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Original Research

Assessment of the Tribological Performance of Bio-Based Lubricants Using Analysis of Variance

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Abstract

The purpose of this article is to determine the coefficient of friction of a DC04 steel sheet using a specially designed flat-die strip drawing test. Four different bio-based lubricants, edible (sunflower and rape-seed) and non-edible (karanja and moringa) were used in the study. The experiments were carried out for different contact pressure values. The as-received specimens were pre-strained with strains of 7, 14, and 21%. The values of the coefficient of friction as a ratio of the friction force to the normal force were determined. The influence of the viscosity of the lubricant and the contact pressure on the value of the coefficient of friction has been investigated using ANOVA. A tendency to a decrease in the coefficient of friction with increasing contact pressure was observed. Significance results obtained after the ANOVA analysis confirmed the influence of normal pressure and oil viscosity on the value of the coefficient of friction. At the same time, the hypothesis about the influence of the sheet pre-straining on the value of the coefficient of friction was not confirmed by the significant interactions.

Keywords: analysis of variance, ANOVA, friction, plastic working

1. Introduction

The metal forming industry is one of the largest sectors of *a* nation's economy. Chipless forming will ensure the production of finished products without material loss and is much faster than machining methods. For the correct course of the forming process, the parameters of the machining process and the friction conditions need to be properly selected (Dou & Xia, 2019; Wu et al., 2021). Lubrication is a basic and effective way to reduce friction and ensure a proper surface finish (Lachmayer et al., 2022). Surface texturing has also attracted great attention as a geometrical modification approach to improving tribological performance (Shimizu et al., 2019). In cold forming processes, in which the material is subjected to large deformations and high contact pressures, the lubricant is also responsible for cooling the tools (Evin & Tomáš, 2022; Folle et al., 2022). The basic criteria for the division of lubricants are the consistency of the lubricant, the origin (mineral or organic) and the intended use. Due to their consistency, the following types of lubricants are distinguished: solid lubricants, liquid lubricants (oils), emulsions (oil mists) and greases (Alaboodi, 2020). From their origin, lubricants are divided into natural (animal and vegetable), refined and synthetic. The selection of a specific type of grease depends on the conditions of the forming process, that is, contact pressures, surface topography of the tool and workpiece, sliding speed and temperature (Nagendramma & Kaul, 2012; Singh et al., 2022).

During the last decade, due to the tendency to manufacture products in environmentally friendly processes, the engineering industry focused on introducing lubricants with a high degree of biodegradability (Bobzin et al., 2009; Klocke et al., 2005). These are mainly lubricants of animal and vegetable origin (edible and non-edible). A chemical feature of vegetable oils is that they consist mainly of triglycerides of fatty acids, which can vary greatly depending on the plant cultivation conditions (Ilyin et al., 2022). The most advantageous utility feature of vegetable oils from the point of view of environmental protection is the ability to biodegrade, that is, self-decomposition to carbon dioxide (CO_2) and water (H_2O) (Zajezierska, 2016). Compared to petroleum oils and even synthetic esters, vegetable oils show the highest biodegradability (80–100%) (Zajezierska, 2016). Vegetable lubricants are modified by antiwear additives. Antiwear additives (phosphoric acid, zinc dialkyldithiophosphates, nano-particulate potassium borate, etc.) form a lubricious sacrificial coating that protects the metal from wear under boundary lubrication conditions (Stolte et al., 2012).

Due to the large number of parameters affecting friction in sheet metal forming, many analytical techniques are used to determine the influence of process parameters on the value of the coefficient of friction. Bhaumik and Pathak (2016) used the analysis of variance (ANOVA) to predict the significant factors affecting the tribological properties of neat castor oil in a boundary lubrication regime. From the ANOVA it has been observed that the normal load is the significant factor while determining frictional force. Mirahmadi et al. (2015) investigated the coefficient of friction in a ring compression test. The effect of platen speed and temperature on the coefficient of friction was analysed using ANOVA. Carvalho and Lukács (2021) used ANOVA to analyse the friction propeties of austenitic chromium-nickel stainless steel determined using a strip drawing test. It was found that higher velocity resulted in a decreasing coefficient of friction. An increase in contact pressure caused decreasing friction. Dilmec and Arap (2016) investigated the effects of the surface roughness of tools, drawing speed, and lubrication on the dynamic coefficient of friction by using ANOVA. The coefficient of friction in the die radius region was found to be significantly different from that in the flange region. Basavaraj et al. (2014) investigated the friction performance of a metal matrix composite using ANOVA. It was observed that sliding speed and normal pressure influence the coefficient of friction of an LM6 aluminium alloy that has been reinforced with SiC. The purpose of this article is to determine the coefficient of friction of a DC04 steel sheet using the flat-die strip drawing test. Four different bio-based lubricants were used in the study. The influence of the viscosity of the lubricant and the contact pressure on the value of the coefficient of friction has been investigated using ANOVA. The drive to eliminate synthetic and mineral oils, which are difficult to recycle, from the manufacturing process has opened up opportunities for the use of vegetable-based bio-lubricants (Sayhir et al., 2017). This article presents a comparison of the lubrication performance of two non-edible oils (moringa and karanja) with the most frequently tested edible oils. Due to the global food crisis, it seems desirable to replace edible oils with non-edible bio-based oils. Environmentally friendly bio-based lubricants have been found to exhibit superior lubricant properties over the conventional mineral lubricants, with renewability and biodegradability being their strongest suit. There is a need to explore the potential of bio-based lubricants for various applications. In this regard, the aim of this paper is to highlight the potential of non-edible oils for applications in sheet metal forming.

2. Material and installation

2.1. Test sample

Cold-rolled DC04 steel sheet was used as the test material. The sheet thickness was 0.83 mm. The chemical composition of the DC04 steel sheet according to the EN 10130:2009 is as follows: C $\leq$ 0.1 wt.%, Mn $\leq$ 0.45 wt.%, P $\leq$ 0.035 wt.%, S $\leq$ 0.035 wt.%, Fe – remainder. The mechanical properties of the test material according to the EN 10130:2009 standard are listed in Table 1.

Table 1. Basic mechanical parameters of the DC04 steel sheet according to the EN 10130:2009 standard

Yield stress Re, MPa	Ultimate tensile stress R_m, MPa	Elongation A_{80}, %	Anisotropy coefficient r_{90}
140-240	270-370	≥ 34	≥ 1.6

The topography of the sheet surface in the as-received state (Fig. 1) was determined using a Hommel-Etamic T8000RC stationary profilometer. The values of basic surface roughness parameters are as follows: Sq = 2.29 µm, Sku = 2.70, Ssk = −0.022. The basic height parameters of the geometric structure of the countersamples' surface were also determined: maximum profile valley depth Sv (5.11 µm), arithmetical mean height Sa (0.636 µm), kurtosis Sku (3.76), skewness Ssk (-0.544), maximum height Sz (10.0 µm), maximum profile peak height Sp (4.89 µm) and root mean square deviation Sq (0.81 µm). The average hardness was found to be 215 HV10.

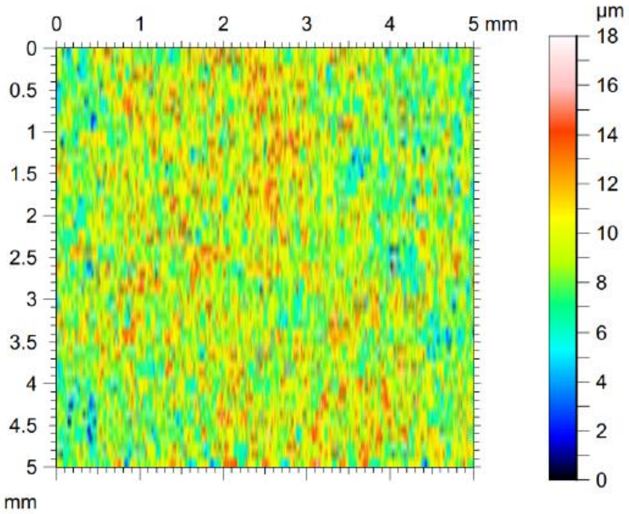

Fig. 1. Topography of the sheet surface in the as-received state

2.2. Test procedure

The coefficients of friction of low-carbon DC04 steel sheets have been determined using the flat-die strip drawing test (Fig. 2). The test involves pulling a strip of sheet metal between two flat countersamples. Friction tests were carried out using a specially designed tester (Fig. 3) which was mounted in the lower grip of a Zwick/Roell Z100 testing machine. Countersamples were made of 145Cr6 cold-work tool steel.

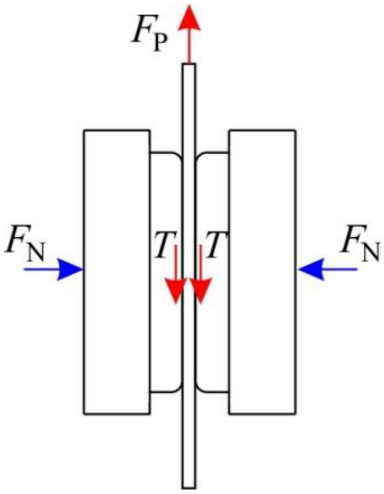

Fig. 2. Schematic diagram of the strip drawing test

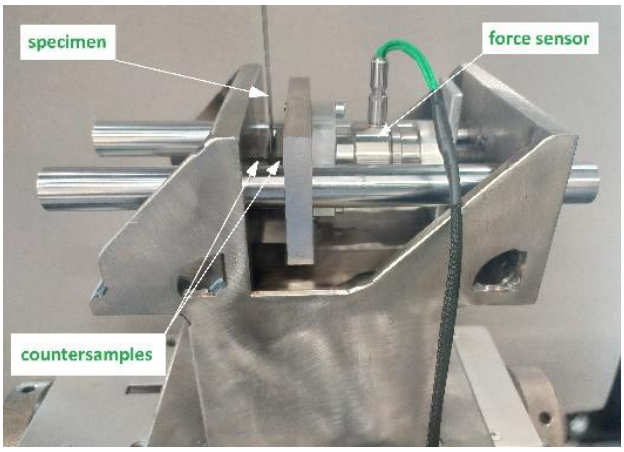

Fig. 3. Photograph of the friction tester

Specimens (130 mm long and 20 mm wide) were cut from a sheet of metal. The tests were carried out for four nominal pressures of 3, 6, 9 and 12 MPa. The as-received specimens were pre-strained with strains of 7, 14, and 21%. The specimens pre-straining was performed using a Zwick Roell Z030 standard tensile machine. The sliding speed of the specimen was 2 mm/s. The contact (normal) force F_N was recorded using the Labview program and a Kistler type 9345B force sensor. The pulling (friction) force F_T was recorded using the measuring system of a uniaxial tensile testing machine. The value of the coefficient of friction was determined according to the relationship:

$$\text{coefficient of friction} = \frac{F_\mathrm{P}}{2F_\mathrm{N}} \tag{1}$$

One specimen was tested for each conditions. However, the sheet was drawn for a distance of about 50 mm. For each of tests, we obtained about 9000–9500 discrete values of the coefficient of friction. The average coefficient of friction was determined using the Eq. (1).

Vegetable oils (edible and non-edible) are extensively used in incremental sheet metal forming (Diabb et al., 2017). Karthik (2016), Carcel et al. (2005) and Syahrullail & Afifah (2017) indicated the usefulness of edible oils in conventional sheet metal forming. However, they can not be used as lubricants if high load magnitudes are applied during forming process (Syahrullaila et al., 2013). The usefulness edible oils (rape-seed oil, olive oil, sunflower oil) has been confirmed by Więckowski & Dyja (2017) in the process of Grade 2 titanium sheet metal forming. In the face of the growing food crisis, more emphasis should be placed on non-edible oils of vegetable origin. The tests were carried out in conditions of dry friction and lubrication of the sheet surface with edible and non-edible oils. The basic physical parameters of the oils used are listed in the Table 2.

Table 2. The basic physical properties of the vegetable oils

Oil	Kinematic viscosity mm^2/s	Density, g/cm^3	Flash point, °C
karanja	75	0.936	212.0
moringa	73	0.897	268.5
rape-seed	51	0.914	314.0
sunflower	58	0.920	319.1

2.3. ANOVA

For the experiment presented, an analysis of variance was performed in the STATISTICA 13 (StatSoft Inc.) program in which the significance of the influence of the controlled factors on the friction phenomenon was determined. In order to trace the influence of nominal pressure, viscosity and sample pre-strain on the examined feature, a three-factor classification model was adopted.

3. Results and discussion

Table 3 shows the influence of individual input parameters and their products on the value of the coefficient of friction. In addition to the impact of individual factors, there is an additional interactional source of variability, that is, the combined effect of input parameters. The interaction shows to what extent the influence of one factor depends on the level of the other factor. As a result of the analysis (Fig. 4 and Table 3), the hypothesis of no influence of the nominal pressure on the value of the coefficient of friction is rejected at the significance level of $p = 0.002$. Furthermore, the hypothesis of no influence of the lubricant viscosity on the value of the coefficient of friction is also rejected at the significance level of $p = 0.000$. It can therefore be concluded that the value of nominal pressure and oil viscosity significantly affect the coefficient of friction.

Table 3. Significance of the input parameters determined using ANOVA

Parameter	Significance level ($p \leq 0.05$)
pressure	0.002
viscosity	0.000
sample pre-strain	0.307
pressure · viscosity	0.951
sample-pre-strain · pressure	0.966
pressure · viscosity · sample pre-strain	0.987

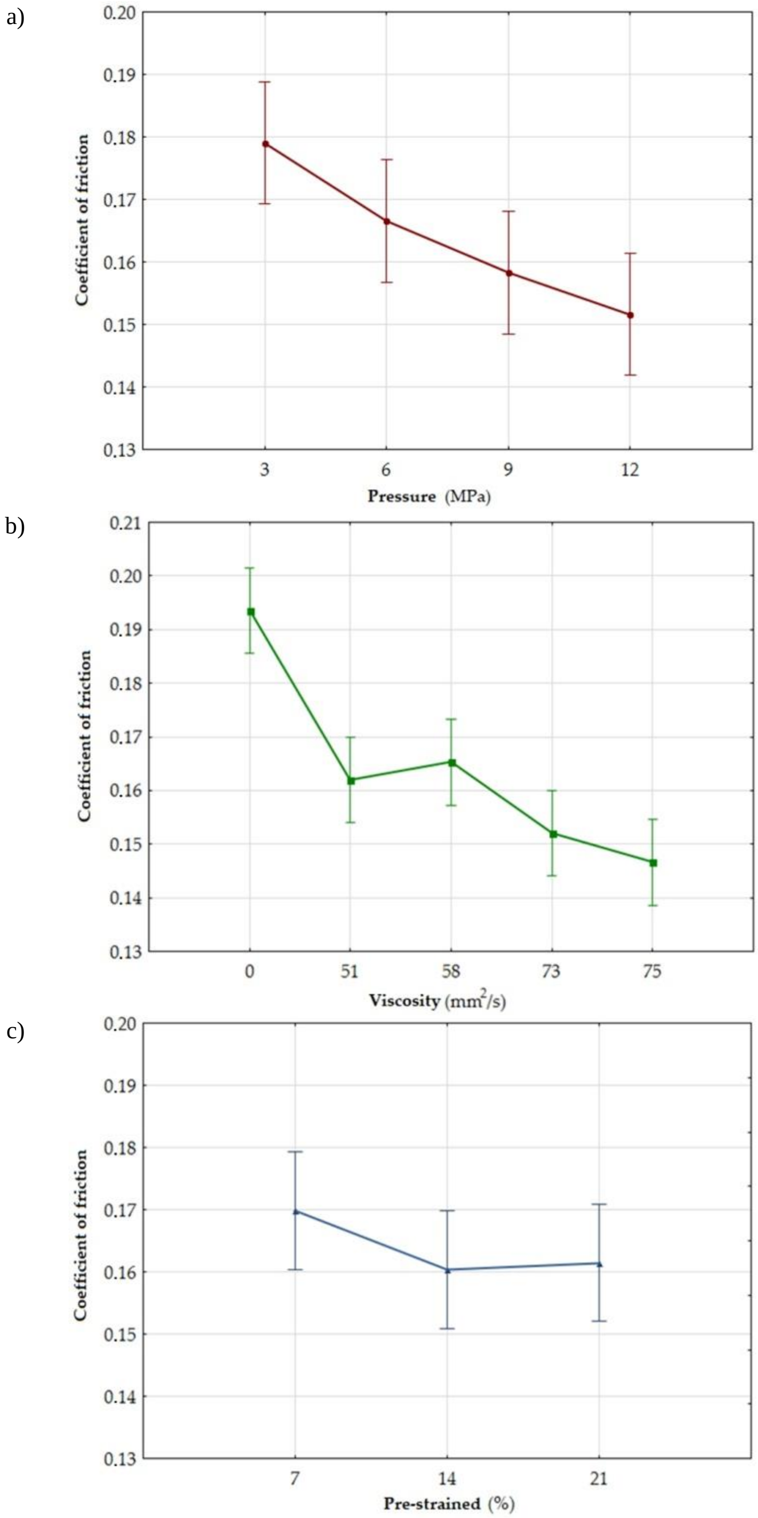

Fig. 4. Effect of (a) nominal pressure, (b) lubricant viscosity and (c) sample pre-strain on the value of the coefficient of friction

The results presented in Table 3 and Fig. 5 make it possible to unequivocally state that in the conducted statistical analysis concerning the occurrence of interactions, no statistically significant interactions between the tested factors were observed. In the tests, it was observed that the value of the coefficient of friction decreased with increasing pressure in the range of 3 to 12 MPa. It was found that at relatively low normal pressures, the friction force does not change proportionally to the normal force.

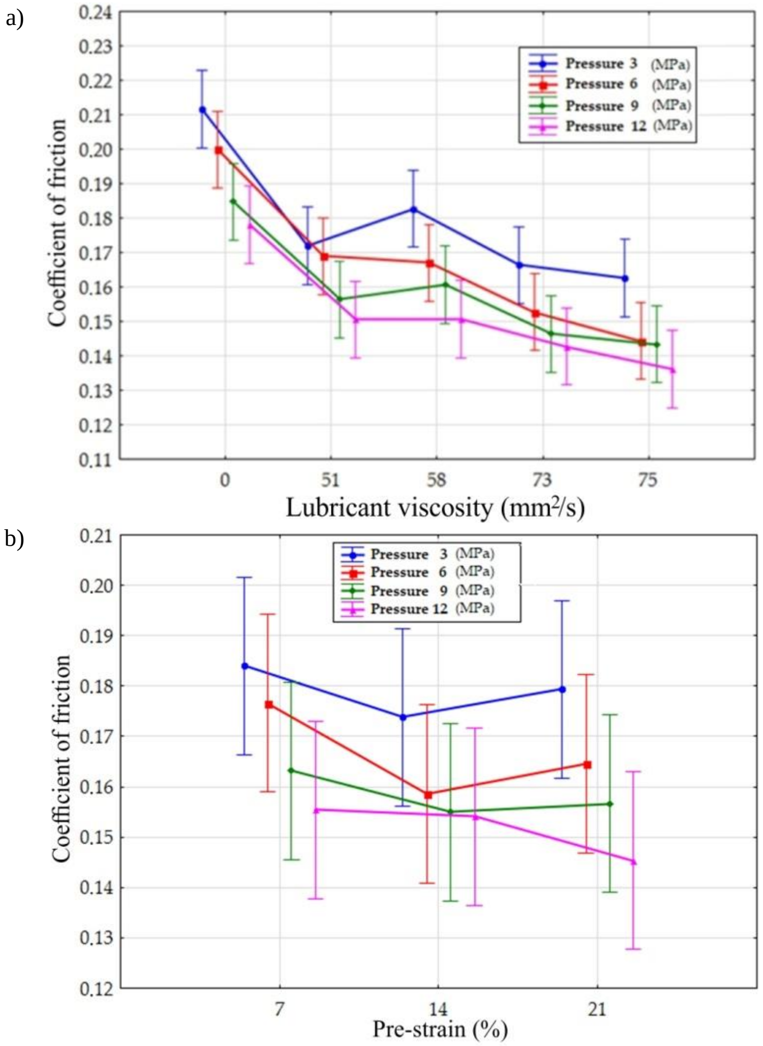

Fig. 5. Interactions between (a) viscosity and (b) sample pre-strain and the coefficient of friction

As expected, the coefficient of friction was highest in dry friction conditions. All the tested oils showed a similar effect of reducing the coefficient of friction depending on the degree of sample pre-strain. In the dry friction conditions for the pre-strained samples with the smallest degree of deformation (7%), an initial decrease in the value of the coefficient of friction was observed, followed by continuously increasing at the highest nominal pressures. Similarly, the curves of the lubrication efficiency of the pre-strained sheets at 14% showed a certain minimum, beyond which the value of the coefficient of friction began to increase. This can be explained by the fact that the additional plastic deformation of the sheet changes the mechanical properties of the sheet material through the work hardening effect. The SEM micrographs of the sheet surface after friction tests were carried out under nominal pressure of 12 MPa (Fig. 6). The sheet surface revealed frictional occurrences of the alignment mechanism. There are also visible grooves in the surface of the sheet, which are oil pockets. In general the flattening mechanism has been revealed in the surface of all specimens tested.

4. Conclusions

In this article, the assessment of the tribological performance of bio-based lubricants using the analysis of variance is presented. Based on the results, the following conclusions can be drawn:

- There is a dominant influence of the nominal pressure and lubricant viscosity on the value of the coefficient of friction in the sheet metal forming process. Both an increase in nominal pressure and oil viscosity result in a decrease in the value of the coefficient of friction for the range of pressures considered.
- The most significant impact on the value of the coefficient of friction was observed for changes in the viscosity value.

- No statistically significant interactions between the analysed factors in the sheet metal forming process were observed.
- All the oils tested showed a similar effect of reducing the coefficient of friction depending on the value of the sample pre-strain.
- Bio-lubricants based on moringa and karanja oils achieved the lowest values of the coefficient of friction.

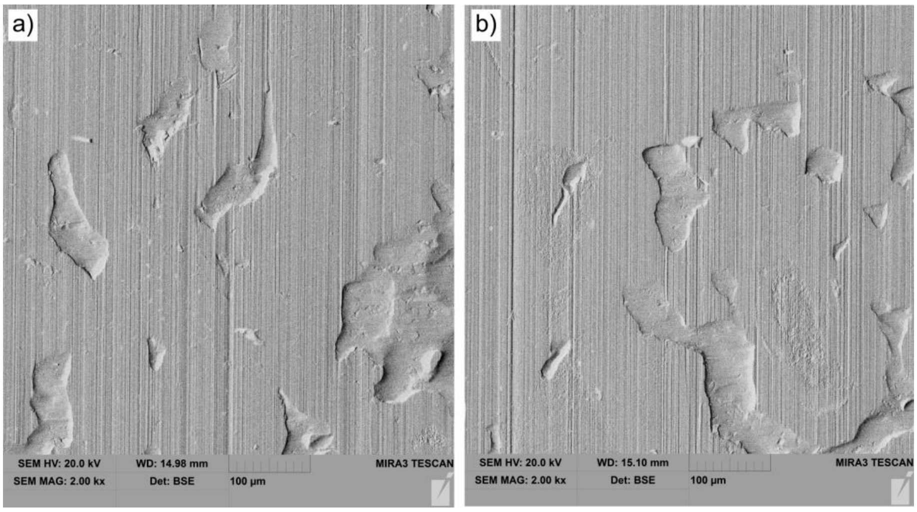

Fig. 6. The SEM micrographs of the sheet surface after friction tests under nominal pressure of 12 MPa: a) moringa and b) karanja oil

Flat-die strip drawing test is used to model friction condition in metal forming, i.e., between the punch and the die wall as well as between the blankholder and flange area of the drawpiece. This article is a part of the authors' effort to the application of artificial neural networks and machine leaning algorithms to understand the effect of the most important parameters on the coefficient of friction. The results obtained will constitute the knowledge base for training the artificial neural network.

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Ocena Właściwości Tribologicznych Smarów Pochodzenia Naturalnego za Pomocą Analizy Wariancji

Streszczenie

Celem artykułu jest wyznaczenie współczynnika tarcia blachy stalowej DC04 za pomocą specjalnego przyrządu do realizacji testu przeciągania pasa blachy. W badaniach wykorzystano cztery różne smary pochodzenia naturalnego: jadalne (oleje słonecznikowy i rzepakowy) oraz niejadalne (karanja i moringa). Eksperymenty przeprowadzono dla różnych wartości nacisku. Próbki w postaci pasów blachy wstępnie odkształcono do wartości 7, 14 i 21%. Wartości współczynnika tarcia wyznaczono jako stosunek siły tarcia do siły normalnej. Wpływ lepkości środka smarnego i nacisku kontaktowego na wartość współczynnika tarcia określono za pomocą analizy ANOVA. Zaobserwowano tendencję do zmniejszania się współczynnika tarcia wraz ze wzrostem nacisku. Wyniki istotności otrzymane po przeprowadzonej analizie ANOVA, potwierdziły zależność współczynnika tarcia od nacisku normalnego i lepkości oleju, jednocześnie zaprzeczając hipotezę o wpływie odkształcenia wstępnego na wartość współczynnika tarcia oraz możliwość wystąpienia istotnych interakcji.

Słowa kluczowe: analiza wariancji, ANOVA, tarcie, obróbka plastyczna