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COMPARATIVE STUDY OF AN ENVIRONMENTALLY FRIENDLY LUBRICANT WITH CONVENTIONAL LUBRICANTS IN STRIP IRONING TEST

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ABSTRACT

Experimental estimates of ecologically acceptable single-bath lubricant, are presented and compared to those of classical lubricants in this paper. A device was created for the realisation of the strip ironing test with double thinning and a appropriate definition of the friction coefficient is used. Strips of 2.5 mm-thick low carbon steel sheets were used in the single-phase process with a maximum thinning deformation of 25%. In addition to the single-bath ecological lubricant, a phosphate layer with mineral oil was applied, as was lithium lubricating grease with MoS_2 and mineral oil with EP additives. The basic criterion for the estimates was the change in the friction coefficient and the secondary criterion was the level of surface microchanges due to sliding. The applied test procedure enables the clear differences between the lubricating properties of the investigated lubricants to be established.

Keywords: deep drawing, variable friction conditions, variable drawbead height, variable contact pressure.

AIMS AND BACKGROUND

The status of lubricants as potentially dangerous pollutants has been confirmed by the introduction of legal regulations as early as 2000 in both Japan and Europe. The European Union introduced new, stricter rules, known as REACH, in 2006–2007 (Ref. 1). These regulations declare that industry is responsible for

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protecting human health and preserving the natural environment. However, classical lubricants, although mainly ecologically harmful, can provide good results in applications, with several decades of development[2]. The new, ecological lubricants are still in the process of proving themselves. An additional problem is that in times of crisis, especially in less economically developed countries, economic survival is more important than preservation of the environment. In such cases, practically without exception, more efficient but cheaper lubricants are used regardless of their ecological harmfulness.

The recent development of dry lubricants without a conversion coating has attracted special attention. The so-called dual-bath lubricants form two layers on the working surface during the procedure of two dippings into water solutions and drying. The first layer, the base coating, adheres well to the part surface, while the second layer, over-coating, has more favourable anti-frictional properties. One type of these lubricants (white) contains wax and metal soaps, while the other (black) contains MoS_2 or graphite[1].

With single-bath lubricants, attempts have been made to create a single layer on the part surface. This layer should have favourable anti-frictional properties after a single dipping into a water solution containing the appropriate inorganic and organic components and drying. Such a procedure would be attractive due to its efficiency, short duration and relatively low cost. Some investigations have found that single-bath lubricants exhibit worse properties under conditions of high contact pressure (for instance, in cold forging) due to their relatively low shear strength and tendency to adhere to the tool surfaces, which can increase friction[3].

In addition to dual- and single-bath lubricants, boric acid has also been used in various investigations[4], which is interesting due to its favourable crystal structure, non-toxicity and fairly favourable tribological properties. The deficiency of boric acid is its tendency to absorb moisture from the air, which significantly worsens its anti-frictional properties[5].

An evaluation of a series of lubricants performances is presented in several papers (e.g. Ref. 2). In the ironing test, applied in Refs 6 and 7, a cup-shaped specimen made of thin sheets is used to evaluate the lubricants. The lubricants were evaluated based on: ironing load, surface quality and apparent shear friction factor. The friction coefficient is not used as an indicator. The specimen material in Ref. 6 was an AKDQ 1008 steel sheet. The influence of temperature on the forming process was also taken into account. In Ref. 7 lubricants were investigated in the ironing of the dual-phase (DP) 590 galvanised (GA) steel sheet. A survey of several tests for investigating lubricants in the metal-sheet forming process is presented in Ref. 8. The production tests were conducted simultaneously. The significance of the later work included the strip reduction test with single-sided thinning where the phenomenon of galling is quantified by the surface roughness measurements. The influences of the coating and lubricant were investigated, in terms of the friction coefficient. The double-sided single-phase ironing test was used for classical lubricant evaluation in Ref. 9. In Ref. 10 complex tribological influences were investigated in strip sliding test.

In this study, the friction coefficient was chosen as the basic criterion for assessing the lubricant performance. Friction coefficient was calculated according to research results given in Ref. 11. The fundamental goal of this paper is to conduct a comparative investigation of a single-bath lubricant and three conventional lubricants during a process with medium-intensity contact pressure, such as the strip ironing test. An experimental apparatus was designed using a methodology based on monitoring the friction coefficient during the process. Main contribution in this study is more proofs for further affirmation of ecological lubricants use in industrial application.

EXPERIMENTAL

Ironing test – device, tooling and procedure. An ironing test with double-sided thinning of the metal sheet, was applied in this experimental investigation, as depicted in the scheme presented in Fig. 1 (F, F_S – tensile and side force, t_0, t_1 – thickness, α – angle). The details of the device are given on the left-hand side of Fig. 2, while 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 realised. After the initial thinning deformation was realised, the tensile force F begins to act, and the ironing process continues until the 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 realised 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

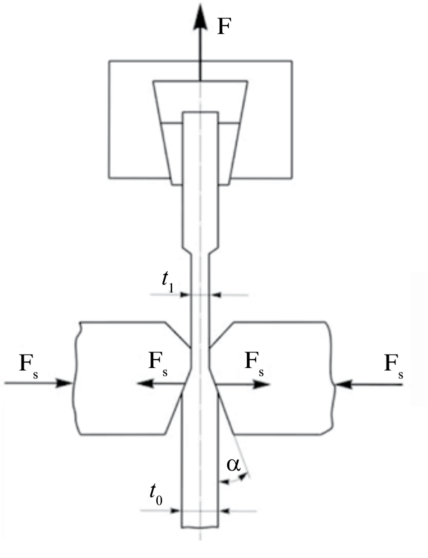


Fig. 1. Tribological model: scheme of the contact between the sliding elements and sample

Fig. 2. Scheme of the experimental device (left), and its physical appearance (right)

Table 1. Material properties

Steel DC04				
R_p (MPa)	R_M (MPa)	A (%)	*r*	*n*
185.2	284.5	35.3	1.68	0.215

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 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 and, converted into the files describing the tensile force dependence on the strip length using the corresponding software.

The geometry of the lateral sliding element is presented in Fig. 3*a*, *b*, while its physical appearance is shown in Fig. 3*c*. Central rounding radius is 1 mm, one side radius 1 mm and other 2 mm. These parts are made of the X210Cr12 tool steel (EN ISO 4957) without the surface coating and have a hardness of HRC 60-62. The

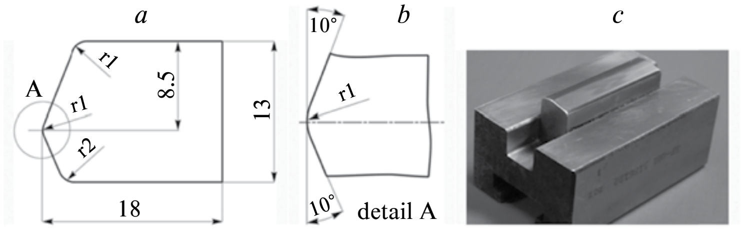


Fig. 3. Geometry (*a*, *b*) and physical appearance of the lateral sliding element (*c*)

surface is polished, and the roughness is expressed by the average absolute roughness height from the centre line R_a (0.08 μm), divided by the reference length of 5 mm.

The samples are strips of DC04 low-carbon steel thin sheets with a thickness of 2.5 mm, an average width of 20.2 mm and a length of 200 mm. Its main mechanical properties and properties of formability are given in Table 1 (R_p, MPa – yield strength, R_M, MPa – tensile strength, A, % – elongation at fracture, n – strain hardening exponent, r – coefficient of normal anisotropy). The surface roughness of the thin sheets, expressed by the average absolute roughness R_a is 1.03 μm over the referent length of 5 mm.

Lubricants. Four lubricants, i.e. four contact conditions, are used in this analysis. The first is the classical phosphate layer of zinc phosphate, with a thickness of approximately 10 μm, over which the mineral oil was deposited (for characteristics see describing of fourth lubricant). The oil was applied considering the less strict requirements for the ironing process with respect to cold forming. This lubricant was denoted as L1.

The second lubricant is an environmentally friendly lubricant, and its evaluation relative to the three classical lubricants represents the essence of this study. This lubricant is the single-bath double-layered lubricant and is dissolvable in water. It consists of an emulsion with 28% wax, metal soap and inorganic compounds. The dry substance content is 21–23%. The concentrated lubricant (60–90%) is a dense white liquid, which is non-reactant and non-toxic.

The preparation and deposition of the lubricant consist of the following phases:

a) Sand-blasting or chemical treatment of the work piece;
b) Dilution of the lubricant in demineralised water;
c) Deposition of the lubricant by dipping (Fig. 4);
d) Drying (Fig. 4).

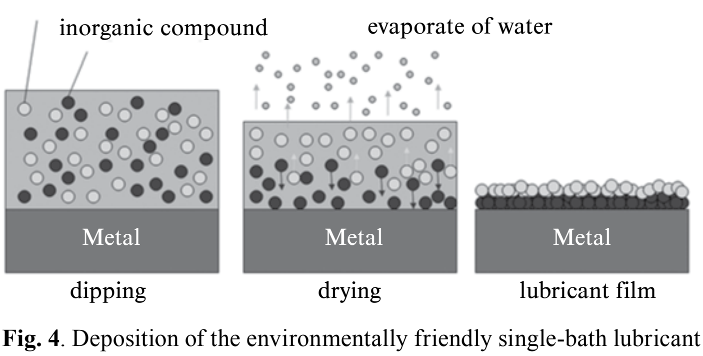


Fig. 4. Deposition of the environmentally friendly single-bath lubricant L2 (Ref. 1)

In this experiment, instead of sand-blasting, chemical treatment in acidic solution was used for the preparation of the samples surfaces. The lubricant manufacturer recommends submerging the parts in a 15% aqueous solution of sulphuric acid (H_2SO_4) for 10 min and then rinsing with hot demineralised water. Following the rinsing, the parts are submerged in 10% hydrochloric acid (HCl) solution for 5 min, followed by rinsing with hot demineralised water. In place of this treatment, it is possible to use a procedure involving degreasing in alkaline chemical compounds. Regardless of the procedure applied (sand-blasting, acidic or alkaline treatment), the last phase of preparation requires rinsing in hot demineralised water.

The hot demineralised water is applied to dissolve the lubricants (60°C), using the recommended ratio of 30% water and 70% concentrated lubricant. Lubricant deposition is performed by dipping the parts into the lubricant bath, where the permissible temperature range is from 50 to 70°C. The deposition can also be performed successfully under industrial conditions using automated lines.

The drying of the deposited lubricant should be performed using hot (100°C) air for 15 min. In this way, the two-component solid dry layer of lubricant is formed (Fig. 4). Due to its hygroscopic properties, the created lubricating layer should be used the same day. In the case of storage, under conditions of increased air moisture, drying should be repeated immediately prior to the forming process.

The lubricant formed according to the described procedure was denoted as L2.

The third lubricant, denoted as L3, is lithium grease, containing molybdenum disulphide MoS_2. Its NLGI consistency number and density are 2 and 0.9 g/cm^3, respectively, and the MoS_2 particle size is approximately 0.75 μm.

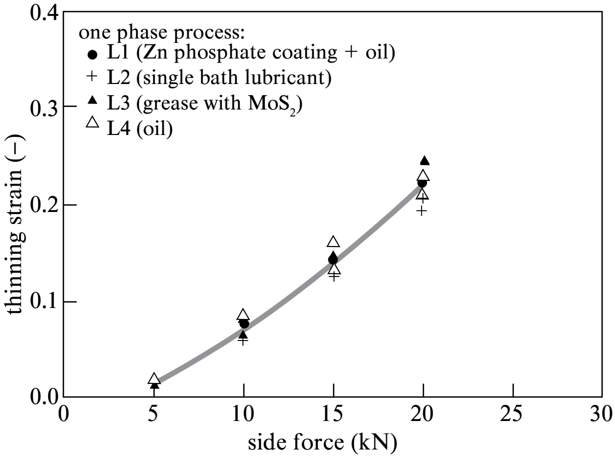
The fourth lubricant is classical mineral oil, containing the EP sulphur-based additives, which uses in thin sheets forming. Its density and kinematic viscosity are 0.93 g/cm^3 and 100 mm^2/s, respectively, at 40°C. The oil was deposited in great quantities onto the surface of the previously degreased sheet. This lubricant was denoted as L4. It should be mentioned that the same oil was used in L4 and in the additional lubricant over the phosphate layer (L1).

Test conditions. As already mentioned, uncoated DC04 steel strips (2.5 mm thick), were used in this experiment. The four lubricants which were described were applied, with emphasis on lubricant L2. The strip sliding speed was 100 mm/min.

Considering the material properties, four lateral force intensities were selected: 5, 10, 15 and 20 kN. The effect of the lateral forces can be seen in Fig. 5, which shows the dependence of the thinning strain on the lateral force intensity.

Lateral forces of 5, 10, 15 and 20 kN yield an average strain of 2, 7, 14 and 22%, respectively. As expected, the lubricant has a negligible influence during the initial thinning, as seen from Fig. 5.

Fig. 5. Thinning strain dependence on side force for different lubricants



This paper presents the results of the single-phase ironing process at a sliding length of approximately 60 mm. During the process, the variation of the tensile force in terms of the strip length was measured simultaneously for each sample. The variation of the friction coefficient during the process was then defined, according to expression (5). The micrographs were also recorded for each sample, and changes on the surfaces were analysed, especially in terms of the appearance of galling.

RESULTS AND DISCUSSION

Figures 6 to 9 present the dependences of the tensile forces on the sliding length for all four types of lubricants and for the four constant intensities of the lateral forces. Each force curve is actually a set of the discrete values, a numerical

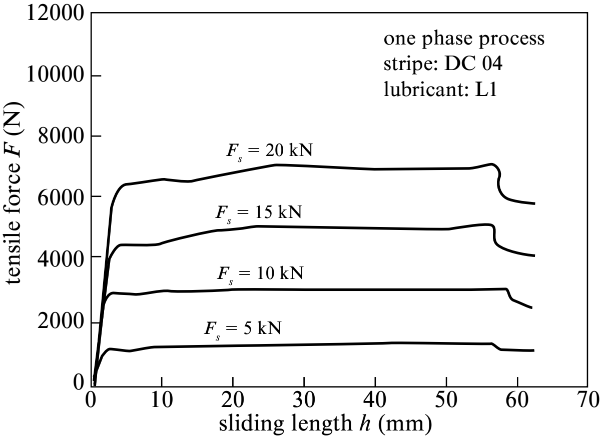


Fig. 6. Tensile force dependence on sliding length for lubricant L1

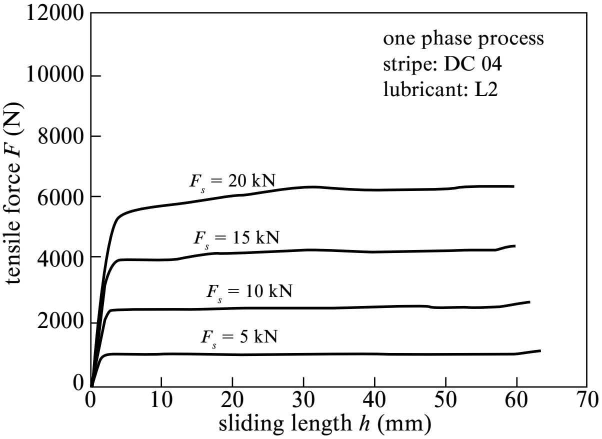


Fig. 7. Tensile force dependence on sliding length for lubricant L2

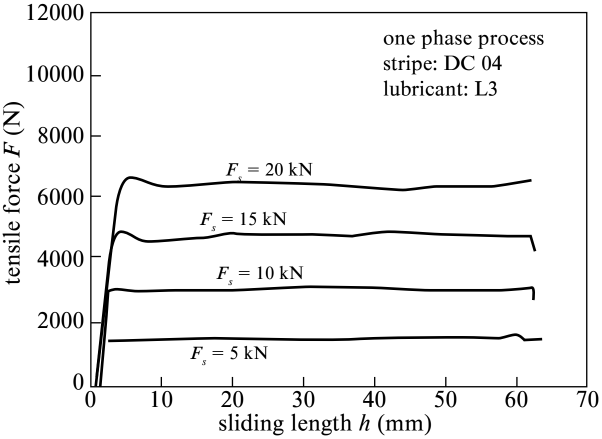


Fig. 8. Tensile force dependence on sliding length for lubricant L3

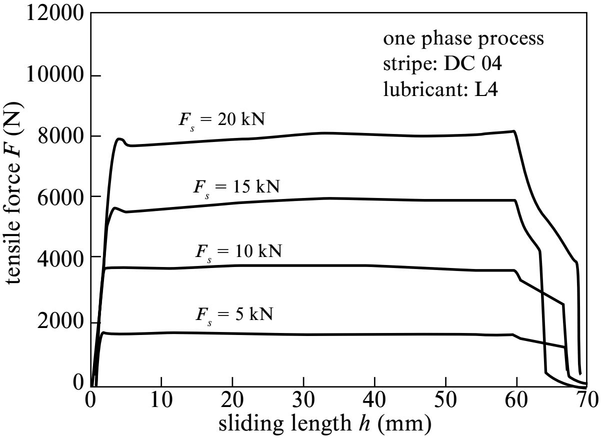


Fig. 9. Tensile force dependence on sliding length for lubricant L4

series with approximately 900 values, for the 60-mm sliding length. In the application of lubricants L1, L2 and L3, the tensile force intensities do not vary strongly during the sliding process. However, in the case of lubricant L4, the tensile force intensity is significantly increased. For instance, the tensile force for lubricant L4 is more than 20% greater than that for lubricant L2 at a lateral force of 20 kN. These findings indicate the favourable lubricating properties of lubricants L1, L2 and L3 relative to that of lubricant L4. It is interesting that the tensile forces for the phosphate layer with oil (L1) are somewhat higher, than those for the environmentally friendly lubricant (L2) and similar to those for the lubricating grease with MoS_2 (L3).

The friction coefficient variation was calculated for each tensile force dependence on the sliding length. The slope angle of the lateral element was $\alpha = 10°$, while $a = 0.7$. In this way, the curves of the friction coefficient variation were obtained (Figs 10 to 13).

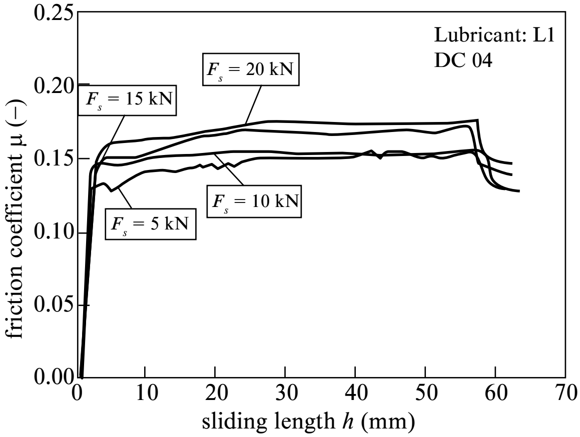


Fig. 10. Friction coefficient dependence sliding length for lubricant L1

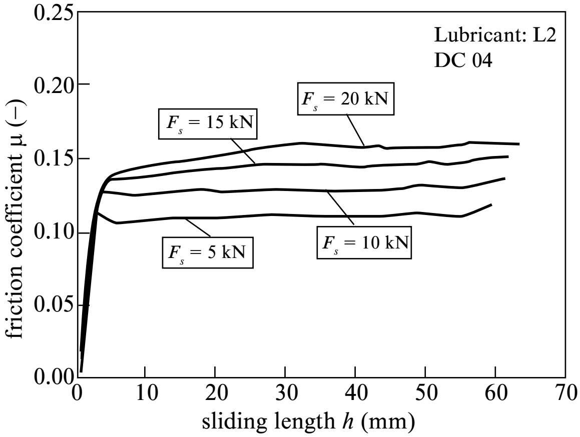


Fig. 11. Friction coefficient dependence sliding length for lubricant L2

It is clear that the friction coefficient was much higher when the mineral oil (L4) was applied, with a range of approximately 0.16 to 0.2. This confirms that these lubricants lubricating properties are worse than those of the other three.

The friction coefficient variation for the lithium grease with MoS_2 (L3) is presented in Fig. 12. The values are relatively low, ranging from 0.15 to approximately 0.165. The increase in the lateral force from 5 to 20 kN does not significantly influence the increase in the friction coefficient.

When the phosphate layer with mineral oil was applied (L1, Fig. 10), the values are similar to those for lubricant L3, ranging from approximately 0.14 to 0.17. The influence of the lateral force variation is somewhat greater than that for L3. The most probable cause is the worse lubricating properties of the mineral oil.

The findings for the environmentally friendly single-bath lubricant (L2) are presented in Fig. 11. Its friction coefficient is the lowest (0.11 to 0.16), but it is more sensitive to the lateral force intensity. It is clear that the lubricating properties of the environmentally friendly lubricant (L2) are good and that it can replace

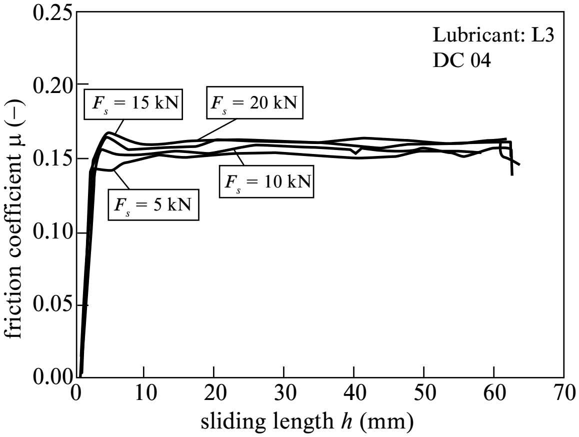


Fig. 12. Friction coefficient dependence sliding length for lubricant L3

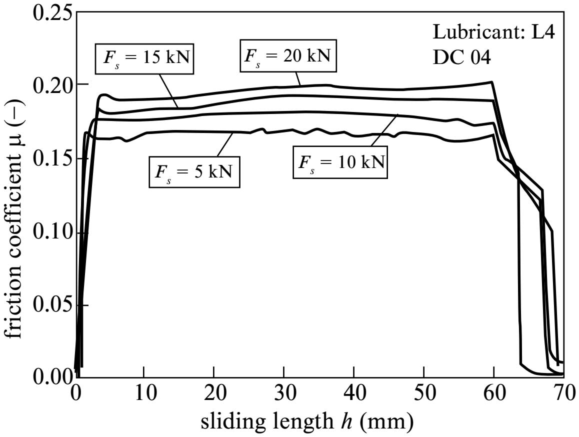


Fig. 13. Friction coefficient dependence sliding length for lubricant L4

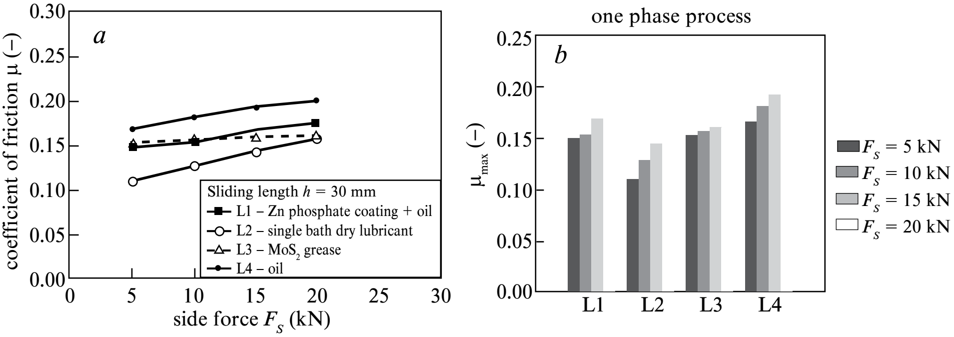


Fig. 14. Friction coefficient dependence on lateral force for different lubricants (*a*) and dependence of the maximum friction coefficient on lubricant type and lateral force (*b*)

any of the other lubricants tested in this study, especially at lower lateral forces intensities.

The results of the lubricant evaluation, based on the variation of the friction coefficient are summarised in Figs 14*a* and *b*. Figure 14*a* presents the dependence of the current values of the friction coefficient at the half of the length (30 mm) on the lateral force. Lubricant L2 is clearly distinguished as the most favourable and lubricant L4 as the least favourable. Lubricants L1 and L3 have similar properties, but lubricant L3 is slightly more favourable at higher lateral forces.

CONCLUSIONS

Based on the analysis of the results of this experimental investigation the following conclusions can be drawn:

– The device for strip ironing testing with double-sided thinning created in this study is convenient for estimating the performance of lubricants in processes with moderate compressive forces and a thinning deformation of the low-carbon steel sheets of up to 25%. The methodology, which is based on measurements of the tensile and lateral forces is simple and provides clear results.

– The friction coefficient was set as the main criterion. The obtained values correspond to the process characteristics and can be used to test the lubricants performances.

– Four lubricants were tested: three toxic classical lubricants and one environmentally friendly, water-soluble single-bath lubricant. The clear differences in the variation and intensity of the friction coefficient during the test enable the reliable estimation of the lubricating properties of the tested lubricants. The environmentally friendly lubricant tested exhibits a more favourable distribution of the friction coefficient during the process, especially under lower compressive forces intensities.

– Future research, using the same testing device, should include tests with multi-phase ironing processes, in which the working conditions are more severe, and the lubricant is expected to possess superior properties.

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