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RESEARCH

# Estimation of Lubricants for Ironing of Steel Pieces

*In the process of ironing, the tribological factors, namely the realised friction forces, play a significant role. The stress-strain state of plastically formed piece, the possibility for successful forming and force necessary for execution of forming depend on the size and distribution of contact stresses. Considering the fact that the metal forming is done in conditions of high contact pressures, absence of lubricants would, in such conditions, lead to direct contact of formed material and the tool, i.e. the micro-welding or sticking of the softer material onto the harder tool would occur, and due to that the severe disruption of forming conditions would take place.*

*The main tribologiocal factors in metal forming by ironing are: forming speed, strain ratio (depends on load and semi-angle of the die cone), state of materials in contact (surfaces topography, physical and chemical characteristics of materials) and type of lubricant. By combining them, one can carry out mixed, i.e. limit friction, and thus minimise the contact between the tool and working piece (sheet metal).*

*Classical methods for estimation of lubricants (Almen-Wieland test, Falex test, Timken-test, four-ball test, etc) are not the most convenient for estimation of lubricants in ironing. Much more convenient tests are those that properly model the real working conditions in such forming. In this paper, the obtained results for the estimation of various lubricants used in ironing will be presented on the adequate tribo-model of sheet metal test-tube sliding between pairs with skewed contact surfaces.*

***Key words:*** *ironing, tribo-modelling, lubricants*

## 1. INTRODUCTION

Ironing is applied in manufacture of cylindrical pieces whose depth is larger than diameter, and bottom thickness is larger than wall thickness, such as bushes, thin-wall pipes, and especially tin cans for food and drinks, whose annual production in the world amounts to hundreds millions of pieces. The specified parts are made out of materials which have sufficient plasticity in cold state, such as low-carbon steels, aluminium, brass and others. During the last few years, the application of this forming method was introduced in electro-optical industry, in the production of optical and magnetic disks for obtainment of mirror-like surface, since it is considerably cheaper that mechanical forming.

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In forming by ironing, the tribological conditions, i.e. realised friction forces, play a significant part. The stress-strain state of plastically formed piece, the possibility for successful forming, as well as force needed for forming performance depend on the size and distribution of contact stresses. Considering the fact that the metal forming is done in conditions of high contact pressures, absence of lubricants would, in such conditions, lead to direct contact of formed material and the tool, i.e. the micro-welding or sticking of the softer material onto the harder tool would occur, and due to that the severe disruption of forming conditions would take place.

The most important tribological factors in forming by ironing are: forming speed, strain ratio (depends on load and semi-angle of the die cone), state of materials in contact (surfaces topography, physical and chemical characteristics of materials) and type of lubricant. By combining them, one can carry out mixed, i.e. limit friction, and thus minimise the contact between the tool and working piece (sheet metal).

## 2. THE ROLE AND FUNCTION OF LUBRICANT IN PLASTIC FORMING PROCESSES

The problem of lubrication of machine parts has been known for a long time, and in parallel with the increase of complexity of technical equipment, a lot was being done on the improvement of both the types of lubricants and lubrication methods. The main aim of lubrication application is the reduction of friction resistance, and at the same time the reduction of loss of energy, inevitable at friction, as well as the reduction of intensity of coupled friction elements wear; as a result of this, it could be possible to increase the life-time and reliability of technical equipment.

Technological lubricants, applied in various technological processes, especially in plastic forming processes, are part of another group. Special properties are required from that group of lubricants, whereat the requests differ a lot in dependence on kind of the process (processes of hot or cold forming).

Lubricants applied in cold plastic forming processes, such as deep drawing without and with ironing, straining, rolling etc, must meet the following requests [1]:

- efficient separation of contact surfaces
- prevention of direct contact of formed metal and tool and appearance of bulges on the tool
- protection of tool against excessive wear
- possibility for effortless supply
- that they can be easily removed from product surface, especially if the product is to undergo further surface forming (painting, galvanisation)
- resistance to normal load and ability to flow easily towards the contact.

Considering the various conditions for realisation of plastic forming processes, and ample gamma of deformable plastic materials, when selecting the technological lubricants for a particular process the following factors must be taken into consideration:

- type (class) of formed material
- forming speed
- contact pressure range
- temperature of formed material;
- tool construction, and
- degree of product complexity.

The need to select the lubricant in dependence on the type of formed material (steel, coloured metals) is the consequence of the fact that some lubricants function well in steel forming, but cannot be applied in forming of non-iron metals, due to corrosive effects. The other very important factor, crucial in the selection of lubricant, is the range of tool work speeds and speed of displacement of formed material on the tool surface [2]. In this way, a lubricant which is considered to be very good (e.g. in drawing process on hydraulic press) can turn out to be completely inappropriate at drawing on fast press.

The range of unit pressures which appear on contact surfaces of formed material and tool is also an influential factor. The oil lubricants, most often applied in technical operations, have the small possibility of coating, because due to high pressure the lubricant film can easily be broken off. Very high pressures which arise in some plastic forming processes (e.g. extrusion, ironing etc) request the application of lubricants other than those used for machine elements, or they request the application of lubricants with special additives (EP additives).

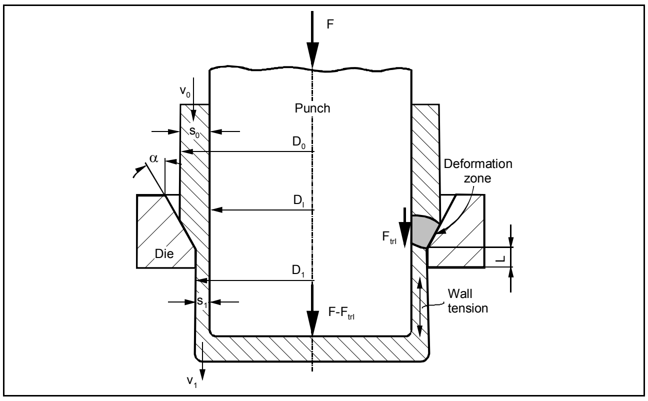


*Figure 1. Scheme of ironing*

When constructing the tool, the tendency should be that the lubrication operation is performed independently (in mechanised way), and that the lubrication cycle is related to machine actions, because only then will the effects of lubrication be visible. Therefore, in the course of tool constructing, some space should be foreseen for placing the proper ejectors which spray the lubricate medium. When selecting a lubricant, the degree of product complexity should also be taken into consideration, as well as the specific character of the process. In some cases, friction resistance can be useful (it alleviates the process realisation) and those tool zones do not need lubrication. Therefore, the problem of lubricant selection cannot be solved easily – it requests a complex approach.

In plastic forming processes, in dependence on type of the process, various kinds of friction arise, ranging from technically dry to hydrodynamic friction. That variability of friction types is mainly the consequence of different efficacy of lubricants performance.

The efficacy of lubrication primarily depends on:

- unit pressures which act in zone of formed material contact with the tool,
- relative speed of displacement of formed material on the tool and
- temperature reached in contact zone.

In dependence on the kind of process, class of formed material, type of applied machine, the range of parameters change can be very extensive, which further influences the changes of lubricant properties.

Considering the huge diversity of plastic forming processes and extensive range of change of parameters of those processes realisation, in industry practice, many kinds of lubricants are applied, ranging from hard coatings to sprayed lubricants (graphite, talc, $MoS_2$, stearins, etc), oil or water-based suspensions, glass-based lubricants, artificial substances of various consistency and many kinds of liquid lubricants, especially oil. Due to that, the mechanism of lubricant interaction with friction surfaces can significantly vary.

Durability of tools for plastic forming depends on many factors which can generally be divided into three main groups:

- materially-constructive
- productive
- exploitative

If we leave out the construction and production errors, which should not appear as a rule, than increase of life-time of tool for plastic forming can be achieved:

- by application of more expensive materials with better resistance properties, instead of tool steels used so far,
- by application of correctly selected methods of surface forming, which enable the achievement of desired properties of surface layers, especially higher resistance at wear,
- by application of lubricants.

It is well-known that the investigation of lubricants is performed in laboratory conditions on appropriate process models, and verification of obtained results is carried out in actual forming process.

Classic methods for estimation of lubricants (Almen-Wieland test, Falex test, Timken test, four-ball test) are not the most convenient for estimation of lubricants used in metal forming. Also, the tests foreseen for evaluation of lubricants in metal forming (Ring compression–Burgdorf's test, Slanting plane test…) are not equally convenient for all kinds of forming. For that purpose, the tests that model the real working conditions for each individual kind of forming are much more convenient. However, even in the most accurate modelling of real working conditions, there is a certain number of factors which are not taken into consideration, and which could, in particular case, play a significant role in real process [1].

The character of cold friction in cold metal forming is conditioned with the following parameters: pressure on contact surfaces, sliding speed and restoring (modification) of piece surface [3]. Regarding that, the investigation of lubricant can be adjusted in such a way that the emphasis is put onto the characteristics which indicate the reduction of contact friction force, increase of lubricant stability at compression and shearing, increase of lubricant capacity regarding separation of contact surfaces and its capabilities to prevent cold welding of metal.

## 3. TRIBO-MODELLING OF IRONING

The ironing process is schematically shown in figure 1, with general presentation of friction force in contact of working piece and die, i.e. punch. The effects of friction forces in forming zone are various; on outer area (between piece and die) these forces ($F_{trM}$) increase tension stresses, an on the inside area (between piece and punch, forces $F_{trI}$) relieve critical section, reducing stresses in the wall part which is being ironed. That is the main reason for achieving high strain degrees and realisation of significant increases of relative depth at ironing.

Ironing is carried out in conditions similar to plane forming state. Increase of friction on punch side reduces critical tension stress, but the total drawing force increases. Thereat, force $F_{trI}$ must not increase so much that, on contact surface, it leads to appearance of rough intrusions and micro-welding (or sticking) of metal particles of working piece on tool, which would lead to damaging of work piece and tool and make difficult the removal of work piece from the punch.

It is clear that the influence of tribological conditions in ironing is of extreme importance and has been studied by many researchers in past years, both in real processes and on tribo models [4, 5, 6, 7, 8, 9]. Investigation of tribological conditions in real processes is significantly longer and more expensive; therefore the investigations on tribo-models are performed more often.

Modelling of tribological conditions in ironing implies the fulfilment of minimum of necessary criteria considering: the similarity in stress-strain characteristics, temperature-speed conditions, properties of surface of tool and material, as well as the state of their contact in the course of forming.

Physical modelling, which is usually the basis of any tribo-investigation, involves the study of real process in laboratory conditions with modification of process realisation conditions, geometrical values or kinds of material being formed, in conformity with similarity laws. The fixed conditions in modelling must completely satisfy geometrical, mechanical and physical similarity of processes to which original and model are subjected. Strict fulfilment of these conditions implies the application of materials-originals (with same properties of strengthening and surface topography).

## 4. EXPERIMENTAL INVESTIGATIONS

For experimental investigations in this paper, the original model (figure 2) was realised and it imitates the zone of contact with die and punch [10] with bilateral symmetry. This model enables the realisation of high contact pressures and respects physical and geometrical conditions of real process (material of die and punch, contact surfaces topography, semi-angle of die cone – α etc). The scheme of specified tribo-model with presentation of figures which act upon the work piece, i.e. die and punch and scheme of measuring chain are given in figure 2.

Device for ironing is installed on the special machine for investigation of thin sheet metals – ERICHSEN 142/12. According to the constructive solution, this device is placed in the frame of the equipment for investigation by tension, whereat the main drive of the machine is used for production of ironing force (force F). The second effect, the pressure on test-tube (force $F_D$), is realised by hydraulic method, through separate pump of 0.75 *kW* power, nominal pressing force 50 *kN*, with its own force gauge.

Bent sheet metal 7 band (test-tube, figure 2c) is placed on the “punch”. It is acted upon by “dies” 2 with force $F_D$. Dies are placed in supports, whereat the left support is motionless, and the right one is movable together with the die. The punch consists of body 3 and front 4 which are inter-connected by gauge with measuring bands 5.The test tube is ironed (it slides) between dies due to the effects of force F on the punch front, in the course of which the test-tube is ironed. Throughout ironing, the outer surface of test-tube slides over die surface (skewed at an angle α), and inner surface of test-tube slides over plates 6 fixed onto the punch body.

The device is made with compact surface of increased stiffness, with possibility of simple modification of contact – pressing elements (die 2 and plate 6), easy cleaning of contact zones and convenient placing of test-tubes.

Plates 6 and dies 2 can be made of various materials, and with different roughness, and dies can be made with different gradient angle α.

During the construction of this device, the main idea was to enable determining of friction coefficient, both on die side and on punch side at various contact conditions.

The total ironing force F represents the sum of friction force between the punch and work piece $F_{trI}$ and force which acts upon the basin bottom $F_z$, i.e.:

$$F = F_{trI} + F_z \,. \tag{1}$$

Total ironing force F is measured on the machine itself, and friction force on punch side $F_{trI}$ is registered with the help of gauge with measuring bands.

On the basis of previous equation it follows that:

$$F_z = F - F_{trI} \,. \tag{2}$$

Force $F_z$, which acts upon the bottom of band (test-tube) loads the band walls with stress $\sigma_z$, which can be calculated on the basis of the following equation:

$$\sigma_z = \frac{F_z}{2 \cdot b \cdot s_1} \,, \tag{3}$$

whereat: b – test-tube width,
$s_1$ – test-tube thickness after ironing.

Friction coefficient on punch side can be calculated on the basis of the following equation:

$$\mu_I = \frac{F_{trI}}{2 \cdot F_D} \,, \tag{4}$$

and friction coefficient on die side by the equation:

$$\mu_M = \frac{F \cdot \cos\alpha - 2 \cdot F_D \cdot \sin\alpha}{F \cdot \sin\alpha + F_D \cdot \cos\alpha} \,. \tag{5}$$

By knowing the dependency of forces F and $F_{trI}$ on sliding path *h*, it is possible, based on previous formulas, to determine the friction coefficients ($\mu_M$ and $\mu_I$) in the function of sliding path.

Medium specific pressure between die and sheet metal represents the quotient of normal force, by which die acts upon sheet metal $N_M$, and contact surface between die and sheet metal $S_k$.

$$p_{sr} = \frac{N_M}{S_k} = \frac{2 \cdot F_D \cdot \cos\alpha \cdot \sin\alpha + F_{iz} \cdot \sin^2\alpha}{b \cdot (s_0 - s_1)} \,. \tag{6}$$

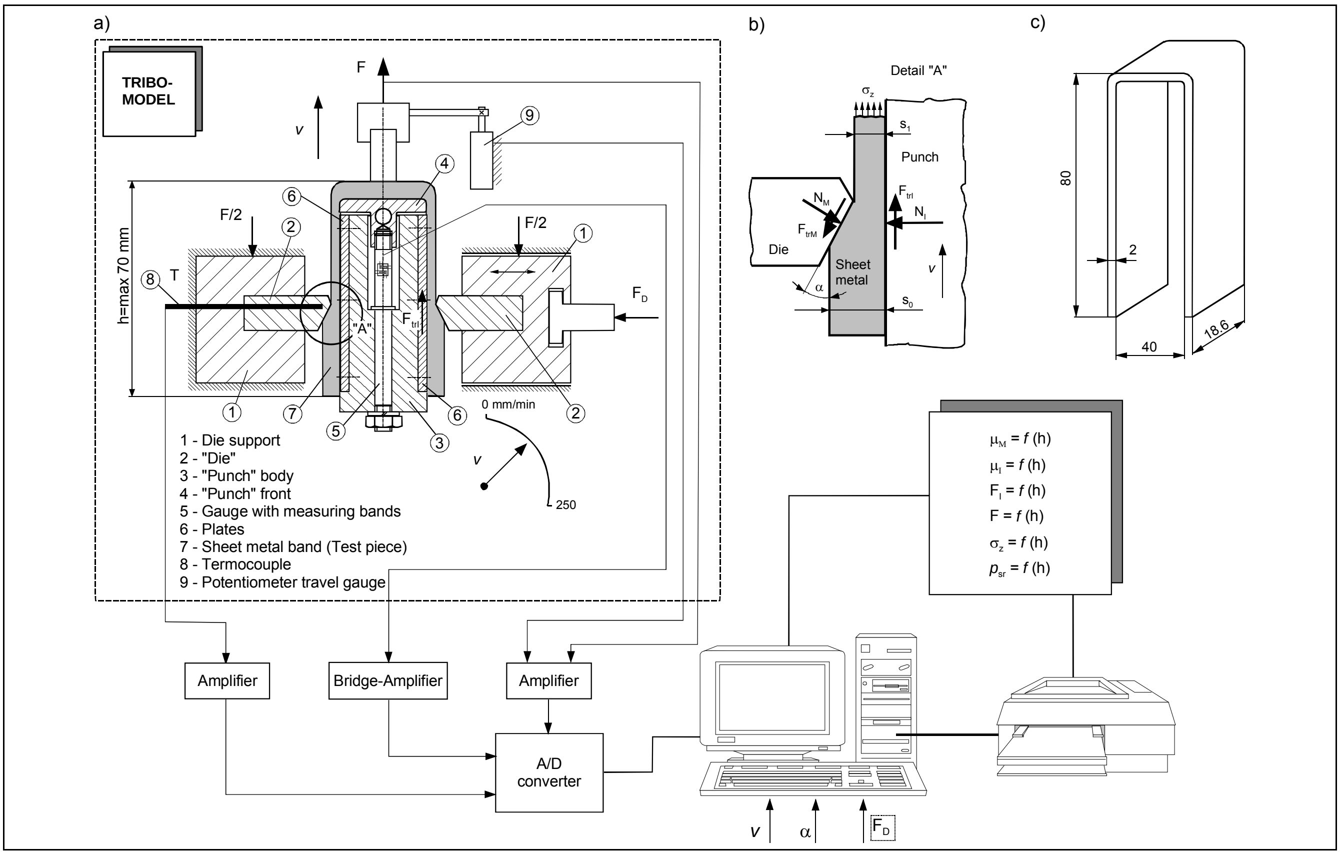


*Figure 2. Scheme of tribo model with measuring chain for data acquisition (a), presentation of forces in strain zone (b) and test-piece form (c)*

## 4.1 Investigation conditions

For experimental investigations in this paper, we have selected low carbon steel sheet metal, soothed with aluminium, marked Č0148P3. It belongs to the group of quality sheet metals foreseen for metal forming and has properties foreseen by standard JUS C.B4.016 for this group of materials.

The form and dimensions of test-tube on which the investigation was performed are given in figure 2c. Mechanical properties and surface characteristics, as well as other important data on investigation, are given in table 1.

*Table 1. Properties of investigated material and investigation conditions*

| | | Material | Mechanical properties | Surface characteristics |
|---|---|---|---|---|
| Tool | Die | Č4750 (AC) | 60÷63 HRC | $R_a$≈0.01 *μm* |
| | Punch plate | Č4750 (AC) | 60÷63 HRC | $R_a$≈0.01; 0.09 and 0.4 *μm* |
| Test-piece | | AlMg3<br>thickness 2.0 *mm*<br>width: 18.6 *mm* | $R_p$ = 186 *MPa*<br>$R_m$ = 283 *MPa*<br>$A_{80}$ = 37.3% | $R_a$ = 0.92 *μm*<br>$R_p$ = 3.62 *μm*<br>$R_v$ = 5.11*μm* |
| Applied lubricants | | On die side | - M1 – Phosphate-coated surface of test tube + molybdenum disulphide ($MoS_2$)<br>- M2 – Mineral emulsifying water-soluble oil with EP, anti-wear and lubricating additives<br>- M3 – Non-emulsifying agency<br>- M4 – Non-emulsifying mineral oil with mild EP properties | |

| | | |
|---|---|---|
| | On punch side | - M1<br>- M2<br>- M3<br>- No lubrication – dry (S) |
| Reduction degree: 1÷55% | | Angle of die gradient: α = 10° |
| Sliding path: max 70 *mm* | | Investigation temperature: room temperature |
| Ironing speed: 20 *mm/min* | | Blank holding force ($F_D$): 8.7; 17.4; 26.1; *kN* |

## 4.2 Experimental results

It is well known that friction force between punch and work piece, at ironing, is useful, i.e. that it reduces total ironing force. Therefore, it is necessary that the lubricant on die side has the best possible properties, and on the punch side the worse possible ones, in order to obtain the smallest total ironing force. On the other hand, lubrication on punch side should not be too bad, because it might cause punch wear and it might make difficult the removal of work piece from the punch.

Experiment carried out in this paper had the aim of showing the possibility for application of realised device for comparative estimation of lubricants applied in ironing process.

The analyses were carried out for the influence of combination of various lubricants on ironing force, coefficient of friction on die and punch side, medium contact pressure and wall tension stress.

Figure 3 shows the change of ironing force in dependence on blank holding force with various lubricants on die side. The smallest ironing force was obtained by application of lubricants M1 ($MoS_2$) in combination with phosphate-coated sheet metal surface. By application of lubricants M2, M3 and M4 similar ironing force values are obtained, which are for about 10% higher than force obtained with lubricant M1.

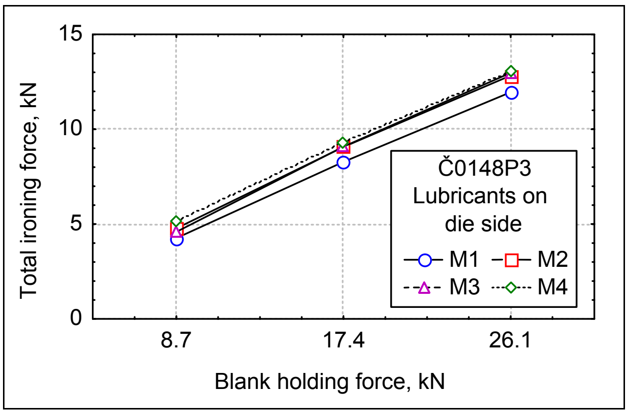


*Figure 3. Dependence of ironing force on blank holding force with various lubricants on die side*

The specific changes of coefficient of friction on die side in dependence on sliding path, for different lubricants on die side, are given in figure 4. The conditions in which the diagrams were obtained are given in the diagram key.

Figure 5 shows the changes of friction coefficient on die in dependence on blank holding force for various lubricants on die, and figure 6 shows the medium values of friction coefficient for all analysed lubricants.

On all specified figures it can clearly be noticed that the smallest friction coefficient is obtained by application of lubricant M1 in combination with phosphate-coated sheet metal. Somewhat higher values of friction coefficient are obtained by application of lubricants M2 and M3, and the highest values are obtained if the lubricant on die is M4, which is logical because the lubricant M4 is standard oil for deep drawing which is not foreseen for operating at extremely high pressures. With the increase of blank holding force, differences between friction coefficients, obtained for various lubricants, decrease.

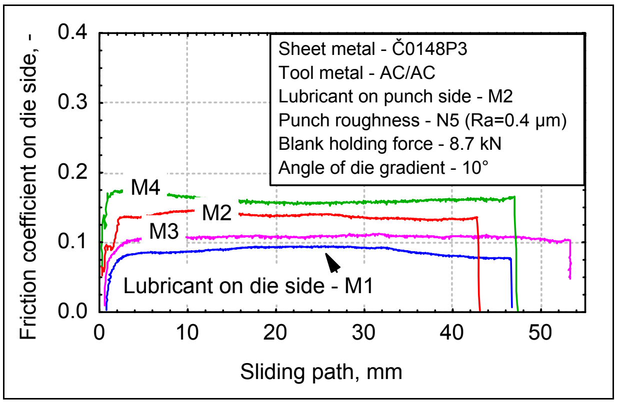


*Figure 4. Change of friction coefficient on die side in dependence on sliding path for various lubricants on die*

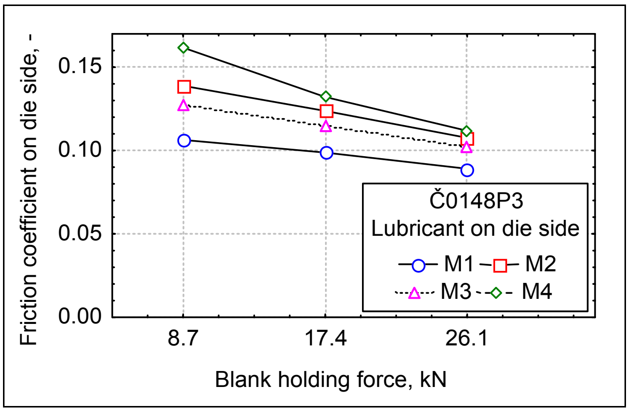


*Figure 5. Change of friction coefficient on die side in dependence on blank holding force for various lubricants on die*

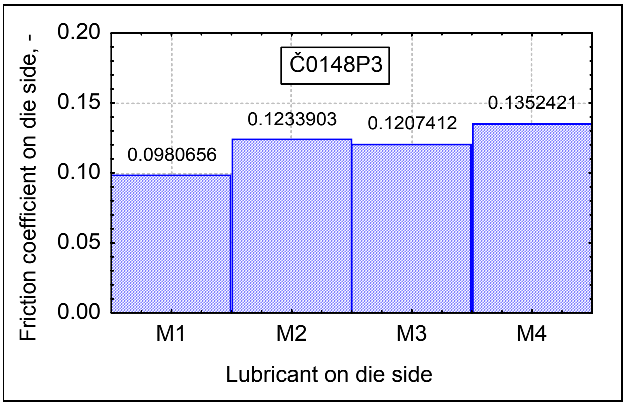


*Figure 6. Medium values of friction coefficient on die side for various lubricants on die*

Values of friction coefficient on die side for various combinations of lubricants on die and punch are given in figure 7. The largest values of friction coefficient $\mu_M$ are obtained with application of lubricant M4 on die side, and the smallest values are obtained with lubricant M1 regardless of the lubricant on pinch side.

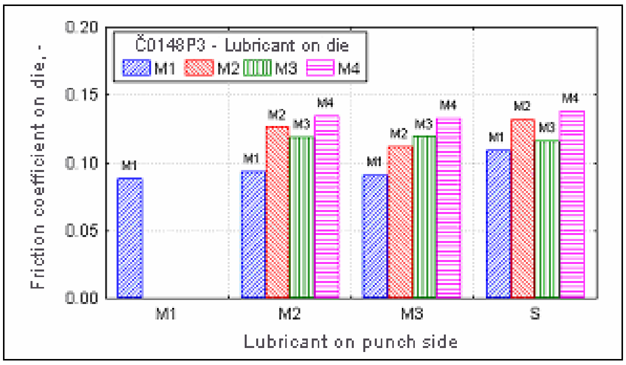


*Figure 7. Friction coefficient on die for various combinations of lubricants on die and punch*

Unlike the friction coefficient on die side, which should have the smallest possible value, friction coefficient on punch side should have the largest possible value so that the wall tension stress would be as small as possible, and cross section strain as large as possible. On the other hand, due to large values of $\mu_I$, the punch wear and difficult removal of piece from the punch occur.

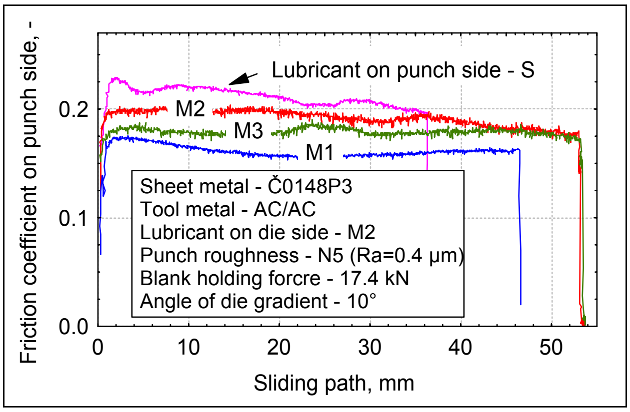


*Figure 8. Change of friction coefficient on punch side in dependence on sliding path for various lubricants on punch*

Change of friction coefficient on punch side in dependence on sliding path for different lubricants on punch is given in figure 8. The conditions in which these diagrams were obtained are shown in diagram key. In order to obtain extremely high friction coefficients, in one of the combinations a dry (degreased) surface (S) was applied on punch. The logical expectations in the experiment were realised – the highest friction coefficient on punch side, for both investigated sheet metals, was obtained without lubrication, but those values are not drastically larger than those obtained by application of lubricants. It can be noticed that at application of same lubricants somewhat higher values of friction coefficient are obtained on punch side in comparison to die. Most probably, that could be explained by different character of material flow on die side and on punch side.

As previously shown, punch roughness and blank holding force have a significant influence on friction coefficient on punch side. The values of friction coefficient $\mu_I$ for various lubricants on punch and various punch blank holding and roughness forces are given in figure 9. For all lubricants, at small punch roughness (N1) and with the increase of blank holding force, the friction coefficient on punch initially decreases, and then it stars increasing, while at higher punch roughness (N5) the friction coefficient $\mu_I$ constantly decreases with the increase of blank holding force.

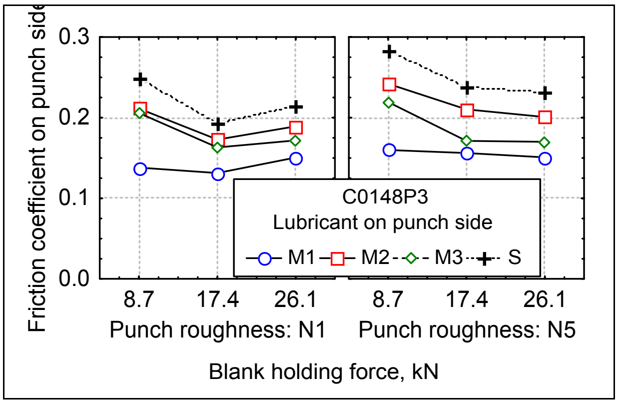


*Figure 9. Change of friction coefficient on punch side in dependence on blank holding force for various lubricants on punch*

Medium values of friction coefficient on punch side, obtained for all blank holding forces and all punch roughnesses, for all investigated lubricants, are shown in figure 10. The largest friction coefficient $\mu_I$ was obtained in the case when sheet metal surface was not lubricated (S).

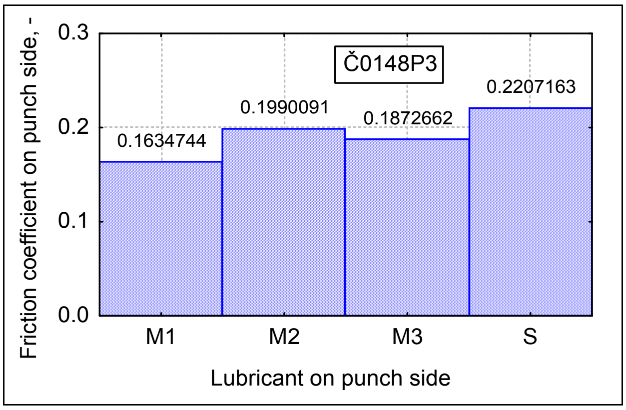


*Figure 10. Medium values of friction coefficient on punch side for various lubricants on punch*

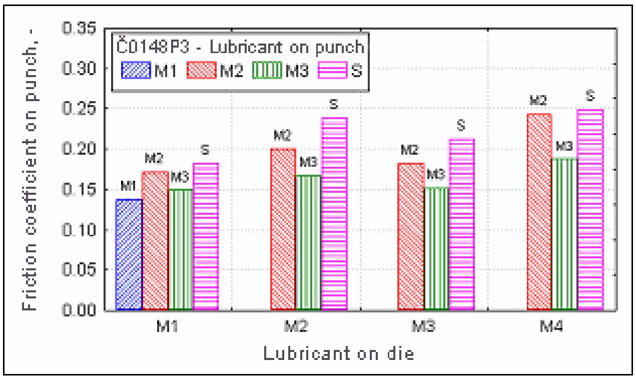


*Figure 11. Friction coefficient on punch for various combinations of lubricants on die and punch*

Medium values of friction coefficient on punch side, obtained for various combinations of lubricants on die and punch are given in figure 11. It can clearly be noticed that coefficient $\mu_I$ , when the same lubricant is applied on punch, depends also on lubricant on die.

Figure 12 shows the dependency of medium contact pressure on blank holding force for various lubricants on die side. It has been noticed that medium contact pressure does not depends on lubricants selected here.

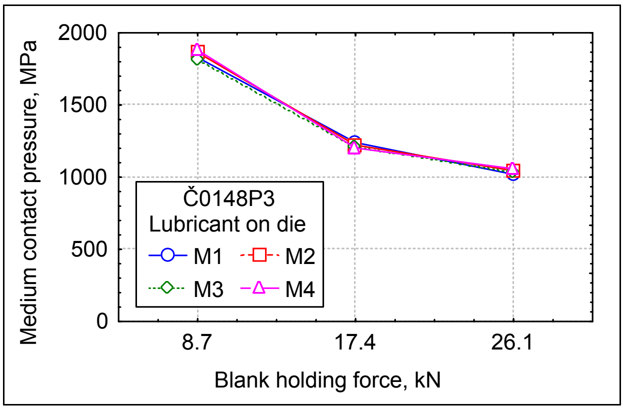


*Figure 12. Dependency of medium contact pressure on blank holding force for various lubricants on die*

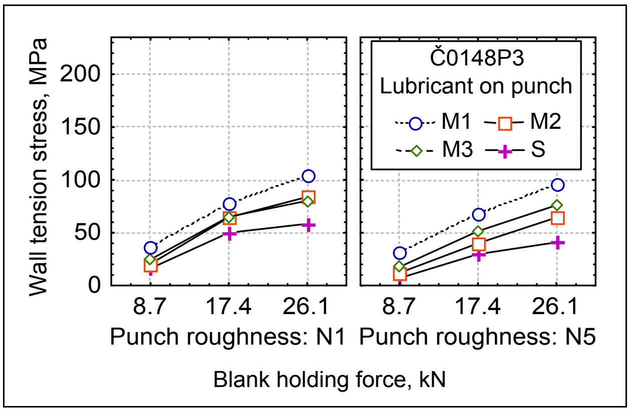


*Figure 13. Dependency of wall tension stress on blank holding force for various punch roughnesses and lubricants on punch*

The force which tightens the wall of part being ironed represents the difference between ironing force and friction force on punch. The worse the lubrication on punch side is, the higher the friction force, and in that way the smaller wall tension force, i.e. wall tension stress.

The change of wall tension stress in dependency on blank holding force at various lubricants on punch is given in figure 13. The smallest wall tension stress is obtained with the lubricant which gives the largest friction coefficient on punch. The dependency of wall tension stress on blank holding force with various lubricants on die is shown in figure 14.

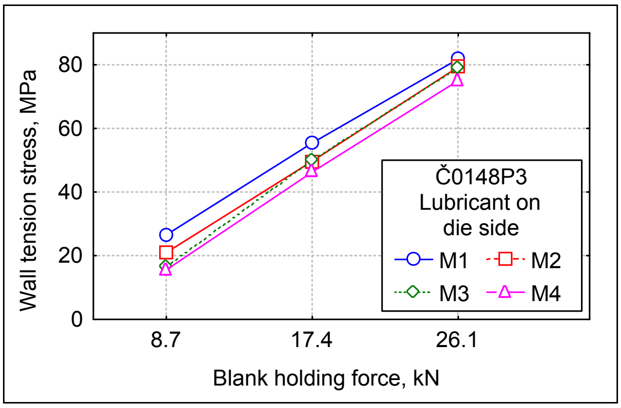


*Figure 14. Dependency of wall tension stress on blank holding force for various lubricants on die*

## 5. CONCLUSION

In model investigations of ironing, carried out in the paper, a stationary process with "constantly low friction" was realised in conditions of high medium contact pressure ($p_{sr}$>1000 *MPa*). The lowest values of friction coefficient were registered for phosphate-coated surfaces of sheet metal and molybdenum-disulphide as lubricant.

By the shown model, with all specified limitations, contact zone of sheet metal and die can be successfully simulated, as well as contact zone of sheet metal and punch, and influence of particular tribological parameters (lubricant, materials in contact, surface topography, specific pressure etc) in ironing process can be studied.

Experiments carried out in this paper clearly show the possibility for application of realised device for comparative evaluation of lubricants which are applied in ironing process.

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