EXPERIMENTAL EVALUATION OF DRAW BEAD COEFFICIENT OF FRICTION

Tomasz Trzepiecinski[1)], Romuald Fejkiel[2)], Andrzej Kubit[3)]*
1)Rzeszow University of Technology, Department of Materials Forming and Processing, Rzeszow, Poland
2) State School of Higher Vocational Education in Krosno, Krosno, Poland
3) Rzeszow University of Technology, Department of Manufacturing and Production Engineering, Rzeszow, Poland

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**Corresponding author: e-mail: tomtrz@prz.edu.pl, Tel.: +48178651714, Department of Materials Forming and Processing, Rzeszow University of Technology, al Powst. Warszawy 8, 35-959 Rzeszów, Poland*

Abstract
In this paper the results of both friction coefficient and springback testing using a drawbead test are presented. Deep drawing quality steel sheet (DC04 according to EN 10130:2009 standard) was used as the test material. The experimental investigations were carried out using a special device that allows a change in the degree of deformation of the sheet metal on the drawbead. The friction tests were carried out for different values of tool surface roughness, specimen widths and degrees of sheet deformation. Three lubrication conditions were analysed: dry friction, machine oil lubrication and lubrication using methacrylic resin. The springback values were determined based on digital image analysis for selected friction conditions. It was found that the effectiveness of reducing the value of the friction coefficient during the pulling of a sheet on the drawbead depends not only on the lubricant used, but also on the degree of sheet deformation (displacement of the middle roll). The sheet widths influence the friction coefficient value through the character of sheet deformation during the pulling of the sheet through the drawbead.

Keywords: friction, sheet metal forming, steel sheet, tribology

1 Introduction

The dimensional and shape accuracy of formed parts is strongly dependent on the friction and lubrication conditions that are acting in the actual production process. The friction conditions are dependent on the tribology system, i.e. the applied pressure load, surface roughness - both of sheet metal and tool and process conditions (static or dynamic loads, forming temperature, sliding speed) [1-4]. The friction mechanism also depends on the material of the tool and the relative hardness of the surface of the specimens to the tool materials [5, 6]. In the sheet metal forming of parts with complex geometry, the magnitude and distribution of friction affect metal flow, part defects and production costs [7]. By controlling the tribological conditions in the process, it is possible to reduce defects or problems like crack formation, shrinkage, wrinkles and tool wear [8-10]. Friction is also a key phenomenon in joining sheet metals [11].

At the microscopic level, friction is due to adhesion between contacting asperities and the ploughing effects between asperities. The ploughing effects between asperities and adhesion

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effects between boundary layers are the main factors causing friction in the boundary lubrication regime [12]. In the lubrication regime the contact pressure is carried by the lubricant flow and asperities. Many experimental and analytical investigations have concerned the determination of frictional phenomena on a drawbead during the forming of sheet metal [13-17]. Many studies have been conducted on the modelling of draw dies using automated design systems [18-20].
This paper presents the results of an experimental investigation which investigates the frictional resistances of DC04 steel sheet using the drawbead simulator test. The experiments were carried out for different values of tool surface roughness, specimen widths and degrees of sheet deformation. Three lubrication conditions were analysed: dry friction, machine oil lubrication and lubrication using methacrylic resin.

2 Material and methods

DC04 steel sheets with a thickness of 0.8 mm were used as the test materials. Tensile tests were carried out in a Zwick Roell Z030 universal testing machine to determine the mechanical properties of the sheets cut along the direction of sheet rolling. The values of the mechanical parameters are as follows: yield stress 185.4 MPa, ultimate tensile strength 303.9 MPa, elongation 23%. The values of the strain-hardening coefficient *C* and strain-hardening exponent *n* in the Hollomon power law are 490.4 MPa and 0.205, respectively. The measurement of surface roughness parameters was carried out using a Talysurf CCI Lite 3D instrument. The selected standard 3D parameters (**Table 1**) determined by this measurement were: roughness average *Sa*, root mean square roughness parameter *Sq*, maximum pit depth *Sv*, highest peak of the surface *Sp*, surface skewness Ssk, maximum profile height *Sz*, root mean square gradient *Sdq*, and the developed interfacial area ratio *Sdr*. The surface morphology (**Fig. 1**) of the sheets was measured with a Bruker Contour GT 3D optical microscope.

Table 1 The basic surface roughness parameters of the DC04 steel sheet tested

***Sa* [μm]**	***Sq* [μm]**	***Sp* [μm]**	***Sv* [μm]**	***Sz* [μm]**	***Ssk***	***Sdq***	***Sdr***
1.178	1.467	8.628	9.273	17.902	-0.128	2.970	0.265

To determine frictional resistances, friction tests were carried out using the drawbead simulator (**Fig. 2**). The design of the simulator allows changes to be made in the frictional resistances of the sheet by changing the angle of wrapping of the middle roll (see 2, **Fig. 2**). The frame (5) of the friction simulator was attached to the lower grip of the Zwick Roell Z030 tensile testing machine, and the tension member (6) was attached to the upper grip of the testing machine. During the tests, the pulling force and the clamping force were registered by the computer program using two tension gauges (7 and 8). One specimen was pulled between freely rotating cylindrical rolls, and then the pulling force measured and the clamping force gave the bending and unbending resistance respectively of the sheet under 'frictionless' conditions.
The sheet was displaced between the rotating rolls so that the friction between the sheet and rolls was minimised whereas the second specimen was pulled between the fixed rolls. The coefficient of friction value μ was calculated according to the expression:

$$\mu = \frac{F_C^z - F_C^r}{F_D^z} \cdot \frac{\sin\Theta}{2\Theta} \qquad (1.)$$

where: F_C^z [N] - the pulling force obtained with the fixed rolls,

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F_C^Z [N] - the pulling force obtained with the freely rotating rolls,
F_D^Z [N] - the normal force or clamping force obtained with the fixed beads,
θ [rad] - the quarter contact angle of actual engagement of the strip over the bead (**Fig. 3**).

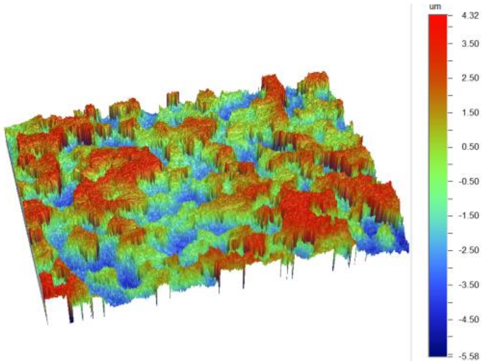

Fig. 1 Surface morphology of the DC04 steel sheet (area 0.94 mm ×1.3 mm)

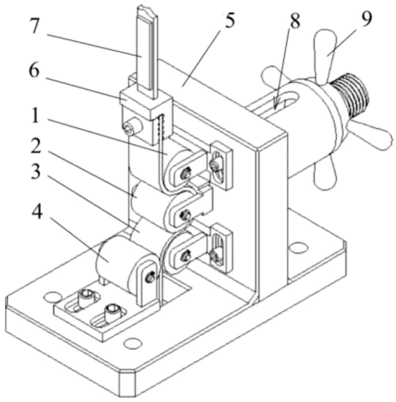

Fig. 2 Measurement system used for friction testing; 1 – front roll; 2 - middle roll; 3 – back roll; 4 – supporting roll; 5 – frame; 6 – tension member; 7 and 8 – extensometers; 9 – handwheel

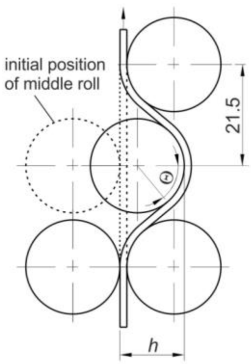

Fig. 3 Model of drawbead

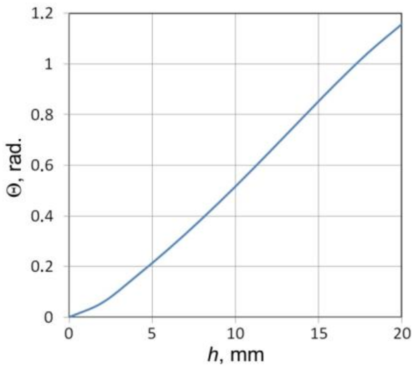

Fig. 4 Effect of middle roll displacement *h* on an angle Θ

The dependence of the middle roll displacement *h* on an angle Θ is shown in **Fig. 4**. Various tribological conditions were obtained using rolls with different surface roughness values (Ra = 0.32, 0.64 and 1.25 μm), measured along the generating line of the rolls. Prior to each friction test, the surface of the rolls was checked and the surface was cleaned with acetone to remove potential products of the abrasive wear of the surface of the DC04 sheet. Machine oil L-AN 46 with 44 mm^2s^{-1} viscosity at 40°C was used for lubricated conditions. Methacrylic resin combined with chlorinated hydrocarbons was used as a second lubricant. The measurement of

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the amount of springback is carried out in AutoCAD software based on the images of the samples. To ensure the comparability of the results obtained under different friction conditions, the measurement of springback angle is started at a distance of z = 130 mm (**Fig. 5**) from the sample edge.

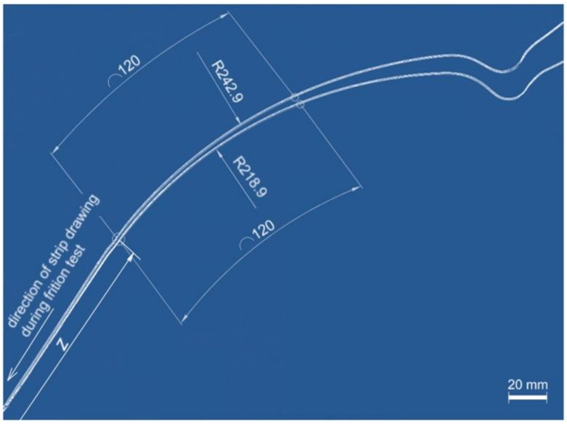

Fig. 5 Method of springback measurement

3 Results and discussion

The values of the measurement forces with their standard deviations (SDs) are presented in **Table 2**. The forces were measured with an accuracy of 0.001 kN.

Table 2 The measurement forces from the drawbead friction test

Displacement of middle roll *h*, mm	Sample width *w*, mm	Friction conditions	F_C^Z, kN		F_C^T, kN		F_D^Z, kN	
			value	SD	value	SD	value	SD
6	7	dry	160.3	2.386	97.2	2.819	112.4	1.385
		oil	143.9	2.037	92.4	1.094	111.8	1.503
		resin	122.2	4.582	95.5	1.595	109.7	1.643
	14	dry	326.5	12.831	169.8	2.559	243.1	8.975
		oil	312.0	13.179	186.5	2.419	249.8	10.821
		resin	284.1	3.259	187.2	3.705	226.4	3.179
	20	dry	425.2	5.682	251.6	2.843	321.2	3.247
		oil	375.8	4.357	258.8	8.395	314.4	2.499
		resin	405.0	3.264	299.5	9.031	332.6	1.939
12	7	dry	320.3	7.307	180.6	1.436	273.9	5.688
		oil	308.2	16.637	207.5	3.788	259.8	11.987
		resin	246.6	6.917	199.2	2.003	189.5	2.477
	14	dry	568.1	8.759	361.3	2.664	380.5	3.380
		oil	536.2	4.441	339.5	1.424	451.8	3.734
		resin	682.8	12.862	485.2	5.622	641.8	11.823
	20	dry	693.6	7.006	388.0	11.210	635.8	2.947
		oil	705.3	19.134	498.3	3.639	652.7	19.134
		resin	660.7	10.125	467.9	4.865	629.8	12.184

18	7	dry	428.9	4.417	273.0	3.368	382.3	4.417
		oil	418.5	2.839	283.6	3.761	395.1	3.383
		resin	333.4	8.612	270.4	2.104	312.0	6.941
	14	dry	716.4	18.127	489.2	4.828	640.8	18.259
		oil	692.5	15.286	485.0	5.858	623.5	19.184
		resin	610.0	8.107	482.7	3.615	589.6	10.692
	20	dry	1012.5	7.125	773.8	5.127	573.0	5.579
		oil	915.2	6.642	721.2	3.124	529.3	4.303
		resin	909.1	21.815	681.5	6.801	649.3	18.941

In the case of all friction conditions for a sample width of 7 mm, the friction coefficient value increased with an increase in the middle roll displacement up to 14 mm (**Fig. 6a**). Next the inverse relationship was noted. In the case of a sample width of 14 mm, a decreasing value of the friction coefficient with sample width is observed (**Fig. 6b**). For a sample width of 20 mm, the recorded friction coefficient values were the most similar across the whole range of middle roll displacement (**Fig. 6c**). The effectiveness of friction reduction by resin is highest in the case of testing a specimen width of 7 mm: a twofold decrease of friction coefficient is observed. As observed by Trzepieciński et al. [1], in sheet metal forming, the real contact area plays an important role in determining the frictional resistance. The character of sheet deformation during the passing of the sheet strip on the drawbead depends on sheet width and is manifested by a change of the shape of the rectangular cross-section into a convex cross-section (**Fig. 7**).

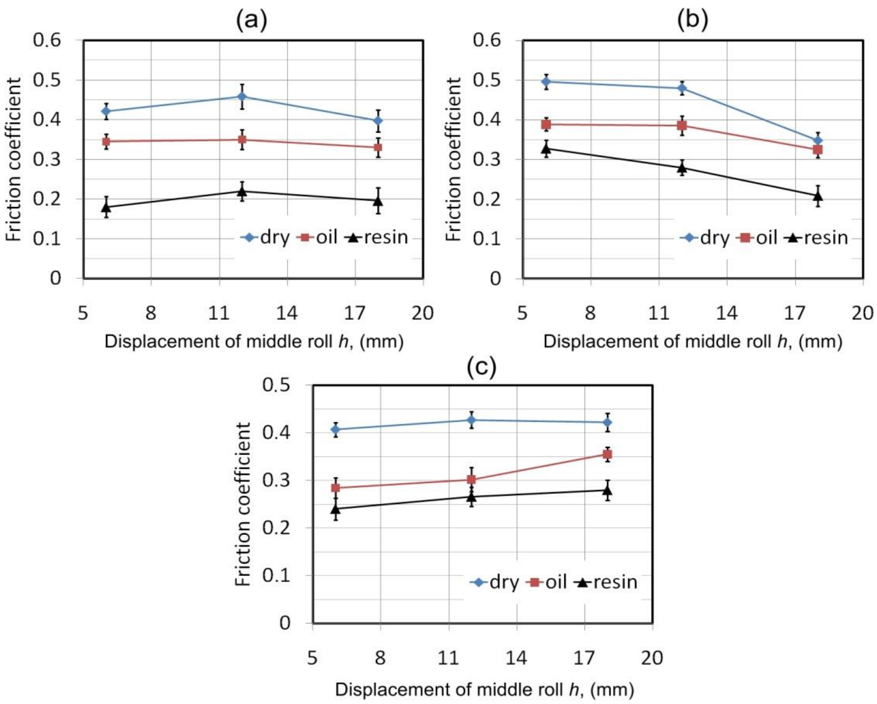

Fig. 6 Effect of displacement of the middle roll on the value of the friction coefficient determined for sample widths: (a) 7, (b) 14, and (c) 20 mm, at Ra of rolls equals of 0.63 µm

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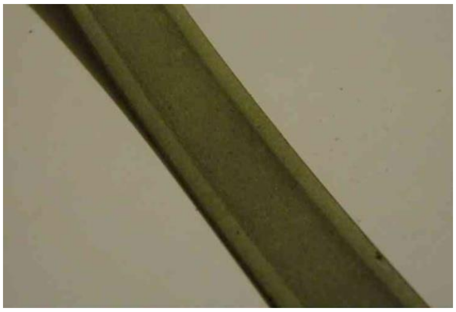

Fig. 7 View of the specimen surface (w = 20 mm) tested under conditions of dry friction, Ra of rolls equals of 0.63 μm and middle roll displacement h = 18 mm

Increasing the specimen width used made it possible to increase the friction coefficient values for different middle roll displacements. The change in lubrication conditions does not affect the tendency to increase the friction coefficient tested at different roll surface roughnesses and middle roll displacements. In general, the highest values of friction coefficient are observed for the lowest displacement of the middle roll.
It was found that increasing the displacement of the middle roll causes an increase in the radius of curvature of the specimen after friction tests carried out with fixed rolls and freely rotating rolls (**Table 2**). However, the specimens tested with fixed rolls exhibit higher springback radius. The character of deformation of the strip specimen (see **Fig. 7**) allows for a deviation of the amount of springback within the specimen widths used. It is clear that increasing the sample width leads to an increase of curvature radius of the specimen (**Table 3**).

Table 3 Effect of middle roll displacement on amount of springback (dry friction conditions)

Displacement of middle roll *h* [mm]	***Ra* of rolls [μm]**					
	0.32		**0.63**		**1.25**	
6	R_o = 234.0	R_n = 244.2	R_o = 200.3	R_n = 240.8	R_o = 214.2	R_n = 237.9
12	R_o = 252.2	R_n = 282.5	R_o = 206.4	R_n = 254.9	R_o = 219.6	R_n = 243.1
18	R_o = 278.3	R_n = 289.1	R_o = 245.8	R_n = 264.5	R_o = 234.9	R_n = 265.2

where *Ro* [mm] **-** radius of the strip profile after friction test realised with the freely rotating rolls,
R_n [mm] **-** radius of the strip profile after friction test realised with the fixed beads.

Table 4 Effect of specimen width on amount of springback (dry friction conditions)

Specimen width *w* [mm]	***Ra* of rolls [μm]**					
	0.32		**0.63**		**1.25**	
7	R_o = 241.1	R_n = 255.3	R_o = 220.4	R_n = 240.1	R_o = 220.4	R_n = 230.5
14	R_o = 245.1	R_n = 269.8	R_o = 245.8	R_n = 268.3	R_o = 225.5	R_n = 239.6
20	R_o = 252.2	R_n = 282.5	R_o = 246.1	R_n = 278.8	R_o = 222.8	R_n = 243.1

The relations presented are observed under all friction conditions analysed. The effect of roll surface roughness is not equivocal. So, the effect of surface roughness is not an important parameter in an analysis of the springback of sheets tested using the drawbead simulator.

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Conclusions

This paper presents the effects of tool surface roughness, amount of deformation, strip width and lubrication conditions on the springback phenomenon and the friction coefficient of a DC04 steel sheet. The main conclusions drawn are as follows:

1) The strip width has a crucial effect on the character of sheet deformation and the real contact area; an increase in specimen width leads to an increase in the value of the friction coefficient.
2) The value of the friction coefficient depends on the degree of sheet deformation on the drawbead.
3) Methacrylic resin combined with chlorinated hydrocarbons was the most effective lubricant; the friction coefficient value determined with epoxy resin lubrication was as much as two times smaller than the friction coefficient determined under dry friction conditions.
4) An increase in the displacement of the middle roll and sample width causes an increase in the amount of sheet springback in the case of all roll roughnesses used.
5) It was found that the surface roughness of rolls had a dominant affect on the friction resistance.

In further analysis, it is necessary to find the optimal strip width, depending on sheet thickness, which ensures full contact of the sheet with the rolls on the whole width of the specimen.

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