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Original Research

Application of the Finite Element Method to Simulate the Friction Phenomenon in a Strip Drawing Test

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Abstract

Friction is an undesirable phenomenon in the flange area of the drawpiece in sheet metal forming processes, causing a deterioration in surface finish and a decrease in the formability limits of the sheet metal. The aim of this work is numerical analysis using the finite element method of the strip drawing test with two rounded countersamples. This test simulates friction conditions in the flange area of the drawpiece. The results of the experimental research on the influence of surface roughness on the value of the friction coefficient of S235 steel samples were used to verify the numerical results. The relation between the real contact area and the mean roughness Ra of the countersamples was determined. The real contact area increases with the increase of the mean roughness Ra. In sheet metal forming processes, the coefficient of friction depends on the real contact area, and its value increases with the increase of the real contact area.

Keywords: coefficient of friction, finite element method, friction, sheet metal forming

1. Introduction

Sheet metal forming processes require the establishment of appropriate process conditions, that is, forming speed, temperature and contact conditions. Friction is one of the basic phenomena that should be considered when designing the deep drawing processes (Sigvant et al., 2019). A quantitative indicator of the friction phenomena is the coefficient of friction, the value of which depends on many parameters related to the workpiece material, tool material, contact conditions, forming temperature and lubricants used (Xu et al., 2020; Zabala et al., 2022). Due to the variety of pressure values occurring in different areas of the drawpieces formed, it is necessary to use various tribological tests to assess the friction and lubrication conditions. These tests include the drawbead test, the bending under tension test and the strip drawing test. Among the many tribological tests used to assess friction conditions in sheet metal forming processes, the strip drawing test is the most common method (Schell et al. 2022). It consists of pulling the sheet metal between two countersamples with different profiles (flat or rounded). The strip drawing test is used to determine the friction and wear of sheets under cold or hot forming conditions (Venema et al., 2022).

In addition to conventional friction testing methods, in recent years dynamic development of computer techniques has been observed, among which the finite element method (Pop et al., 2011), the boundary element method (Lu et al., 2020) and the extended finite element method (Khoei & Nikbakht, 2019) are the leaders. The most important problems subjected to numerical simulations are determination of the real contact area (Buchner et al., 2009), determination of the character of cooperation between rough bodies (Wang & Schipper, 2019; Zhai et al., 2016) and analysis of the lubrication conditions (Guiggiani, 2020).

Modelling and simulation of the behaviour of tribological systems in the areas of cooperating surfaces, the modelling of damage and wear, the flow dynamics of lubricating fluids, and the behaviour of non-Newtonian lubricating fluids pose serious methodological difficulties, resulting from a very large number of factors influencing the lubrication conditions and the wear process (Korzyński and Sęp, 2007). Using numerical methods also allows modelling of the friction in concentrated contact, where significant plastic deformations occur (Abo-Elkhier, 1997; Karpenko and Akay, 2001). Mahrenholtz et al. (2005) and Zhang et al. (2003) developed a numerical model describing the phenomenon of the deformation of the asperities of surface roughness of a friction pair. The use of the developed model allowed the authors to determine the coefficient of friction associated with the surface roughness of materials. Forecasting the wear of rubbing elements based on analysis of the conditions prevailing in the friction pair is also possible using the finite element method. Numerical models are extensively described in the works of Pereira et al. (2008) and Yan et al. (2000), who found that the wear rate of tools depends on the values of the maximum pressures. Numerical studies using the finite element method, the aim of which was to determine the value and distribution of contact pressure on the rounded surfaces of the punch and die, are the subject of works by Boher et al. (2005), Coubrough et al. (2002) and Eriksen (1997).

Based on the results of the bending under tension tests, a numerical simulation of the flow of the material at the draw bead and at the edge of the punch was carried out (Chabrand, 1996). The numerical results confirmed that it is possible to predict the value of the coefficient of friction, ensuring high consistency of the predictions of experimental results. An extensive review of scientific papers on the application of numerical methods in tribology, including finite element methods is provided by Popov and Psakhie (2007).

This article presents a finite element numerical analysis of a strip drawing test between two rounded countersamples. This test simulates friction conditions in the flange area of the drawpiece. The results of experimental investigations into the influence of the surface roughness of countersamples on the value of the coefficient of friction of S235 steel samples were used to verify the numerical results.

2. Material and experimentation

2.1. Test sample

The test material consisted of 20 mm wide and 300 mm long strips made of 1-mm-thick S235 steel sheet. S235 is a non-alloy structural steel that meets the requirements of the EN 10025-6:2019 standard. S235 grade steel is a weldable low carbon manganese steel with good impact resistance. This steel is used for welded, load-bearing and dynamically loaded structures, such as columns, beams and extension arms. The mechanical properties of test material are shown in Table 1.

Table 1. The basic mechanical parameters of steel tested (Ansys, 2019)

Density, kg/mm^3	Young's modulus, MPa	Poisson's ratio	Bulk modulus, MPa	Shear modulus, MPa	Yield stress, MPa
$7.85 \cdot 10^{-6}$	200000	0.3	166670	76923	260

2.2. Experiment setup

The strip drawing test is used to describe the friction phenomenon occurring between the sheet metal and the blankholder in the sheet metal forming process. It involves pulling the specimen between two stationary rollers with a diameter of 20 mm, which are pressed against the specimen with a constant force F_N. The diagram of the test device is shown in Fig. 1.

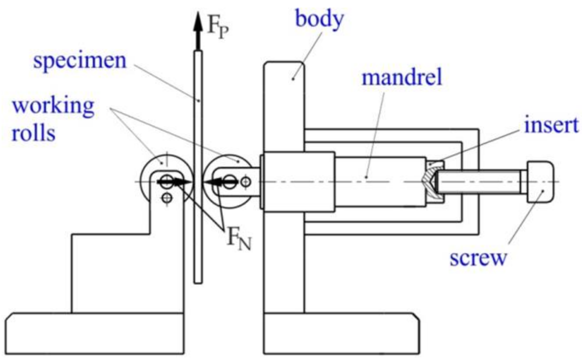

Fig. 1. Diagram of the strip drawing test

During the test, the pulling force F_T is measured using the control system of a Zwick/Roell Z100 uniaxial tensile testing machine. The tests were carried out at the Laboratory of Strength of Materials and Tensometry at the Carpathian State School in Krosno. Three sets of countersamples with a mean roughness Ra of 1.36 μm, 1.53 μm and 1.83 μm were used. During the friction tests of the sheet metal (1 mm thick, 20 mm wide and a 300 mm long), the value of the pulling force F_P was measured.

2.3. Numerical modelling

The 3D finite element method (FEM) model of the strip drawing test was prepared in the SolidWorks program. In the next step, the model was saved in the STEP format and launched in the ANSYS program (Fig. 2). The countersample material was steel NL with bilinear isotropic hardening (tangent modulus 1450 MPa) which was selected from the ANSYS program library.

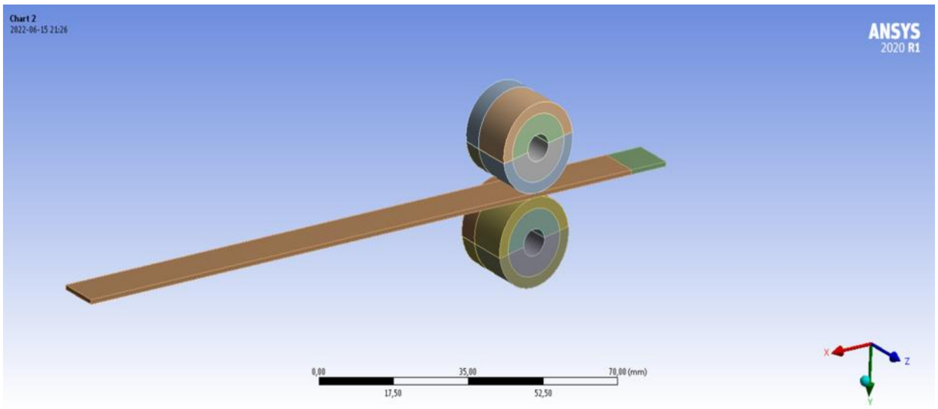

Fig. 2. Model of the strip drawing test prepared in the ANSYS program

A clamping force of 2654 N was applied to the countersamples. The analysis was carried out with several different values for the real contact area, a function of the surface roughness $A_n = f(Ra)$. The measured value was the pulling force F_P applied to the end of the sheet metal strip. The boundary conditions are defined in Fig. 3. To discretise the model of countersamples and sheet metal, brick-type spatial elements were used (Fig. 4).

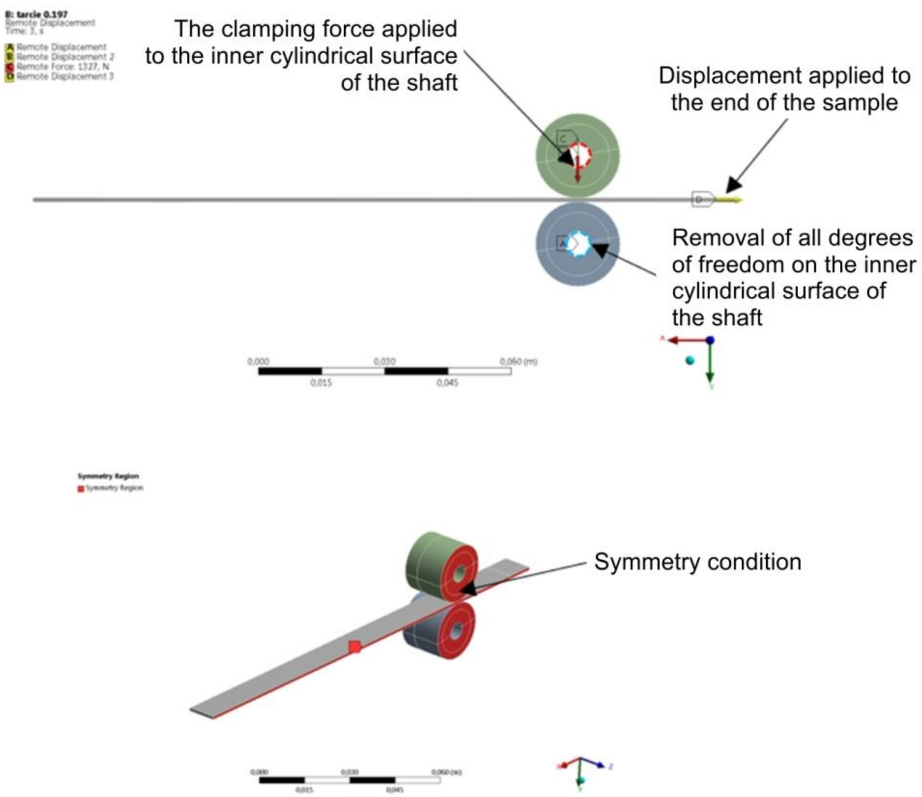

Fig. 3. The boundary conditions for the FEM model of the strip drawing test

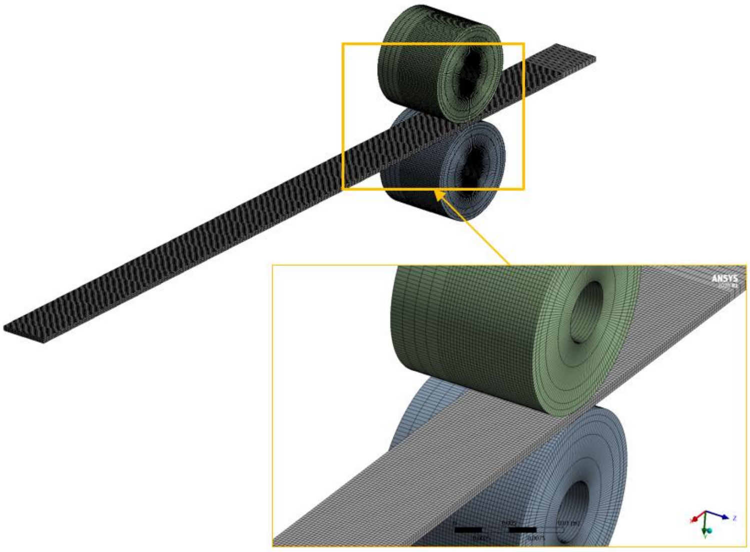

Fig. 4. Finite element mesh

In the ANSYS program, it is not possible to introduce a variable surface roughness value, therefore the relationship resulting from the Bowden and Tabor friction theory was used. According to the Bowden and Tabor (1950) model of friction, the friction force T is not proportional to the normal load, but depends on the contact area A_n and the shear strength R_t of the softer metal of the friction pair:

$$T = A_n \cdot R_t \tag{1}$$

3. Material and experimentation

In the first stage of the FEM analyses, the average values of the pulling force (Table 1) for the individual mean roughness Ra values were determined based on the results of the experimental tests.

Table 2. Average value of pulling force for the selected mean roughness Ra

Mean roughness Ra, µm	Mean value of pulling force, N
1.83	1160
1.53	725
1.36	670

Since the friction force T is equivalent to the pulling force F_P, the results of the experimental tests presented in Table 2 were used to determine the real contact area A_n, which in the FEM model is a dependent variable $A_n = f(Ra)$. Hence:

$$A_n = \frac{F_P}{R_t} \tag{2}$$

where R_t is the shear strength equal to 0.65 R_m (R_m – ultimate tensile strength).

For the tested S235 grade sheet, R_m equal to 360 MPa was assumed in the calculations, therefore $R_t = 0.65 \cdot R_m = 234$ MPa. After substituting into Eq. (2), the results shown in Table 3 were obtained for each Ra value.

Table 3. Real contact areas for the selected mean roughness Ra

Mean roughness Ra, µm	Real contact area A_n, N
1.83	4.96
1.53	3.1
1.36	2.86

For the values of the real contact surface area listed in Table 4, friction analyses were performed in the ANSYS program. Changes in the value of the pulling force with a specific clamping force were obtained. An exemplary graph of the changes in the pulling force for the contact area of A_n = 2.86 mm^2 is shown in Fig. 5.

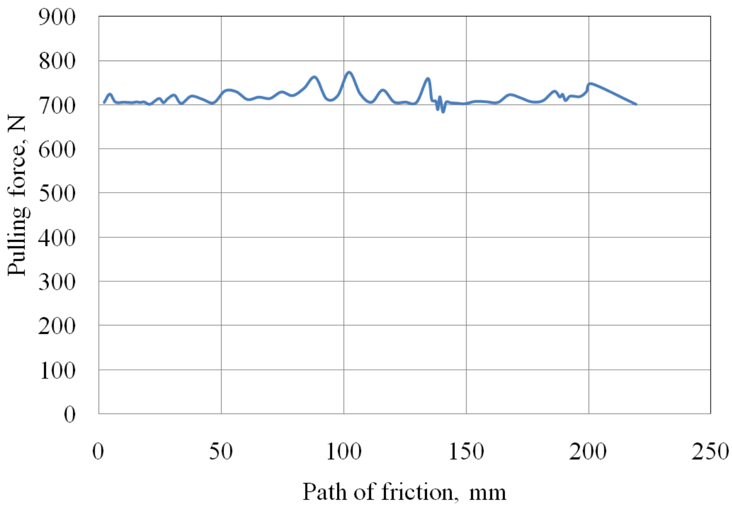

Fig. 5. Variations of pulling force for the contact area A_n = 2.86 mm^2

In addition, on the basis of the test results, it is possible to determine the interpolation of the relationship between the real contact area A_n and the mean roughness Ra. The interpolation graph is shown in Fig. 6. The red points indicate the values of the real contact area determined on the basis of the experiment, and the white points indicate the values determined by the approximation. From the graph obtained, it is also possible to see the extrapolated values of A_n = f(Rt) for selected values of the mean roughness Ra (Table 4).

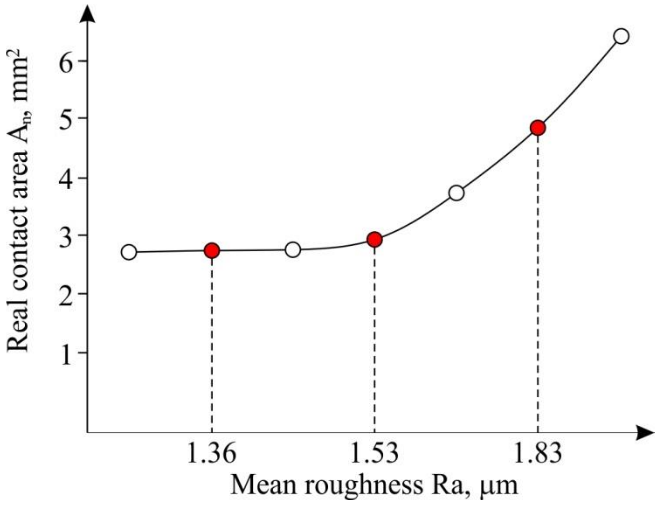

Fig. 6. Variation of the real contact area A_n

Table 4. The value of the real contact area A_n (experimental results)

Mean roughness Ra, µm	Real contact area A_n, N
1.26	2.7
1.46	2.95
1.68	3.9
2	5.8

FEM simulations were carried using the real contact values presented in Table 4. The value of the coefficient of friction was calculated from the relationship:

$$\mu = \frac{A_n R_t}{2F_N} \tag{3}$$

where F_N is the clamping force of the countersamples.

A clamping force of 2654 N was assumed for the calculations. The value of the coefficient of friction for the individual mean roughness Ra is shown in Table 5. The coefficient of friction increases with the increase in the real contact area (Fig. 7).

Table 5. Values of the coefficient of friction for individual mean roughness Ra

Mean roughness Ra, µm	Real contact area A, mm^2	Coefficient of friction
1.26	2.7	0.12
1.36	2.86	0.126
1.46	2.95	0.13
1.53	3.1	0.14
1.68	3.9	0.17
1.83	4.96	0.21
2.0	5.8	0.26

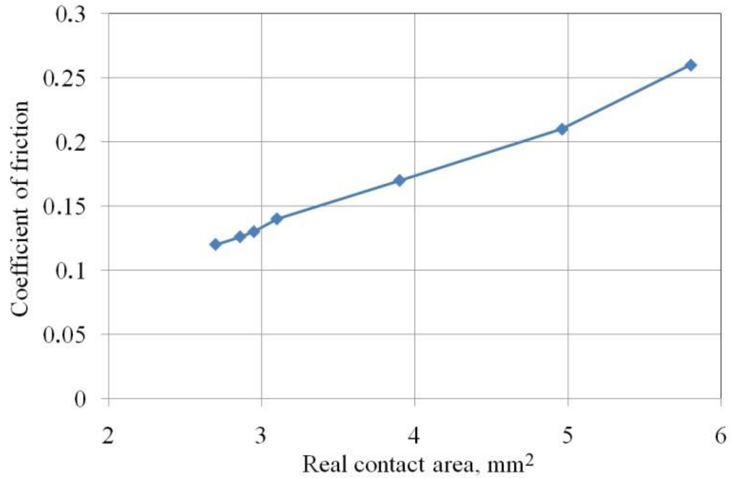

Fig. 7. Effect of the real contact area on the coefficient of friction

Unlike friction in machine nodes, in sheet metal forming there is contact between a relatively soft metal sheet and a hard tool. Under these conditions, the friction force is the result of severe mechanical cooperation between the surface asperities. In machine nodes, there is cooperation between a friction pair characterised by similar mechanical properties. Coulomb's law then remains valid.

4. Conclusions

Based on the results of the numerical and experimental investigations, it was found that the real contact area increases with the increase in the initial mean roughness of the sheet surface. In plastic working processes, two materials with significantly different mechanical properties, especially hardness, come into contact. Under these conditions, one of the rubbing pair bodies is subjected to plastic deformation caused by high normal pressures. Under these conditions, the mechanisms of mechanical interaction of the summits of the asperities and the continuous evolution of the surface topography are intensified. The influence of sheet material properties and countersample roughness on changes to the sheet surface roughness of sheet metals caused by the friction process and normal pressures need to be further studied. The use of numerical modelling makes it possible to carry out analyses that are limited by expensive and time-consuming experimental research.

References

Abo-Elkhier, M. (1997). Elasto-plastic finite element modelling of strip cold rolling using Eulerian fixed mesh technique. *Finite Elements in Analysis and Design*, *27*(4), 323-334. https://doi.org/10.1016/S0168-874X(97)81966-X

Ansys (2019). ANSYS Workbench. Product Release Notes 18. Ansys, Inc.

Boher, C., Attaf, D., Penazzi, D., & Levaillant C. (2005). Wear behaviour on the radius portion of a die in deep-drawing: Identification, localisation and evolution of the surface damage. *Wear*, *259*(7-12), 1097–1108. https://doi.org/10.1016/j.wear. 2005.02.101

Bowden, F. P., & Tabor, D. (1950). *The friction and lubrication of solids*. University Press.

Buchner, B., Buchner, M., & Buchmayr, B. (2008). Determination of the real contact area for numerical simulation. *Tribology International*, *42*(6), 897-901. https://doi.org/ 10.1016/j.triboint.2008.12.009

Chabrand P., Dubois F., & Gelin J. C. (1996). Modelling drawbeads in sheet metal forming. *International Journal of Mechanical Sciences*, *38*(1), 59-77. https://doi.org/10.1016/0020-7403(95)00033-T

Coubrough, G. J., Alinger, M. J., & Van Tyne C. J. (2002). Angle of contact between sheet and die during stretch-bend deformation as determined on the bending under-tension friction test system. *Journal of Materials Processing Technology*, 130–131, 69–75. https://doi.org/10.1016/S0924-0136(02)00781-1

Eriksen, M. (1997). The influence of die geometry on tool wear in deep drawing. *Wear*, *207*(1-2), 10–15. https://doi.org/10.1016/S0043-1648(96)07461-3

Guiggiani, M. (2020). Lubrication problems solved by the boundary element method. Engineer*ing Analysis with Boundary Elements*, 119, 183-188. https://doi.org/ 10.1016/j.enganabound.2020.07.011

Karpenko, Y. A., & Akay, A. (2001). A numerical model of friction between rough surfaces. *Tribology International*, *34*(8), 531–545. https://doi.org/10.1016/S0301-679X(01)00044-5

Khoei, A. R., & Nikbakht, M. (2006). Contact friction modeling with the extended finite element method (X-FEM). *Journal of Materials Processing Technology*, *177*(1-3), 58-62. https://doi.org/10.1016/j.jmatprotec.2006.03.185

Korzyński, M., & Sęp J., (2007). Komputerowe wspomaganie badań tribologicznych. *Zagadnienia Eksploatacji Maszyn*, 42, 57-72.

Lu, K., Coombs, W. M., Auearde, C. E., & Hu, Z. (2020) An implicit boundary finite element method with extension to frictional sliding boundary conditions and elasto-plastic analyses. *Computer Methods in Applied Mechanics and Engineering*, 358, 112620. https://doi.org/10.1016/j.cma.2019.112620

Mahrenholtz, O., Bontcheva, N., & Iankov, R. (2005). Influence of surface roughness on friction during metal forming processes. *Journal of Materials Processing Technology*, *159*(1), 9-16. https://doi.org/10.1016/j.jmatprotec.2003.10.009

Pereira, M. P., Yan, W., & Rolfe, B. F. (2008). Contact pressure evolution and its relation to wear in sheet metal forming. *Wear*, *265*(11-12), 1687-1699. https://doi.org/10.1016/j.wear.2008.04.042

Pop, N., Cioban, H., & Horvat-Marc, A. (2009). Finite element method used in contact problems with dry friction. *Computational Materials Science*, *50*(4), 1283-1285. https://doi.org/10.1016/j.commatsci.2010.03.018

Popov, V. L., & Psakhie, S. G. (2007). Numerical simulation methods in tribology. *Tribology International*, *40*(6), 916-923. https://doi.org/10.1016/j.triboint.2006. 02.020

Schell, L., Emele, M., Holzbeck, A., & Groche, P. (2022). Investigation of different lubricant classes for aluminium warm and hot forming based on a strip drawing test. *Tribology International*, 168, 107449. https://doi.org/10.1016/j.triboint.2022.107449

Sigvant, M., Pilthammar, J., Hol, J., Wiebenga, J. H., Chezan, T., Carleer, B., & van den Boogaard, T. (2019). Friction in sheet metal forming: influence of surface roughness and strain rate on sheet metal forming simulation results. *Procedia Manufacturing*, 29, 512-519. https://doi.org/10.1016/j.promfg.2019.02.169

Venema, J., Hazrati, J., Atzema, E., Matthews, D., & van den Boogaard, T. (2022). Multiscale friction model for hot sheet metal forming. *Friction*, *10*(2), 316-334. https://doi.org/10.1007/s40544-021-0504-6

Wang, C., & Schipper, D. J. (2020). A numerical-analytical approach to determining the real contact area of rough surface contact. *Tribology - Materials, Surfaces & Interfaces*, *14*(3), 166-176. https://doi.org/10.1080/17515831.2020.1720382

Xu, Z., Huang, J., Mao, M., Peng, L., & Lai, X. (2020). An investigation on the friction in a micro sheet metal roll forming processes considering adhesion and ploughing. *Journal of Materials Processing Technology*, 285, 116790. https://doi.org/ 10.1016/j.jmatprotec.2020.116790

Yan, W., Busso, E. P., & O'Dowd, N. P. (2000). A micromechanics investigation of sliding wear in coated components. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 456, 2387–2407. https://doi.org/ 10.1098/rspa.2000.0617

Zabala, A., de Argandoña, E. S., Cañizares, D., Llavori, I., Otegi, N., & Mendiguren, J. (2022). Numerical study of advanced friction modelling for sheet metal forming: Influence of the die local roughness. *Tribology International*, 165, 107259. https://doi.org/10.1016/j.triboint.2021.107259

Zhai, C. P., Gan, Y. X., & Hanaor, D. (2016). Numerical analysis of normal contact stiffness of rough surfaces. *Applied Mechanics and Materials*, 846, 300-305. https://doi.org/10.4028/www.scientific.net/AMM.846.300

Zhang, S., Hodgson, P. D., Cardew-Hall, M. J., & Kalayanasundaram, S. (2003). A finite element simulation of micro-mechanical frictional behaviour in metal forming. *Journal of Materials Processing Technology*, *134*(1), 81-91. https://doi.org/10.1016/S0924-0136(02)00926-3

Zastosowanie Metody Elementów Skończonych do Symulacji Zjawiska Tarcia w Teście Przeciągania Pasa Blachy

Streszczenie

Tarcie jest zjawiskiem niepożądanym w strefie kołnierzowej wytłoczki w procesach kształtowania blach powodującym obniżenie jakości powierzchni wyrobu i zmniejszenie odkształceń granicznych blachy. Celem pracy jest analiza numeryczna metodą elementów skończonych testu przeciągania pasa blachy pomiędzy dwoma zaokrąglonymi przeciwpróbkami. Test ten symuluje warunki tarcia w strefie kołnierza wytłoczki. Do weryfikacji wyników numerycznych wykorzystano wyniki badań eksperymentalnych wpływu chropowatości powierzchni na wartość współczynnika tarcia próbek ze stali S235. Wyznaczono zależności pola rzeczywistej powierzchni kontaktu od parametru chropowatości przeciwpróbek Ra. Rozmiar rzeczywistej powierzchni kontaktu zwiększa się wraz ze zwiększeniem wartości parametru Ra. W procesach kształtowania blach współczynnik tarcia zależy od pola rzeczywistej powierzchni kontaktu, wraz ze wzrostem pola powierzchni styku rośnie jego wartość.

Słowa kluczowe: współczynnik tarcia, metoda elementów skończonych, tarcie, kształtowanie blach