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# INVESTIGATION OF FRICTIONAL CONDITIONS OF STEEL SHEETS USING PIN-ON-DISK TRIBOMETER

**[1]Trzepieciński T., [1]Stachowicz F., [2]Bosiakov S., [2]Rogosin S.**

[1] *Rzeszow University of Technology, Poland*
[2] *Belarusian State University, Minsk*

**Introduction.** Friction regimes encountered during deep drawing of thin metal sheets are very complex and depend on several parameters such as the contact pressure, sliding velocity, sheet metal and tool surface roughness, kinematics of tool motion, tool and blank material, lubrication and temperature [1-3]. One of the main factors influencing frictional resistance is surface topography of deformed sheet. As friction between the sheet and tools is one of the important factors affecting the quality of drawpiece, clarifying the frictional condition for modeling and analysis of sheet metal forming processes is very essential. The workpiece surface topography and asperity contact are also important factors that control the mechanisms of lubrication in metal forming process.

This paper presents a method of determining the anisotropic friction model in metal forming based on experimental data obtained from the pin-on-disk tribometer. The experimental research of friction was carried out for deep-drawing car body steel sheet metal. The experimental results of friction tests show that the friction coefficient depends on the measured angle from the rolling direction and corresponds to the surface topography. To confirm that steel sheets are characterized by the anisotropy of tribological properties, frictional anisotropy on a given surface has to be clearly distinguished from frictional anisotropy for different perpendicular orientations between the pin and the surface. In this study, the friction coefficient as a function of angular position with respect to the rolling direction of the sheet metal was measure.

**Experimental procedure.** The frictional experiments presented in this work were conducted for deep drawing quality (DDQ) cold-rolled steel sheet with a sheet thickness of 1 mm. The mechanical properties of the sheet metal (Tab. 1) have been determined through uniaxial tensile tests along three directions with respect to the rolling direction. The parameters *C* and *n* in Hollomon equation have been fitted on stress-strain curve of the tensile test. The anisotropy of plastic behavior of sheet metals is characterized by the Lankford's coefficient *r* [5]. A measured *r*-value that differs from unity shows that there is a difference between mechanical properties measured in plane and through-thickness, which is usually characterized by the normal plastic anisotropy ratio, defined as:

$$\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4} \tag{1}$$

where $r_0$ is the strain ratio in the longitudinal direction, $r_{45}$ is the strain ratio measured 45° to the rolling direction and $r_{90}$ the strain ratio in the transverse direction.

**Table 1.** Mechanical properties of DDQ steel sheet metal

| Orientation | Yield stress $\zeta_y$ [MPa] | Ultimate tensile strength $\zeta_u$ [MPa] | Hardening coefficient *C* [MPa] | Strain hardening exponent *n* | Lankford's coefficient *r* |
|---|---|---|---|---|---|
| 0º | 162 | 310 | 554 | 0.21 | 1.55 |
| 45 | 163 | 322 | 542 | 0.20 | 1.27 |
| 90º | 168 | 312 | 530 | 0.21 | 1.67 |

The sheet metal exhibits in-plane anisotropy in the yield stress and the *r* value, while the hardening exponent value is not significantly affected by the sample orientation. The r value in the rolling direction is smaller than measured value in the transverse direction because it is inversely proportional to the thickness strain. The accommodation of strain in the width of the specimen is easier if the basal planes are more tilted to the width direction of the specimen. As the study by Yi *et al*. [6] asserts, the variation of the r value in different loading directions has a strong relationship with the texture. Moreover, the yield stress in the transverse direction is higher than the one measured at 45° and in the rolling direction, while the maximum ultimate tensile strength is measured at 45° from the rolling direction. The variation in the yield stress can be explained by its directional texture. Further, the values in the table show that the yield stress measured in the rolling direction is lower than in transverse direction, and the higher calculated material constant C value occurs for rolling direction and tends to decrease from the rolling to the transverse direction.

The friction properties of the deep drawing quality steel sheets used in the experiments were determined by using the pin-on-disc tribometer T01-M [7]. The values of friction coefficient were determined in dry friction conditions. Prior to each test, the pins and disks were degreased using acetone to remove metal fragments and oil from the surface. The tests were conducted under the following conditions:

- speed of sample rotation ω: 36 rpm,
- ball pressure: 450 and 640 MPa,
- track: circle of radius R: 5 mm.

Cyclical nature of the friction contact of pin-on-disk surfaces during tribometer test is the reason for the accumulation of wear products [8] and, consequently, may lead to a seizure of mating surfaces so the friction coefficients were determined for first sample rotation using the formulae:

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

where $F_T$ - friction force, $F_N$ - pin loading force.

To confirm that steel sheets are characterized by the anisotropy of tribological properties, friction anisotropy on a given surface has to be clearly distinguished from friction anisotropy for different perpendicular orientations between the pin and the surface. As shown in Fig. 1, changes of friction coefficient value exhibit two maxima for a rotation through 360º. They correspond to the measurement of friction coefficient value transverse to the rolling direction.

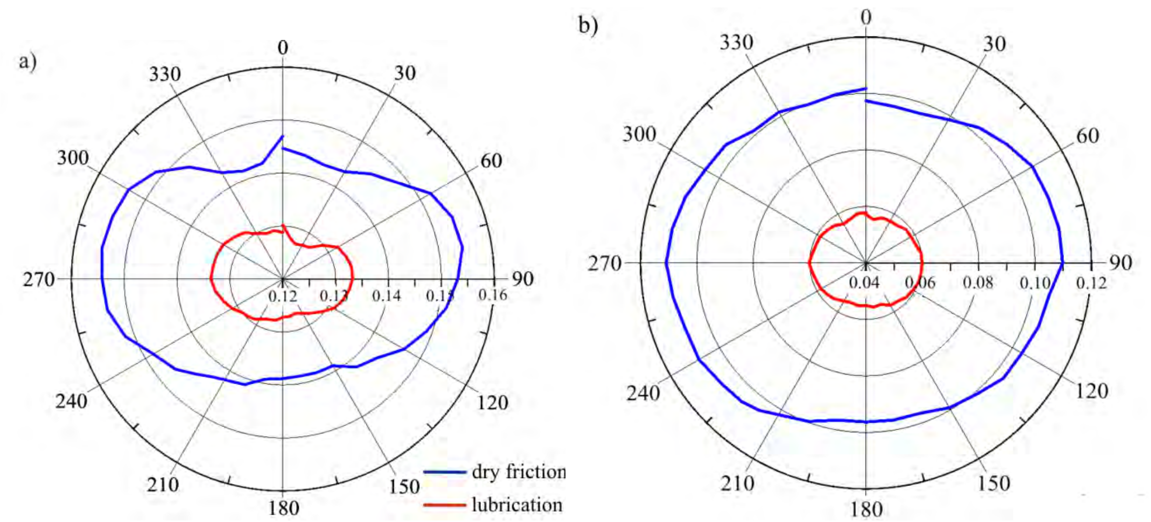


*Figure 1. The variation of friction coefficient value as a function of measurement orientation (°) according to the rolling direction of sheet, dry friction conditions, ball pressure: 640 MPa (a) and 450 MPa (b)*

**Contact conditions.** The tribometer's friction conditions involve both indentation and rotating sliding behaviour. Most of the researches of normal contact and sliding contact are focused on the analysis of elastic and elasto-plastic solids. The analytical analysis of the stresses at the contact of two elastic solids relating to spherical contacts was first studied by Hertz [9] and is based on four assumptions specified by Johnson [10]: the surfaces are continuous and non-conforming, the strains are small (within the elastic limit), bodies in contact are considered as elastic half-spaces and the contact is frictionless. The pressure distribution over the contact area is given as:

$$P = \frac{3W}{2\pi a^2}\sqrt{1-\left(\frac{r}{a}\right)^2} \tag{3}$$

where $W$ is the normal load, $r$ - wear scare radius , $a$ -radius of point contact circle given as:

$$a = \sqrt[3]{\frac{3WR}{4}\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)} \tag{4}$$

where $\nu_1$ and $\nu_2$ are the Poisson's ratios for bodies *1* and *2* respectively, and $E_1$ and $E_2$ are their Young's moduli, $R$ is the relative curvature defined as:

$$R = \frac{R_1 + R_2}{R_1 R_2} \tag{5}$$

where $R_1$ and $R_2$ are the radius of the curvature of bodies *1* and *2* respectively.

When response of the solid material is elastic-plastic Hertzian theory is limited. The influence of strain hardening on contact pressure and contact stress was done by Kral et al. [11]. The analysis is based on a rigid sphere on an elastic-plastic half-space model considered Huber-Mises-Hencky material model. However, Kral's model was frictionless. Taljat and Pharr [12] considered friction in your indentation model and concluded that the contact friction affects the pile-up geometry. They found that friction affects pile-up in a manner that depends on strain hardening exponent *n*. Most numerical studies of sliding contact are focused on the two-dimensional linear tangential loading and sliding of the fixed slider (Fig.2). The indenter, carrying the normal load $F_N$, moves from right to left over the fixed flat surface in a direction parallel to the x-axis.

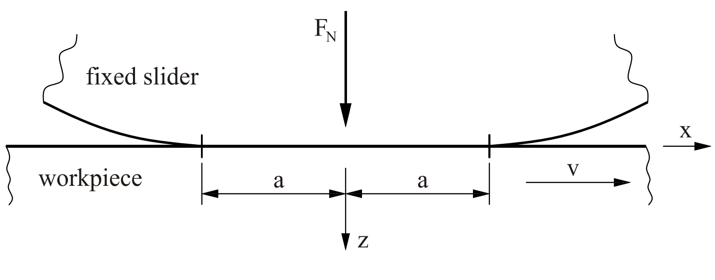


*Figure 2. Schematic of two parts in a sliding contact*

**Numerical modeling.** The limit surface is usually assumed to be isotropic predicting a frictional behavior independent of the sliding direction. For many industrial applications, this assumption seems to be unrealistic and many experimental studies show that the frictional behavior can change drastically with the sliding direction, requiring an anisotropic model [4]. The origin of this anisotropy can be attributed to two different sources. The first one is the material itself where the anisotropies of the materials constituting the bodies manifest themselves on the contact surface. The second one is technological. The industrial process used to fabricate the bodies can create striations along preferential directions. Currently, there are not so many publications focusing on frictional anisotropy and its implementation in numerical simulations of sheet metal forming processes.

The anisotropic friction model corresponded to experimental results was implemented into a finite element (FE) model built using the commercial FE-package ABAQUS. An elastic-plastic material model approach was implemented. The elastic behavior is specified in numerical simulations by the value of Young's modulus, E = 210000 MPa, and of Poisson's ratio $\nu$ = 0.3. In the numerical model, the anisotropy of the material has been established using Hill (1948) yield criterion (AM) [14] which is the most frequently used yield function for steel sheet metals [5]. Furthermore, the isotropic Huber-Mises-Hencky material model (IM) is considered. The isotropic hardening behaviour in the FEM model uses the Hollomon power-type law.

For the blank meshing the 3-dimensional 8-node brick elements were used. The hardness of the indenter is considerably higher than the blank hardness so the pin is considered to be rigid, no deformation is assumed in this part during the simulation [15]. The blank model is composed of 22880 of C3D8R type elements (Fig. 4). In order to increase the accuracy of the solution the local densification of the mesh along the contact track is applied.

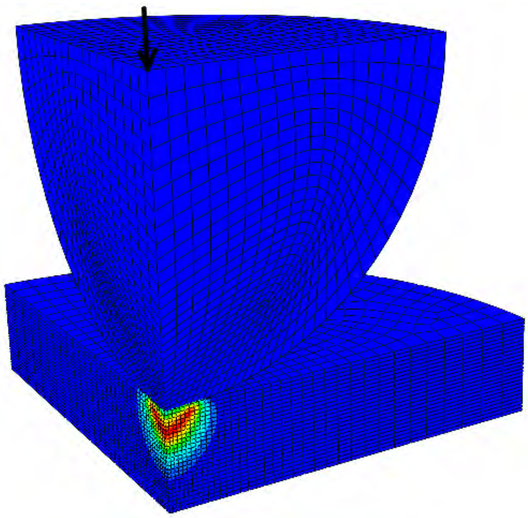

*Figure 4. Finite element model of the ball indentation process*

As it was found in previous investigations [15] the anisotropic elliptic friction model (AF) approximate well the experimental variations of friction coefficient value. The minimal and maximal values of friction coefficient in implemented elliptic model were 0.128 and 0.157, respectively. For the isotropic frictional conditions (IF) an average value of friction coefficient 0.1425 was used.

**Numerical results and discussion.** The small errors could be attributed to the averaging of the stress data from integration points to boundary nodes and the discretization of the continuous surface. As the pin load increases, the plastic zone continues to grow until the edge of the plastic zone reaches the surface near the edge of the contact radius. The maximum value of total equivalent plastic strain is found at the subsurface, some distance below the centre of the contact region (Fig. 5). The anisotropy of both material and friction conditions was influenced on non-uniformity of the stress distribution around the pin axis, which is clearly visible for higher values of pin indentations. As the load increases, for both material models, the plastic zone continues to grow until the edge of the plastic zone reaches the surface near the edge of the contact radius. Furthermore, the zone of maximum equivalent plastic strain moves radially from the centre towards the surface inside the maximum contact radius which is in agreement with the analytical results of the research made by Kral et al. [13].

As shown in Fig. 5 the change of isotropic friction to anisotropic conditions for both material models slightly influenced on the change of equivalent plastic strain distribution. Similar dependence is observed for equivalent plastic strain value measured along the rolling the rolling direction of the sheet (Fig. 6). The maximal difference in equivalent plastic strain between AM+AF and IM+IF is equal of about 0.002 and is observed at the subsurface, some distance below the centre of the contact region. The maximal difference in equivalent plastic strain between AM+AF and IM+IF is equal of about 29 MPa.

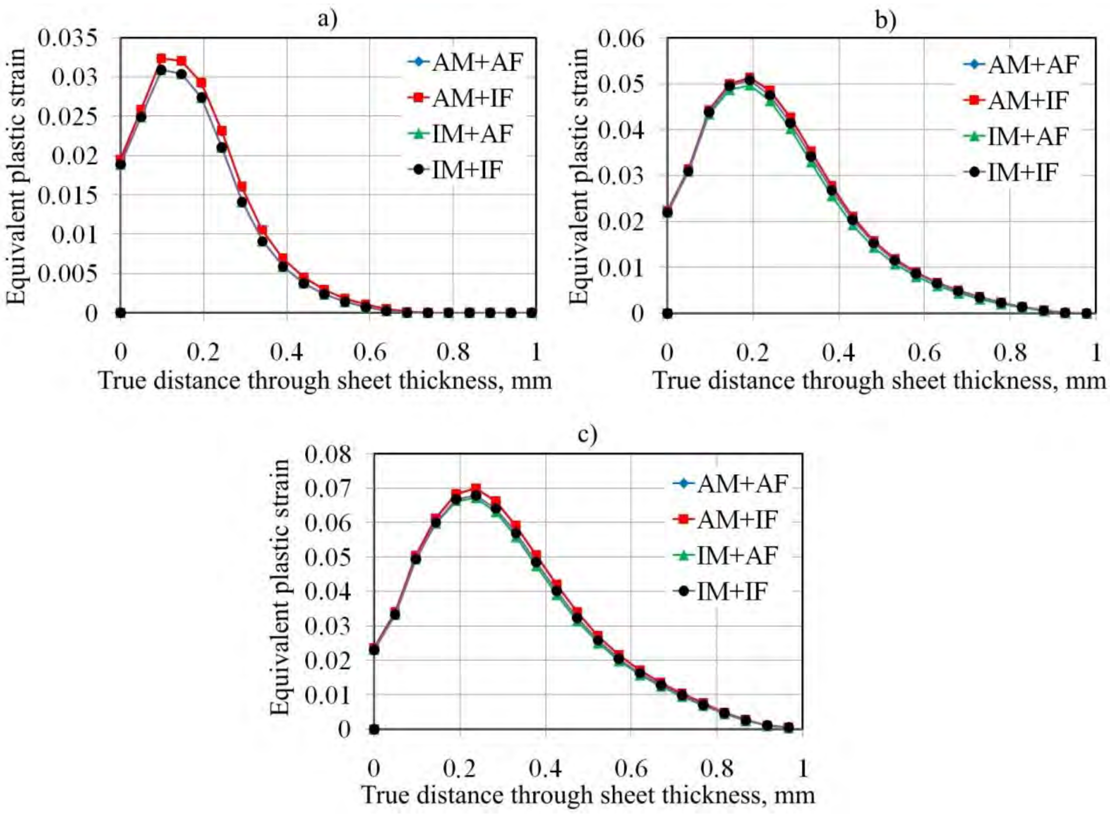


*Figure 5. Distribution of total equivalent plastic strain for indentation depths: a) 0.012 mm , b) 0.024 mm and c) 0.036 mm*

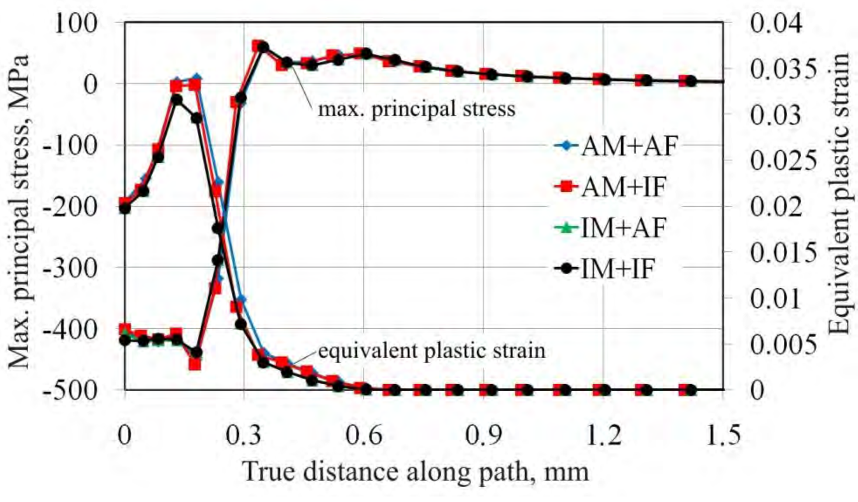


*Figure 6. The value of maximal principal stress and equivalent plastic strain measured along the rolling direction*

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**SUMMARY**

This paper presents a method of determining the anisotropic friction model for sheet metal forming processes based on experimental data obtained from the pin-on-disk tribometer test. Friction coefficient value was measured as a function of angular position with respect to the rolling direction of the sheet metal. The frictional investigations presented in this work were conducted for deep drawing quality cold-rolled steel sheet with a sheet thickness of 1 mm. The anisotropic friction model corresponded to experimental results was implemented into a finite element (FE) model built using the ABAQUS software. In the numerical investigations the hemispherical contact against an elastic-plastic flat was analysed. In the numerical model to describe the material behaviour the isotropic Huber-Mises-Hencky and anisotropic Hill (1948) yield criteria have been assumed. The anisotropy of both material and friction was influenced on non-uniformity of the stress distribution around the hemisphere axis, which is clearly visible for higher values of hemispherical solid indentations. It was found that the change of isotropic friction to anisotropic conditions for both material models slightly influences on the value and the change of equivalent plastic strain distribution in contact zone.

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**E-mail:** bosiakov@bsu.by

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