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POSSIBILITIES TO MEASURE CONTACT FRICTION IN BULK METAL FORMING

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Original scientific paper
Friction occurs in all metal forming operations and, in general, it has a negative impact on process parameters, die life, as well as workpiece quality. In cold metal forming processes high interface pressures between die and material take place. These pressures can be the limiting factor of application of cold forming. By reducing interfacial friction, contact pressures can be reduced too. Knowledge of friction amount (factor of friction μ and/or friction ratio m) is essential for calculation of the main process parameters (load, energy), for choosing a proper lubricant but also for numerical modelling of forming operations. There exist a number of experimental methods to determine friction in metal forming processes. Current paper deals with the possibilities to evaluate friction. It analyses and assesses a number of existing friction models in cold metal operations. Proposal of a new friction model for cold metal forming operations is presented and discussed. Measurement of friction force in backward extrusion for different lubrication conditions was also preformed.

Keywords: *cold backward extrusion, experimental tooling, friction models*

Mjerenje kontaktnog trenja u obradama prostornog deformiranja

Izvorni znanstveni članak
Trenje je neizbježna pojava u svim postupciima plastičnog deformiranja metala i ima negativan utjecaj na parametre procesa, radni vijek alata, kao i kvalitetu radnog komada. U hladnom prostornom deformiranju veliki pritisci djeluju između alata i radnog komada. Ovi pritisci mogu biti limitirajući faktor prilikom primjene tehnologija deformiranja. Smanjenjem kontaktnog trenja, smanjuju se i kontaktni pritisci. Poznavanje parametara trenja (faktora trenja μ i/ili omjera trenja m) je od velikog značaja prilikom proračuna parametara procesa (npr. sila ili energija) i odabira odgovarajućeg sredstva za podmazivanje, kao i numeričku simulaciju obrade. Postoje mnogobrojne metode za određivanje parametara trenja u obradama deformiranjem. Neke od ovih metoda opisane su u ovom radu. Također je predstavljen i novi model za određivanje parametara trenja u obradama deformiranjem. U radu je izvršeno i mjerenje sile trenja u procesu protusmjernog istiskivanja za različite vrste maziva.

Ključne riječi: *eksperimentalni alati, hladno protusmjerno istiskivanje, modeli trenja*

1 Introduction

One of the important influential factors in all metal forming operations is friction which arises between the die and workpiece material. Friction increases load and energy requirement as well as die wear. Reduction of friction amount is therefore one of the main tasks in planning and realization of metal forming processes. It can be achieved by different measures: by selecting die materials that exhibit low adhesion (i.e. ceramics), by reducing roughness of the die surface, by subjecting die-workpiece interface to ultrasonic vibrations [1]. But, in practical realization of metal forming operations the most effective and most employed way to reduce friction is lubrication of interfacial surfaces during deformation. There exist a wide range of different lubricants for metal forming processes whose function is not only to reduce friction but also to cool the die-workpiece contact, to reduce wear, to prevent cold welding and to control surface finish of the workpiece [1].

Knowledge of friction magnitude is needed for three reasons. First, forming load and energy requirement cannot be calculated without knowledge of friction. Second, in numerical analysis (i.e. finite element analysis) friction is an essential input parameter, and third, the amount of friction is the main criterion for the selection of lubricant [4].

Friction amount is quantified by a non-dimensional parameter: factor of friction (μ) or/and friction ratio (m). Both friction indicators are obtained experimentally. For knowing μ (m), frictional shear stress τ_f can be expressed as (Coulomb friction model):

$$\tau_f = \mu \cdot p, \qquad (1)$$
$$0 \le \mu \le 0{,}5\ (0{,}577).$$

If there is no relative sliding at the die-workpiece interface (in cases where pressure p is significantly higher than effective stress K: $p >> K$) frictional shear stress is determined as (Constant friction model):

$$\tau_f = m \cdot \tau_{max} \qquad (2)$$

m – friction ratio, $0 \le m \le 1$
τ_{max} – yield stress of the material in pure shear.

General friction model states that the frictional stress is expressed by:

$$\tau = f \cdot \alpha \cdot k \qquad (3)$$

f – friction factor expressing the friction in real contact ($0 \le f \le 1$)
k – shear flow stress, where $k = \tau_{max}$ in expression (2)
α – real to apparent contact area ratio.

In this model friction is proportional to normal stress at low pressures and fairly constant at high pressures as shown in Figure 1 [6].

For determination of non-dimensional parameter μ and m different experimental models have been developed. All of them simulate real metal forming processes such as sheet metal forming, extrusion, hot forging, cold forging, etc.

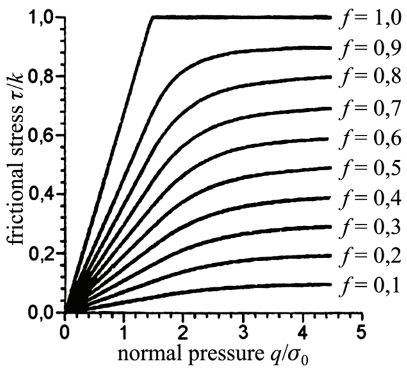


Figure 1 Friction stress in general friction model [6]

Current paper elaborates a number of most employed friction models in cold bulk metal forming, including own model proposal for determination of factor of friction μ. Furthermore, friction force in backward extrusion of steel has been obtained experimentally, for different lubrication cases. For that reason special tooling was designed and made.

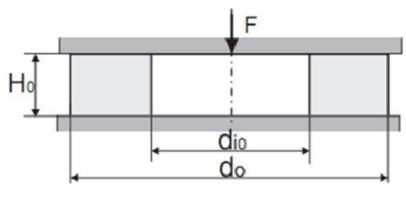
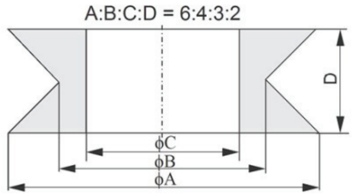
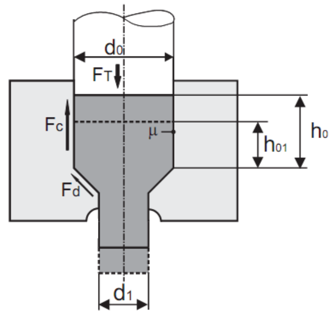
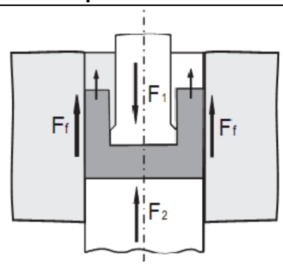
2 Models for measurement of friction in bulk metal forming

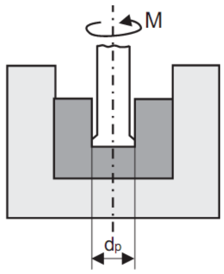
Great variety of metal forming processes differ from each other in terms of pressure, temperature, velocity, stress state, tribological conditions etc. Therefore, there is no universal friction model which would enable evaluation of friction conditions in all metal forming processes. Most of them are developed for specific operations.

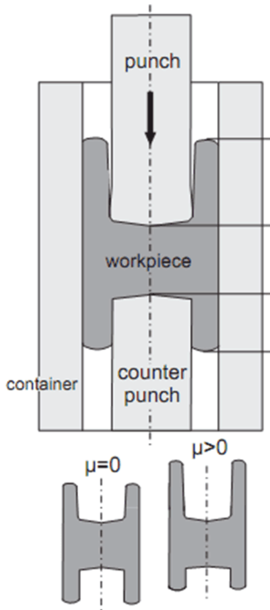
Although tribological conditions during one metal forming operation change at certain contact point with time (and therewith μ changes also), most of the experimental models only enable determination of average value of μ and m.

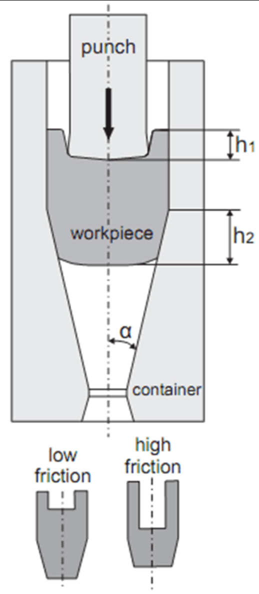
In Tab. 1 some of the most applied experimental models for determination of friction in bulk metal forming are presented and evaluated.

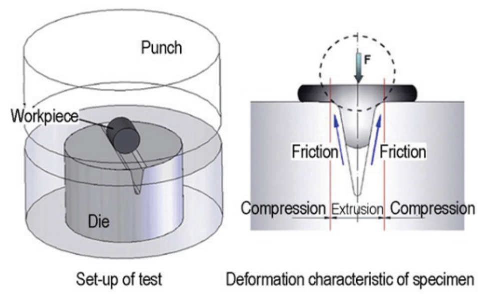
Table 1 Models for friction assessment

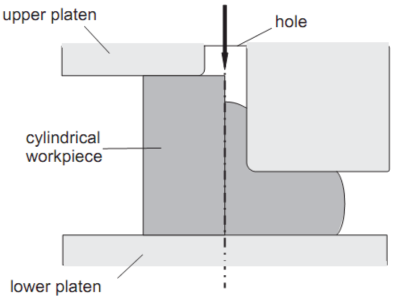
Ring – compression test	
Schema	 [7]
Principle	A ring-shaped billet is compressed by two plates in several increments. Deformation of diameter and height is measured after each increment. Friction is evaluated by comparing obtained results (curve) with friction calibration curves given in literature.
Application field	It is a very simple test. There is no need for load measurement or knowledge of material yield stress. This test is most suitable for processes with low effective strains.
New billet shape for ring – compression test	
Schema	 [6]
Principle	The only difference between this test and conventional ring test is in the billet's shape. Original height/diameter proportions of conventional ring test are maintained.
Application field	This test is for processes where low nominal pressure and high friction is anticipated.
Forward bar extrusion	
Schema	 [18]
Principle	In this test cylindrical billet is extruded through conventional forward extrusion die. During observed interval, height h_0 decreases to h_{01} and load F_T decreases for ΔF_T. Load reduction ΔF_T is a function of only F_C (other force components during this interval remain constant). Friction coefficient is a function of ΔF_T, die geometry and material yield stress.
Application field	This method can be used where more severe strains prevail. Forward bar extrusion test requires load measurement and knowledge of material yield stress.
Backward cup extrusion	
Schema	 [22]
Principle	In backward cup extrusion punch forces the billet's material to flow sideways through the gap between the punch head and container. By measuring forces F_1, F_2 and F_f and by knowing tool/die geometry and material yield stress, friction can be calculated.
Application field	This test is most suitable for processes with high effective strains. Loads measurements, as well as material yield stress are needed.

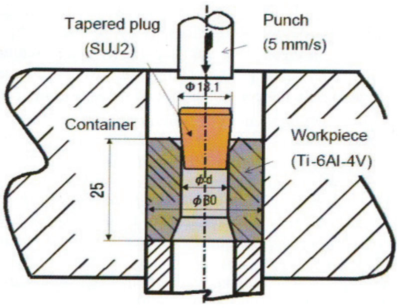
Backward extrusion with a twist	
Schema	 [23]
Principle	Billet is first backward extruded and then the punch is rotated while the die is kept stationary. By introducing another punch (with different punch land), both momentums are measured and friction is calculated.
Application field	This test is friction evaluation in processes with low strains. Two different punches and mechanism for punch rotation are needed

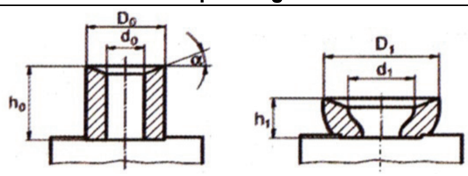
Backward – forward hollow extrusion	
Schema	 [18]
Principle	In this method a cylindrical billet is extruded in both upward and downward direction. Ratio h_1/h_2 is friction sensitive, i.e. the higher the friction, the more material flows upwards.
Application field	This test is for friction assessment in processes with high pressures and deformations.

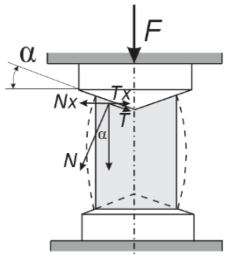
Combined forward – backward extrusion	
Schema	 [18]
Principle	Cylindrical billet is extruded in both forward and backward direction. Therefore material flows through the opening at the bottom of the die and through the gap between the punch and die. The higher the friction, the more material flows backward. Ratio h_1/h_2 is the indicator of friction magnitude.
Application field	Both backward and forward deformation occurs in this test. In this test large strains and pressures occur.

T – Shape compression	
Schema	 [25]
Principle	In this test cylindrical specimen is placed at the die with a V – groove. During compression by flat punch, material flows in two directions: downwards in the groove and sideways between the tools. The amount of material that flows in the groove is friction sensitive. By FE simulation friction calibration curves are generated.
Application field	Oil is easily applied in the test by filling the groove. This test is for friction assessment in processes with severe deformations (both extrusion and compression). Specimens with different diameters can be used with the same tools.

Open die backward extrusion test	
Schema	 [26]
Principle	Cylindrical billet is compressed by a punch with a hole and flat die. Material flows both upwards, through the punch hole and horizontally, between the punch and die. Height of the billet at the end of the process is the indicator of friction magnitude. Friction calibration curves are obtained by FE analysis.
Application field	In this test it is possible to vary billets' initial geometry without changing tools. This test can be used to obtain friction magnitude in processes where large deformations prevail.

Tapered – plug penetration test	
Schema	 [27]
Principle	Tapered – plug is penetrated into hollow billet made from titanium alloy. Tapered – plug penetration load is measured and used as indicator of lubricant performance.
Application field	This test is used for comparison of different lubricants.

Conical Tube – upsetting test	
Schema	 [28]
Principle	In this test a cylinder with a drilled hole is upset by plane die (at the bottom) and conical die (at the top). Friction is evaluated by measuring final height and outside diameter of the billet.
Application field	There is no sticking zone (unlike in ring compression test). However, geometries of the tools are more complex. This method is for friction evaluation in processes where low strains occur.

Upsetting of cylinder by using conical compression platens	
Schema	 [29]
Principle	When horizontal components of normal and friction force are in balance (N_x = T_x) cylinder deforms uniformly, no barrelling takes place. In this case $\mu = \tan\alpha$. When the friction component is higher ($T_x > N_x$), cylinder barrelling occurs and in case that horizontal component of normal force prevails ($N_x > T_x$) the end faces spread.
Application field	This test is convenient for frictional study and lubricant evaluation in bulk metal forming. Drawback of this method is requirement for a large number of conical dies with different angles and corresponding specimens.

3 Proposal of a new friction model for bulk cold forming

Double - backward extrusion model is a new method for friction determination. The principle of this model is shown in Figure 2. A cylinder-shaped billet is backward extruded with a special punch that contains a hole drilled through the center. In this way material flows in two directions:

1) Between the outer punch surface and the container (like in standard backward extrusion).
2) Through the central hole.

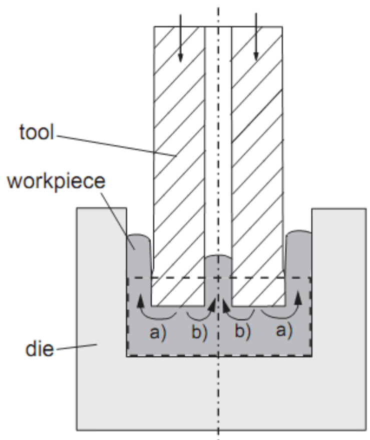


Figure 2 Schematics of double - backward extrusion method

The amount of material that flows through the central opening is dependant on friction magnitude, i.e. the higher the friction, the more material flows through the centre (Figure 3) and vice versa, the lower the friction, the more material flows sideways, between the punch and the container wall.

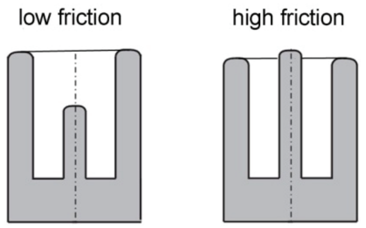


Figure 3 Material flow in low and high friction cases

In the Laboratory for Technology of Plasticity (FTS, University of Novi Sad) experimental investigation of this model was conducted. Experiment was performed on Sack & Kiesselbach 6,3 MN hydraulic press. Billet was a cylinder Ø40×35 mm. As billet material, aluminium alloy with stress - strain curve $K = 315,2 + 117,1 \cdot \varphi^{0,2}$ MPa was used. Geometry of the punch is given in Figure 4 (left). Standard die for conventional backward extrusion was used with inner diameter of Ø40,4 mm. Total of 22 mm stroke was conducted with oil used as lubricant. Specimen after double – backward extrusion process is shown in Figure 4 (right).

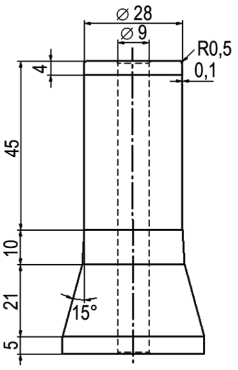


Figure 4 Geometry of the punch (left) and specimen after extrusion (right)

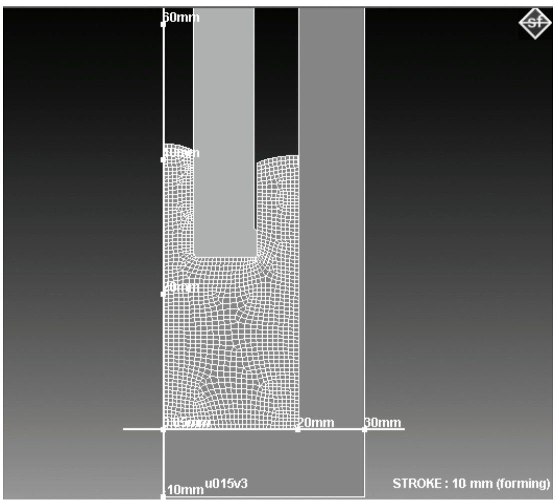


Figure 5 FE simulation in Simufact Forming 9.0

In order to determine friction coefficient, friction calibration curves (FCC) were obtained by FE simulation [32].

In FE simulation (Figure 5), the same process parameters (tool/die geometry, billet material, stroke, press velocity…) were used as in experiment. Axisymetric 2D simulation with Advanced Front Quad mesher and 0,6 mm element size was used. Both punch and die were set as rigid bodies in order to prevent their deformation. As well as in experiment, the total of 22 mm stroke was conducted. Friction factor was varied in range from μ = 0,01 to μ = 0,25 in order to obtain a wide spectrum of friction curves. Results were measured after every 2 mm of stroke increment and FCC were obtained by measuring and imposing bulge height (h_1) on vertical axle and press stroke on horizontal axle for different friction values.

Experimentally obtained height of the bulge (h_1), was imposed on FCC (Figure 6, black dot) previously obtained by FE simulation. From Fig. 6 it can be seen that the friction factor in the process was μ = 0,12.

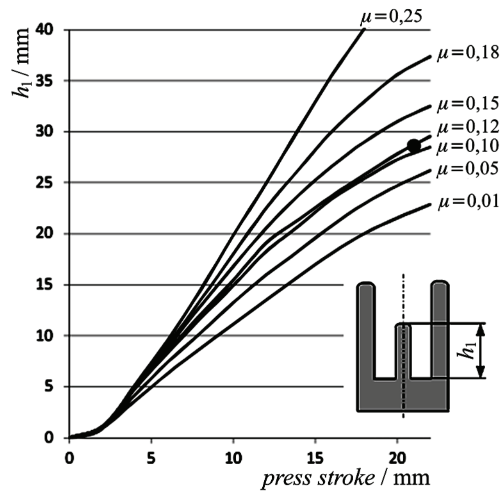


Figure 6 Experimental result imposed on FCC obtained by FE simulation

4 Measurement of friction force in cold backward extrusion

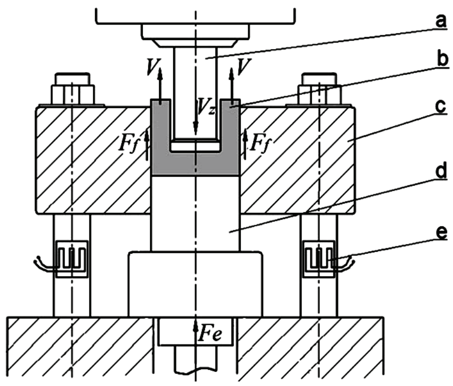


Figure 7 Basic concept of the experimental tooling (a – punch, b – workpiece, c – container, d – bottom of the die, e – strain gauges)

In scope of broader investigation of cold extrusion processes measurement of friction force which occurs during deformation at the contact between specimen and container wall was conducted. For that purpose special tooling was designed and made. Principle of laboratory tooling for friction measurement is given in Figure 7.

The main elements of the tooling are punch (a), container (c), bottom of the container (d) and four measuring elements (screws) at which two active and two compensating wire resistance strain gauges were cemented (e). These elements measured friction force which took place between workpiece and the container wall. The principle of the friction measurement is as follows: during backward extrusion material flows with the velocity V in opposite direction of punch movement (V_z). This causes occurrence of friction force F_f at the die wall.

Figure 8 Sack&Kieselbach 6,3MN hydraulic press

This force induces tensile loading at four screws which is measured by strain gauges. In Figure 8 tooling, machine and measuring equipment are shown.

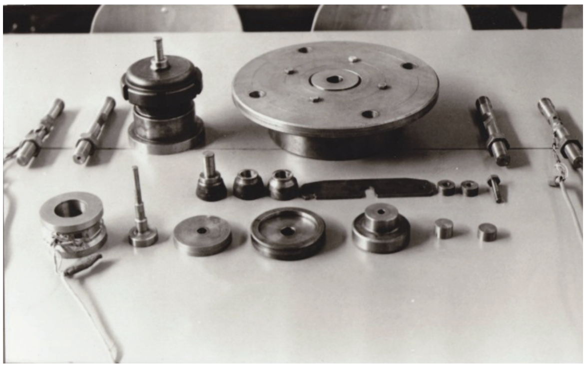


Figure 9 Experimental tooling in disassembled position

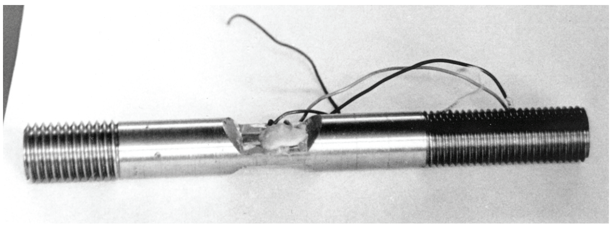


Figure 10 Measuring element with cemented strain gauges

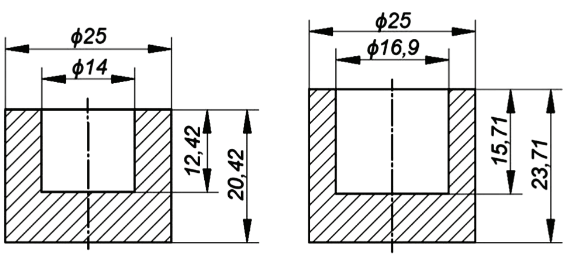


Figure 11 Specimen geometries

In Figure 9 all elements of the experimental tooling are shown in disassembled position and in Figure 10 measuring element is given. Two different specimen geometries (area reductions) are employed in experimental investigation (Figure 11). Material of the billets was low carbon steel C15E with the following curve: $K_1 = 276,44 + 397,715\varphi^{0,317}$ MPa.

The state of specimen surface and applied lubricants are given in Tab. 2.

Table 2 State of specimen surface and lubricants type

No.	Surface of specimen	Lubricant
1	Phosphate coated	Molybdenum disulphide (MoS_2)
2	Phosphate coated	Machine oil
3	Uncoated	Molybdenum disulphide (MoS_2)
4	Uncoated	Machine oil

For every combination: state of the specimen surface – lubricant – area of reduction, measuring of friction force F_1 at the contained wall was repeated three times. In this way total number of measurement was 18. Magnitude of friction force F_f for every combination is given in Tab. 3.

Table 3 Friction force at the container wall

Friction force at container wall					
Surface of specimen	Lubricant	Area reduction / %	F_f / kN	Average	
Uncoated	MoS_2	38	19,20 19,70 19,00	19,30	17,7
Uncoated	MoS_2	61	14,90 16,20 17,30	16,13	
Phosphate coated	Machine oil	38	22,20 19,60 18,90	20,23	19,65
Phosphate coated	Machine oil	61	21,00 19,30 16,80	19,00	
Phosphate coated	MoS_2	38	13,30 17,20 11,40	14,00	14,07
Phosphate coated	MoS_2	61	13,40 18,10 11,70	14,14	

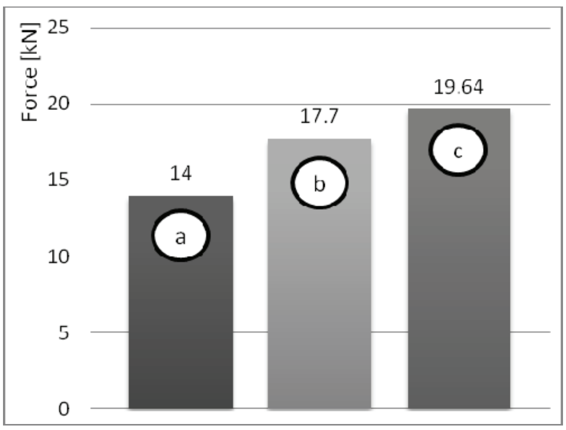


Figure 12: Friction force at the container wall for different lubricants: a) Ph. + M_oS_2, b) M_oS_2, c) Ph. + oil

Summarized measuring results are shown in Figure 12 where the average value of friction force F_f which occurs at the container wall in backward extrusion process is given for every combination of surface state and lubrication.

5 Conclusion

Friction is a very important parameter in all metal forming processes. It affects in unfavourable way all main process parameters as well as workpiece quality.

For the analytical analysis and process simulation knowledge of friction magnitude is essential. In order to quantify friction value in metal forming, several methods have been invented and applied. The most employed method is ring – compression test, presumably due to its simplicity. However, because of the low strains and low contact pressures which occur in this test, it is not adequate for processes where severe deformation conditions occur. Therefore a number of alternative methods have been developed which make it possible to predict the amount of friction in cold bulk metal forming.

In current paper new model for determination of friction factor μ is proposed, which is based on the process of double-backward extrusion. In this process large strains occur, which makes this model appropriate for determination of μ in cold extrusion operations. Friction evaluation by using double – backward extrusion method of aluminium alloy billet lubricated with oil was given in this paper. Experimental investigations in conjunction with FE simulation analysis showed that the friction factor (μ) in this process was 0,12.

Friction in backward extrusion of steel has been investigated experimentally. For that purpose special tooling was designed and made which enables measuring of friction force at the interface contact between workpiece and container wall.

In the experiments, state of the specimen surface and lubricant type varied. The highest value of the friction force was obtained for the combination: phosphate + oil and the lowest for the phosphated billets lubricated with MoS_2.

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