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RESEARCH PAPER

EFFECT OF THE PLASTIC STRAIN AND DRAWING QUALITY ON THE FRICTIONAL RESISTANCE OF STEEL SHEETS

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ABSTRACT

The aim of the research presented in this article is to investigate the frictional resistance of steel sheets with different drawing quality. Friction tests have been carried out using the bending under tension (BUT) test which simulates the contact conditions at the rounded edge of the punch in sheet metal forming operations. The effect of sheet deformation and temper state on the value of the coefficient of friction has been studied. It was found that increasing the value of elongation of the sheet is associated with an increase in the value of the COF for both friction conditions analysed. The intensity of work hardening, by changing the mechanical properties of the sheet, is a factor that changes contact conditions. The lubricant which is typically used in plastic working provided a reduction of frictional resistance by approximately 3.6-14%, depending on the degree of sheet deformation.

Keywords: coefficient of friction; friction; mechanical engineering; sheet metal forming; steel sheets; work hardening

INTRODUCTION

The frictional resistances between the surfaces of both the deformed material and the tools in the sheet metal forming (SMF) process are one of the most important factors affecting the distribution of deformation in different zones of the workpiece. Many factors affect processes that arise in the contact zone, i.e. the normal pressures, surface topography of sheet plate and tools, physicochemical phenomena, mechanical properties of the sheet material, and type of lubricant [1-4]. Physicochemical phenomena occurring in the contact interface depend on the kinds of materials and chemical affinity of the friction pair. Friction connections between two bodies in contact are destroyed during reciprocal transition of contact pairs. The amount of frictional resistance arising is mainly determined by the shear strength of the friction connections [5, 6].
Friction and elastic deformation of the sheet metal have a great effect on the implementation of metal forming processes [7, 8]. Friction causes tangential stresses on the contact surface that change the stress state and cause non-uniformity in deformation and an increase in forming forces. Moreover, friction acts as a brake on the flow of material in the surface layers, which can lead to crack initiation. In addition, friction significantly increases tool wear [9, 10]. Lubrication of tools and the workpiece is used to reduce friction. It is important that the lubricant should have sufficient viscosity at the forming temperature and that it forms a thin, continuous film in an interface which is resistant to high pressures [11-14].
In SMF, there is initially a small actual area of contact between the tools and the workpiece. After applying pressure the elastic-plastic deformation of surface asperities occurs, which increases the actual area of contact [15, 16]. This leads to an increase in tangential stresses when the contacting surfaces move together. The shape of the contact surface affects the size of the nominal area of the contact surface. Furthermore, the stretching of the sheet metal and the work hardening phenomenon lead to a perpetual change in the surface topography of the sheet metal [17, 18]. Due to the occurrence of different contact conditions in particular areas of the drawpiece with regard to the state of stress and strain, and the speed of sliding, a number of tests have been developed to model friction conditions, i.e. the strip drawing test, bending under tension test, drawbead test, or a special test which simulates the material flow in specific areas of the stamping tools [19-21].
In this paper, the bending under tension (BUT) test has been used to investigate the effect of plastic strain (specimen elongation) and drawing quality on the amount of frictional resistance. The test sheets have been fabricated in three states: drawing quality (DD), deep drawing quality (DDQ) and extra deep drawing quality (EDDQ). The BUT test has been carried out using a special tribological simulator.

EXPERIMENTAL

Material

Steel sheets in three states of fabrication: DQ, DDQ and EDDQ, were used as test material. The mechanical properties of the sheets were determined in a uniaxial tensile test on a Schenck type UTS 100 testing machine according to the ISO 6892-1 standard. The samples were cut along (0°) and transverse (90°) to the sheet rolling direction. The strain hardening properties have been determined by approximation of the true stress-true strain relation using the Hollomon equation $\sigma = K \cdot \varepsilon^n$, where σ is the true stress, ε is the true strain, K is the strength coefficient and n is the strain hardening exponent. Three samples were tested for each direction and then the average values of specific parameters were determined (Table 1).
In order to compare the effect of temper state on the frictional resistance of the sheets, the surface roughness of the sheets should be as similar as possible. The sheets for friction tests were selected so that the roughness average *Sa* was in the smallest possible range. *Sa* is a commonly used parameter to characterise surface roughness in industry. The *Sa* of the test sheets was in the range 0.302-0.362 μm. Surface roughness was measured using a Taylor-Hobson Surtronic 3+ device.

Test method

The bending under tension test permits the determination of the frictional resistance at the rounded edge of the punch (Fig. 1) in SMF. Friction tests have been conducted using a special friction simulator (Fig. 2) mounted on a universal tensile testing machine. A strip sheet was held at both ends in tension members. The specimen is wrapped around a cylindrical fixed roll with a diameter of 20 mm and loaded in a universal tensile testing machine. A roll made of cold-working tool steel was used with surface parameters *Ra* measured parallel to the roll axis: 0.32 μm. The coefficient of friction (COF) has been determined based on the back tension force *F*2 [N] and front tension force *F*1 [N] according to the relationship:

$$\mu = \frac{2}{\pi} ln\left(\frac{F1}{F2}\right) \quad (1.)$$

where: $F1$ [N] - front tension force,
$F2$ [N] - back tension force.

Table 1 Basic mechanical properties of steel sheets

State	Nominal sheet thickness *t*, mm	Yield stress σ_p, MPa	Ultimate tensile stress R_m, MPa	Elongation, %	Strength coefficient *K*, MPa	Strain hardening exponent *n*
DQ	1.0	193	352	35	558	0.17
DDQ	1.0	162	311	41	452	0.21
EDDQ	1.0	152	281	43	484	0.22

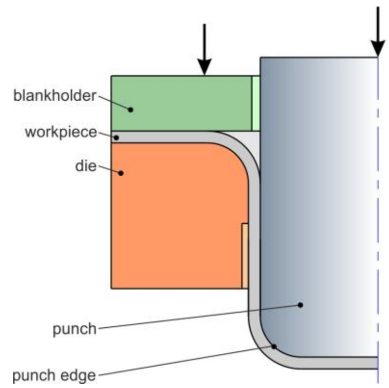

Fig. 1 Region of the rounded edge of punch

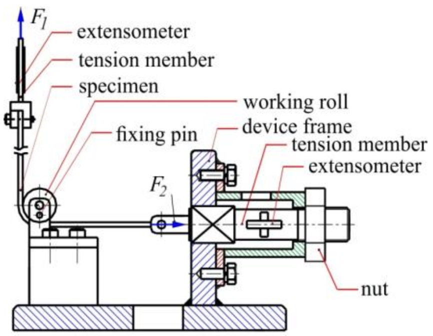

Fig. 2 Schematic view of the testing device

Tensile forces were measured using extensometers. The deduction of equation 1 may be found in [5]. Both tensile forces were measured simultaneously during the test so that it was possible to determine the COF for the specific strain of the strip sheet. The constant stretching speed was set as 0.3 mm·s^{-1}. Strip specimens were cut along the sheet rolling direction and were carefully prepared to assure a constant width of 10 mm. The initial length of the specimen measured between the load cells was L_0 = 135 mm. The friction tests were carried out in dry and lubricated conditions. Machine oil LAN-46 (Orlen Oil) with a kinematic viscosity of 43.9 mm^2·s^{-1} (at 40°C), viscosity index 94, ignition temperature 232°C, and flow temperature -10°C was used as lubricant. To produce both conditions, rolls and specimens were degreased using acetone.
The lubricant was distributed uniformly on the surface of the samples at 2 g·m^2 using a shaft [22]. The specimen elongation was measured according to the relationship:

$$\lambda = \frac{\Delta L}{L0} \cdot 100\% \qquad (2.)$$

where: ΔL [mm] – the displacement of the gripper of a tensile machine,
$L0$ [mm] - the initial length of the specimen measured between the load cells.

RESULTS AND DISCUSSION

In general, increasing the value of elongation of the sheet is associated with an increase in the value of COF for both friction conditions analysed (Figs. 3, 4). Under dry friction conditions, stabilisation of the frictional resistance is visible after exceeding a deformation of approximately λ = 0.2 (Fig. 3). This effect is also invisible in the case of lubricated conditions (Fig. 4). The work hardening of the sheet increases its hardness and stabilises the topography of the sheet surface.

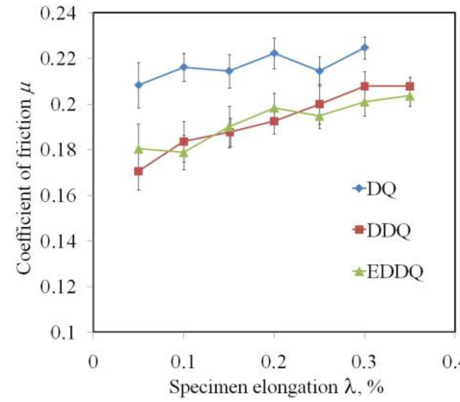

Fig. 3 Effect of specimen elongation on the COF for dry friction conditions

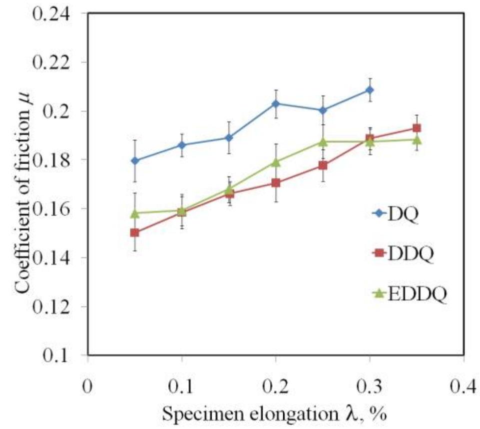

Fig. 4 Effect of specimen elongation on the COF for lubricated conditions

Pressure is then transmitted through the material core, while the actual area of contact does not change further. The greater the elongation of the specimen, the greater the contact pressure acts on the surface of the countersample which is associated with work hardening [23]. The greater is the pressure, the lower is the lubrication efficiency. The lubricant in the oil pockets is subjected to increased pressure, which is not able to balance the increasing resistance of the contacting surfaces as a result of ploughing and flattening of the workpiece surface. It can be concluded that the dominant mechanism under high pressure was the mechanical interaction of the surface asperities. The highest frictional resistance was observed for the DQ sheet, which is characterised by the largest susceptibility to material strengthening (Fig. 5).
To study the degree of friction reduction induced by the lubricant, the following coefficient has been introduced:

$$\gamma = \frac{\mu d - \mu l}{\mu l} \cdot 100\% \qquad (3.)$$

where: μd - the COF determined in dry conditions,
μl - the COFs determined in lubricated conditions.

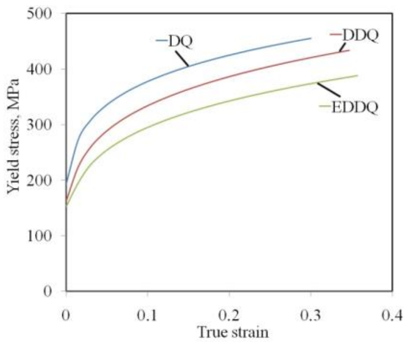

Fig. 5 Strain hardening curves

Lubrication efficiency described by the coefficient γ decreases most with the degree of deformation of the DQ sheet (Fig. 6). With a sheet deformation of λ = 0.15 mm, very similar efficiency was observed for all sheets tested. The sheet that exhibits the largest work hardening at larger deformations shows a significant reduction in lubrication efficiency. The most favourable properties of the lubricant were demonstrated during the testing of the DDQ sheet.
In the case of this sheet, the most uniform lubricant interaction was observed over the entire range of sheet deformation. The ability of the lubricant to reduce frictional resistance under high pressure is particularly important in the automotive industry where the components are fabricated with surface finish. The roughness valleys (Fig. 7) that entrap lubricant between the tool surface and the workpiece surface act as lubricant reservoirs.

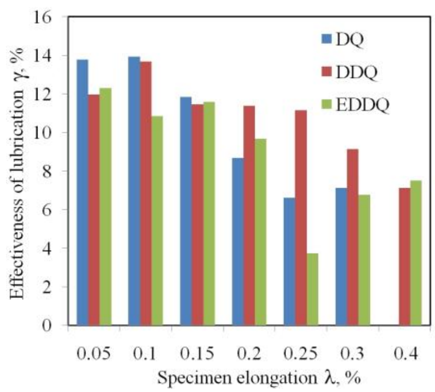

Fig. 6 Effect of specimen elongation on the effectiveness of lubrication

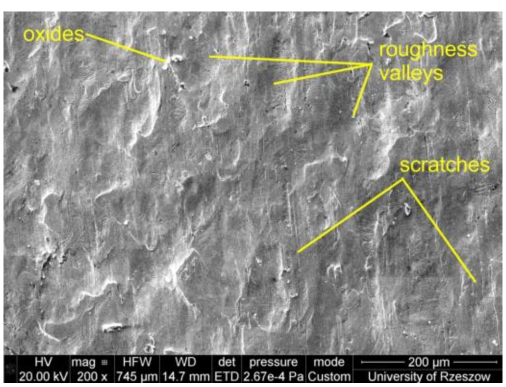

Fig. 7 Scanning Electron Microscopy (SEM) micrograph of sheet surface (λ = 0.2, DDQ sheet metal, dry friction).

CONCLUSION

The difference in the COF values between DDQ and EDDQ sheets over the entire range of deformations is very similar. The intensity of work hardening is a factor that changes contact conditions since it changes the mechanical properties of the sheet. The COF value for the DQ sheet was about 0.02-0.03 higher compared to the other sheets. The typical lubricant used in plastic working provided a reduction of frictional resistance of approximately 3.6-14%, depending on the value of the sheet deformation (Fig. 6). Lubrication efficiency decreased with increasing normal pressure as a result of the increasing of both front and back tensile forces. This leads to intensification of the mechanical interactions of the surface asperities. Under such conditions the lubricant could not balance these resistances.

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