

EFFECT OF PUNCH COATINGS ON BLANKING FORCE AND NUMERICAL PREDICTION OF FRACTURE ANGLE IN NON-ORIENTED ELECTRICAL STEEL

VLADIMIR ROHAL¹, PETER MULIDRAN¹,
TOMAS JEZNY¹, EMIL SPISAK¹

¹Technical University of Kosice, Faculty of Mechanical Engineering, Kosice, Slovakia

DOI: 10.17973/MMSJ.2026_10_2026034

vladimir.rohal@tuke.sk

This paper presents an experimental and numerical evaluation of the blanking process of non-oriented electrical steel designated as material G. The experimental study evaluated the effect of FeinAl, Movic, and FeinAl + Movic coatings on blanking force at 1 % and 7 % punch-die clearances. In addition, the fracture angle of the blank was determined at punch-die clearances of 1 %, 3 %, 5 %, 7 %, and 10 % of the sheet thickness. The fracture angle was predicted using numerical simulation in Simufact Forming software, and the predicted values were compared with the experimentally determined values. The results showed that the use of coatings reduced the blanking force at both evaluated punch-die clearances. The most significant effect was achieved with the Movic coating. At 1 % punch-die clearance, F15, corresponding to blanking the inner hole, decreased by 23.4 %, while F25, corresponding to blanking the outer circumference of the blank, decreased by 17.0 %. At 7 % punch-die clearance, the decrease was 8.9 % for F15 and 21.7 % for F25. The experimentally determined fracture angle varied only slightly at punch-die clearances of 1 %, 3 %, and 5 %, whereas a more pronounced decrease was observed at 7 % and 10 %. The mean absolute deviation between the experimentally determined and predicted fracture angle values was 3.09°, indicating the applicability of the numerical model for fracture angle prediction under the evaluated blanking conditions.

KEYWORDS

Non-oriented electrical steel, blanking force, coatings, fracture angle, numerical simulation

1 INTRODUCTION

Electrical steels are among the basic soft magnetic materials used in the production of transformers, generators, and electric motors. Their practical application results from high magnetic permeability, low core losses, and a favourable balance between technical properties and material cost [Beckley 2002, Tong 2014, Steiner Petrovic 2010, Tumanski 2011]. In electric motors, electrical steel sheets are mainly used to produce stator and rotor laminations, where the quality of the blanks may affect the magnetic properties and efficiency of the motor. Increasing requirements for electric motor efficiency therefore place higher demands not only on the properties of the material used, but also on the manufacturing quality of the blanks [Moses 2012, Hayakawa 2020, Karami 2024].

In mass production of laminations, blanking is most used because it enables high productivity, low production costs, and the

production of geometrically complex blanks in large series [Altan 2012, Kalpakjian 2010, Paquin 1987]. During blanking, local plastic deformation, residual stresses, and strain hardening occur in the shear zone. These phenomena affect the resulting profile of the sheared surface and may adversely influence the local magnetic properties of electrical steel. Near the sheared surface, plastic deformation and residual stress hinder the movement of domain walls and may contribute to an increase in magnetic losses [Naumoski 2015, Weiss 2017, Leuning 2020, Boehm 2021]. The quality of the blanking process depends on several process, tool design, and material factors. The most important include punch-die clearance, punch and die geometry, tool wear, friction between the tool and the sheet material, and the mechanical properties of the sheet being blanked [Al-Momani 2008, Hambli 2002, Mucha 2010, Bohdal 2022]. Punch-die clearance affects the plastic deformation process, crack initiation and propagation, subsequent material separation, blanking force, and the resulting profile of the sheared surface [Rohan 2022]. An improperly selected punch-die clearance may lead to deterioration of the sheared surface quality, an increase in burr height, and changes in the proportions of the individual zones of the sheared surface [Hambli 2002, Bohdal 2022, Okada 2025]. Current research therefore also focuses on modifying the blanking conditions of non-oriented electrical steels to reduce plastic deformation and microstructural changes in the shear surface [Simonetto 2025]. The sheared surface produced during blanking consists of characteristic zones, including the rollover zone, burnished zone, fracture zone, and burr. The relative proportions and shape of these zones depend mainly on the punch-die clearance, material properties, and tool geometry [Bohdal 2022, Okada 2025]. Since the fracture angle is related to the inclination of the fracture zone, it was evaluated experimentally and compared with values predicted by numerical simulation [Husain 2021]. Besides punch-die clearance, the properties of the working surface of the punch are also important. The use of coatings can reduce friction in the contact area between the punch and the sheet material, contribute to reducing adhesive wear, and thus affect the blanking force. Hard AlCrN-based coatings are mainly used to increase the hardness and wear resistance of the functional parts of the tool, whereas MoS₂-based lubricating layers are primarily intended to reduce the coefficient of friction [Mucha 2010, Okada 2025]. For this reason, the effects of the hard FeinAl coating, the lubricating Movic coating, and their combination were compared under the same blanking conditions.

Numerical simulations represent an important tool for the analysis and optimization of sheet metal processing technologies. Their use makes it possible to reduce the number of experimental tests, shorten the time required for the design of technological parameters, and reduce the costs associated with the production of test tools and specimens. However, the reliability of numerical simulation depends on correctly defined input data, particularly the material model, boundary conditions, coefficient of friction, definition of tool-material contact, and appropriate experimental validation of the predicted results [Spisak 2022, Mulidran 2024]. In sheet blanking simulations, these requirements are particularly important because the process involves intense local plastic deformation, crack initiation and propagation, and subsequent material separation. Therefore, in numerical modelling of the blanking process, it is necessary to correctly define the tool geometry, punch-die clearance, element size in the blanking zone, friction, tool-sheet contact, and material failure criterion [Hambli 2002, Husson 2008, Al-Momani 2008, Slota 2018]. Experimental validation of the simulation is essential, especially when predicting the fracture angle, as it is an indicator of sheared surface quality associated

with material failure during blanking.

The aim of this paper is to experimentally evaluate the effect of the used coatings on blanking force during the blanking of non-oriented electrical steel designated as material G. The second aim was to compare the experimentally determined fracture angle with values predicted by numerical simulation for different values of blanking clearance. In the blanking force evaluation, uncoated punches and punches coated with FeinAl, Movic, and the combined FeinAl + Movic coating were compared. The comparison of experimentally determined and predicted fracture angle values was performed at punch–die clearances of 1 %, 3 %, 5 %, 7 %, and 10 % of the sheet thickness with no coating applied to the punch.

2 MATERIALS AND METHODS

In this study, a 0.50 mm-thick sheet of non-oriented electrical steel designated as material G was used for experimental tests. Annular blanks with an outer diameter of 25 mm and an inner diameter of 15 mm were produced from the material. These blanks were used to evaluate the effect of the applied coatings on blanking force. The experimentally determined fracture angle was subsequently compared with the results of numerical simulation of the blanking process.

The microstructure of material G is shown in Fig. 1. The material has a polyhedral ferritic microstructure typical of non-oriented electrical steels. The relatively uniform microstructure is important with regard to plastic deformation during blanking, since grain size and grain shape can affect local deformation near the sheared surface of the blank and, consequently, the resulting fracture angle.

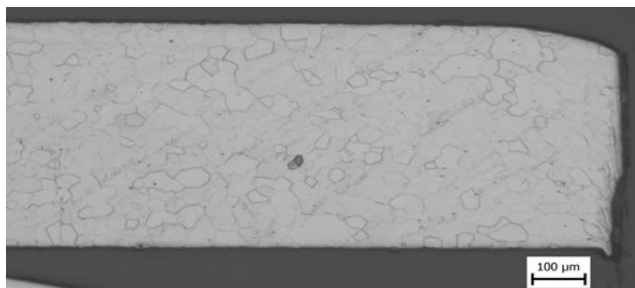


Figure 1. Microstructure of material G

The chemical composition of material G is given in Table 1. For electrical steels, the silicon content is particularly important because it primarily affects the magnetic properties and electrical resistivity of the material. At higher silicon contents, the strength, formability, and processability of electrical steels are also affected. In material G, the silicon content was 0.898 wt. %, corresponding to approximately 0.90 wt. %.

Meas. / Element	Fe	C	Si	Mn	P	S	Al
M.1	98.22	<0.002	0.892	0.385	0.095	<0.002	0.195
M.2	98.21	<0.002	0.890	0.388	0.098	<0.002	0.197
M.3	98.15	<0.002	0.913	0.396	0.102	<0.002	0.207
Avg.	98.19	<0.002	0.898	0.390	0.098	<0.002	0.199

Table 1. Chemical composition of material G – main elements [wt. %]

The mechanical properties of material G were determined by uniaxial tensile testing at 0°, 45°, and 90° to the rolling direction. The yield strength Rp0.2, tensile strength Rm, elongation A80, plastic strain ratio r, and strain hardening exponent n were determined. The measured values are summarized in Table 2.

Direction [°]	Rp0.2 [MPa]	Rm [MPa]	A80 [%]	r [-]	n [-]
0	280	428	35.6	1.112	0.253
45	309	449	33.6	0.906	0.245
90	300	437	34.4	1.493	0.247

Table 2. Mechanical properties of material G

2.1 Experimental methodology of the blanking process

In the experiment, a progressive blanking tool with a blank holder was used to produce annular blanks with an outer diameter of 25 mm and an inner diameter of 15 mm (Fig. 2). The punch–die clearance was defined as a percentage of the sheet thickness. Punch–die clearances of 1 %, 3 %, 5 %, 7 %, and 10 % of the sheet thickness were used for evaluating the impact of die clearance on the fracture angle of annular blanks. No coating was applied on the punch for this part of the experiment.



Figure 2. Annular blanks produced from material G

The effect of the applied coatings on blanking force was evaluated at 1 % and 7 % punch–die clearances. Uncoated punches and punches coated with FeinAl, FeinAl + Movic, and Movic were compared. The punches are shown in Fig. 3. They were hardened and tempered to a hardness of 61 ± 2 HRC. After heat treatment, the working end faces and lateral cylindrical surfaces of the punches were polished to a surface roughness of $R_a = 0.01 \mu\text{m}$.



Figure 3. Uncoated punches and punches with FeinAl, FeinAl + Movic, and Movic coatings used in the experiment

The FeinAl and Movic coatings were selected to compare the effect of a hard wear-resistant coating (FeinAl) and a lubricating layer (Movic) on blanking force during blanking of material G. FeinAl is a nanostructured multilayer AlCrN-based coating with a total thickness of approximately 2 to 4 μm , hardness up to 3500 HV, and high oxidation resistance. Its application is mainly aimed at increasing the hardness, toughness, and wear resistance of the working parts of the tool.

The Movic coating is a MoS_2 -based lubricating layer deposited by PVD technology. Its main function is to reduce friction between the tool and the sheet material, while the coefficient of friction can reach approximately 0.1 depending on the contact conditions [Krenicky 2024].

The combined FeinAl + Movic coating was used to assess the effect of combining a hard load-bearing coating with a lubricating top layer.

Blanking force was measured at 1 % and 7 % punch–die clearances using a VEB ZD40 hydraulic testing press. A digital measuring system connected to the press recorded the punch displacement and blanking force during the working stroke. The force required to produce the inner hole with a diameter of 15 mm was

designated as F15, while the force required to blank the outer diameter of 25 mm was designated as F25. The fracture angle was evaluated on blanks produced at the individual punch-die clearances. The measurement was carried out using a KEYENCE VHX-5000 digital microscope. The sheared surfaces of the blanks were measured in the as-blanked condition, without any additional surface preparation, to preserve their original profile after the blanking process.

2.2 Numerical simulation of the blanking process

Numerical simulation of the blanking process was carried out in Simufact Forming software using the Cold Forming module and the CuttingFe2D process. The aim of the simulation was to predict the fracture angle during blanking of material G and subsequently compare the predicted values with the experimentally determined values.

The simulation was performed as a two-dimensional axisymmetric problem. The model geometry was based on an experimental blanking tool. The punch was defined as the moving part of the tool, while the die was defined as the fixed part. The blank-holding force was set to 6.4 kN and the punch velocity to 10 mm/min. The coefficient of friction between the tool and the sheet material was set to 0.2.

The finite element mesh was generated using Advancing Front Quad elements. The initial element size was 0.03 mm, and 16 elements were used through the sheet thickness. The plastic behaviour of the material was described using the Hill48 yield criterion. Strain hardening was defined by the Ludwik hardening model, and material failure was described using the Cockcroft–Latham criterion.

The simulations were performed for punch-die clearances of 1 %, 3 %, 5 %, 7 %, and 10 % of the sheet thickness. Each simulation provided a predicted fracture angle, which was subsequently compared with the experimentally determined fracture angle at the corresponding punch-die clearance.

3 RESULTS

3.1 Effect of coatings on blanking force

The measured blanking force values F15 and F25 at a 1 % punch-die clearance are given in Table 3. The table presents a comparison of the results obtained using an uncoated punch and punches coated with FeinAl, FeinAl + Movic, and Movic.

Sample	Coating	Sheet thickness [mm]	Punch-die clearance [%]	F15 [kN]	F25 [kN]
G1	No coating	0.50	1	8.46	13.19
FG1	FeinAl	0.50	1	7.26	11.76
FMG1	FeinAl + Movic	0.50	1	7.04	11.32
MG1	Movic	0.50	1	6.48	10.95

Table 3. Effect of coatings on blanking force at a 1 % punch-die clearance

At a 1 % punch-die clearance, the blanking force values F15 and F25 decreased for all applied coatings compared with the uncoated punch. The greatest reduction was achieved with the Movic coating, for which F15 decreased from 8.46 kN to 6.48 kN, corresponding to a reduction of approximately 23.4 %. For the same coating, F25 decreased from 13.19 kN to 10.95 kN, corresponding to a reduction of approximately 17.0 %. The FeinAl and FeinAl + Movic coatings also reduced the blanking force, although to a lesser extent. This behaviour can be attributed to the lubricating nature of the Movic coating, which reduces friction in the punch–sheet contact.

A graphical comparison of the measured blanking force values F15 and F25 at a 1 % punch-die clearance is shown in Fig. 4.

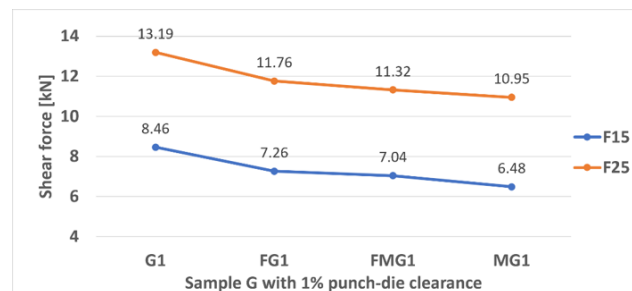


Figure 4. Effect of coatings on blanking force at a 1 % punch-die clearance

The measured blanking force values F15 and F25 at a 7 % punch-die clearance are given in Table 4.

Sample	Coating	Sheet thickness [mm]	Punch-die clearance [%]	F15 [kN]	F25 [kN]
G7	No coating	0.50	7	7.38	13.15
FG7	FeinAl	0.50	7	6.96	11.68
FMG7	FeinAl + Movic	0.50	7	6.85	11.71
MG7	Movic	0.50	7	6.72	10.29

Table 4. Effect of coatings on blanking force at a 7 % punch-die clearance

At a 7 % punch-die clearance, the blanking force decreased for all applied coatings. The greatest reduction was achieved with the Movic coating, for which F15 decreased from 7.38 kN to 6.72 kN, corresponding to a reduction of approximately 8.9 %. For the same coating, F25 decreased from 13.15 kN to 10.29 kN, corresponding to a reduction of approximately 21.7 %. The FeinAl and FeinAl + Movic coatings also reduced the blanking force, although to a lesser extent. The more pronounced decrease in F25 indicates that, at a 7 % punch-die clearance, the effect of the coating was more significant during blanking of the outer circumference of the blank.

A graphical comparison of the measured blanking force values F15 and F25 at a 7 % punch-die clearance is shown in Fig. 5. The results show that the use of coatings led to a reduction in blanking force at both evaluated punch-die clearances. The most pronounced reduction was achieved with the Movic coating, which can be attributed to its lubricating nature and its ability to reduce friction in the punch–sheet contact.

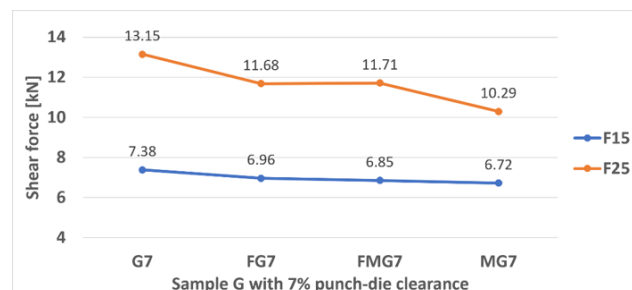


Figure 5. Effect of coatings on blanking force at a 7 % punch-die clearance

The FeinAl coating also reduced the blanking force, although to a lesser extent than the Movic coating, which is related mainly to its high hardness and wear resistance. The combined FeinAl + Movic coating reduced the blanking force compared with the uncoated punch, and its effect was comparable to that of the FeinAl coating in most of the evaluated cases.

3.2 Effect of punch-die clearance on the fracture angle

The experimentally determined fracture angle values for material G are given in Table 5. The data show that, at punch-die clearances of 1 %, 3 %, and 5 %, the fracture angle varied only slightly, ranging from 84.94° to 85.94°. The maximum value was obtained at a punch-die clearance of 5 %. With a further increase in punch-die clearance, a more pronounced decrease in the fracture angle was observed. At clearances of 7 % and 10 %, the fracture angle decreased to 80.18° and 70.82°, respectively.

Sample	Sheet thickness [mm]	Punch-die clearance [%]	Fracture angle α [°]
G1	0.50	1	85.09
G3	0.50	3	84.94
G5	0.50	5	85.94
G7	0.50	7	80.18
G10	0.50	10	70.82

Table 5. Experimentally determined fracture angle values for material G

A visual comparison of the experimentally determined fracture angle at punch-die clearances of 1 % and 10 % is shown in Fig. 6. The figure also shows the difference in the sheared surface profile of material G at the smallest and largest evaluated punch-die clearances.

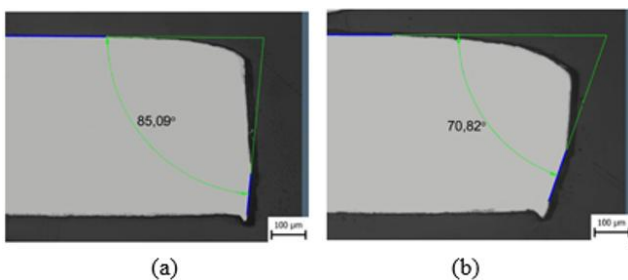


Figure 6. Effect of punch-die clearance on the fracture angle of material G: (a) 1 % punch-die clearance, (b) 10 % punch-die clearance

At punch-die clearances of 1 %, 3 %, and 5 %, the fracture angle values varied only within a narrow range, from 84.94° to 85.94°. This suggests that, within this clearance range, no significant change occurred in the sheared surface profile within the fracture zone. The more pronounced decrease in the angle at 7 %, and especially at 10 % punch-die clearance, indicates a change in the sheared surface profile, probably associated with differences in crack initiation and propagation during blanking. The larger punch-die clearance was therefore associated with a lower fracture angle value.

3.3 Comparison of experimentally determined and numerically predicted fracture angle

Numerical simulation was used to predict the fracture angle during blanking of material G using different values of punch-die clearance. The predicted values were compared with the experimentally determined values at the corresponding punch-die clearances, and the results are summarized in Table 6. The presented data show that the numerical model captured the basic trend in fracture angle variation as a function of punch-die clearance. At clearances of 1 %, 3 %, and 5 %, the deviations between the predicted and experimentally determined values were small. The smallest deviation was found at a 5 % punch-die clearance, where it reached 1.53°. At a 3 % punch-die clearance, the deviation was 1.89°, and at a 1 % punch-die clearance, it was 2.91°.

Sample	Sheet thickness [mm]	Punch-die clearance [%]	Sim. [°]	Exp. [°]	Difference [°]
G1	0.50	1	82.18	85.09	-2.91
G3	0.50	3	86.83	84.94	1.89
G5	0.50	5	84.41	85.94	-1.53
G7	0.50	7	83.77	80.18	3.59
G10	0.50	10	76.34	70.82	5.52

Table 6. Comparison of experimentally determined and numerically predicted fracture angle α

At larger punch-die clearances, the difference between the experimentally determined and predicted values increased. At a 7 % punch-die clearance, the difference reached 3.59°, while at a 10 % punch-die clearance, it reached 5.52°. The largest deviation was therefore observed at the largest punch-die clearance used. This result indicates lower accuracy of the numerical prediction at larger punch-die clearances, where the fracture angle may be more strongly affected by tool-sheet contact, friction, local plastic deformation, and crack initiation and propagation. A visual comparison of the experimentally determined and predicted fracture angles at the investigated punch-die clearances is shown in Figs. 7–11.

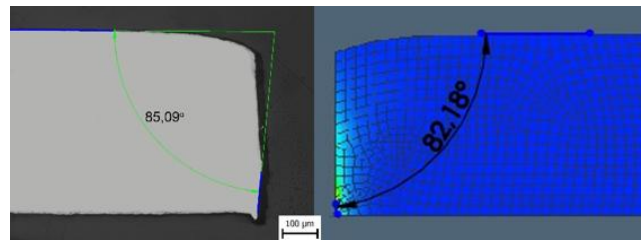


Figure 7. Experimental and predicted fracture angle of the blank – material G, 1 % punch-die clearance

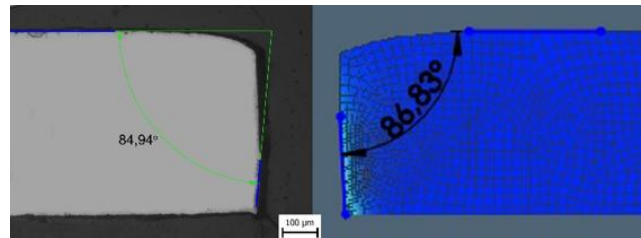


Figure 8. Experimental and predicted fracture angle of the blank – material G, 3 % punch-die clearance

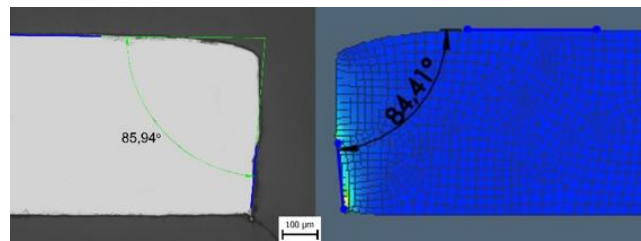


Figure 9. Experimental and predicted fracture angle of the blank – material G, 5 % punch-die clearance

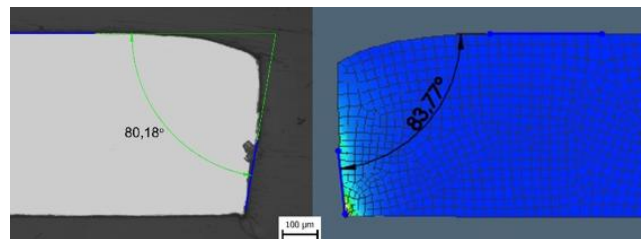


Figure 10. Experimental and predicted fracture angle of the blank – material G, 7 % punch-die clearance

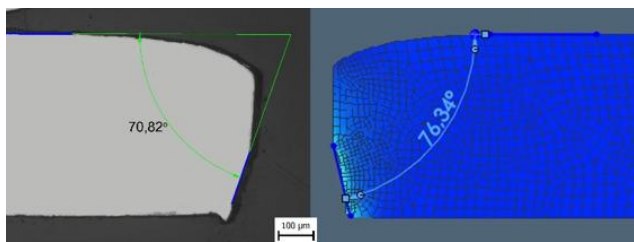


Figure 11. Experimental and predicted fracture angle of the blank – material G, 10 % punch-die clearance

The mean absolute deviation between the experimentally determined and predicted fracture angle values was 3.09° . The best agreement with the experimental results was achieved at punch-die clearances in the range of 1 % to 5 %. At a 10 % punch-die clearance, the largest deviation was observed, indicating lower prediction accuracy at the largest evaluated clearance. This difference may be related to the sensitivity of the result to the material failure criterion, coefficient of friction, and definition of tool-sheet contact.

CONCLUSIONS

Based on the experimental evaluation and numerical simulation of the blanking process of material G, the following conclusions can be drawn:

- The use of coatings led to a reduction in blanking force at both evaluated punch-die clearances compared to the uncoated punch.
- The most significant reduction in blanking force was achieved with the Movic coating. At 1 % punch-die clearance, F15, corresponding to the formation of the 15 mm inner hole, decreased by approximately 23.4 %, while F25, corresponding to blanking the 25 mm outer circumference of the blank, decreased by approximately 17.0 %. At 7 % punch-die clearance, the decrease was approximately 8.9 % for F15 and 21.7 % for F25. This result can be attributed to the lubricating nature of the Movic coating and its ability to reduce friction in the punch-sheet contact.
- At punch-die clearances of 1 %, 3 %, and 5 %, the experimentally determined fracture angle values changed only within a narrow range, from 84.94° to 85.94° . At larger punch-die clearances, a more pronounced decrease in the fracture angle was observed, reaching 80.18° at 7 % punch-die clearance and 70.82° at 10 % punch-die clearance.
- The numerical model captured the basic trend in fracture angle variation as a function of punch-die clearance. The smallest deviation between the experimentally determined and predicted value was found at 5 % punch-die clearance, where it reached 1.53° . The largest deviation was found at 10 % punch-die clearance, where it reached 5.52° .
- The mean absolute deviation between the experimentally determined and predicted fracture angle values was 3.09° . The results indicate the applicability of the numerical model, particularly for punch-die clearances in the range of 1 % to 5 %. At 10 % punch-die clearance, the prediction accuracy was lower, which may be related to the higher sensitivity of the result to the material failure criterion, coefficient of friction, and definition of tool-sheet contact.

ACKNOWLEDGMENTS

This paper was prepared within the framework of the grant project KEGA 018TUKE-4/24.

REFERENCES

- [Al-Momani 2008] Al-Momani, E., Rawabdeh, I. An Application of Finite Element Method and Design of Experiments in the Optimization of Sheet Metal Blanking Process. *Jordan Journal of Mechanical and Industrial Engineering*, 2008, Vol. 2, No. 1, pp. 53-63. ISSN 1995-6665.
- [Beckley 2002] Beckley, P. *Electrical Steels for Rotating Machines*. London: Institution of Engineering and Technology, 2002. DOI: 10.1049/PBPO037E.
- [Boehm 2021] Boehm, L., Hartmann, C., Gilch, I., Stoecker, A., Kawalla, R., Wei, X., Hirt, G., Heller, M., Korte-Kerzel, S., Leuning, N., et al. Grain Size Influence on the Magnetic Property Deterioration of Blanked Non-Oriented Electrical Steels. *Materials*, 2021, Vol. 14, No. 22, 7055. DOI: 10.3390/ma14227055.
- [Bohdal 2022] Bohdal, L., Kulakowska, A., Patyk, R., et al. Experimental Research on Sheared Edge Formation in the Shear-Slitting of Grain-Oriented Electrical Steel Workpieces. *Materials*, 2022, Vol. 15, No. 24, 8824. DOI: 10.3390/ma15248824.
- [Hambli 2002] Hambli, R. Design of Experiment Based Analysis for Sheet Metal Blanking Processes Optimisation. *International Journal of Advanced Manufacturing Technology*, 2002, Vol. 19, No. 6, pp. 403-410. DOI: 10.1007/s001700200041.
- [Hayakawa 2020] Hayakawa, Y. *Electrical Steels*. In: Reference Module in Materials Science and Materials Engineering. Elsevier, 2020. DOI: 10.1016/B978-0-12-819726-4.00004-1.
- [Husain 2021] Husain, H., Hazdra, Z., Kudlacek, J., Kuchar, J. Risk factors for B4C composite utilization in tribological processes. In: *Metal 2021 - 30th Anniversary Int. Conf. on Metallurgy and Materials, Conf. Proceedings*. Brno, 26-28 May 2021. Ostrava: Tanger Ltd., 2021, pp. 801-806. DOI: 10.37904/metal.2021.4186
- [Husson 2008] Husson, C., Correia, J.P.M., Daridon, L., Ahzi, S. Finite Elements Simulations of Thin Copper Sheets Blanking: Study of Blanking Parameters on Sheared Edge Quality. *Journal of Materials Processing Technology*, 2008, Vol. 199, No. 1-3, pp. 74-83. DOI: 10.1016/j.jmatprotec.2007.08.034.
- [Karami 2024] Karami, R., Butler, D., Tamimi, S. Manufacturing of Non-Grain-Oriented Electrical Steels: Review. *International Journal of Advanced Manufacturing Technology*, 2024, Vol. 133, pp. 1083-1109. DOI: 10.1007/s00170-024-13837-9.
- [Krenicky 2024] Krenicky, T., Goncharov, O.Y., Kuchar, J., et al. Chemical Vapor Deposition of Tantalum Carbide in the TaBr₅-CCl₄-Cd System. *Coatings*, 2024, Vol. 14, No. 5, 547. DOI: 10.3390/coatings14050547
- [Leuning 2020] Leuning, N., Steentjes, S., Hameyer, K. Impact of Grain Size Distribution on the Magnetic Deterioration Due to Cutting of Electrical Steel Sheets. *Journal of Magnetism and Magnetic Materials*, 2020, Vol. 497, 166080. DOI: 10.1016/j.jmmm.2019.166080.
- [Moses 2012] Moses, A.J. Energy Efficient Electrical Steels: Magnetic Performance Prediction and Optimization. *Scripta Materialia*, 2012, Vol. 67, No. 6, pp. 560-565. DOI: 10.1016/j.scriptamat.2012.02.027.
- [Mucha 2010] Mucha, J. An Experimental Analysis of Effects of Various Material Tool's Wear on Burr during Generator Sheets Blanking. *International Journal of Advanced Manufacturing Technology*, 2010, Vol. 50, No. 5-8, pp. 495-507. DOI: 10.1007/s00170-010-2554-1.

- [Mulidran 2024] Mulidran, P., Spisak, E., Tomas, M., Majernikova, J., Rohal, V. Numerical Simulation of Bending Process for Steel Sheets Used in Automotive Industry with Emphasis on Springback. *Acta Metallurgica Slovaca*, 2024, Vol. 30, No. 1, pp. 41-46. DOI: 10.36547/ams.30.1.2003.
- [Naumoski 2015] Naumoski, H., Riedmuller, B., Minkow, A., Herr, U. Investigation of the Influence of Different Cutting Procedures on the Global and Local Magnetic Properties of Non-Oriented Electrical Steel. *Journal of Magnetism and Magnetic Materials*, 2015, Vol. 392, pp. 126-133. DOI: 10.1016/j.jmmm.2015.05.032.
- [Okada 2025] Okada, R., Ito, K., Funazuka, T., Aizawa, T., Shiratori, T. Punch Edge Topological Design for Reduction of Work Hardening Damage in Shearing of Non-Oriented Electrical Steel Sheets. *Materials*, 2025, Vol. 18, No. 4, 878. DOI: 10.3390/ma18040878.
- [Paquin 1987] Paquin, J.R., Crowley, R.E. *Die Design Fundamentals*. 2nd ed. New York: Industrial Press, 1987. ISBN 9780831111724.
- [Rohan 2022] Rohan, P., Lukac, F., Kolarikova, M., et al. Pulsed Plasma Surfacing of Titanium Matrix Cermet Based on B4C. *J Therm Spray Tech*, 2022, Vol. 31, pp. 1975-1984. DOI: 10.1007/s11666-022-01421-0
- [Slota 2018] Slota, J., Kascak, L., Kut, S. FEM Modeling of Shear Cutting of Electrical Steel Sheets under Various Technological Conditions. *Acta Mechanica Slovaca*, 2018, Vol. 22, No. 4, pp. 24-30. DOI: 10.21496/ams.2018.031.
- [Spisak 2020] Spisak, E., Majernikova, J., Kascak, L., Mulidran, P. The Impact of Shear Gap Size on the Quality of the Sheared Surface in Electrical Steel Sheet Blanking. *Acta Metallurgica Slovaca*, 2020, Vol. 26, No. 2, pp. 49-53. DOI: 10.36547/ams.26.2.545.
- [Spisak 2022] Spisak, E., Majernikova, J., Kascak, L., Mulidran, P., Rohal, V., Bidulsky, R. Experimental and Numerical Thickness Analysis of TRIP Steel under Various Degrees of Deformation in Bulge Test. *Materials*, 2022, Vol. 15, No. 6, 2299. DOI: 10.3390/ma15062299.
- [Steiner Petrovic 2010] Steiner Petrovic, D. Non-Oriented Electrical Steel Sheets. *Materials and Technology*, 2010, Vol. 44, No. 6, pp. 317-325. ISSN 1580-2949.
- [Tong 2014] Tong, W. *Mechanical Design of Electric Motors*. Boca Raton: CRC Press, 2014. DOI: 10.1201/b16863.
- [Tumanski 2011] Tumanski, S. *Handbook of Magnetic Measurements*. Boca Raton: CRC Press, Taylor & Francis Group, 2011. DOI: 10.1201/b10979.
- [Weiss 2017] Weiss, H.A., Leuning, N., Steentjes, S., Hameyer, K., Andorfer, T., Jenner, S., Volk, W. Influence of Shear Cutting Parameters on the Electromagnetic Properties of Non-Oriented Electrical Steel Sheets. *Journal of Magnetism and Magnetic Materials*, 2017, Vol. 421, pp. 250-259. DOI: 10.1016/j.jmmm.2016.08.002
- [Zhu 2024] Zhu, Y., Yan, Q., Lu, J., Xu, W. Effects of Shearing Processing on the Quality and Magnetic Properties of Electric Steel Sheet. *Ain Shams Engineering Journal*, 2024, Vol. 15, 102395. DOI: 10.1016/j.asej.2023.102395.

CONTACTS:

Vladimir Rohal, Peter Mulidran, Emil Spisak, Tomas Jezny
 Technical University of Kosice
 Faculty of Mechanical Engineering
 Department of Mechanical Engineering Technologies and Materials
 Masiarska 74, 040 01 Kosice, Slovakia
 vladimir.rohal@tuke.sk

LICENSE CREATIVE COMMONS:

The article is published under the terms and conditions of the Creative Commons Attribution 4.0 International License (CC BY 4.0).