Advances in Mechanical and Materials Engineering

Volume 41, 2024, Pages 79-87
https://doi.org/10.7862/rm.2024.8

THE FACULTY OF MECHANICAL ENGINEERING AND AERONAUTICS
RZESZOW UNIVERSITY OF TECHNOLOGY

Original Research

Frictional Characteristics of EN AW-6082 Aluminium Alloy Sheets Used in Metal Forming

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Received: 1 February 2024 / Accepted: 9 May 2024 / Published online: 20 May 2024

Abstract

This article is devoted to testing EN AW-6082 aluminium alloy sheets in friction pair with NC6 (1.2063) tool steel. A special tribometer designed to simulate the friction conditions in sheet metal forming processes was used for friction testing. The research aimed to determine the influence of contact pressure, surface roughness of the tool, and lubrication conditions on the value of the coefficient of friction in the strip drawing test. Three grades of typical petroleum-based lubricants with kinematic viscosities between 21.9 and 97 mm^2/s were used in the tests. The surface morphologies of the sheet metal after the friction process were observed using a scanning electron microscope. A tendency for the coefficient of friction to decrease with increasing contact pressure was observed. LHL32 and 75W-85 oils lost their lubricating properties at a certain pressure value and with further increase in pressure, the coefficient of friction value tended to increase. The 10W-40 oil with the highest viscosity reduced the coefficient of friction more intensively than the LHL32 oil.

Keywords: EN AW-6082-T6, friction, sheet metal forming, strip drawing test

1. Introduction

A 6xxx-series Al-based alloy sheets are used for stamping aluminium profiles used in the aerospace, marine, automobile, and defence sectors (Dubey et al., 2023; Kaščák et al., 2021; Mukhopadhyay, 2012). Ensuring the desired quality of products is related to the phenomenon of friction (Tan & Liew, 2023). In each plastic forming process, there is metallic contact between the tool and the formed sheet. Apart from the phenomenon of friction, the second important problem in sheet metal forming is springback (Slota et al., 2017). Depending on the type of forming process (stamping, bending, spinning, incremental forming, etc.), there are different contact conditions, depending mainly on contact pressures (Mulidrán et al., 2023), sliding velocity (Luiz et al., 2023), temperature (Lukovic, 2019) and surface treatment (Nasake & Sakuragi, 2017).

Reducing friction can be easily achieved by using lubricants (Hol et al., 2017; Ludwig et al., 2010). Due to their widespread availability and relatively low cost, liquid oils are the most frequently used lubricants in sheet metal forming (Lachmayer et al., 2022). In addition to oils specifically intended for forming, oils intended for other purposes are also used (machine oils, hydraulic oils, gear oils, etc.). Dry film lubricants (Meiler et al., 2003) have also been developed. Understanding the phenomenon of friction in metal forming operations involves carrying out special tribological tests intended for modeling specific friction conditions in contact zone (Bay et al., 2008; Reichardt et al., 2020). For this reason, research on determining the coefficient of friction of sheet metal is somewhat limited. Chruściński et al. (2017) tested an EN AW-6060 sheet in friction pair with a countersample made of 100Cr6 steel under conditions of dry friction and titalite grease lubrication. A block-ring friction tester was used in investigations. Under lubrication conditions, a reduction in the coefficient of friction was observed by over 80% compared to dry friction conditions. Xu et al. (2018) investigated the frictional performance of 6xxx-series aluminium alloy with various lubrication conditions in the draw bead friction test. It was found that the value of the pulling force of samples cut in the transverse direction relative to the sheet rolling direction was lower than of samples cut across the sheet rolling direction. Bellini et al. (2019) studied the effect of friction on the formability of EN AW-6060 aluminium alloy sheet. It was found that the distance between the specimen centre and the necking point effects on the friction coefficient value. Aiman and Syahrullail (2020) used the ring compression test to study the tribological performance of EN AW-6060 aluminium alloy sheets in the presence of palm oil-based lubricants and typical metal-forming lubricant. It was found that palm-oil base lubricant reduced the forming load however, its high friction lead to high surface roughness. Domitner et al. (2021) investigated friction between EN AW-6016 aluminium alloy sheets and 1.2343 tool steel using strip drawing test. They concluded that the coefficient of friction determined for as-delivered and naturally aged conditions did not differ significantly. An increase in sliding velocity resulted in a decrease in the intensity of the flattening of our asperities. Sabet et al. (2021) investigated the tribological condition of EN AW-6016-T4 aluminium alloy using the pin-on-plate test. Contact pressures between 4 and 16 MPa were considered. They found that the coefficient of friction decreased with increasing the sliding speed and the nominal contact pressure and sliding velocity. Hu et al. (2019) investigated the formation of a transfer layer between cast iron G3500 and EN AW-6082 aluminium alloy. It was concluded that the aluminium transfer increases with increasing sliding distance. Mohamed et al. (2017) studied the effect of friction on the formability of EN AW 6061-T4 aluminium alloy sheet under various lubrication conditions. The results of cup tests showed the significant effect of friction conditions on the formability of sheet metals. Reddy and Vadivuchezhian (2020) studied the effect of normal load on the coefficient of friction of EN AW-6082 aluminium alloy sheets under dry sliding conditions. The results of pin-on-disc tests revealed that the increase in wear volume resulting from an increase in normal load. Dubois et al. (2024) analysed the effect of lubrication (mineral oil, paraffin oil and mineral oil) and normal loads ranging from 5 to 600 N on the galling behaviour and coefficient of friction of EN AW-6082-T6 aluminium alloy sheets. Results of pin-on-disc tests showed the beneficial effect of liquid lubricants in limiting the galling phenomenon. Furthermore, it was found that onset of galling is sensitive to surface roughness on countersamples.

Tribological tests of the EN AW-6082 alloy under sheet metal forming conditions are limited. Therefore, this article is devoted to testing EN AW-6082 sheets in friction pair with NC6 (1.2063) tool steel. Strip drawing tests were performed using a special tribotester. The research campaign took into account various contact pressure conditions and various oils with kinematic viscosity of 21.9–97 mm^2/s.

2. Material and methods

2.1. Test material

The 1-mm-thick EN AW-6082-T6 aluminium alloy sheet used as test material. The mechanical properties of the sheets were determined three times in a uniaxial tensile test. Test samples were cut in three directions (0°, 45° and 90°) in relation to the sheet rolling direction. Three samples were tested for each condition. Selected mechanical properties are presented in Table 1. Basic surface roughness parameters of EN AW-6082-T6 sheet metal were measured using a T8000-RC (Hommel-Etamic) profilometer. The surface topography and bearing area curve of the workpiece surface are shown in Figs. 1a and 1b, respectively.

The values of the selected 3D roughness parameters are as follows: Sa = 0.141 µm, Sq = 0.178 µm, Sp = 0.559 µm, Sv = 0.880 µm, Sz = 1.44 µm, Sku = 3.29 and Ssk = –0.253. The morphology of surfaces of the sheet metals before and after friction testing were analysed using a scanning electron microscope (SEM). SEM micrograph of the surface of as-received sheet metal is presented in Fig. 2. The surface of the sheets is characterized by directional grooves as a result of the rolling process and surface cracks.

Table 1. Basic mechanical parameters of the test material.

Sample orientation, °	Yield stress, MPa	Ultimate tensile stress, MPa	Elongation (A_{80}), %
0	314	342	13.7
45	307	337	14.2
90	313	341	12.0

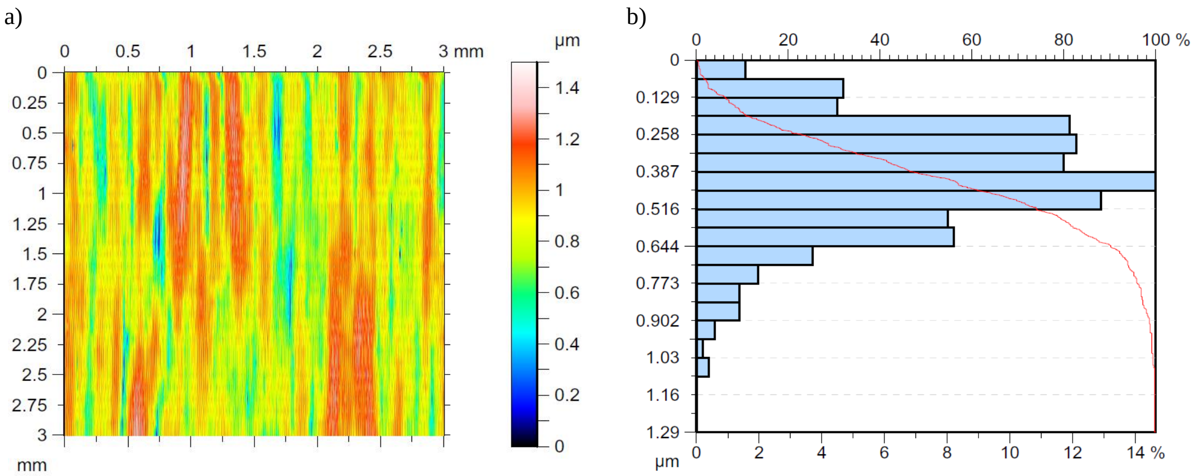

Fig. 1. a) surface topography and b) bearing area curve of the sheet metal tested.

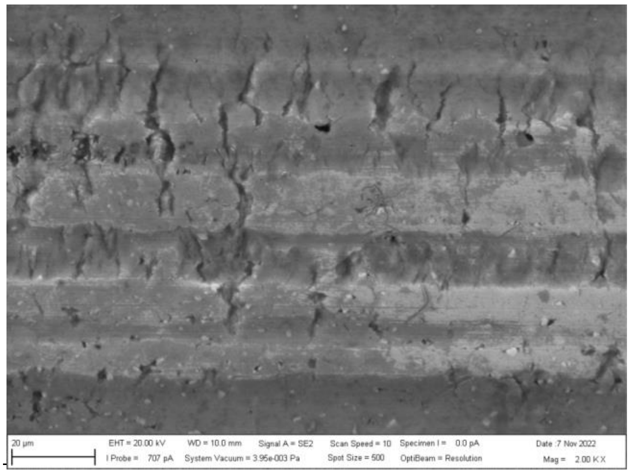

Fig. 2. SEM micrograph of the as-received EN AW-6068-T6 sheet metal.

2.2. Friction test

The tests were carried out by pulling a strip of sheet metal 240 mm long and 18 mm wide between two countersamples with a radius of rounding the working surface R = 200 mm. Specimens for friction test were cut along the sheet rolling direction. Sliding speed was 10 mm/min. The countersamples were made of NC6 steel (1.2063). The selected 3D roughness parameters of the countersamples are as follows: Sa = 1.89 µm, Sq = 2.27 µm, Sp = 9.76 µm, Sv = 10.7 µm, Sz = 20.4 µm, Sku = 2.60 and Ssk = –0.585. The surface topography and linear profilogram of the countersample surface are shown in Figs. 3 and 4, respectively.

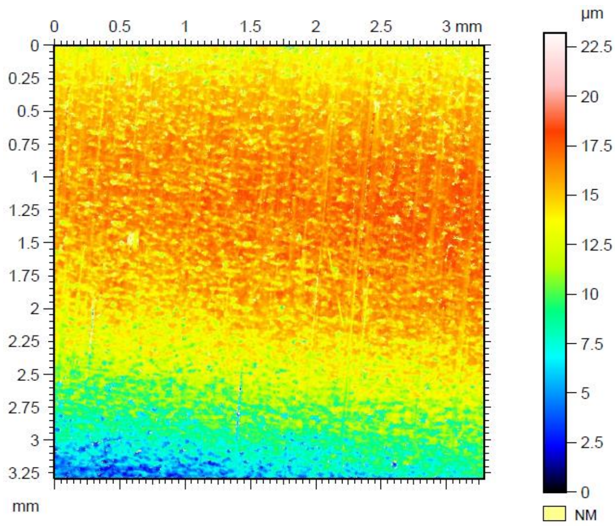

Fig. 3. Topography of the surface of countersample.

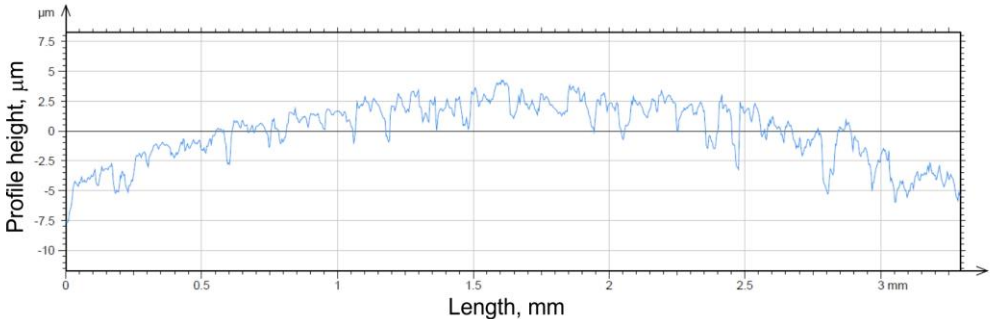

Fig. 4. Linear profilogram of the surface of countersample.

The research tribotester (Fig. 5), the structure of which was presented by Haar (1996), was mounted in the lower gripper of the Zwick/Roell Z100 testing machine. Meanwhile, the upper end of the sample was fixed in the upper gripper of the testing machine. The upper gripper of the testing machine can only move in the drawing direction (Fig. 5). The contact force F_N was exerted on the sample material by a spring with the known characteristic force = f(deflection). On the basis of shortening the spring length by tightening the set bolt (Fig. 5), the spring reaction force was obtained (from the force = f(deflection) characteristic), which is directly equal to F_N. Pulling force F_T was measured by the measuring system of the testing machine. Based on the values of the average friction force and the pulling force, the value of the coefficient of friction μ was determined from Eq. (1) (Jewvattanarak et al., 2016):

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

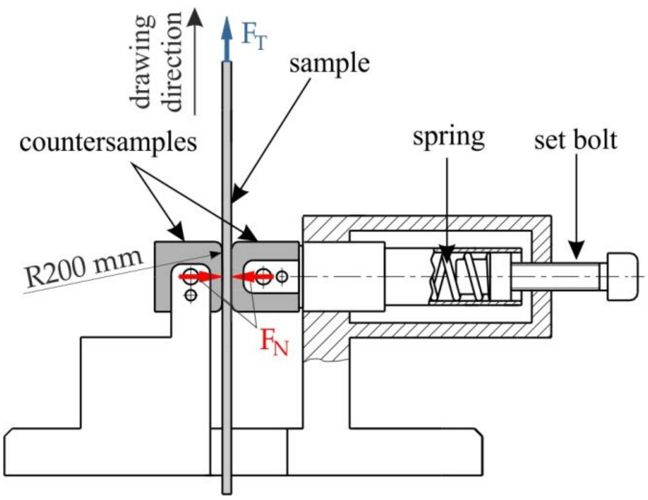

Fig. 5. Schematic diagram of the friction tribometer.

Friction tests were carried out under lubrication conditions with hydraulic oil LHL32 (kinematic viscosity 21.9 mm^2/s, density 874.1 kg/m^3), gear oil 75W-85 (kinematic viscosity 64.3 mm^2/s, density 862.0 kg/m^3) and engine oil 10W-40 (kinematic viscosity 97 mm^2/s, density 870.0 kg/m^3). Reference tests were performed for as-received surfaces of sheet metals. The tests assumed the value of contact pressures occurring in the blankholder zone in the deep-drawing process. Based on the values of contact forces, the average contact pressure was determined according to Eq. (2) (Haar, 1996):

$$p_{\text{mean}} = \frac{\pi}{4} \cdot \sqrt{\frac{\frac{F_N}{w} \cdot \frac{2E_1E_2}{E_2 \cdot (1-\nu_1^2) + E_1 \cdot (1-\nu_2^2)}}{2\pi R}} \tag{2}$$

where w is sample width; E_1 = 200000 MPa (Graba, 2020) and E_2 = 69000 MPa (6082-T6 Aluminum, 2023) are Young's moduli of steel countersample and sheet metal, respectively; ν_1 = 0.3 MPa (6082-T6 Aluminum, 2023) and ν_2 = 0.33 MPa (6082-T6 Aluminum, 2023) are Poisson's ratios of steel countersample and sheet metal, respectively.

3. Results and discussion

Figure 6 shows the influence of contact pressure on the coefficient of friction of the tested sheets. In the conditions of testing the sheet in the as-received state, a tendency was observed for the coefficient of friction to decrease from 0.28 for a contact pressure of 4.4 MPa to 0.24 for a contact pressure of 11.7 MPa. The tendency for the coefficient of friction to decrease with increasing contact pressure is the result of the non-linear relationship between the friction force and the contact force. A similar relationship was previously observed by Dou and Xia (2019), Sabet et al. (2021) and Xia et al. (2022). At low pressures, the dominant phenomenon is the flattening of the summits of the sheet metal asperities (Fig. 7) by the surface of the countersamples.

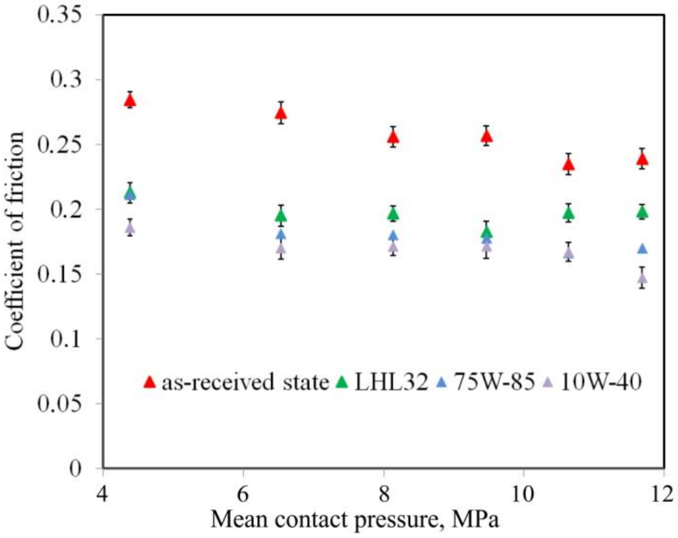

Fig. 6. Effect of mean contact pressure on the coefficient of friction.

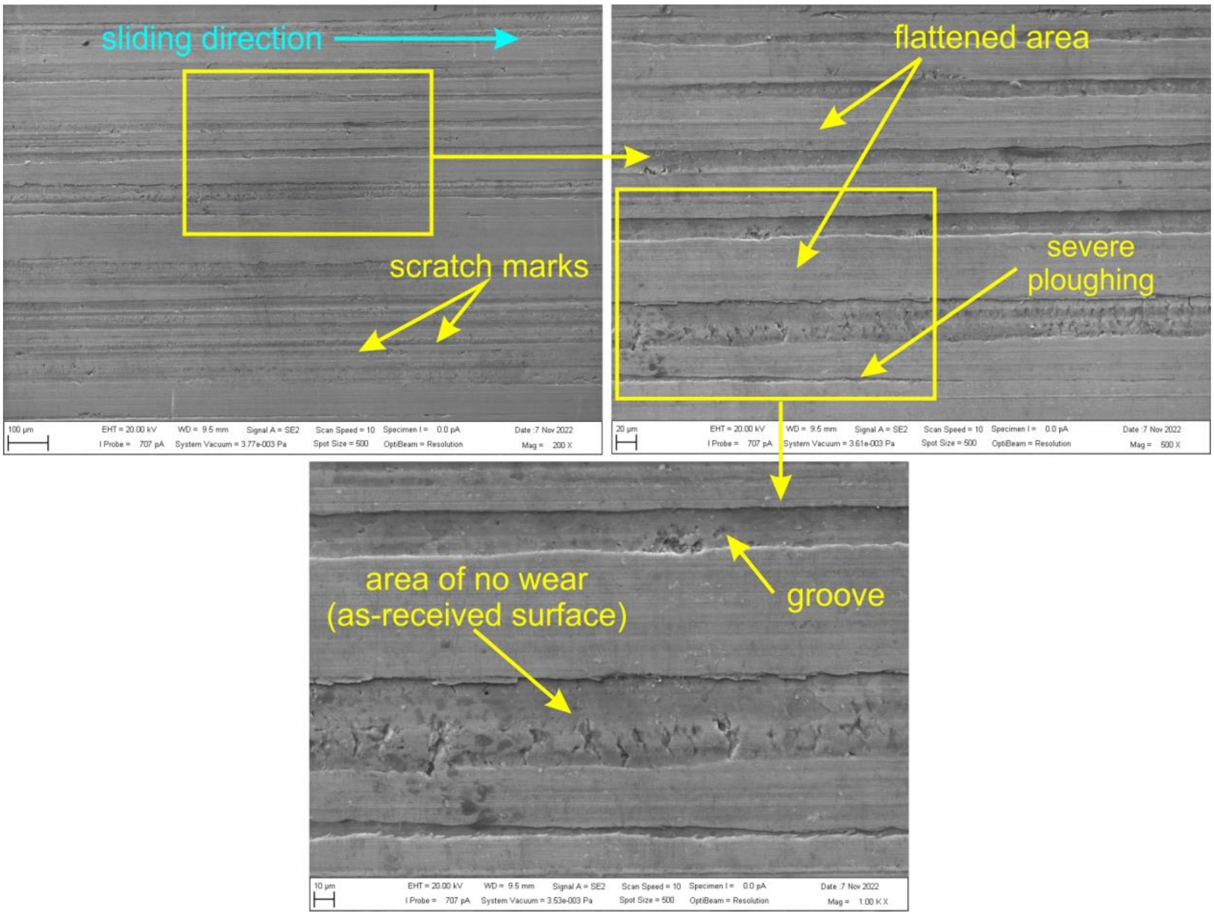

Fig. 7. View of the sheet metal surface after friction test (no lubrication, contact pressure 11.69 MPa).

Under lubrication conditions with LHL32 and 75W-85 oils, the coefficient of friction also tends to decrease with increasing pressure, but only up to a certain value of contact pressure, beyond which it tends to increase. However, when lubricating the sheet metal surface with 10W-40 oil, the value of the coefficient of friction decreases over the entire pressure range. Under lubricated conditions, friction occurs due to two mechanisms.

When the pressure is increased, the contact of the surface asperities intensifies, so that under unfavorable conditions a ploughing phenomenon may occur (Fig. 7). At the same time, greater contact pressure increases the pressure of the lubricant located in the valleys of surface asperities. Friction therefore results from the interaction of many mechanisms at the same time. Under lubricated conditions, the flattening phenomenon as a result of plastic deformation of the surface asperities under the influence of contact pressure was also observed (Fig. 8).

From the trend lines, it can be concluded that the 10W-40 oil provided the lowest coefficient of friction (Fig. 6). There is a clear influence of viscosity on the coefficient of friction. The higher the viscosity of the oil, the lower the coefficient of friction. It is also visible that under certain pressure during lubrication with LHL32 and 75W-85 oils, the lubricant film was broken, leading to an increase in the coefficient of friction. The 10W-40 oil with a higher viscosity than LHL32 and 75W-85 oils shows good lubricating properties in the entire range of pressures tested.

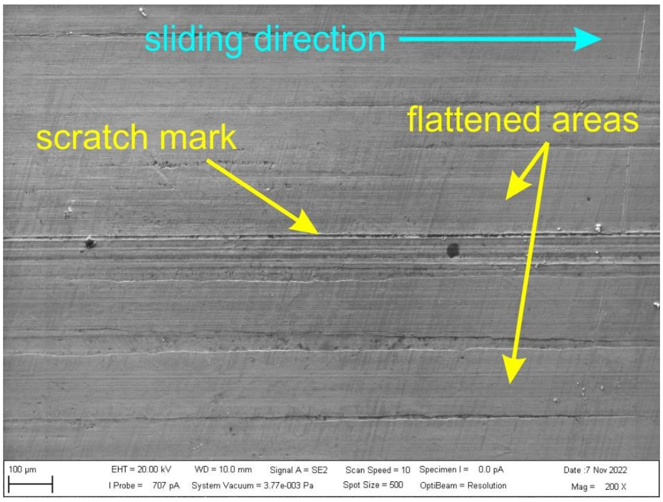

Fig. 8. View of the sheet metal surface after friction test (LHL32 lubricant, contact pressure 10.63 MPa).

An additional parameter, effectiveness of lubrication (EoL), was introduced to quantitatively assess the effect of lubrication on the coefficient of friction:

$$\mathrm{EoL} = \left(1 - \left(\frac{\mu(\text{lubricated conditions})}{\mu(\text{dry friction})}\right)\right) \cdot 100\% \quad (3)$$

LHL32 oil shows a tendency to decrease lubrication efficiency with increasing contact pressure, although the lowest lubrication efficiency occurs for contact pressures in the range between 10.63 and 11.69 MPa (Fig. 9). Pressures of this value clearly led to the breakdown of the lubricating film and the intensification of the metallic interaction of the rubbing surfaces. It should be noted that LHL32 oil was characterized by the lowest value of kinematic viscosity. The lubrication efficiency of LHL32, 75W-85 and 10W-40 oils in the entire range of analyzed pressures is between 16.1 and 29%, between 25.8 and 34.1% and between 28.9 and 34.6%, respectively. At contact pressures between 10.63 and 11.69 MPa, 75W-85 and 10W-40 oils provided almost twice the EoL index. 75W-85 and 10W40 oils initially show an increased EoL index and then decrease to a minimum value of approximately 30 %. This is typical behaviour observed when rubbing a soft sheet metal and a hard tool. The continuous evolution of the surface topography produces a specific surface topography with valleys in which the lubricant is located. The increase in the EoL index for the 10W-40 grease under contact pressures of 11.69 MPa can be explained by the appropriate viscosity of the oil, which allowed the creation of a pressure cushion separating the rubbing surfaces.

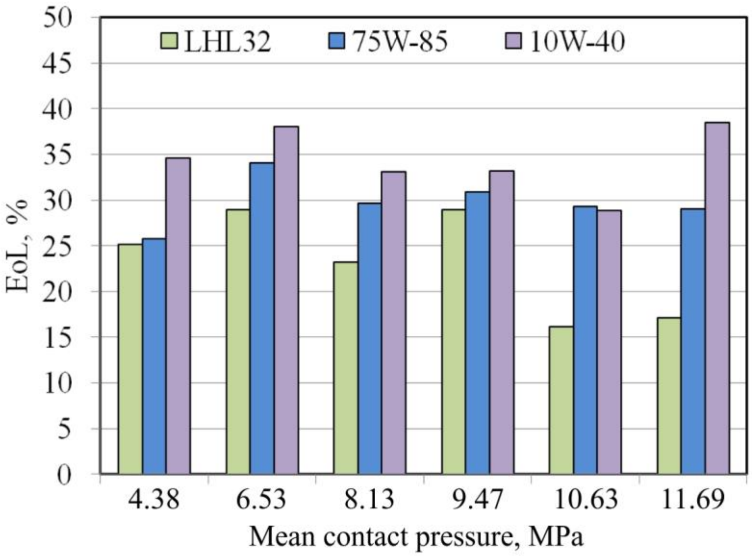

Fig. 9. Effect of mean contact pressure on the EoL index.

4. Conclusions

As a result of the friction tests carried out on the EN AW-6082-T6 sheets using the strip drawing test, a tendency for the coefficient of friction to decrease with the increase in contact pressure was observed. The values of the coefficient of friction of the sheets in the as-received state varied in the range between 0.235 and 0.284 for the considered range of contact pressures between 4.38 and 11.69 MPa. Under lubricated conditions with LHL32 and 75W-85 oils, the coefficient of friction also tends to decrease with increasing contact pressure, but only up to a certain value of contact pressure, beyond which it tends to increase (LHL32) or stabilise (75W-85). In the case of 10W-40 oil, which has the highest viscosity, it was found that the coefficient of friction decreased in the entire range of pressures considered. The basic friction mechanism observed during experimental tests was flattening the surface asperities of sheet metal as a result of plastic deformation. The as-received sheet metal showed longitudinal grooves resulting from the manufacturing process. As a result of the friction process, the bottoms of these grooves remained unchangeable, providing spaces containing lubricant. LHL32 oil showed the lowest EoL index between 16.1 and 29 % depending on the contact pressure.

The conducted research inspired the authors to expand the investigations to a wide range of contact pressures in the future. Sheets made of aluminium alloys are prone to seizing. It is also necessary to check the friction conditions for various sheet metal-tool material combinations. Another unexplored area is the influence of temperature generated in the contact zone on the friction behaviour of the sheet metal surface. There is a really limited number of articles published in this area.

Acknowledgments

This work was supported by the Slovak Research and Development Agency and Polish National Agency for Academic Exchange, project title: Research on the possibilities of forming and joining innovative metal-plastic composites in the production of lightweight thin-walled structures”, project numbers: SK-PL-23-0040 and BPN/BSK/2023/1/00038/U/00001. The authors are also grateful for the support in the experimental work to the Grant Agency of the Ministry of Education, Science, Research, and Sport of the Slovak Republic (grant number VEGA 1/0539/23).

Friction tests were carried out at The University College of Applied Sciences in Krosno. The authors wish to express their thanks to Dr. Romuald Fejkiel from The University College of Applied Sciences in Krosno for his help in conducting friction research.

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Charakterystyka Tarciowa Blach ze Stopu Aluminium EN AW-6082 Stosowanych w Obróbce Plastycznej Metali

Streszczenie

Artykuł poświęcony jest badaniom tarciowym blach ze stopu aluminium EN AW-6082 w parze ciernej ze stalą narzędziową NC6 (1.2063). Do badań tarcia wykorzystano specjalny tribotester przeznaczony do symulacji warunków tarcia w procesach kształtowania blach. Celem badań było określenie wpływu nacisku kontaktowego, chropowatości powierzchni narzędzia i warunków smarowania na wartość współczynnika tarcia w próbie ciągnienia pasa blachy. Do badań wykorzystano trzy gatunki typowych smarów na bazie ropy naftowej o lepkości kinematycznej od 21,9 do 97 mm^2/s. Morfologię powierzchni blach po procesie tarcia obserwowano za pomocą skaningowego mikroskopu elektronowego. Zaobserwowano tendencję do zmniejszania się wartości współczynnika tarcia wraz ze wzrostem nacisku kontaktowego. Oleje LHL32 i 75W-85 przy określonej wartości nacisku kontaktowego traciły swoje właściwości smarne i wraz z dalszym wzrostem nacisku zaobserwowano zwiększanie się wartości współczynnika tarcia. Olej 10W-40 o najwyższej lepkości kinematycznej zapewnił większe zmniejszenie wartości współczynnika tarcia niż olej LHL32.

Słowa kluczowe: AW-6082-T6, tarcie, kształtowanie blach, test przeciągania pasa blachy