ADVANCES IN MATERIALS SCIENCE, Vol. 23, No. 2 (76), June 2023

DOI: 10.2478/adms-2023-0011

Tomasz Trzepieciński[1*], Valmir Dias Luiz[2], Krzysztof Szwajka[3], Marek Szewczyk[3], Marcin Szpunar[4]

[1] *Department of Manufacturing Processes and Production Engineering, Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Poland*
[2] *Department of Metallurgy and Chemistry, Centro Federal de Educação Tecnológica de Minas Gerais, Timóteo, Brazil*
[3] *Department of Integrated Design and Tribology Systems, Faculty of Mechanics and Technology, Rzeszow University of Technology, Poland*
[4] *Doctoral School of Engineering and Technical Sciences at the Rzeszow University of Technology, Poland*

** tomtrz@prz.edu.pl*

ANALYSIS OF THE LUBRICATION PERFORMANCE OF LOW-CARBON STEEL SHEETS IN THE PRESENCE OF PRESSURISED LUBRICANT

ABSTRACT

In sheet metal forming processes, friction increases the force parameters of the forming process and produces a deterioration in the quality of the surface of the components. The basic way to reduce the unfavourable impact of friction is to lubricate the sheet metal surface with commercial oils. This article presents the results of experimental studies and analysis of variance (ANOVA) of the friction of DC01 low-carbon steel sheets using a strip drawing test. For these tests, a special device was built containing countersamples with a flat surface made of 145Cr6 steel covered with a protective AlTiN coating. Lubricants of different viscosities were fed into the contact zone under forced pressure. The effect of contact pressure on the value of the coefficient of friction was also determined. The predicted R^2 of 0.9227 was in reasonable agreement with the adjusted R^2 of 0.9411 confirming that the ANOVA model was reliable. It was found that increasing the lubricant pressure had a beneficial effect in reducing the value of the coefficient of friction. The higher the contact pressure, the more effectively the pressurised oil reduced the value of the coefficient of friction.

Keywords: *ANOVA; Coefficient of friction; Friction; Sheet metal forming; Steel sheets*

INTRODUCTION

Sheet metal forming is a common method of producing components in the automotive industry [1, 2]. In addition to providing tools with an appropriate design, it is necessary to use suitable technological parameters of the forming process and friction conditions [3]. In general, friction has an unfavourable effect in the forming process, reducing the surface quality of products [4] and increasing the forming forces. Too high friction can lead to

premature cracking of the sheet metal [5], increase of temperature in the friction node [6-8] and accelerated tool wear [9]. PVD coatings reduces coefficient of friction (COF) and increase the durability of the metallic tools [6-8].

Proper lubrication reduces friction [10]. Currently, lubricants of various consistencies are used in sheet metal forming: liquid, solid and applied in the form of an aerosol. The lubricant should be adjusted to the value of contact pressures [11] and should have appropriate viscosity to prevent breakage of the lubricating film [12]. During the forming process, the lubricant changes the surface topography and the flow character of the deformed metal, reduces the unit pressures and the coefficient of friction and improves the surface quality of the product [13, 14]. The nature of the lubricant's impact depends also on the surface roughness of the contacting surfaces [15]. In conditions of closed oil pockets, the lubricant transfers part of the load, creating a kind of 'lubricant cushion' between the rubbing surfaces [16]. In sheet metal forming processes, the coefficient of friction depends on the contact area which determines the area of the mechanical interaction of surface asperities [17].

The character of the interaction between the two surfaces and the resulting layers of oxides and wear products is constantly changing during the forming process and is strongly dependent on the pressures in the contact zone, the properties of the sheet material and the surface of the tool (type of protective coating). The oxides formed on the surface of the metal sheet in metallurgical conditions can only act as lubricants to a limited extent [18, 19]. The presence of oxides formed on the surface of the workpiece may affect the mechanisms of tool surface wear [20].

Experimental studies of friction using the strip drawing test, in which lubricant was applied to the surface of the sheet immediately before the forming process, are widespread in the literature. Trzepieciński et al. [10] investigated the effect of lubricant type on the frictional performance of AW-6082 aluminium alloy sheets. The lowest value of COF was recorded when lubricating with 5W40 C3 engine oil, which is the most viscous of all the lubricants tested. In another paper, Trzepieciński [21] showed the results of analysis of variance (ANOVA) of friction tests of AW-2024-T3 aluminium alloy sheets. The main conclusion was that the coefficient of friction decreases with increase in lubricant viscosity and contact pressure. Schell et al. [22] used the strip drawing test to examine the wear performance of different lubricant classes in tool lubrication. It was found that while oil lubricants show excellent lubricity, the stability of the lubricant layer is not sufficient to effectively prevent wear in tool lubrication. Tavares et al. [23] studied the effects of transfer layers on friction mechanisms of coated forming tools. The results of the strip drawing tests revealed that the tools coated with CrN/TiN produced the best performance. Vollertsen and Hu [24] used the strip drawing test to analyse the size of the tribological effects when forming Al99.5 aluminium sheets. It was found that the coefficient of friction decreases with increasing contact pressure in the range of 1-16 MPa. Żaba et al. [25] used the strip drawing test to analyse the tribological performance of new composite inserts for stamping dies. It was found that the coefficient of friction decreases with increasing contact pressure when testing AMS5599 (Inconel 625) Ni-based alloy, AMS5510 (321) stainless steel, AMS6061-T4 aluminium alloy against countersamples containing polyurethane resin and mineral filler $Al(OH)_3$.

This article presents a new approach to reducing the coefficient of friction in sheet metal forming. A special friction tester has been designed which has flat countersamples and pressurised lubricant supply to the contact zone. Pilot investigations were carried out for different values of contact pressure and oil pressure and for lubricants of different viscosities.

MATERIAL AND METHODS

Friction tests were carried out on low-carbon DC01 steel sheets with a thickness of 1 mm. The sheets meet the quality requirements for their chemical composition (wt%) in accordance with the EN10130:2006: C (max.) 0.12, Mn (max.) 0.6, S (max.) 0.045, P (max.) 0.045 and Fe (balance). The values of the basic mechanical parameters of DC01 steel sheet according to the requirements of EN 10130:2006 standard and are as follows: yield stress 140-280 MPa, ultimate tensile stress 270-410 MPa, elongation A_{80} = 28% and hardness 105 HV. The values of the basic roughness parameters of the surface of the as-received DC01 steel sheet and countersamples were determined using a Hommel - Etamic T8000RC profilometer and are as follows: the Sa - 1.44 mm, Sq - 1.82 mm, Sp - 9.13 mm, Sv - 5.31 mm, Sz - 14.4 mm, Sku - 3.32 and Ssk - 0.553. The surface of a test sheet composed of the metal was examined using a MIRA3 scanning electron microscope (SEM). The surface topography and SEM micrograph of the DC01 steel sheet are shown in Figs. 1a and 1b, respectively.

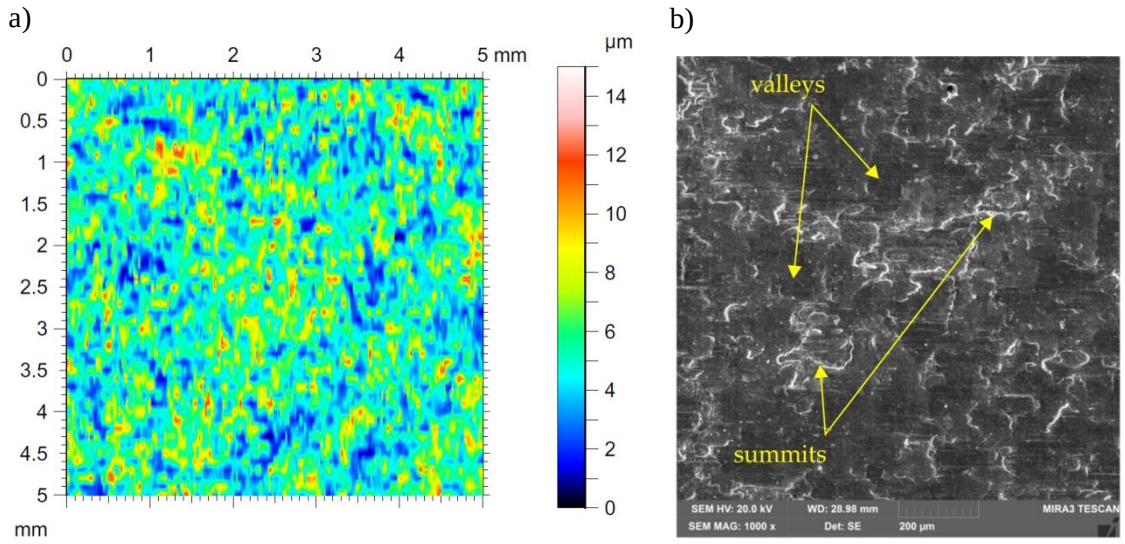


Fig. 1. a) Surface topography and b) SEM micrograph of the surface of the as-received DC01 steel sheet

Friction tests were carried out using a tester specially designed for performing the strip drawing test. The test consists in pulling a strip of sheet metal 25 mm wide and 130 mm long between two flat countersamples made of 146Cr6 steel covered with TiAlN anti-wear coating. The hardness of the coating was 2778 HV0.05 which is in good agreement with the hardness of TiAlN coating investigated by Walczak et al. [26]. The surface topography and basic surface roughness parameters of the countersamples covered with TiAlN anti-wear coating are shown in Fig. 2.

The countersamples have channels for applying pressurised lubricant to the contact zone by means of an Argo-Hytos hydraulic pump (Fig. 3a). The tester was mounted on the Z100 (ZwickRoell) universal testing machine. The value of the contact force F_N of the countersamples (Fig. 3b) was set up using a force sensor type 9345B (Kistler) in such a way as to obtain contact pressures p_N of 2, 4, 6 and 8 MPa. The value of the friction force F_T was measured using the measuring system of the Zwick/Roell Z100 testing machine, and the value of the contact force was recorded using the Labview program. Both forces were correlated and the values of COF were determined according to Eq. (1).

$$\mu = \frac{F_T}{2F_N} \tag{1}$$

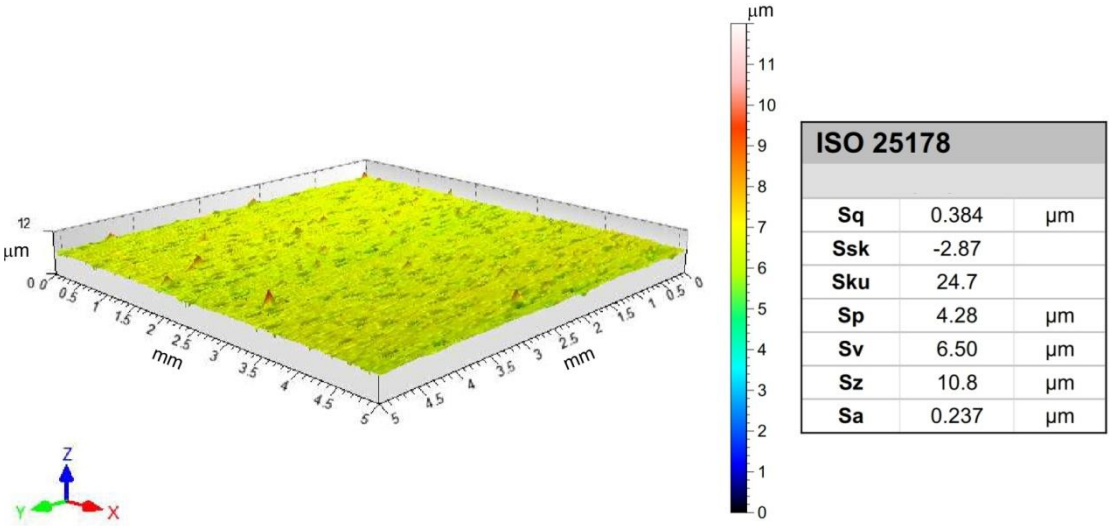


Fig. 2. The surface topography and basic surface roughness parameters of the countersamples covered with TiAlN anti-wear coating

The tests were carried out using oils typical of those used in metal working operations: S100 Plus oil for deep-drawing with viscosity 110 mm^2/s and S300 oil for deep-drawing operations with viscosity 300 mm^2/s, both delivered by Naftochem (Kraków, Poland). The oil was fed into the zone at a pressure p_L of 0.6, 1.2 and 1.8 MPa. For comparative purposes, tests were also carried out in conventional conditions (p_L = 0 MPa). Each of the friction tests was repeated three times. Variation of the friction force, normal force and COF during selected friction test is shown in Fig. 4.

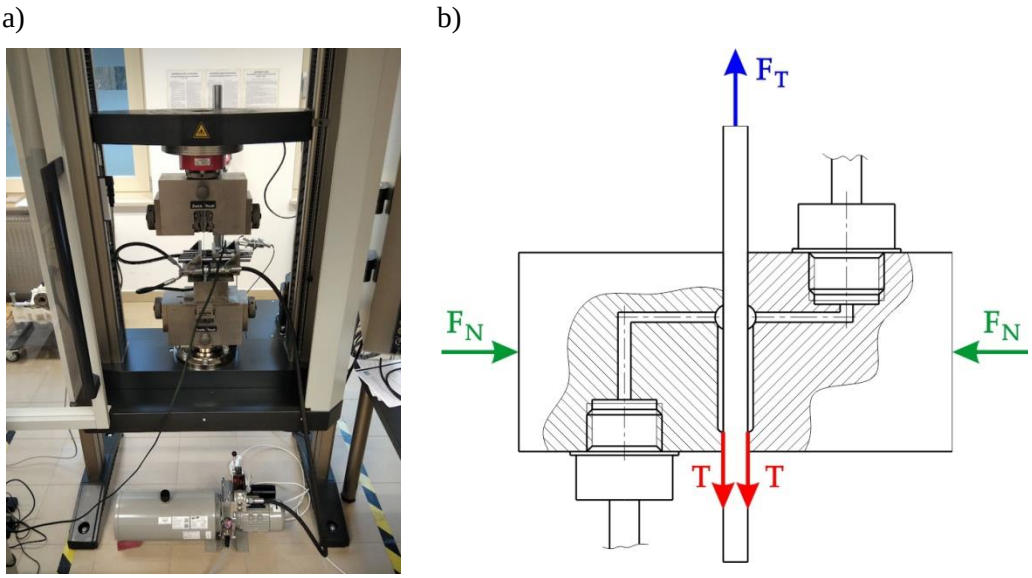


Fig. 3. a) Friction tester mounted on the Zwick/Roell testing machine and b) cross-section of the countersamples

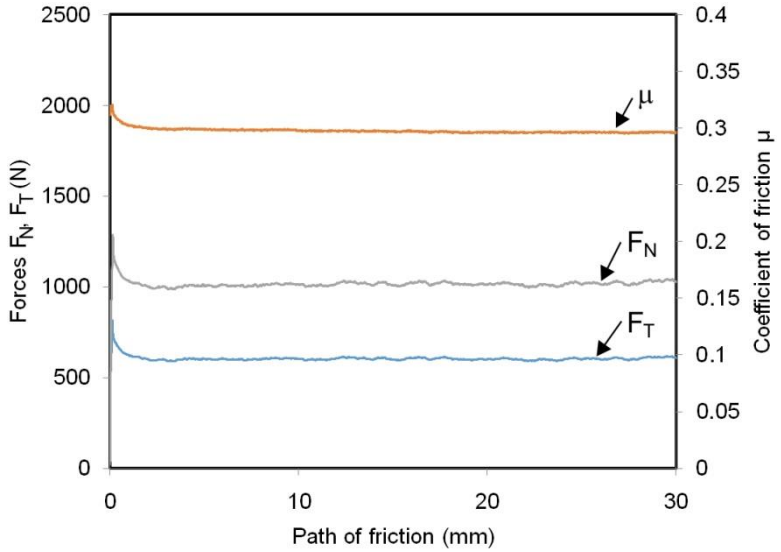


Fig. 4. Variation of the friction force, normal force and COF during friction test (S100 Plus oil, p_N = 6 MPa, p_L = 1.8 MPa)

ANOVA is a statistical technique employed to compare the means of multiple groups, aiming to identify significant differences that may indicate the influence of independent variables on the dependent variable. By partitioning the dataset's variance into within-group and between-group components, it allows for the evaluation of whether the discrepancies in group means are statistically significant or attributable to random chance. ANOVA proves advantageous when analyzing more than two groups, with results typically reported as F-statistics, degrees of freedom, and p-values to assess the significance of the differences observed. In this study, ANOVA has been conducted to predict the COF response based on input factors: oil viscosity, nominal pressure, and oil pressure. The input factors were coded as shown in Table 1.

Table 1. *Factors and levels used in the ANOVA*

Factor	Name	Unit	Min.	Max.	Coded Low	Coded High
A	oil viscosity	mm^2/s	110	300	-1 ↔ 110	+1 ↔ 300
B	nominal pressure	MPa	2	8	-1 ↔ 2	+1 ↔ 8
C	oil pressure	MPa	0	1.8	-1 ↔ 0	+1 ↔ 1.8

Building upon the ANOVA approach, the significance threshold for p-values was set at 0.05. This threshold helps to determine whether the observed differences in the means are statistically significant or can be attributed to random chance. When the p-value is at or below the threshold of 0.05, the null hypothesis is not supported, signifying that the variations among the groups hold statistical relevance. To refine the ANOVA model and exclude insignificant terms, a backward elimination algorithm was applied. This iterative procedure begins with a full model, containing all input factors and interactions, and progressively removes the least significant terms based on their p-values. At each step of the algorithm, the term with the highest p-value greater than 0.05 is removed from the model, and the process is repeated until all remaining terms are statistically significant (have p-values less than or equal to 0.05). This streamlined model, containing only significant factors and interactions, enables a more accurate and reliable prediction.

EXPERIMENTAL RESULTS

At the outset of the analysis, various types of models were evaluated by comparing in a fit summary (Table 2). The objective was to identify the most suitable model that effectively captured the relationships between the input factors (oil viscosity, nominal pressure, and oil pressure) and the COF response. After a thorough comparison of different types of models, the Two Factor Interaction (2FI) model was chosen due to its lowest sequential p-value, and the highest R^2, adjusted R^2 and predicted R^2 values, which indicate that the model shows a strong fit and high predictive capability. It is important to note that the quadratic model was aliased, rendering it unsuitable for use in this analysis. Consequently, the 2FI model was deemed the most appropriate for further investigation and application of the backward elimination algorithm.

Table 2. *ANOVA results of the COF*

Source	Sequential p-value	R^2	Adjusted R^2	Predicted R^2	Decision
Linear	< 0.0001	0.8813	0.8685	0.8342	
2FI	< 0.0001	0.9499	0.9379	0.9054	Selected
Quadratic	0.0470	0.9616	0.9483	0.9155	Aliased

Following the selection of the 2FI model, the backward elimination algorithm was applied to refine the model further and exclude insignificant terms. The process aimed to remove terms with p-values greater than 0.05, resulting in a more accurate and reliable model. The term AC was excluded from the final model as it had a p-value of 0.9624, which is above the significance threshold of 0.05. Next, the term AB was also removed from the final model due to its p-value of 0.4329, again exceeding the threshold. After the removal of these terms, the algorithm could not identify any additional terms with p-values greater than 0.05. Consequently, no further terms were removed from the model in any of its types. With the backward elimination process complete, the final model contained only statistically significant terms, ensuring a robust and reliable prediction of the COF response based on the input factors of oil viscosity, nominal pressure, and oil pressure.

The model F-value of 124.80 and p-value of less than 0.05 (Table 3) implies the model is significant. Moreover, input parameters A, B, C, and BC are significant model terms. The predicted R^2 of 0.9227 is in reasonable agreement with the adjusted R^2 of 0.9411, that is, the difference is less than 0.2 (Table 4). Adequacy precision is greater than 4, this indicates an adequate signal.

Table 3. *ANOVA results of the COF*

Source	Sum of squares	df	Mean square	F-value	p-value	meaning
Model	0.0148	4	0.0037	124.80	< 0.0001	significant
A – oil viscosity	0.0013	1	0.0013	43.53	< 0.0001	
B – nominal pressure	0.0017	1	0.0017	56.75	< 0.0001	
C – oil pressure	0.0108	1	0.0108	363.43	< 0.0001	
BC	0.0011	1	0.0011	35.48	< 0.0001	
Residual	0.0008	27	0.0000			
Correlation total	0.0156	33				

Fig. 5 illustrates a normal probability plot with externally studentized residuals on the horizontal axis and normal percentage probability on the vertical axis. This graphical tool is

used to assess the normality and homoscedasticity of the residuals generated by the model that is developed.

Table 4. *Fit statistics of the ANOVA model*

Parameter	Value
standard deviation	0.0054
mean	0.1780
coefficient of variation, %	3.06
R^2	0.9487
adjusted R^2	0.9411
predicted R^2	0.9227
adequacy precision	38.3672

In this plot, if the residuals are normally distributed and exhibit constant variance (homoscedastic), the data points are expected to closely align with the diagonal reference line (also known as the "normal quantile plot" or the "probability-probability plot"). If the data points deviate significantly from this line, it may indicate non-normality or heteroscedasticity in the residuals. A close adherence of the data points to the reference line suggests that the model's assumptions of normality and homoscedasticity are valid, which contributes to the reliability and robustness of the model.

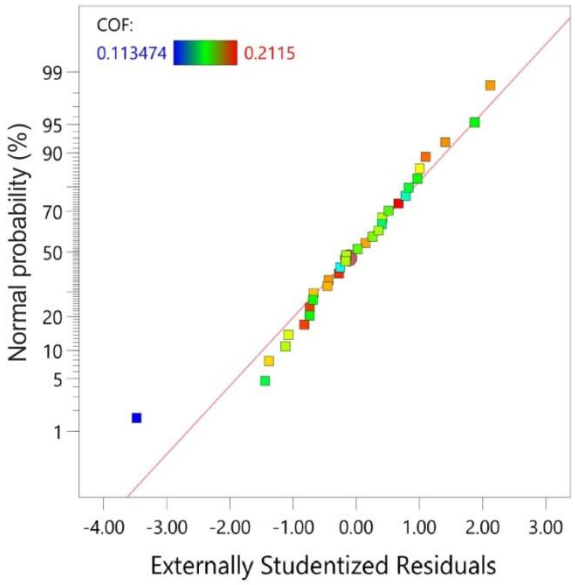


Fig. 5. Predicted versus actual response for COF

Based on the results of friction tests, it can be concluded that the coefficient of friction decreased with increasing contact pressure (Figs. 6a, 6b). However, this conclusion applies only to conditions with pressurised oil lubrication. In the conditions when the lubricant was delivered to the contact zone in a conventional way (p_L = 0 MPa), no significant effect of the change in contact pressure on the COF was observed. This conclusion can be attributed to the friction conditions with both oils tested. The increase in the lubricant pressure had a beneficial effect on the reduction of the coefficient of friction. The greater the contact pressure, the more effectively the grease supplied under pressure reduced the COF value. Under friction conditions without forced pressure, only lubricant enclosed in open lubricant pockets is able, under the influence of a sufficiently high contact pressure, to create an ‘lubricant cushion’ in which hydrostatic pressure prevails. If the sheet surface is free of closed oil pockets (Figs. 7a,

7b), high contact pressure causes intensification of the mechanical interaction of the flattened areas, while the formation of a lubricating cushion will not be possible.

When the sheet surface was lubricated with S300 oil (Fig. 6b), the values of the coefficient of friction were lower than when lubricated with S100 Plus oil (Fig. 6a) with almost twice lower viscosity. This conclusion applies to the entire range of changes in contact pressure and oil pressure.

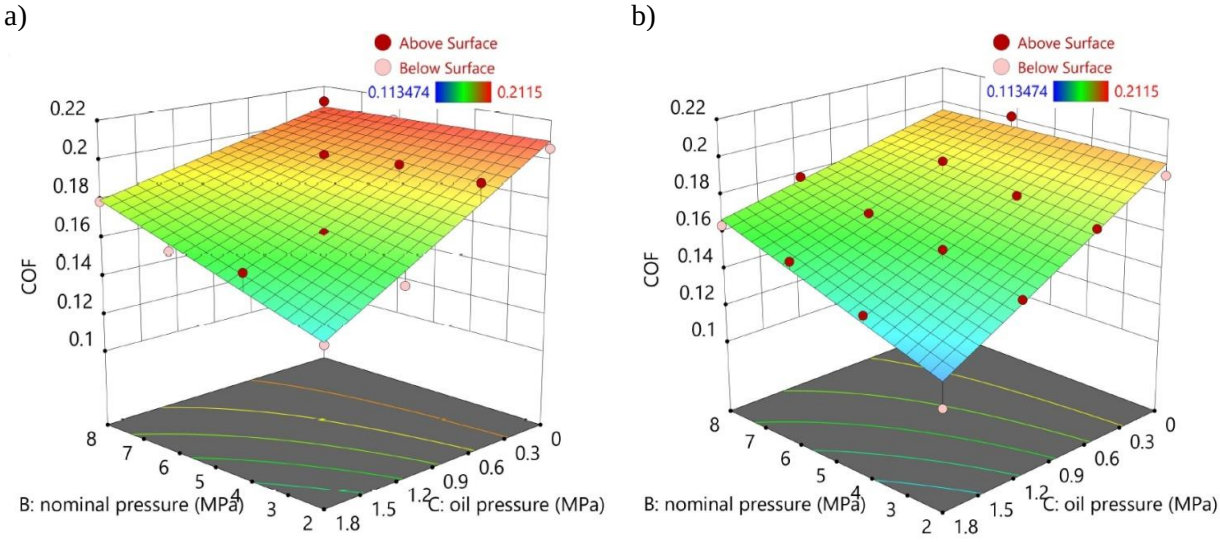


Fig. 6. Interaction between contact pressure and oil pressure affecting the COF for lubrication using a) P100 Plus oil and b) P300 oil

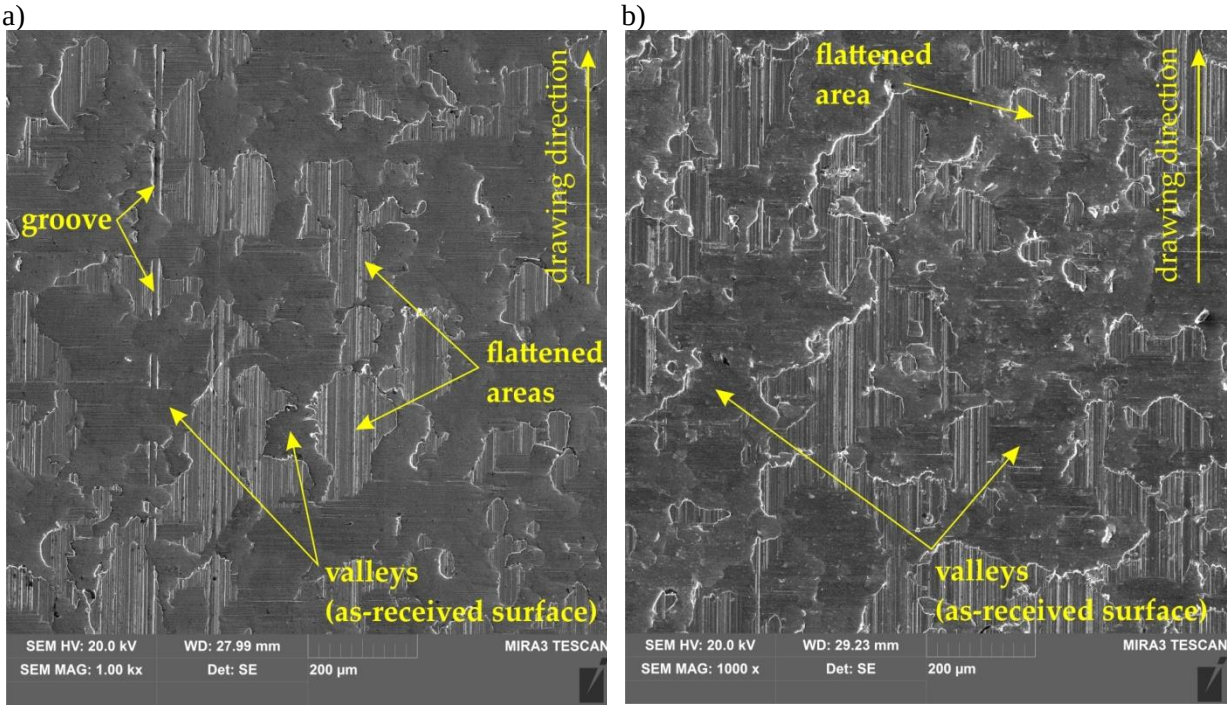


Fig. 7. SEM micrograph of the specimen surfaces tested under the following conditions: a) S100 Plus oil, p_N = 8 MPa, p_L = 1.8 MPa and b) S300 oil, p_N = 8 MPa, p_L = 1.8 MPa

The friction surface has large areas of flattened summits of surface asperities separated from each other by valleys, which does not create the conditions for the formation of closed oil pockets (Figs. 7a, 7b). With this character of the surface topography, only the supply of lubricant under forced pressure is capable of reducing friction. A similar observational

conclusion can be applied to the surface of the sheets tested under various friction conditions. Surface flattening was the main mechanism of interaction of the tool surface with the sheet surface.

The sheet material shows much greater hardness than the tool material, therefore the topography of the tool determines the character of the friction mechanisms accompanying the sheet metal deformation process in real deep-drawing conditions. The tests carried out with a wide range of changes in contact pressure showed that in each of the test conditions the phenomenon of flattening of the surface asperities (Fig. 8) in relation to as-the received sheet metal (Fig. 1a) occurred.

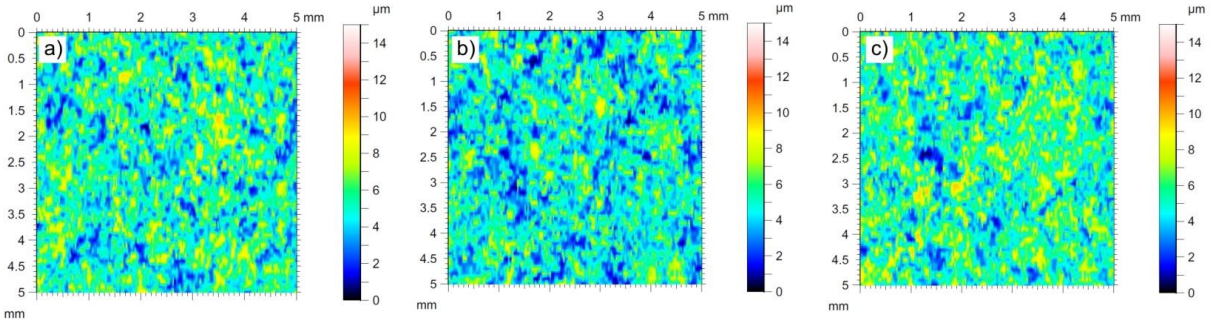


Fig. 8. The surface topography of test sheets after friction tests carried out under the following conditions: a) p_N = 2 MPa, p_L = 0 MPa, S100 Plus oil; b) p_N = 2 MPa, p_L = 0.6 MPa, S100 Plus oil; c) p_N = 2 MPa, p_L = 1.2 MPa, S100 Plus oil

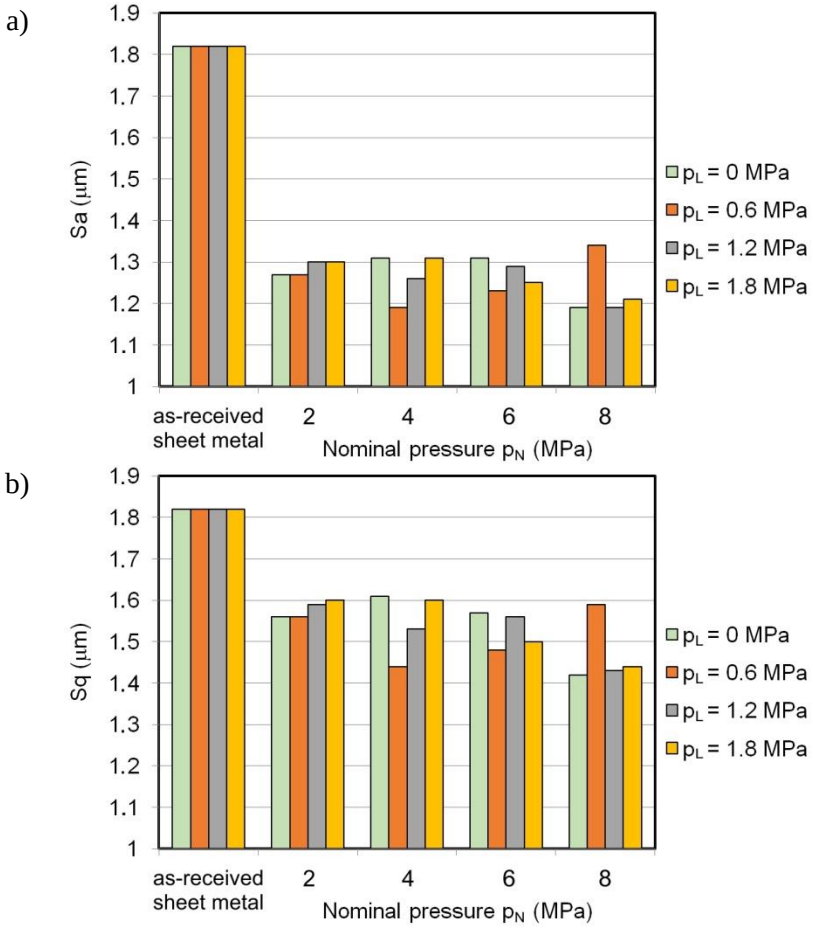


Fig. 9. Effect of friction conditions on the a) Sa and b) Sq parameter for lubrication with S100 Plus oil

Even under lubrication conditions involving grease supplied under pressure, a flattening mechanism was observed. The total friction force is the result of the force associated with overcoming the mechanical interaction of the surface asperities and the presence of a lubricating film on the interface between the rubbing surfaces.

In general, the friction process causes a decrease in the average roughness Sa and the root mean square roughness parameter Sq as a result of surface flattening. During friction tests carried out under lubrication with S100 Plus oil, the value of the average roughness Sa decreases by at least 25% compared to as-received sheet surface (Fig. 9a). Under the conditions of lubrication with the same oil, the value of the root mean square roughness parameter Sq decreases by at least 12% compared to the as-received sheet surface (Fig. 9b). When lubricating with S300 oil, a tendency to decrease of the considered roughness parameters with increasing nominal pressure can be observed (Fig. 10a, 10b). Due to the complexity of the friction phenomenon, which depends on many factors, there is no clear effect of oil pressure on the change in average roughness Sa and the root mean square roughness parameter Sq.

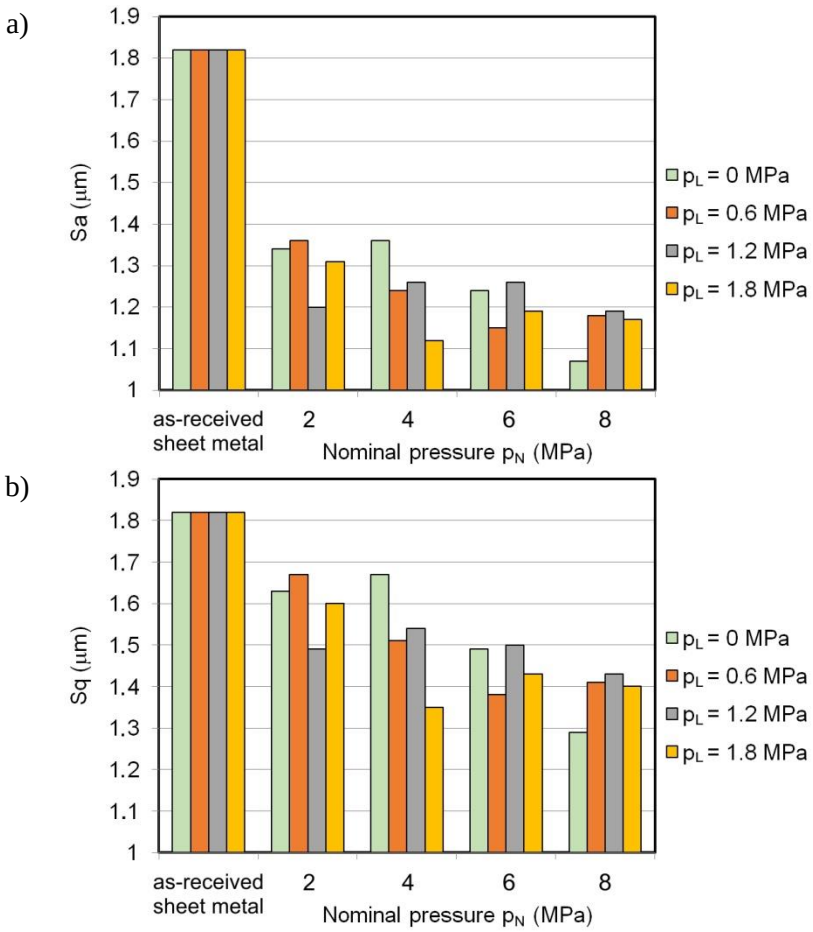


Fig. 10. Effect of friction conditions on the a) Sa and b) Sq parameter for lubrication with S300 oil

CONCLUSIONS

In this article, the results of analysis of variance for experimental data on friction tests of 1-mm-thick low-carbon DC01 steel sheets are presented. The tests were carried out using a strip drawing test using flat countersamples and under the conditions of supplying lubricant under pressure. Based on the ANOVA model with $R^2 = 0.9227$, the following conclusions can be drawn.

- The use of grease with higher viscosity (S300) reduced the value of the COF in the entire range of changes in the friction process parameter analysed, when compared to the friction with the use of S100 Plus lubricant.
- The coefficient of friction decreased with increasing contact pressure. This pressure affected not only the asperities of the tool surface roughness, but also the oil in the valleys of the surface topography.
- Compared to the conditions with the conventional supply of grease without pressurised lubricant ($p_L = 0$ MPa), the approach of supplying oil under pressure clearly reduced the value of the coefficient of friction.
- The improvement of the friction conditions is the greater the greater the lubricant pressure applied.

No oil leaks were observed during testing, but future testing should consider the effect of surface topography and contact pressure on maximum oil pressure. Another problem to be solved in the future is the selection of the viscosity of the grease according to the surface topography of the tool and work piece and prevailing contact pressures.

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