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ASSESSMENT OF FRICTIONAL PERFORMANCE OF DEEP DRAWING QUALITY STEEL SHEETS USED IN AUTOMOTIVE INDUSTRY

OCENA WŁAŚCIWOŚCI TARCIOWYCH BLACH STALOWYCH GŁĘBOKOTŁOCZNYCH STOSOWANYCH W PRZEMYŚLE MOTORYZACYJNYM

Abstract

This article presents the results of tribological tests of three grades of deep-drawing quality steel sheets used in the automotive industry. The frictional properties of the sheets were anaysed using a strip drawing test. Friction tests were performed under dry friction and lubrication conditions using machine oil L-AN 46. Additionally, friction tests of pre-strained sheets were also carried out. Cylindrical countersamples with different surface roughness were used. Relationship between the surface roughness, pressure force, lubrication conditions and the value of the friction coefficient were evaluated. It was found that increasing the roughness of the countersamples increased the value of the friction coefficient in both friction conditions analysed. The greater the pressure force, the lower efficiency of lubrication. The effectiveness of reducing the value of the friction coefficient ranged from 20-30% and depended on the pressure force, roughness of the countersamples and the degree of specimen pre-straining.

Keywords: coefficient of friction, friction, sheet metal forming, steel sheet

Streszczenie

W artykule przedstawiono wyniki badań tribologicznych trzech gatunków blach stalowych głębokotłocznych stosowanych w przemyśle motoryzacyjnym. Do oceny właściwości tarciowych blach wykorzystano test przeciągania pasa blachy. Testy tarcia przeprowadzono w warunkach tarcia suchego i smarowania olejem maszynowym L-AN 46. Dodatkowo przeprowadzono badania tarcia blach poddanych odkształceniu wstępnemu. Zastosowano przeciwpróbki walcowe o różnej chropowatości powierzchni. Pozwoliło to na określenie relacji pomiędzy chropowatością powierzchni, wartością nacisku, warunkami smarowania oraz wartością współczynnika tarcia. Stwierdzono, że zwiększenie chropowatości przeciwpróbek powodowało zwiększenie wartości współczynnika tarcia w obydwu zastosowanych warunkach tarcia. Im większa siła docisku tym efektywność smarowania olejem maszynowym zmniejszała się. Efektywność zmniejszania wartości współczynnika tarcia wahała się w zakresie 20-30% i zależała od siły nacisku, chropowatości przeciwpróbek oraz stopnia wstępnego odkształcenia próbek.

Słowa kluczowe: współczynnik tarcia, tarcie, kształtowanie blach, blacha stalowa

1. Introduction

One of the key phenomena in sheet metal forming (SMF) is the friction between the surfaces of the tool and the workpiece material [2]. The initial topography of the sheet surface under the influence of large deformations constantly evolving during the forming process [1]. The wear resulting from the mechanical interaction of materials in contact is a phenomenon that makes it difficult to obtain products with the suitable surface quality [21]. The technologist has many means and methods of selecting optimal lubrication conditions in order to increase the lubrication efficiency and reliability of the forming process [19, 20].

Friction and wear is an indispensable physical phenomenon accompanying the contact of two bodies [12]. It is assumed that approx. 23% of world energy consumption comes from tribological contacts [9]. 20% of this energy is used to overcome friction, and 3% is the cost of regenerating worn parts due to failure or wear. The phenomenon of friction occurring in the

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SMF processes differs significantly from the phenomena occurring at low loads and in the kinematic pairs due to the high influence of plastic deformation that can intensify many phenomena in the contact zone [14]. The value of friction coefficient strongly depends on the roughness of the contacting surfaces and the value of normal pressures. Friction is a phenomenon that has a key impact on the plastic flow of the material, the quality of the surface of the finished product, and also directly affects the wear of tools [8, 25].

Friction during sheet forming is a complex function of the physical and mechanical properties of the tool and workpiece, forming parameters, sheet and tool topography and lubrication conditions [18]. SMF is one of the most important forming technology, especially in the engineering, automotive and aviation industries. During SMF, the relative movement of the tool and the workpiece makes the properties of the deformed material (e.g. hardness, topography and surface roughness) and preparation of the tool surface (e.g. texture, protective coating, thermomechanical properties) of great importance [27]. In order to optimally design the forming process, improve SMF conditions and finally control tribological phenomena, it is necessary to understand the interactions between tribological and surface engineering aspects [6].

The strip drawing test is the basic tribological test used to model the friction conditions in the flange of the drawpiece. In this method, the countersample surfaces represented tool surfaces are pressed against the sheet metal strip, which is simultaneously drawn [24]. The sheet metal strip is pulled between non-rotating countersamples with flat [15] or cylindrical shape [5, 24]. The change of friction conditions is realized by changing the sliding speed, radius of the countersamples, surface roughness of countersamples and lubrication conditions [19, 22]. Many authors have used the strip drawing test to determine the value of the coefficient of friction over a wide range of process parameters. The frictional behavior of sheets made of aluminum alloys 5754, 6111 and 6451 was the subject of research carried out by Masters et al. [15]. It was found that the coefficient of friction increases with the degree of sheet deformation, but the use of waxy solid lubricants helps to minimize this effect, keeping the friction coefficient constant with sample deformation up to 10%. The problem of the influence of the drawing speed and directional surface topography on the value of the friction coefficient and the change of the surface topography under mixed lubrication conditions in the strip drawing test was presented by Roizard and von Stebut [17]. Coello et al. [3] tested the electron beam textured galvanized steel sheet TRIP700 in a strip drawing test with flat dies. It was found that the microhydrodynamic conditions of boundary lubrication arise due to the plastic deformation of surface asperities, which creates high pressure in the volume of the lubricant filling the valleys surface topography.

In this paper, the results of tribological tests of three grades of deep-drawing steel sheets used in the automotive industry are presented. To assess the frictional performance of sheet metals the strip drawing test was used. Friction tests were performed under dry friction and lubricated conditions. Additionally, friction tests of pre-strained sheets were carried out. Cylindrical countersamples with different surface roughness were used.

2. Experimental investigations

2.1. Test material

In the friction tests the steel sheets of different deep drawing quality i.e., SB, BSB and Z II T were used. The basic mechanical parameters of the sheets (Table 1) were determined using an uniaxial tensile testing machine. Specimens for tensile test were cut along the sheet rolling direction (0°) and transversely (90°) in relation to the sheet rolling direction. Based on the measurement data, the work hardening characteristics of the examined sheets were determined. True stress-true strain relations were approximated by the Hollomon equation $\sigma = K \cdot \varepsilon n$, where σ = true stress, ε – true strain, K – strength coefficient, n – strain hardening exponent.

Table 1. Selected mechanical parameters of sheets tested

Material	Specimen orientation	Yield stress $R_{p0,2}$, MPa	Ultimate tensile stress R_m, MPa	Strength coefficient K, MPa	Strain hardening exponent n
SB	0°	162	310	554	0.21
	90°	163	312	530	0.21
BSB/SSB	0°	151	282	494	0.221
	90°	153	281	475	0.21
Z II T	0°	166	313	543	0.22
	90°	171	321	551	0.241

2.2. Friction test

Assessment of friction performance of steel sheets has been carried out using strip drawing test simulator (Fig. 1). The test consists in pulling a sheet metal strip between two stationary countersamples with a cylindrical surface. Friction test considered is easy to carry out. Strip drawing test is characterized by possibility of uncomplicated measurement of the forces necessary to determine the value of the friction coefficient.

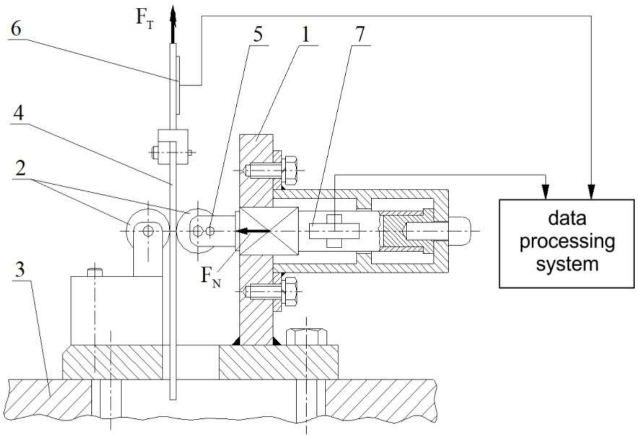

Fig. 1. Schematic view of strip drawing test: 1 – frame, 2 – countersamples, 3 – base, 4 – specimen, 5 – fixing pin, 6,7 – load cell

Friction test specimens approximately 200 mm long and 20 mm wide were cut along the sheet rolling direction. Countersamples in the form of rolls with a diameter of 20 mm were made of cold work tool steel. Three sets of countersamples with the following roughness parameters Ra = 0.32 μm, Ra = 0.63 μm and Ra = 1.25 μm, were used in the tests. The tests were carried out in dry friction and lubricated (L-AN 46 machine oil) conditions. In order to eliminate the influence of external factors, the surfaces of the samples and rolls were degreased with acetone. On the basis of the prepared data set, the value of the friction coefficient μ was determined according to the relationship:

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

where: F_T – friction force, F_N – pressure force.

The value of the pressure force was considered in the range between 0.4 kN and 2 kN.

3. Results and discussion

The general relationship that can be noticed was the reduction of the value of coefficient of friction with the increase of the clamping force at both lubricated and dry friction conditions (Fig. 2). This may be due to the fact that after a certain load value is exceeded, the relationship between the friction force and the clamping force is nonlinear, and the friction coefficient (as defined by Amontons' law) does not have a constant value and changes with increasing pressure. This effect is especially visible during friction with cylindrical countersamples for which the contact surface changes nonlinearly with pressure force. This relation has been also observed by Kirkhorn et al. [11], Trzepieciński et al. [23] and Trzepieciński and Fejkiel [24].

The friction occurring at high pressures may significantly differ from the phenomena occurring at low loads and in the kinematic pairs due to the high influence of plastic deformation that can intensify many phenomena in the contact zone [29]. In comparison with conventional kinematic pairs, in SMF processes, the material strength of one element of the friction pair (tool) is assumed to be much greater than the strength of the workpiece material, which undergoes intentional plastic deformation [4]. In such conditions, the share of the adhesion mechanism and the mechanical interaction of the surface asperities is dominant. The reduction of the value of friction coefficient by the use of lubricant depends on the roughness of the countersamples and the value of the contact force FN. The greater the contact pressure, the lubrication efficiency tends to reduce.

In general, increasing the surface roughness of the countersamples increases the value of the coefficient of friction of Z II T sheets in both applied friction conditions (Fig. 3). However, the increase in the value of the friction coefficient does not exceed the value of 0.06 when the roughness of countersamples changes from 0.32 μm to 1.25 μm. Such a nature of changes in the friction coefficient in the lubricated conditions proves the high contribution of the mechanism of mechanical interaction of the surface asperities in the conditions of cooperation of rollers with high surface roughness and the workpiece surface. In spite of the increase in the volume of lubricant pockets that can hold the oil, the value of the coefficient of friction increases. In the range of low contact forces, the lubricant to a greater extent reduced the coefficient of friction. Similar conclusions can be drawn for SB and BSB sheets

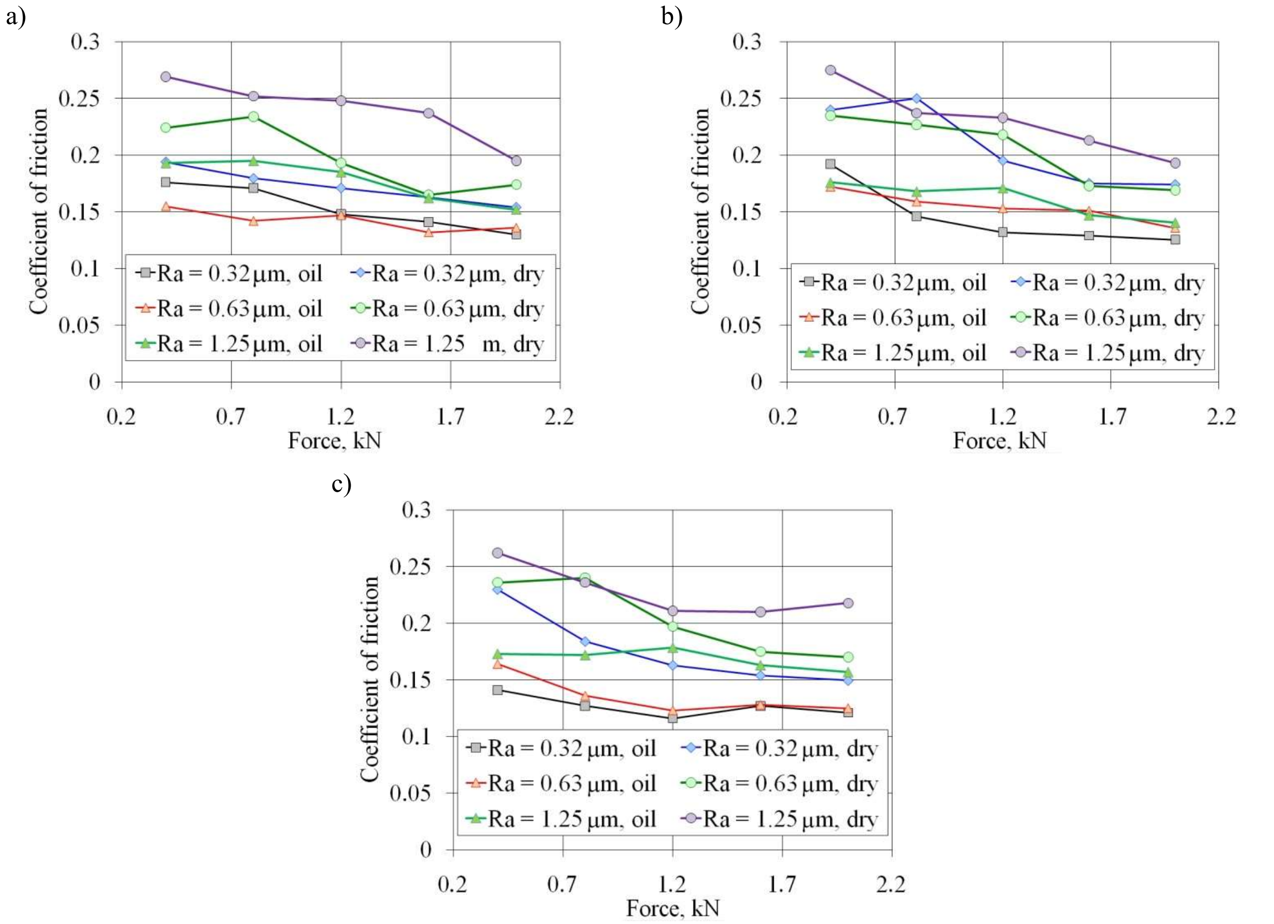

Fig. 2. Effect of pressure force F_N on the value of coefficient of friction for the following grades of steel: a) SB, b) BSB and c) Z II T

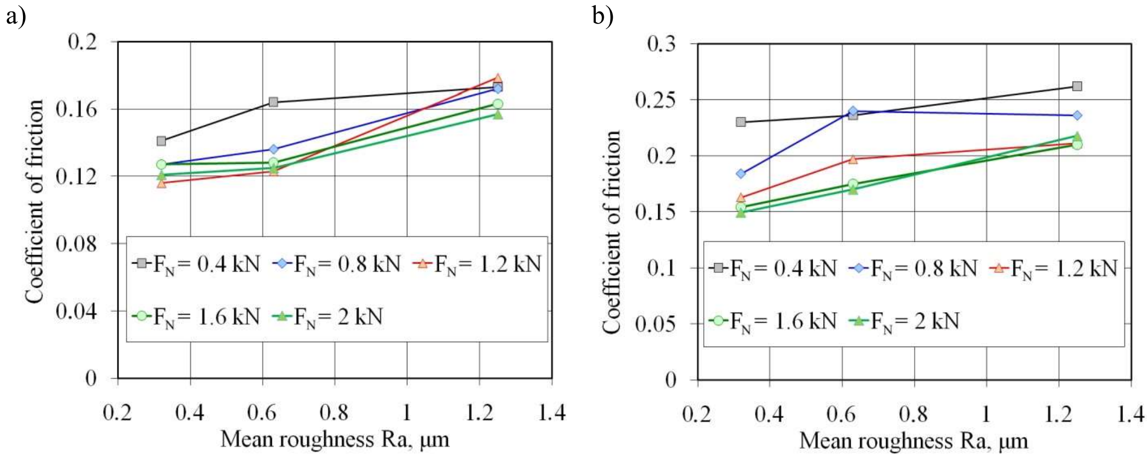

Fig. 3. Effect of average roughness of countersamples on the value of coefficient of friction for Z II T tested at a) lubricated conditions and b) dry friction

The highest average lubrication efficiency of BSB and Z II T sheets was recorded for the pressure force FN = 0.8 kN. For this pressure force, the lubrication resulted in a reduction of the value of friction coefficient by about 20-30%. Increasing the pressure force above value of 0.8 kN increases the value of the friction coefficient. The contact force under lubrication conditions determines the pressure of the lubricant in the closed lubricant pockets. And when the surface roughness of countersamples is high, then the friction force determines the intensification of the phenomenon of ploughing of the sheet surface by the hard asperities of the tool surface.

Changes in the properties of the surface layer of the samples are related to the change of friction conditions. The most frequently used 3D parameters were used to describe changes in surface roughness during sheet metal forming. The measurements of the surface roughness of the sheet metal after the friction tests (Table 2) did not give an unambiguous answer to the question about the influence of friction conditions on the change of surface roughness of workpiece. Sheet strips after friction tests carried out with the use of countersamples with a roughness of Ra = 0.63 µm and at an initial pressure force 1.2 kN were selected for the analysis of surface roughness change. The friction process of steel sheets was accompanied by a decrease in the Sa (Fig. 4) and Sq (Table 2) parameters. No clear relationship was observed between the coefficient of friction and mean roughness Ra of sheets. Meanwhile, the lubrication of the sheet surface significantly reduced the number of summits per surface area of specimens compared to the dry friction conditions (Table 2).

Table 2. Selected spatial parameters of the sheet metal surface roughness before and after the SDT (Sa – the mean roughness, Sds – the summit density, Sdq – root mean square gradient)

Material	Friction conditions	Sq, µm	Sds, n_p/mm^2*	Sdq, µm/µm
SB	original surface dry friction lubrication	1.89 1.46 1.64	272 319 290	0.103 0.0902 0.0995
BSB	original surface dry friction lubrication	2.21 1.56 1.4	320 343 303	0.133 0.0849 0.0874
Z II T	original surface dry friction lubrication	2.08 1.58 1.48	312 311 283	0.131 0.109 0.0926

* n_p – number of summits

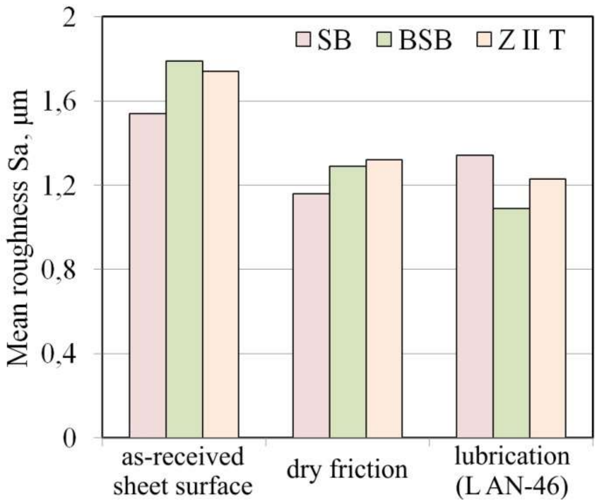

Fig. 4. Effect of test conditions on the mean roughness Sa

In the next part of the investigations, the pre-stretched samples were tested. For this purpose, the samples were stretched on the uniaxial tensile testing machine in order to obtain true strains ε equal to 0.095, 0.14 and 0.182. The most important parameters of surface roughness of the pre-strained samples were measured with the use of a Taylor Hobson Subtronic 3+ measuring system. On the basis of the results (Table 3), it was found that the values of the parameter Ra measured along (0°) rolling direction and transversely (90°) to this direction were proportional (Fig. 5). It should be emphasized that the values of Ra and Rz parameters increase with the increase of the true strain of the sheet strips. Moreover, in the whole range of true strains of the specimens, the value of the roughness parameter Ra increases almost linearly (Fig. 5). The change in roughness parameters measured in two perpendicular directions (0° and 90°) shows a different character. Mean spacing of profile irregularities increases in the direction of sheet strip stretching and decreases in the lateral direction.

Table 3. The influence of sample pre-strain on the change in the value of 2D roughness parameters of SB sheet surface (Ry – the maximum height, Rz – the maximum height of the assessed profile, Sm – mean spacing of profile irregularities)

Orientation	True strain φ	Surface roughness parameters		
		Ry, µm	Rz, µm	Sm, µm
0°	0	10.2	8.8	149
	0,095	11.1	9.6	167
	0,14	14	12	196
	0,182	14.2	12.4	177
90°	0	12.4	9.4	160
	0,095	18	11.2	146
	0,14	22.2	13.8	145
	0,182	18.5	14.3	152

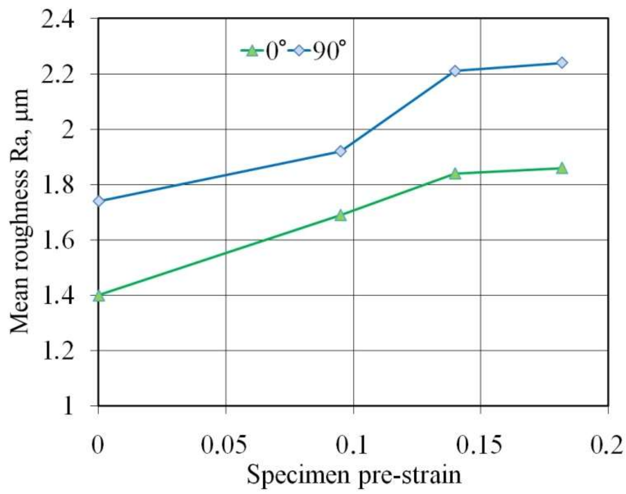

Fig. 5. Effect of specimen pre-strain on the value of mean roughness measured at rolling direction (0°) and transverse to the rolling direction (90°)

The value of the friction coefficient decreases with increasing contact force and true strain of pre-strained samples. Pre-straining process caused both a change in the surface topography and mechanical properties of the sheet material as a result of work hardening phenomenon. The lowest values of the coefficient of friction were recorded during friction with the participation of a countersample with surface roughness Ra = 0.63 μm, tested in both analysed friction conditions (Fig. 6). The pre-strained samples tested with the countersample with roughness Ra = 1.25 μm were characterized by the lowest lubrication efficiency. Due to the high surface roughness of the countersample in the form of open lubricant pockets and high hardness caused by the severe work hardening, the lubricant was not able to effectively reduce the frictional resistance. During friction with the countersample with mean roughness Ra = 0.63 μm, after exceeding the pressure force FN of about 1 kN, the stabilization of the value of friction coefficient with increasing load is visible.

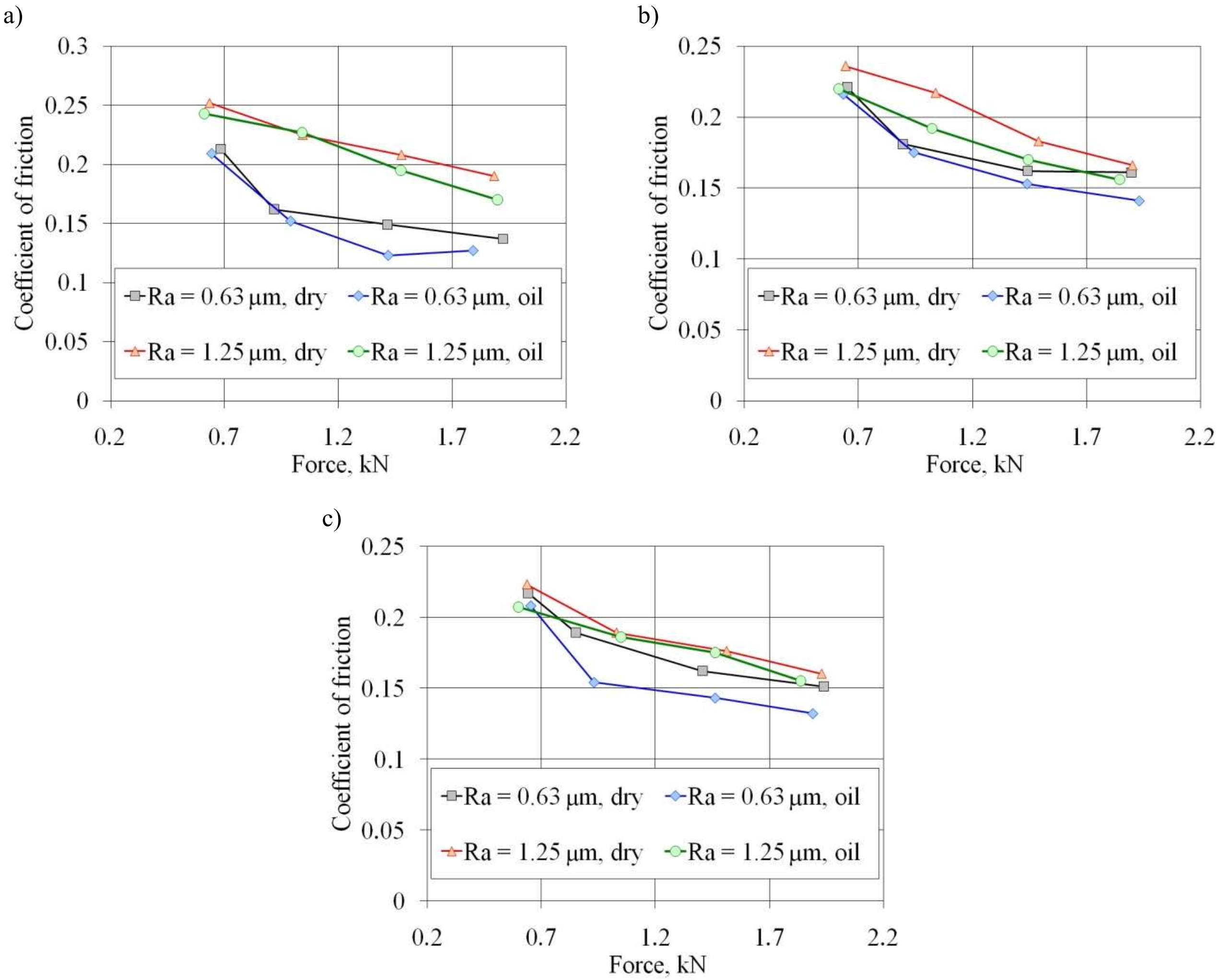

Fig. 6. Effect of force F_N on the value of coefficient of friction for pre-strained sheets a) φ = 0.095, b) φ = 0.139 and c) φ = 0.182

During the plastic working of metals there is initially a small effective contact area. The surfaces stick to each other only by the peaks of the asperities, which then, under the influence of the pressure forces, are plastically deformed until the contact surface created in this way is sufficient to transfer the load [10, 28]. The asperities of the surface are sheared and elastically deformed, which increases the real contact area. For small values of the surface roughness parameters, adhesion is the dominant tribological phenomenon occurring during metallic contact. As the surface roughness increases, the influence of adhesion decreases, while the share of the mechanical ploughing of the asperities during the contact of two metallic bodies increases [2].

In the conditions of dry friction, the coefficient of friction is the main factor limiting the movement of the workpiece material on the surface of the tools [16]. Under loading, the asperities deform elastically and plastically, changing the topography of the surface and lubricant flow between asperities [13]. In the case of elastic-plastic metals, the increase in pressure during sliding movement causes an increase in the real contact surface, which may lead to a reduction in the volume of the lubricant pockets [7]. Closed lubricant pockets are separated from the outer edges of the material and hold the lubricant in the closed volume of the valleys. Under load, the pressure of the lubricant in pockets increases, forming a kind of hydrostatic cushion [7]. Open lubricant pockets located on the edges of the surface are not able to hold the lubricant during the friction process. According to the theory of lubricating pockets presented in [26], an increase in the friction coefficient is observed in the conditions of open lubricant pockets and its reduction in the presence of closed lubricant pockets.

4. Conclusions

In sheet metal forming processes the friction is the result of two main mechanisms: adhesion in the areas of real contact and resistance resulting from the mechanical interaction of the peaks of surface asperities as a result of flattening and ploughing of the workpiece surface by asperities of the hard surface of tool. The results of SDT presented in this article allow the following conclusions to be drawn:

- in the friction conditions with cylindrical countersamples, the increase in pressure force is accompanied by a decrease in the value of the friction coefficient,
- the greater the contact pressure, the lubrication efficiency tends to reduce,
- increasing the roughness of the countersamples increases the value of the friction coefficient in both analysed friction conditions,
- in the range of low contact pressure forces, the lubricant to a greater extent reduced the coefficient of friction,
- the lubricant reduced the value of the friction coefficient by about 20-30% depending on the roughness of the countersamples and the pressure force,
- the lubrication of the sheet surface significantly reduced the number of summits per surface area of specimen compared to the dry friction conditions,
- pre-straining of the specimens increased the maximum height of the assessed profile.

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