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EFFECT OF THE LUBRICATION ON THE FRICTION CHARACTERISTICS OF EN AW-2024-T3 ALUMINIUM ALLOY SHEETS

Abstract: The article presents the results of friction tests conducted on EN AW-2024 Alclad aluminium alloy sheets. The lubrication efficiency of oleic acid, mineral and vegetable oils with the addition of SiO_2 and TiO_2 nanoparticles was determined using the strip drawing test to assess the friction conditions in the flange area in the deep drawing process. The samples in the form of sheet metal strips were pulled between countersamples with a rounded surface at a speed of 2.5 mm/s. Gear oil and oleic acid demonstrated the lowest value of the coefficient of friction (COF) in the whole range of nominal pressures investigated. The lowest efficiency in reducing the COF was shown by hydraulic oil, olive oil and machine oil. A high content of TiO_2 nanoparticles (0.5-0.9%wt%) is beneficial in the friction process involving oleic acid.

Keywords: aluminium alloy, lubrication, nanoparticles, strip drawing test, coefficient of friction

1. Introduction

Sheet metal forming (SMF) processes are one of the most frequently used methods of manufacturing finished sheet metal products. Friction is the phenomenon that determines whether of a product with an appropriate surface finish is obtained (Dou et al., 2020; Dou & Xia, 2019; Seshacharyulu et al., 2018). One of the basic ways of reducing the value of the coefficient of friction (COF) in sheet metal forming (SMF) is the use of lubricants (Sigvant et al., 2019; Zabala et al., 2021). The following requirements are imposed on technological grease: ease of application, resistance to high normal pressures, stability in reducing frictional

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resistance over a wide range of pressures, ease of removal from the product and biodegradability (Krasowski, 2021). Despite the fact that most of the process lubricants used in SMF operations are based on synthetic oils, Carcel et al. (2005), Idegwu et al. (2019), Rao et al. (2009) indicate that vegetable oils can be an effective alternative.

The mineral and synthetic oils usually used in sheet metal processing can be successfully replaced with vegetable oils, even when stamping galvanised sheets (Więckowski et al., 2020; Yu et al., 2010). The presence of long chains of fatty acids in vegetable oils enables effective separation of the friction surface between the tool and the sheet under boundary friction conditions. In addition, these oils provide sufficient protection against corrosion, have a high viscosity index, and are environmentally friendly and biodegradable (Liñeira del Río et al., 2022). Over the same period that 80% of vegetable oils were degraded, only 15–20% of mineral oils degraded (Padgurskas et al., 2016). The major disadvantage of vegetable oils is weak oxidation (Fox et al., 2007).

To improve the properties of lubricating oils, nanoparticle additives are used (Pang & Ngaile, 2020; Zareh-Desari & Davoodi, 2016). The research of Hernández Battez et al. (2008) and Peng et al. (2009) on the use of nanoparticles ZnO, CuO, ZrO_2, TiO_2, SiO_2 as additives in vegetable oils and paraffin oil showed a reduction in the value of the COF and wear. Cortes et al. (2020) investigated the tribological performance of nanoparticles of titanium dioxide (TiO_2) with a purity of 99.5% and SiO_2 with a purity of 99.9%, which were dosed into oils in the amount of 0.1, 0.5 and 0.9% by weight. The experimental results showed that the COF decreased with the addition of SiO_2 and TiO_2 nanoparticles by 77.7% and 93.7%, respectively when compared to base sunflower oil. Although nanoparticles have proven to enhance lubricant properties, the current issue is compatibility Gulzar et al. (2017). Peng et al. (2008) investigated the tribological properties of liquid paraffin to which diamond and SiO2 nanoparticles, which were prepared by the surface modification method using oleic acid. It was found that both nanoparticles as additives in liquid paraffin have better antiwear and antifriction properties than the pure paraffin oil. A ball-on-ring friction tests conducted by Peng et. al. (2010) indicated that the sizes of the synthesized SiO_2 nanoparticles are distributed uniformly and that the optimal concentrations of SiO_2 nanoparticles in liquid paraffin is associated with better tribological properties than pure paraffin oil.

The strip drawing test (SDT) is commonly used to evaluate the coefficient of friction at the sheet metal-blankholder interface. In this paper, the performance of mineral and biodegradable oils with additions of the SiO_2 and TiO_2 nanoparticles was investigated using the SDT using EN AW-2024-T3 aluminium alloy sheets were used as test material. The effect of nominal pressure and oil type has been presented and discussed.

2. Material and Methods

The experimental tests of friction in the SDT were carried out on a 1-mm-thick EN AW-2024-T3 Alclad aluminium alloy sheet strips. The average surface roughness of the sheets is 0.78 µm. The SDT consists in pulling a sheet strip crimped between two non-rotating countersamples with a radius of working surface R = 200 mm. Surface morphology of the countersamples was measured with the 3D optical profiler Talysurf CCI Lite. The values of basic surface roughness parameters are as follows: arithmetical mean height Sa = 1.53 µm, kurtosis Sku = 2.07, skewness Ssk = -0.014. Views of the test stand and countersamples are shown in Figs. 1a and 1b, respectively. A friction simulator frame was mounted in the lower bracket of the Zwick/Roell Z100 testing machine, and one of the ends of the sheet metal is mounted in the upper bracket of the machine. The value of the COF, which is a reference point for the qualitative assessment of a lubricant in reducing friction, can be determined from the relationship:

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

where: F_T – pulling force, F_N – clamping force.

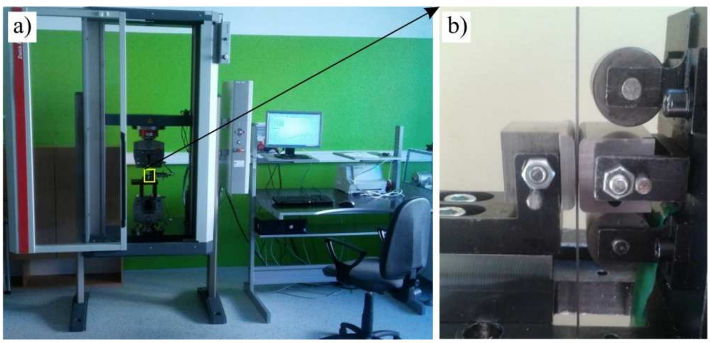


Fig. 1. View of a) the test stand and b) countersamples

The frame (1) of the device (Fig. 2) was mounted in the mounting base of the testing machine. An adjusting screw (6) is used to adjust the clamping (normal) force. The clamping force was determined by tightening the screw (6) with the appropriate torque. The sample (2) was pulled through the fixed countersamples made of cold-work tool steel with a constant sliding speed of 2.5 mm/s. The friction force was recorded continuously by the control system of the testing machine.

Based on the review of articles by Ahmad et al. (2020), Bay et al. (2010), Rodrigues et al. (2020), Zavala et al. (2021), the following lubricants were selected for testing: L-AN46 machine oil, L-HM 46 hydraulic oil, 75W- 85 gear oil, oleic acid, sunflower oil and olive oil. The basic properties of the lubricants declared by the manufacturers in the product cards are presented in Table 1. The basic physical properties of oleic acid $C_{18}H_{34}O_2$ are as follows: density ρ = 895 kg/m^3, molar mass 283.47 g/mol, boiling point T_w = 360°C. TiO_2 and SiO_2 nanoparticles were added to the two selected oils that showed the lowest COF values during the tests. The following amounts of nanopowders were used: 0.1, 0.5 and 0.9 wt.%. The particle size of TiO_2 was 16 nm and SiO_2 15 nm.

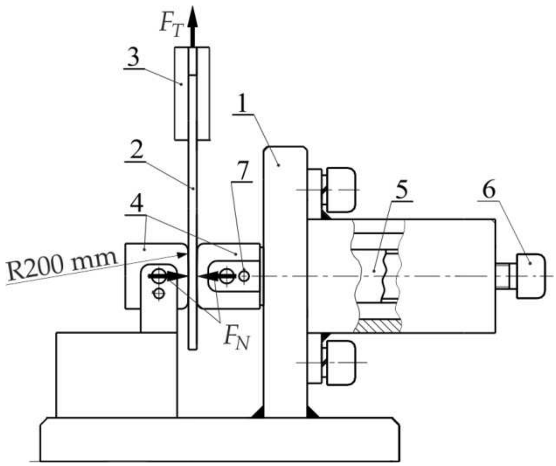


Fig. 2. Diagram of the friction tester: 1 - frame, 2 - sample, 3 - upper bracket of the testing machine, 4 - countersamples, 5 - sleeve, 6 - screw, 7 - blocking pin

Table 1. Basic physical properties of the lubricants used in the tests

Oil	Density ρ, kg/m^3	Kinematic viscosity η_k, mm^2/s
machine oil LAN-46	875	43.9
hydraulic oil L-HM 46	877	44.2
gear oil 75W-85	837	64.6
oleic acid	895	4.50
sunflover oil	883	4.45
olive oil	890	4.50

3. Results and Discussion

For simplification, the following oil acronyms have been adopted: machine oil (MO), hydraulic oil (HO), gear oil (GO), oleic acid (OA), sunflower oil (SO) and olive oil (OO). Under dry friction conditions, EN AW-2024-T3 Alclad sheets exhibited a higher friction coefficient of about 0.2 (Fig. 3). The pressures between the materials of the friction pair (Alclad and cold-work tool steel) are transferred through the micro-areas of real contact. In these areas, the yield point of the

Alclad material is exceeded (50.25 MPa according to Vinay and Vinoth, 2014). This causes an increase in shear stresses and a local increase in temperature in the micro-contact areas. Such a situation - large deformations and high temperature - favours the formation of non-diffusion adhesive tacking, which increases the COF (Abe et al. 2016). Among unmodified oils, GO and OA provided the lowest value of COF in the entire range of nominal pressures investigated (Fig. 3).

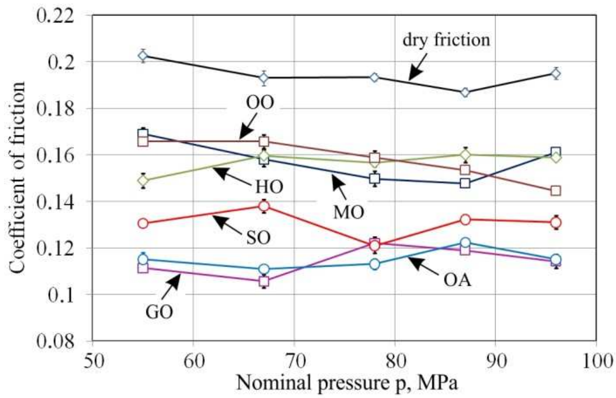


Fig. 3. Effect of nominal pressure on the value of the COF of sheets tested with the use of non-modified oils

The low value of the yield strength of Alclad consisting of technically pure aluminium favours seizing of the coating surface (Fig. 4), also contributing to increasing the value of the COF, especially in conditions of high pressures of 87-96 MPa. The result is a rapid increase in the real contact area by flattening the surface asperities of the Alclad. High pressures combined with intensive flattening of the surface asperities lead to the formation of a network of cracks and discontinuities in the surface layer of the coating (Fig. 5). In order to determine the efficiency with which the oil used reduces the COF by the oil used, the coefficient of lubrication efficiency was introduced:

$$\delta = \frac{\mu_{dry} - \mu_{lub}}{\mu_{lub}} \cdot 100\% \tag{2}$$

where μ_{dry} and μ_{lub} are the COFs determined in dry and lubricated conditions, respectively.

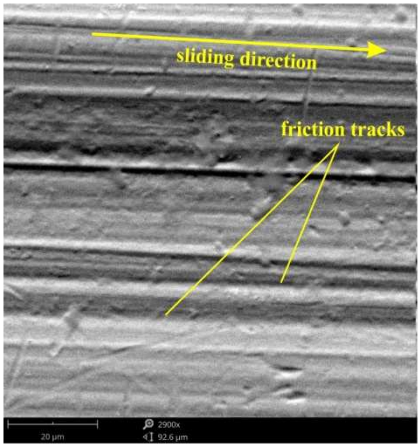


Fig. 4. SEM micrograph of a sheet surface tested under conditions of lubrication with MO at a pressure p = 55 MPa

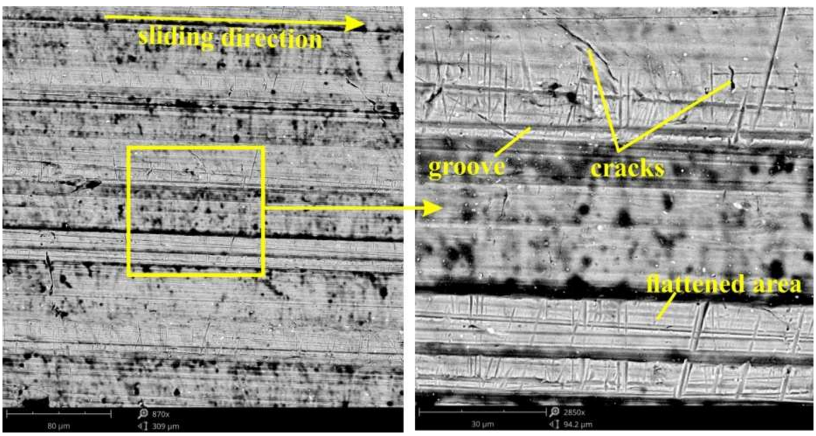


Fig. 5. SEM micrographs of a sheet surface tested under conditions of lubrication with HO at the nominal pressure of 78 MPa

The value of the coefficient lubrication efficiency during the friction process with gear oil and oleic acid fluctuates for both oils in a similar range of 35-45% (Fig. 6). At low pressures, the COF was least effectively reduced by MO and OO, and at high pressures by HO and MO. Under these conditions, these oils ensured a coefficient of lubrication efficiency in the range of 14-26%.

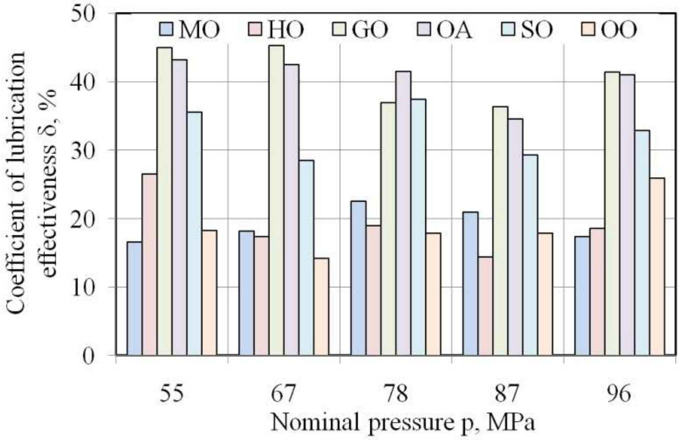


Fig. 6. Influence of nominal pressure on the coefficient of lubrication efficiency on non-modified oils

Under the conditions of lubrication with gear oil, within the range of the nominal pressures considered of 55-67 MPa, a clear tendency was observed for the value of the COF to increase with increasing content of TiO_2 nanoparticles (Fig. 7). A high content of TiO_2 nanoparticles during the friction process is advantageous under the highest of the nominal pressures considered, 87 and 96 MPa, when lubricated with oleic acid containing 0.5-0.9 wt% of TiO_2 nanoparticles. Under these nominal pressures, the values of the COF were reduced by about 10.9% (87 MPa) and 11.1% (96 MPa) in relation to the lubrication with the use of non-modified oils. The most favourable effect of reducing the value of the COF resulting from the addition of SiO_2 nanoparticles was observed for oleic acid with a nanoparticle content of 0.5wt% (Fig. 8a). Modification of oleic acid with SiO_2 nanoparticles reduced the value of the COF by about 1.5% at pressures of 67-78 MPa and 8.9% at pressures of 87-98 MPa. However, in the case of modifying the gear oil with SiO_2 nanoparticles, no significant reduction of COF was found, only a slight decrease was recorded for the nominal pressure of 78 MPa (Fig. 8b).

Additions of nanoparticles of hard materials reduce friction by transferring part of the load in the valleys between the contacting materials. Under high pressure conditions, the particles can disintegrate, which changes the contact conditions. If the surface roughness of the tools is too high in relation to the roughness of the deformed sheet, then the mechanism of mechanical ploughing of the sheet surface is activated. Under such conditions, the lubricant is not able to sufficiently reduce the value of the COF. High pressures acting on the Alclad through the countersample caused the phenomenon of coating material build-up (Fig. 9a) and the formation of adhesive (Fig. 10a) and cohesive cracks (Fig. 9b). The low yield stress of the coating material favours the sticking of the nanoparticles into the Alclad (Fig. 10b).

a)

b)

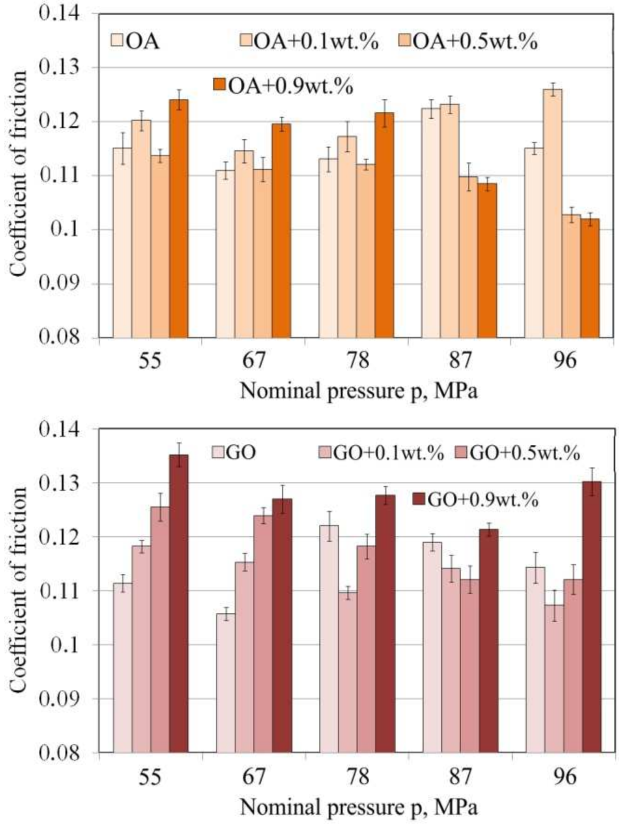
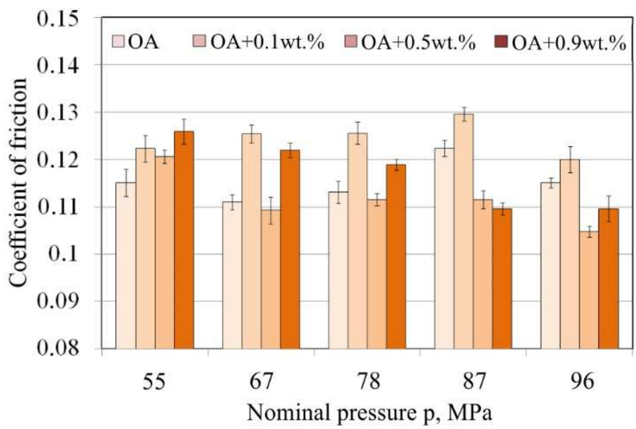


Fig. 7. Influence of nominal pressure on the value of the COF in friction conditions with a) oleic acid and b) gear oil containing TiO_2 nanoparticles

a)



b)

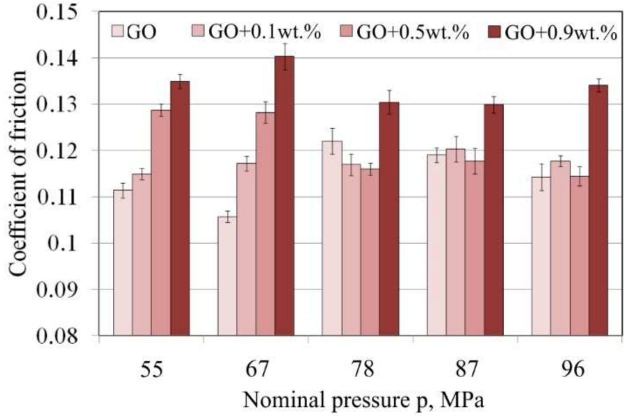


Fig. 8. Influence of nominal pressure on the value of the COF in friction conditions with a) oleic acid and b) gear oil containing SiO_2 nanoparticles

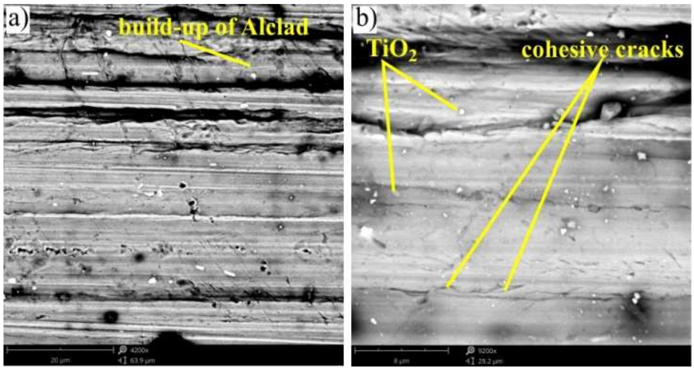


Fig. 9. SEM micrographs of a sheet surface tested under following conditions: a) OA + 0.5wt.% SiO_2, p = 67 MPa, b) OA + 0.1wt .% TiO_2, p = 55 MPa

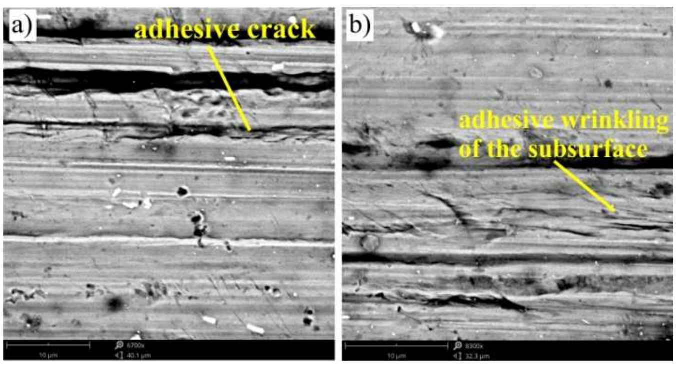


Fig. 10. SEM micrographs of the sheet surface tested in the following conditions: a) GO + 0.5wt.% SiO2, p = 78 MPa, b) GO + 0.9wt.% SiO_2, p = 87 MPa, c) GO + 0.1wt.% TiO_2, p = 55 MPa, c) GO + 0.1wt.% TiO_2, p = 55 MPa

4. Conclusions

This paper examines the effect of lubricant type on the value of the COF of EN AW-2024-T3 Alclad aluminium alloy sheets as determined in the strip drawing test. Based on the research results, the following conclusions can be drawn:

- The influence of the content of nanoparticles in the oil and the grade of nanoparticles on the value of the COF changes with increasing nominal pressure.
- Among non-modified oils, gear oil and oleic acid provided the lowest value of friction coefficient in the entire range of nominal pressures investigated.
- The lowest efficiency in reducing the COF was shown by hydraulic oil, olive oil and machine oil.
- The most favourable effect of reducing the value of the COF resulting from the addition of SiO_2 nanoparticles was observed for oleic acid with a nanoparticle content of 0.5wt%.
- Under the conditions of lubrication with gear oil, within the range of the nominal pressures considered of 55-67 MPa, a clear tendency of increasing the value of the COF with increasing content of TiO_2 nanoparticles was found.

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WPŁYW SMAROWANIA NA WŁAŚCIWOŚCI TARCIOWE BLACH ZE STOPU ALUMINIUM EN AW-2024-T3

Streszczenie

W artykule przedstawiono wyniki badań tarcia blach ze stopu aluminium EN AW-2024-T3 Alclad. Efektywność smarowania za pomocą kwasu oleinowego, olejów mineralnych oraz roślinnych z dodatkami nanocząstek SiO_2 oraz TiO_2 została określona za pomocą testu przeciągania blachy używanego do oceny warunków tarcia panujących w kołnierzowej części wytłoczki w procesie głębokiego wytłaczania. Próbki w postaci pasów blachy przeciągano pomiędzy przeciwpróbkami o zaokrąglonej powierzchni (R = 200 mm) z prędkością 2,5 mm/s. Olej przekładniowy oraz kwas oleinowy zapewniły najmniejszą wartość współczynnika tarcia w całym zakresie analizowanych nacisków nominalnych. Najmniejszą efektywność zmniejszania współczynnika tarcia wykazały olej hydrauliczny, oliwa z oliwek oraz olej maszynowy. Najkorzystniejszy efekt zmniejszenia wartości współczynnika tarcia wynikający z dodatku nanocząstek SiO_2 jest widoczny dla kwasu oleinowego przy zawartości nanocząstek 0,5% (wagowo). Wysoka zawartość nanocząstek TiO_2 (0,5-0,9% wagowo) jest korzystna podczas procesu tarcia z udziałem kwasu oleinowego.

Słowa kluczowe: stop aluminium, smarowanie, nanocząstki, test przeciągania blachy, współczynnik tarcia

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