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RESEARCH

Friction Studies Utilizing the Ring - Compression Test - *Part I*

The paper deals with contact friction problems, both in real processes of bulk forming (in the first part of the paper) and in modelling experiments with plasticine, since the tribological mechanism is both similar and complicated as in the modelled processes. After the short introduction on friction laws and theories, the method of free compression of the ring (ring test) was described, which was also used for experimental determination of coefficient/factor of friction in modelling experiments with plasticine (Friction studies utilizing the ring-compression test - part I). Several kinds of calibration (etalon) curves of various authors were used for reading these indicators of contact friction, and the critical review of differences which exist between them was given as well as recommendations for their application. Also, on the basis of the numerical simulation of free compression of the plasticine ring, new CAMPform calibration curves were obtained, with aim of testing the friction model in this FEM program package and defining the more precise input data of FEM analysis at simulation of bulk forming processes.

Keywords: *Contact friction, free ring compression, numerical FEM simulation, modelling materials.*

1. INTRODUCTION

Plastic forming of materials, working pressures amounts and forming forces of processes are not influenced only by material properties, but also by contact friction conditions. This influence is reflected in micro-structural changes of materials, tool wear and increase of energy necessary for forming. In bulk metal forming processes, the conditions of contact friction keep continuously changing during the process and they represent the complex analytical problem, which makes difficult the obtaining of the reliable mathematical model for describing the contact friction. The results of numerical FEM simulation of the process highly depend upon the boundary conditions which are related to contact friction. Besides that, the key step in the physicals modelling of the process is the selection of the adequate lubricant, with purpose of establishing the conditions of similarity of real and modelling process and validity of the modelling results. The tribological mechanism in modelling processes is similar to the one in real processes; therefore, the first part of the paper is dedicated to the tribological problems of real forming processes, to mathematical description of contact friction, as well as to the methods of its qualitative and quantitative determination by means of friction indicators.

All researches within the forming processes tribology were conducted in two directions:

- defining of friction mechanism through laws and theories on friction;
- development of methods for integrating these definitions into models of forming processes and quantitative estimation of friction indicators.

For mathematical description of contact friction in forming processes, three laws and theories on friction, are used, whereat the latter ones have more modifications. General categorisation of laws and theories on friction is: 1. *Amonton*'s and *Coulomb*-s law

$$\tau = \mu\, \mathrm{p}, \quad 0 \le \mu \le 0.577 \qquad (1)$$

2. Law of constant friction

$$\tau = m\, \mathrm{k}, \quad 0 \le m \le 1 \qquad (2)$$

3. Adhesion theories, which take into consideration the real roughness of contact surfaces.

In the first model (1) the friction is proportional to the normal pressure p, and the proportionality measure is expressed through friction coefficient μ. It has importance only in areas of small normal

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pressures. The second friction model (2) assumes the constant tangential friction stress in contact surfaces, proportional to the friction factor *m*, which, in reality, is the case at existence of large normal pressures. It has been pointed out in many papers, which deal with friction problems, that not both laws have the general significance and that neither of them "covers" the area of medium normal pressures [1].

Wanheim and others [2] have developed the model of friction which has the general importance and covers all pressure areas. Model is based on the analysis of plastic forming of rough work piece, with ideal roughnesses, with initial slope angle γ_o, between flat smooth plates of tool. The analysis of plastic forming and mathematical formulation of the model are performed by the slip-line theory. Wanheim-Bay-s model of friction is expressed analytically as

$$\tau = \mathrm{f}\,\alpha\,\mathrm{k} \qquad (3)$$

where α is the ratio between real and apparent area of contact, f is friction factor and k is yield stress in pure shear. The graphic illustration of this friction model is given in papers [1], [2]. It is obvious that this friction model represents the combination of two laws, because at small pressures the friction stress is proportional to pressure, and at large pressures the tangential stress is constant. The advantage of this model is that it gives the true presentation of contact conditions in areas of medium stresses as well.

The friction model (see equat. 3) has been tested experimentally, by determining the tangential and normal stresses in processes of free compression [3], extrusion and rolling [1]. The largest congruence of experimental and numerical results appeared at application of Wanheim-Bay friction model (3). Petersen, Martins and Bay [4] used FEM program PLAST 2 for numerical simulation and testing of friction model, into which they integrated the friction models (2) and (3).

For qualitative estimation of friction and quantitative determining of its indicators, coeffici-ents / factors of friction, direct and indirect methods are used. Direct methods imply the experimental measuring of local friction force or some other indicators, in dependence on the applied method and kind of forming. Multi-component transducers of force and pressure, which are integrated into experimental tools, on places in which contact conditions are investigated, are used for that purpose [5].

Indirect methods for determining contact friction represent the monitoring of certain geometrical values of samples in conditions of divided material flow (*divided flow tests*). Geometrical changes of sample which is being formed, in different processes, are the consequence of friction in inter-contact. By such methods the individual influences of tribological parameters cannot be investigated, but the obtained results refer to the investigated case "tool-lubricant-material" instead. They are used in determining friction in cold and hot forming processes. The most applied method from this group is the free ring compression method (*ring test,* Burgdorf's method). This method, since it is used in the paper for determining coefficient / factor of friction in modelling experiments with plasticine, will be explained in detail in the following section

2. RING TEST METHOD

The method of free ring compression is the most widely applied method for determining contact conditions in bulk forming processes; therefore it is treated as the standard, universal method for determining coefficient / factor of friction. Originally, it was conceived as the qualitative method for comparing the lubrication conditions to the influence of various lubricants onto the contact friction in cold extrusion processes, as prescribed by Kunogi in 1954. The application and development of this method have been the subject of many investigations.

The method consists of monitoring the changes of inner diameter of the ring which is being compresses, because the changes are considered to be the representatives of the level of sensitivity to active contact friction. Graphic dependence between height strain and inner diameter strain, at various influences of friction, gives calibration curves for reading the value of coefficient / factor of friction. Many authors were engaged in establishing these curves, by applying different methods, plasticity theory and assuming some of friction laws. In order to keep the further presentation concise the term μ-friction will be used for friction model (1), *m*-friction for friction model (2) and f-friction for model (3).

Male and Cocroft established the calibration curves by experimental method, assuming μ-friction in inter-contact of ring and tool [6]. The initial dimensions of the ring in the following ratios of measures – outer diameter : inner diameter : height = 6:3:2, were adopted as standard dimensions in *ring test* method (see fig. 1 (b)). Figure 2 shows calibration curves which were recommended by Male and Cocroft, for the ring 6:3:2.

Lee and Altan [7] applied the upper bound method in the analysis of free ring compression, taking into consideration the barrelling of outer and inner profile of the ring at forming. Calibration curves for ring

6:3:2 and *m*-friction in contact are shown in figure 3. Liu [8] also determined the calibration curves for this method by applying the upper bound method (see fig.4).

Danckert and Wanheim [9] obtained the set of calibration curves on the basis of strain-stress ratios and kinematics of flowing, taking into consideration the strain hardening of the material. Figure 5 shows the calibration curves for ideally plastic material of the ring 6:3:2, assuming *m*-friction, and figure 6 shows calibration curves for material which is hardened by forming, assuming f-friction in inter-contact.

It has been proved that conventional geometry of the ring 6:3:2 in such investigations, in the compression process, leads to appearance of medium normal pressures in range $p/\sigma_o=1\div1.5$. That fact makes this method dissatisfying in the estimation of contact friction in processes where small normal pressures are created on contact surfaces, e.g. forward extrusion with small reductions, some cases of rolling etc. Petersen and others [10] came to the idea to use the devised changes of ring geometry in order to create the conditions such that at the ring compression small normal stresses ($p/\sigma_o<1$) are realised. That is how so called complementary *ring test* method was created. Figure 1 (a) shows the ring geometry 6:4:3:2 for this method. Calibration curves were obtained by FEM analysis (PLAST 2) with application of friction models, f-friction and *m*-friction. The specified paper shows the experimental results as the confirmation of numerical simulation and estimation of accuracy and reliability of thus obtained calibration curves and applied friction models. One other alternative geometry of the ring (see fig. 1(c)) for investigation of contact friction at existence of large normal pressures was proposed [11].

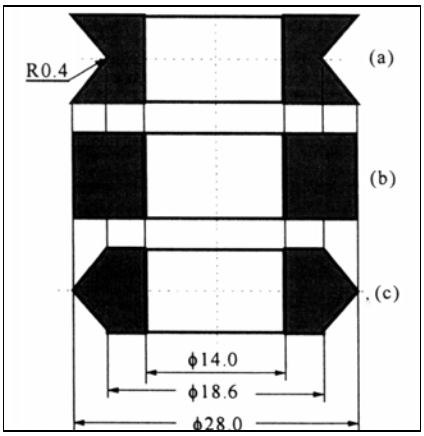

Figure 1. Ring geometry for ring test method at: (a) small pressures, (b) normal pressures, (c) large pressures [11]

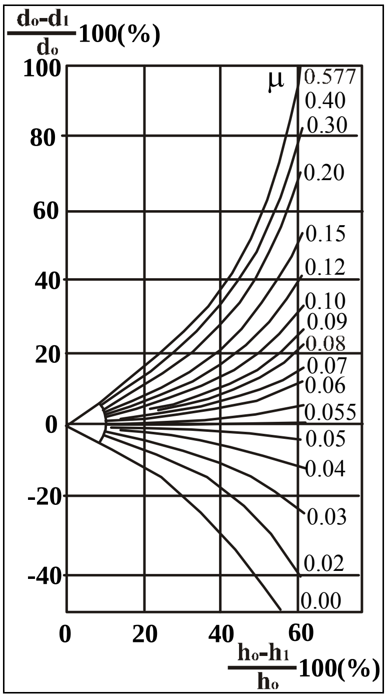

Figure 2. Male-Cocroft calibration curves [6]

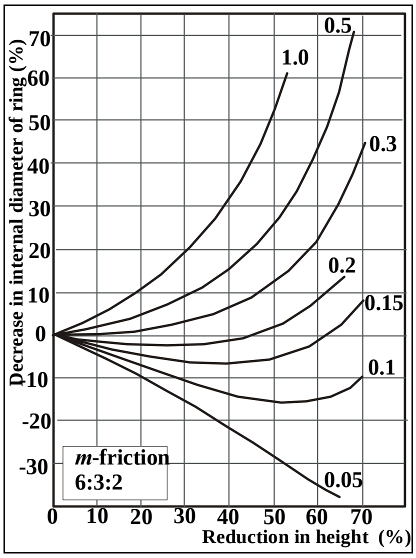

Figure 3. Lee-Altan calibration curves [7]

When comparing the calibration curves of various authors, shown in figures 2 to 6, differences can be observed, which are the consequence of the application of various ring compression analysis methods, various friction models, allowance for the strain hardening of the material or not and, finally, the ring geometry itself. Which calibration curves will be used for determining the coefficient / factor of friction will depend upon the investigator and his estimation of the real conditions in which the experiment of ring compression is conducted, and also upon the material properties. Besides that, if the obtained values of coefficients/ factors of friction are used for numerical simulation of the process, it is necessary to know which friction model was integrated into available FEM program. Such numerical programs are generally developed on the basis of *m*-friction model. If the calibration curves are used for determining the friction coefficient μ instead, the value of friction factor f can easily be determined, by means of equation proposed by *Bowden* and *Tabor*

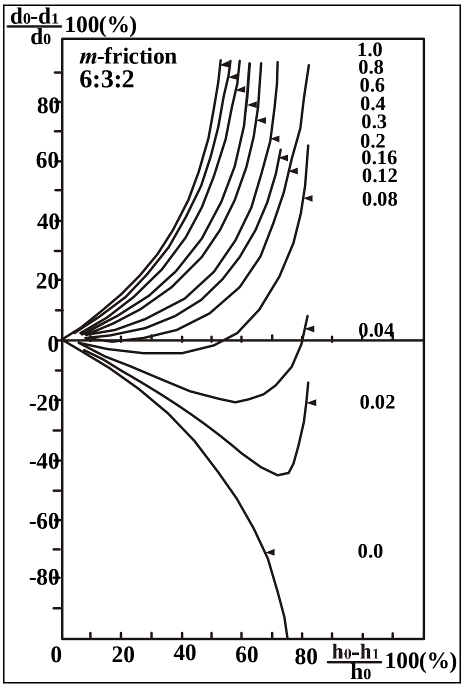

Figure 4. Liu calibration curves [8]

$$\mu = \frac{f}{\sqrt{27\left(1 - f^2\right)}} \tag{4}$$

Realation between friction coefficient μ and friction factor *m* was defined by equation

$$\mu = \frac{m}{\sqrt{3}} \tag{5}$$

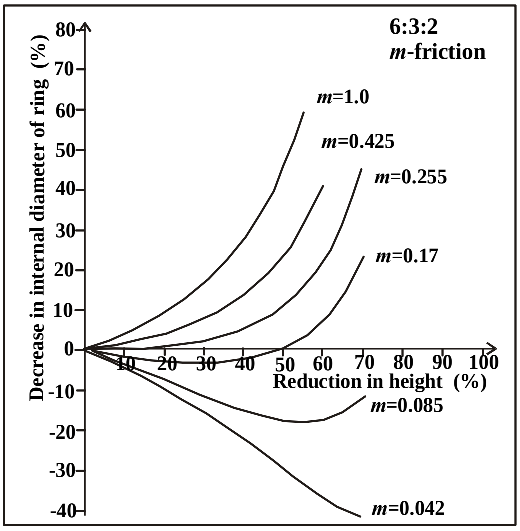

Figure 5. Danckert-Wanheim calibration curves [9]

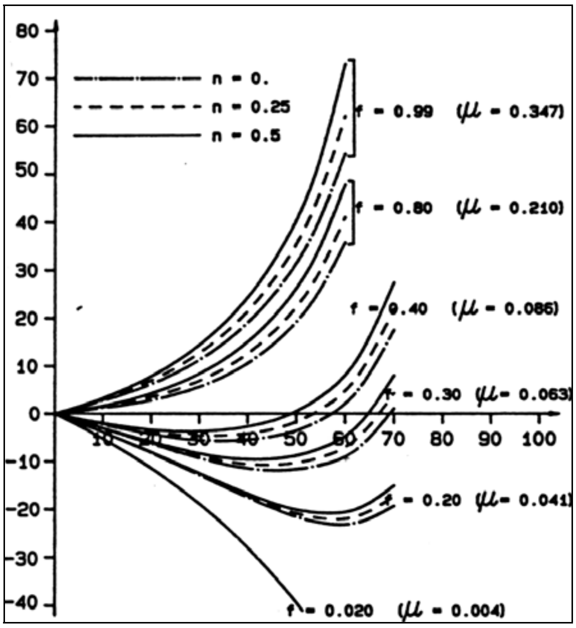

Figure 6. Danckert-Wanhieim calibration curves (f-friction) [9]

For some values of coefficients / factors of friction, it is always necessary to specify which calibration curves were used for reading the values because of their differences, so that the experimental results would be reliable and applicable.

3. FEM SIMULATION OF PLASTICINE RING COMPRESSION

The results of the numerical simulation of the process are highly dependable upon the stipulated boundary conditions of the analysis, especially upon the conditions which define the contact friction. Commercial FEM program packages, intended for 2D or 3D simulation of bulk forming process usually use *m*-friction model for describing the friction in inter-contact. Through stipulated values of coefficients / factors of friction, the user influences the simulation course and accuracy and applicability of obtained results.

In this paper, the program package CAMPform 2D is used for numerical simulation of 2D process of bulk forming by strain [12]. The calculation module on the basis of thermo-rigid-visco-plasticity approach, excellent user interface and AMG module for automatic generation of initial FE mesh and remeshing are the properties of this program which make possible the easy entering of input data for the final user and also the various displays of output simulation results: strain, stress, velocity, temperature fields, strain velocity fields, diagram of the forming force of process, stress analysis of tool, tool wear and life-time as well as estimation of fracture criteria.

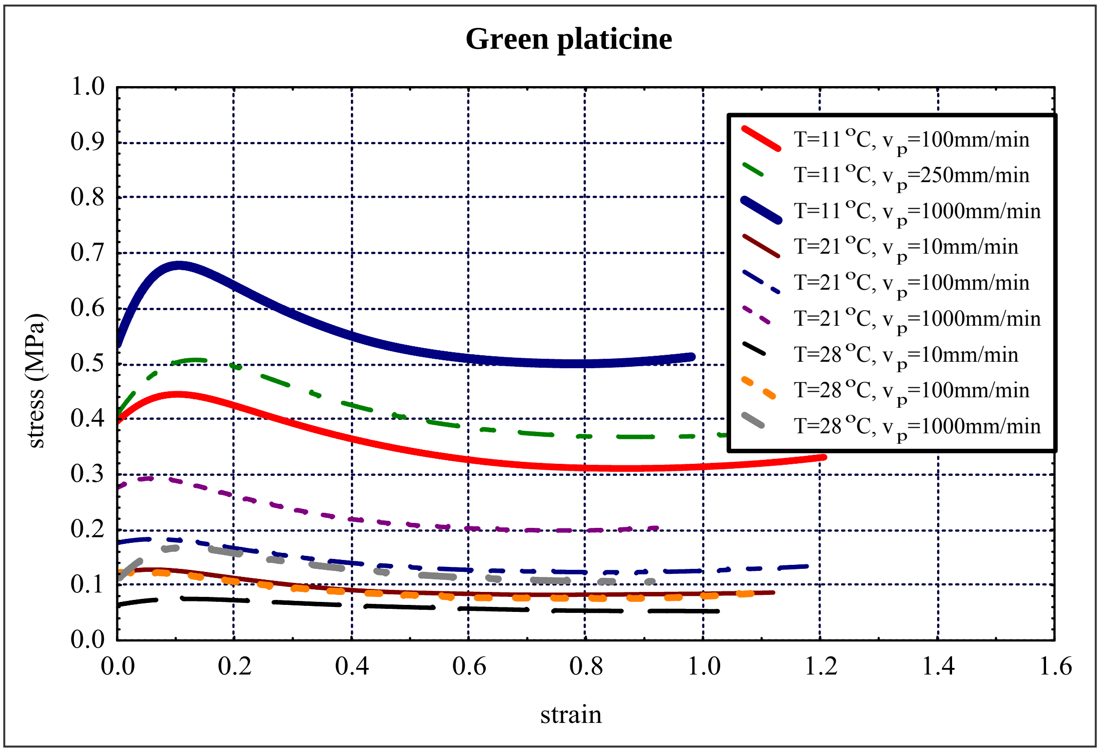

Figure 7. Green plasticine flow curves

Also, there is a possibility for displaying the defects of overlapping in forging processes. The aims of numerical simulation of free plasticine ring compression, by the application of this program, are:

- testing of friction model, which is integrated into CAMPform program;
- monitoring of geometrical changes of the ring, during the entire compression process, at different values of stipulated friction factor *m*;
- studying of ring compression process and analysis of influential parameters;
- formation of calibration curves for plasticine ring compression;
- determining of friction factor by means of experimental results and CAMform calibration curves;
- comparison to other calibration curves.

CAMPform simulation is performed with the same process parameters as the experiments with plasticine (*Friction studies utilizing the ring-compression test - part II*): v_p=10mm/min, T=20°C. 6:3:2 ring geometry, which corresponds to plasticine models geometry (58:29:19.3mm) was stipulated.

The flow curve for green plasticine was determined by compression test, in function of strain, strain rate and temperature [5]. Figure 7 shows the comparative diagram of flow curves of green plasticine for all investigation conditions.

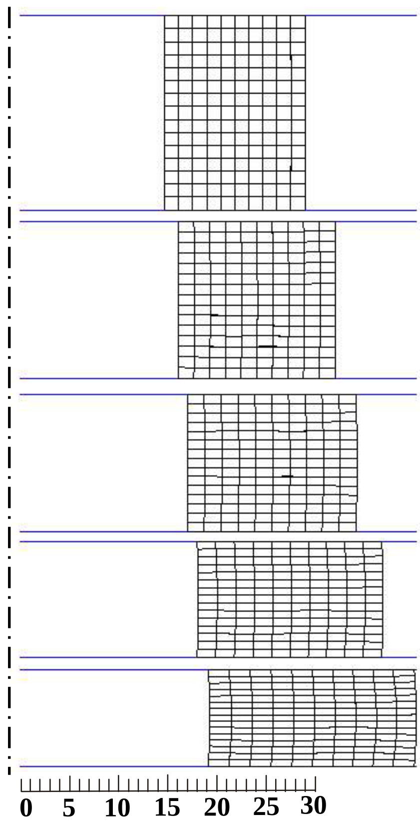

Figure 8. CAMPform simulation of plasticine ring compression, m=0.05

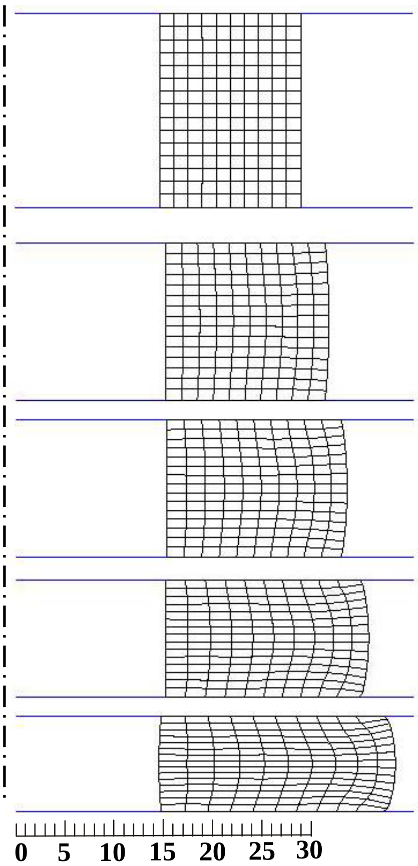

Figure 9. CAMPform simulation of plasticine ring compression, m=0.3

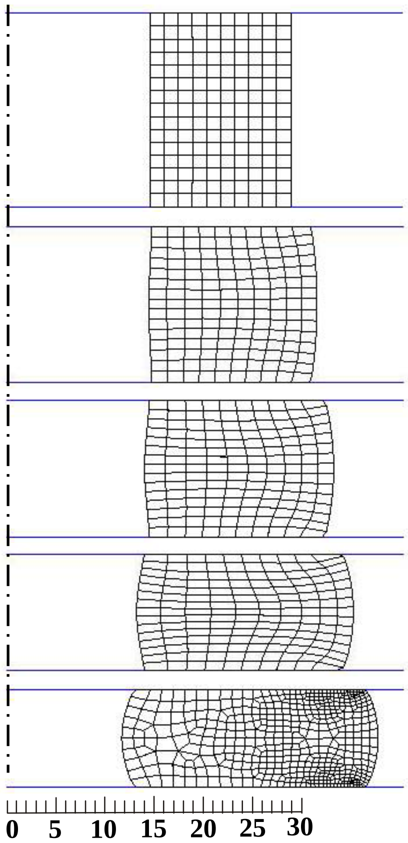

Figure 10. CAMPform simulation of plasticine ring compression, m=0.6

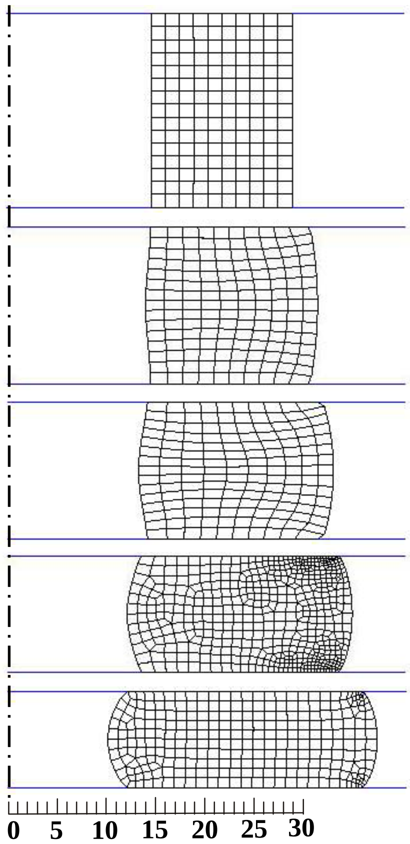

Figure 11. CAMPform simulation of plasticine ring compression, m=0.9

The highly relative mathematical models of flow curves were obtained by regression analysis, with correlation factor larger than 0.987. The mathematical model of flow curve for green plasticine, at T=20°, is shown by equation (6).

$$\sigma = 0.1966\,\varepsilon^{-0.06698}\,\dot{\varepsilon}^{0.1836}\text{, MPa} \qquad (6)$$

The FEM analysis parameters were defined by program as offered values (*default*), and considering the simplicity of process and geometry there was no need for changing them. The initial density of FE mesh with 150 elements in one half of the section was selected, and 200 elements for automatic remeshing. Simulation of ring compression was performed for the following values of friction factor *m*: 0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 0.99.

For the display of simulation results, in the form of strained FE mesh, the process phases at shortening of ring height for 4, 6, 8 and 10mm were selected, as for plasticine models. Figures 8-11 show some of the results of simulation of plasticine ring compression, at various values of friction factor *m*. One half of FE model was shown.

At small values of friction factor, in course of ring compression, the increase of inner ring diameter occurs, because the material slides over tool contact surface effortlessly. The increase of contact fiction influence causes the resistance to material sliding, and therefore the inner diameter of the ring is decreased. It is obvious that the change of that diameter can be representative for the estimation of contact friction. The dependence of plasticine ring inner diameter on reduction of height, with friction factor as the parameter, gives new CAMPform calibration curves, for estimation of friction factor values in modelling experiments with plasticine. New calibration curves for ring test method, but for the stipulated material – plasticine, are shown in figure 12.

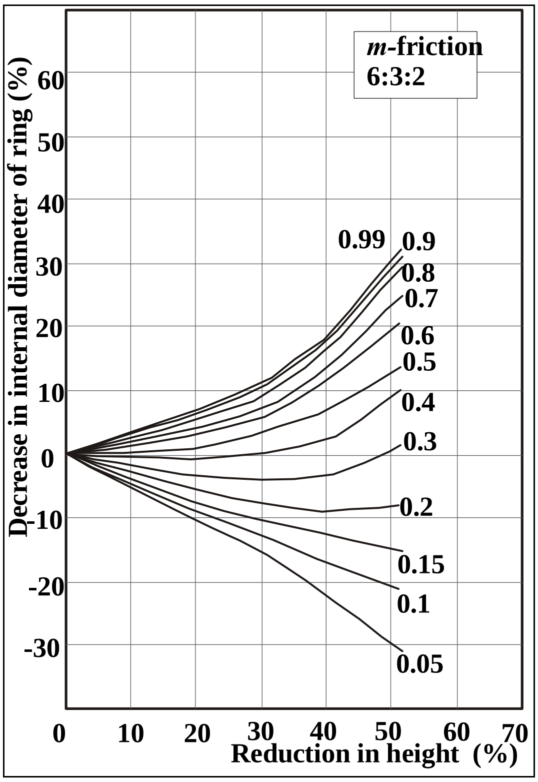

Figure 12. CAMPform calibration curves for plasticine

The shown curves are different from the previous calibration curves, in the area of large contact friction, for friction factors m>0.8. To be precise, at these factor values, the maximal shortening of inner ring diameter, at height reduction 51%, goes up to 32%, while at curves proposed by Wanheim or Lee that shortening goes up to 52%. The reason for that might be the approach in determining the curves and the behaviour of material. These curves were obtained by FEM analysis with rigid-visco-plastic approach, i.e. taking into consideration the strain rate hardening of the material and strain softening, through the negative value of coefficient n in flow curve equation. Wanheim and Lee determined the calibration curves for ideally plastic material. It is obvious that even at standard ring compression, besides the dominant influence of friction, the influence of material properties through flow stress cannot be neglected. According to that, it can be assumed that such calibration curves realistically describe the state in inter-contact for one highly-plastic material, such as plasticine, which is also the case with metals and alloys at high temperatures, which have prominent forming softening due to recrystallisation and have a considerate sensitivity to strain rate changes.

4. CONCLUSIONS

The ring test method represents the reliable and most widely applied indirect method for estimation of contact friction in bulk forming processes. The change of inner diameter at compression of the ring realistically represents the condition in inter-contact of tool and material.

Considering the differences which exist in shown calibration curves, which were obtained by various methods in ring compression analysis, the read values of coefficients/factors of friction show significant imbalance. In order to give the practical significance to these values we must also specify the following data – which curves were the specified values read from. When selecting the calibration curves, the following should be taken intro consideration:

- the kind of forming process for which the contact friction conditions are estimated,
- anticipated work pressures, and on the basis of them the friction model and, possibly, the ring geometry itself (complementary ring test method),
- if the values of coefficients / factors of friction are used for describing contact conditions at numerical FEM simulation of the process, the selection of the friction model is conditioned by the model integrated in the available software,
- calibration curves obtained by FEM simulation of ring compression, for actual material, are the most reliable. In this case that was plasticine, but it could also be the arbitrary real material, metal, steel or even alloy. In that way the real behaviour of the material in course of forming is taken into consideration.

At physical modelling of the process by application of modelling materials, the selection of the adequate lubricant is the crucial step and it must be performed meticulously. The results of modelling and their transfer onto the real processes highly depend on the similarities of contact friction conditions in modelling and real process.

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