MICROFORMING FRICTION IN METAL FORMING

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***Key words**: metalforming, microforming, friction*

Abstract:

The work carried out some microforming analysis. Microforming in metal forming the production of small dimensions in at least two axes not exceeding 2 mm. Technology of microforming differs in many ways from the conventional technology of metal forming.

It is well recognized that expertise, experience, and theoretical knowledge available in conventionally sized metal forming cannot be simply transferred to microforming. This is so -

called size effects, which has distinctive effect on material flow, friction and other process characteristics. Today, process simulation is a standard tool in industry, applied to support process lay - out and its optimization.

However, as it is based on continuum mechanics, it is size-invariant at least for cold forging. Hence, it is obvious that due to the size effects, conventional simulation cannot be applied to microforming. In this paper, two approaches are presented how to model specific phenomena of microforming in particular concerning material flow and friction. These are the mesoscopic model and a combination of the general friction law and mechanical rheological model, respectively. Both models are brought together to be finally applied to a combined micro cold-extrusion process.

Metalforming: Microforming fine grains, macroforming coarse grains.

1. INTRODUCTION

Friction is sometimes helpful. For example, high friction on the punch surface helps increasing reductions in deep drawing and ironing. In a few instances, it has to have at least some value, as in rolling where it assures entry of the workpiece into the roll gap and helps to maintain rolling without skidding of the workpiece. However, in most cases, friction is preferably reduced to zero with the introduction of a lubricant.

For purposes of predicting interface pressures, deforming forces, and energy requirements, the magnitude of τ_{TR} must be known. However, analysis is usually easyer if effect of friction is expressed by some non - dimensional parameter. To date, two such parameters have found wide acceptance.

Following Coulomb's classical definition, the coefficient of friction μ is simply the ratio of frictional force to normal force, or of frictional stress to normal stress (die pressure).

$$\mu = \frac{F_{FR}}{F_n} = \frac{\tau_{FR}}{p} \tag{1}$$

It's possible that τ_{FR} increases linearly with p, and then μ may reach any constant value (figure 1 a). This is the case, for example, in the blankholder zone of a deep - drawing operation. However, μ cannot rise indefinitely because sticking friction sets in when $\mu_p \geq k$. [3]

In many bulk deformation processes $p \gg k$, and because k remains constant, the calculated μ actually drops (figure 1b). Since $k \approx 0.5\sigma_f$ (or 0.557 σ_f according to von Mises), it is sometimes said that $\mu_{max} = 0.5$, but this is true only when $p = \sigma_f$ ($\sigma_f = k_f$) (figure 1.c).

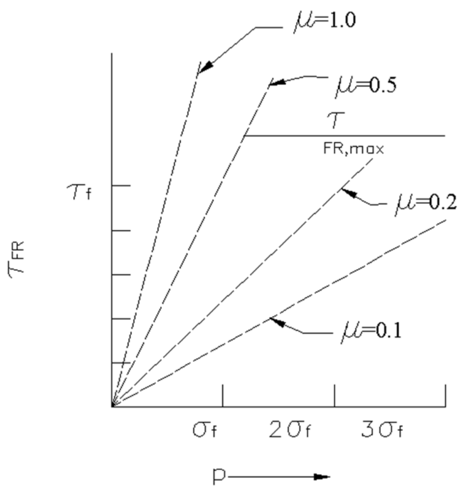

Figure 1 a. *Variation of interface shear strength*

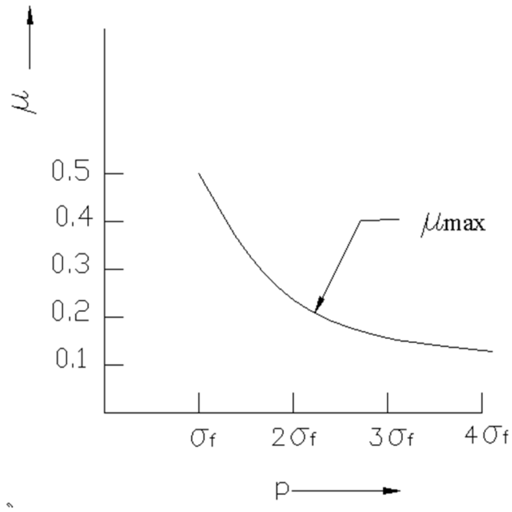

Figure 1 b. *Variation of maximum coefficient of friction with pressure*

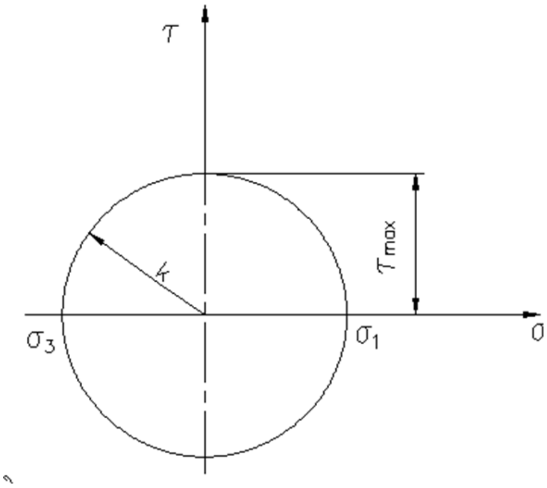

Figure 1c. *Mohr's circle for pure shear*

Here:

$$\sigma_3 = -\sigma_1$$

$$\sigma_2 = 0$$

According to the shear-stress criterion, one obtains:

$$\sigma_1 - \sigma_3 = k_f$$

$$\sigma_3 = -\sigma_1$$

$$\sigma_1 - (-\sigma_1) = k_f$$

$$2\sigma_1 = k_f$$

$$\sigma_1 = 0{,}5\,k_f$$

$$\tau_{max} = \sigma_1 = 0{,}5\,k_f$$

$$\mu_{max} = \frac{\tau_{max}}{k_f} = \frac{0.5k_f}{k_f} = 0{,}5 \qquad (2)$$

while the von Mises criterion yields:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2k_f^2$$

σ_3 = - σ_1 and $\sigma_2 = 0 \Rightarrow$

$$(\sigma_1 - 0)^2 + (0 - \sigma_1)^2 + [\sigma_1 - (-\sigma_1)]^2 = 2k_f^2$$

$$6\sigma_1^2 = 2k_f^2$$

$$\sigma_1 = \frac{k_f}{\sqrt{3}} = 0{,}577\,k_f$$

$$\tau_{max} = \sigma_1 = 0{,}577\,k_f$$

$$\mu_{max} = \frac{\tau_{max}}{k_f} = \frac{0.577k_f}{k_f} = 0{,}577 \qquad (3)$$

Light is the shift figure 1 d, then figure 1e.

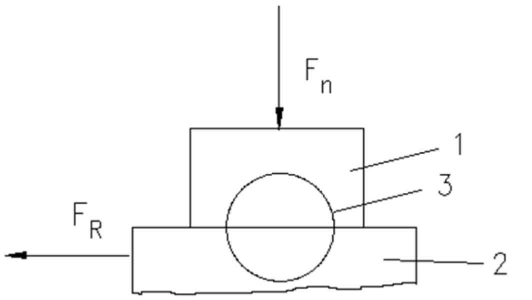

Figure 1 d. *Friction: 1- die, 2 - workpiece, 3 – increased*

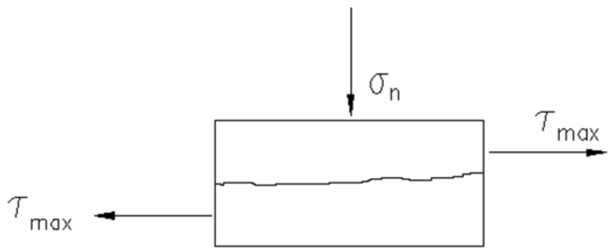

Figure 1e*. Pure shear*

It is much more accurate to say that the coefficient of friction becomes meaningless when $\mu p \geq k$,since there is no relative sliding at the interface. The possible misinterpretation of μ has led to the introduction of the frictional shear factor m defined as:

$$\tau_{FR} = mk \tag{4}$$

Since τ_{FR} is now linked to a workpiece material property k, which is a priori known (rather than to p which must be calculated), the use of m simplifies calculations, especially those based on upper - bound theory or numerical techniques.

Whether μ or m is a better descriptor of interface properties has been a matter of debate, and not even a preliminary judgment can be made until the properties of real interfaces are examined [3].The work carried out some analysis microforming. Microforming in metal forming the production of small dimensions in at least two axes not exceeding 2 mm. Technology, microforming differs in many ways from the conventional technology of metal forming. As it can be shown by analyzing the increasing market volume of electronic and micromechanical components, a general trend towards higher integrated functional density and miniaturization is obvious. Thus, the technology of microforming becomes more and more attractive when smallest metallic parts with high accuracy and production output are demanded [1].

Application: micro system technology and microelectromechanical system. Despite all of the advantages of microforming technology most of these parts are still made by machining processes. One of the main reasons is that forming technology cannot simply be transferred from conventional length scale to the 'microworld'. This is due to material and process being subjected to so - called *size effects*. In order to evaluate and describe these effects, basic investigations on various metal forming processes (bending, extrusion, upsetting and others) have been done by performing experiments scaled down according to the similarity theory.

In this way, two main effects have been identified: the size effect on the material flow and the one on the friction. The former can be traced back to the dependency of the material flow to the initial state of the grain structure or more precisely to the ratio between mean grain size and part dimension [2].

For the purpose of simulation, first approach is given by the surface layer model yielding size-dependent results such as forming force in good agreement to what is observed [1]. If additional aspects as e.g. process scatter or mould filling are to be considered, there is a necessity in describing the forming behaviour of the material in a more detailed way. This can be realized by the more advanced approach the so-called mesoscopic model. The first of the objectives of the present paper is to explain this model by describing the experimental basis and the theoretical background. The second deals with the size dependence of friction.

The size - effect in friction has first been investigated by scaled ring-test experiments keeping the geometrical similarity. The observed increase in friction was studied in more detail using double-cup extrusion tests. The results not only confirm the previously detected effect but have also been used as a basis for a theoretical approach capable to describe the size dependence of the friction factor m [1].

With respect to process simulation, this approach enables for the first time to model the specific characteristics of friction in microforming by simply applying conventional friction laws such as the law of constant friction stress $\tau = mk$.

2. GENERAL STRATEGY

Putting in mind that size effects in microforming are mainly controlled by first ratio between grain size and workpiece dimension and second the dependence of friction on specimen size, both becoming effective in parallel. For basic investigations it must be the objective to separate both effects as far as possible. For that purpose in the present approach two processes are considered: the flat upsetting of a cylindrical bar and the DCE-test.

In the final step, the results are applied to a combined full - forward/cup-backward extrusion process for purpose of validation. The size effect related to material structure can be investigated in two different ways. The straightforward approach is to scale down the process. However, in this case the size effect on friction has to be considered. In order to exclude this effect i.e. to ensure constant friction conditions, the workpiece geometry is kept unchanged, and grain size is varied in a broad range. In this kind of physical modelling fine and coarse grained material represent the macro and micro case, respectively. Process and process dimension has to be chosen adequately. This is the approach realized in the present study, in which the cylindrical flat upsetting test on “micro” specimen is considered. In order to get significant information about the scatter of process factors like forming limit and development of shape, a new simulation model is being developed which combines the advantages of grain modelling with a more realistic material behaviour.

The behaviour of each grain is characterized by its size and by its position within the workpiece. The results of simulation are finally compared to the experimental results. The size effect related to friction is measured by the DCE-test (double cup extrusion), which is in particular suited to reflect the load situation in cold forging. [1]

Starting from the results of scaled experiments the modelling approach is realized on the basis of the general friction law developed by Wanheim/Bay and the mechanical - rheological model.

3. EXPERIMENT

Experimental results using material with different grain structure figure 2.

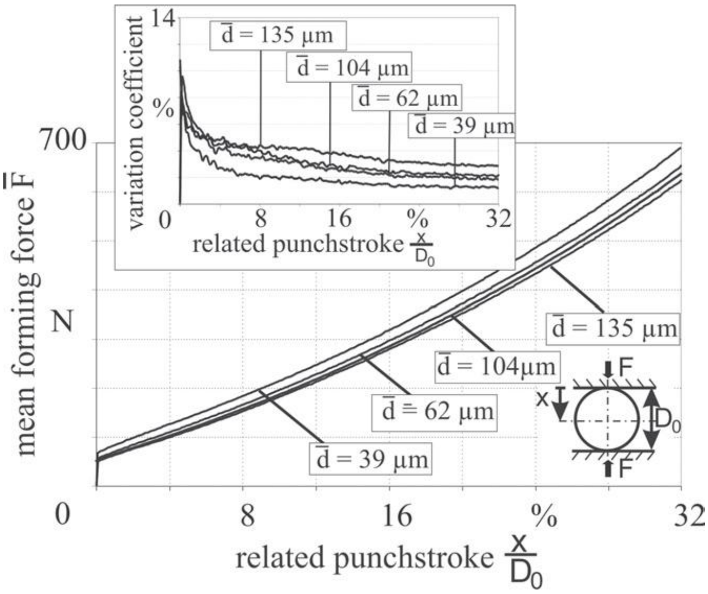

***Figure 2.** Experimental results using material with different grain structure*

Setup of DCE (the double cup extrusion) test and friction dependent material flow [1] is shown at figure 3.

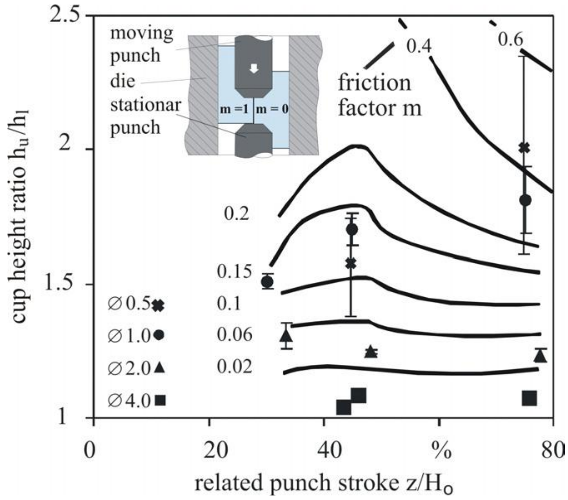

***Figure 3.** Setup of DCE (the double cup extrusion) test and friction dependent material flow*

4. THEORETICAL BACKGROUND

In the advanced approach, the mesoscopic model, the material is subdivided into single grains with individual properties, depending on their size and position within the material. Thus it will be possible to model even the local forming behaviour controlled by the local grain structure. The modelling of grain structure is based on the algorithm of the Monte-Carlo-Potts model enabling the generation of synthetic 2D as well as 3D grain structures with predefined parameters. [1]

The synthetically generated grain structures are verified by a comparison with metallographically analyzed real ones. Comprehensive studies have shown that the differences in the parameters of interest – mean linear grain size and its standard deviation – are below 2% and 15% respectively, both related to the values of the real grain structure, showing the efficiency of this method. The calculation of the flow stress of a single grain is based on two effects.

On the one hand, it's calculated by means of the Hall - Petch equation which can be applied as long as the grain size is not at nanoscale, and on the other hand, on the position of the grain within the material which can be considered according to Ashby [1].

On this basis the yield stress τ is given by:

$$\tau = \tau_0 + \frac{m_{1,2} \cdot \tau_{\mathrm{i}} \cdot \sqrt{\lambda}}{\sqrt{d_G}} \tag{5}$$

$m_{1,2}$ represents a transformation matrix for the different sliding systems in the adjoining grains, τ_0 is the critical shear stress in the considered grain and the factor λ represents the distance between the pile-up source and the dislocation.

Dislocations are assumed to pile up until the stress concentration exceeds the stress τ_{i} . From this point on, dislocation sources will be activated in neighbouring grains. The fact, that the Hall-Petch factor for a single grain K_{i} is different to the integral Hall - Petch factor K leads to:

$$\tau = \tau_0 + \frac{K_{\mathrm{i}}}{\sqrt{d_G}} \text{ with } K_{\mathrm{i}} = m_{1,2} \cdot \tau_{\mathrm{i}} \cdot \sqrt{\lambda} \tag{6}$$

The correlation between K_{i} and K is given by:

$$K_i = K \cdot \xi_i \tag{7}$$

where a newly introduced pile-up factor ξ_i describes simplified the amount of dislocation pile-up at the grain boundary region of a single grain and is defined by:

$$\xi_i = \frac{\overline{k_{nG}}}{k_G} = \frac{1}{k_G} \frac{1}{l_G} \sum l_c \cdot k_{nG} \tag{8}$$

$\overline{k_{nG}}$ is the mean yield stress of the neighbouring grains related to the contact length l_c. Since dislocation pile-up is not possible at a free surface, the pile-up factor there is set to zero and increases with the distance of the grains from the surface. Thus, the flow stress of grains positioned close to the free surface is reduced compared to grains being placed in the inner area of the specimen. Applying this model to macroscopic dimensions there is a large number of grains n within the workpiece and the influence of the surface on the integral material properties is very low.

The simulation of the flat upsetting test is carried out using the finite element simulation program MSC Superform 2003. The model consists of 11048 quadrilateral four node elements. The friction factor *m* is set to 0.2 arbitrarily. Simulations of the flat upsetting process varying the friction factor *m* in a range from 0.05 to 0.5 have shown that there is only a small influence of *m* on the forming results.

With the above described generation of a synthetic grain structure and the calculation of the material properties based on macroscopic determined values, the simulation model is able to show the experimentally determined reduction of the forming force depending on the mean grain size. The results for the forming force as a function of punch displacement for different mean grain sizes, selected correspondingly to the experimentally determined ones, are shown in figure 4.

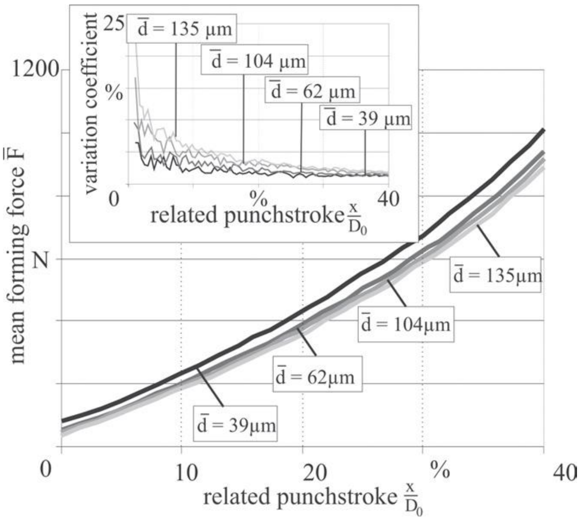

Figure 4. *Simulation results with specimen characterized by different mean grain sizes*

The verification of the simulation model is done by the comparison between simulation and experimental results for distinct mean grain sizes. The values of interest are the forming force and its scatter respectively. These two parameters are identified as relevant parameters representing size effects. In order to compare simulation results with experiments, simulation is carried out with parameters equivalent to experimental determined grain structure attributes. The results from the simulations reflect the experimentally detected correlation between the mean grain size and the forming force in a quite acceptable way, figure 4.

More detailed comparison is given in figure 5, showing the good agreement in the runs of the forming forces. The maximum and mean differences are 10% and 2%, respectively related to the experimental data. Thus, the obtained results confirm the mesoscopic model including the algorithm of calculating the material properties of the grain structure.

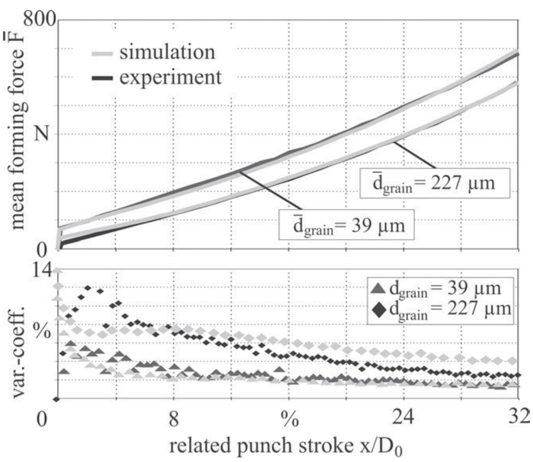

Figure 5. *Comparison of the forming force between simulation und experimentally obtained results*

5. MECHANICAL – RHEOLOGICAL MODEL

The high increase in the friction – as detected by the DCE-test – can be explained by use of a mechanical rheological model introduced by. Applying a forming load to a lubricated workpiece leads to a plastic deformation of the asperities (roughness peaks).

Thus, the pressure on the lubricant trapped in the lubricant valleys is increased if they do not have connection to the edge of the surface (CLP: **C**losed **L**ubricant **P**ockets, figure 6b) or squeezed out (OLP: **O**pen **L**ubricant **P**ockets, figure 6a).

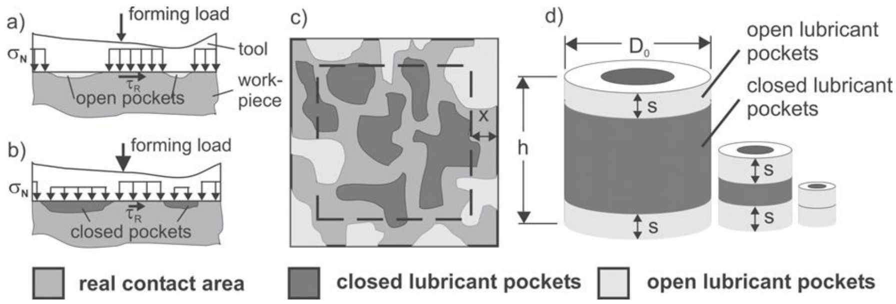

***Figure 6 a - c**. Effect of OLP and CLPs on friction conditions, (d) Increasing ratio of OLPs to CLPs with decreasing specimen sitze*

In case of OLPs the forming load acts only on the asperities which results in a higher contact stress, a higher degree of surface flattening and thus a higher fraction of the real contact area (RCA) and higher friction. CLPs – in contrast to OLPs – do not have any connection to the surface, thus the lubricant will be trapped in those pockets and pressurized during the forming process, resulting in a reduced normal pressure on the asperities and leading to lower friction.

Applying this model to the DCE - test, there must be a scaling effect on the ratio of open to closed lubricant pockets. Because of the scale invariance of the topography, it is obvious that a region of constant width exists where the open lubricant pockets become effective. By reducing the specimen size, the share of open lubricant pockets increases as well as the friction factor does. The model of OLP's and CLP's and its effect in scaling has been confirmed by additional and independent investigations which are described in detail in [5].

6. CONCLUSION

The work carried out some analysis microforming. Microforming in metal forming the production of small dimensions in at least two axes not exceeding 2 mm. Technology of microforming differs in many ways from the conventional technology of metal forming.

Simulation of microforming processes close to the results of experiments is winning a growing interest in microforming society. It is well recognized, that simulation represents an important presupposition for pushing forward the application of microforming technology in practice. As it has been shown for some selected cold forging processes, a first step has been done successfully to reach this goal.

The instruments developed so far are capable to model essential phenomena of microforming at least on a qualitative level. Additionally, on the basis of experimental and simulative results, the most relevant gaps in modeling are identified as well as the methods to fill them. Hence, progress can be expected in near future towards generalization of the modelling approach and its applicability on other processes relevant for microforming.

7. LITERATURA

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