ANALYSIS OF THE CUTTING AREA OBTAINED THROUGH MECHANICAL AND ELECTRICAL DISCHARGE TEHNOLOGIES IN NON ORIENTED SILICON IRON SHEETS

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The practical application of low energy loss steels and an optimal magnetic core design are important, to minimize the energy losses in electrical machines. It is of great importance to reduce the deterioration of magnetic properties, during the magnetic core fabrication process. The influence of the cutting area on the energy losses was studied and it can be concluded, that the energy losses are strongly influenced by cutting technologies. There were tested sheet samples of M400-65A industrial steel grade (thickness of 0.65 mm), cut through mechanical and electrical discharge technologies. All samples have the length equal to 300 mm and the width of 30, 15, 10, 7.5 and 5 mm. The magnetic characterization was performed using a Brockhaus magnetic measurement unit, which can make measurements on samples with an area of 300×30 mm^2. In order to have the standard width of 30 mm, there were put together side by side 2, 3, 4 and 6 pieces with different widths. The magnetic properties were analyzed at 250 mT, 500 mT, 1000 mT and 1500 mT in the frequency range $10 \div 200$ Hz.

1. INTRODUCTION

An important part of the electric energy that is produced in the European Union is generated by rotating electrical machines and more than half of it is used to drive electrical motors. Improvement of energy efficiency of electrical machines leads to a large influence on energy consumption, which has become vital as part of the worldwide trend toward saving energy and environmental protection.

The cores of the electrical motors are manufactured from non-oriented electrical steel sheets (NO FeSi). This steel must have low iron losses, in order to reduce the total energy losses in machines. The silicon iron sheets as part of the magnetic core of the rotating machine has increased energy losses in comparison to the material energy losses, given by the manufacturer in data sheets. In order to obtain an optimal motor core desing it is important to reduce the core losses.

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It has been observed [1, 2] that after the electrical machine is assembled the core losses are modified and the degree of this deterioration is called the building factor. When a motor has a small building factor it has also small energy losses. The factors, which determine the core loss deterioration are: the rotational magnetic field, the magnetic flux distribution, the stress and strain, the space and time harmonics, the flux superposition and the temperature [1].

Electrical machines are produced by cutting the NO FeSi alloys into a proper shape, then laminating and fixing the cut sheets. It is known that every cutting technology influences the magnetic properties of the cut zone [1, 3].

The mechanical cutting induces a plastic deformation, visible near the cut line. The cross section of the cut zone has an impact on the air gap of the electrical machine core, with a large gap that determines an increase of the magnetizing forces [4]. During the cutting process microstructural defects appear, which are pinning sites for the domain walls. This results in a local modification of the microstructure (dislocations, internal stresses and grain morphology) that has an influence on the magnetic and mechanical properties of the alloys [5, 6].

Mechanical cutting is a worldwide method and it is preferred by many machines' manufactures, because it is very easy and cheap. On the other hand, the Wire Electric Discharge Machining (WEDM) is used in the case of small-lot production and trial manufacture. EDM leaves a totally random pattern on the surface as compared to tooling marks left by milling cutters and grinding wheels. The EDM process leaves no residual burrs on the workpiece, which reduces or eliminates the need for subsequent finishing operations. WEDM also gives designers more latitude in designing dies, and management more control of manufacturing, since the machining is completely automated.

In this article, there are compared the total, hysteresis, classical (Foucault) and excess energy losses of M400-65A non-oriented electrical steel sheets cut by mechanical technology and WEDM.

2. **EXPERIMENTAL PROCEDURE**

M400-65A industrial grade steel alloy, manufactured by Erdemir Romania was used for the experimental determinations. The steel sheets were cut with different widths as follows: 30, 15, 10, 7.5 and 5 mm. The length was kept equal to 300 mm and the thickness of the sheets was 0.65 mm. The sheets were cut parallel to the rolling direction of the steel. To have the standard Epstein and Single Sheet Tester width of 30 mm, there were put together side by side 2, 3, 4 and 6 pieces (Fig. 1).

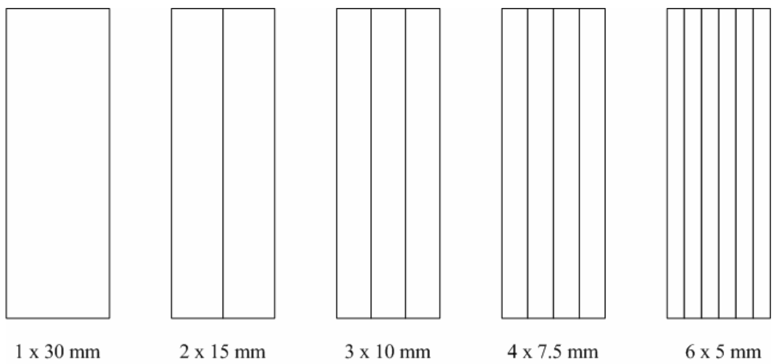


Fig. 1 – Schematic representation of the standard SST strip of 300 × 30 mm^2.

Two cutting methods were applied: shearing and wire electric discharge machining with the following conditions: for the shearing it was adopted a clearance of 4 % and in the case of WEDM a brass wire electrod with a diameter of 0.25 mm with a cutting speed of 30 mm/min was used.

The magnetic properties were measured with a Brockhaus Single Sheet Tester device. The magnetic measurements were conducted at room temperature, by appling an ac-external magnetic field, parallel to the rolling direction of the samples. The frequency f was variated between 10 and 200 Hz, and the peak magnetic polarization was chosen equal to 250 mT, 500 mT, 1000 mT and 1500 mT.

The Brockhaus Single Sheet Tester uses for the measurement of the magnetic field strength H the magnetizing current method, in which the value for the magnetic path length is fixed, by neglecting the potential drop along air gaps and yokes and the losses, which are dissipated by the yokes. The magnetic properties of the yokes were improved by grinding them against each other to homogenize the air gap width and, to increase the resistance between the laminations. The losses dissipated in the yokes are very small and they do not increase significantly the energy losses of the tested alloy.

During the measurement process the samples were demagnetized automatically by increasing the magnetic polarization to a value of 0.2 T above the highest polarization to be measured, and after 10 s at the reached value, decreasing it to zero in about 10 s. The secondary voltage was controlled by a precise digital voltmeter. The measurements were made accordingly to the existing standards [7–9]. The integral of the secondary voltage represents the magnetic polarization J. If there is no control during this process, the shape of the secondary voltage is not sinusoidal, as required by the international standards IEC 60404-2 [7] and IEC 60404-3 [10]. This is caused by the nonlinear performance of the magnetic material. In order to obtain a sinusoidal voltage, it is necessary to control the primary current with a feedback of the secondary voltage.

3. **RESULTS AND DISCUSSIONS**

The physical and geometrical properties of M400-65A samples are presented in Table 1 for the mechanical cut strips and in Table 2 in the case of WEDM.

Table 1

Physical and geometrical properties of M400-65A samples cut through mechanical technology

Number of pieces	Density [g/cm^3]	Resistivity [Ωm]	Mass [g]	Length [mm]	Width [mm]	Thickness [mm]
1			45.46		30	
2			43.76		15	
3	7.65	47.7×10^{-8}	43.66	300	10	0.65
4			44.29		7.5	
6			44.62		5	

Table 2

Physical and geometrical properties of M400-65A samples cut through WEDM

Number of pieces	Density [g/cm^3]	Resistivity [Ωm]	Mass [g]	Length [mm]	Width [mm]	Thickness [mm]
1			41.56		30	
2			40.55		15	
3	7.65	47.7×10^{-8}	40.07	300	10	0.65
4			40.92		7.5	
6			40.85		5	

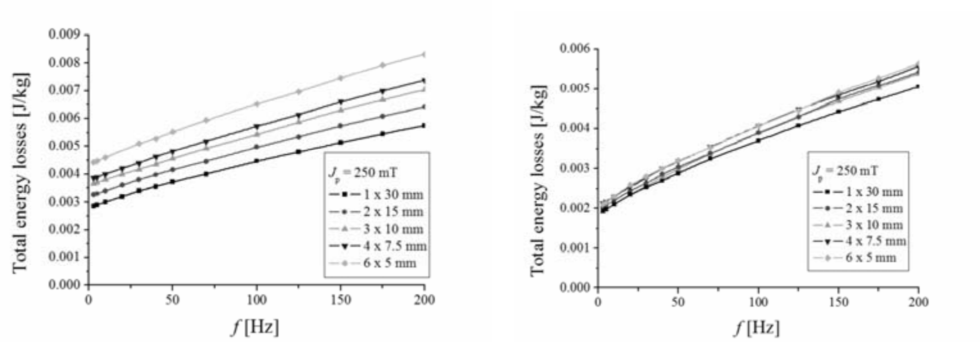


Fig. 2 – Total energy losses as a function of frequency at J_p = 250 mT: a – punching; b – WEDM.

Figure 2 shows, that the total energy losses, measured in the case of WEDM are lower than those, determined for the punching technology, because WEDM is a procedure that does not influence the magnetic properties of the silicon iron alloy. In the case of mechanical cut sheets the total energy losses vary between 0.003 J/kg for the 1 × 30 mm width sample and 0.008 J/kg for the 6 × 5 mm width strip. For the electro-erosion technology these losses are between 0.002 J/kg and 0.005 J/kg for the same kind of samples.

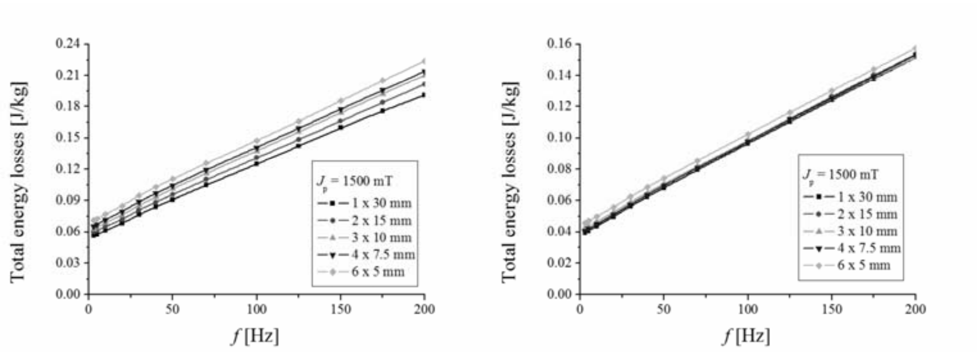


Fig. 3 – Total energy losses as a function of frequency at J_p = 1500 mT: a – punching; b – WEDM.

One can notice from Fig. 3, that the increase of the peak magnetic polarization J_p determines higher total energy losses by an order of magnitude than in the case of low magnetic polarization (Fig. 2). The differences, obtained for the five types of samples, decrease and one can notice a reduced influence of the cutting technology, either mechanical or WEDM.

In order to have a better representation of the influence of the cutting method on the total energy losses, it has been calculated ΔW_{tot} according to:

$$\Delta W_{tot} = \frac{W_{tot-6pieces} - W_{tot-1piece}}{W_{tot-6pieces}} \times 100\,, \tag{1}$$

where, $W_{tot-6pieces}$ are the total energy losses, measured in the case of 6 × 5 mm width strip and $W_{tot-1piece}$ is measured for the 1 × 30 mm width strip.

As peak magnetic polarization J_p increases, it decreases the influence of the mechanical or WEDM cut perimeter on the total energy losses, because ΔW_{tot} has the lowest values in the case of J_p = 1500 mT (mechanical and WEDM) and the highest values for J_p = 250 mT. This quantity varies in a small amount with the frequency, but it can be observed (Fig. 4) that the smallest results are calculated in the case of f = 200 Hz, for all the values of the peak magnetic polarization and for all types of samples. As seen in Fig. 4. in the case of WEDM technology ΔW_{tot} is lower than in the case of mechanical cutting, because the magnetic properties of the alloy are not deteriorated during the WEDM cutting process.

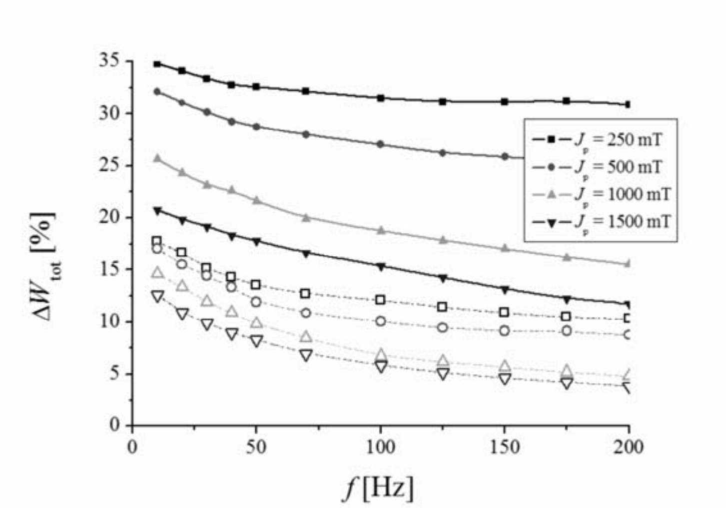


Fig. 4 – ΔW_{tot} versus frequency in the case of four peak magnetic polarizations and two cutting methods (full symbols and line – mechanical cutting technology; open symbols and dot-line – WEDM).

The energy loss separation method, presented in [11], was used to determine the hysteresis, classical (Foucalt) and excess energy losses.

In NO FeSi alloys the hysteresis energy losses are usually associated with the Barkhausen jumps (BJ). After the metallurgical manufacture, the electrical steel sheet contains a number of pinning centers (dislocations, grain boundaries, voids, precipitates) that hinder the free domain wall motion.

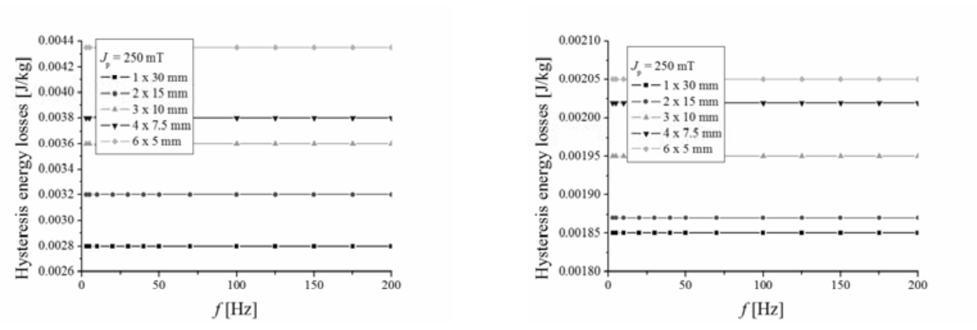
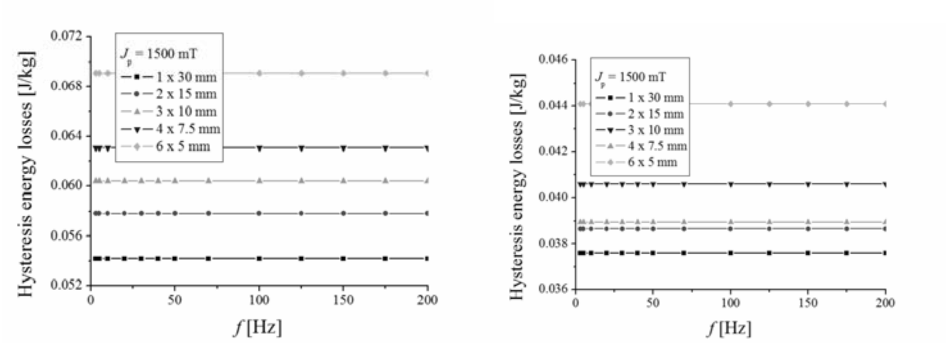


Fig. 5 – Hysteresis energy losses as a function of frequency at J_p = 250 mT: a – punching; b – WEDM.

A Barkhausen jump is possible, when the external applied field is increased to a value, which favorates the movement of the domain wall over the lattice defects, in order to further increase the magnetization of the sample. For the NO FeSi alloys the Barkhausen jumps are related to the irreversible domain wall motion in the case of low magnetic polarization values. In the range of medium to high magnetic polarization values, the BJ are associated with nucleation and annihilation of 180° and 90° domain walls. At high enough magnetic field strength levels the magnetization of the sample evolves mainly through the irreversible rotation magnetization processes [12, 13].

In Figs. 5, 6 are presented the hysteresis energy loss values in the case of low and high peak magnetic polarizations for both types of cutting technologies. It can be observed that the hysteresis losses are direct proportional to the cutting perimeter with higher values in the case of mechanical cut samples. This is due to the additional pinning centers, generated by the deformation of the crystalline structure near the edge of the sample, during the mechanical cutting process.



a) b)

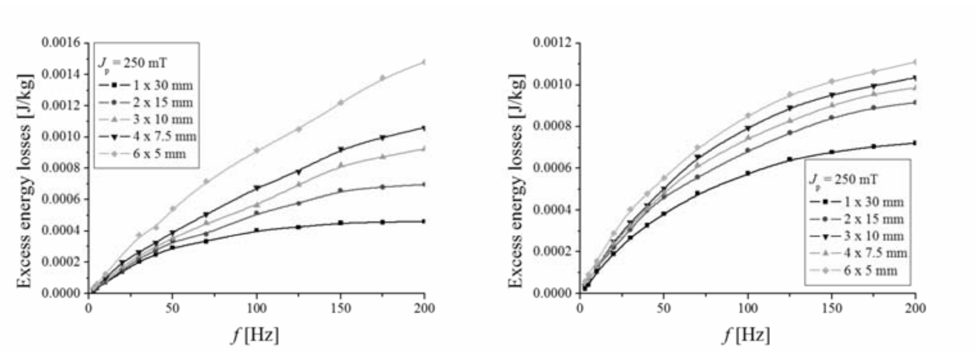
Fig. 6 – Hysteresis energy losses as a function of frequency at J_p = 1500 mT: a – punching; b – WEDM.

Table 3
Comparison of hysteresis energy losses

J_p [mT]	Cutting technologies	$W_{h\text{-}1piece}$ [J/kg]	$W_{h\text{-}6pieces}$ [J/kg]	ΔW_h [J/kg]*
250	Mechanical	0.00277	0.00435	0.0016
	WEDM	0.00185	0.00202	0.00017
1500	Mechanical	0.0542	0.0691	0.0149
	WEDM	0.0376	0.0441	0.0065

Also it can be noticed, that the range distribution of the hysteresis energy values $\Delta W_h = W_{h-6pieces} - W_{h-1piece}$ is much lower in the case of WEDM than for the mechanical cutting (Table 3).

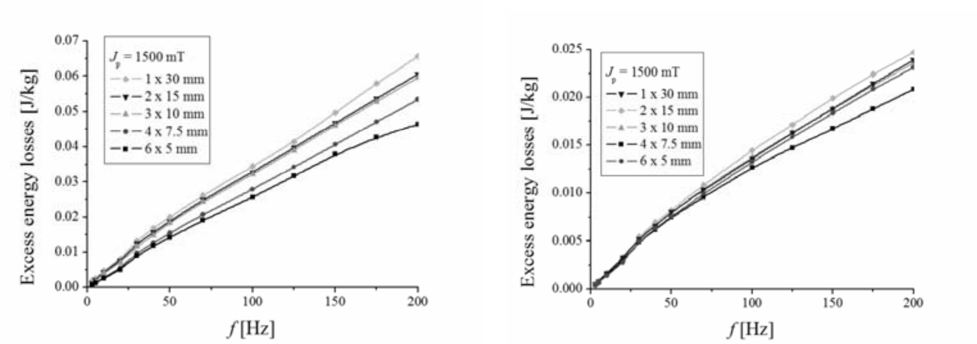
In Fig. 7 and Fig. 8 are presented the excess energy loss values in the case of low and high peak magnetic polarizations for both types of cutting technologies.



a) b)

Fig. 7 – Excess energy losses as a function of frequency
at J_p = 250 mT: a – punching; b – WEDM.

The excess energy losses are generated by the small eddy currents that exist in the vicinity of the domain walls. In NO FeSi alloys, in the range of low to medium magnetic polarizations, excess energy losses have a greater contribution to the total energy losses, because the magnetization process is made by domain wall movement and nucleation of magnetic domains [14].



a) b)

Fig. 8 – Excess energy losses as a function of frequency
at J_p = 1500 mT: a – punching; b – WEDM.

At low magnetic polarizations (Fig. 7), the mechanical cutting and WEDM do not have a great influence on the excess energy losses, because the principal part of the total energy losses are the hysteresis losses, as it was seen in Fig. 5.

4. **CONCLUSIONS**

The energy loss variation as a function of the length of the cut perimeter of samples, obtained by shearing and WEDM, was investigated in this paper.

The WEDM determines lower energy losses in comparison to the classical mechanical cutting, because in this case the cut is made without an important deterioration of the crystallographic structure of the electrical steel sheet. As one can observe in Fig. 9, the increase of the cut perimeter leads to higher values of the total energy losses with a more pronounced effect for the mechanical cutting than for the WEDM.

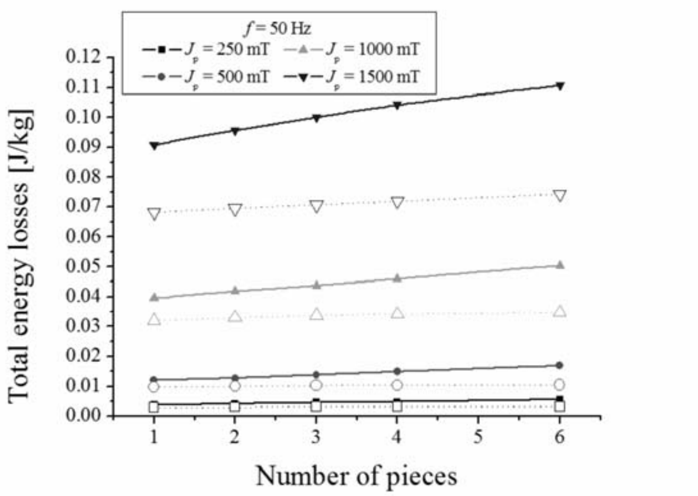


Fig. 9 –Total energy losses as a function of the number of pieces at f = 50 Hz for the two cutting methods (full symbols and line – mechanical cutting technology; open symbols and dot-line – WEDM).

The processing conditions must be controlled and optimized, in order to maintain a low deterioration of the magnetic properties. In the case of WEDM technology an increase of the cutting speed will be useful for the introduction of this method in the large scale manufacturing of the electrical machines.

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