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DETERMINATION OF FRICTION IN BULK METAL FORMING PROCESSES

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Abstract: *Consideration of tribological phenomena in bulk metal forming processes is very important as friction affects all relevant process parameters such as tool life, forming load and work, integrity of workpiece, quality of workpiece surface, material flow, etc. For the theoretical analysis of the metal forming process as well as for process modeling and simulation, knowledge of coefficient of friction (or friction factor) is indispensable. In metal forming operations in most cases two different friction laws are applied: Coulomb friction model and constant friction model. Evaluation of coefficient of friction is possible by different experimental trials such as backward extrusion, double cup extrusion test, forward bar extrusion, tube extrusion, etc. One of the most applied methods is ring compression test. The concept of this test is to observe and measure increase or decrease of the inner ring diameter during upsetting between two parallel plates. In case of low friction internal diameter increases, while if friction is high internal diameter decreases. Based upon this occurrence, friction calibration curves (FCCs) are created, which makes it possible to obtain coefficient of friction in every specific case.*

This paper is concerned with the possibilities to evaluate friction in metal forming processes. Different friction models are analyzed and assessed. Focus has been placed on the ring compression test and construction of friction curves. Our own modeling and experimental results are shown and analyzed.

Keywords: *metal forming, friction, ring compression test, FE modeling.*

1. INTRODUCTION

In metal forming processes friction is a very important variable which influences all relevant process parameters (force, load, work, temperature, material flow, etc) as well as quality of workpiece. Friction occurs due to relative motion between the tools or dies and workpiece material.

Many scientists have contributed to the research and explanation of physical phenomena which cause friction between two surfaces in relative motion. One of the most significant works is [1] in which authors developed their own approach known as "Adhesion Theory". They concluded that the true contact area between workpiece and tool/die contact is only a small percentage of the apparent contact area (Fig. 1).

Beside Bowden & Tabor's "Adhesion Theory", some other approaches to explain physical nature of friction have been elaborated, such as "Roughness Theory" and "Plowing Theory" [1], [2].

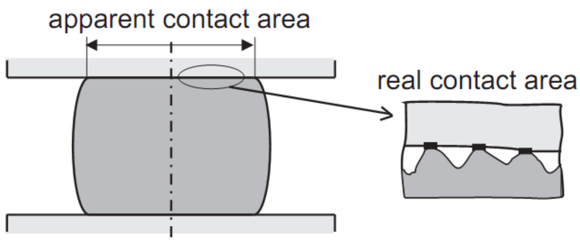

Figure 1. Real and apparent contact area

In recent time new technological developments, such as Scanning force microscope (SFM), contributed to the more sophisticated and more reliable investigation of friction in metal forming.

Characterization of friction (quantification of friction amount) is possible in different ways [3], [8]. Most common way is by Coulomb model:

$$\tau = \mu \cdot p \tag{1}$$

τ – tangential friction stress
μ - coefficient of friction
p – local normal pressure

Constant friction model proposes that friction stress is constant and proportional to the yield stress in pure shear "τ_{max}" and friction factor:

$$\tau = m \cdot \tau_{max} \quad (2)$$

Both models are insufficient for exact description of friction phenomenon as they do not take into account a number of other influential factors such as relative velocity, material properties, surface roughness, lubrication conditions and etc. However, due to their simplicity, they are commonly used for friction description in analytical or numerical modeling of metal forming processes [5], [7], [12].

Coefficient of friction (μ) and friction factor (m) can be obtained in different experimental trials which simulate real metal forming processes [5], [9], [12].

In further text, some of the most applied experimental methods to evaluate "μ" and "m" in bulk metal forming operations are presented [10], [13], [14].

2. EXPERIMENTAL TECHNIQUES FOR FRICTION MEASUREMENT IN BULK METAL FORMING

2.1 Forward bar extrusion (FBE)

In figure 2 schematic diagram of forward extrusion process is shown. Due to friction on the container wall, friction force F_c occurs.

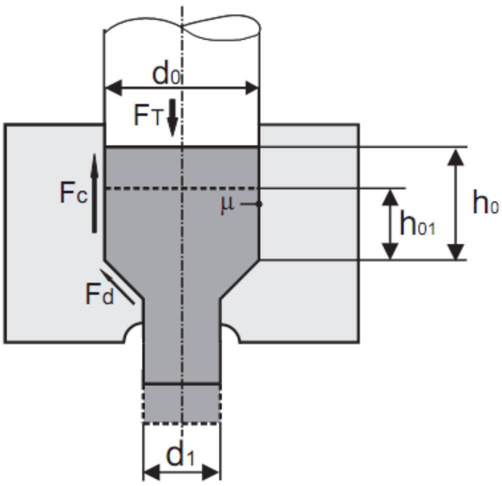

Figure 2. Forward bar extrusion

Total extrusion force is:

$$F_T = F_c + F_d + F_{dd} \quad (3)$$

F_c - friction force at the workpiece container interface

F_d – friction force at the conical die/workpiece interface

F_{dd} – deformation force in conical die

Friction force can be obtained as:

$$F_c = \tau \cdot \pi \cdot d_0 \cdot h_0 \quad (4)$$

τ – shear stress at the billet/container interface

$$\tau = \mu \cdot \sigma \quad (5)$$

σ – flow stress

With (5) equation (4) becomes:

$$F_c = \mu \cdot \sigma \cdot \pi \cdot d_0 \cdot h_0 \quad (6)$$

During steady state forward extrusion forces "F_d" and "F_{dd}" remain constant while friction force "F_c" decreases, as the length of the billet "h_0" decreases to "h_{01}". This means that equation (3) transforms to:

$$\Delta F_T = \Delta F_c + \Delta F_d + \Delta F_{dd} = \Delta F_c \quad (7)$$

(as ΔF_d and ΔF_{dd} are zero).

$$\Delta F_c = \Delta F_T = F_{T0} - F_{T1} \quad (8)$$

From the experimentally obtained diagram $F_T = f(\text{stroke})$ – Fig. 3. difference F_{T0} - F_{T1} can be obtained.

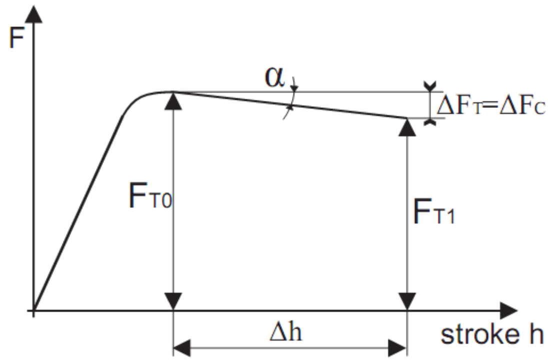

Figure 3. Load-stroke diagram

$$\Delta F_c = \Delta F_T = \mu \cdot \sigma \cdot \pi \cdot d_0 \cdot (h_0 - h_{01}) \quad (9)$$

From (9), coefficient of friction is:

$$\mu = \frac{\Delta F_T}{\sigma \cdot \pi \cdot d_0 \cdot \Delta h} = \frac{tg\alpha}{\sigma \pi \, d_0} \quad (10)$$

Coefficient of friction is proportional to the slope of load-stroke diagram in steady state phase.

2.2 Backward cup extrusion (BCE)

In backward extrusion, punch acts on the billet with the load F_1 (Fig. 4.). Billet material is extruded thought the gap between punch head and container, at which wall friction force F_f occurs. This force can be calculated as:

$$F_f = F_1 - F_2 \quad (11)$$

Friction force F_f is equal to:

$$F_f = \tau \cdot A = \mu \cdot \sigma \cdot A \quad (12)$$

σ – flow stress

A – contact area between container wall and billet.

From (11) and (12), coefficient of friction is:

$$\mu = \frac{F_f}{\sigma \cdot A} = \frac{F_1 - F_2}{\sigma \cdot A} \quad (13)$$

Forces at the punch head (F_1) and at the die bottom (F_2) are measured by separate load cells.

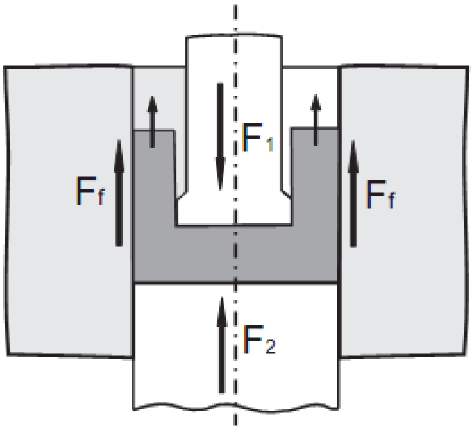

Figure 4. Backward cup extrusion

2.3 Backward extrusion with twist

There are a couple of variants of this test [9]. In one of them, workpece is deformed in backward extrusion process and then die with workpece is kept stationary, while the punch is rotated.

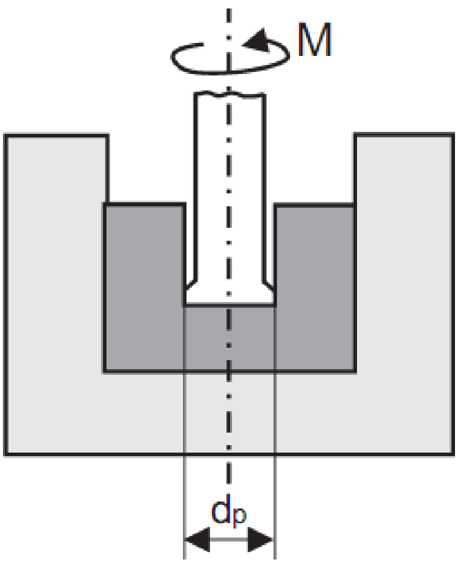

Figure 5. Backward extrusion with twist

Two different punches are used: one with and the other without land. While rotating, moments M_1 and M_2 are measured (each for every punch) and friction constant "m" can be obtained from:

$$m = \frac{2\sqrt{3}(M_1 - M_2)}{\pi \cdot d_p^2 \cdot h_c \cdot \sigma} \quad (14)$$

where d_p is the diameter of the punch, h_c is the length of the punch land and σ is flow stress of the material. The schematic of this process is shown in figure 5 [9].

3. RING COMPRESSION TEST

Ring compression test is a standard method to evaluate friction coefficient "μ" or friction factor "m" in bulk metal forming processes. Theoretical bases of this method was introduced by Male & Cockroft [4] and since then a number of authors have been involved in theoretical and experimental investigation on this issue [5], [6], [7], [12].

During ring compression between two parallel plates, two different situations can occur: in case of low friction internal diameter deforms outwards (Fig. 6a) and if the friction is high internal diameter decreases (Fig. 6b). Radius where no material flow takes place is known as neutral radius (r_n).

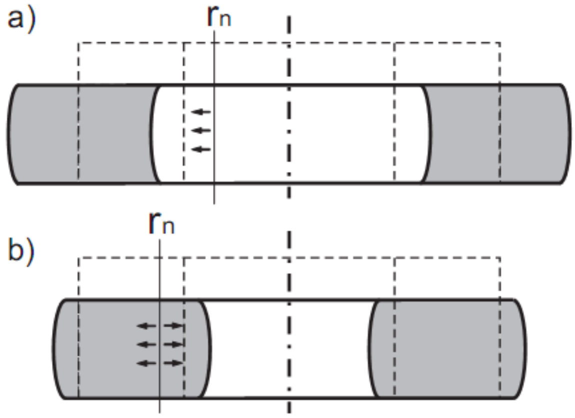

Figure 6. Material flow in low friction conditions (up) and high friction conditions (down)

By superimposing the experimentally obtained function $\varepsilon_d = f(\varepsilon_h)$ on the friction calibration curve (FCC), coefficient of friction (or friction factor) can be obtained ($\varepsilon_d = \frac{D_0 - D}{D_0} \cdot 100\%, \varepsilon_h = \frac{H_0 - H}{H_0} \cdot 100\%$).

Friction calibration diagram (curves) can be obtained in analytical and numerical way [6], [12]. Current paper presents FE modeling of ring compression test and subsequent construction of FCCs.

4. FE MODELING BY SIMUFACT FORMING 9.0

Simufact Forming 9.0 (SF 9.0) is a software solution capable of simulating almost all metal forming processes. It is developed by Simufact Engineering GmbH in Hamburg, Germany.

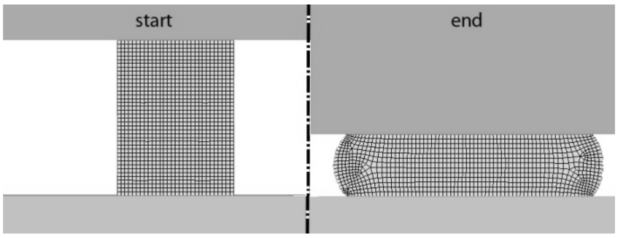

Figure 7. Ring between flat tools in Simufact Forming 9.0 (left: at beginning, right: at end of the process)

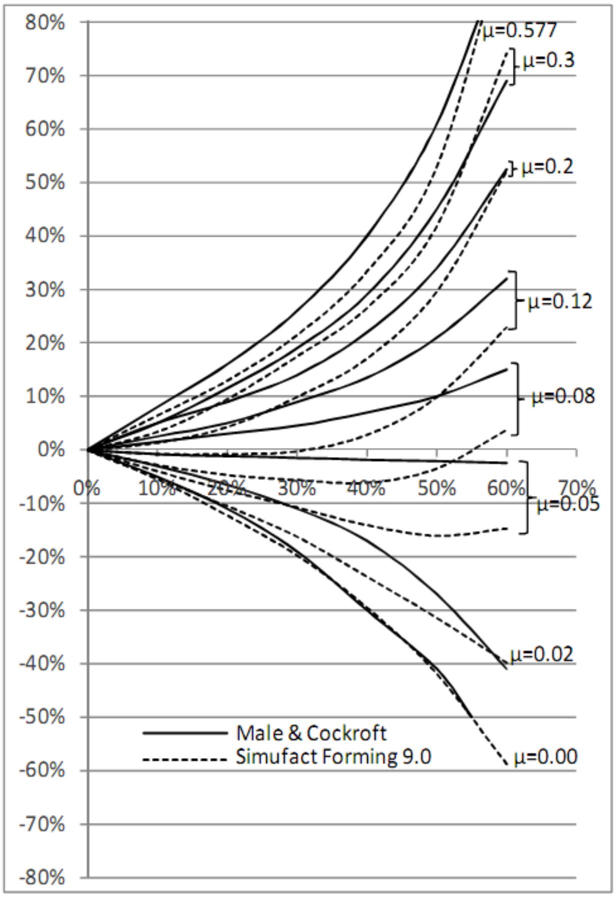

Figure 8. FCCs obtained by SF 9.0 simulation compared with Male & Cockroft curves

2D axisymmetric simulation of ring compression test with finite element solver was performed with SF 9.0 (Fig. 7). Ring with initial dimensions of 30x15x10mm (outer diameter, inner diameter, thickness) was used in simulation. This geometry ratio (6:3:2) is established as standard in most ring compression tests. Material of the billet was steel C1531 (C45) with stress-strain curve $\sigma = 289.671 + 668.779e^{0.3184}$. Upper and lower flat tool were set as rigid bodies, which means that no deformation of the tools takes place. Simulation was done at room temperature and Advanced Front Quad mesher was set to the billet with 0.25mm element size. Also, the remeshing process was not included. Total stroke of 7mm was conducted and results were attained for every 1mm of upper tool increment. After each increment, inner diameter of the ring was determined and deformation of the ring's thickness as well as deformation of the ring's inner radius was calculated. The total of 11 simulations were performed by varying Coulomb friction coefficient (μ) from μ = 0.00 to μ = 0.577. Obtained friction calibration curves are shown in Fig. 8. At the same figure, Male & Cockroft FC curves for 8 different coefficients of friction are given.

5. EXPERIMENT

Ring with dimensions 18:9:6mm was compressed in 6 increments to the final height of 2.4mm. Process was realized on Sack & Kieselbach hydraulic press of 6300kN. Two different kinds of lubrication were applied: (1) oil and (2) phosphate sulphate + MoS_2.

In Fig. 9. initial rings and rings after last increment for both lubrication cases are shown.

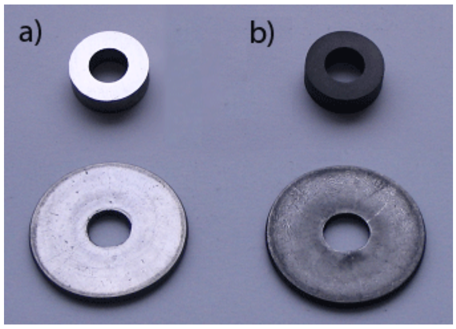

Figure 9. Rings before and after compression (a – oil; b – phosphate sulphate + MoS_2.)

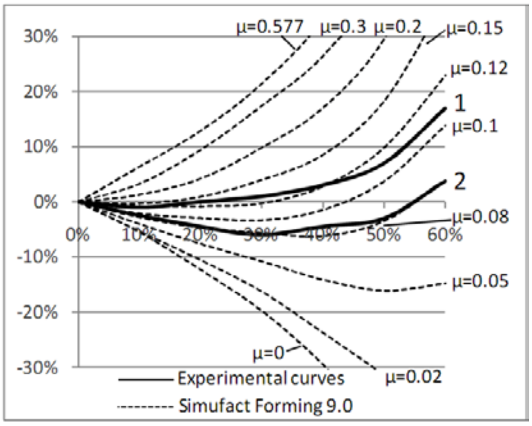

Figure 10. Determination of friction coefficient in experiments based upon FCCs obtained from SF 9.0. (1)-lubrication with oil, (2)-lubrication with phosphate sulphate + M_0S_2

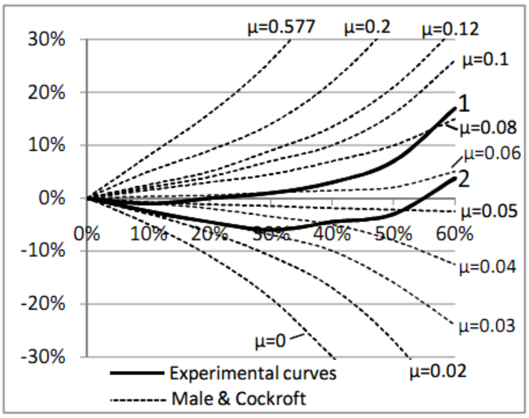

Figure 11. Determination of friction coefficient in experiments based upon FCCs from Male & Cockroft (1)-lubrication with oil, (2)-lubrication with phosphate sulphate + M_0S_2

Based upon measurement of "*Δh*" (height) and "*ΔD*" (internal diameter) after every increment, function ΔD = f(Δh) was established for both lubrication cases. Both curves are then superimposed on FCCs obtained by FE modelling with Simufact package (Fig. 10.) and Male & Cockroft friction calibration curves (Fig. 11.).

Coefficient of friction for both experimental cases, using SF – FC curves, are $\mu \approx 0.12$ (lubricated with oil) and $\mu \approx 0.08$ (phosphate sulphate + M_0S_2) – Fig. 10. By using Male & Cockroft FC curves these values are: $\mu \approx 0.07$ (oil) and $\mu \approx 0.05$ (phosphate sulphate + M_0S_2).

It should be noted that all extracted "μ" magnitudes represent an average value, i.e. there is no exact match between experimentally obtained function ΔD = f(Δh) and corresponding curves in FCCs diagram (Male & Cockroft and Simufact FCCs).

6. CONCLUSIONS

Current paper elaborates possibilities to determine friction value in bulk metal forming operations. Some models to evaluate friction are described and focus is placed on ring compression test. Due to its simplicity this method is commonly applied for determination of coefficient of friction ("*μ*") and friction factor ("*m*").

In order to obtain "*μ*" ("*m*") by ring compression trial, friction calibration curves (FCCs) are needed. These curves can be obtained by theoretical analysis and by appropriate FE modelling.

In this work FCCs were determined by FE modelling, using Simufact Forming package.

Additionally, ring compression experiments are performed in order to verify FE-modelling results.

Comparison of FCCs obtained by SF 9.0 modelling and M&C FC curves shows a certain degree of discrepancies (Fig. 8.). These discrepancies are more apparent for "μ" values between 0.05 - 0.12, whereas for extreme low and extreme high friction values, differences between M&C and SF 9.0 FC curves are smaller.

As a consequence of those deviations, different "μ" values for the same ring compression experiments are obtained, depending which FC curves are used.

In further work on this subject, focus will be placed on the establishing of FCCs for specific deformation cases and under specific process conditions (pressure, temperature, velocity, material).

Also, assessment of different lubricants for cold bulk metal forming, using FC curves will be performed.

7. ACKNOWLEDGEMENT

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