Experimental and finite element analysis of the shear cutting process of electrical steel sheets under various process conditions

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Abstract. Almost every electrical machine consists of the stator and rotor cores, which are made of stacked non-oriented electric steel sheets. Punching and blanking are the two commonly used shear cutting operations for manufacturing electrical machine components. The presented research was aimed to evaluate the shear cutting process of two grades of electrical steel sheets. The shear cutting process causes the formation of residual stresses in the cut segments from the non-oriented electric sheet metal, resulting in increased iron losses. Numerical modeling and experimental research were used to investigate the influence of cutting clearance as well as blunt cutting edge of the shear cutting tool on the residual stresses induced by shear cutting under different shear cutting parameters. The data derived from experiments were applied in finite element analysis of the shear cutting part in the shape of a toroid. Comparison between the results of the experiments and the FE simulations showed that the shear cutting process can be accurately predicted.

Keywords: Shear cutting; Cutting surface; Residual stress distribution; Microhardness; Electrical steel sheets

1. Introduction

The electrotechnical industry produces various types of electrical machines and apparatus in which magnetic circuits are used. The alternating magnetic circuits consist of individual electrically insulated sheets (segments) with good magnetic properties. For steel with a higher silicon content, the electrical resistance of steel and permeability are significantly increased. Increasing the resistivity of steel means suppressing of specific losses and thus reducing overall magnetic losses. In practice, sheets with a silicon content of 0.3 to 4.6% are used. Magnetic quality and practical usability of silicon steel for the electrotechnical industry depend on the content of silicon, sheet thickness, and manufacturing technology.

Shear cutting in a cutting tool and laser cutting are the two most commonly used technologies for producing electrical machine segments (in particular the stator and rotor core). While laser cutting is often associated with making prototypes, shear cutting in a cutting tool is used to produce a large number of these components [1]. Regardless of which of these technologies is used, it changes the magnetic properties of the produced segments [1, 2, 6]. This change is mainly due to the fact, that plastic and elastic deformations lead to residual stress of the cutting segment, which is induced next to the cutting
surface. Although a lot of research has been conducted in this area [3–9], the distribution of residual stresses around the cutting edge and its impact on magnetic losses is still a highly topical subject of research. When a segment containing residual stresses is magnetized, these stresses prevent the magnetic domains from being aligned in the direction of the outer magnetic field [2]. The extent of this effect is determined by the residual stresses [7]. According to [2, 5, 6], a smaller cutting clearance provides better magnetic properties of the specimens than a large cutting clearance.

In this work, the effect of the size of the cutting clearance of the tool on the size and distribution of the residual stresses in the cutting samples was investigated both experimentally and by means of the FE analysis.

2. Experimental materials and methods

2.1. Experimental setup

The experimental investigation into the shear cutting conditions of sheet metal for the electrotechnical industry used the punched parts of the annular shape with the same cutting gap on both inner and outer diameters of the toroid. The shape and dimensions of the blank are shown in Figure 1.

An experimental shear cutting tool was used for punching ring-shaped annular parts from electrical steel sheet metal in a finishing state with four different cutting clearances corresponding to 1%, 3%, 5% and 7% of the sheet thickness. The chemical composition of two grades of the electrical steel sheets used in the experiment is shown in Table 1 and Table 2. The chemical composition was measured by BELEC Compact Port spectrometer. High silicon contents lead to higher material hardness, higher ultimate tensile strength, and lower uniform elongation. The specific loss decreases with increasing the silicon content at constant sheet metal thickness. Mechanical characteristics like yield stress, ultimate tensile
strength or elongation are determined in tensile test according to EN ISO 6892-1. The basic mechanical properties of the investigated sheet metals are shown in Table 3.

### Table 1. Chemical composition of the material D [wt %]

| Element | C    | Mn  | Si  | P    | S    | Al  | Cu  | Ni  | Cr  | As  | Ti  | V  |
|---------|------|-----|-----|------|------|-----|-----|-----|-----|-----|-----|----|
|          | 0.0023 | 0.268 | 2.419 | 0.014 | 0.0054 | 0.388 | 0.014 | 0.006 | 0.022 | <0.001 | <0.001 | <0.001 |
| Nb      | <0.002 | <0.002 | <0.002 | 0.056 | <0.003 | <0.0002 | <0.0002 | <0.001 | 0.0019 | 0.0021 | 0.387 |

### Table 2. Chemical composition of the material E [wt %]

| Element | C    | Mn  | Si  | P    | S    | Al  | Cu  | Ni  | Cr  | As  | Ti  | V  |
|---------|------|-----|-----|------|------|-----|-----|-----|-----|-----|-----|----|
|          | 0.0027 | 0.209 | 1.630 | 0.046 | 0.0010 | 0.138 | 0.013 | 0.018 | 0.030 | <0.001 | 0.002 | <0.001 |
| Nb      | <0.002 | <0.002 | <0.002 | 0.056 | <0.003 | <0.0002 | <0.0002 | <0.001 | 0.0056 | 0.0056 | 0.136 |

### Table 3. Mechanical properties of the electrical steel grades

| Material | Thickness [mm] | E [GPa] | R_p0,2 [MPa] | R_m [MPa] | A_g [%] | A_50 [%] |
|----------|----------------|---------|--------------|-----------|---------|---------|
| D        | 0.49           | 214.5   | 321          | 450       | 19.5    | 26.0    |
| E        | 0.49           | 213     | 317          | 440       | 24.0    | 34.8    |

2.2. Finite element analysis (FEA) setup

A die and the punch radius of R_s=R_m=10μm was used, which should simulate a sharp shear cutting tool (see Figure 3). Determination of these values is based on real instrument measurement after grinding of the tool. The specimens for the measurement were produced with the punch velocity of 0.2 m/s. The blankholder force used for the experiments was set to 2kN. The effect of cutting speed in this work was not evaluated.

![Figure 3. FEM model of the shear cutting process. (1) – symmetry plane, (2) – die, (3) – sheet metal, (4) – blankholder, (5) – punch, L_j – cutting clearance, R_s – punch radius, R_m – die radius.](image-url)

The shear cutting processes are preferably modeled using the finite element method in the range of elastic and plastic deformations until the start of the fracture phase, which is usually determined by some
of the generally accepted fracture criteria such as Cockroft-Latham, Rice-Tracey, Oyane, Atkins, Goijaerts, Johnson-Cook and others. The simulation model was solved in MSC MARC™ FEM software using an advanced nonlinear solver. Due to the planar symmetry of the blank, a half two-dimensional simulation model was created (Figure 3). The model was solved in plane strain condition. In order to create a mesh on the blank, square elements from 0.025 mm to 0.005 mm size next to cutting surface were used. The size of elements outside of this area was set to 0.05 mm with global remeshing for the blank. The Coulomb friction model defined the contact between the tool, and the electrical steel sheet with the friction coefficient was set to 0.1. An elastoplastic constitutive model of the H-M-H yield criterion with the isotropic hardening described material properties of the blank. The hardening curve of the tested electrical steel sheet was extrapolated by Hollomon (Ludwik) model – see Table 4.

| Material | Hollomon (Ludwik) |
|----------|------------------|
|          | K [MPa] | n |
| D        | 749.7     | 0.191 |
| E        | 791.3     | 0.24  |

The Cocroft-Latham fracture model (1) as the fracture criterion was used.

\[
C = \int_0^{\varepsilon_f} \frac{\sigma_m}{\bar{\sigma}} d\bar{\varepsilon}
\]

where \(\sigma_m\) is the maximum component of the tensile stress, \(\bar{\varepsilon}\) is the effective strain, \(\bar{\sigma}\) is the effective stress, and \(C\) is the constant indicating the initiation of the crack. Since the aim of this FE analysis was to qualitatively compare the residual stresses in the specimens after the shear cutting process, the hardening curve and the fracture model were calibrated both based on the “punch force vs. punch travel” and on the shear surface analysis.

3. Results and discussion

3.1. FEA results of the shear cutting process

The results of the FE analysis (Figures 4-7) show the residual stress distribution in the cutting surface. The results of the shear cutting process with 5% the cutting clearance of D and E materials are presented in Figures 4 and 6, and the results of shear cutting process with 7% the cutting clearance of D and E materials are in Figures 5 and 7, respectively.

Figure 4. Residual stress distribution, \(\sigma_{\text{red}}, L_j = 5\%\), material D.

Figure 5. Residual stress distribution, \(\sigma_{\text{red}}, L_j = 7\%\), material D.
The results of residual stress distribution show that the largest residual stresses occur next to the cutting surface where the fracture begins. The effect of the change in the cutting clearance is also evident from Figures 4-7.

The depth of the penetration of residual stresses in the area of the cutting surface was significantly lower when the shear cutting process was performed with smaller cutting clearance. In contrast, the FEA showed that smaller cutting clearances may lead to higher residual stresses immediately next to the cutting surface. The results also show that a smaller cutting clearance reduces the size of the area affected by shearing. Furthermore, it can be stated from the results that with the increased cutting clearance, the shear zone $h_F$ on the cutting surface increases as well. These results were confirmed by experiments. A comparison between the experimentally and numerically determined punch force curves of E material for cutting clearance $5\%$ is shown in Figure 8.

3.2. Microhardness measurement in the cutting zone
In order to determinate the material hardening next to cutting surface, the microindentation measurement perpendicular to the cutting surface was performed. The measurement of the microhardness was carried out using the Agilent G200 indenter with Berkovich tip. The measurement was performed in a 45 micron pitch in both a parallel and perpendicular plane to the specimen in nine parallel rows (X-1 to X-9) spaced by 45 microns. The coordinates of the indentation were measured from the cutting edge in each row (see Figures 9 – 12). The ratio of microindentation hardness in each measured point and away from the shear area was determined as the work hardening intensity. The hardening intensity was determined by the measuring position and the cutting clearance. In some cases, the nanoindentation hardness was
decreasing close to the cutting surface. It can be caused by that the measurement near to the edge where
the dentacryl is located can affect the hardness value. Another reason may be the local place of
measurement. The microhardness inside the grain may be different than in the grain boundary.

Figure 9. Material D, the cutting clearance = 5% of t₀. a) microhardness measurement grid, b) the
work hardening intensity in three locations

Figure 10. Material D, the cutting clearance = 7% of t₀. a) microhardness measurement grid, b) the
work hardening intensity in three locations

Figure 11. Material E, the cutting clearance = 5% of t₀. a) microhardness measurement grid, b) the
work hardening intensity in three locations
Figure 12. Material E, the cutting clearance = 7% of t<sub>0</sub>. a) microhardness measurement grid, b) the work hardening intensity in three locations.

3.3. Analysis of the crystallographic texture and stress-strain state of the investigated electrical steel sheets in the cutting edge area

The microstructural and textural parameters of the investigated electrical steel sheets in the cutting surface were obtained using EBSD methodology, which allows the detection of crystallographic grain parameters (crystal orientation maps) and elasto-plastic changes determined through the intensity of the small angles in the individual planes of the sheet metal. These maps really reflect the locally discovered crystal orientation. The crystallographic orientation of the grains in the evaluated materials next to the cutting surface is shown in Figure 13a and 13b. As can be seen, both materials are characterized by a homogeneous distribution of microstructure grains along the thickness of the sheet. The material E is characterized by a distinct cubic <100> [001] (red color) and Goss <100> [110] (green color) texture component, unlike material D, which is characterized by more grains with the shear plane [111] (blue color) so-called deformation texture.

Figure 13. Inverse pole figure (IPF) maps next to the cutting surface, a) material D, b) material E, c) the description of individual crystallographic orientations in Z0 plane for IPF maps.

In the case of these electrical steels, the most desirable crystallographic orientation is cubic and Goss’s texture components that provide their desired final magnetic properties. At the same time, in terms of good shear cutting ability, the deformation texture component is desirable. The stress-strain state in the cutting surface area of the investigated materials using a map of local misorientation at the grain boundaries is shown in Figure 13.
As can be seen, the work hardening intensity (Figure 14a,b) is presented as the local misorientation with the angular range from 3.5 to 5 degrees (see Figure 14c). It is obvious that higher hardening is achieved directly in the cutting edge. Material E is characterized by plastic deformation over the entire sheet thickness (Figure 14b), unlike material D (Figure 14a), which is work hardened only next to the cutting edge. This phenomenon is probably related to the strength properties as well as the microstructure of tested materials, which are mainly affected by the silicon content.

3.4. Measurement of magnetic properties of the tested electrical steel sheets

The analysis of the influence of the cutting clearance on the final magnetic properties of the tested materials was performed on samples in the form of rings (toroids) – see Figure 1. The measurements were made on two electrical steel sheets with a silicon content of 2.42% (D) and 1.63% (E). The samples were cut with a cutting tool with the cutting clearance of both 5% and 7% of the sheet thickness. The measurements of the specific losses of the investigated steels were performed in a magnetic field with a frequency of 10, 20, 30, 40, 50, 100, 200, 300 and 400 Hz. The measurements were made on the samples after cutting as well as heat-treatment (annealing). The dependence of the specific losses of the investigated steels on the frequency of the magnetic field is shown in Figure 15. As can be seen, the curves have a linear trend and demonstrate much lower values of the specific loss for samples with lower silicon content for both pre- and post-heat treatment conditions.
It can be seen in Figure 15a) that in the case of samples without heat treatment, higher values of specific losses were obtained for the cutting clearance of 7%. In the case of the measurements after the heat treatment, it has been shown that higher specific losses were obtained for the 5% cutting clearance, as we can see in Figure 15b). This is related to the higher microhardness and work hardening on the sample E5. This means that by changing the cutting clearance, it is possible to influence the value of the final magnetic properties for the individual technological processes of the shear cutting of the specimens depending on their application. The specimens that are not intended for the heat treatment should be cut with the smallest possible cutting clearance. In the case of specimens intended for the heat treatment, the increase in the cutting gap positively affects their final magnetic properties. Hysteresis (B-H) loops measured on the tested materials at 200Hz are shown in Figure 16. As can be seen, the cutting surface affects not only specific losses, but also their magnetic polarization and induction.

4. Conclusion

From the point of view of improving the quality of the stator and rotor cores of the electrical machines as well as the transformers, it is crucial to handle the shear cutting process in the punching tool so that this process has a minimal effect on the shear surface. The cutting clearance and the wear state of the punch and die have a significant influence on the induced residual stress when shear cutting electrical steel sheets. The depth of the penetration of residual stresses in the area of the cutting surface is significantly lower when the shear cutting process was performed with smaller cutting clearance. In contrast, the FEA showed that smaller cutting clearances may lead to higher residual stresses immediately next to the cutting surface. There is an increase of the burr height and also the depth of the penetration of residual stresses in the cutting zone is higher. The greatest changes in the quality of the cutting surface were observed with the largest cutting clearance (7%). Also, there is a greater distribution of residual stresses from the cutting surface inside the specimen, which causes deterioration of the magnetic properties and increases the specific losses. It is possible to change the final magnetic properties of shear cut samples for rotor and stator cores of electrical machines for the individual technological processes by changing the cutting clearance, depending on their application.

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