Slaviša Djačić
Milan T. Djordjević
Dušan Arsić ✉
Srbislav Aleksandrović
Marko Delić
Djordje Ivković
Vukić Lazić

https://doi.org/10.21278/TOF.492061723
ISSN 1333-1124
eISSN 1849-1391

POSSIBILITIES OF CONTROLLING THE IRONING PROCESS IN CONDITIONS OF A CONTINUOUSLY VARIABLE LATERAL FORCE

Summary

In this research, a tribological model of the sliding of sheet metal between the two contact elements that perform thinning was investigated. Unlike usual thinning procedures, what is applied here are the previously set variable functional dependences of the lateral force on the stroke, which are given simultaneously during the thinning procedure. In this way, the authors attempt to better master the process of deep drawing with thinning and to manage the change in thickness by the application of a variable lateral force. The process of thinning was studied through the development and application of an appropriate mechanical-mathematical model. Two functional dependences of a variable lateral force were applied, and two types of lubricants were used: oil and a lubricant based on MoS_2 on steel and brass sheet samples. In addition, an original computerised testing device was developed. Based on the obtained diagrams, it was possible to calculate the coefficient of friction and to evaluate the obtained results. Finally, thickness distribution diagrams were obtained by measuring the thickness of the sample at several points.

Key words: *strip ironing test, friction coefficient, contact pressure, continuously variable lateral force, variable sheet thickness*

1. Introduction

This research is based on a model examination of the deep drawing process with thinning, which involves the use of sheets of greater thickness (about 3 mm) and a planned reduction of their thickness during the process, to greater degrees of deformation. According to its characteristics, the process belongs to three-dimensional moulding and is qualitatively different from the process of the deep drawing of thin sheets (where the thickness is usually at most 1 mm), where the change in thickness is mainly ignored.

The mechanical model chosen in this case is the pulling of a thicker sheet metal strip with double-sided thinning. This is a reliable and proven model applied in a large number of studies, both by other authors [1-20] and in our own [21-28]. Research in this area began a long time ago, and the first significant works were published in the early 1970s. Some of the basics of the process were then laid out by Schlosser [1]. Later research was concerned with verification of the methods that he had proposed. Thus, the authors in papers [2-4] conducted not only experimental but also numerical research in an attempt to form a valid numerical model for simulation of the deep drawing process. Since the deep drawing process can be greatly influenced by the applied lubricant, a large amount of research has aimed at determining the influence of the lubricant on the deformability of sheets during the drawing. For this purpose, classic lubricants [4-6], classic coatings [7], polymer coatings [8], and the latest environmentally friendly (green) oils [9-14] are often used. The authors who analysed the environmentally friendly lubricants consider that their research has proven that these lubricants can be as good as conventional lubricants or even better in adhering to the material and are superior in reducing the friction between the material and the die at high contact pressures. Besides, these lubricants have a great advantage in preserving the environment. The investigation of the deep drawing process, and the possible control of the force during the drawing, is not only of a research character. This was proven by the authors in works where the mentioned research was used in practice for the production of various working elements of the system, such as: automobile engine piston heads [15], ring grooves on the inner surface of a cylindrical blank [16], flanged microparts [17], double curved parts [18] or even unconventional tooling [19]. By "unconventional" parts, the authors [19] imply axisymmetric work pieces. The study confirmed that deep drawing can successfully be used to produce the relevant parts. The study has analysed the impact of deep drawing process variables, including die radius, blank holder force, and lubrication conditions, on the distribution of the wall thickness and changes in radius.

Part of the mentioned research has already been conducted by the author of this work. The research included: the flat die deep drawing process by variable contact pressure [21], determination of the friction coefficient and the drawing force in the deep drawing process of AlMg4.5Mn0.7 and steel thin sheets [22-24], numerical simulation of the process with the development of appropriate drawing models [25], and studying the influence of lubricants on the process of the deep drawing of different materials [26-28].

Current research is based on studying double-sided ironing, which was begun by [29]. The idea was to investigate the possibility of applying the lateral forces of a continuously variable non-linear (parabolic) intensity and to monitor the effect of that action on the change in strip thickness. Factors influencing the process that can be variable are: the intensity of the lateral force, the geometry of the tool, the condition of the tool surface, the tool material, the type of material of the sheet metal strip, the thickness, i.e., the strip geometry, the applied lubricant, strip pulling speed, etc. The main output is the dependence of the drawing force on the sliding stroke (or time). Based on this dependence and the formed theoretical mechanical-mathematical model, it is possible to determine the change in the coefficient of friction and the change in contact pressure.

The main goal was to assess to what extent it is possible to achieve the planned (projected) continuous change of the strip thickness, based on the variable lateral force, in combination with other influencing factors. If it turns out to be possible, the process can be applied to obtain different profiles of working parts in one tool with the use of one lubricant, which would significantly speed up the process and increase its reliability. Based on our research of available literature in this field, we could not find a similar model to the one proposed in this paper.

2. Mechanical model

For the purposes of this work, a mechanical–mathematical model was developed to determine the parameters of the deep drawing process with thinning, on the model of drawing a strip of sheet metal of greater thickness, with double-sided thinning. The model was verified by publication in [26] and it showed significantly more realistic values of the coefficient of friction and contact pressure compared to other models used so far.

It is important to mention that the authors did not present the classical process of deep drawing with thinning on one specific device, which can secure appropriate drawing force and lateral forces, but the term thinning is used for the specific process given in the text below.

The main input variables for the model formulas are: drawing force dependences on the stroke, i.e. time (obtained in the experiment), the previously defined lateral force dependences [19] and geometric data on the tool, i.e. contact pairs. The output quantities are the coefficient of friction, the actual contact pressure and the precisely measured change in the thickness of the deformed strips in all the conditions. It is very important to distinguish between the previously adopted model [18] for the application of the constant values of lateral force (Fig. 1) and the current model for the application of the variable lateral force (Fig. 2). Based on the character of the lateral force, the character of thinning can be predicted, i.e. the changes in sheet thickness, which would be visible on the thickness distribution diagram as part of the experimental results.

This model is considered reliable and has been widely employed in numerous studies, including those conducted by other researchers [1, 2, 6, 7, 20] as well as our own [21-28]. Part of the mentioned research has already been completed by the author of this work. Current research is based on studies of double-sided ironing, begun by [29]. The main goal was to assess to what extent it is possible to achieve the planned (projected) continuous change of the strip thickness, based on the variable lateral force, in combination with other influencing factors. If it turns out to be possible, the process can be applied to obtain different profiles of working parts in one tool with the use of one lubricant, which would significantly speed up the process and increase its reliability. Based on our research of available literature in this field, we could not find a similar model to the one proposed in this manuscript. Additionally, the mathematical formulations of variable lateral forces and their method of assignment are fundamentally the same as in studies [21, 22]. The difference between the current and previous research is that in the mentioned studies, the contact elements had flat surfaces and there was no thinning of the sheet metal, whereas here, the contact elements are angled and induce a change in the sheet metal thickness according to predefined changes in the lateral forces.

The coefficient of friction, as an important output parameter, was determined based on the previously adopted model [26], according to expression (1), and the model in [29]. The actual contact pressure (2) was calculated in the same way:

$$\mu = \frac{F}{0.17101 \cdot F + 1.357785 \cdot F_S + 0.6 \cdot F_S}, \tag{1}$$

$$p = \frac{0.03015 \cdot F + 0.34202 \cdot F_S}{b \cdot (s_0 - s_1) + 0.0302302}, \tag{2}$$

where μ is the coefficient of friction, F is the traction force, F_S is the lateral force, b is the sheet sample width, and s_0 and s_1 are the initial and final thickness of the sheet sample, respectively.

The model was developed on the basis of several studies, the flat-die deep drawing test by variable contact pressure in [21, 22], and the strip reduction test in [28, 29]. In our earlier research [21-27], the model of the strip reduction test was applied, and the values of the lateral forces are constant and mostly applied over the entire sliding length or in three phases (sliding divided into three lengths by applying three different constant lateral force values), (Fig. 1). In the authors' research [21, 22], a sliding sheet metal model between flat contact surfaces (the flat die test) with variable pre-defined pressure forces was applied. The research in this paper is entirely original and relates to controlling the variable lateral force by applying contact elements that thin the sheet metal (Fig. 2). It is important to compare the change in the sheet metal thickness with the change in the lateral force over the duration of the process.

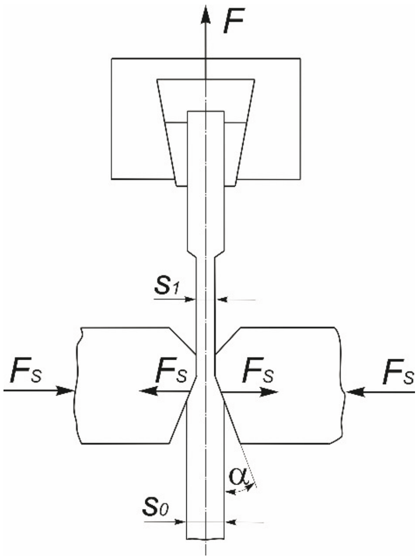

Fig. 1 Contact zones during ironing with a constant lateral force [28, 29]

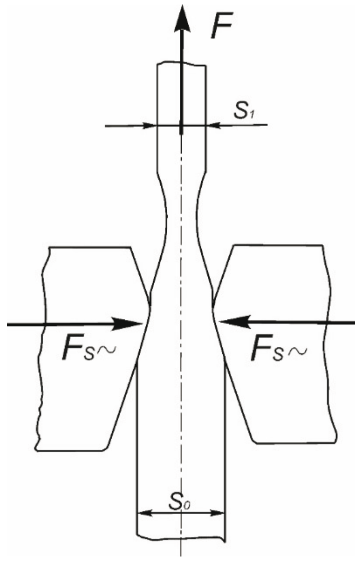

Fig. 2 Contact zones during ironing with a variable lateral force

3. Experimental investigation

The deep drawing process with thinning is accompanied by intense friction with tool wear and potential negative impacts on the quality of the workpiece surface and dimensional accuracy. Therefore, it is of great importance to understand the influence of the state of the surfaces in contact, the tool material type, the workpiece material type, the applied lubricant and the contact pressure on the friction coefficient, as the most important parameter in contact. To vary the contact conditions, two types of materials were used: steel sheet DC04 with a surface roughness of Ra = 1.018 μm, and a brass sheet CuZn37 with a surface roughness of Ra = 0.239 μm. Sheet metal strips are cut longitudinally with respect to the rolling direction. The dimensions of the strips of both materials were approximately the following: length 300 mm, width 20 mm, and thickness 3 mm. The chemical compositions of the mentioned two materials are given in Tables 1 and 2, respectively, and the mechanical properties are given in Tables 3 and 4 [24].

Table 1 Chemical composition of the steel DC04 sheets

	Alloying elements content, %					Microstructure
	C	Si	Mn	P	S	
Prescribed	≤ 0.10	≤ 0.20	0.20-0.45	max 0.030	max 0.035	ferritic
Analysed	0.06	in traces	0.28	0.014	0.021	

Table 2 Chemical composition of the brass CuZn37 sheets

Alloying elements content, %					
Cu	Pb	Fe	Ni	Al	Sn
63.60	0.0032	0.014	0.01	0.0003	0.0083

Table 3 Mechanical properties of the steel DC04 sheets

Yield strength Re, MPa (max.)	Tensile strength Rm, MPa	Elongation at fracture A_{80}, % (min.)	Anisotropy r_{90}, - (min.)	Strain hardening exponent n_{90}, - (min.)
210	270-350	38	1.6	0.18

Table 4 Mechanical properties of the brass CuZn37 sheets

Tensile strength Rm, MPa	Yield strength Re, MPa (max.)	Elongation at fracture A_{50}, % (min.)
300-370	180	38

Two types of lubricants were used: oil for deep drawing and lubricating grease based on MoS_2. The characteristics of the two applied lubricants are given in Tables 5 and 6, respectively [30].

Table 5 Properties of the deep drawing oil [30]

	Unit	Deep drawing oil	Method
Concentrate appearance	-	Clear oil	Visual
Density at 20 °C	g/cm^3	0.950	ISO 3675
Kinematic viscosity at 40 °C	mm^2/s	170	ISO 3104
Corrosion on copper (100 °C/3h)	degree	1a	ISO 2160
Degreasing ability	-	Very good	FIAT ST 50505

Table 6 Properties of the lubricating grease based on MoS_2 [30]

	Unit	Lubricating grease based on MoS_2	Method
Concentrate appearance	-	Consistent lubricant	Visual
The lowest dripping temperature	ºC	195	ISO 2176
Kinematic viscosity at 100 °C	mm^2/s	11	ISO 3104
Corrosion on copper (100 °C/3h)	degree	1a	ISO 2160
Corrosion on steel	-	bez	ISO 7120

The sliding speed was 20 mm/min in all cases. The material samples in the first part of the experiment were 2.5 mm thick, 20 mm wide and 200 mm long strips, made of mild steel DC04. The lateral forces were 5, 10 and 15 kN. The applied lubricants was mineral oil (kinematic viscosity 170 mm^2/s at 40 °C, density 0.950 g/cm^3 at 20 °C), produced by FAM Kruševac, Serbia [27]. In the second part of the experiment, all the parameters were the same, except for the strip thickness of 3 mm. The contact elements were made of tool steel X210Cr12, ground to a roughness of Ra = 0.107 µm and hardness of 60 HRC (Figs 3 and 4). The high hardness of these types of materials is achieved by the formation of an area of complex carbides which ensure the secure and good tribological performance of the tool [31].

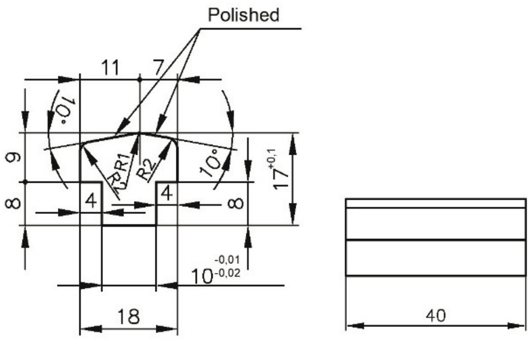

Fig. 3 Drawing of the contact element

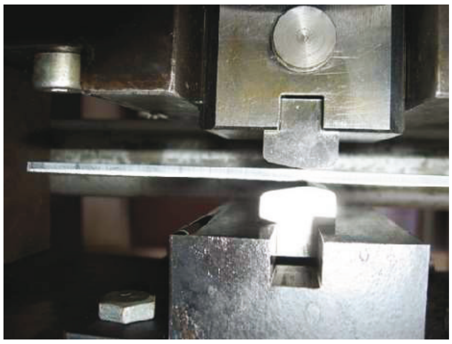

Fig. 4 Real tool assembly

The realised device (Fig. 5) is an original solution and was created to provide all the requirements that are foreseen in the research plan. The basic structure of the device consists of a mechanical-hydraulic, hydraulic and electro-control module. It is important to note that this device has a certain universality. In addition to the sheet metal strip pulling model with a change in thickness (thinning), it is possible to use it successfully for testing on other physical-tribological models (e.g. a model with a tension rib, a model of sliding between flat contact surfaces [26]), with corresponding necessary changes in the mechanical part of the device, i.e. on the tool itself. With this aim, the device was made with two hydraulic cylinders within the mechanical-hydraulic module, and the entire control system is adjusted accordingly.

The principle of operation of the experimental equipment used in this work, as well as the method of assigning the previously defined dependencies of the lateral forces, are explained in detail in [25, 26].

Fig. 5 Experimental equipment [26]

3.1 Results for the lateral force dependence type P3

The previously defined dependences of the lateral force F_s on the gait are of a parabolic type with an increasing-decreasing trend (P3) and a decreasing-increasing trend (P4) [26, 29].

Figures 6 to 9 show the functional dependences of lateral force, drawing force, contact pressure and friction coefficient on the sliding stroke of the sample (≈ 60 mm). Samples from steel sheet DC04 in combination with oil for deep drawing, and samples from brass sheet CuZn37 in combination with lubricating grease based on MoS_2 were applied. The actual change in lateral force (Fig. 6) fully follows the theoretically determined nonlinear continuous function of an increasing-decreasing character, here designated as P3. The drawing force curve (Fig. 6) in a certain sense follows the curve from Fig. 6, where the values for the brass sheet (Fig. 6 left) are noticeably higher. The friction coefficient and contact pressure are determined according to expressions (1) and (2). The contact pressure changes curves (Fig. 7 left and right) follow the trend of the curves in Fig. 6.

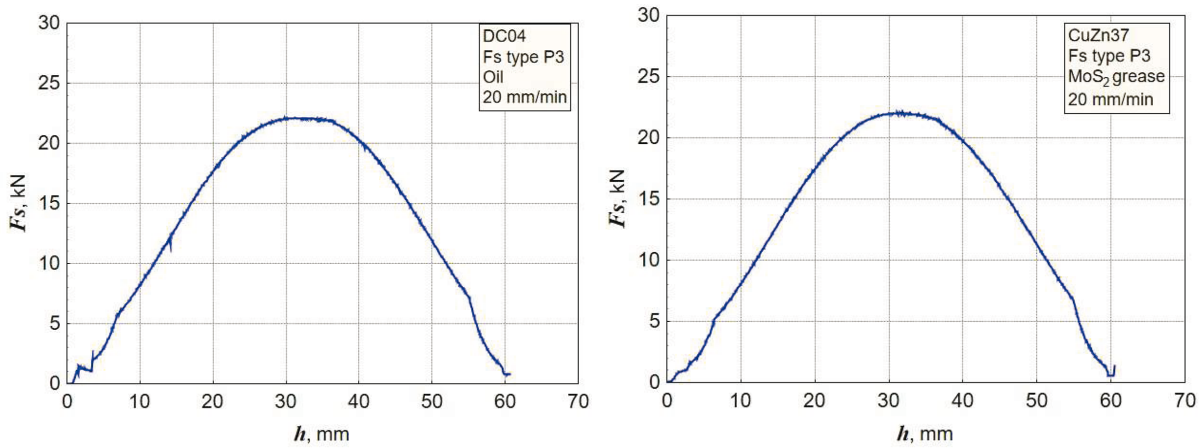

Fig. 6 Dependence of the lateral force on the stroke for conditions: steel sheet-oil (left), brass sheet-grease based on MoS_2 (right) and for F_s type P3

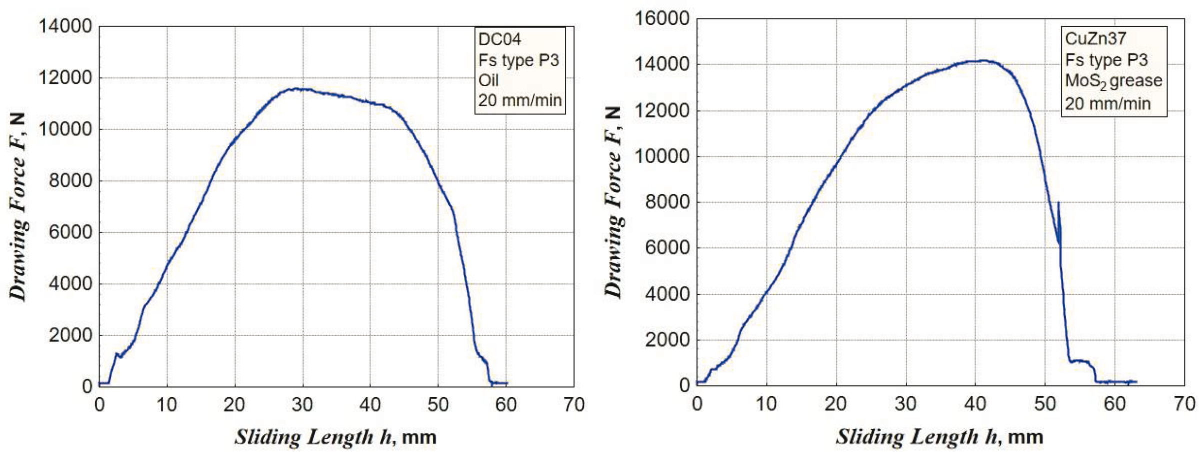

Fig. 7 Dependence of drawing force on the stroke for conditions: steel sheet-oil (left), brass sheet-grease based on MoS_2 (right) and for F_s type P3

The curves of the friction coefficient (Fig. 9) in the initial and final phases of the stroke (left and right of the dotted vertical line) give unrealistic values that are not shown. The probable reason is a certain instability of the thinning process at the beginning and end, as well as the property of expression (1) that results in a sudden increase in the coefficient of friction with a sudden decrease in the intensity of the lateral force, which already starts after a stroke length of 43 mm. In the stationary part of the stroke, the values are completely correct. It can be noticed that the coefficient of friction for the brass sheet and MoS_2-based lubricant increases sharply already from 30 mm of the stroke (Fig. 9 right) compared to the steel sheet and oil (Fig. 9 left). A similar observation can be made in the drawing force diagram (Fig. 7 right), which is reflected in the increase in force intensity and can be attributed to slightly worse tribological conditions in the contact between the brass and MoS_2-based lubricant.

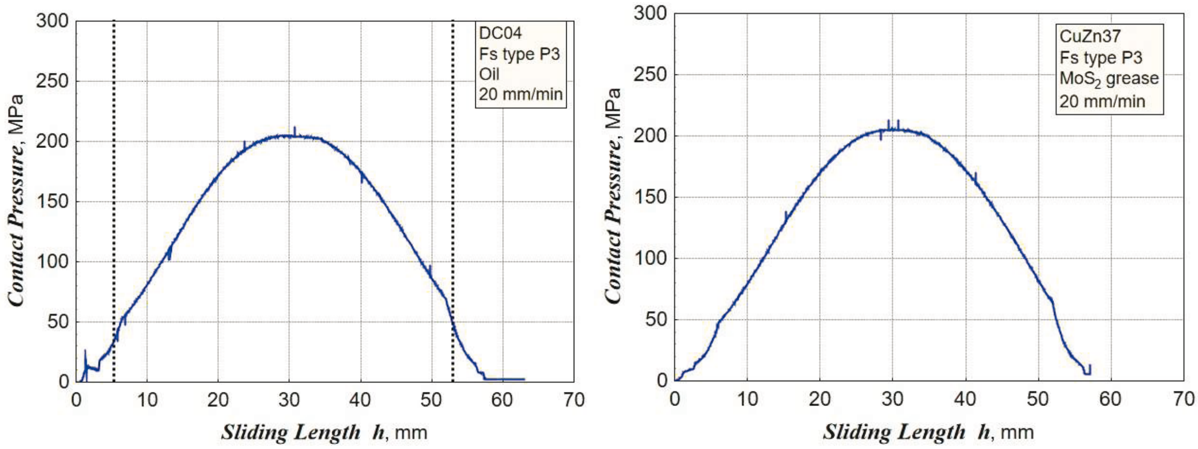

Fig. 8 Dependence of the contact pressure on the stroke for conditions: steel sheet-oil (left), brass sheet-grease based on MoS_2 (right) and for F_s type P3

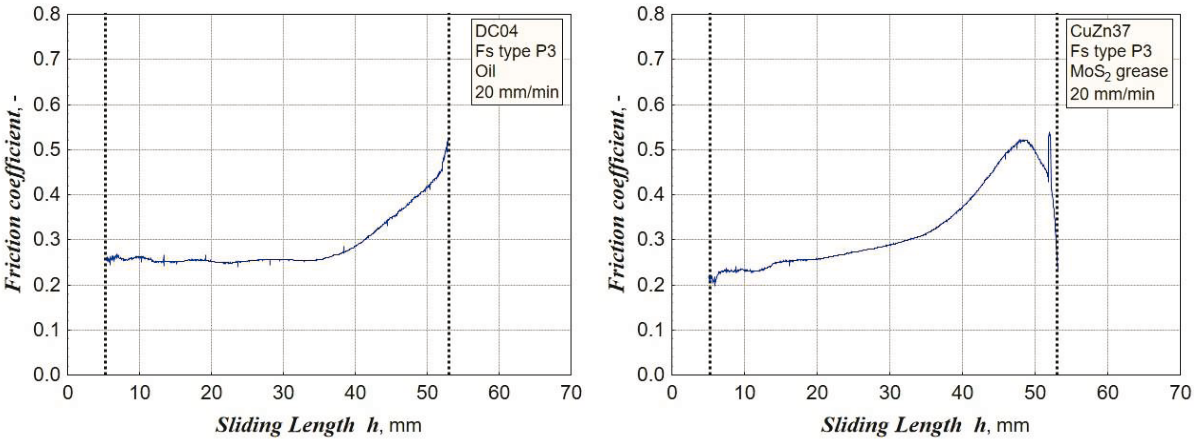

Fig. 9 Dependence of the friction coefficient on the stroke for conditions: steel sheet-oil (left), brass sheet-grease based on MoS_2 (right) and for F_s type P3

Figure 10 shows the thickness distributions of the sample during the sliding process with the given variable function of the lateral force P3 for both materials and both types of lubricants. The thinning of the sample was the greatest in the central part of the stroke, where the lateral force has the highest values (Fig. 6). In this way, the main goal of the entire experiment, managing the change in the thickness of the piece, was accomplished.

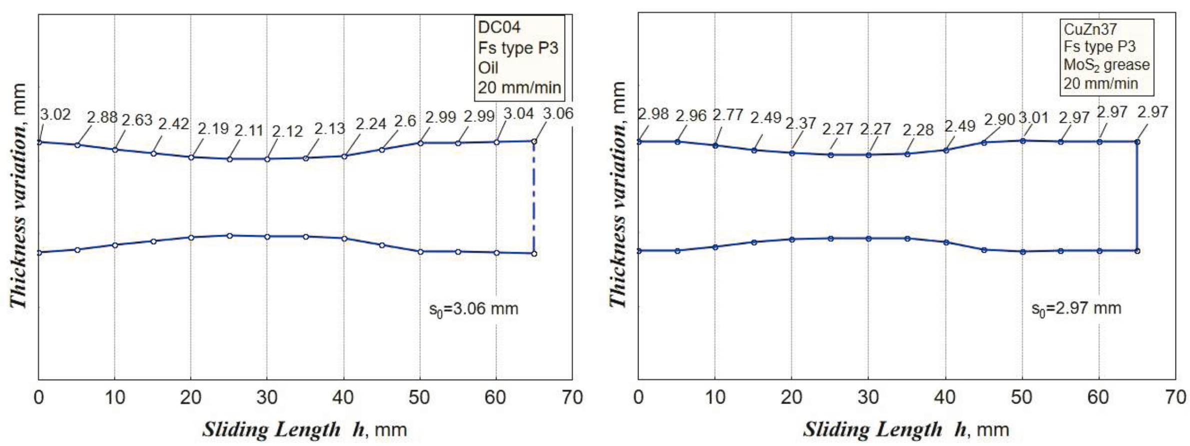

Fig. 10 Variation of the sample's thickness along the stroke for conditions: steel sheet-oil (left), brass sheet-grease based on MoS_2 (right) and for F_s type P3

3.2 Results for the lateral force dependence type P4

Figures 11 to 14 present the diagrams of dependences of the lateral force, drawing force, contact pressure and friction coefficient on the stroke, respectively, for the conditions: steel sheet-oil and brass sheet-grease based on MoS_2. The drawing force and friction coefficient curves are dominated by the decreasing-increasing character of the change in the P4 type lateral force.

The change in the coefficient of friction determined by formula (1) is caused, first of all, by the character of the changes in the lateral and drawing force, as well as by the distinct jumps and drops in intensity. At a part of the stroke approximately between 20 and 40 mm, in both cases, both lateral and drawing forces (Fig. 11 and 12, respectively) have extremely low values (almost extreme intensity), so expression (1) again gives unrealistically high values of the friction coefficient. In addition, the small oscillatory changes of the lateral force are expressed in the diagram in Figure 14 left, which shows the sensitivity of expression (1). Therefore, the values and appearance in Figure 14 left should be considered indicative. The combination of the P4 change of the lateral force and combination CuZn37 – grease based on MoS_2 gives significantly lower values of the drawing force in the central part of the stroke (Fig. 12 right), and thus the low values of the friction coefficient (Fig. 14 right), which emphasises the importance to the tribological conditions in contact.

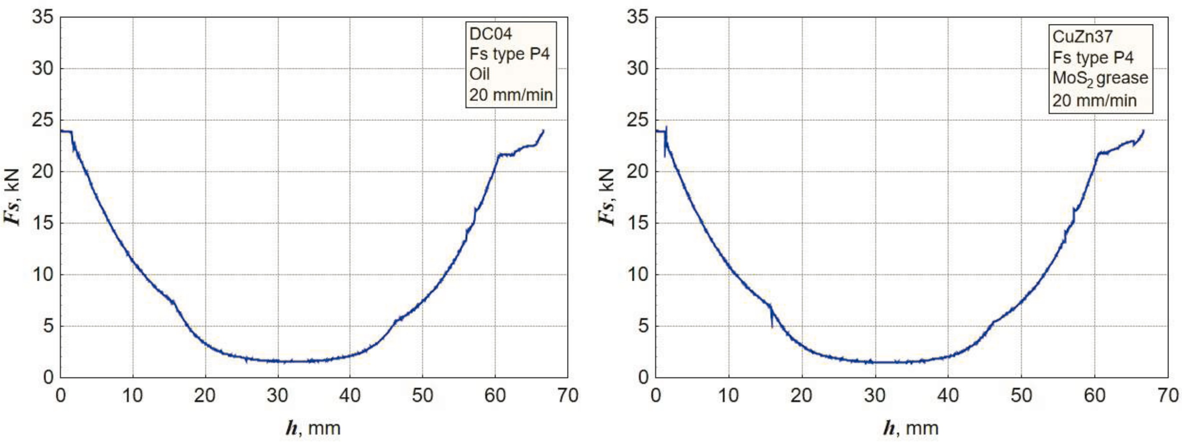

Fig. 11 Dependence of the lateral force on the stroke for conditions: steel sheet-oil (left), brass sheet-grease based on MoS_2 (right) and for F_s type P4

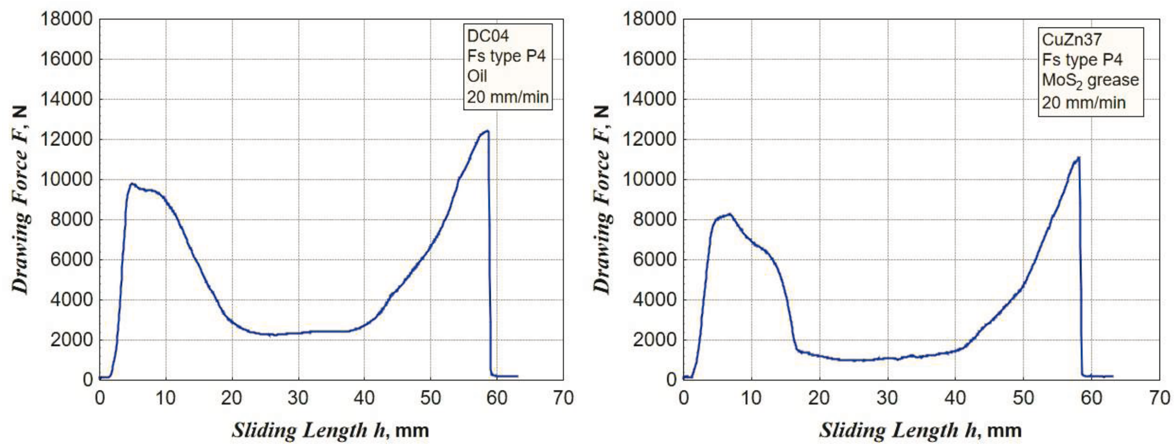

Fig. 12 Dependence of the drawing force on the stroke for conditions: steel sheet-oil (left), brass sheet-grease based on MoS_2 (right) and for F_s type P4

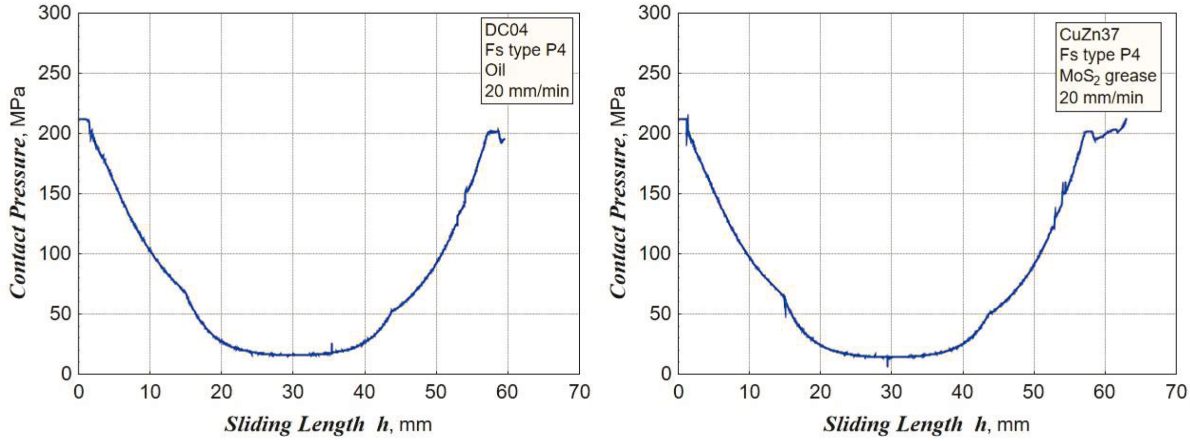

Fig. 13 Dependence of the contact pressure on the stroke for conditions: steel sheet-oil (left), brass sheet-grease based on MoS_2 (right) and for F_s type P4

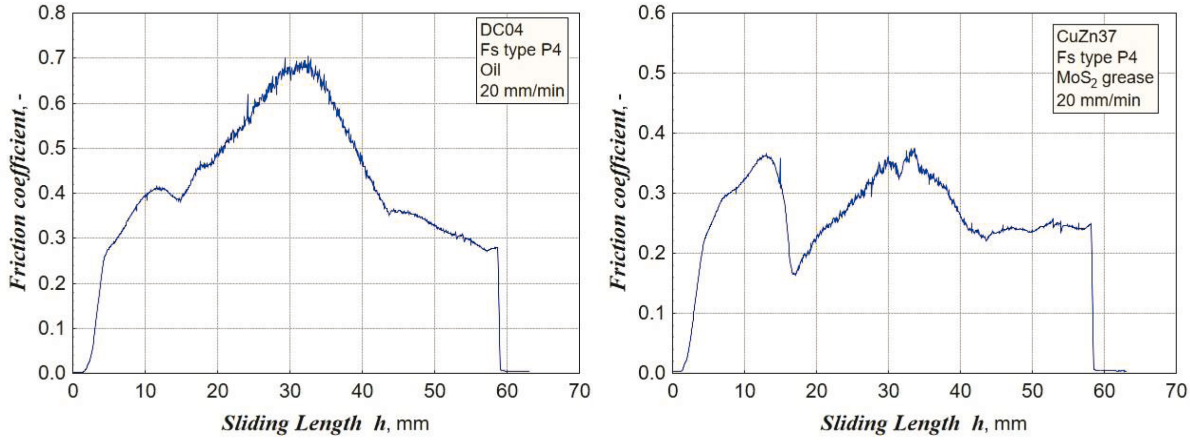

Fig. 14 Dependence of the friction coefficient on the stroke for conditions: steel sheet-oil (left), brass sheet-grease based on MoS_2 (right) and for F_s type P4

Figure 15 shows the thickness distribution of the sample using the functional change type P4 of the lateral force. The change in thickness – thinning is the largest at the 50 mm stroke, where the values of the contact pressure, lateral and drawing forces record a sudden increase.

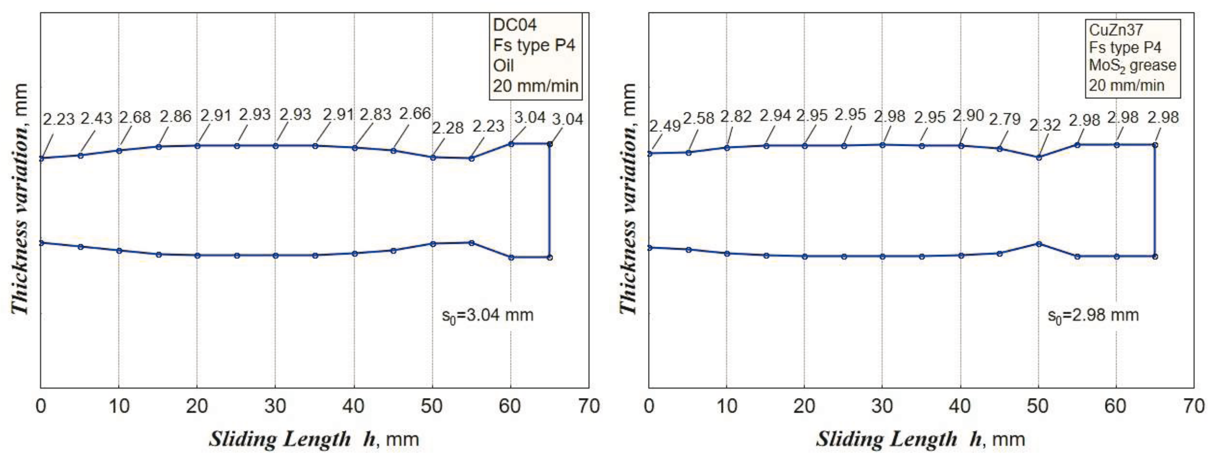

Fig. 15 Variation of the sample's thickness along the stroke for conditions: steel sheet-oil (left), brass sheet-grease based on MoS_2 (right) and for F_s type P4

4. Conclusions

Based on the conducted experiments and obtained results, several conclusions can be drawn:

- For the purposes of experimental research, an original tribological model of the deep drawing procedure with thinning was developed, which was achieved through the appropriate control apparatus. The device has the possibility of the continuous, simultaneous assignment of variable values of the lateral force (F_s) and measurement of the deformation force (traction force F), real pressure in contact, and the realised real values of the lateral force;
- Based on the obtained diagrams of the actual contact pressure (Figs 8 and 15), it can be concluded that the apparatus achieves the set changes P3 and P4 very well, which can be seen based on the expected trend of the given diagrams;
- The character of the specified functional changes (P3, P4) of the lateral force F_s (Figs 9 and 14), as well as the tribological conditions in contact, exerts a key influence on the friction coefficient value. It was shown that the combination of change P3 and steel sheet with oil lubrication (Fig. 9 left) is more favourable than change P4 and the same conditions (Fig. 14 left). On the other hand, the combination of the change in lateral force P4 in the case of the brass sheet when lubricated with grease based on MoS_2 (Fig. 14 right) is more favourable compared to the change in P3 and the mentioned conditions (Fig. 9 right). These findings are analogous to the drawing force diagrams (Figs 7 and 12);
- With both lateral force changes P3 and P4, there is a limitation when calculating the friction coefficient for the case when the lateral force has the lowest values at P3 (Fig. 9, the first 6 mm of the stroke and from 53 mm of the stroke) and P4 (Fig. 14 left, at approximately 18 to 40 mm of the stroke), which results in unrealistic values of the coefficient of friction for this procedure. The values of the friction coefficient for the conditions P4-CuZn37-MoS_2 (Fig. 14 right) can be considered acceptable along the entire stroke;
- The diagrams in Figures 10 and 15 show that the distribution of the thickness of the samples is in accordance with the character of the given changes P3 and P4. The thinning is the greatest in the part of the stroke where the highest values of the lateral force are present, or where a trend of increasing lateral force is observed. In this sense, it is possible to manage the change in thickness with a variable lateral force;
- By applying the more suitable tribological conditions (the surface of contact elements of the tool with less roughness, e.g., a polished surface) and aluminium sheet samples, an attempt could be made to reduce the unrealistically high values of the coefficient of friction in the critical part of the stroke. At the same time, the deformation force (drawing force) would be less intensive along the stroke. A wider range of functional changes of the lateral force F_s can be specified, in addition to the shown changes of types P3 and P4, which would give a broader picture of this phenomenon.

REFERENCES

[1] Schlosser, D. Influence of friction during the strip drawing of austenitic sheet metal: different lubricants and tools made of sintered hard materials, *Bänder, Bleche, Rohre*, No. 7/8, pp. 302-306, 1975. (In German).

[2] Deneuville, P.; Lecot, R. The study of friction in ironing process by physical and numerical modelling. *Journal of Materials Processing Technology* 1994, 45(1-4), 625-630. https://doi.org/10.1016/0924-0136(94)90409-X

[3] Gao, H; Fan, Q.; Chu, Z. Simulation research on the forming process of large axles rolled by cross-wedge rolling. *Transactions of FAMENA* 2022, 46(3), 63-80. https://doi.org/10.21278/TOF.463043422

[4] Andreasen, J.L.; Bay, N.; Andersen, M.; Christensen, E.; Bjerrum, N. Screening the performance of lubricants for the ironing of stainless steel with a strip reduction test. *Wear* 1997, 207(1-2), 1-5. https://doi.org/10.1016/S0043-1648(96)07462-5

[5] Havaej, P.; Degroote, J.; Fauconnier, D. Sensitivity of TEHL Simulations to the use of different models for the constitutive behaviour of lubricants. *Lubricants* 2023, 11(3), 151. https://doi.org/10.3390/lubricants11030151

[6] Sulaiman, M.H.; Christiansen, P.; Bay, N. The influence of tool texture on friction and lubrication in strip reduction testing. *Lubricants* 2017, 5(1), 3. https://doi.org/10.3390/lubricants5010003

[7] Van der Aa H.C.E.; Van der Aa M.A.H.; Schreurs P.J.G.; Baaijens F.P.T.; Van Veenen W.J. An experimental and numerical study of the wall ironing process of polymer coated sheet metal. *Mechanics of Materials* 2000, 32(7), 423-443. https://doi.org/10.1016/S0167-6636(00)00013-2

[8] Trzepiecinski, T.; Szewczyk, M.; Szwajka, K. The use of non-edible green oils to lubricate DC04 steel sheets in sheet metal forming process. *Lubricants* 2022, 10(9), 210. https://doi.org/10.3390/lubricants10090210

[9] Sagisaka, Y.; Ishibashi, I.; Nakamura, T.; Sekizawa, M.; Sumioka, Y.; Kawano, M.; Evaluation of environmentally friendly lubricants for cold forging. *Journal of Materials Processing Technology* 2012, 212(9), 1869-1874. https://doi.org/10.1016/j.jmatprotec.2012.04.011

[10] Bay, N.; Azushima, A.; Groche, P.; Ishibashi, I.; Merklein, M.; Morishita, M.; Nakamura, T.; Schmid, S.; Yoshida, M. Environmentally benign tribo-systems for metal forming. *CIRP Annals - Manufacturing Technology* 2010, 59(2), 760-780, 2010. https://doi.org/10.1016/j.cirp.2010.05.007

[11] Ustunyagiz, E.; Nielsen, C.; Christiansen, P.; Martins, P.; Bay, N. Continuous strip reduction test simulating tribological conditions in ironing. *Procedia Engineering* 2017, 207, 2286-2291. https://doi.org/10.1016/j.proeng.2017.10.996

[12] Trzepiecinski, T.; Szwajka, K.; Szewczyk, M. Pressure-assisted lubrication of DC01 steel sheets to reduce friction in sheet-metal-forming processes. *Lubricants* 2023, 11(4), 169. https://doi.org/10.3390/lubricants11040169

[13] Moghadam, M.; Christiansen, P.; Bay N. Detection of the onset of galling in strip reduction testing using acoustic emission. *Procedia Engineering* 2017, 183, 59-64. https://doi.org/10.1016/j.proeng.2017.04.011

[14] Üstünyagiz, E; Nielsen, C.V.; Christiansen, P.; Martins, P.A.F.; Altan, T.; Bay, N. A combined numerical and experimental approach for determining the contact temperature in an industrial ironing operation. *Journal of Materials Processing Technology* 2019, 264, 249-258. https://doi.org/10.1016/j.jmatprotec.2018.09.015

[15] Nayak, K.C.; Prashan, P.D. Manufacturing of light automobile engine piston head using sheet metal, *Procedia Manufacturing* 2018, 15, 940-948, 2018. https://doi.org/10.1016/j.promfg.2018.07.402

[16] Ozawa, T.; Kuboki, T.; Kajikawa, S.; Yamauchi, A.; Gunji, A.; Onishi, K. Fabrication of ring groove on inner surface of cylindrical blank by ironing from outer surface. *Procedia Manufacturing* 2018, 15, 899-906. https://doi.org/10.1016/j.promfg.2018.07.407

[17] Sulaiman, M.H.; Farahana, R.N.; Bienk, K.; Nielsen, C.V.; Bay, N. Effects of DLC/TiAlN-coated die on friction and wear in sheet-metal forming under dry and oil-lubricated conditions: Experimental and numerical studies. *Wear* 2019, 438-439, 203040. https://doi.org/10.1016/j.wear.2019.203040

[18] Meng, B.; Fu, M.W.; Shi, S.Q. Deformation characteristic and geometrical size effect in continuous manufacturing of cylindrical and variable-thickness flanged microparts. *Journal of Materials Processing Technology* 2018, 252, 546-558. https://doi.org/10.1016/j.jmatprotec.2017.10.022

[19] Zhang, Z.; Xue, Q.; Wen, L; Peng, W.; Shao, H; Fu, W. Study on multi-step paths for double curved parts of 1561 aluminium alloy. *Transactions of FAMENA* 2023, 47(2), 31-44. https://doi.org/10.21278/TOF.472051222

[20] Ilić, J.; Grbić, T.; Hadžistević, M.; Milutinović, M.; Kraišnik, M.; Movrin, D. Deep drawing with unconventional tooling: impact of process parameters on a part accuracy. *Advanced Technology and Materials* 2023, 48(1), 27-31. doi:10.24867/ATM-2023-1-005

[21] Djordjević, M.; Aleksandrović, S.; Djačić, S.; Sedmak, A.; Lazić, V.; Arsić, D.; Mutavdžić, M., Simulation of flat die deep drawing process by variable contact pressure sliding model. *Tehnički vjesnik-Technical Gazette* 2019, 26(5), 1199-1204. https://doi.org/10.17559/TV-20161215205553

[22] Djordjević, M.T.; Aleksandrović, S.; Arsić, D.; Nikolić, R.R.; Szmidla, J.; Todić, A.; Čukanović, D.; Ulewicz R. Influence of TiN coating on the drawing force and friction coefficient in the deep drawing process of AlMg4.5Mn0.7 thin sheets. *Materials* 2023, 16(11), 3968. https://doi.org/10.3390/ma16113968

[23] Aleksandrović, S.; Đorđević, M.; Stefanović, M.; Lazić, V.; Adamović, D.; Arsić, D. Different ways of friction coefficient determination in strip ironing test. *Tribology in industry* 2014, 36(3), 293-299.

[24] Djacic, S. Metal forming with double sided ironing, Master thesis, Faculty of Engineering, University of Kragujevac, 2016. (In Serbian)

[25] Djordjević, M.; Aleksandrović, S.; Arsić, D.; Lazic, V. Experimental-numerical analysis of contact conditions influence on the ironing strip drawing process. *Industrial lubrication and tribology* 2017, 69(4), 464-470. doi 10.1108/ILT-05-2016-0113

[26] Aleksandrović, S.; Đačić, S.; Stefanović, M.; Đorđević, M.; Lazic, V.; Arsić D. Influence of process parameters on the friction coefficient in one and multi-phase steel strip drawing ironing test, *ACTA TECHNICA CORVINIENSIS – Bulletin of Engineering* 2018, XI(2), 29-33.

[27] Djordjevic, M.; Aleksandrovic, S.; Lazic, V.; Arsic, D.; Stefanovic, M.; Milosavljevic, D. Two-phase ironing process in conditions of ecologic and classic lubricants application, in Proceedings of the International conference on Tribology SERBIATRIB 2015, 13-15 May, Belgrade, Serbia, pp. 407-413.

[28] Đorđević, M.; Arsić, D.; Aleksandrović, S.; Lazić, V.; Milosavljević, D.; Nikolić, R. Comparative study of an environmentally friendly single-bath lubricant and conventional lubricants in a strip ironing test. *Journal of Balkan Tribological Association* 2016, 22(1A-II), 947-958.

[29] Aleksandrović, S.; Đačić S.; Đorđević M.; Ratković N.; Arsić D.; Lazić V. New method of defining of process parameters in double side thinning strip ironing test. *Tribology in industry* 2020, 42(1), 59-69. https:// doi.org/10.24874/ti.2020.42.01.06

[30] https://fam.co.rs/cat/363/sredstva-za-hladjenje-i-podmazivanje-u-obradi-metala/obrada-metala-deformacijom.html. Accessed: November 6th 2023, 10 a.m.

[31] Todić, A.; Djordjević, M.; Arsić, D.; Džunić, D.; Lazić, V.; Aleksandrović, S.; Krstić, B. Influence of vanadium content on the tribological behaviour of X140CrMo12-1 air-hardening steel. *Transactions of FAMENA* 2022, 46(2), 15-22. Doi https://doi.org/10.21278/TOF.462035021

Submitted: 14.12.2023

Accepted: 14.4.2024

Slaviša Djačić
Dušan Arsić*
Srbislav Aleksandrović
Marko Delić
Djordje Ivković
Vukić Lazić
Faculty of Engineering, University of Kragujevac, Kragujevac, Serbia

Milan T. Djordjević
Faculty of Technical Sciences, University of Priština, Kosovska Mitrovica

*Corresponding author: dusan.arsic@fink.rs