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EVALUATION OF FRICTION COEFFICIENT OF AN AUTO-BODY STEEL SHEET

In this paper the results of strip drawing tests aimed to determine the friction coefficient in sheet metal forming operations are presented. The tests were conducted using a specially designed tribological simulator. The deep drawing quality steel sheet used in the automotive industry was tested. The relationship that shows the effect of sheet normal load, tool surface roughness, lubrication conditions and sample orientation according the rolling direction of the sheet on the value of friction coefficient are presented and discussed. The Scanning Electron Microscope (SEM) micrographs of sheet surfaces after the friction test allowed us to identify the mechanisms that occur at the contact of two bodies with rough surfaces. The results of the tests indicate that the relationship between friction force and normal force is nonlinear. Thus, the value of the friction coefficient is changed with the change of the load value.

Keywords: coefficient of friction, friction, strip-drawing test, surface roughness

1. Introduction

Sheet metal forming is one of the most popular methods of preparing finished products in the automotive industry. The protective coating is sometimes applied as the last stage of the operation and requires an appropriate surface roughness of a drawpiece. Friction forces have a significant influence on the distribution and the value of strains and thus the quality of the product. The most important factors that determine obtaining a high quality product is the size of the thinning walls. Non-heterogeneity of the drawpiece deformation is

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mainly conditioned by the presence of friction forces at the interface of the deformed material and tools.

The processes taking place in the contact zone are affected by many factors, including by the size of normal pressure, material and surface topography, sheets, tools and lubricant, among others. The factors that depend on the forming process include the value of normal pressure and speed of deformation. The correct selection of the values of process parameters determines obtaining a product of desired dimensional and shape quality. The role and effects of the occurrence of frictional resistance are difficult to define. The unfavourable effects of the presence of frictional resistance include, among others [1-3]: non-heterogeneity of drawpiece deformation, an increase of the pressure exerted by the punch causing a danger of crack occurrence, as well as the worsening of the surface quality of a drawpiece. Beneficial effects of the frictional resistance on the forming process may include friction existing between the sheet metal and the punch because it increases the permissible value for the maximum force in deep-drawing. Disadvantageous phenomenon of friction can be counteracted through the use of appropriate lubricants and an increase in the hardness of tools.

The main factors influencing the tribological phenomena in plastic working processes include macro- and microgeometry of contacts, the kinematics of the tool, physical and chemical phenomena at the contact surface and the temperature [1, 4, 5]. Physical and chemical phenomena occurring in the contact zone depend, among others things, on the materials of the frictional pair and the chemical affinity of the materials in contact. During the sheet metal formation frictional connections are created using metallic dyes that are destroyed during the friction process [6, 7]. The value of the frictional resistance essentially depends on the shear strength of frictional connections. The effects of contact pressure and sliding velocity under mixed lubrication based on a friction testing of steel sheet was investigated by Tamai et al. [8]. A proposed new nonlinear friction coefficient model allows us to evaluate the change in the friction coefficient during continuous sliding and predictions of the friction coefficient were extremely accurate in comparison with the conventional methods.

In the processes of sheet metal forming using rigid tools, macro- and microgeometry contact friction pairs have a significant impact on the amount of frictional resistance. Generally, the friction is due to the ploughing effect between asperities [9] and adhesion between contacting asperities [10]. The three dominating fattening mechanisms during sheet forming are: flattening due to sliding, flattening due to normal load and flattening due to normal loading. Flattening increases the real area of contact, resulting in a higher value of friction coefficient [10]. Asperity flattening due to combined normal loading and deformation of the underlying bulk material is described in a flattening model proposed by Wasteneng [11]. Surface changes due to asperity deformations influence the load-carrying capacity of the lubricant [12]. Ma et al. [13] calculated the asperity flattening in metal forming and showed that the area of contact ratio increased as a function of normal pressure. Furthermore the relative sliding between a tool and a sheet can increase the area of the contact ratio. As the lubricant viscosity becomes lower, the friction coefficient is higher [14].

Methods such as strip drawing testing [15], draw bead testing [16], bending under tension testing [17], strip reduction testing [18] and testing using slider-on-sheet tribometer [19] are widely used to estimate the frictional resistance and wear behaviour between rough surfaces. Tisza and Fülöp [20] classified friction tests for sheet metal forming as a function of the main performed operations: stretch drawing, stretch forming and deep drawing. The stretch-drawing type tests are widely used to investigate the effect of several material and technological parameters on frictional resistances [21, 22]. Significant advances regarding friction behaviours in plastic forming were summarised by Wang et al. [23, 24] from four aspects, namely, friction testing, characterising, modelling and controlling.

The strip drawing test is one of the simplest tribological tests to determine the friction coefficient in sheet metal forming. This paper presents the results of the strip drawing test aim to determine the friction coefficient of deep drawing quality steel sheet used in the automotive industry. Several relationships that illustrate the effect of sheet metal surface roughness, lubrication conditions and sheet orientation on the value of the friction coefficient are presented and discussed.

2. Material and method

The friction tests were conducted by strip drawing tests in which the flat sample was placed between two fixed cylindrical rolls with equal radii (Fig. 1). The test was carried out in such a way that a strip of the sheet was clamped with specified force between two cylindrical rolls of equal radii of 20 mm. The values of both forces, the normal force F_N and the pulling force F_P, were constantly recorded using electric resistance strain gauge technique, 8-channel universal amplifier of HBM's QuantumX data acquisition system and computer PC. The specimens for the friction tests were made of deep-drawing quality 1 mm thick 09J steel sheet used in the automotive industry. According to the standard PN-EN 10130+A1:1999 the tested steel sheet with drawing category SB is intended for hard to form drawpieces with complex shapes. The samples were prepared as a strip with a width of 20 mm and a length of about 200 mm, cut along the rolling direction of the sheet. The rolls were made of cold working tool steel. The tests were performed under the following conditions:

- surface roughness of rolls was measured along the generating line of rolls: 0.63 and 1.25 μm,
- clamping force: 0.6, 1.05, 1.45 and 1.85 kN,

– lubrication conditions: dry friction and lubrication using machine oil LAN-46.

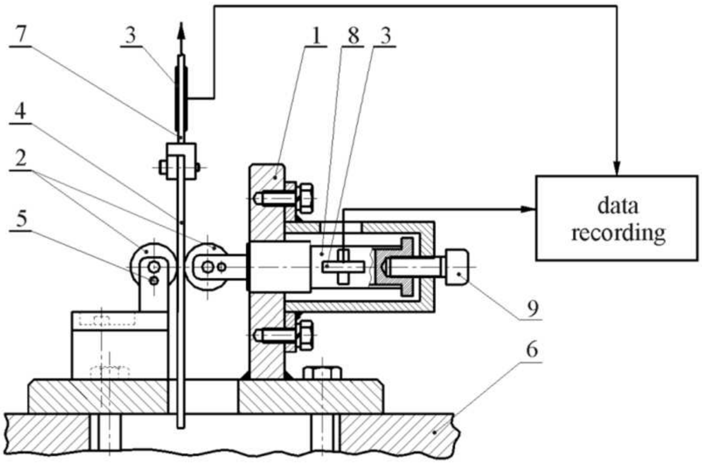

Fig. 1. Scheme of measuring device: 1 – frame; 2 – working rolls; 3 – load cells; 4 – specimen; 5 – blocked pin; 6 – grip of testing machine; 7, 8 – tension members; 9 – set bolt.

During the recording of the pulling and clamping forces, the sheet was drawn for a distance of about 10 mm. Next, the clamping force value was increased simultaneously during the tests.

The mean value of the friction coefficient, μ, was determined according to the equation (1) for the stabilised range of values of F_P and F_N. The coefficient of friction is evaluated separately for all levels of variation of clamping force (f in figure 2). For these ranges we received about 120-160 values of the coefficient of friction (range μ_i in figure 2). So it was assumed that such number of the values of the coefficient of friction is sufficient to evaluate the average coefficient of friction representative for analysed lubrication conditions.

$$\mu = \frac{F_P}{2 \cdot F_N} \tag{1}$$

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

To realise dry conditions both rolls and sheet specimens were degreased using acetone.

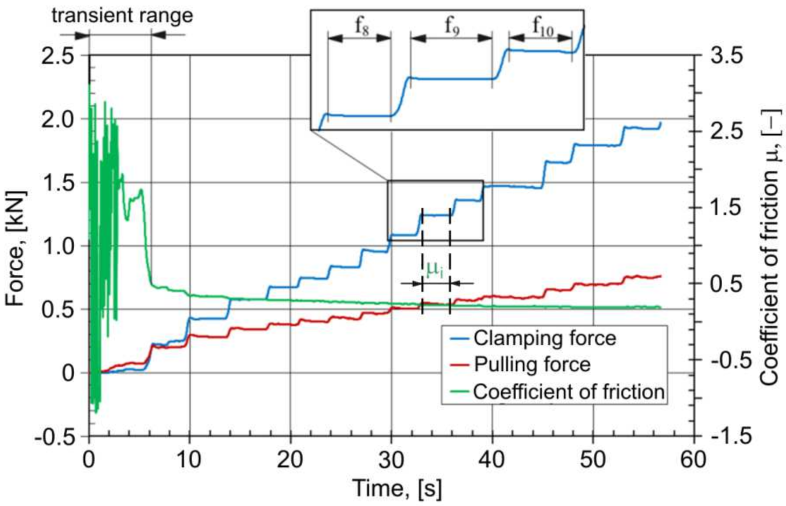

Fig. 2. Exemplary plot of variation of values of clamping force F_N and pulling force F_T versus specimen displacement

To study the effect of sample strain on the change of the surface topography and friction coefficient the samples were straightened using the uniaxial tensile test to receive different strain values logarithmic strain ε_l: 0.095, 0.14 and 0.182.

To determine the mechanical properties (Table 1), the tensile test was carried out in the universal testing machine. Surface roughness 3D parameters of the sheets (Table 2) were measured by using Taylor Hobson Surtronic 3+ instrument. It was assumed that one measurement is representative to characterize the sheet surface roughness. Table 1 presents the mechanical properties and selected spatial parameters of the sheets.

Table 1. Basic mechanical parameters of tested sheet

Sample orientation	Yield stress $R_{p0,2}$ MPa	Ultimate strength R_m MPa	Elongation A_{50}	Strain hardening coefficient C MPa	Strain hardening exponent n
0°	162	310	0.42	554	0.21
90°	163	312	0.41	530	0.21

Table 2. Selected roughness parameters of tested sheet

Measurement orientation according to sheet rolling direction	Surface roughness parameters					
	Ra, μm	Rq, μm	Rt, μm	Rp, μm	Rsk	Rz, μm
0º	1.4	1.68	9.6	5.8	0.36	9.4
90º	1.74	1.92	10.1	6.2	0.14	8.7

3. Results and discussion

The change of the contact surface is accompanied by a continuous change in the geometry of the contact. The values of arithmetical mean deviation of the surface roughness profile Ra (Fig. 3a) and maximum height of the roughness profile Rz (Fig. 3b) increase with the sample pre-strain value. For both measurement orientations, according to the sheet rolling direction, this tendency is similar. The sample pre-strain causes not only the change of the surface topography but also, by strain hardening phenomena, changes the mechanical parameters of the surface asperities. An increase of maximum height of the roughness profile does not increase the frictional resistances. The strain-hardened asperities are less susceptible to the flattening process, which causes the intensification of surface mechanical wear.

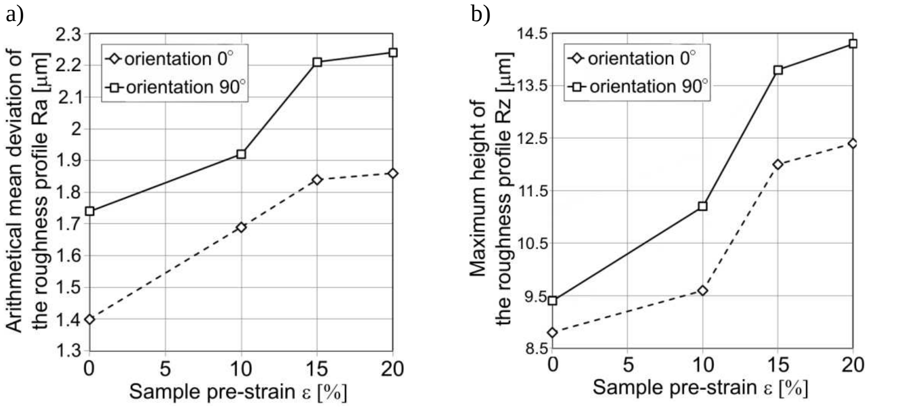

Fig. 3. Effect of sample pre-strain value on variation of the roughness parameters Ra (a) and Rz (b)

The width of the sample changes with an increase of the sample pre-strain value. However, according to the Coulomb model of friction the value of the friction coefficient does not depend on the contact area. It allows one to compare the values of the friction coefficients determined for different sample pre-strains. The value of the friction coefficient decreases as the clamping force increases for both dry (Fig. 4) and lubricated conditions (Fig. 5). It can be concluded that the relationship between the normal force and friction force is non-linear. In consequence the coefficient of friction value changes with the change of load. This relationship is also observed in other recent studies [2].

In general, at low values of load the coefficient of the friction value increases with the load and after reaching a certain value of load the value of friction coefficient rapidly decreases in the case of metals with a small capacity for strain-hardening. In the case of metals with a high capacity for strain hardening, the friction coefficient value is almost constant [3].

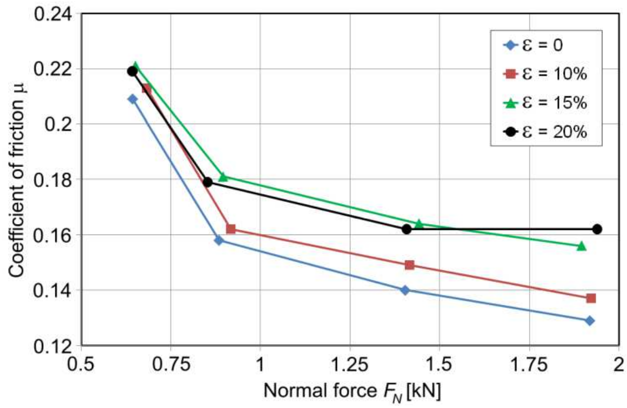

Fig. 4. Relation of friction coefficient value versus normal force F_N determined by using rolls with surface roughness Ra = 0.63 μm in dry friction condition

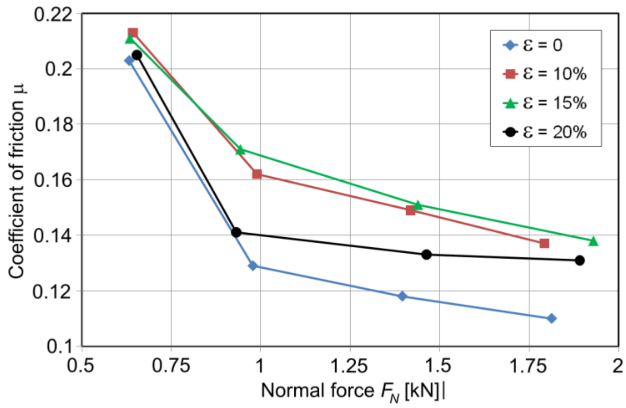

Fig. 5. Relation of friction coefficient value versus normal force F_N determined by using rolls with surface roughness Ra = 0.63 μm in lubricated condition

The increasing of a samples' pre-strain value causes an increase in the coefficient of the friction value. However, character of this relationship depends on the friction conditions. In both friction conditions the fast decrease of the friction coefficient is observed in the case of normal loads less than about 1 kN. After exceeding this value of normal load the intensity of decreasing friction coefficient is smaller. Roughening of asperities, observed during testing the sheets at normal load value exceeding 1 kN, tends to decrease the real area of contact resulting in a lower coefficient of friction. The samples pre-strained to 15 and 20% exhibit the highest and similar coefficient of friction values but only in the case of dry friction. The small difference in the value of the coefficient of friction determined for both dry and lubricated conditions, especially in the case of small values of normal force can be a result of a dominant influence both of flattening and ploughing mechanisms on the value of the coefficient of friction. The surface roughness valleys are too small to supply effectively lubricant to asperity contact area.

The evaluation of the average normal force $F_N^{(av)}$ for all tests performed at similar value of normal load allows us to make a generalised qualitative assessment of the effect of normal load on the coefficient of the friction value. An increase of normal load value causes a decrease of the coefficient of friction value (Fig. 6). For all used levels of normal load, the sample pre-strain at 10% increases the friction coefficient value in comparison to the test of original sheet surface. Further increase of sample pre-strain causes a decrease of the friction coefficient value. This relation depends on the ratio of frictional resistances at boundary lubrication regime and flattening mechanism.

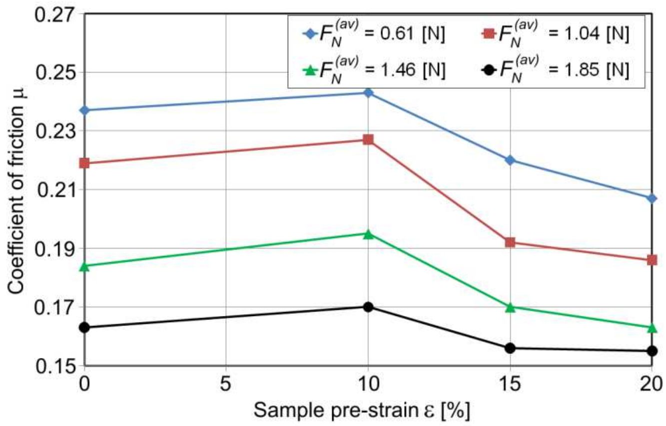

Fig. 6. Relation of friction coefficient value versus sample pre-strain determined by using rolls with surface roughness Ra = 1.25 μm in lubricated condition

In the case of the highest pre-strain value (20%) the lubrication of the contact surface causes the coefficient of friction to be smaller than in the case of pre-strains 10 and 15%. This can be explained by the fact that roughness valleys act as oil reservoirs (Fig. 7b). The profile height of samples pre-strained at 10 and 15% is not able to supply the suitable oil volume and the mechanism of surface roughness flattening (Fig. 7c) dominates. The phenomenon of flattening causes an increase in the real contact area. The increase in the real contact area occurs gradually from the initial peak surface roughness contact to full contact after balancing normal force and the force required to deform roughness [2].

In the boundary lubrication regime, friction is mainly described by adhesion and ploughing between contacting asperities. The intensification of the ploughing mechanism is observed mainly in the case of dry friction conditions (Fig. 7c) rather than in lubricated conditions (Fig. 7d).

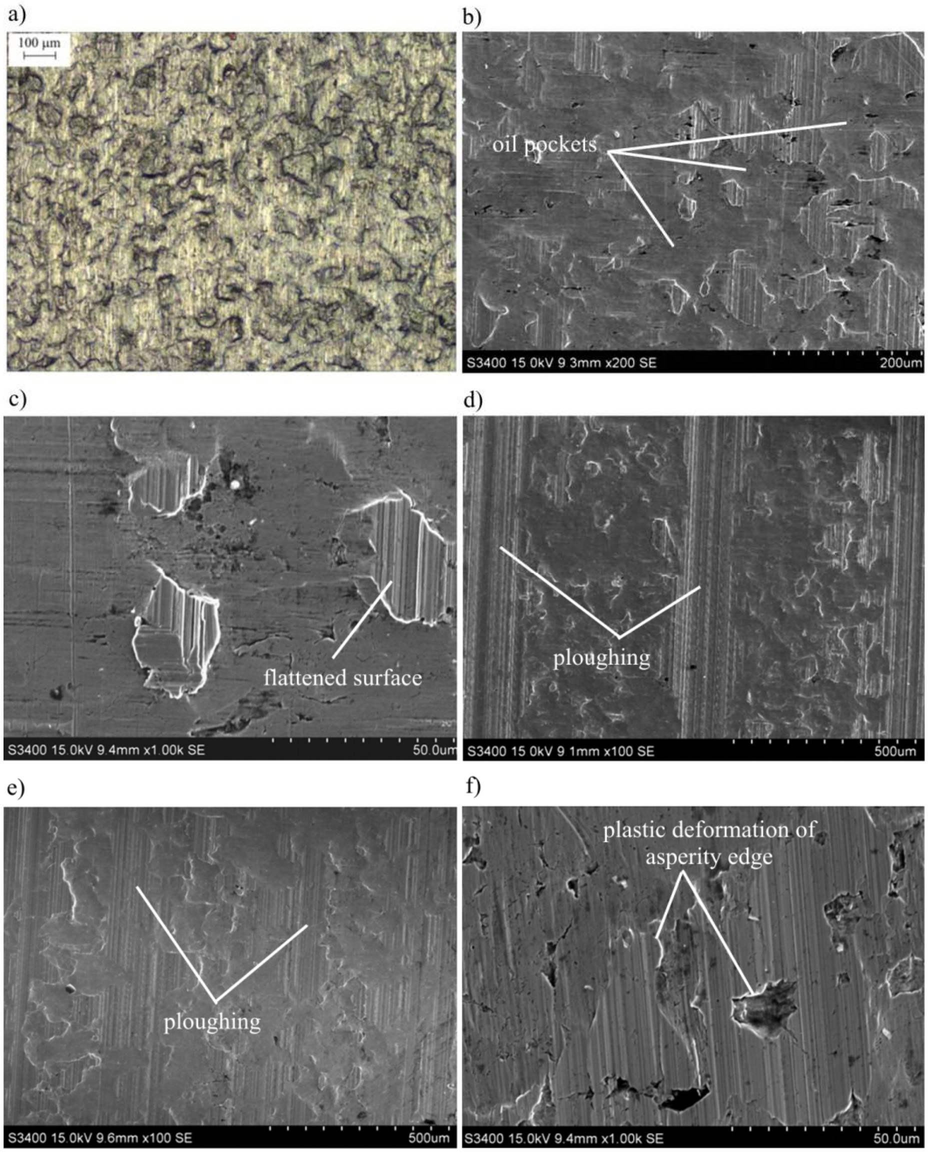

Fig. 7. View of original surface of tested steel sheet (a) and Scanning Electron Microscope micrographs of tested sheets: oil reservoirs (b), flattened asperities (c), ploughed surface observed in dry (d) and lubricated surfaces (e), and plastic deformation of the asperities edge

4. Summary and conclusions

Initially during sheet metal forming there is little real contact area. The surfaces adhere to each other only at the asperities, which are then deformed plastically until the contact surface becomes sufficient to transfer the load under the action of pressure. One of the main mechanisms during sheet forming is flattening and elastic-plastic deformation of surface asperities. It causes an increase of the real area of contact, which leads to an increase of the shear stress during the movement of the contacted surfaces. Conducted investigations of frictional resistance of auto-body steel sheets allow us to conclude that:

- the values of arithmetical mean deviation of the surface roughness profile and maximum height of the roughness profile increase with the sample pre-strain value,
- the dominant contact mechanism in the case of dry friction is asperity flattening,
- the value of the friction coefficient decreases as the clamping force increases for both dry and lubricated conditions,
- the relation between the normal force and friction force is nonlinear.

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WYZNACZANIE WSPÓŁCZYNNNIKA TARCIA STALOWEJ BLACHY KAROSERYJNEJ

Streszczenie

W artykule przedstawiono wyniki testów przeciągania pasa blachy mających na celu określenie wartości współczynnika tarcia w procesach kształtowania blach. Badania przeprowadzono za pomocą specjalnie zaprojektowanego symulatora tribologicznego. Badaniom poddano blachę stalową głębokotłoczną wykorzystywaną w przemyśle motoryzacyjnym. Przedstawiono i omówiono zależności pomiędzy siłą nacisku, chropowatością powierzchni narzędzia, warunkami tarcia oraz orientacją próbki względem kierunku walcowania a wartością współczynnika tarcia. Zdjęcia SEM (Scanning Electron Microscopy) powierzchni blach po procesie tarcia pozwoliły na rozpoznanie mechanizmów tarcia występujących podczas kontaktu dwóch ciał o powierzchni chropowatej. Wyniki badań wskazały, że zależność pomiędzy siłą tarcia i siłą normalną jest nieliniowa, dlatego wartość współczynnika tarcia zmienia się wraz ze zmianą wartości obciążenia.

Słowa kluczowe: współczynnik tarcia, tarcie, test przeciągania pasa blachy, chropowatość powierzchni

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