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EXPERIMENTAL AND NUMERICAL INVESTIGATIONS AND OPTIMISATION OF GRAIN-ORIENTED SILICON STEEL MECHANICAL CUTTING PROCESS

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Abstract: The process of mechanical cutting of magnetic materials has many advantages in the form of high efficiency with reduced process costs in relation to other cutting technologies; no thermal stresses in the material, which significantly deteriorate the magnetic properties; or the possibility of shaping materials taking into account long cutting lines. In industrial practice, it is very difficult to ensure appropriate conditions for the cutting process and its proper control. Currently, there are no data on the selection of technological parameters of the mechanical shear slitting process of grain-oriented silicon steel in terms of the obtained cutting surface quality and the obtained magnetic properties of the workpiece. The article presents the possibilities of forecasting the characteristic features of the cut edge and selected magnetic properties of grain-oriented silicon steel. For this purpose, proprietary numerical models using FEA (Finite Element Analysis) were used. Then, experimental studies were carried out, and the optimisation task was developed. The developed results enable the correct selection of technological parameters of the process, ensuring the appropriate quality of the cut edge of steel and minimal interference with the magnetic properties.

Key words: magnetic materials, shear slitting, sheared edge, magnetic properties

1. INTRODUCTION

Mechanical cutting is a very popular technological process in shaping electrical steel. This is due to the high efficiency of the process and its lower costs compared with other cutting techniques. Electrical steel, as soft magnetic materials in industrial practice, must be characterised by low magnetic losses and high magnetic induction because it is used in the construction of electrical machines and devices such as magnetic circuits of electric motors, transformers and generator cores. Negative changes in the magnetic properties of these materials after production processes often cause problems with obtaining appropriate technical and operational properties of these devices. The main influence on the deterioration of the magnetic properties of steel is the successive technological operations it is subjected to, as well as its transport and storage (impact, compression, bending). This causes stresses, deformations and microcracks in these materials [1–3].

In the mechanical cutting process, material separation is accompanied by large plastic deformations, which leads to the deterioration of the integrity of the material. Therefore, in the area of the cut edge, zones of stress concentration and deformation, as well as changes in the orientation of the grains of the microstructure, are formed. In many cases, the process is accompanied by the phenomenon of burr formation on the cut edge, which is difficult to analyse and predict because it depends on many factors. Excessive burr formation causes breaking insulating layers among laminated cores. The negative influence of burrs on the shapes of the magnetic hysteresis loop of electrical steel and its characteristic parameters was also demonstrated [4, 5].

Among the works in the processing of electrical steel by means of cutting operations, attention is paid mainly to the influence of cutting technology (e.g., mechanical, water and laser) on selected magnetic properties [6, 7]. Much less consideration concerns the appropriate configuration and optimisation of these technologies and the determination of their impact on both the stress and deformation states, the characteristic features of the cut edge of the material and its magnetic properties. Some works have focussed on searching for connections between the mechanical properties of the materials cut, the geometrical properties of the tools and the quality of the cut edge [8, 9].

Much less work concerns the analysis of cutting forces, cutting technological parameters on the stress and strain concentration in the shearing region, burr formation and change magnetic properties. The available works concern mainly punching and blanking processes, where the decisive factor for the quality of the product is the appropriate selection of the blanking clearance [10].

In the work [3], experimental tests were carried out on the process of cutting silicon electrical steel with thicknesses t = 0.2 mm and t = 0.35 mm. It was found that a significant parameter influencing the degree of deformation in the cutting zone is the punching speed, which also affects punching forces. The deformation values in the cutting zone were analysed using the digital image correlation (DIC) method. Impact was also found for the blanking speed on the hysteresis losses, where cutting at high speed can reduce this magnetic loss. In the study mentioned in Ref [11], the effect of three different cutting techniques such as punching, waterjet and laser cutting on the magnetic properties of the grain-oriented electrical steel sheets was investigated. The comparative analysis shows the superiority of the punching and waterjet cutting techniques over laser cutting. For the punching process, a significant influence of the clearance between the punch and the die on the level of material distortion was demonstrated. It was assumed that it is possible to control the clearance of the cut so as to obtain the least interference in the magnetic properties, but it is necessary to know the characteristics of the hysteresis loop in the areas of the cut edge. The authors of the study mentioned in Ref [12] showed that stresses in electrical steel actually increase the total losses and that compressive stress aggravates the total losses much more than tensile stress.

In the study mentioned in Ref [13], the authors evaluated the influence of the grain size of the material on its iron losses after the blanking process. Samples for the single sheet test were blanked at different cutting clearances (15–70 μm) from sheets with identical chemical composition (3.2 wt.% Si) but varying average grain size (28–210 μm) and thickness (t = 0.25 mm and t = 0.5 mm). The measurements of blanking force and punch travel were carried out. In the study mentioned in Ref [14], the influence of the blanking process on the magnetic properties of non-oriented electrical steel lamination was analysed. The influence of residual stress distribution on selected magnetic property deterioration was investigated. A flat punch and concave punch were used as blanking tools. The magnetic property deterioration of non-oriented electrical steel lamination was mainly related to peak residual stress. With the help of appropriate tool geometries and clearance values, it was possible to reduce magnetic property deterioration.

In the work mentioned in Ref [15], research was carried out on the determination of changes in the magnetic properties of thin non-oriented electrical sheets depending on their microstructure and clearance. In the study mentioned in Ref [16], the influence of the conditions of the punching process on stresses and the structure of the magnetic domain in the cutting zone of non-oriented silicon steel was investigated. The Suresh theoretical model was characterised, by means of which the stress values on the cut edge were calculated. In the article mentioned in Ref [3], plastic deformations were measured in the cutting zone using the DIC technique. The influence of the clearance on the width of the deformation zone was determined.

The analysis of the state of knowledge shows that the deterioration of the magnetic properties is caused, in addition to the formation of excessive burrs, as well as by the wide deformation-affected zone. The authors of the works mentioned in Ref [17, 18] analysed the influence of the width of this zone on the selected magnetic properties of grain-oriented and non-grain-oriented silicon steel. Based on the results, it can be concluded that the deterioration of the magnetic properties of electrical sheets in the areas along the cut line may occur not only in the vicinity of the cut edge, but also in areas located more than 10 mm from the cut edge. For sheets with a high silicon content, deterioration may be up to 15 mm from the cut edge, while for low silicon content, it is about 10 mm [17]. In the works mentioned in Ref [3, 19], it was shown that the degradation of the magnetic properties of the material depends on the width of the cut elements. This confirms the importance of the influence of the width of the deformation zone on the product quality, which has a particularly negative effect on the magnetic properties in the case of cutting small details. Particularly large changes in magnetic properties occur when cutting narrow 20-mm-wide strips from metal sheets.

The concentration of high-tensile stress values in the cutting zone causes the instability of the material cracking process, which causes the formation of slivers and burrs on the cut surface of workpieces. According to the authors of the works mentioned in Ref [8, 20, 21], the cutting speed may also have an impact on the stress distributions and their maximum values in the cutting zone.

The analysis of the state of knowledge shows that the goal is to properly control the conditions of the cutting process so as to limit the width of the deformed zone and the concentration of maximum stresses in the cutting zone and to obtain a cutting edge free from defects in the form of edge waviness, burrs and slivers. This may result in minimal changes to the magnetic properties of sheets. This is difficult due to many factors affecting both the plastic flow and material separation process. Information on process conditions and guidelines for their design is often generalised to all cases, which does not give good results in the form of appropriate dimensional accuracy of details and their magnetic properties. Each of the mechanical cutting processes has its own specific features and parameters that do not always occur in another process and may have a crucial impact on the course of physical phenomena in the cutting zone when shaping certain types of steel. There is a lack of information related to the influence of the cutting process parameters on the stress and deformation states, their relationship with the quality of the cut surface and the magnetic properties of the material after the process.

The aim of the work is to analyse the influence of the main technological parameters of the mechanical cutting process on the quality of the cut edge and the magnetic properties of grain-oriented silicon steel with a 3% silicon content. Experimental research was carried out on the shear slitting machine, which is a popular industrial tool for separating electrical sheet strips. The advantage of this device is the possibility of extensive interference in the parameters of the cutting process; however, currently, the knowledge on the correct selection of processing parameters in terms of obtaining a high-quality product is limited. Physical, mathematical and simulation models of the shear slitting process were developed using a finite element method to predict the width of the deformed zone concentrated along the cut line after the process. The developed models take into account the spatial state of stresses and strains, the actual geometries of the sheet and tools, and the length of the cutting line and enable the analysis of crucial physical phenomena of the process at any time during the process. The experimental research included the analysis of the quality of the cut edge and selected magnetic properties of the material. As a result of numerical and experimental research, a multi-criteria optimisation task was formulated, assuming the criteria of maximum process efficiency while maintaining the highest quality of the cutting edge free form burrs and slivers and minimal changes in magnetic properties of workpiece.

2. FE MODELLING OF SHEAR SLITTING PROCESS

Cutting materials are subject to very complex levels of stress. Therefore, in order to analyse this process, it is necessary to use computer methods of mechanics and very advanced mathematical tools. Problems with many variables should be dealt with taking into account their nonlinearity [22, 23]. The cutting process should be viewed as a geometrically and physically nonlinear boundary-start problem with boundary conditions that are unknown in the tool–workpiece contact area. In this work, the cutting process is modelled with variational and finite element methods according to the following steps:

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1. Mathematical modelling of physical models from which continuous and incremental mathematical models are obtained are as follows: tool–object contact models, constitutive equations, motion dynamics equations and uniqueness conditions. As a result of the application of the variation formula, one also obtains a variational equation of the motion of the object.
2. Construction of discrete physical models.
3. Physical modelling of real objects. The effect of this phase is the development of a physical model of the cutting process, distinguishing between the adopted assumptions and simplifications.
4. Construction of computer models, creation of proprietary applications enabling comprehensive time analysis of deformation states occurring in objects during the analysis, determining the type of problem, its solution and its essential parameters and finally, preparing the data for calculations, calculating and editing the result – the program performs calculations based on these data and saves the result. The obtained results can be presented, analysed and archived.
5. Approximation of continuous mathematical models using finite element methods or mathematical modelling of discrete physical models. The result is a discrete, incremental mathematical model of the physical model.

The numerical model uses the updated Lagrange description, which was used to describe nonlinear phenomena on a typical incremental step in the cutting process [24, 25]. The task of the incremental analysis is to formulate the geometry of the material being cut, as well as the existing state of increase in displacement, velocity, acceleration, deformation, stress, strain, velocity, etc. in subsequent discrete moments of $\tau = 0, \Delta t, 2\Delta t, \ldots$, corresponding to a specific slight increment of time. Within the incremental description, there are many important issues related to the nonlinear analysis of the cutting process. They include the selection of an appropriate coordinate system, determination of measurements of strains and stresses and their increments, as well as determination of the rules of their accumulation at each increment step. The strain increments and stresses are described by the increment of the nonlinear symmetric Green–Lagrange strain tensor and the increment of the second Pioli–Kirchhoff symmetric stress tensor. In order to formulate the incremental variational equation of object motion, in the case of cutting, a variational functional is introduced in which there is only one independent field – the field of incremental displacement.

The constitutive material model reported by Johnson and Cook [26] was employed in this study to represent the cutting material behaviour. The model can be represented by Eq. (1):

$$\sigma_Y = [A + B(\bar{\varepsilon}^p)^n][1 + Cln\dot{\varepsilon}^*][1 - (T^*)^m], \tag{1}$$

where A, B and n are strain-hardening constants; C is the strain rate hardening constant; σ_Y is the equivalent flow stress; $\bar{\varepsilon}^p$ is the equivalent plastic strain; and m is the thermal softening constant that modifies the homologous temperature term, T^*. The homologous temperature is defined as $T^* = \frac{T - T_r}{T_m - T_r}$, where T is the temperature of the material, T_r is a reference temperature (typically room temperature) and T_m is the melt temperature of the material. The term $\dot{\varepsilon}^*$, is the normalised strain rate of the material or $\dot{\varepsilon}^* = \frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}_0}$, where $\dot{\varepsilon}_0 = 1.0\ s^{-1}$. ET 122-30 with thickness of *t* = 0.3 mm grain oriented silicon steel was used in analysis (Tabs. 1 and 2).

The mechanical properties of the material were tested on a Zwick Roel Z400 testing machine (Fig. 1) at a temperature T = 20˚C. Ten tensile tests along the length and 10 tests across the direction of rolling were made on standardised specimens. It was found that the material did not exhibit mechanical anisotropy, which was confirmed by photos of the metallographic structure. The material hardness was measured on a table Fervi hardness meter with the measurements repeated 10 times. The value of the arithmetic mean of the measurements is presented in Tabs. 1 and 2.

Tab. 1. Johnson–Cook constitutive model constants for ET 122-30 steel [27]

$A\ (MPa)$	$B\ (MPa)$	C	n	m
104.3	445.6	0.041	0.46	0.54

Tab. 2. Mechanical properties of ET 122-30 steel

Density (kg/dm^3)	Yield point (MPa)	Elongation (%)	Hardness (HV_5)
7.65	300 ± 5	11 ± 1,5	160 ± 7

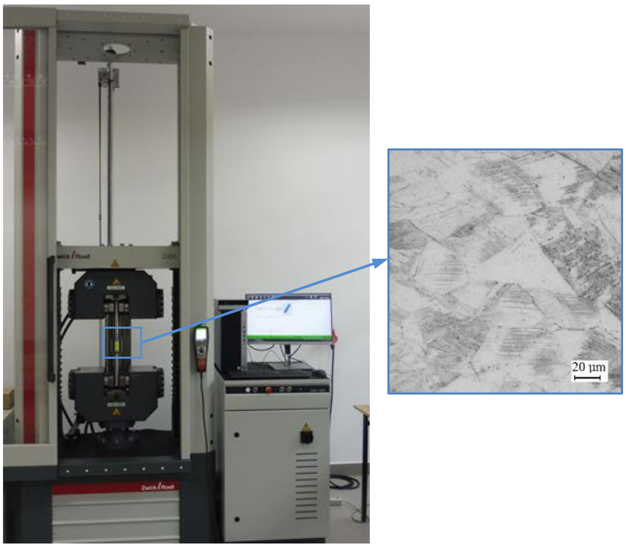

Fig. 1. Zwick/Roell Z400 testing machine for determining material characteristics

An important element in the analysis of the shear slitting process is the correct construction of a geometric model with the same parameters as the real research object. Therefore, it is necessary to take into account the rotation of the knifes and the longitudinal movement of the sheet metal during the process. The developed numerical model in the LS-DYNA solver for the 3D state of stresses and strains takes into account the actual boundary conditions of the process (Fig. 2). The model takes into account the value of the rake angle (α), the value of the radius of the knives, the length of the cutting line and the method of supporting the material sheet. In industrial conditions, the first step is to determine the overlap (vertical clearance value c_v) of the knives and then start the rotation of the knives and polyurethane roll with the set cutting speed v_x and horizontal clearance h_c. The tests were carried out for the following geometric parameters of the test stand: $r_1 = r_2 = 15$ mm, $r_3 = 20$ mm, $l = 80$ mm, $w_i = 40$ mm and the process control variables in the range of $v_2 = 3$–24 m/min and

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h_c = 0.02–0.1 mm, and rake angle α = 5°–40°. A constant value of tool overlap c_v = 0.1 mm was assumed. Simulation models were used to analyse the influence of technological parameters of the cutting process on the width of the deformed zone (Figs. 3–6).

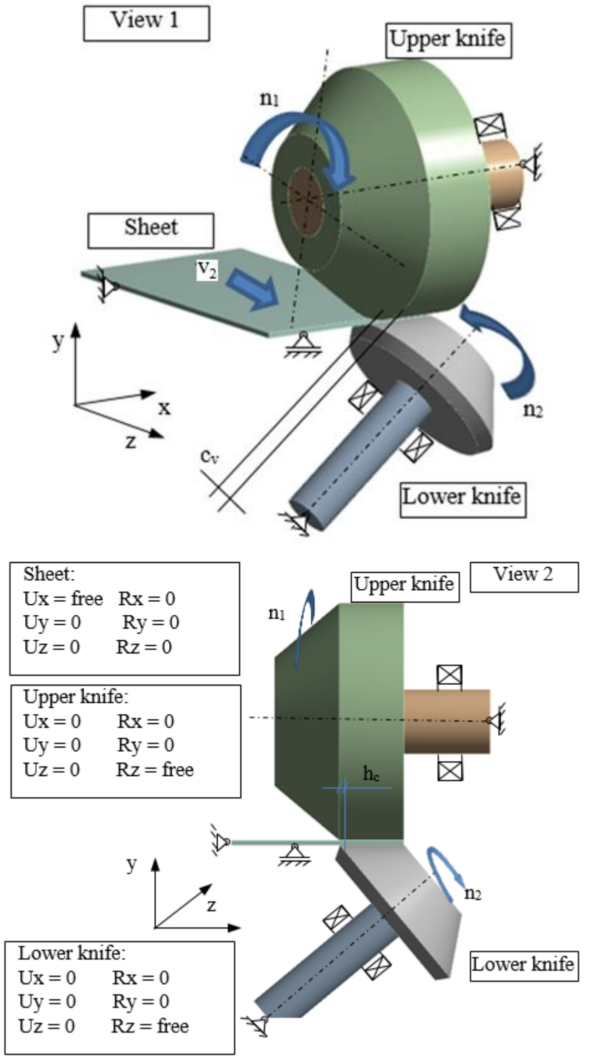

Fig. 2. FE model with boundary conditions

3. FE MODELLING RESULTS

The authors' research so far has shown that the residual stresses after blanking in workpiece extend further into the material than the area reinforced with deformation. According to many studies, the plastic deformation zone after mechanical cutting in the sheared edge is at least D_{mz} = 0.1 mm and increases rapidly with increasing wear of the cutting tools [28–30]. Currently, the literature has not specified the extent to which this zone extends inside the material depending on other criteria, for example, the geometry of the cutting tool. It is known, however, that deformations along the cut line may result in the formation of an elastic stress zone in the depths adjacent to the plastically deformed area [31–33]. As a result, both zones strongly influence the magnetic properties. The proposed approach makes it possible to precisely determine both the size of the deformation in the cutting zone and the width of this zone, depending on the adopted machining parameters. During the cutting process, in order to analyse the physical phenomena in the cutting zone, a high-speed i-SPEED TR camera with a computer was used, which in the subsequent steps of the process recorded a set of consecutive images of the sample surface. The obtained measurement results were used to validate the numerical results by means of comparative analyses of the values of displacement and deformation of the material during and after the end of the process. The DIC technique was used to determine these features. Image-based displacement and deformation measurements are non-invasive, which means that the magnetic properties are not negatively affected. The OLYMPUS LEXT OLS4000 confocal laser microscope was used to measure the burr height after cutting.

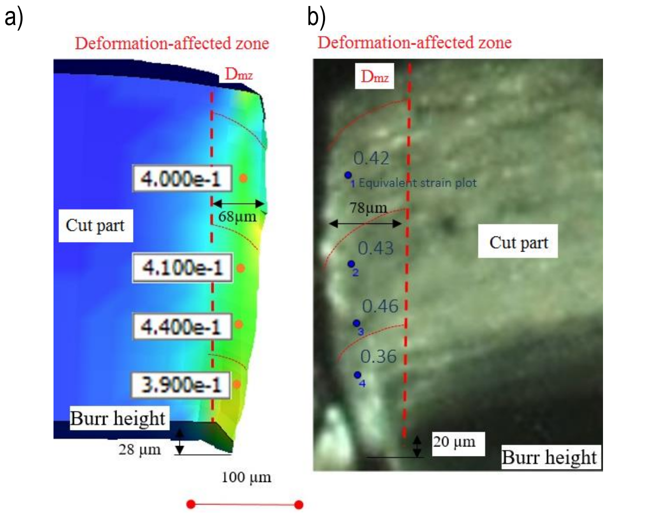

Fig. 3. Analysis of deformation-affected zone and equivalent strain values in shearing region obtained numerically (a) and experimentally (b)

The comparative analysis of the test results showed the maximum differences in the values of equivalent strain values, width of the deformation-affected zone and the burr height amount to about 15%.

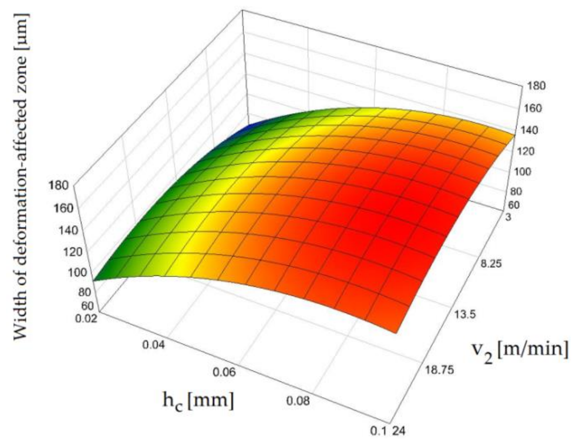

Fig. 4. Influence of the process parameters on the width of the deformation-affected zone for α = 5

The obtained results show that the rake angle of the upper knife α, horizontal clearance h_c and the cutting speed v_2 have a key influence on the formation of the deformed zone. With an increase in the clearance value, the width of the deformed zone increases (Figs. 4–6). The maximum width of the deformed zone is approxi-

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mately D_{mz} = 180 µm for h_c = 0.08 – 0.1 mm, when α = 5° and for h_c = 0.06 – 0.08 mm, when α = 40°, where v = 13.5 m/min. The clearance value is especially important when using α = 5°–25°. In this range of variability, an increase in the horizontal clearance above the value of h_c = 0.06 mm is particularly unfavourable. With small clearances h_c = 0.02 mm ÷ 0.03 mm, the change of the angle α does not significantly change the width of the deformed zone. The minimum width of this zone reaches approximately D_{mz} = 60 µm. This value has been obtained for h_c = 0.02 mm, α = 5° and 40° and v = 3 m/min. When using an rake angle value α = 25°, the zone value increased to about D_{mz} = 90 µm for the same cutting speed and horizontal clearance configuration. When using α = 40° deformation-affected zone, it is less sensitive to changes in the value of clearance and cutting speed than for other variants of α parameter, but such an rake angle value may cause an increased concentration of contact pressures on the edge of the upper knife and cause its accelerated abrasive wear.

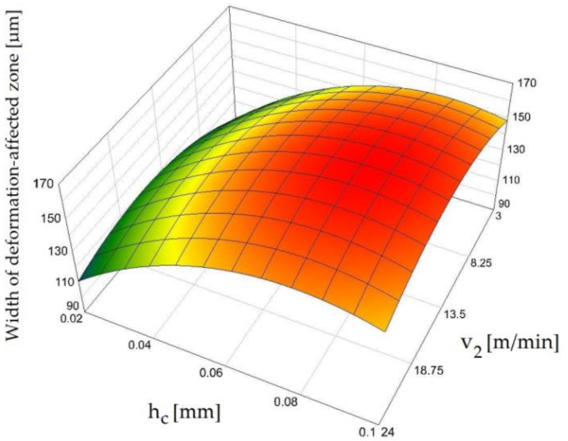

Fig. 5. Influence of the process parameters on the width of the deformation-affected zone for α = 25°

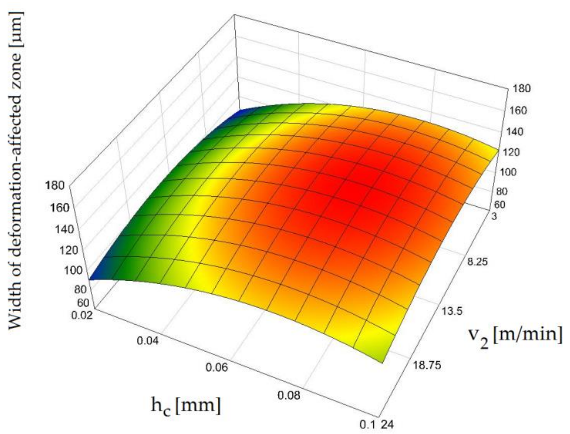

Fig. 6. Influence of the process parameters on the width of the deformation-affected zone for α = 40°

4. EXPERIMENTAL RESEARCH

The experimental tests were carried out on a specially designed test stand presented in Fig. 7. The Prinzing Maschinenbau KSE 10/10 circular shears were used for the tests. Specially purchased additional components allow, among others, high cutting speeds, precise settings of the horizontal and vertical clearances, as well as internal or external flaring on cut discs and rings. As a result of preliminary tests and simulation analysis, factors significantly influencing the cutting process and product quality were distinguished. The input factors include horizontal clearance h_c in the range of variation h_c = 0.02–0.1 mm and cutting speed v in the range of variation v_2 = 3–32 m/min. These are factors that are mainly controlled on production lines. The constant factors were as follows: rake angle α = 30° and vertical clearance c_v = 0.1 mm.

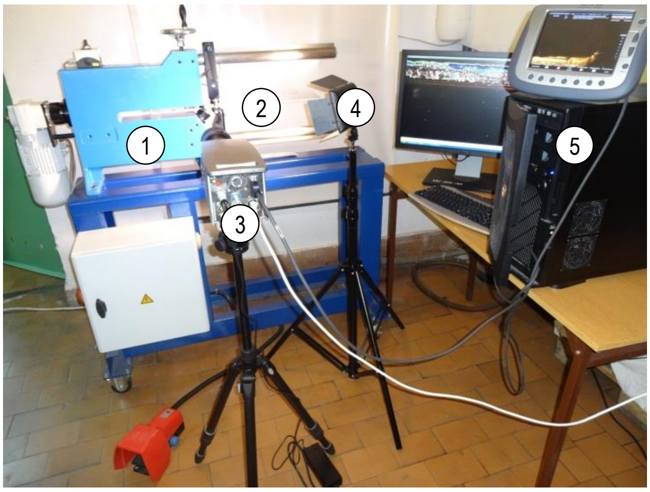

Fig. 7. Experimental test stand: 1 – shear slitting machine, 2 – sheet, 3 – i-SPEED TR camera, 4 – light source and 5 – PC

Experimental studies were carried out using a five-level rotatable experimental matrix. The study of magnetic properties was carried out on a test stand consisting of the components shown in Fig. 8. A magnetising winding and a measuring winding were wound on each of the samples, each winding being wound uniformly in order to create a closed magnetic circuit and avoid magnetic flux dispersion in the material. The measurements of the magnetic characteristics were made for various values of the amplitude of the magnetic field intensity H_m. The frequency of the demagnetising waveform was 10 Hz. Measurements of magnetic characteristics were made for variable values of the amplitude of the magnetic field intensity H_m = 214.35 (A/m), H_m = 497.84 (A/m) and H_m = 568.79 (A/m).

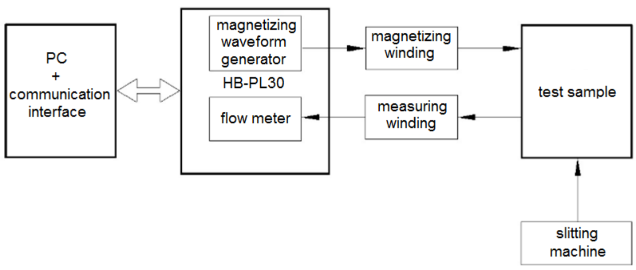

Fig. 8. Diagram of magnetic property measurement

5. RESULTS OF ANALYSIS

Figs. 9–11 show the influence of the analysed conditions of the shear slitting process and configuration of parameters on the burr height on the cut edge. According to the analysis of the

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state of knowledge and industrial practice, the burr height above 30% of the sheet thickness generates waste [31, 32, 35–37]. However, due to the negative influence of the burr on the magnetic properties in the cut surface areas, it is recommended to reduce this defect to a minimum.

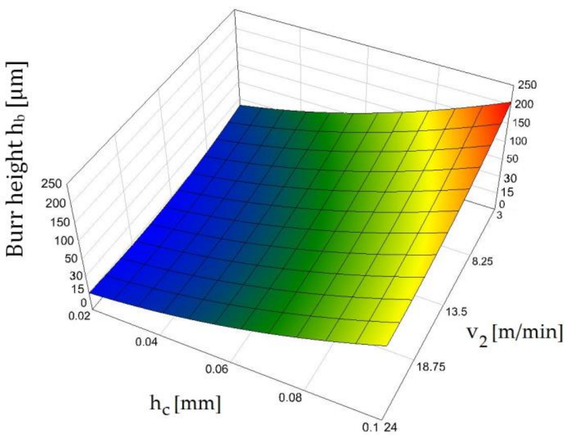

Fig. 9. Influence of the process parameters on burr height for α = 5°

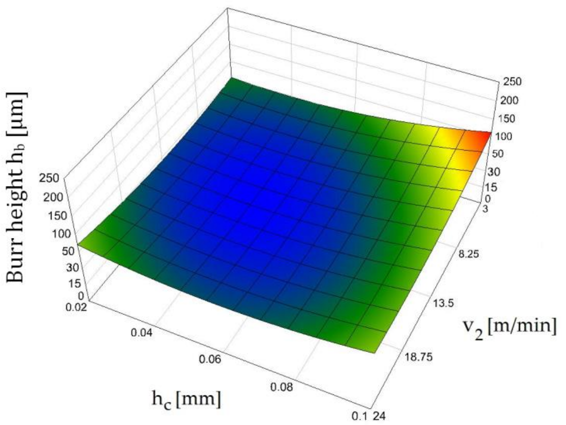

Fig. 10. Influence of the process parameters on burr height for α = 25°

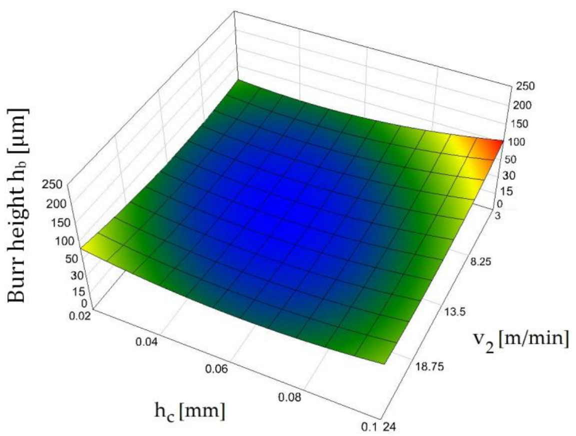

Fig. 11. Influence of process parameters on burr height for α = 40°

The aforementioned results show a significant dependence of the burr height on the horizontal clearance. It is preferable to use minimum clearances of h_c = 0.02–0.04 mm for an angle α = 5°. In this case, the minimum burr heights can then be achieved. In the case when the rake angle is set α = 5°, it is easier to estimate the height of the burr as a function of the horizontal clearance because there is a linear dependence where the increase in the clearance causes the increase in the burr height. For the maximum clearance h_c = 0.1 mm, the burr height is the highest, especially for low cutting speeds, v_2 = 3–5 m/min. By increasing the cutting speed for h_c = 0.1 mm clearance value, the burr height can be reduced, but the process conditions will still be unfavourable. When using rake angles of α = 25° and α = 40°, the influence of the cutting speed on the burr height decreases, and the horizontal clearance should be selected in the range of h_c = 0.04–0.06 mm. As the authors' previous research has shown, in such a case, an increase in the rollover of the cut edge should be expected, but the burr height will be within the acceptable range [24, 27].

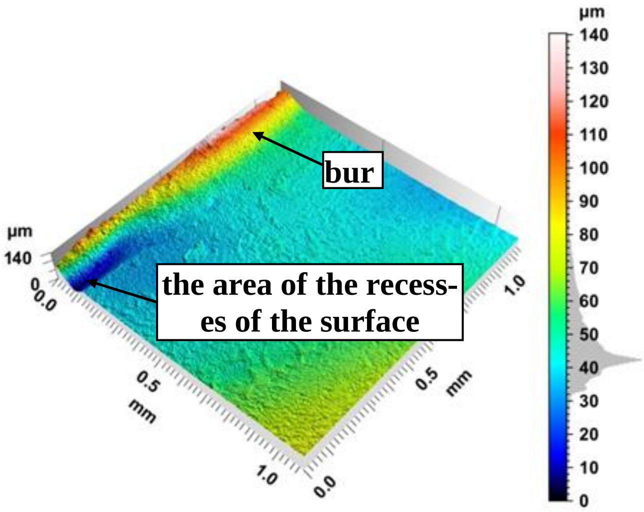

Fig. 12. Geometric structure of the lower surface of the sheet in the area of the cut edge with a visible regular burr for h_c = 0,08 mm, α = 5 and v_2 = 8 m/min

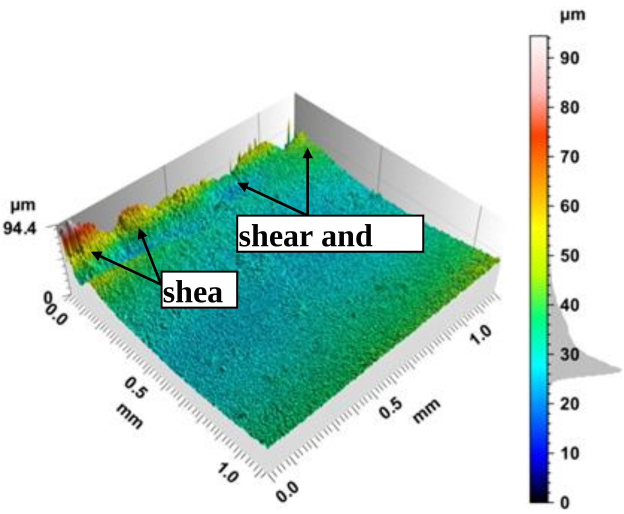

Fig. 13. Geometric structure of the lower surface of the sheet in the area of the cut edge with a visible irregular burr for h_c = 0,08 mm, α = 5° and v_2 =20 m/min

In the case of using increased cutting clearances h_c = 0.08 mm, the influence of cutting speed on the tensile stress values in the cutting zone was observed, which is reflected in the irregularity of the burr on the cut surface. Similar phenomena occur in the process of cutting metal materials in guillotining [27, 31, 32]. For low cutting speeds v_2 = 3–8 m/min, the burr is higher but more regular along cutting line when h_c = 0.08 mm (Fig. 12). It can be

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seen that the fracture process becomes less steady as the cutting speed increases and progresses in a non-uniform manner. The transition of the material fracture from the "shear mode" to the "shear and tear mode" is observed (Fig. 13). The burr formation is a result of the transition of the material fracture. As a result, the material may tear locally, the flow phase will be broken and burr-free areas will be formed due to the "shear and tear mode".

Experimental analysis showed the formation of a characteristic recess just behind the burr line in the case where h_c = 0.08 mm and v_2 = 8 m/min, which may indicate the area of local microcracks (Fig. 12). It is presumed that the microcracks located in the burr areas damage the magnetic domains and increase the hysteresis losses [28, 30].

Based on numerical research and experimental studies, using the theory of identification of multidimensional objects, regression functions for the following results factors were developed:

1. The width of the deformation-affected zone:

$$D_{mz} = 99.28 + 889.58 \cdot h_c + 1.07 \cdot v_2 + 0.61 \cdot \alpha + -130.83 \cdot c_v - 6.54 \cdot h_c \cdot v_2 - 11.07 \cdot h_c \cdot \alpha + 375 \cdot h_c \cdot c_v - 0.02 \cdot v_2 \cdot \alpha + 3.33 \cdot v_2 \cdot c_v + 2 \cdot \alpha \cdot c_v;\ R^2 = 0.98 \quad (1)$$

2. Burr height:

$$h_b = 82.32 - 195.38 \cdot h_c - 4.32 \cdot v_2 + 8.87 \cdot \alpha + -2735.11 \cdot c_v - 35.11 \cdot h_c \cdot v_2 - 104.64 \cdot h_c \cdot \alpha + 16375 \cdot h_c \cdot c_v + 0.11 \cdot v_2 \cdot \alpha - 20.47 \cdot v_2 \cdot c_v - 36.85 \cdot \alpha \cdot c_v + 16848.95 \cdot h_c^2 + 0.19 \cdot v_2^2 + 0.008 \cdot \alpha^2 + 13783.33 \cdot c_v^2;\ R^2 = 0.98 \quad (2)$$

3. Hysteresis loop area:

$$h_f = c + b_h h_c + b_v v_2 + b_{hv} h_c v_2 - a_h {h_c}^2 + a_v {v_2}^2 \quad (3)$$

$R^2 = 0.98.$

The data from the experiments allowed determining the coefficients of Eq. (3) for three average amplitudes of the magnetic field intensity. They are summarised in Tab. 1.

Tab. 1. List of coefficients of Eq. (3) for various field values H_m

$H_m[\frac{A}{m}]$	c	b_h	b_v	b_{hv}	a_h	a_v
214.32	6,502	281,020	282.6	–449.9	32,229,250	–9.56
497.84	17,306	394,350	467.2	763.4	3,451,370	–15.17
568.79	22,723	358,710	295.5	–558.9	3,122,970	6.4

Fig. 14 shows three surfaces for three values of the magnetic field intensity. Graph reveals the characteristic maximum hysteresis area for all three surfaces. The value of this parameter is particularly sensitive to changes in vertical clearance.

Fig. 15 shows the hysteresis loops of ET 122-30 steel with a thickness of t = 0.3 mm after the cutting process with variable values of the cutting clearance h_c. The example results presented were performed for the value of the rake angle α = 7°, cutting speed v_2 = 15 m/min, overlap of the knives c_v = 0.1 mm and H_m = 285 A/m. The hysteresis loop of the soft magnetic material is narrow due to the low values of the coercivity intensity H_k. In the case of hard magnetic materials (permanent magnets), the most important feature is the amount of stored magnetic energy, the aim is to obtain the maximum width of the hysteresis loop and large H_k values. The negative influence of the increased cutting clearance above h_c = 0.06 mm on the characteristics of the hysteresis loop is noticed (Fig. 15). Changes in the shapes of the hysteresis loop can be observed in the areas of the upper bend of the characteristic and saturation. With cutting clearance h_c = 0.02 mm, no significant changes were observed in the characteristics of the saturation area and the maximum saturation induction value B_{max}. This is related to the area of concentration of the maximum plastic deformations occurring only in the vicinity of the cutting edge of the material. In the case of increased cutting clearances, the value of the saturation induction decreases. It is especially visible above the clearance value h_c = 0.06 mm. The increase in the h_c parameter also causes an increase in the intensity of coercivity and induction of remanence B_s. This is probably related to the increased deformed zone and the concentration of maximum deformations on a larger area of the cut edge, as well as the occurrence of burr and rollover edges. The least unfavourable changes in the parameters of the hysteresis loop occur for the experiments performed with the cutting clearance $h_c \leq$ 0.04 mm. Then, there is the highest maximum induction and the smallest coercivity intensity.

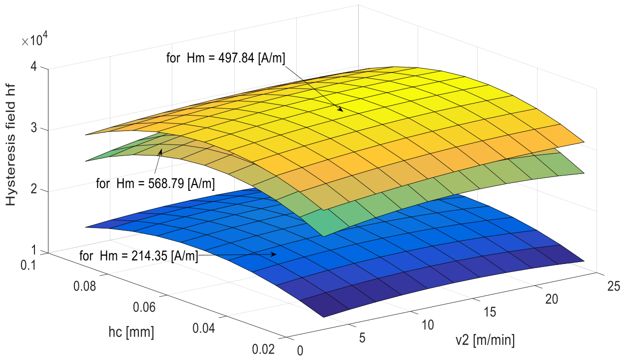

Fig. 14. Graph of the function $h_f = f(h_c, v_2)$ for chosen amplitudes of field intensity H (H_m = 214.35 [A/m], H_m = 497.84 [A/m] and H_m = 568.79 [A/m])

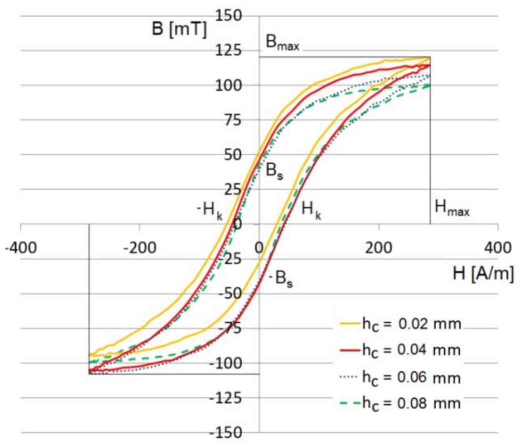

Fig. 15. Influence of selected values of clearance h_c on the magnetic B(H) characteristics of the ET 122-30 steel after shear slitting

6. SHEAR SLITTING PROCESS OPTIMISATION

The available literature includes models that allow controlling the technological quality of the mechanical cutting process, for example, in terms of the obtained quality of the sheared edge of construction steel [15, 31, 32]. However, there are no data and guidelines for the selection of parameters for the mechanical cutting of soft magnetic materials, where apart from the quality of the cut edge, attention should be paid to the condition of the magnetic properties after the process. A defined problem occurs in the manufacture of electrical machinery such as electric motor cores and transformers.

Based on developed mathematical models of the process (type II regression functions of D_{mz}, h_b and h_f), an optimisation task was developed. From the industrial production point of view, it is necessary to deliver products of planned, repeatable technological quality while maintaining high process efficiency. Therefore, the characteristics responsible for ensuring structural quality (important, e.g., from the point of view of sheet metal assembly) and electromagnetic quality (important, e.g., from the point of view of the efficiency of manufactured machines and electrical devices) should be specified. In order to carry out multi-parameter optimisation of the mechanical cutting process of grain-oriented silicon steel, the gradient method and the MATLAB Optimisation toolbox were used. In the considered case, the efficiency of the mechanical cutting process was defined as $W = v_2$, where v_2 – cutting speed.

The optimisation task has been defined as follows using a type II regression function, which can be an objective function or a constraint function:

$W=f(v_2) \rightarrow \max$	Cutting process efficiency W → maximum
$h_f < 3200$ (mT·A/m)	Area of magnetic hysteresis loop limitation
$D_{mz} < 130$ (μm)	Limitation on the width of the damage zone
$h_b < 60$ (μm)	Burr height limitation
$3 < v_2 < 24$ (m/min)	Limitation on cutting speed
$0.02 < h_c < 0.1$ (mm)	Limitation on the horizontal clearance

Fig. 16 shows a set of acceptable variants in the area of controllable variables. From a technological point of view, the use of low cutting speeds significantly reduces the efficiency of the process. Therefore, in the case under consideration, it is most advantageous to use the following technological parameters of the process: v_{2op}= 11.85 m/min and h_c = 0.026 mm. The applied approach makes it possible to carry out analyses for other input data. This is important because optimisation analyses should be carried out each time when selecting technological parameters of the electrical sheet cutting process because the elements for the construction of electric transformer cores should be cut with different technological parameters depending on the transformer operating conditions.

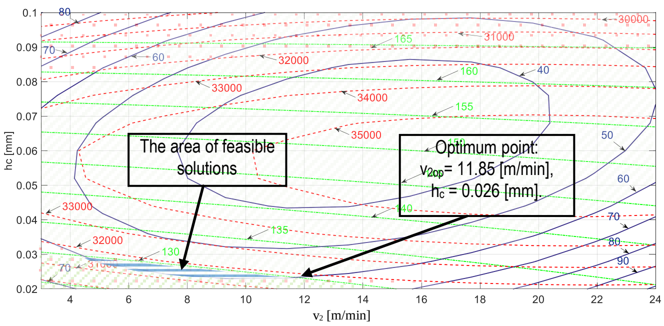

Fig. 16. Result of solving the optimisation task with a set of possible variants in the area of controllable variables

7. CONCLUSIONS

The mechanical cutting process of magnetically soft materials is complicated due to nonlinearities and distortions. The selection of technological parameters is difficult, which results in the generation of waste on production lines. In the case of industrial production, the process parameters should be selected so as to obtain high production efficiency and high product quality. After the research, the following detailed conclusions can be drawn:

– The obtained test results indicate that the lowest process stability is obtained at high cutting speeds of v_2 = 20 m/min or above this value. This especially applies to the variants of clearances h_c = 0.06–0.08 mm. The cut edge in this case is characterised by the presence of burrs and an excessive deformation-affected zone.
– The shear slitting process changes the characteristics of the hysteresis loop in the areas of the upper curve and saturation bend. In the case of increased cutting clearances, the value of the saturation induction decreases. It is particularly noticeable with the value of the clearance h_c = 0.08 mm. The increase in cutting clearance causes an increase in the intensity of coercivity and induction of remanence.
– The increase in the width of the deformation-affected zone and the height of burrs was associated with greater changes in the characteristics of the magnetic hysteresis loop. Therefore, it can be predicted that there are certain ranges of variability of the technological parameters of the process, which will enable obtaining minimal changes in magnetic properties depending on the given thickness of the sheet and the type of material being cut.
– The developed optimisation task makes it easier for the technologist to choose the best solution for the given cutting conditions and optimisation criteria. This is of great importance in practical applications, where the key is to control the performance of the product. For the analysed case, the optimal parameters for shear slitting were determined, which are v_{2op}= 11.85 m/min and h_c = 0.026 mm.

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