INFLUENCE OF CUTTING ON THE PROPERTIES OF CLIPPINGS FROM ELECTRICAL SHEETS

Emil Spišák [1)], Janka Majerníková [1)], Ľuboš Kaščák [1)], Ján Slota [1)]*
[1)] Technical University of Košice, Faculty of Metallurgy, Košice, Slovakia

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* Corresponding author: *e-mail: emil.spisak@tuke.sk, Tel.: +421 55 6023502, Department of Technology and Materials, Faculty of Mechanical Engineering, Technical university of Košice, Mäsiarska 74, 040 01 Košice, Slovakia*

Abstract
During cutting, there is a plastic deformation in the cutting area and subsequent hardening of material occurs in this area. The hardening of material in the cutting area causes a change in its mechanical properties, which also has an impact on the physical properties of the material. The hardening manifests as an increase in strength, hardness and yield strength and reduction in the elongation and impact strength. The hardened area increases "watts losses" and reduces the magnetic induction in iron. The electrical resistance increases, which is related with failures in the atomic lattice. The degradation of the electrical conductivity can be explained by the fact that any defect resulting in cold forming causes a dispersion of electron waves. The magnetic properties of iron depend on the distribution of the magnetic field in the crystallographic structure. Violation of the crystallographic structure by forming destroys the magnetic field distribution. The magnetic properties get worse. In the end it causes a reduction in the efficiency of electric machines. The paper analyses the influence of cutting on microhardness in the cutting area.

Keywords: Cutting Edge, Hardening Layer, Thin Steel Sheets

1 Introduction

Major part of driving engines in electro vehicles and hybrid vehicles currently consist of a stator with a coil and a rotor with a permanent magnet. The material of the rotor core is valuable in the area of higher frequencies and it has to show good electromagnetic parameters not only in the area of common frequencies of 50-60 Hz, but also in the area over 400 Hz up to several kHz [1]. Considering that rotor is exposed to rapid changes of mechanical stress, because of quick changes in rotation speed and high centrifugal force at high rotation speed, there are high requirement on the mechanical quality of rotor core material [2, 3].
While the stator of driving engine consists of segments cut out from the sheets of grain non-oriented electrotechnical steel, the rotor is usually made by casting or sintering of powder materials, which considerably increases already high production costs. Also the resistance of these sintered materials toward dynamic fatigue is not sufficient [4, 5].
Nowadays the attention is focused on the development of high-strength electrotechnical steels exhibiting the combination of demanding mechanical and good electro-magnetic properties. Non-oriented electrotechnical steel sheets are used for stators of engines and small transformers. The

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use of steel sheets with little losses in iron is an effective way how to reduce energetic losses in the engine [6, 7].

So called High-efficiency electrotechnical non-oriented steel sheets are widely used for stators of highly effective engines (e.g. engines which are found in electrical and hybrid vehicles and compressors with high effectivity) [8, 9].

The degradation of losses in the stator is influenced by many factors [9-11], including:

- unequal magnetic stream and inequality of its density, which follow from the structure of iron and its nonlinearity of magnetization properties,
- rotation of the magnetic stream in the stator (local) resulting from rotor rotation,
- strain and stress in sheets (cuttings) forming the stator, which arise as a result of pressing,
- increase in the temperature of the stator as a result of losses in iron (copper) and the change in temperature affected by the cooling method,
- thickness of insulation between sheets and etc.

All these factors cause the increase in the losses of iron. There are known methods how to reduce losses of the stator, such as the reduction of the sheet thickness, the improvement in alloy purity and crystallographic texture.

By cutting the sheet a hardened area is created in the cutting area. However, the cutting also creates a plastic deformation, which is caused by a movement of dislocations. The accumulation of dislocations and reduction of their mobility leads to hardening of the material. During the cutting in the moment of plastic deformation, some of the dislocations are immobilized (they block up) and cause internal stress, which prevents movement of other dislocations. Therefore, during hardening, there occurs an increase in the density of the dislocations [13, 14].

Hardening is externally manifested as an increase in strength, hardness and yield strength and a reduction in elongation and impact strength.

Turning the slip planes in the direction of the acting forces leads to the elongation of grains in the direction of deformation. This turning of the slip planes and the elongation of grains in the direction of the slip causes disappearing of the original disposition of lattice planes and the directions of individual crystals. The crystal are now orientated in the direction of the acting force. The grains around the cutting plane in the so called hardened area are deformed in the direction of the acting shearing stresses [15-17].

In the production of clippings it is necessary to ensure such conditions, so that the width of the hardened area is minimal, because the hardened layer on the clippings´ edges negatively manifests itself in further processing. For example, during bending cracks occur in the area of the hardened layer [18, 19].

The hardened area increases watts losses and decreases magnetic induction in iron. The electrical resistance increases, which is connected with damages in atom lattice. Degradation of electrical conductivity can be explained by the fact, that any damage done during the cold forming causes dispersion of electron waves. Magnetic properties of iron depend on the allocation of magnetic field in the crystallographic structure. When the forming disrupts the crystallographic structure, there is also a disruption of the allocation of magnetic field. Magnetic properties get worse. Permeability of metals decreases with a degree of deformation, and coercive force increases. Ultimately it causes a decrease in the effectivity of the electric machines. Several producers of electric machines solve this problem by recrystallization annealing of clippings in the form of rotor and stator bonds.

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2 Experimental material and methods

Experimental research was done on two types of cold rolled isotropic electrical sheets from the production of U. S. Steel Košice. Sheets were marked with letters A and C. Chemical composition of the tested materials is shown in **Table 1**. The mechanical properties were determined on standard specimens by uniaxial tensile static test according to standard STN EN ISO 6982-1. Tests of hardness by Vickers were conducted according to standard STN EN ISO 6507-1. The measured mechanical properties and hardness of tested sheets are shown in **Table 2**. From each type of tested sheet, five samples were taken for uniaxial tensile test. Verification of hardening was examined on 10 samples of each tested material.

Table 1 Chemical composition of sheets [wt. %]

Marking of sheets	C	Mn	Si	P	S	Al	N
A	0.030	0.35	1.10	0.090	0.009	0.155	0.007
C	0.030	0.26	2.62	0.004	0.008	0.487	0.006

Table 2 Mechanical properties of sheets

Marking of sheet	Thickness [mm]	R_e [MPa]	R_m [MPa]	R_e/R_m	A_{80} [%]	HV5	HV10
A	0.66	248	383	0.648	34.0	130	120
C	0.51	291	392	0.742	21.0	158	151

The cutting tool used in the experimental research is also used in the production of sheets for magnetic circuits of electrical rotary machines. The nominal diameter of shearing holes is 160 mm. The tool was placed in a compacting machine LE 160. The nominal force is 1600kN and the frequency of slide strokes was 50 min-1. Before the beginning of experiments the geometrical dimensions of punch and die were measured in four places, as shown in **Fig. 1** and the results are shown in **Table 3**.

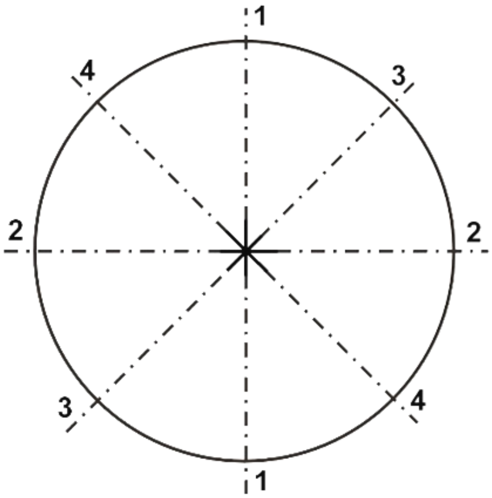

Fig. 1 Places of measuring of punch and die diameter

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Measuring of micorhardness was done on the samples which were taken from the clippings in direction 0°, 45° and 90° regarding to the direction of sheet rolling, according to **Fig. 2**. Microhardness was measured in the places shown in **Fig. 3**.

Table 3 Diameters of active parts of cutting tool

Place of measuring	Diameter [mm]		Cutting clearance [mm]
	Punch	Die	
1 - 1	160.060	160.072	0.012
2 - 2	160.062	160.086	0.024
3 - 3	160.061	160.075	0.014
4 - 4	160.055	160.075	0.020

The examination of material hardening around the cutting area used a method of microhardness measurement and evaluation of surface obtained by mathematical description of function HVi = f (xi) in interval <0.05 - 0.3>. Such surface sufficiently characterizes the size of material hardening around the cutting area. The microhardness was gradually measured from the cutting area by the step of 0.05 mm into the depth of 0.30 mm. In each distance, four measurements were made, which were 0.1 mm from each other. The microhardness was measured on SHIMADZU-DUH 202, loading force 0.15 N, the speed of movement of the indenter was 0.0135 N.s-1, holding time 5 s, penetration depth of the indenter 10 μm, 1000 x magnification, and indenter - VICKERS (diamond).

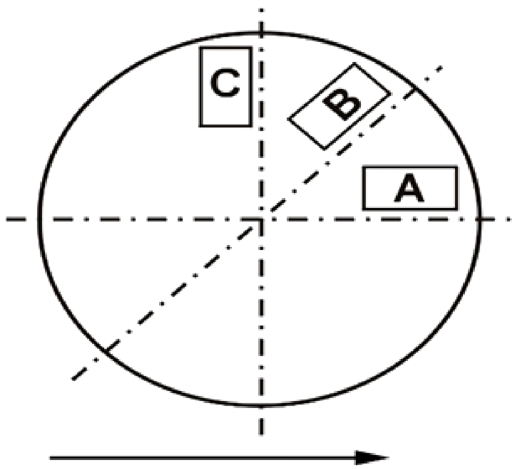

Fig. 2 Places of taking samples

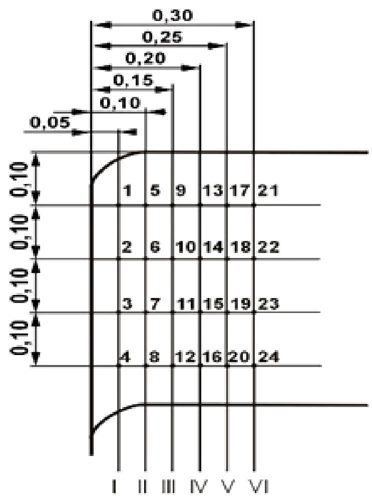

Fig. 3 Places of measuring hardness

Table 4 shows values of hardness measured on samples from the sheet A. **Table 5** shows values of hardness measured on the samples from sheet C. No increase in hardness was discovered in the distance greater than 0.3 mm from the cutting area.

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Table 4 Measured microhardness of sheet A

Place of measuring hardness	Place of taking sample		
	A [0°]	B [45°]	C [90°]
1	247	240	228
2	226	229	211
3	235	219	216
4	224	209	203
5	199	200	195
6	220	215	210
7	220	211	205
8	192	199	190
9	185	190	183
10	200	195	195
11	202	191	190
12	198	190	192
13	183	185	180
14	195	190	185
15	191	188	187
16	189	185	180
17	178	180	172
18	180	185	176
19	182	181	170
20	175	176	171
21	175	174	166
22	170	170	165
23	176	175	160
24	174	172	167

Table 5 Measured microhardness of sheet C

Place of measuring hardness	Place of taking sample		
	A [0°]	B [45°]	C [90°]
1	302	311	282
2	265	274	260
3	259	277	255
4	233	239	231
5	246	225	211
6	250	219	235
7	235	226	231
8	223	229	217
9	235	208	215
10	237	218	223
11	239	203	219
12	222	199	210
13	205	200	213
14	219	198	195
15	220	191	191
16	215	194	177
17	199	184	185
18	194	185	188
19	204	188	186
20	207	199	178
21	197	179	183
22	193	184	185
23	206	193	185
24	205	182	175

3 Results and discussion

An optimal way of seeking a regressive function which expresses the process of dependency between dependent and independent variables, is a solution of a regressive task of correlative count by the method of the smallest squares.

Experimentally observed progresses of microhardness HVi in dependence on the distance of Xi from the cutting area were approximated by various functions. By solving the regressive task of correlative count, a degree in which dependent variable HVi depends on the variable Xi was considered. As a ratio of tightness of a statistical dependence, a coefficient of determination was calculated. For more complex consideration, that the chosen regressive curve is an appropriate type of function for statement of dependent variable HVi on Xi, an absolute error, standard deviation and relative standard deviation were also calculated.

After considering the above-mentioned criteria, it was found out that the most suitable type of a curve for a statement of functional dependence HVi = f (xi) is logarithmic curve of type:

$$y = a.\ \ln(x)+b \qquad (1.)$$

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where: a, b – are regression coefficients of the curve
x - place of measuring (distance from the cutting area and the upper sheet edge)

By setting of this curve in the interval <0.05 - 0.3> we get a mathematical description of microhardness in the distance from the cutting area. Such mathematical models can be considered as a sufficient criterion for determining the size of the hardened layer around the cutting area. Given mathematical models of microhardness dependence (hardening) from the cutting area are shown in **Figs. 4** and **5**. We chose two kinds of examined materials for comparison, which were significantly different on measured values of microhardness. **Figs. 4** and **5** graphically show the measured results of microhardness for the sheets made from material marked as A (**Fig. 4**) and material marked as C (**Fig. 5**).

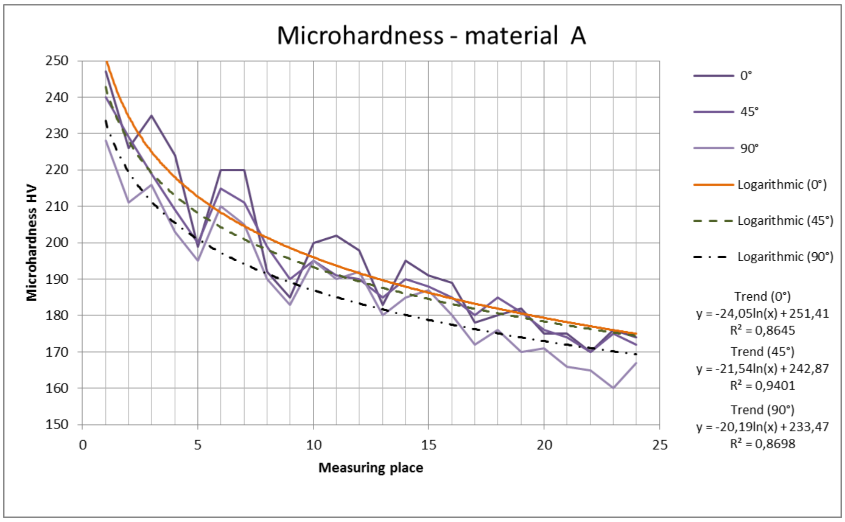

Fig. 4 Progress of measured microhardness and given regressive curves for sheet A

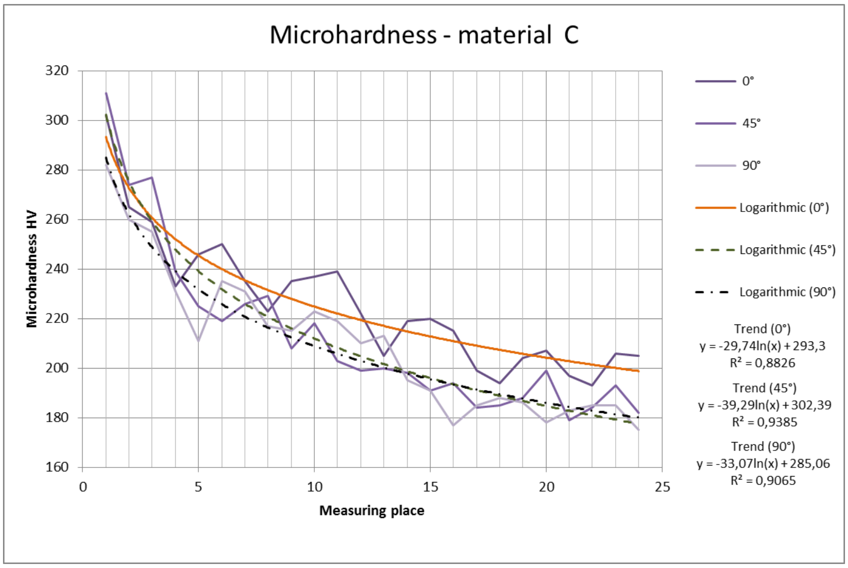

Fig. 5 Progress of measured microhardness and given regressive curves for sheet C

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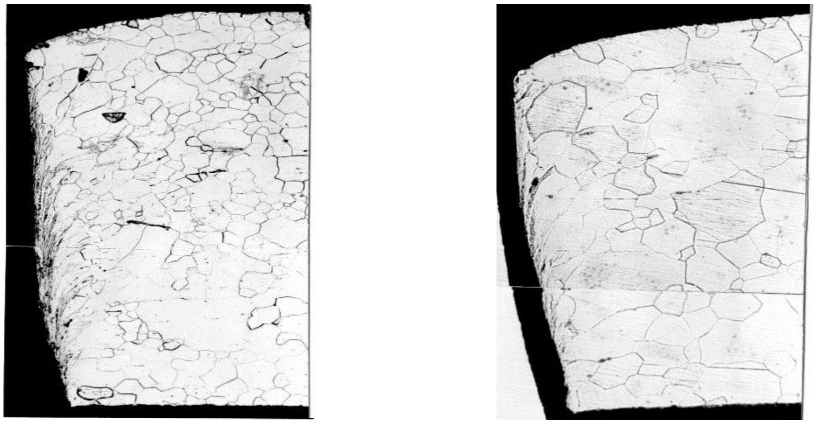
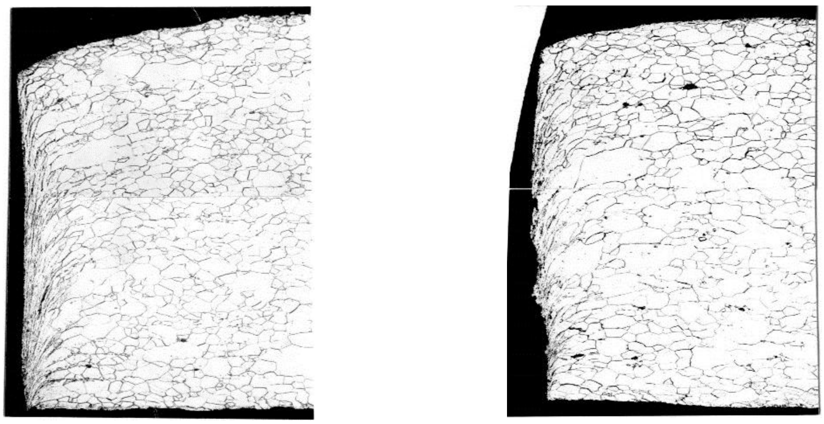
Figs. 6 and **7** show microstructures of the sheets made from materials A and C, which were taken from the cutting area in which there were different cutting gaps. The deformed area is different for both researched materials, as is shown in the figures. The microstructure of both compared materials A and C consists of ferrite grains. The carbon content of these steels is the same, C = 0.03%. They are different in silicon content; Si = 1.10 % in material A and Si = 2.62 in material C. These materials vary in aluminum content as well.

The result of the chemical composition of materials and their processing is different grain sizes and different mechanical properties. The elongation of material A was significantly higher (34 %) in comparison with elongation of the material C (21 %). The difference in elongations was manifested in the cutting area of material A as the increase of plastic deformation; since the microhardness values are lower in this area (**Fig. 4**). In material C, the cutting plane is more perpendicular to the sheet surface, and microhardness values in the cutting area are higher (**Fig. 5**).



a) b)

Fig. 6 Microstructure in the cutting area of material A a) cutting gap 0.006mm b) cutting gap 0.012mm enlarged 500x



a) b)

Fig. 7 Microstructure in the cutting area of material C a) cutting gap 0.006mm b) cutting gap 0.012mm enlarged 500x

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4 Conclusions

The results obtained in the experimental research show that:

1. The maximum hardness and thus also hardening of material is in the cutting area and gradually decreases.
2. The hardened zone around the cutting area is comparable with the thickness of material and in case of a sheet with a thickness of 0.5 mm it reaches a distance of 0.3 mm from the cutting area. This fact needs to be taken into consideration during calculations and construction of electric machines.
3. In cause of the samples made from materials with higher silicon content and lower phosphorus content an increase in hardness was observed, as well as hardening of material in the cutting area. In cause of the samples made from steel which contains 2.26 % Si and 0.004% P there was an increase in hardness by 30 – 40% and in cause of the samples made from steel which contains 1.1% Si and 0.090% P, it was just 10 – 20 %.
4. The maximum hardness was measured in samples taken in the rolling direction (place A, **Fig. 2**). The lowest hardness was measured in samples taken perpendicularly to the rolling direction (place C, **Fig. 2**).
5. In cause of the samples which were cut out at larger cutting clearances between the punch and the die, a greater hardness was measured, and thus also greater hardening of the material around the cutting area occurred. It can be concluded that with the increase in cutting clearance, the hardening around the cutting area increases as well.

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