Advances in Mechanical and Materials Engineering

Volume 40, 2023, Pages 55-62
https://doi.org/10.7862/rm.2023.7

THE FACULTY OF MECHANICAL ENGINEERING AND AERONAUTICS
RZESZOW UNIVERSITY OF TECHNOLOGY

Original Research

Analysis of Tribological Performance of New Stamping Die Composite Inserts Using Strip Drawing Test

Krzysztof Żaba [1,*], Łukasz Kuczek [1], Sandra Puchlerska [1], Marcel Wiewióra [2], Marek Góral [3], Tomasz Trzepieciński [4]

[1] Department of Metal Working and Physical Metallurgy of Non-Ferrous Metals, AGH—University of Science and Technology, al. Adama Mickiewcza 30, 30-059 Cracow, Poland
[2] ERKO sp. z o.o. sp.k., Czeluśnica 80, 38-204 Tarnowiec, Poland
[3] Research and Development Laboratory for Aerospace Materials, Rzeszow University of Technology, Powstancow Warszawy 12, 35-959 Rzeszow, Poland
[4] Department of Manufacturing Processes and Production Engineering, Rzeszow University of Technology, al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland

* Correspondence: krzyzaba@agh.edu.pl

Received: 5 December 2022 / Accepted: 20 December 2022 / Published online: 17 February 2023

Abstract

This article assesses the tribological performance of new composite tool sets for stamping dies. Four sets of composite countersamples were tested. These consisted of polyurethane resin with mineral filler (base variant) and modified with aluminium powder (10wt%) and roving fabric (5wt%). Strip samples for the strip drawing tests were cut from AMS5599 (Inconel 625) corrosion-resistant nickel alloy, AMS5510 (321) corrosion and heat-resistant steel and AMS6061-T4 heat treatable aluminium alloy sheet metals. The influence of the type of sample material on the coefficient of friction (COF) was observed. The smallest values of the COF over the entire range of clamping force values used on AMS5599 and AMS5510 sheets were observed during tests with countersamples made of the base variant of composite. When testing the AMS6061-T4 aluminium alloy sheet, the countersamples modified with roving fabric provided the lowest value of COF, which stabilised at a value of about 0.197 as pressure was increased.

Keywords: friction, coefficient of friction, composite tool, stamping tool

1. Introduction

Plastic working is a manufacturing technique in which the shape and dimensions of the workpiece change under the influence of applied external forces, causing the metal to undergo a plastic deformation. Plastic working techniques also permit give the appropriate performance properties to be given to the material, which depend on the rheological conditions of the forming process and on the thermo-plastic treatments carried out during or immediately after the end of processing (Birkhold et al., 2013). Plastic forming processes involve high unit pressures. The condition of the surface layer of the product determines its operational and functional features, such as durability and reliability (Ersoy-Nürnberg et al., 2008). Uncontrolled tool wear reduces the quality of components and increases the total cost of production (Domitner et al., 2021). As a result of heat exchange between the deformed material and the tools, their temperature increases, which results in a decrease in their strength. The designer has many means and methods to design the optimal tool in order to increase the efficiency and reliability of the forming process. In particular, it is possible to select the parameters of plastic working with which, under conditions of normal tool wear, the required probability of meeting all the quality requirements of the workpiece is ensured, and the reliability of the process is conditioned by the desired tool life (Groche et al., 2019).

The operating conditions of plastic forming tools depend primarily on the temperature, the contact pressures and the history of loading (Hol et al., 2012). Friction is the basic factor that determines the flow character of the workpiece and enables an element to be manufactured with the desired dimensions and shape (Vierzigmann et al., 2011). One way to ensure appropriate friction conditions is the selection of the tool material (Schmoeckel et al., 1986). Because of the requirements regarding wear resistance and form stability, deep drawing tools are mainly made of tooling steel or cast iron (Liewald & de Souza, 2008). In addition to commonly used metal tools, it is possible to use tools made of elastomers or composites based on metals and plastics (Bergweiler et al., 2021). Liewald and de Souza (2008) investigated tribological and tool design aspects for the use of polymeric materials (polyurethane with Al hydroxide and Al powder fillers) in sheet metal forming. They developed a new test method for measuring polymer/sheet wear. Using polymeric materials with a minimal Young's modulus of 11,000 MPa and compressive strength of 110 MPa, it is possible to produce prototype-series using high strength steels. Polymeric materials (resins filled with steel powder or sand) can be used in the manufacture of prototype tools or in the production of small size series (Park & Colton, 2003). Schuh et al. (2020) investigated the application of additively manufactured functional elements made by fused filament fabrication (FFF) polymer additive manufacturing in deep drawing tools. They concluded that 3D printed polylactic acid tools are sufficiently stable and provide results that are similar and as good as metal tools in terms of formability. Bergweiler et al. (2019) developed the use of polymer based additive FFF manufactured tools to shorten development cycles and respond to increasing individualisation of forming tools. Frank (1999) used cast polyurethane tools and proved that this tool material shows extraordinarily good friction behaviour. To improve the mechanical properties of laminated object manufacturing-tools Schell (2005) infiltrated the tools with epoxy resin. Selective laser melting and sintering are other methods of producing stamping tools (Leal et al., 2017; Levy et al., 2003).

This article presents the results of investigations into the tribological performance of new materials for the production of tools for sheet metal forming of AMS5599 nickel alloy, AMS5510 corrosion and heat resistant steel and AMS6061-T4 aluminium alloy sheets. The new tool materials include base composites consisting of polyurethane resin and mineral filler as well as composites modified with aluminium powder and roving fabrics. The evaluation of the frictional properties was carried out using a strip drawing test under dry friction conditions.

2. Experimental

2.1. Test material

Friction tests were carried out on four sets of composite countersamples containing polyurethane resin (PR) consisting of two components (isocyanate + polyol) and mineral filler (powdered aluminium hydroxide $Al(OH)_3$). This base variant was modified by adding aluminium powder (10wt.%) and roving fabric (5wt.%). Countersamples were cut from commercial materials in the form of sheets produced by rolling. Cuboid-shaped countersamples with a working surface radius of R = 200 mm (Fig. 1) were coded according to the symbols listed in Table 1. Specimens were fabricated from AMS5599 nickel alloy, AMS5510 corrosion and heat resistant steel and AMS6061-T4 aluminium alloy sheets with a thickness of 1 mm, 1 mm and 2 mm, respectively.

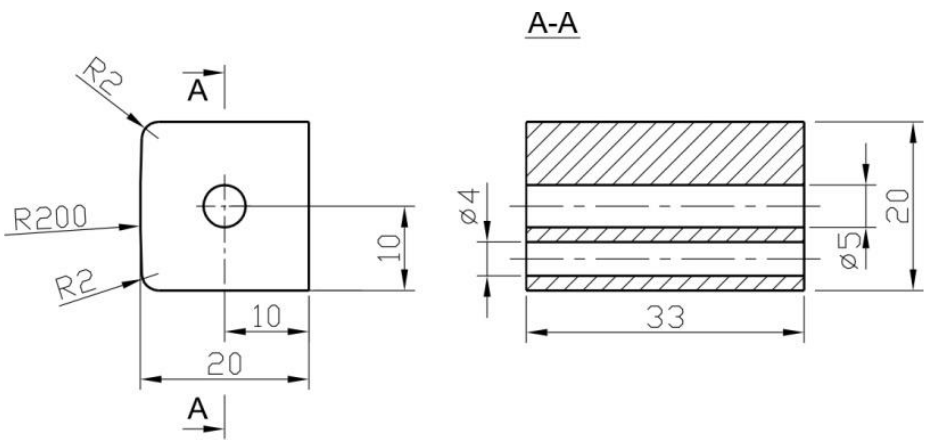

Fig. 1. Shape and dimensions of the countersamples

Table 1. Designation and composition of the countersample material

Countersample type	Aluminium powder, wt.%	Roving fabric, wt.%
F1 (base variant)	-	-
F2	-	5
F3	10	-
F4	10	5

The surface topography of the countersamples (Fig. 2) and sheet metals (Fig. 3) was measured with a Hommel-Etamic T8000RC stationary profilometer in accordance with the requirements of the ISO 25178 standard. The values of the basic surface roughness parameters of the sheets and countersamples are listed in Table 2.

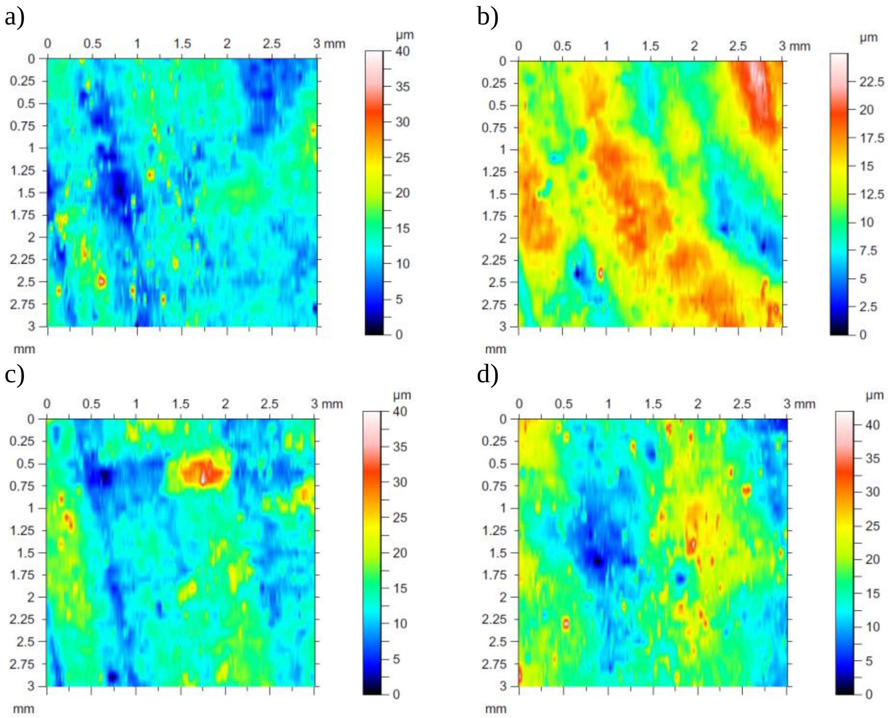

Fig. 2. Topography and basic surface roughness parameters of the countersamples: a) F1, b) F2, c) F3 and d) F4

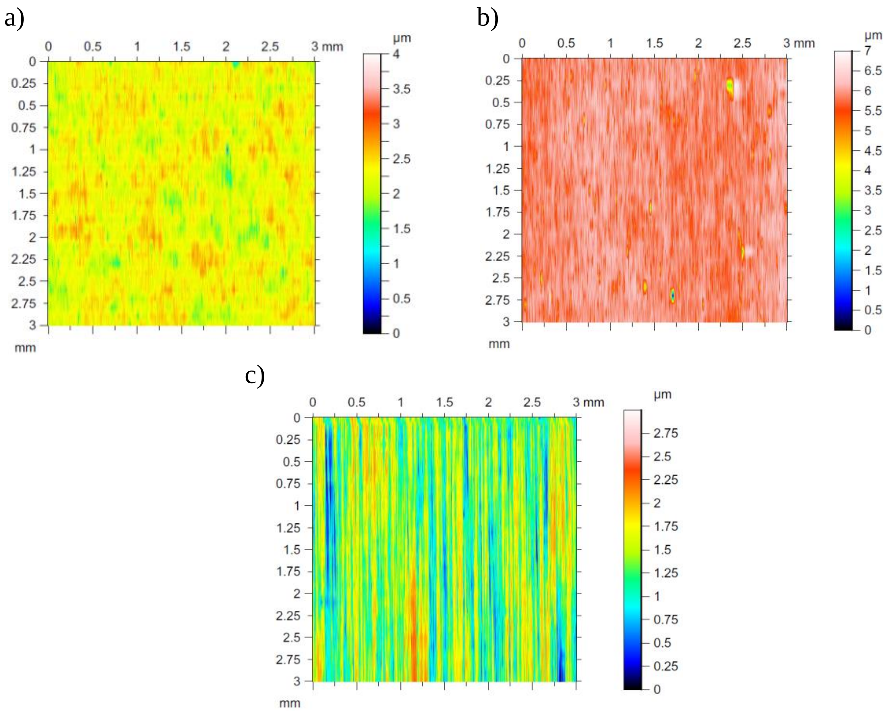

Fig. 3. Topography and basic surface roughness parameters of the sheets in their as-received state: a) AMS5599, b) AMS5510 and c) AMS6061-T4

Table 2. Basic surface roughness parameters of the sheets and countersamples

Material	Sq, µm	Ssk	Sku	Sp, µm	Sv, µm	Sa, µm
AMS5599	0.206	-0.385	4.06	0.825	2.28	0.162
AMS5510	0.246	-2.98	34.0	1.04	5.89	0.170
AMS6061-T4	0.383	-0.251	2.32	1.01	1.36	0.322
F1	3.05	0.587	6.42	26.4	11.8	2.25
F2	3.41	-0.116	2.55	12.0	13.0	2.80
F3	3.85	1.12	6.22	26.1	13.3	2.86
F4	4.73	0.293	3.21	25.1	16.0	3.81

2.2. Strip drawing test

The value of the coefficient of friction (COF) was determined using a tribotester to carry out the strip drawing test (SDT). The tribotester consists of a body in which cuboid-shaped countersamples are placed horizontally (Fig. 4). The SDT device is mounted in a Zwick/Roell Z100. During the tests, a strip of sheet metal approximately 400 mm long and 18 mm wide is placed between the countersamples.

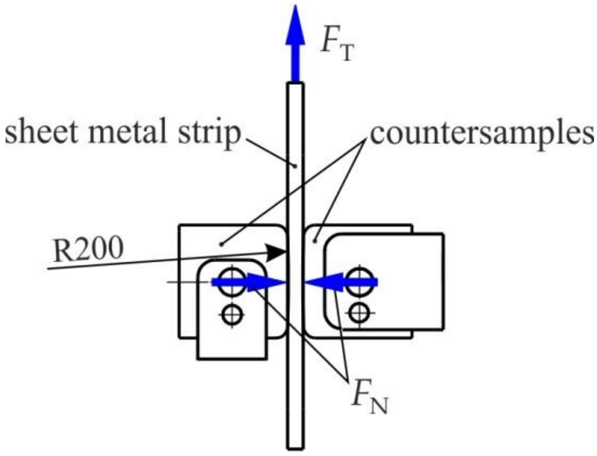

Fig. 4. Schematic diagram of the strip drawing test

The countersamples were pressed against the surface of the samples with a pressing force F_N equal to: 23, 46, 69, 92, 115, 138 and 160 N. During the movement of the sheet between the countersamples, the measuring system of the testing machine registers the value of the tangential force (friction force) F_T. The value of the COF was determined on the basis of the value of the friction force F_T and the pressure force F_N from the relationship:

$$\mu = \frac{F_T}{2F_N} \tag{1}$$

The average value of the COF was separately determined according to Eq. (1) for each of the various levels of contact force applied.

3. Results and discussion

A tendency to decrease the value of the COF was observed with an increase in the value of the contact force. On the other hand, above the clamping force value of 100 N, stabilising effect occurs with regards to the value of the coefficient of friction. This may be due to the fact that after exceeding a certain load value, the relationship between the friction force and the normal force is nonlinear, and the coefficient of friction is not constant and changes with increasing pressure. The same phenomenon was observed by Kirkhorn et al. (2013), Murtagh et al. (1995) and ten Thije et al. (2008). As the friction force increases, it does not change proportionally to the normal force. As a result, the coefficient of friction varies nonlinearly with a change in contact pressure. The nonlinear relationship between the tangential force (friction force) and the normal force suggests that there are additional phenomena in certain load ranges that should be reflected in friction models.

The difference in the value of COF of AMS5599 sheet determined for individual sets of countersamples ranges from 0.0122 (F_N = 138 N) to 0.0311 (F_N = 92 N). The smallest values of the coefficient of friction in the entire range of clamping forces were observed for countersamples fabricated from materials F1 and F2 (Fig. 5). The difference in the value of COF of AMS5510 sheet determined for individual variants of the countersamples ranges between 0.0159 (F_N = 69 N) and 0.0357 (F_N = 23 N). In the range of clamping forces exceeding F_N = 100 N, the lowest value of the coefficient of friction (about 0.175) is provided by the countersamples made of the base material F1 (Fig. 6). The COF reached the highest values over the entire range of clamping forces applied with the countersamples made of material F4.

In the entire range of clamping forces applied, the highest value of COF of AMS6061-T4 sheet was recorded for countersamples marked F4. The countersamples of the material F2 provided the lowest value of the friction coefficient, which stabilised on reaching a value of about 0.197 (Fig. 7). The difference in the value of COF of AMS5510 sheet determined for individual variants of countersamples ranges between 0.0129 (F_N = 138 N) and 0.0254 (F_N = 69 N).

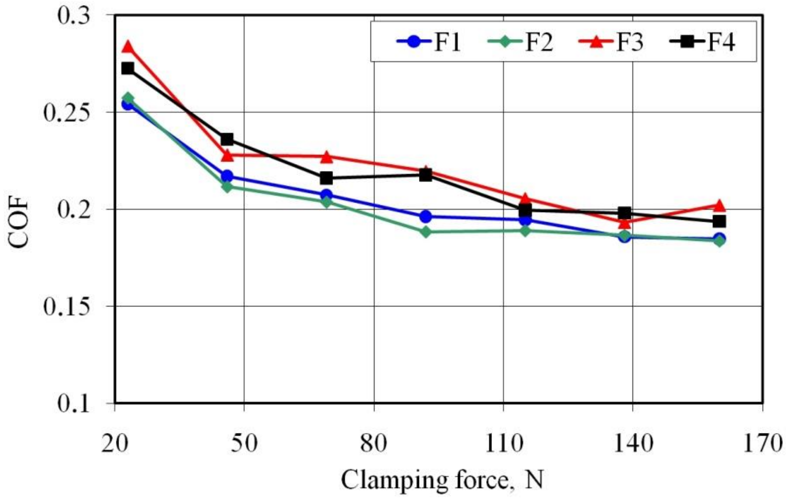

Fig. 5. Effect of clamping force on the value of COF of AMS5599 sheet

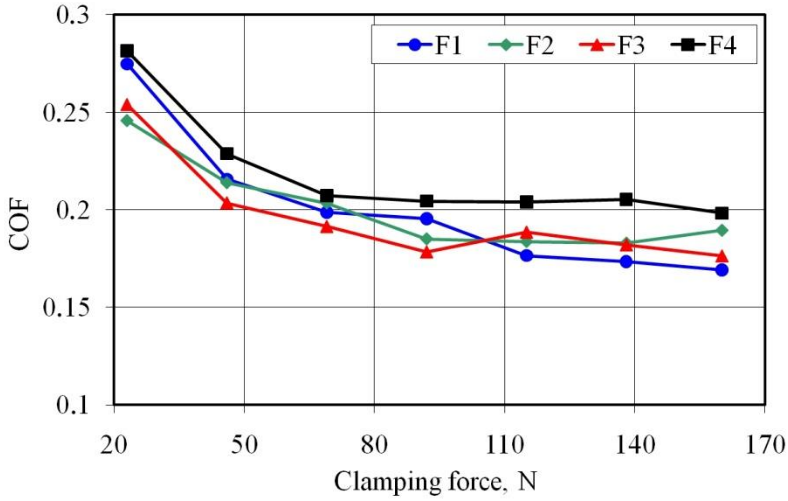

Fig. 6. Effect of clamping force on the value of COF of AMS5510 sheet

Figures 8, 9 and 10 show the percentage change in the value of the friction coefficient in relation to the unmodified base variant F1 of the countersample material. During the friction tests on the AMS5599 sheet, variants of countersamples containing aluminium powder at a rate of 10 wt.% resulted in an increase in the value of COF over the entire range of pressure forces tested, a difference even reaching about 12% (Fig. 8). Only the variant containing 5 wt% of roving fabric in the clamping force range of F_N = 46-115 N showed a noteworthy effect reducing the COF by about 2-4%.

When testing the AMS5510 stainless steel sheet in the clamping force range of F_N = 115-160 N, all the modified countersamples increased the COF by approximately 4-18% (Fig. 9). However, the most unfavourable friction conditions were observed when testing countersamples modified with aluminium powder (10 wt%) and roving fabric (5 wt%). This countersample showed an unfavourable effect on the friction conditions in the entire range of clamping forces tested. Countersamples modified only with the addition of 10wt.% of aluminium powder, in the clamping force range of F_N = 23-92 N, provided a decrease in the COF by about 3.9-8.4%.

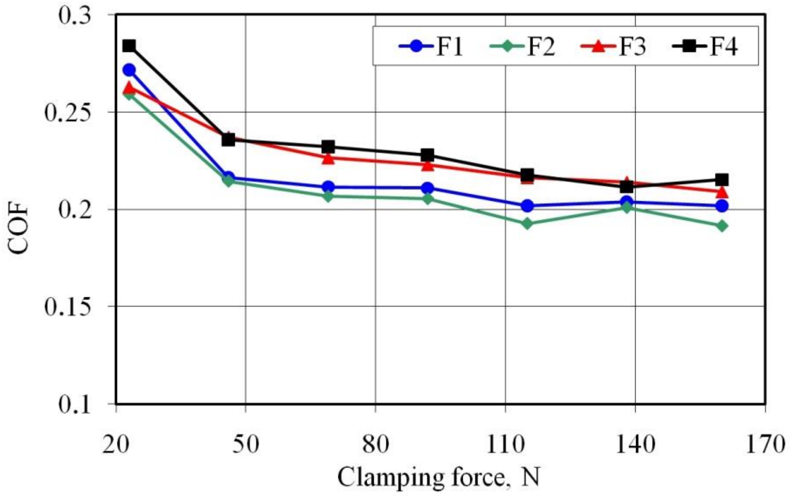

Fig. 7. Effect of clamping force on the value of COF of AMS6061-T4 sheet

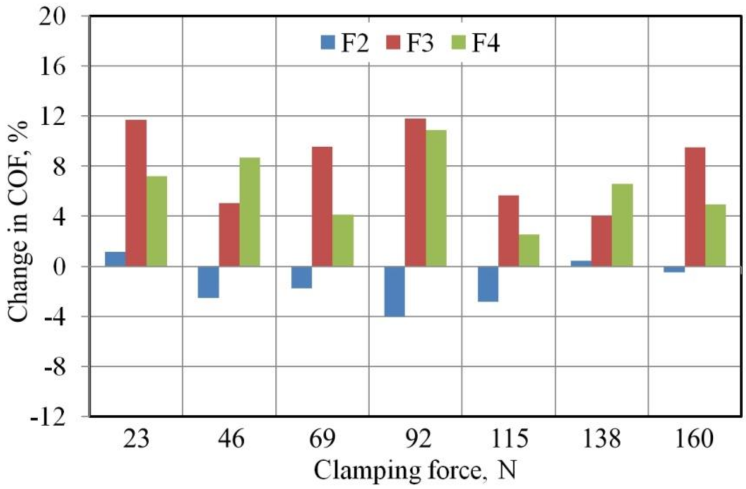

Fig. 8. Change of the value of COF of AMS5599 sheet in relation to the base variant F1

Countersamples modified only with roving fabric content are the most suitable for use with AMS6061-T4 aluminium alloy sheet. A reduction in the COF value was observed across the entire range of clamping forces tested. Countersamples modified with aluminium powder and roving fabric showed unfavourable friction values, increasing the value of the COF in the range of 3.6-9.7% (Fig. 10). There is a tendency for these materials to have a synergistic effect on the coefficient of friction with increasing clamping force.

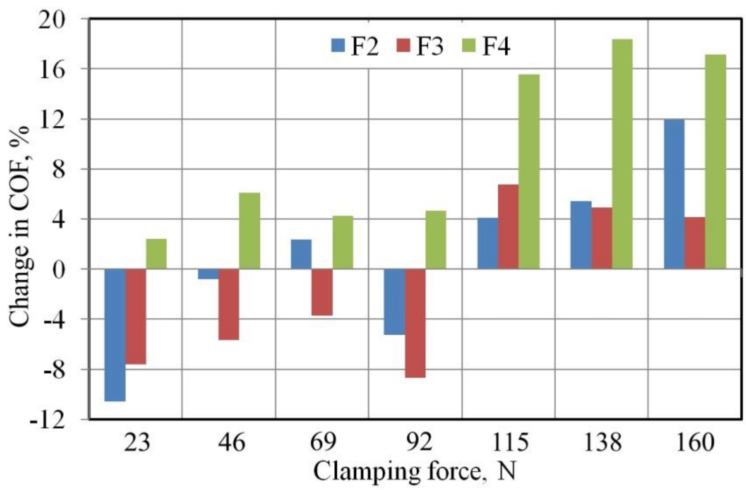

Fig. 9. Change of the value of COF of AMS5510 sheet in relation to the base variant F1

No visible change in the surface topography of the samples after the friction process was observed. This may be due to the much greater hardness of the materials of the tested samples in relation to the composite material of the countersamples. However, the specimens were tested at a distance of about 340 mm. Further studies are needed to determine the effect of the countersamples material on the surface roughness of the samples and vice versa.

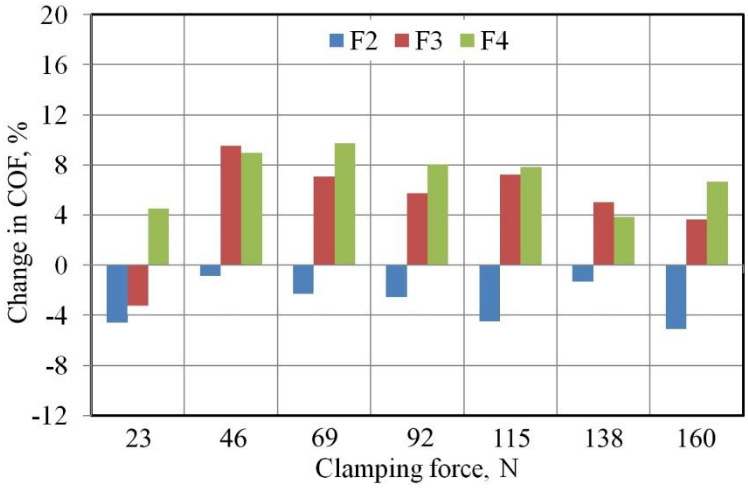

Fig. 10. Change of the value of COF of AMS6061-T4 sheet in relation to the base variant F1

4. Conclusions

Composite inserts in stamping dies are a promising method of changing the friction conditions in selected areas of the drawpiece. The aim of this work was to test the friction of selected composite materials using the strip drawing test, commonly used to simulate friction conditions in sheet metal forming. It was found that when testing AMS5599 nickel-based alloy sheets the smallest values of COF in the entire range of clamping forces were observed for countersamples fabricated from base material which was modified with aluminium powder and roving fabric. In the case of sample material AMS5510 the highest values of COF in the entire range of clamping forces applied were observed for the base variant of the countersamples. The most suitable material for forming AMS6061-T6 aluminium alloy sheets is found in countersamples modified only with the roving fabric content. Their application has the effect of reducing the COF value by 0.9-5.1% depending on the value of the pressing force.

Acknowledgements

This work was financed from the POIR.01.01.01-00-1529/20 project, entitled: "New technology of plastic forming of products for aviation and electrical engineering using innovative composite, elastomeric and metal tools with coatings produced by 3D printing, CVD and PVD methods with improved friction and wear properties”.

References

Bergweiler, G., Fiedler, F., Kampker, A., & Lichtenthäler, K. (2019). Additively manufactured forming tools in prototype construction (in German). Umformtechnik Blech Rohre Profile.

Bergweiler, G., Fiedler, F., Shaukat, A., & Loffler, B. (2021). Experimental investigation of dimensional precision of deep drawn cups using direct polymer additive tooling. *Journal of Manufacturing and Materials Processing*, *5*(1), 3. https://www.mdpi.com/2504-4494/5/1/3

Birkhold, M., Pauli, F.B., Lechler, A., & Verl, A. (2013). On the development of transformable sheet metal forming tools. *IFAC Proceedings Volumes*, *46*(16), 391-396. https://doi.org/10.3182/20130825-4-US-2038.00040

Domitner, J., Silvayeh, Z., Shafiee Sebet, A., Öksüz, K.I., Pelcastre, L., & Hardell, J. (2021). Characterization of wear and friction between tool steel and aluminum alloys in sheet forming at room temperature. *Journal of Manufacturing Processes*, *64*, 774-784. https://doi.org/10.1016/j.jmapro.2021.02.007

Ersoy-Nürnberg, K., Nürnberg, G., Golle, M., & Hoffmann, H. (2008). Simulation of wear on sheet metal forming tools—An energy approach. *Wear*, *265*(11-12), 1801-1807. https://doi.org/10.1016/ j.wear.2008.04.039

Frank, C. (1999). Polymers as tooling material for deep drawing of sheet metal (in German). PhD thesis. Leibniz University Hannover.

Groche, P., Christiany, M., & Wu, Y. (2019). Load-dependent wear in sheet metal forming. *Wear*, *422-423*, 252-260. https://doi.org/10.1016/j.wear.2019.01.071

Hol, J., Cid Alfaro, M.V., de Rooij, M.B., & Meinders, T. (2012). Advanced friction modeling for sheet metal forming. *Wear*, *286-287*, 66-78. https://doi.org/10.1016/ j.wear.2011.04.004

Kirkhorn, L., Bushlya, V., Andersson, M., & Ståhl, J. E. (2013). The influence of tool microstructure on friction in sheet metal forming. *Wear*, *302*, 1268–1278. https://doi.org/10.1016/ j.wear.2013.01.050

Leal, R., Barreiros F., Alves L. (2017). Additive manufacturing tooling for the automotive industry. *International Journal of Advanced Manufacturing Technology*, *92*, 1671-1676. https://doi.org/10.1007/s00170-017-0239-8

Levy, G.N., Schindel, R., Schleiss, P., Micari, F., & Fratini, L. (2003). On the use of SLS tools in sheet metal stamping. *CIRP Annals*, *52*(1), 249-252. https://doi.org/ 10.1016/S0007-8506(07)60577-0

Liewald, M. & de Souza, J. H. C. (2008). New developments on the use of polymeric materials in sheet metal forming. *Production Engineering*, 2, 63-72. https://doi.org/10.1007/s11740-008-0077-5

Murtagh, A. M., Lennon, J. J., & Mallon, P. J. (1995). Surface friction effects related to pressforming of continuous fibre thermoplastic composites. *Composites Manufacturing*, *6*, 169–175. https://doi.org/10.1016/ 0956-7143(95)95008-M

Park, Y., & Colton, J.S. (2003). Sheet metal forming using polymer composite rapid prototype tooling. *Journal of Engineering Materials and Technology*, *125*(3), 247-255. https://doi.org/10.1115/1.1543971

Schell, T. (2005). Basic investigations of a new Rapid Tooling technique for sheet metal forming" (in German). PhD thesis. University of Erlangen-Nürnberg.

Schmoeckel, D., Frontek, H., & von Finckenstein, E. (1986). Reduction of wear on sheet metal forming tools. *CIRP Annals*, *35*(1), 195-198. https://doi.org/10.1016/S0007-8506(07)61869-1

Schuh, G., Bergweiler, G., Bickendorf, P., Fiedler, F. & Cong, C. (2020), Sheet metal forming using additively manufactured polymer tools. *Procedia CIRP*, *93*, 20-25. https://doi.org/10.1016/j.procir.2020.04.013

ten Thije, R. H. W., Akkerman, R., van der Meer, L., & Ubbink, M. P. (2008). Tool-ply friction in thermoplastic composite forming. *International Journal of Material Forming*, 1, 953–956. https://doi.org/10.1007/ s12289-008-0215-9

Vierzigmann, H.U., Merklein, M., & Engel, U. Friction conditions in sheet-bulk metal forming. *Procedia Engineering*, *19*, 377-382. https://doi.org/10.1016/j.proeng.2011.11.128

Analiza Właściwości Tribologicznych Nowych Wkładek Kompozytowych Tłoczników za Pomocą Testu Przeciągania Pasa Blachy

Streszczenie

Celem artykułu jest ocena właściwości tribologicznych nowych kompozytowych wkładek do tłoczników. Badaniom poddano cztery zestawy przeciwpróbek kompozytowych składających się z żywicy poliuretanowej z wypełniaczem mineralnym (wariant bazowy) oraz modyfikowanych proszkiem aluminiowym (10% mas.) i tkaniną rowingową (5% mas.). Próbki do testu przeciągania pasa blachy wycięto z blach AMS5599, AMS5510 i AMS6061-T4. Zaobserwowano wpływ rodzaju materiału przeciwpróbki na współczynnik tarcia. Najmniejsze wartości współczynnika tarcia w całym zakresie zmian siły docisku dla blach AMS5599 i AMS5510 zaobserwowano podczas badań z przeciwpróbkami wykonanymi z bazowego wariantu kompozytu. Podczas badania blachy ze stopu aluminium AMS6061-T4 przeciwpróbki modyfikowane tkaniną rowingową zapewniły najmniejszą wartość współczynnika tarcia, która w zakresie ustabilizowanym osiągnęła wartość około 0,197.

Słowa kluczowe: tarcie, współczynnik tarcia, narzędzie kompozytowe, tłocznik