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# Influence of shear cutting parameters on the electromagnetic properties of non-oriented electrical steel sheets

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ABSTRACT

Mechanical stress occurring during the manufacturing process of electrical machines detrimentally alters the magnetic properties (iron losses and magnetizability). This affects the efficiency and performance of the machine. Improvement of the manufacturing process in terms of reduced magnetic property deterioration enables the full potential of the magnetic materials to be exploited, and as a result, the performance of the machine to be improved. A high quantity of electrical machine components is needed, with shear cutting (punching, blanking) being the most efficient manufacturing technology. The cutting process leads to residual stresses inside the non-oriented electrical sheet metal, resulting in increased iron losses. This paper studies the residual stresses induced by punching with different shear cutting parameters, taking a qualitative approach using finite element analysis. In order to calibrate the finite element analysis, shear cutting experiments are performed. A single sheet tester analysis of the cut blanks allows the correlation between residual stresses, micro hardness measurements, cutting surface parameters and magnetic properties to be studied.



## 1. Introduction

Manufacturing the core of electrical machines affects the magnetic properties of the electrical steel sheets in terms of the deterioration of energy loss and magnetizability. The degraded magnetic properties, compared to those obtained by standardized metrological measurements carried out on the cold-rolled product, directly affect the efficiency and performance of the electrical machines. Among the different steps from the raw material to the final assembled electrical machine, the shape-giving process is critical to magnetic property deterioration.

In this regard, one possible means of reducing the power loss of an electrical machine is to improve the manufacturing process of the electromagnetic components. Two main components used in nearly every electrical machine are the stator and rotor cores, which are made from stacked non-oriented electric steel sheets. Shear cutting (punching, blanking) and laser cutting are the two most commonly-used manufacturing technologies. While laser cutting is often deployed within the construction of a prototype, shear cutting is used to manufacture large numbers of components. No matter which of these two manufacturing methods is used, the materials' magnetic properties are altered [1]. This is caused by an increasing amount of residual stress induced near the cutting edge. Although investigations have been undertaken using magneto-optical Kerr effect [2] or neutron grating interferometry (nGI) [3] to identify the residual stress penetration depth away from the cutting edge, the residual stress distribution in the zone affected by shear cutting (ZASC) is unknown.

Each processing step in a manufacturing chain leads to residual stresses inside a material [4]. Consider a punching process – the material failure occurs when the shear fracture limit due to high work hardening is reached. The strain induced by the high deformation causes stress in the ZASC. Even once the parts have been cut and all external loads have been removed, the strains are still present. The stress left in the material is known as residual stress. When an electrical steel sheet affected by residual stress is magnetized, the stress prevents the magnetic domains from being aligned in the direction of the external magnetic field [5]. The extent of this effect is determined by the magnitude of the residual stress [6,7].

Besides the magnitude of residual stress, the penetration depth of the ZASC also has an impact on the overall specific losses. In particular, on a stator tooth of small electric machines, the ZASC of both tooth sides can overlap. Depending on the electrical steel material used, the degraded zone may extend up to 15 mm away from the cut edge [8]. Whereas [9] postulated that the affected area is less than 10 mm wide, [10] measures a penetration depth of 0.4 mm for the ZASC using nanoindentation.

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The influence of sharp and blunt cutting tools on the magnetic properties is studied in [11]. Increasing wear on the cut edge results in higher specific losses. According to [12], a small distance between the punch and the die implicates better magnetic properties than a large distance when a guillotine is used to separate electrical steel sheets. The distance between the two cutting elements is also known as cutting clearance (CCL). [13] investigates the effect of shear cutting with different CCLs and tool wear states using an industrial cutting tool. The cut specimens are examined with an Epstein frame. This shows that higher cutting clearances and increasing tool wear lead to higher specific losses.

The influence of an increase in volume affected by residual stresses has also been investigated with a single sheet tester for guillotining [14] and for industrial shear cutting [15]. Both studies confirm the results of the Epstein frame tests, where an increasing cutting line length, i.e. volume of the ZASC, results in higher specific losses.

The aim of this paper is to show the coherence between electromagnetic properties and residual stress states that originate from cutting with different process parameters. Therefore, specimens are cut using an industrial shear cutting tool. The specimens are analyzed with regard to their geometrical and mechanical cutting influence using tactile and micro hardness measurement systems. Single sheet tests of the processed electrical steel sheets are performed to identify the magnetic properties for each parameter variation. To identify the magnitude and distribution of the residual stresses in the ZASC for varying shear cutting parameters and blank thicknesses, a finite element analysis (FEA) of the shear cutting process is carried out. In order to do this, the material has to be mechanically characterized. To ensure a good quality of the FEA, the virtual results are correlated with shear cutting experiments using the same cutting parameters. The experimental as well as the virtual results are compared with each other in order to find a correlation between residual stresses, hardness measurements, cutting surface parameters and magnetic properties.

## 2. Materials

This paper studies two electrical steel grades, material A and material B, with a silicon content of 2.4 wt% and a thickness $s_0$ of 0.35 and 0.5 mm. Both materials are produced by the same hot-rolled material. The material is quantified using a spark spectrometer. The chemical composition is shown in Table 1. Optical micrographs of the electrical steel sheet both in the direction of and perpendicular to the rolling direction (RD) show that the tempering of the material has led to equiaxed grains with a slightly smaller average grain size for material A (Fig. 1). The number of grains over the sheet metal thickness and the values obtained from the micro hardness analysis can be found in Table 2.

The small number of grains across the sheet thickness is characteristic for non-oriented electrical sheet metal. After cold rolling and tempering, the material is coated with an organic EC3 coating. A comparison between the coated and non-coated material determined that there is neither a difference in grain size nor in the material's micro hardness.

For the FEA, it is necessary to know the stress-strain behavior of the material. Therefore, uniaxial tension tests according to [16] were carried out. In addition to the tension tests in 0°, 45° and 90° to RD, the experiments were also carried out using higher tension speeds $v_t$ of 200 and 750 mm/min. Table 3 shows the yield strength $R_{p0.2}$, ultimate tensile strength $R_m$, uniform elongation $A_g$ and the elongation at fracture $A_{80}$ for both materials for the standardized testing speed and a speed of 750 mm/min.

The results show that the crystalline texture, i.e. the angle of the applied tension with respect to the RD, has a significant influence on all mechanical properties (Table 3). No matter which material is objected, the yield and ultimate tensile strength rise whereas the uniform and fracture elongations fall when the specimens are oriented perpendicular to RD. An increasing tension test speed also leads to slightly higher tension strengths and smaller uniform elongations, regardless of the specimen's orientation to RD.

The friction values of the coated material also have to be considered when a shear cutting process is numerically simulated. A strip-pull-out test was performed to obtain the coefficient of the kinetic friction in between the coated material and the tool material. The tool material used in the strip-pull-out test is the same as the material of the blank holder, punch and die of the shear cutting tool. The tests were carried out at pull-out speeds of 50, 200 and 500 mm/min. For two different contact pressures, 4 and 40 MPa, the coefficient of the kinetic friction resulted in the same value of 0.15. The value also stays the same for higher pull-out speeds and does not depend on the RD.

**Table 1**
Chemical composition.

| Material | Alloying element in mass percent (wt%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fe | C | Si | Mn | P | S | Cr | Al |
| A and B | 97.00 | 0.02 | 2.42 | 0.16 | 0.02 | 0.01 | 0.03 | 0.34 |

## 3. Experimental setup

To calibrate the fracture behavior of the materials in the FEA, shear cutting experiments were performed on an industrial mechanical single action press. In addition to the calibration experiments, specimens for the single sheet tester (SST) were produced with the same cutting tool. Fig. 2 (a) shows the schematic setup of the shear cutting tool used. The sheet metal is clamped between the blank holder and the die and is separated by the punch that travels towards the die. To prevent the tool from flattening the burr and, in this way, changing the material's stress state when small sample widths were cut, grooves were ground into the die (Fig. 2 (a)).

Important tool parameters are the relative CCL between the punch and die as well as the radii of the cutting edges of the punch and die ($R_P$ and $R_D$). For the investigations within this paper, the clearance was set to 30 μm. Hence, the relative cutting clearance of material A and B results in 10% and 6% of the sheet metal thickness $s_0$. Two different cutting edge radii were investigated. On the one hand, a die and punch radius of 15 μm should simulate a new sharp cutting tool, while on the other hand a radius of 70 μm on both cutting edges should represent a blunt, worn tool. The surface pressure under the blank holder amounts to 300 MPa. The specimens for the single sheet measurements were produced with two different cutting velocities, 0.04 and 0.15 m/s. These two velocities correspond to a stroke speed of 60 and 200 strokes per minute. Hence the influence of the velocity is not examined within the FEA; a slow testing speed of 0.83 mm/s is used to calibrate the material model.

The influence of the cutting process on the electromagnetic properties is analyzed by increasing the length of the cutting line of the specimens for SST measurements. Fig. 2 (b) shows a processed steel sheet. The positioning system allows the strip widths to be varied in order to increase the length of the shear cutting line inside the test area of the single sheet tester. This leads directly to a bigger material volume, which is affected by the emerging residual stresses. The cut specimen widths $w_S$ as well as the