Experimental-numerical analysis of contact conditions influence on the ironing strip drawing process

Milan Djordjević, Vesna Mandić, Srbislav Aleksandrović, Vukić Lazić and Dušan Arsić
Faculty of Engineering, University of Kragujevac, Kragujevac, Serbia
Ružica R. Nikolić
Research Center, University of Zilina, Zilina, Slovakia, and
Zvonko Gulišija
Institute for Technology of Nuclear and other Mineral Raw Materials (ITNMS), Belgrade, Serbia

Abstract

Purpose – The purpose of this paper is comparison of experimental values of the drawing forces to numerical values in different contact conditions, taking into account the appearance of galling which occurs due to of difficult drawing process conditions.

Design/methodology/approach – The following two research approaches are used in this paper – the physical modeling, realized by the laboratory experiment, and the numerical simulation of the ironing drawing process. By analyzing the obtained results, the technique of physical modeling, with help of the laboratory equipment and numerical simulation by application of the finite element method, can be successfully used in studying the thin sheet ironing – strip drawing process.

Findings – It is significant to compare values of the deformation forces obtained by physical experiment to values obtained by the numerical simulation. In that way, it is possible to compare applied contact conditions (four lubricants in that case) and estimate matching of experimentally and numerically obtained results of the deformation forces. Presented results point out very good technological characteristics of ecologically friendly lubricant (single-bath) and grease based on MoS2. Significant decrease of the deformation force was achieved by its application, as well as maintaining of the lubricant's layer during the forming process and almost complete elimination of galling on the contact.

Practical implications – Numerical analysis of stresses in the working piece wall, during the thin sheet strip drawing, requires precise values of the friction coefficient. It is an important indicator because one can define the contact conditions as the input data for the numerical simulation, based on its values for each type of lubricants and each value of the compressive lateral force.

Originality/value – The environmentally friendly lubricant tested exhibits a more favorable distribution of the drawing force during the process, mainly in experimental case. Grease based on MoS2 has good lubricating properties but that lubricant is conventional and environmentally unacceptable. Ecologically friendly lubricant can be successfully used in real ironing strip drawing process especially for high values of holding force achieving an increased tool life.

Keywords Friction, Lubrication, Finite element analysis, Drawing force, Strip drawing

Paper type Research paper

1. Introduction

Simultaneous modeling of a product and virtual manufacturing, i.e. simulation of the production processes, is applied in early design phases of both the new products and tools for their manufacturing (Adamović *et al.*, 2013). Significant financial savings are realized, and delays in products placing on the market are avoided by application of the physical and numerical modeling (Singh *et al.*, 2014).

Software, based on the finite element method (FEM), is used widely for optimization of the process parameters, eliminating the flaws during the material flowing, determination and minimizing the stresses in the tool, etc. (Neto *et al.*, 2014). Material's behavior during the forming process can be completely predicted by application of the corresponding software in the stress–strain analysis (Jao and Cao, 2001; Morovvati *et al.*, 2010). Analysis and simulation of the real processes can be done on cold and hot by correction of tolerances between the die and the drawing tool, what directly influences the thin sheet thickness during the forming (Dhaiban *et al.*, 2014). In that way, the higher degrees of drawing can be achieved without the appearance of destruction. Similarly, simulation results should lead to

The current issue and full text archive of this journal is available on Emerald Insight at: **www.emeraldinsight.com/0036-8792.htm**

Industrial Lubrication and Tribology
69/4 (2017) 464–470

[ISSN 0036-8792]
[DOI 10.1108/ILT-05-2016-0113]

The work reported in this paper was partially financially supported by the Serbian Ministry of Education, Science and Technological development, through contracts ON174004, TR32036, TR34002, TR35024 and by European regional development fund and Slovak state budget by the project "Research Centre of the University of Žilina" – ITMS 26220220183.

Received 16 May 2016
Accepted 12 September 2016

optimization of the process, so that the fast and efficient reaction to market needs would be achieved. Thus, for instance, authors of paper (Vrh *et al.*, 2014) have shown that conceiving and designing of products can be done in the virtual CA-x environment, without large investments and longtime consumption. After several iterations, by analysis of all the parameters, varying the geometry of the product and the tool, one reaches the optimal procedure, which then can be optimized further. Authors in paper (Delarbre and Montmitonnet, 1999) have studied the ironing of austenitic stainless steel cups by the real experiment and FEM analysis. Aim of paper was to quantify the discrepancy (due to tool deformation) between nominal die-punch gap and real final wall thickness. As a result, the states of stress in the cup's wall, during and after the drawing, obtained by the FEM, were compared to results obtained by the analytical model. Because in processes of this kind the friction has the strong influence, the procedure for determination of the friction coefficient between the tool and the thin sheet during the strip drawing process is presented in detail in paper Aleksandrović *et al.* (2014), whereas the experimental results of tribological investigations of specified materials' properties at sliding tests is presented in papers Aleksandrović *et al.* (2009), Chowdhurya and Nuruzzamanb (2013) and Peña-Parás *et al.* (2016). Since the objective is to achieve lower resistance, and by that also lower deformation forces in the ironing process, authors in papers Bachchhav *et al.* (2014) and Djordjević *et al.* (2013) have shown an analysis of lubricants that are used in the multi-phase ironing process. It was concluded that the new group of ecological lubricants possesses somewhat better lubricating properties with respect to conventional lubricants (the zinc-phosphate layer, oil for deep drawing, etc.) (Djordjević *et al.*, 2013; 2016).

This paper consists of experimental investigations report and numerical analysis of the strip drawing with change of thickness (ironing), with application of the physical and numerical modeling concepts. The experimental part, where the original physical model was developed had, as an objective, the analysis of application of various lubricants in the ironing process. The purpose of experiment was to test the influence of four types of lubricants on the forming process and to identify the optimal lubricant for the adopted physical-tribological model for the process to be brought to an end successfully, with the deforming forces as least as possible. Within the experimental part of this work, the special attention was paid to lubricants that are used in the ironing process and to modern ecological lubricants (Djordjević *et al.*, 2013). The schematic is presented of the adopted physical model, as well as the used equipment, applied lubricants and the experimental results. They are used, together with the physical model, as the input variables for the numerical analysis of the strip deep drawing (Djordjević *et al.*, 2012). The FEM simulation was done by the Simufact.forming software. Experimental values of the friction coefficient were used for definition of the contact conditions.

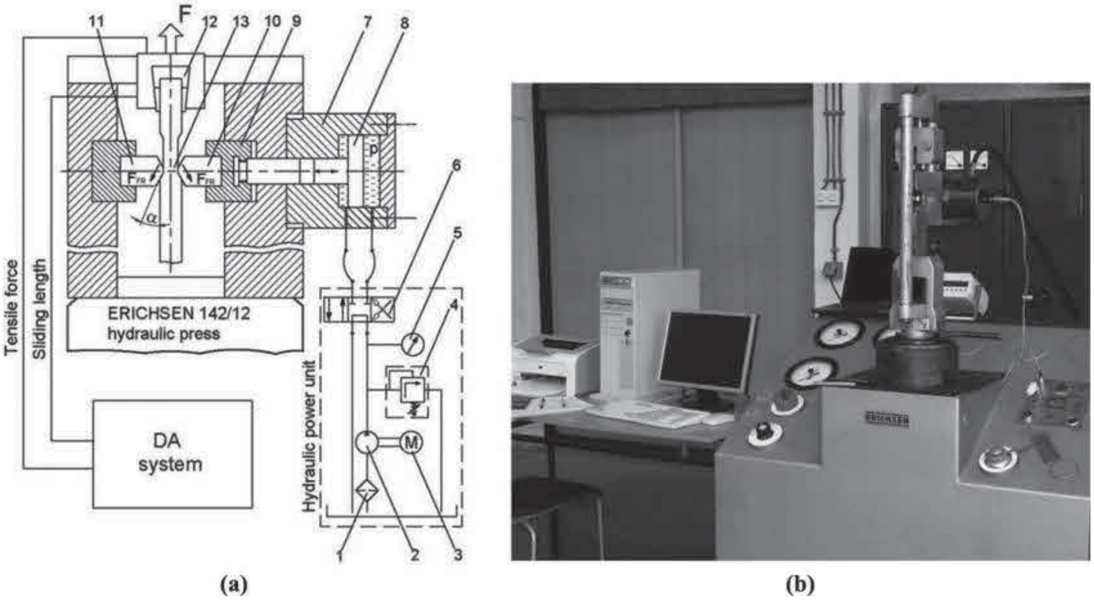
2. Experimental investigations

2.1 Description of experimental equipment, physical and numerical model

A special device that models the symmetrical contact between the sheet and the die in strip deep drawing was constructed for experimental investigations in this work, Figure 1 (Djordjević *et al.*, 2013, 2015).

The details of the device are given on the left-hand side of Figure 1, whereas its physical appearance is shown on the right-hand side. The sheet metal sample (13) is placed in the fastening jaws (12) vertically. In the initial phase, the thinning occurs such that the right-hand moving sliding element (10) acts upon the thin strip by lateral force. Due to the fixed side element (11) and the action of the sliding element (10), the even double-sided ironing of the metal strip is realized. After the initial thinning deformation was realized, the tensile force F begins to act, and the ironing process continues until the

Figure 1 (a) Scheme of the experimental device; (b) physical appearance of experimental device



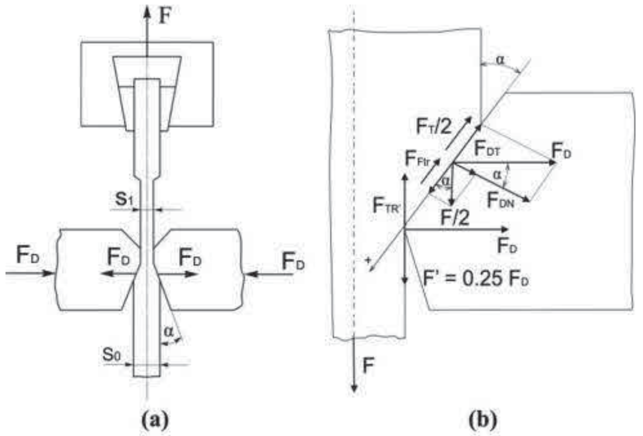
sample length is executed. The main action of the ERICHSEN 142/12 laboratory hydraulic press is used as the tensile force across the measurement range of 0-20 kN at a speed of 100 mm/min. The lateral force is realized by the hydro-cylinder (7). The measurement range of the lateral force is also 0-20 kN. The piston (8) pushes the element (9), which is coupled to the sliding element (10). The hydro-cylinder (7) is powered by the independent hydraulic aggregate, which contains the filter (1), pump (2), electric motor (3), valve for pressure and lateral force adjustment (4), manometer (5) and the two-position directional control valve (6). The data acquisition system measures the tensile force dependence on the sliding length or time and the constant intensity lateral force.

Sensors are placed within the ERICHSEN machine. The voltage signals, after amplification and filtering, are input into the A/D converter where they are converted into the files describing the tensile force dependence on the strip length using the corresponding software.

The physical model, used in this experiment, was realized based on previous research (Chowdhurya and Nuruzzamanb, 2013). The applied model enables realization of the high contact pressures [Figure 2(a)]. The idea for realization of this experimental device was to determine the friction coefficient at the contact surface between the sliding elements and the sample [Figure 2(b)]. Calculation of the friction coefficient requires analysis of the forces that are acting at the inclined contact surface, as well as at the input portion of the sliding element [Figure 2(b)]. In that sense, it was proposed to take into account forces F′ and FFR′ in the input zone based on deficiencies of the classical approach in (14). In that way, the inaccuracies of the friction coefficient values, caused by simplifications in the basic model (14), were avoided.

The model is adjusted to the real process conditions by taking into account the friction forces [F_{TR}' and $F' = 0.25 \cdot F_D$, Figure 2(b)]. Based on the scheme of the forces action [Figure 2(b)], one can compose the equilibrium equation, (Peña-Parás *et al.*, 2016):

Figure 2 Tribological model



Notes: (a) Schematics of the sliding elements and the sample contact; (b) schematics of the forces actions

$$\frac{F}{2} \cdot \cos\alpha - F_D \cdot \sin\alpha - \mu \cdot F_D \cdot \cos\alpha - \mu \cdot \frac{F}{2} \cdot \sin\alpha + 0.25 \cdot F_D \cdot \cos\alpha - F_D \cdot \sin\alpha - \mu \cdot F_D \cdot \cos\alpha = 0 \tag{1}$$

By solving equation (1) for μ, one obtains the formula for the friction coefficient:

$$\mu = \frac{F + 2 \cdot F_D \cdot (0.25 - 2 \cdot tg\alpha)}{4 \cdot F_D + F \cdot tg\alpha} \tag{2}$$

The mean values for friction coefficient for each type of lubricants and the compressive force, obtained by application of formula (2), are presented in Table I.

2.2 Material properties

For experimental investigations, in this paper, the low carbon steel sheet (EN: DC 04) was chosen. It belongs to a group of high-quality sheets aimed for ironing. The alloyed tool steel (TS) C4750 (EN: X 160 CrMoV 12 1; DIN17006: X165CrMoV12) was selected for the die and punch material. Because the tested samples were cut in the sheet rolling direction (0°), special attention was devoted to material characteristics in that direction. Specimens were prepared according to SRPS EN ISO 6892-1:2012 standard, and determined material characteristics are shown in Table II (Adamović *et al.*, 2013).

2.3 Numerical model

To be able to perform the simulation of a certain process of plastic forming, it is necessary to enter some input variables into the software for numerical simulation. Primarily, it is necessary to create the 3D model in the corresponding CAD

Table I Friction coefficient values for three values of compressive forces and four types of lubricants

Friction coefficient μ	Lubricant type	Compressive force, kN 10	 15	 20
	L1 – The zinc-phosphate coating with oil	0.154	0.168	0.177
	L2 – Ecological single-bath lubricant	0.127	0.144	0.158
	L3 – Grease based on MoS_2	0.156	0.160	0.161
	L4 – Oil for deep drawing	0.181	0.194	0.203

Table II Properties of tools' and test pieces' materials

Type of element	Materials	Mechanical properties
Tool: die	Tool steel: X 160 CrMoV 12 1	
Tool: punch plate	Tool steel: X 160 CrMoV 12 1	
Test piece	DC 04 Thickness: 2 mm Width: 18.6 mm	R_m = 283.4 MPa R_p = 186.2 MPa A_{80} = 37.3 per cent n = 0.2186; r = 1.31915

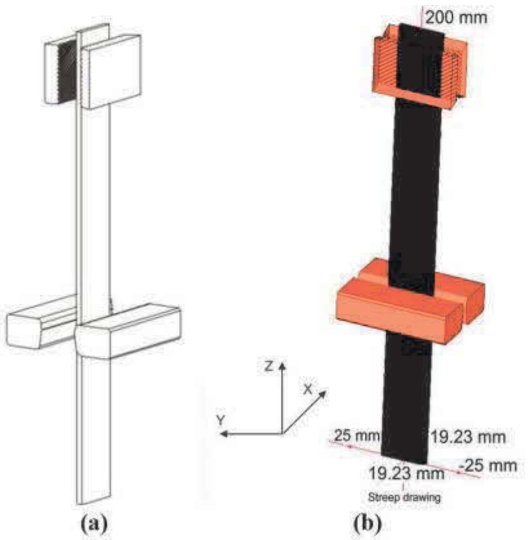
software and adjust its format to formats offered by the numerical simulation software. Besides that, one needs to define the contact conditions between the sliding elements and the thin sheet strip. The contact conditions were simulated by entering the experimental values of the friction coefficient for each type of lubricant and value of compressive force also for each sliding element (Table I). For this research case, the 3D CAD model was created in the 3D programming package CATIA V5 R18, whereas the numerical simulation was done in the specialized software for the plastic forming simulation Simufact.forming 2.1. The 3D model (Figure 3) was created based on dimensions of the real tools that are included in the process of strip drawing between the sliding elements according to the scheme shown in Figure 2. The model was realized as the assembly consisting of the sliding elements, clamping platelets and the steel thin sheet strip DC 04.

The assembly made in the CAD program [Figure 3(a)] was used as the initial 3D model for numerical simulation. The spatial planes were defined based on the sheet strip, whose symmetry axis represents the intersection of the spatial planes. The problem was defined as the plane problem – 2D in the Simufact.forming 2.1 routine. The FEM was used for the numerical analysis. The size of the mesh element was 0.25, whereas the total number of elements was 8,000. The working temperature was 20°C. In simulation, the friction coefficient was varied in accordance with appropriate values obtained from the real experiment.

3. Results and discussion

Within results of this physical-numerical experiment, the drawing forces, obtained in physical experiment were compared to forces obtained by numerical simulation. Diagrams of drawing forces, obtained by physical and numerical experiments, are presented first (Figures 4 and 5). Obtained values of the drawing forces in the strip drawing process are different for all the types of lubricants and values of the compressive forces of the sliding elements. The largest values of the drawing forces were realized for the case of lubricant L4 (oil for deep drawing, Table I) and L1 (phosphate layer with oil, Table I) [Figures 5(b) and 4(a), respectively]. Consequence of such large values are the difficult contact conditions in applications of those lubricants, especially for drawing forces values of 15 and 20 kN [Figure 5(b)]. Besides that, the appearance of galling on the tool's sliders was noticed for those experimental conditions, what is a consequence of difficult sliding between the contact surfaces. That phenomenon directly causes increase of the drawing forces, especially for lubricant L4.

Figure 3 Appearance of the numerical model



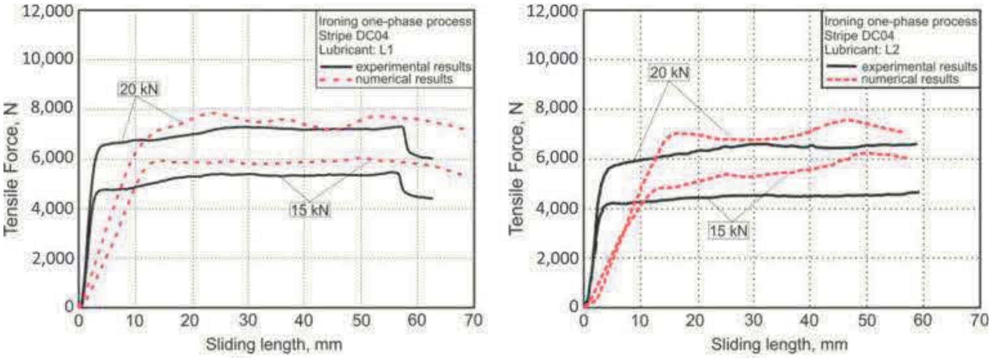
Notes: (a) After creating in the CAD program; (b) during the formation of numerical model

The lowest values of the drawing forces were obtained in the case of the single stage experiment of the ecological single-bath lubricant L2 and lubricant L3, which represent oil based on MoS_2 [Figures 4(b) and 5(a), respectively]. Comparing to values of the drawing forces for other lubricants, one can conclude that the L2 lubricant exhibits the best lubricating properties, what is especially prominent for the friction coefficient values (Table I). Considering the drawing forces diagrams for various types of lubricants, it could be assumed that the L2 lubricant has the better properties than the conventional ones.

Results of numerical analysis are in agreement with results of the physical experiment, to the great extent. This is the best illustrated for lubricant L4, where the highest values of the drawing forces were registered [Figure 5(b)]. Appearance of galling, which was registered in physical experiment (lubricant L4), is manifested in numerical results by the high values of the drawing forces, especially at compressive forces of 15 and 20 kN. With increasing compressive force, the appearance of galling is more prominent because the squeezing of lubricant out of the contact zone occurs.

The good correlation of experimental and numerical results was especially realized with both values of the compressive forces of the sliding elements of 15 and 20 kN for numerical experiments 15L1, 15L3, 15L4, 20L2, 20L3, 20L4. The average value of the drawing force, obtained by numerical experiment 15L1, was approximately 5.85 kN [Figure 4(a)], whereas the drawing force obtained experimentally had the average value of about 5.45 kN, which can be noticed on a diagram in Figure 4(a). Matching of drawing forces values obtained numerically and experimentally was realized for numerical experiment 15L3. There, the average value of the drawing force, obtained by numerical simulation was 4.95 kN [Figure 5(a)], whereas the experimental drawing force had the negligibly lower value of 4.90 kN [Figure 5(a)]. For numerical experiment 15L4, the drawing force had somewhat lower value of 5.95 kN [Figure 5(b)] with respect to experimentally obtained value of 6.05 kN [Figure 5(b)]. Somewhat larger discrepancies between numerical and experimental results was noticed in the case of 15L2, where the numerical simulation gave the average value of the drawing force of approximately 5.4 kN, whereas experimentally the value of about 4.3 kN was obtained [Figure 4(b)]. This discrepancy can be ascribed to the error in the measurement chain during the drawing force recording in the physical experiment. Results of average values of drawing forces, obtained for the compressive force of the slider of 20 kN, are presented in Table III.

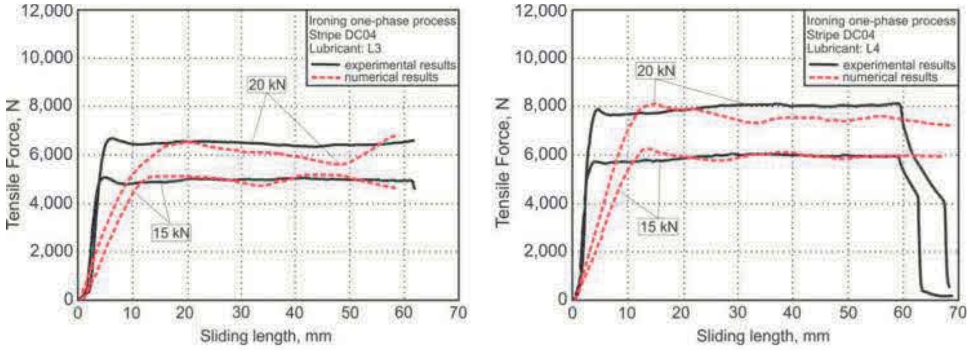
Figure 4 Experimental-numerical results of the drawing forces obtained by application of different lubricants



(a) (b)

Notes: (a) L1 (phosphate layer with oil); (b) L2 (single-bath lubricant)

Figure 5 Experimental-numerical results of the drawing forces obtained by application of different lubricants



(a) (b)

Notes: (a) L3 (grease based on MoS2); (b) L4 (oil for deep drawing)

Table III Average value of drawing forces for the compressive force of 20 kN

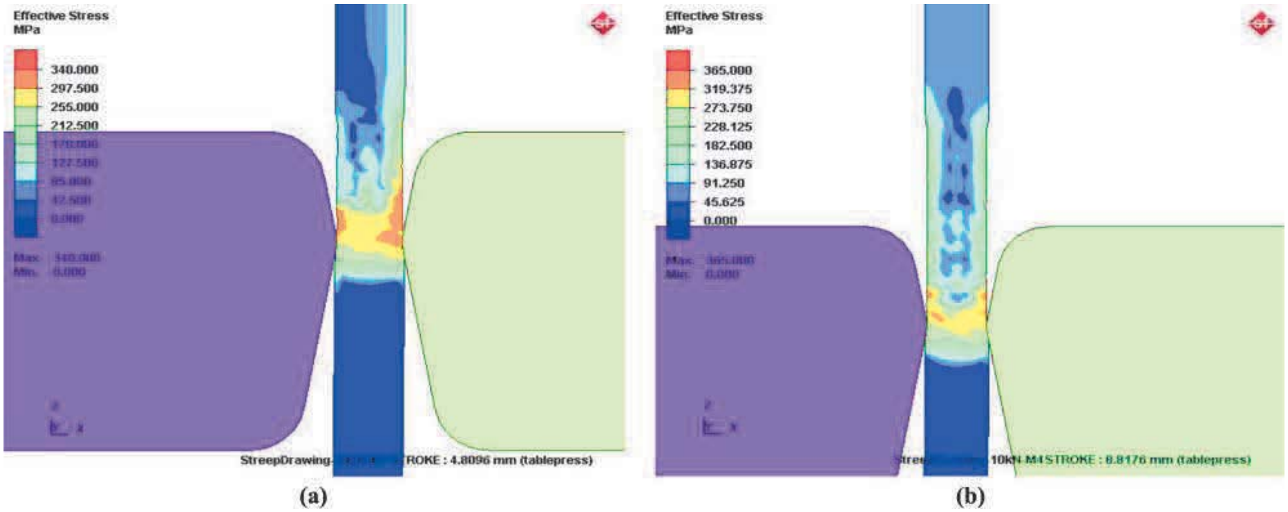
Experiment	Numerical value kN	Experimental value kN	Figure
20L1	7.25	6.95	4a
20L2	6.40	6.20	4b
20L3	6.25	6.50	5a
20L4	7.75	8.05	5b

Numerical and experimental results of average values of the drawing forces for experiments 20L1, 20L2, 20L3 and 20L4 mainly had the similar values, so it could be concluded that there exists high correlation of the experimental and numerical results, what verifies that the numerical model was properly created. The high value of the drawing force for experiment 20L4 [8.05 kN, Figure 5(b)], obtained in physical experiment, is the consequence of difficult conditions for the sample sliding between the sliders, due to appearance of galling on sliders. That phenomenon results in a very high friction coefficient due to worsen lubricating properties of lubricant L4 (oil for deep drawing). Subsequently, the drawing force must be greater to overcome the sliding resistance.

Influence of the contact conditions between the thin sheet strip and the sliding elements can be also monitored via the distribution of the effective stress (Figures 6 and 7). Increasing of the compressive force of the sliding elements (15 and 20 kN) causes increase of stresses within the thin sheet strip, what is to be expected. Besides that, it is important to monitor the change of stresses for various lubricants for the same compressive force.

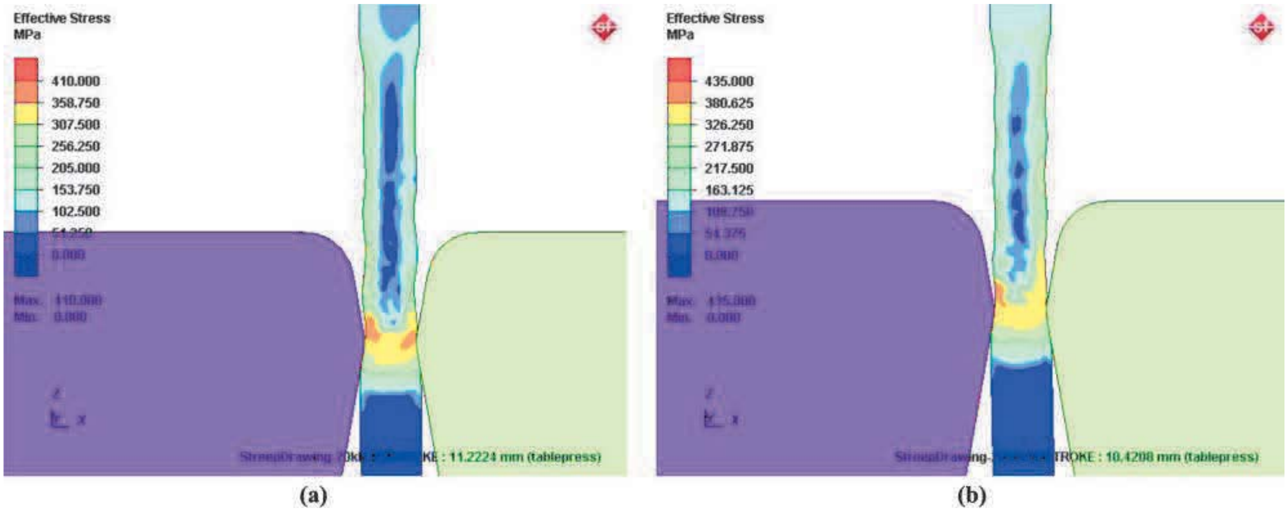
For the compressive force of 15 kN and lubricant L2 the maximum effective stress in the thin sheet strip amounts to 340 MPa [Figure 6(a)], whereas for the lubricant L4 it amounts to 365 MPa [Figure 6(b)]. Increasing of the compressive force to 20 kN causes increase of the effective stresses. In this case, as well, the effective stresses values are lower for the lubricant L2 [410 MPa, Figure 7(a)], with respect to lubricant L4 [435 MPa, Figure 7(b)]. Increase of stresses, for the same value of the compressive force, is explained by the contact conditions between the sliding elements and the strip during the drawing process. For the lubricant L4 case, sliding is difficult because of worse lubricating conditions, squeezing of lubricant out of the contact zone and appearance of micro galling. The worse lubricating conditions were being manifested by increase of the drawing force due to the more difficult sliding between the contact elements, as it was already emphasized earlier [Figure 5(b)]. The properties of lubricant L2, which belongs into a group of the new ecological lubricants, could be considered as very good, what is especially reflected in low values of the

Figure 6 Effective stress distribution in the thin sheet strip at compressive force of 15 kN for: (a) lubricant L2; (b) lubricant L4



(a) (b)

Figure 7 Effective stress distribution in the thin sheet strip at compressive force of 20 kN for: (a) lubricant L2; (b) lubricant L4



(a) (b)

friction coefficient, drawing force, stress distribution in the material and absence of appearance of galling on the contact surfaces of the sliding elements.

4. Conclusions

The two research approaches are united in this paper – the physical modeling, realized by the laboratory experiment, and the numerical simulation of the ironing drawing process. By analyzing the obtained results, one can say that the technique of physical modeling, with help of the laboratory equipment and numerical simulation by application of the FEM, can be successfully used in studying the thin sheet ironing – strip drawing process. Considering the deficiencies and limitations of experimental and numerical methods, applied individually, this research shows that their integrated application has complementary advantages in determination of the process output parameters and effects.

The conclusions of these investigations can be summarized in the following:

- Physical experiment is necessary to define the precise input data for numerical analysis, so that combination of physical-numerical approach would represent the best way for investigating the strip drawing process or some similar thin sheet forming process. In that way, it is possible to create the numerical model based on experimentally obtained values of the friction coefficient, real tool and working piece geometry, values of the compressive force of the tool elements that provide for thinning.
- It is significant to compare values of the deformation forces obtained by physical experiment to values obtained by the numerical simulation. In that way, it is possible to compare applied contact conditions (lubricants) and estimate matching of experimentally and numerically obtained values of the deformation forces.
- Presented results point to very good technological characteristics of ecologically friendly lubricant L2 (single-bath). Significant decrease of the friction coefficient was achieved by its application, as well as

maintaining of the lubricant's layer during the forming process and almost complete elimination of galling on the contact surfaces. Appearance of galling was almost impossible to avoid by application of the conventional types of lubricants (especially in the cases of oil for deep drawing – L4 and grease based on Molybdenum-disulfide – L3).

Numerical analysis of stresses in the working piece wall, during the thin sheet strip drawing, requires precise values of the friction coefficient. It is the important indicator, because one can define the contact conditions as the input data for the numerical simulation, based on its values for each type of lubricants and each value of the compressive force.

References

Adamović, D., Mandić, V., Živković, M., Gulišija, Z., Stefanović, M., Topalović, M. and Aleksandrović, S. (2013), "Numerical modeling of ironing process", *Journal for Technology of Plasticity*, Vol. 38 No. 2, pp. 109-123.

Aleksandrović, S., Nedeljković, B., Stefanović, M., Milosavljević, D. and Lazić, V. (2009), "Tribological properties of steel and Al-alloys sheet metals intended for deep drawing", *Tribology in Industry*, Vol. 31 No. 3, pp. 11-16.

Aleksandrović, S., Djordjević, M., Stefanović, M., Lazić, V., Adamović, D. and Arsić, D. (2014), "Different ways of friction coefficient determination in stripe ironing test", *Tribology in Industry*, Vol. 36 No. 3, pp. 293-299.

Bachchhav, B.D., Lathkar, G.S. and Bagchi, H. (2014), "Tribology of drawing lubricants for low carbon steel", *Industrial Lubrication and Tribology*, Vol. 66 No. 6, pp. 640-644.

Chowdhurya, M.A. and Nuruzzamanb, D.M. (2013), "Experimental investigation on friction and wear properties of different steel materials", *Tribology in Industry*, Vol. 35 No. 1, pp. 42-50.

Delarbre, D. and Montmitonnet, P. (1999), "Experimental and numerical study of the ironing of stainless steel cups", *Journal of Materials Processing Technology*, Vol. 91, pp. 95-104.

Dhaiban, A.A., Soliman, M.-E.S. and EL-Sebaie, M.G. (2014), "Finite element modeling and experimental results of brass elliptic cups using a new deep drawing process through conical dies", *Journal of Materials Processing Technology*, Vol. 214, pp. 828-838.

Djordjević, M., Aleksandrović, S., Lazić, V., Stefanović, M., Nikolić, R. and Arsić, D. (2013), "Experimental analysis of influence of different lubricants types on the multi-phase ironing process", *Materials Engineering*, Vol. 20 No. 3, pp. 147-152.

Djordjević, M., Arsić, D., Aleksandrović, S., Lazić, V., Milosavljević, D. and Nikolić, R. (2016), "Comparative study of an environmentally friendly single-bath lubricant and conventional lubricants in a strip ironing test", *Journal of the Balkan Tribological Association*, Vol. 22, No. 1A, pp. 959-970.

Djordjević, M., Aleksandrović, S., Vujinović, T., Stefanović, M., Lazić, V. and Nikolić, R. (2012), "Computer controlled experimental device for investigations of tribological influences in sheet metal forming", *Materials Engineering – Materialove inžinierstvo*, Vol. 19 No. 2, pp. 88-94.

Djordjević, M., Aleksandrović, S., Lazić, V., Arsić, D., Nikolić, R., Hadzima, B. and Koteš, P. (2015), "Investigation of the lubricants influence on the ironing process", *Procedia Engineering*, Vol. 111, pp. 149-154.

Jao, H. and Cao, J. (2001), "Assessment of corner failure depths in the deep drawing of 3D panels using simplified 2D numerical and analytical Models", *Journal of Manufacturing Science and Engineering*, Vol. 123, pp. 248-257.

Morovvati, M.R., Mollaei-Dariani, B. and Haddadzadeh, M. (2010), "Initial blank optimization in multilayer deep drawing process using GONNS", *Journal of Manufacturing Science and Engineering*, Vol. 132, p. 10.

Neto, D.M., Oliveira, M.C., Alves, J.L. and Menezes, L.F. (2014), "Influence of the plastic anisotropy modeling in the reverse deep drawing process simulation", *Materials and Design*, Vol. 60, pp. 368-379.

Peña-Parás, L., Maldonado-Cortés, D., Taha-Tijerina, J., García-Pineda, P., Tadeo, G., Irigoyen, G.M., Gutiérrez, J. and Sánchez, D. (2016), "Extreme pressure properties of nanolubricants for metal-forming applications", *Industrial Lubrication and Tribology*, Vol. 68 No. 1, pp. 30-34.

Singh, S.K., Kumar, V., Reddy, P.P. and Gupta, A.K. (2014), "Finite element simulation of ironing process under warm conditions", *Journal of Materials Processing Technology*, Vol. 3 No. 1, pp. 71-78.

Vrh, M., Halilovič, M., Starman, B., Stok, B., Comsa, D.S. and Banabić, D. (2014), "Capability of the BBC2008 yield criterion in predicting the earing profile in cup deep drawing simulations", *European Journal of Mechanics A/Solids*, Vol. 45, pp. 59-74.

Further reading

Kalbarczyk, M., Michalczewski, R., Piekoszewski, W. and Szczerek, M. (2013), "The influence of oils on the scuffing of concentrated friction joints with low-friction coated elements", *Eksploatacja i Niezawodnosc – Maintenance and Reliability*, Vol. 15 No. 4, pp. 319-324.

Murariu, C.A., Crasteti, S. and Birdeanu, A.V. (2016), "Active infrared thermography method for non-destructive examinatiuon of coating layers", *Structural Integrity and Life*, Vol. 16 No. 1, pp. 3-8.

Plonka, S. and Zaborski, A. (2015), "Operational wear of the neck of spindle coating in cooperation with yarn", *Eksploatacja i Niezawodnosc – Maintenance and Reliability*, Vol. 17 No. 4, pp. 496-503.

Corresponding author

Dušan Arsić can be contacted at: dusan.arsic@fink.rs