sqrt{3}} \sigma_t \frac{2(L - x)}{H} \tau_r \]  

(2.8)
\[ P_d = WL \left( \frac{2}{\sqrt{3}} \sigma_f + \frac{L}{H} r_f \right) \]  
\[ \text{(2.9)} \]

3. the Ramaekers-Kals friction model \( r_f = \frac{q \mu H}{A_0} \):

\[ \sigma_z = -\frac{2}{\sqrt{3}} \sigma_f \exp \left[ \frac{q}{H} \left( \frac{H_0}{H} - 1 \right) \left( L^2 - x^2 \right) \right] \]  
\[ \text{(2.10)} \]

\[ r_f = -\frac{2}{\sqrt{3}} \sigma_f x \left( \frac{H_0}{H} - 1 \right) \exp \left[ \frac{q}{H} \left( \frac{H_0}{H} - 1 \right) \left( L^2 - x^2 \right) \right] \]  
\[ \text{(2.11)} \]

The deformation force \( P_d \) is solved by numerical integration on \( \sigma_z \).

The comparison of the total load, normal pressure and friction distribution at the die and workpiece interface (when \( \Delta H = 3 \text{mm} \)) will be given in chapter 3.

2.3 Tool stiffness analysis

2.3.1. The analysis

Fig. 2.2 The plane strain compression with inclined tools

In the real plane strain compression process, there is deformation of the tools caused by the nonuniform metal flow and the deviation between the centre of loading forces and the centre of the resultant of deformation force. So, a study of the influence of the tool deformation on the deformation force and on the friction force is necessary.

A linear deformation of tools is assumed (Fig. 2.2). The tools have a \( \tan \alpha \) slope to the \( x \) direction.

The static equilibrium of forces in the \( x \) direction is expressed as follows:
\[
\sigma_x dH + H d\sigma_x - 2\tau_p dx - 2pdxtana = 0
\]  
(2.12)

The force equilibrium in z direction gives:
\[
\sigma_z - P + \tau_p \tan a = 0
\]  
(2.13)

Considering the geometry of the deforming specimen:
\[
dH = -2dx \tan a
\]  
(2.14)

\[
H = H_c - 2x \tan a
\]  
(2.15)

\(H_c, H_b\) : centre and boundary height of the workpiece respectively;

For \(\alpha\) is small, the Von Mises yielding criterion becomes:
\[
\sigma_x - \sigma_z = \frac{2}{\sqrt{3}} \sigma_f
\]  
(2.16)

Introducing equations (2.13) --(2.16) into equation (2.12), neglecting the high order small quantity and being suitably rearranged,
\[
\frac{d\sigma_z}{dx} = \frac{4}{\sqrt{3}} \frac{\sigma_f \tan a + 2\tau_{fr}}{H_c - 2x \tan a}
\]  
(2.17)

Let \(C_1 = -2*\tan a; \quad C_2 = (4*\tan a*\sigma_f)/\sqrt{3} + 2\tau_{fr}\)
and assuming that the friction force \(\tau_{fr}\) is constant, then
\[
\sigma_z = \int_{0}^{x} \frac{C_2}{H_c + C_1 x} dx = \frac{C_2}{C_1} \ln(H_c + C_1 x) + c
\]  
(2.18)

Introducing the boundary and geometry conditions, the final solution for \(\sigma_z\) can be expressed as:
\[
\sigma_z = -\frac{2}{\sqrt{3}} \sigma_f + \frac{C_2}{C_1} \ln \left(\frac{H_c + C_1 x}{H_b}\right)
\]  
(2.19)

The total deformation force \(P_t\) is the integration of \(\sigma_z\) over the deformation zone:
\[
P_t = W \int_0^L -\sigma_z dx = -W C_2 \left[ H_b (\ln H_b - 1) - H_c (\ln H_c - 1) \right] + \frac{2}{\sqrt{3}} \sigma_f + \frac{C_2}{C_1} \ln H_b LW
\]  
(2.20)

From Fig. 2.2, the total horizontal force can be expressed as:
\[
F_x = W \int_0^L (\tau_{fr} \cos \alpha + \rho \sin \alpha) dx
\]
For $\alpha$ is a small angle, neglecting the high orders, we get:

$$F_x = W \int_{0}^{L} (r_{fr} - \sigma_z \sin \alpha) dx$$  \hfill (2.21)

So, $F_x$ consists of two parts: one for friction, another for tool deformation. The percentage of the two parts is:

$$\frac{F_{dx}}{F_x} = \frac{W \int_{0}^{L} (-\sigma_z \sin \alpha) dx}{W \int_{0}^{L} (r_{fr} - \sigma_z \sin \alpha) dx} = \frac{P_{\text{sina}}}{F_{fr} + P_{\text{sina}}}$$  \hfill (2.22)

Here, $F_{fr}$ is the total friction force in the horizontal direction.

2.3.2. The discussion

The workpiece dimensions are: $L_0 = 25$mm, $W = 50$mm, $H_0 = 20$mm. The material flow stress is obtained by $\sigma_t = C \cdot e^n$, here $C = 120$ N/mm$^2$, $n = 0.24$, with reduction rate $\Delta H = 3$mm. Assuming the friction factor is $m = 0.3$, the friction stress $r_{fr} = (0.3 \cdot \sigma_t) / \sqrt{3}$.

Fig. 2.3 shows the percentage of the influence of the tool deflection on the total horizontal force and the deformation force. $F_{dx}$ is the horizontal force caused by the tool deformation. $F_x$ is the total horizontal force. $P_t$ is the total vertical force. $P_d$ is the deformation force calculated without tool deflection.

Fig. 2.3 reveals that small amounts of tool deflection have little influence on the total deformation force measured and the total friction force measured.

2.4 Design of the tribometer

2.4.1 The principle

Most bulk forming processes are compression processes. Plane strain
compression is chosen as the prototype of bulk forming processes. The friction influence on the material flow of the plane strain compression can be evaluated by the bulging (when friction is low) and fold over (when friction is high) of the free surface (Fig. 2.4a). Since the friction force is self balanced, it can be detected by the pin sensor inserted in the tools. As to the difficulty of the design and the low accuracy of the pin sensor, we tried a new way: to design a tribometer to measure the total friction and deformation force in order to derive the average $\mu$, $m$ and material flow stress easily.

In this design, the half workpiece is plane strain compressed (Fig. 2.4b). The total friction force is exposed, and it is easy to detect it.

$$F_{fr} = 2F_{fr1} + 2F_{fr2}$$

To ensure the plane strain condition, the friction force on the two side surfaces ABCD and EFGH, $F_{fr2}$, should be reduced as much as possible. To avoid lubricant contamination on the testing surfaces, the grease, powder and liquid are not allowed to be used on the side surface. Teflon foil is chosen as the lubricant for the side surfaces. The workpiece dimensions are chosen as that area $A\overline{DEH}$ is
much larger than that of ABCD. Through this treatment, the weight of the friction on the side surface, $F_{fr2}$, in the total friction, $F_{fr}$, is very small. So $F_{fr2}$ can be neglected and $F_{fr} \approx 2F_{fr1}$.

2.4.2 Design of the overall structure

The test is carried out at room temperature which is used to simulate the cold forming processes.

There are several requirements for the tribometer:

a. High stiffness of the die-base to assure the plane strain condition.

b. Changeable upper and lower platens to evaluate different die coatings and different tool surface finishes.

c. The total deformation force and friction force should be recorded accurately.

A high-stiffness die-base can ensure that there is no deformation (that is to say, very little deformation) in the constrained direction. In the Laboratory of Forming Technology, Department of Production Technology and Automation, Eindhoven University of Technology, there is a vessel-shaped, high-stiffness die-base (Fig. 2.6). The experimental set-up was designed and built using this die-base.

Fig. 2.6 is the schematic drawing of the tribometer. Once the workpiece is pressed, the friction force will be detected by the Kistler cell 7; the deformation force and the vertical displacement are also recorded.

Several special points have to be looked at carefully:

(1). The surface finish of side platen 8 and 9, has to be good, so that it is easy to eliminate (reduce) the influence of the side friction, $F_{fr2}$, on the material flow.

(2). The width of blocks 2, 3, 5, 6 should be less than or equal to the workpiece length, so that in the early stages of the experiment, the friction force is detected instead of both material expansions in the restricted $y$ direction and material flow in the $x$ direction.

(3). The central line of the Kistler cell should coincide with the central line of the test piece. But with the process of the pressing, the workpiece height changes. Therefore the average height is used in the design with the consideration that the relative reduction $\Delta H/H_0 = 40\%$. 

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Fig. 2.6 The schematic drawing of the tribometer

(1. die-base  2. steel blocks  3. upper tool  
4. workpiece  5. lower tool  7. Kistler cell  
8. adjustable side platens  9. side platen  
10. pre-stress screw  11. position fix screw)
2.4.3 Design of the parts

2.4.3.1 Workpiece dimension

From the overall structure and with the plane strain compression in mind, the length (the restricted direction) is chosen as twice that of the width. The nominal dimension is:

- Length (L) : 50mm
- Width (W) : 25mm
- Height (H) : 20mm

This dimension is helpful in reducing the influence of the side platens. The actual dimension of the workpiece is:

- \( L = 50.02 \text{mm} \)
- \( W = 25.00 \text{mm} \)
- \( H = 19.84 \text{mm} \)
2.4.3.2 The dimensions of block 2, 3, 5, 6.

<table>
<thead>
<tr>
<th>block</th>
<th>L(mm)</th>
<th>W(mm)</th>
<th>H(mm)</th>
</tr>
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<tbody>
<tr>
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<td>72.3(72.31)</td>
<td>50(50.01)</td>
<td>50(49.98)</td>
</tr>
<tr>
<td>3</td>
<td>50(50.09)</td>
<td>50(50.01)</td>
<td>50(49.95)</td>
</tr>
<tr>
<td>5</td>
<td>50(50.12)</td>
<td>50(50.01)</td>
<td>15.2(15.20)</td>
</tr>
<tr>
<td>6</td>
<td>71.8(71.85)</td>
<td>50(50.01)</td>
<td>50(49.96)</td>
</tr>
</tbody>
</table>

* numbers in brackets are the actual dimensions.

2.4.3.3 The side platens

![Fig. 2.10 The side platens](image)

The dimension of platen 9: L*W*H=194.8*80.00*30.00
Platen 8 is a pair of adjustable, inclined (5°) platens.

2.5 Data acquisition

2.5.1. The adjustment and calibration of the tribometer

The parts are assembled and adjusted. Fig. 2.11 is the experimental arrangement. Three signals need to be recorded: the vertical force, the friction force, and the vertical reduction displacement.

2.5.1.1 The vertical force

The vertical force is recorded by a strain-gauge typed sensor, installed in the 3500 KN SACK & KIESSELBACH hydraulic press. The analogue voltage signal is amplified (KWS-3-S5, WT 2639). The calibration is 4 volt/1000/1.32, with 1 volt=250KN.
2.5.1.2 The friction force

The friction force is recorded by a Kistler cell (SN 488475 (4.3 Pc/N)). The sensor component is pressure-sensitive crystal. The calibration is \( T = 4.3 \times 10^0 \), \( S = 1.00 \times 10^3 \), with 1 volt = 10 KN.

2.5.1.3 The vertical displacement

An inductive displacement sensor is used. The sensor should be as close to the workpiece as possible. For the closed chamber, it is difficult to put the sensor in between the upper and lower tools. So, the sensor is put in between the die-base and the press ram (Fig. 2.12).

The analogue signal is amplified (KWS-3-S5). The calibration is 4 volt/5000/4.00, with 1 volt = 1 mm (-4 volt to 4 volt).
2.5.2. Data acquisition

The three channel signals are displayed by a multichannel displayer. For rapid and accurate data acquisition, a PCL718 card is used.

The PCL718 card is a 12 bit, 60KHz, auto-channel scan card. It can detect 8 differential analogue inputs. For the linearity of the output of the vertical displacement sensor, the output of the displacement signal is from -4 volt to +4 volt. The PCL718 card input range is set at ±10 volt. The readings are from -2047 to +2048.

The standard functions of the PCL718 card are used to collect the data with the user made software trigger. The programme was written in Turbo Pascal as in Appendix.

Here are some comments:

a). signal channel 0: vertical force;
    signal channel 1: friction force;
    signal channel 2: vertical displacement;

b). the accuracy of the A/D conversion is 1 bit, but the environment (through inductive charge, etc.) causes 1--2 bit instability of the readings. This can be solved by: hardware, using the same electric power for the PCL718 card and the input signal amplifier, plus a good connection for the common zero point; software, in which a group of data is recorded every 500 ms and the sum after 10 times (which stands for the average value during 5 seconds). All this is stored in a data file. The result is checked by constant detecting signals which proved to have an instability of 1 bit.

The data acquisition software offers a notice for the experimental procedure.

**************************************************************************

*  
*  
ATTENTION!  
*  
Read the following paragraph carefully!  
*  
1. The computer, PCL718 card, amplifier, sensors must use the same power;  
*  
2. Clean blocks 2,3,5,6 and side platens 8,9 carefully with Acetone;  
*  
3. Side surfaces of workpiece, blocks 3,5 must be lubricated by Teflon foil;  
*  
4. Workpiece must be put as close to block 6 as possible;  
*  
5. Reset Kistler cell, turn screw 11 till friction sensor displays 00;  
*  
6. Pre-stress screw 10 to assure plane strain deformation.  
*  
**************************************************************************
2.6. Test and evaluation of the tribometer

To check the usefulness of the newly developed tribometer, experiments were done to see the reproducibility and Moiré pattern.

2.6.1 Reproducibility

Two sets of experiments were carried out at room temperature with average strain rate $\dot{\varepsilon} = 8 \times 10^{-4} \text{ s}^{-1}$. One set uses Tallow as lubricant, another set uses no lubricant. Fig. 2.13 and Fig 2.14 give the results.

![Fig. 2.13 Reproducibility experiment (Tallow lubricant)]

![Fig. 2.14 Reproducibility experiment (no lubricant)]

From Fig. 2.13 and Fig. 2.14, it can be seen that the reproducibility is very good. This shows the new apparatus works well and the experiments are controlled very well. After unloading, the displays of the friction were also noted and proved to very small.
2.6.2 The Moiré experiment.

Fig. 2.15 is the Moiré pattern with 12 l/mm gratings and Tallow lubricant. The symmetry and the regularity of the Moiré pattern show the success of the experimental set-up.

![Moiré pattern image]

Fig. 12 The Moiré pattern

2.7 Discussion and Conclusion

In this chapter, a plane strain compression test set-up is developed, adjusted and examined. This test set-up can perform plane strain compression accurately, the vertical force, friction force and vertical displacement are recorded automatically by the PCL718 card with the PC. It is easy to handle and less expensive. The average friction coefficient $\mu$, friction factor $m$ can be obtained easily. The examples show the success of the test set-up.

The new tribometer can reproduce the characteristics of the real bulk forming processes very well. It can easily be used to continuously get the friction coefficients during the whole forming process. The changeable blocks make the new apparatus easy to use in the evaluation of the tribological properties of different tool surface finishes, different tool materials and different surface coatings. The simple structure means that it can be developed to an elevated temperature tribometer.
3. EXPERIMENTAL RESULTS

3.1 Introduction

Using the newly designed apparatus, the total friction force, deformation force and vertical displacement are recorded. So, the mean value of the friction coefficient $\mu$, friction factor $m$ and the friction constant $q$ during the forming process can be derived. By using the formulas derived by the slab method in section 2.2, the theoretical load-displacement curves can be obtained, which are used as a comparison for the experimental data. With the experimental data and careful consideration of the friction influence, the material flow stress are also determined. For the stress state is compressive during plane strain compression, the material can be deformed under fairly large strain. This allows that the flow curve to be used more conveniently and reliably in the numerical simulations of bulk forming processes.

3.2. Preparation of the experiment

3.2.1 Workpiece

All workpieces are made from the same soft aluminium plate, and for the uniformity of the surface finish, all the surfaces of workpieces are processed by grind powder. The workpiece dimensions are:

- Length: 50.02mm
- Height: 19.84mm
- Width: 25.00mm

3.2.2 Tool

The tools (upper and lower) are made from High Speed Steel. The surfaces are polished with roughness $R_a=1.25--2.5\mu m$.

3.2.3 Standard test

The standard Rastegaev compression test was carried out. The average strain rate was $\varepsilon=8*10^{-4}\text{s}^{-1}$. The flow stress was obtained as follows:

$$\sigma_f=120 \overline{\varepsilon}^{0.24}$$
3.3. Derivation of coefficients \( \mu, m, q \)

3.3.1 Derivation of \( \mu \)

From Coulomb friction model, the coefficient \( \mu \) can be simply obtained as:

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

Here \( F_{tr} \): the total friction force measured
\( F_{ver} \): the vertical force measured

3.3.2 Derivation of \( m \)

The friction factor \( m \) is defined with the help of the shear flow stress \( K \). \( m \) can be derived as: \( m = \frac{F_t}{2*L*W*K} \)

3.3.3 Derivation of \( q \)

In section 2.2, the \( \tau_{tr} \) was derived by the slab method:

\[
\tau_{tr} = \frac{2}{\sqrt{3}} \sigma_{tr} q x \frac{\Delta H}{H} \exp\left[\frac{q \Delta H (L^2-x^2)}{H^2}\right]
\]

Integrating the above formula, the total friction force can be expressed:

\[
F_{tr} = \frac{4}{\sqrt{3}} \sigma_{tr} W q \frac{\Delta H}{H} \int_0^L \exp\left[\frac{q \Delta H (L^2-x^2)}{H^2}\right] dx
\]

The coefficient \( q \) can be obtained:

\[
q = \frac{H^2}{\Delta HL^2} \ln\left[1 + \frac{\sqrt{3}F_{tr}}{2\sigma_{tr}WH}\right]
\]

The experimental results are processed by the computer program DATA_PRO.PAS (see Appendix). The program is a menu-driven one. The main menu is:

```
* Data Processing Program
* MAIN MENU
* A. Coulomb model: friction coefficient \( \mu \), load, friction, norm_pressure;
* B. von Mises model: friction factor \( m \), load, friction, norm_pressure;
* C. R–K model: coefficient \( q \), modified \( q_1 \), load, friction, norm_pressure;
* D. Material flow stress;
* E. Exit program.
```
3.4 Experimental results (friction test)

Fig. 3.1 Friction coefficients $\mu$, m q

Fig. 3.2 Load--displacement curve
Fig. 3.3 Friction distribution

(a) Tallow lubricant

(b) no lubricant

Fig. 3.4 Normal pressure distribution

(a) Tallow lubricant

(b) no lubricant
Two sets of experiments were carried out at room temperature with an average strain rate $\dot{\varepsilon} = 8 \times 10^{-4}$ s$^{-1}$. One set (a) uses Tallow as lubricant, the other (b) uses no lubricant. Fig. 3.1 and 3.2 show the results.

Comparing Fig. 3.1, we can see that the use of Tallow lubricant gives lower friction coefficients. So, the new apparatus can be used to evaluate the frictional property of various lubricants. It can also be seen that the coefficients are not constant in all three friction models during the forming processes. $\mu$ and $m$ increase with the punch travel, $q$ increases rapidly at first and then decreases dramatically with the punch travel. Thus all the three friction models run into difficulties when used in forming processes.

Fig. 3.2 displays the load versus punch travel curves, which are obtained by using the experimental results of $\mu$, $m$, $q$ and the theoretical derivation by slab method in section 2. It can be seen that both the curves, for Coulomb model and von Mises model, underestimate the deformation load. The load by R–K model agree very well with the experimental result. This shows two points: first, the slab method results are strongly influenced by the friction model (friction distribution on the interface); second, the R–K model is better in predicting friction distribution at the interface than the Coulomb and von Mises friction model.

Fig. 3.3 and 3.4 give the friction and normal pressure distribution on the interface with $\Delta H = 3$ mm. The friction distribution and normal pressure distribution obtained through the R–K model agree the best with the results measured by Wanheim [20] among the three friction models. The integration of friction and normal pressure over the contact length has to be equal to the total friction and vertical force measured, but one can see that the area between the curves in Fig. 3.3 and 3.4 is not the same. From section 2.2, by using slab method, the vertical force $F_{\text{ver}}$ and the total friction force $F_f$ are all functions of friction coefficients $\mu$, $m$ and $q$. The total friction and total vertical force only agree well when the friction model represents the real situation well. This also suggest that the R–K model gives better results in metal-forming analysis, as we can obtain the coefficient $q$ from total friction force $F_f$, and the derived vertical force $F_{\text{ver}}$ agrees well with the experiment.

3.5 Experimental results (material flow stress)

Material flow stress is a very important input parameter that has to be used in the numerical simulation of material processing processes. There are many important factors of influence on the material flow stress. The influence of stress
state (hydrostatic stress) on the material flow stress has been studied extensively. Most of the bulk forming processes are realised under compressive stress state. Therefore the Rastegaev test is widely used to obtain the material flow stress. As the friction at the tool/workpiece can never been totally eliminated, when the deformation is high, the barrelling of the free surface will cause errors in deriving the material flow stress under large deformation. Using the newly designed apparatus, the plane strain compression can be carried out accurately. It is possible to derive the material flow stress taking the friction distribution at the interface into account. Since only one free surface is exposed and good lubricant (Teflon foil) can be used, the deformation can be fairly large. The new apparatus can easily obtain material flow stress being used for the bulk forming processes.

3.5.1. Principle

During the experiments, the deformation force, total friction force and vertical displacement are recorded. The experimental values of the friction coefficients $\mu$, $m$, $q$ can all be derived as described in section 3.3. Once these coefficients have been obtained, from the equations derived in section 2, the material flow stress can be derived with the help of the specimen geometry and total deformation force.

From section 3.4, the load predicted with slab method by using R--K friction model agrees well with the experimental results. So, it can be concluded that using the coefficient $q$ which is derived from experimental data and total vertical force measured, the material flow stress can be derived.

$$\sigma_t = \sqrt{3}\frac{F_{\text{ver}}}{2W\int_0^L \exp\left[\frac{q\Delta H}{H^2}(L^2-x^2)\right]dx}$$

3.5.2 Results

First, a standard Rastegaev test was carried out. A standard flow curve was obtained. Then using the program DATA_PRO.PAS, two material flow stress curves were derived from the plane strain experiments (one marked by Tallow lubricant, another marked by no lubricant). Fig. 3.5 shows the results.

In Fig. 3.5, the material flow stress obtained by the plane strain compression experiments is in reasonable agreement with the standard Rastegaev test,
especially where the surface friction is low (i.e. when Tallow lubricant was used). This shows that when the interface friction is carefully considered, the plane strain compression test can be used to obtain the material flow stress. If a good lubricant is used, as there is a compressive static stress during the forming process, a fairly large deformation can be reached which normally is the case in bulk forming processes. Therefore the new apparatus is an alternative to the Rastegaev test.

3.6 Conclusions

The experimental results on friction coefficients show that the coefficients $\mu$, $m$, $q$ are not constants during metal-forming processes. As a consequence the Coulomb, von Mises and R--K model all have difficulties being used in metal-forming processes. Using R--K model, a comparatively reasonable friction and normal pressure distribution can be obtained. Also, the load predicted by using R--K model agrees very well with the experimental results.

The material flow stress obtained by the plane strain compression test agrees very well with the standard Rastegaev test, where the R--K model is used to take the friction into account. Using the new apparatus, the friction coefficients and material flow stress can be obtained in the same experiment. The new experiment can be used as an alternative to the Rastegaev experiment.
4. MOIRÉ EXPERIMENT

4.1 Introduction

The fact that there are no constant friction coefficients of Coulomb, Von Mises and R--K models in forming processes, stimulates the search for a more accurate friction model. The simplicity, clear physical background and good agreement with the experimental results of the R--K model make it possible for a slight modification to be made in order to find a nearly constant coefficient during forming processes.

An experimental technique -- Moiré method -- is introduced which can be used to acquire the local displacement, velocity, normal pressure and shear stress at the interface. The Moiré method is used to verify the modified friction models.

4.2 Modification on R--K model

4.2.1 The modified model

One way to modify the R--K friction model is to make the coefficient q dimensionless. From the experimental results, we know that the coefficient q is not constant during the forming processes. So a modification is made here: the friction stress \( \tau_f \) increases with the relative slip ratio \( u/v_t \) between the tool and the workpiece, the normal pressure and the surface strain (relative increase of the nominal surface):

\[
\tau_f = q_1 \rho \frac{u_s A}{v_t A_0}
\]

Here \( u_s \) is the relative velocity between tool and workpiece and \( v_t \) is the tool velocity. In this way, the coefficient \( q_1 \) becomes dimensionless. The concerned lubrication regime is mixed film lubrication as in the R--K model.

4.2.2 Experimental results on the modified model

Using the slab method, the normal pressure \( p \) and the friction stress \( \tau_f \) can be derived. The coefficient \( q_1 \) in the modified model is calculated using the data measured and \( q \).
\[ q_1 = q \Delta H \]

The \( q_1 \) during forming processes is given in Fig. 4.1 and Fig. 4.2. It can be seen that when \( \Delta H/H_0 < 0.05 \), \( q_1 \) increases linearly with the increase of strain; after \( \Delta H/H_0 > 0.05 \), \( q_1 \) is nearly a constant during the forming processes. This proves the modified model is more easy to use than the original R--K model.

![Fig. 4.1 q1 curve (no lubricant)](image)

![Fig. 4.2 q1 curve (Tallow lubricant)](image)

The modified model is based on a clear physical background. \( q_1 \) first increases linearly with the strain then becomes a nearly constant during forming process.

Once the relative slip velocity is constant (which means there is no plastic deformation of the workpiece), the modified R--K model turns out to be the Coulomb friction model.

4.3. Moiré experiment

4.3.1. Introduction

The development of plasticity theory provided the possibility to simulate the metal-forming processes systematically. But in solving the practical problems,
besides the problems of accurately describing the material behaviour, the accurate description of boundary conditions and the solution of the plasticity equations are still very difficult. This means that the physical simulation is still an important means to solve plasticity problems.

The Moiré method is a rather new experimental technique. It is a combination of physical modelling with numerical calculation. It uses the Moiré effect which is the mechanical interference of two sets of regular gratings to form fringes which represents the loci of equal displacement components in the direction normal to the master grating direction. It has many advantages compared with the other methods in solving plasticity problems: whole field measurement; large measurement scope (elastic deformation, plastic deformation to fracture); distinct information which is easy to process. Using the Moiré method, the velocity field, strain rate and stress distribution can all be obtained. So, it can be used to check the results of numerical simulation and to check the validity of friction models.

4.3.2. Experimental procedure

The procedure in the Moiré experiment is: prepare the specimen and clean the specimen with Acetone; stick Moiré gratings on the specific surface of the specimen; put the specimen in a special tool and deform it; put the master grating on the specimen grating to get the Moiré fringes; use an image-processing system to analyze the Moiré information; process the data to obtain velocity field, strain and stress distribution.

In this work, the central section of the specimen is cleaned with Acetone and then 12 l/mm single direction reflective Moiré gratings are stuck on it (Fig. 4.3). It must be prepared carefully to ensure the Moiré gratings are parallel to the coordinate direction. The whole area has to be stuck very well and the border has to be amended very well too.

Fig. 4.3 Sketch diagram of the direction of specimen gratings
After the specimen is carefully prepared, we deform the specimen with the
desired strain rate to a given reduction ratio in the experimental set-up. By removing the specimen from the tool then putting the master gratings on the specimen and adjusting the master grating, a symmetry Moiré pattern is obtained. Because of the symmetry, only half of the specimen is needed for processing. By dividing the half specimen into rows and columns (mesh) (Fig. 4.4), and then using the CCD video camera (with the resolution of 512*512 pixel) and image processing system, the coordinates and grade numbers of Moiré fringes on the rows and columns are obtained.

Fig. 4.4 Division of the specimen

Since the product of the grade number and grating pitch is the displacement of that point, the displacement corresponding to the coordinate is obtained.

In Moiré analysis, the static plasticity is assumed which means that the influence of strain rate on the material behaviour is neglected and the increments of displacement between two loading step takes place in a unit time. So the strain can be treated as the strain rate increment.

Fitting the diverse displacement/coordinate points into a cubic spline function, the displacement on the mesh point can be found. As a result, the first derivative of the displacement can be found. During small amounts of deformation (as in the case of engineering strain $< 5\%$), the strain rate can be obtained.

$$
\varepsilon_x = \frac{\partial u}{\partial x},
$$

$$
\varepsilon_y = \frac{\partial v}{\partial y},
$$

$$
\dot{\varepsilon}_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}.
$$

The stress deviator $S_{ij}$ can be obtained by using the Levy-Mises plasticity theory. The Moiré method is a whole field experimental method, so the whole field shear stress distribution is obtained. The stress components are obtained by changing the equilibrium equation into a difference equation. Fig. 4.5 gives the flow chart of the data processing program.
read the node coordinate of the mesh

read the coordinate and grade number of Moiré fringes to get the velocity field

fit the velocity using the cubic spline method and output the velocity at the node point

fit the velocity at the mesh point to get the first order derivatives \( \frac{\partial u}{\partial x}, \frac{\partial v}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial v}{\partial y} \)

calculate and output strain rate and effective strain rate \( \dot{e}_x, \dot{e}_y, \dot{\gamma}_{xy}, \dot{\epsilon}_i \)

use Levy-Mises theory to get the stress deviator \( S_x, S_y, \tau_{xy} \)

use equilibrium equation to get the stress component \( \sigma_x, \sigma_y, \sigma_m \)

Fig. 4.5 Flow chart diagram of data processing program
4.3.3. Results

One experiment is done by using the Tallow lubricant. Fig. 4.9 is the Moiré pattern.

Fig. 4.6 The Moiré pattern (12 l/mm, ΔH/H0=4.2%)

Fig. 4.7 Reconstructed Moiré pattern
Because of the symmetry of the workpiece, only half of it is analyzed. Fig. 4.7 is the mathematically reconstructed Moiré pattern using the experimental data. It can be seen that it can represent the experimental Moiré pattern quite well. This shows that the data processing system is reliable.

Fig. 4.8 The effective strain distribution

Fig. 4.8 is the effective strain distribution within the workpiece. Since the Tallow lubricant is used in the experiment, the strain distribution is rather uniform. It can be seen that the effective strain at the workpiece's upper left and upper right corner is comparatively small. This is in agreement with the well known three-zone theory established by Unksov[14]: stick zone, slip zone and drag zone.

Fig. 4.9 The slip velocity at the interface

Fig. 4.9 is the slip velocity at the interface. It can be seen that the slip velocity increases slowly at first and then increases nearly linearly, finally increasing slowly again. This variation is consistent with the three-zone theory.

Fig. 4.10 is the normal pressure distribution at the interface. Comparing the theoretical results in section 3.4 and Fig. 3.4, it can be seen that the normal pressure obtained by Moiré analysis agrees well with that by R--K model.
Fig. 4.10 The normal pressure distribution at the interface

Fig. 4.11 The shear stress distribution at the interface

Fig. 4.11 is the shear stress distribution at the interface. From the Moiré analysis, it can be seen that three zones clearly exists. When $x = 0$, the shear stress is zero, then it increases to a certain value, which corresponds to the stick zone. After the shear stress reaches to a certain value, it maintains a constant in a distance which corresponds to the drag zone. Then the shear stress drops which corresponds to the slip zone. Assuming the upper tool moves in a unit velocity, then the relative slip velocity $u_r/u_t$ is obtained. Since the normal pressure is obtained and the friction coefficient can be obtained from Fig. 4.3, $q_1 = 0.025$, surface strain $A/A_0 = H_0/H$, so a shear stress distribution can be obtained by using the R–K model. From Fig. 4.14, it can be seen that there is a fairly large difference between the Moiré results and the R–K model results. This implies that even the R–K model is better than the widely used Coulomb model and Von Mises model. However, continued modification is necessary to describe the interfacial conditions more accurately. New friction model should be developed on the basis of micro-analysis of the friction phenomena.
4.3.4. Accuracy analysis

The Moiré technique demands many procedures of experiment and calculation, every step can introduce errors into the final results. It is very important to control every step carefully. During the preparation of the specimen, the surface to stick Moiré gratings on has to be cleaned carefully by Acetone. The gratings have to be stuck on parallel to the coordinate system. During the experiment, the upper and lower tools must have the same boundary conditions, and ensure the plane strain compressions. The resolution of the image-processing system must be high enough, 512*512 is necessary, but a 1024*1024 system is recommended. Since the Moiré strain analysis is based on the displacement difference, its accuracy is based on a large quantity minus a large quantity, so the data processing system has to be carefully designed.

In this analysis, from the point of experiment, the preparation of specimen and tools are carefully controlled. This ensures that a symmetrical and very regular Moiré pattern is obtained. From the point of data analysis, the 512*512 image processing system ensured the accuracy of Moiré data. The internal inhomogeneities of the specimen material make the Moiré fringes a little shaking, so the spline smooth method is used in getting the velocity components at the mesh points, which ensures a smooth and accurate velocity curve.

4.4 Discussion

The modified R--K friction model not only has a clear physical background but is also easy to use in metal-forming analysis.

The Moiré technique is useful in verifying the theoretical results and numerical results. The Moiré analysis shows that the modified R--K friction model has to be continue investigated. Since the physical meaning of the Moiré fringes is the loci of the points which have the same displacement component in the direction normal to the master gratings. Therefore, it is a useful method for constructing the admissible velocity field for Upper Bound analysis. Some work have to done to see the surface asperity deformation with Moiré technique.
5. CONCLUDING REMARKS

In the present project, a plane strain compression tribometer has been developed.

The plane strain compression process has been analyzed and the influence of tool stiffness on the experimental results has been obtained. The design of the whole structure has made it possible to simultaneously measure the two important parameters in plasticity process analysis -- friction coefficient and material flow stress -- in one experimental set-up.

The data acquisition system is realised by using a PC with a PCL718 card. The data processing software is programmed with Turbo Pascal language. The experimental data reveal that the theoretical results obtained by using the R-K friction model agree best. By using the R-K model, accurate material flow curve can be obtained. The experimental results show that all the friction coefficients in the discussed three friction models are not constant during metal-forming processes. So, a modification on R-K model has been made and a nearly constant coefficient is obtained.

An experimental technique -- Moiré method -- is used to verify the modified R-K model. The experimental results show that there still is a large difference between the experimental data and the theoretically determined friction distribution. So, continuing work still has to be done to describe friction accurately.

Based on the above work, some remarks are made here:

a). try a new method to eliminate the influence of side surface friction on the total friction measured, like using different specimen dimensions, or a new method in side surface lubrication;

b). try to stick the specimen onto the block 6, which can simulate the half plane strain compression better;

c). do more experiments on different tool materials, tool surface finish (like coatings etc);

d). a further development into an elevated temperature tribometer is necessary;

e). try to make the experimental set-up a standard one;

f). work out an experimental (Moiré method) analysis of surface asperity deformation and investigate friction mechanism, finally constructing a more accurate friction model.
REFERENCES

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Department of Production Technology and Automation
Faculty of Mechanical Engineering
Eindhoven University of Technology

Development of a plane strain compression tribometer
Appendix

S.L. Wang
Feb. 1994

WPA nr 120005
program Measurement(input,output);

{ This program uses the standard functions accompanied with the PCL 718 card for detecting the data and the standard Turbo Pascal procedure DELAY for making software trigger.  

{$F+}$
{$L$ TP718}

uses
    dos, crt;

procedure pcl718(f:integer; var a,b,c,d: integer); external;

type
    smallarray = array[0..5] of integer;
    data_array = array[0..50] of integer;
CONST

dire = 'c:\tp\wang\';

VAR

parm ary1, ary2 i, j, er, func_no, k, n load, friction, stroke, data temp0, temp1, temp2, temp tem0, tem1, tem2 x, y key_selection lo, str, fri, tri

: smallarray;
: data_array;
: integer;
: text;
: integer;
: real;
: integer;
: char;
: char;

{*********************************************************}

PROCEDURE func0;

{Initialization of the driver}

BEGIN er := 0;
func_no := 0;
parm[0] := $300; {set I/O port base address}
parm[1] := 3; {use interrupt level 3}
parm[2] := 1; {use DMA channel}
pcl718(func_no, parm[0], ary1[0], ary2[0], er);
{ary1[ ], ary2[ ] are dummy}
if er <> 0 then begin
  writeln('initialization failed!');
  exit
end;

END;

{*********************************************************}

PROCEDURE func1;
{Set the multiplexer scan range}

BEGIN

parm[0] := 0; {start scan channel}
parm[1] := 2; {stop scan channel}
func_no := 1; {set function number}
pcl718(func_no, parm[0], ary1[0], ary2[0], er);

if er <> 0 then begin
    writeln('set scan channel failed!');
    exit
end;

END;

PROCEDURE func2;

{Read the next conversion channel number and current input scan range}

BEGIN

func_no := 2;
pcl718(func_no, parm[0], ary1[0], ary2[0], er);
if er <> 0 then begin
    writeln('read channel setting failed!');
    exit
end;

END;

PROCEDURE func3;

{Perform a software triggered single A/D conversion}
BEGIN

func_no := 3;
pci718(func_no, parm[0], ary1[0], ary2[0], er);
if er <> 0 then begin
    writeln('software trigger failed!');
    exit
end;
{display scan channel # & reading}
{writeln('scan channel =', parm[1]);
 writeln('reading =', parm[0]);}
if parm[1] = 0 then
begin
    temp0 := temp0 + parm[0];
    writeln(load, ' ', parm[0]);
end;
if parm[1] = 1 then
begin
    temp1 := temp1 + parm[0];
    writeln(friction, ' ', parm[0]);
end;
if parm[1] = 2 then
begin
    temp2 := temp2 + parm[0];
    writeln(stroke, ' ', parm[0]);
end;
END;

{***********************************************************************}

BEGIN

clrscr;
writeln;
writeln;
writeln('ATTENTION!');
writeln;
writeln('Read the following paragraph carefully!');
writeln;

4
writeln(‘ 1. The computer, PCL718, amplifier, sensors must use same power;’);
writeln;
writeln(‘ 2. Clean blocks 2,3,5,6 and side platens 8,9 carefully with acetone;’);
writeln;
writeln(‘ 3. Workpiece side surfaces, block 3,5 must be lubricated by Teflon;’);
writeln;
writeln(‘ 4. Workpiece must be put as close to block 6 as possible; ’);
writeln;
writeln(‘ 5. Reset Kistler cell, turn screw 11 till friction display 00; ’);
writeln;
writeln(‘ 6. Pre-stress screw 10 to assure plane strain deformation. ’);
writeln;
writeln(‘Press any key to continue!’);
key_selection := readkey;

writeln(‘Enter names of datafiles:’);
writeln;
writeln(‘data file of load:’);
readln(lo);
writeln;
writeln(‘data file of friction:’);
readln(fri);
writeln;
writeln(‘data file of stroke:’);
readln(str);
writeln;
writeln(‘file name of three data together:’);
readln(tri);
writeln;

assign(load, dire + lo + ‘.dat’);
assign(friction, dire + fri + ‘.dat’);
assign(stroke, dire + str + ‘.dat’);
assign(data, dire + tri + ‘.dat’);
rewrite(load);
rewrite(friction);
rewrite(stroke);
rewrite(data);
func0;
func1;
begin
  for i := 1 to n do
    begin
      temp0 := 0;
temp1 := 0;
temp2 := 0;
      for k := 1 to 10 do
        begin
          delay(500);
          for j := 1 to 3 do
            begin
              func3;
              func2;
            end;
        end;
      if i = 1 then temp := temp2;
      temp0 := temp0/2048;  \{friction unit N\}
temp1 := temp1/2048;  \{displacement unit mm\}
temp2 := (temp2 - temp)/2048;  \{vertical load unit N\}
      writeln(data, temp2, ', ', temp0, ', ', temp1);
      writeln(' ', i);
    end;
end;
close(load);
close(friction);
close(stroke);
close(data);

END.
PROGRAM Data_processing(input,output);

USES CRT;

CONST
cc = 120; {material constant N/mm2}
nn = 0.24; {strain hardening exponent}
l0 = 25.00; {initial workpiece length}
h0 = 19.84; {initial workpiece height}
w0 = 50.02; {initial workpiece width}
n = 98; {total recorded data}
alfa = 0.98; {bulging factor}
dir = 'd:\tp\wang\';

TYPE
arrayty1 = array[0..n] of real;
arrayty2 = array[0..2] of real;
VAR

    x, y : integer;
    menu_selection : char;
    i, j, k : integer;
    l, h : real;
    data : text;

{*******************************************************}

PROCEDURE Coulomb_model;

VAR

    coulombfile, edata : string [10];
    nptauCoulo : string [10];
    xx : array[0..2] of real;
    tau, npressure : real;
    epsilon : real;
    mu, sigma_f : real;
    load, x : real;
    height : real;
    muc, sigma_fc : real;
    results1, results2 : text;

BEGIN

    writeln('Enter the name of output file: Coulomb_file ');
    readln(coulombfile);
    writeln('Enter the name of experimental data file: edata ');
    readln(edata);
    assign (results1, dir + coulombfile + '.dat');
    rewrite (results1);
    assign (data, dir + edata + '.dat');
    reset(data);
    writeln('Enter the file name of norm_pressure and friction: nptauco');

readln(nptauCoulo);
assign(results2, dir + nptauCoulo + '.dat');
rewrite(results2);
writeln('Enter the final height for calculating Nor_Presu and friction: height');
readln(height);

for i := 0 to n do
begin
  readln(data, xx[0], xx[1], xx[2]);
  h := h0-xx[2];
  I := (I0*h0)/h;
  I := I*alfa;
  epsilon := 2/sqrt(3)*ln(h0/h);
  if epsilon = 0 then sigma_f := 0
  else sigma_f := cc*exp(nn*ln(epsilon));
  mu := 0.5*xx[1]/xx[0];
  if mu = 0 then load := 2*I0*w0*sigma_f/sqrt(3) else
          load := w0*h*sigma_f/(sqrt(3)*mu)*(exp(2*mu*I/h)-1);
  writeln(results1, xx[2], epsilon, mu, load/1000);
  writeln(xx[2], epsilon, mu, load/1000);
  if xx[2] < h0-height then
    begin
      muc := mu;
      sigma_fc := sigma_f;
    end;
end;
close(results1);

h := height;
I := (I0*h0)/h;
I := I*alfa;
for i := 0 to 10 do
begin
  x := i*I/10;
  npressure := 2*sigma_fc/sqrt(3)*(exp(2*muc/h*(I-x)));
tau := muc \cdot n\text{pressure};
writeLn(i/10, n\text{pressure}, \tau);
writeLn(results2, i/10, n\text{pressure}, \tau);
end;
close (results2);

writeLn;
write('Hit any key to return to MENU: ');
menu_selection := readkey;

END;

{*******************************************************}

PROCEDURE von_Mises_model;

VAR
  misesfile, edata : string [10];
  nptauMises : string [10];
  xx : array[0..2] of real;
  \tau, n\text{pressure} : real;
  epsilon : real;
  m, sigma_f : real;
  load, x : real;
  height : real;
  mc, sigma_fc : real;
  results1, results2 : text;

BEGIN

  writeln('Enter the name of output file: Mises_file ');
  readln(misesfile);
  writeln('Enter the name of experimental data file: edata ');
  readln(edata);
  assign (results1, dir + Misesfile + '.dat');
  rewrite (results1);
assign (data, dir + edata + ' .dat');
reset(data);
writeln('Enter the file name of norm_pressure and friction: nptauMises ');
readln(nptauMises);
assign(results2, dir + nptauMises + ' .dat');
rewrite(results2);
writeln('Enter the final height for calculating Nor_Presu and friction: height');
readln(height);

for i := 0 to n do
begin
readln(data, xx[0], xx[1], xx[2]);
h := h0-xx[2];
l := (l0*h0)/h;
l := l*alfa;
epsilon := 2/sqrt(3) *ln(h0/h);
if epsilon = 0 then sigma_f := 0
else sigma_f := cc*exp(nn*ln(epsilon));
tau := 0.5*xx[1]*1000/(l*w0);
load := (w0*h0*l0)/h*(2/sqrt(3)*sigma_f + tau*l0*h0/(h*h));
if epsilon = 0 then m := 0 else
m := sqrt(3)*tau/sigma_f;
writeln(results1, xx[2], epsilon, m, load/1000);
writeln(xx[2], epsilon, m, load/1000);
if xx[2] < h0-height then
begin
mc := m;
sigma_fc := sigma_f;
end;
end;
close(results1);

h := height;
l := (l0*h0)/h;
l := l*alfa;
for i := 0 to 10 do
begin
    x := i*I/10;
    tau := mc*sigma_fc/sqrt(3);
    npressure := 2*sigma_fc/sqrt(3) + 2*tau*(l-x)/h;
    writeln(i/10, npressure, tau);
    writeln(results2, i/10, npressure, tau);
end;
close (results2);

writeln;
write('Hit any key to return to MENU: \');
menu_selection := readkey;

END;

{*****************************************************************************}

PROCEDURE R_K_model;

VAR

    rkfile, edata : string[10];
    nptaurk : string[10];
    xx : arrayty2;
    stroke,v : arrayty1;
    tau, npressure : real;
    epsilon : real;
    q, q1, sigma_f : real;
    load, x, sigma_z : real;
    height, aa : real;
    qc, sigma_fc : real;
    results1, results2 : text;

BEGIN
writeln('Enter the name of output file: RKfile '); readln(rkfile);
writeln('Enter the name of experimental data file: edata '); readln(edata);
assign(results1, dir + rkfile + '.dat'); rewrite(results1);
assign(data, dir + edata + '.dat'); reset(data);
writeln('Enter the file name of norm_pressure and friction: np_tau_r_k '); readln(nptaurk);
assign(results2, dir + nptaurk + '.dat'); rewrite(results2);
writeln('Enter the final height for calculating Nor_Presu and friction: height'); readln(height);

for k := 1 to n do
begin
  readln(data, xx[0], xx[1], xx[2]);
assign(data, dir + edata + '.dat'); reset(data);
for i := 0 to n do
begin
  readln(data, xx[0], xx[1], xx[2]);
  h := h0-xx[2];
  l := l0*h0/h;
  I := I*alfa;
  epsilon := 2/sqrt(3)*ln(h0/h);
  if epsilon = 0 then sigma_f := 0
    else sigma_f := cc*exp(nn*ln(epsilon));
  if xx[2]=0 then q := 0 else
    begin
      aa := xx[1]*1000*sqrt(3)/(2*sigma_f*w0*h);
      q := ln(aa+1)*h*h/(xx[2]*sqr(l));
    end;
  q1 := q*xx[2];
  load := 0;
for j := 0 to 100 do
begin
    x := j*I/100;
    sigma_z := 2/sqrt(3)*sigma_f*exp(q*(hO-h)/(h*h)*(sqr(l)-sqr(x)));
    load := load + sigma_z;
end;
load := w0*load*I/101;

writeln(results1, xx[2], ', epsilon,' ', q,' ', q1,' ', load/1000);
writeln(xx[2], ', epsilon, ', q, ', q1, ', load/1000);
if xx[2] <= h0-height then
begin
    qc := q;
    sigma_fc := sigma_f;
end;
end;
close (results1);

h := height;
l := (l0*h0)/h;
l := l*alfa;
writeln(qc, ', sigma_fc,' ', l);
for i := 0 to 10 do
begin
    x := i*I/10;
    npressure := 2/sqrt(3)*sigma_fc*exp(qc/h*(h0/h-1)*(sqr(l)-sqr(x)));
    tau := qc*npressure*x*(h0-h)/h;
    writeln(i/10, npressure, tau);
    writeln(results2, i/10, npressure, tau);
end;
close (results2);

writeln;
write('Hit any key to return to MENU: ');
menu_selection := readkey;
PROCEDURE Flow_stress;

VAR
  stress_file, rk_file, edata : string[10];
  ce, ne : real;
  xx, xy : arrayty2;
  x1, sigma_f1, sigma_f2, temp : real;
  results, ndata : text;

BEGIN

  writeln('Enter the name of output file: stress_file ');
  readln(stress_file);
  writeln(stress_file) ;
  writeln('Enter the name of experimental data file: edata ');
  readln(edata);
  writeln('Enter the name of q coefficient file: rk_file');
  readln(rk_file);
  writeln;
  assign (results, dir + stress_file +' .dat');
  rewrite (results);
  assign (data, dir + edata + ' .dat');
  reset (data);
  assign (ndata, dir + rk_file +' .dat');
  reset (ndata);

  for i:= 0 to n do
    begin
      readln(data, xx[0], xx[1], xx[2]);
      readln(ndata, xy[0], xy[1], xy[2]);
      h := h0-xx[2];
    end;

  
END;

{******************************************}
I := h0*l0/h*alfa;

temp := 0;

for j := 0 to 200 do
begin
  x1 := j*1/200;
  temp := temp + exp(xy[2]*xx[2]/(h*h)*((l*l-x1*x1)));  
end;

temp := temp*l/200;

sigma_f1 := xx[0]*1000*sqrt(3)/(2*w0*temp);

sigma_f2 := cc*exp(nn*In(xy[1]));

writeln(xy[1], ' ', sigma_f1, ' ', sigma_f2);

writeln(results, xy[0], xy[1], sigma_f1,sigma_f2);

end;

close (results);

writeln;
write('Hit any key to return to MENU: '); menu_selection := readkey;

END;

{*****************************************************
BEGIN {main program}

repeat
begin
clrscr;

writeln ('Data Processing Program':50);
writeln;

writeln('MENU':40);
writeln;

writeln(' A. Coulomb model: friction coefficient mu, load, friction, norm_pressure');
writeln;

writeln(' B. von Mises model: friction factor m, load, friction, norm_pressure');
writeln;

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writeln(’C. R--K model: coefficient q, modified q1, load, friction, norm_pressure’);
writeln;
writeln(’D. Material flow stress’);
writeln;
writeln(’E. Exit program’);
writeln;
x := wherex;
y := wherey;
gotoxy (x,y);
write(’Enter a valid selection: ’);
menu_selection := readkey;
writeln;
case menu_selection of
A’, ‘a’ : Coulomb_model;
B’, ‘b’ : von_Mises_model;
C’, ‘c’ : R_K_model;
D’, ‘d’ : flow_stress;
end;
end;
until menu_selection in [’E’, ‘e’]

END. {main program}