THE EFFECT OF MECHANICAL AND ELECTRICAL DISCHARGE CUTTING TECHNOLOGIES ON THE MAGNETIC PROPERTIES OF NON-ORIENTED SILICON IRON STEELS

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The magnetic cores of electrical machines are cut especially through mechanical methods nowadays. In the zone near the cutting edge, a plastic deformation of the silicon iron steel will appear, with harmfull effect on the magnetic properties of the alloy. On the contrary, the electro-erosion cutting technology does not induce mechanical stresses in the cutting edge zone, because the material is removed from the work-piece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subjected to an electric voltage. There were tested different samples of non-oriented silicon iron steel (NO FeSi) grades, M400-65A and M800-65A, with an area of 300 × 30 mm^2. The magnetic properties were measured with a single strip tester in the range of frequency from 10 ÷ 400 Hz at 1 T peak magnetic polarization.

1. INTRODUCTION

Today, the worldwide industrial electricity consumption represents nearly 42% of the total generated electrical energy. The electric motors use about two-thirds of this and convert it into mechanical energy. To reduce electrical energy consumption, the manufacturers must consider electrical machines, which must be more efficient than the units in use today, to comply with the current legislation [1, 2].

Efficiency classes of three-phase, cage induction rotating electrical machines, are according to [3]: base standard IE1, high efficiency IE2 and premium efficiency IE3. The international standard refers to a future level above IE3, which is called super premium efficiency IE4. From 2015 all rotating electrical machines sold and installed in the European Union must comply to the IE3 standard and it is predicted

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that, by replacing gradually almost 30 milion existing industrial motors, will result in a 5.5 TWh/year reduction and a corresponding decrease of carbon dioxide emissions of 3.4 Mt/year.

The IE3 rotating electrical machines use low-loss grades of non-oriented silicon iron steels for the magnetic core and more active material (steel sheets, copper and aluminium) than the IE2 standard.

Electrical machine laminations are manufactured by mechanical cutting technologies, which induce plastic deformation in the area near the cut edge. These induced stresses determine the deterioration of magnetic properties, i.e. the increase of the magnetic losses and the decrease of the magnetic permeability. Some research [4, 5] has identified that the degraded volume may extend up to 1000 μm from the cut edge [6]. In this area, investigations made by micro hardness measurements [7–11] confirm some changes in the grain morphology, which are followed by a decrease of the local values of the magnetic polarization. The wire-cut electrical discharge machining (EDM) is based on removing parts from a material by means of repeated electrical discharges between the electrode (wire) and the work-piece in the presence of a dielectric fluid. Magnetic cores, made from silicon iron steels, can be cut using EDM tools and the magnetic properties will be less affected by the machining process. The most important deterioration of the magnetic properties in the manufacturing steps of an electrical machine is in the case of punching method [12, 13], making the EDM an interesting solution for obtaining laminations with low energy losses.

2. MECHANICAL AND ELECTRICAL DISCHARGE CUTTING TECHNOLOGIES

The most common *mechanical cutting* processes are performed by applying a shearing force, and therefore they are referred as shearing processes. A given material will fail and separate at the cut place when the shear stress in the material will exceed the shear strength, by using a shearing force that is applied by means of two tools, one above and one below the sheet. Whether these tools are a punch and a die or upper and lower blades, the tool above the sheet delivers a quick downward blow to the sheet metal that rests over the lower tool. The fracture of the material is facilitated by a small clearance, which is present between the edges of the upper and lower tools. The size of this clearance is typically 2–10% of the material thickness and depends on several factors, such as the specific shearing process, material, and sheet thickness. As the cut progresses, the damages, made by the shearing of the material, are different and they are visible on the edge of the sheared material [14, 15]. When the punch or blade interacts with the sheet, the clearance between the tools allows the sheet to deform plastically and “rollover” the edge. As the tool penetrates the steel, it results in a vertical burnished zone in the cut edge of the material. Finally, the material fractures at an angle with a small burr [16, 17]. The height of each of these portions of the cut depends on several factors, including the sharpness of the punch and the clearance between the tools. The cross section of the cut edge affects the air gap of the motor core, a large gap causing magnetizing forces to increase. The shearing deformation is followed by a bending deformation pattern. It leads to shape defects such as bowing and twisting of the sheets. This is especially pronounced when the laminations are narrow and the cut is performed along the longest side.

If certain requirements with respect to clearance, positioning and quality of the cutting tools are met, then this procedure can also provide sufficiently good precision of the final geometry. A more advanced punching system contains a counterpunch underneath the punch, which induces a hydrostatic pressure on the sheet [18]. A superimposed hydrostatic pressure significantly increases the strain at fracture. The ductile fracture can be delayed in terms of the knife displacement or even completely eliminated. The shearing zone obviously increases. It results in a shinier cut compared to conventional punching. Therefore this process is often called the fine-blanking. With respect to the shape quality, the fine-blanking procedure is more favorable. But due to the need for significantly more sophisticated equipment fine-blanking is also more expensive. So up to now conventional punching remains the dominant procedure for the production of the sheets of electrical machines and transformers.

In the *EDM process* an electric spark is used as cutting tool to separate the work-piece from the material, to produce the finished part to the desired shape. The metal-removal process is performed by applying a pulsating electrical charge of high-frequency current through the electrode to the work-piece. This erodes very tiny pieces of metal from the work-piece at a controlled rate [19]. There are two types of EDM processes. The first type uses a formed electrode, usually made of graphite or copper that is shaped to the form of the cavity, which it must reproduce. The formed electrode is fed vertically down and the reverse shape of the electrode is burned into the solid work-piece. The second type uses a continuous moving vertical wire electrode (Traveling Wire EDM – TW EDM). For that the wire must have a very small diameter and it has to follow a program path to cut a narrow slot through the work-piece to produce the required shape.

TW EDM is used for both roughing and finishing machining. Common practice is to rough cut to about 0.1 mm of finished dimensions and then follow with two or three finishing passes. A finishing cut takes about twice as long as a roughing cut, since lower spark energies and a lower metal removal rate must be used. A TW EDM surface exhibits a matte texture with typically 0.8 to 1.3 μm average roughness. The recast and heat affected layers are very small and in most applications do not need to be removed. TW EDM is commonly used to produce cores, pins, and stamping dies for the prototype production of parts in small quantities, and to produce precise round or irregular shaped holes as small as 0.05 mm in diameter [19, 20].

3. RESULTS AND DICUSSIONS

Measurements of the magnetic parameters have been performed on eight non-oriented silicon iron sheets NO FeSi M400-65A and M800-65A industrial grades, cut through mechanical and electrical discharge technologies. The physical properties of these steel alloys are listed in Tables 1 and 2.

Table 1
Physical and geometrical properties of M400-65A samples

Cutting technology	Mass [g]	Density [g/cm3]	Length [mm]	Width [mm]	Thickness [mm]	Resistivity [Ωm]
Mechanical	41.56	7.65	303	30.02	0.6	47.7×10^{-8}
	43.8				0.638	
EDM	45.44				0.66	
	41.94				0.62	

Table 2
Physical and geometrical properties of M800-65A samples

Cutting technology	Mass [g]	Density [g/cm3]	Length [mm]	Width [mm]	Thickness [mm]	Resistivity [Ωm]
Mechanical	44.63	7.80	303	30.02	0.635	30.8×10^{-8}
	44.73				0.637	
EDM	45.27				0.645	
	44.53				0.638	

The materials have been tested between 10 Hz and 400 Hz by means of a laboratory Single Sheet Tester with digital control of the sinusoidal magnetic flux waveform according to the measuring standard IEC 60404-3 [21]. The form factor of the secondary voltage was kept at all frequencies within the interval 1.1102 ± 0.4%. The primary winding (173 turns) was supplied by a NF HSA4101 power amplifier, driven by an Agilent 33210A arbitrary function generator. The secondary winding (101 turns) was made directly around the surface of the samples.

This device can perform accurate measurements, offer an AC frequency characterization and provide the hysteresis cycle, the relative magnetic permeability and the total power loss data. The values of the magnetic properties, used in the graphical representations, have been calculated by averaging the four experimental sets of data.

In Fig. 1 are presented the normal magnetization curves, defined as the geometrical place of the (H, J) maximum point values, extracted from the symmetric hysteresis loops, extending from the demagnetized state to saturation [22–24]. These dependencies are obtained from the experimental data measurements, made in the case of the two industrial grade samples, cut through mechanical and EDM technologies. It can be observed that the samples, cut through EDM, have a slightly improved magnetization path, especially for medium values of the magnetic polarization (from 0.7 T to 1.3 T). At values higher than 1.3 T, in the saturation zone the two grades have a similar behavior and only the cutting technology has an effect on the magnetization path.

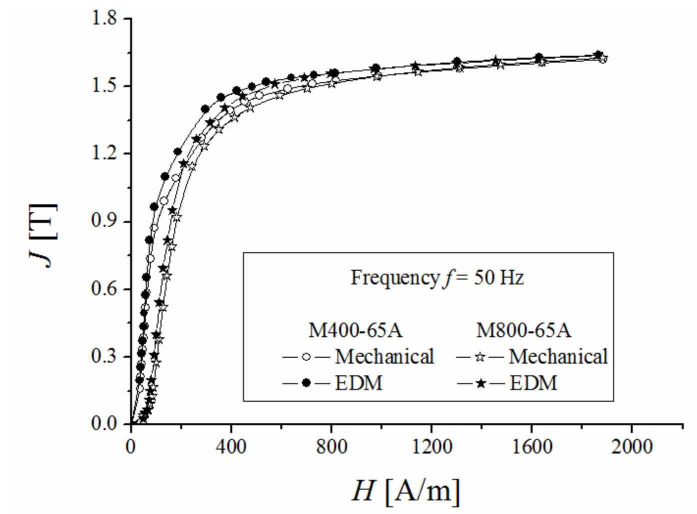
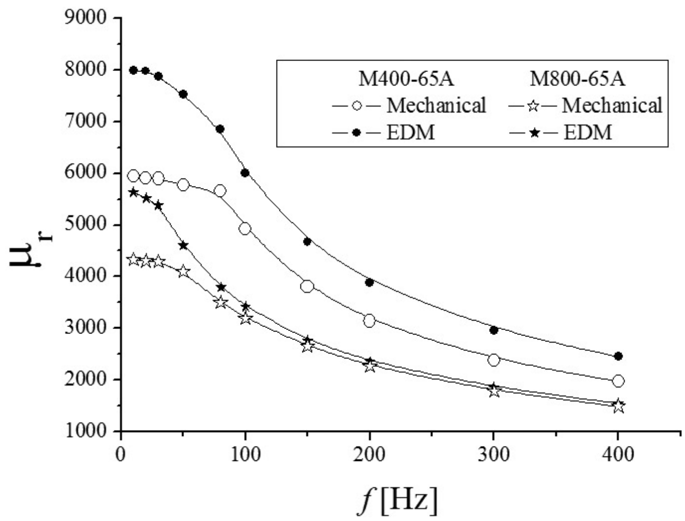
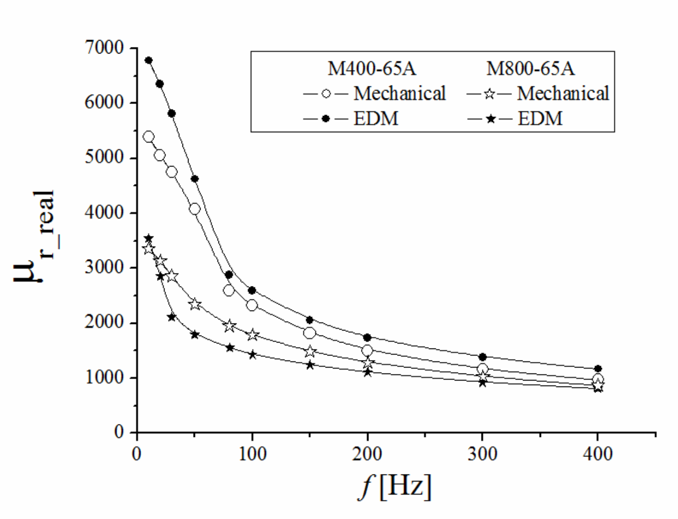


Fig. 1 – The normal magnetization curve measured at 50 Hz.

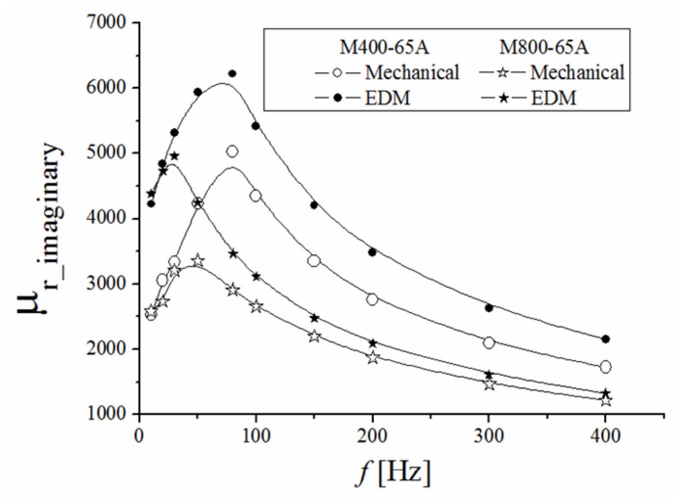
Figure 2 presents the variation of the relative magnetic permeability (modulus, real and imaginary parts), in the case of M400-65A and M800-65A samples, as a function of the frequency at peak magnetic polarization 1 T. The most important influence of the EDM can be observed on both grades up to 100 Hz. After that, only for the M400-65A grade, the EDM technology leads to significant improvements of the magnetic permeability.



a – modulus of the relative magnetic permeability



b – real part of the relative magnetic permeability



c – imaginary part of the relative magnetic permeability

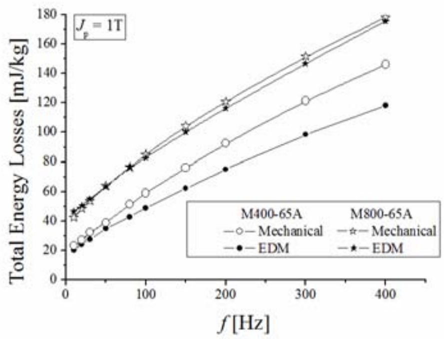
Fig. 2 – Relative magnetic permeability as a function of frequency in the case of M400-65A and M800-65A at 1 T.

Mechanical cutting technology determines lower values of the magnetic relative permeability, in the case of both steel grades, which can have a negative effect on the overall characteristics of the electrical rotating machines.

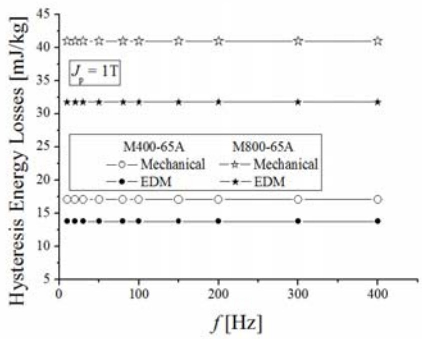
The energy loss analysis was made according to the concept of energy loss separation, which considers, that the total energy can be divided into three individual loss mechanisms: hysteresis, classical (Foucault) and excess losses [25, 26, 27].

In Fig. 3 are presented the variations of total, hysteresis, excess and classical losses *versus* frequency at peak magnetic polarization 1 T. The best results (minimum energy losses) have been obtained in the case of M400-65A grade, cut through EDM technology.

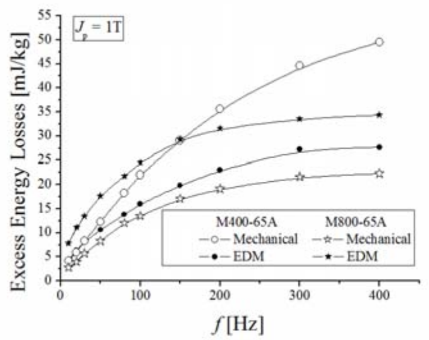
The EDM technique generates an important reduction of the hysteresis energy losses in comparison with those obtained in the case of mechanical cutting, for M800-65A grade. A similar result can be noticed in the case of M400-65A, but in a more reduced amount.



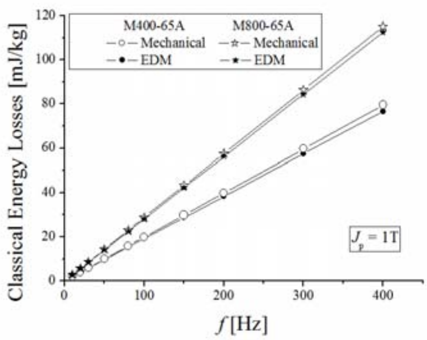
a – total energy losses



b – hysteresys energy losses



c – excess energy losses



d – classical energy losses

Fig. 3 Energy losses as a function of frequency in the case of M400-65A and M800-65A NO FeSi at 1 T.

Regarding the excess losses, which are generated by the small eddy currents formed in the neighbourhood of the domain walls, the EDM leads to an important decrease in the case of M400-65A grade. This observation is justified by the increased number of the magnetic domain walls as a consequence of the improved quality of the steel.

The classical losses (Foucault), generated by eddy currents, are calculated treating the material like a homogenous medium and the sample geometry is essential [26]. The M400-65A has lower classical energy losses than M800-65A grade samples, as a consequence of their lower density and higher resistivity values (Table 1 and Table 2).

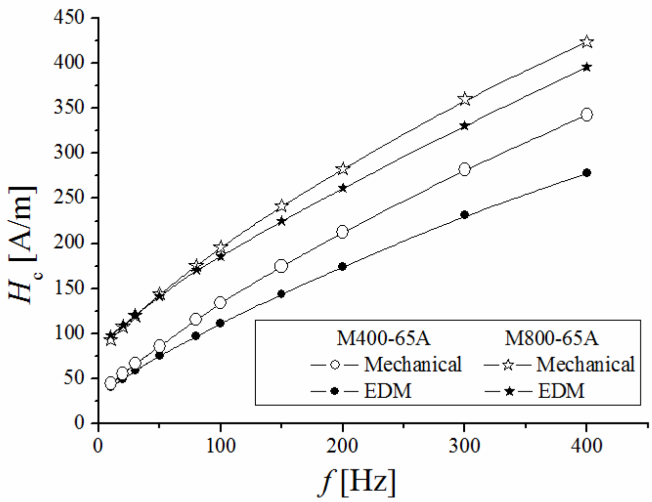


Fig. 4 – Coercive field values in the case of M400-65A and M800-65A grade sheets, cut trough mechanical and electro-erosion technology at 1 T.

The M800-65A alloy is considered an inferior grade steel, because it has a higher number of dopant impurities, which hinder the domain wall displacement. The influence of the cutting technologies on the coercive field values are not so pronounced as in the case of M400-65A grade (Fig. 4). Minimum values of the coercive field are obtained in the case of EDM technology, for both cases of steels.

4. CONCLUSIONS

The fully processed steel sheets are not annealed after being mechanically cut, so that local plastic strains and internal stresses persist and alter their magnetic properties. This deterioration has been related to domain wall pinning, generated by the dislocation network, that affect especially the 180° domain walls [28, 29, 30]. The area affected by punching is mostly located around critical parts of the magnetic core (teeth, air gap) with a strong impact on the global behavior of the machine. The size of the deformation zone due to mechanical cutting approximately corresponds to the thickness of the lamination [31]. The uncertainty of the profile of the sheet in the electrical machines has to be pointed out. The size of the burr can be different depending on the quality of the cutting tools and the clearance used during mechanical cutting.

In the case of EDM technology lower values of energy losses and higher values of relative magnetic permeability are due to the reduced level of interaction between the cutting element and the material.

In order to find the best way to prepare the magnetic core of an electrical machine it should be also considered – excepting the magnetic properties of the NO FeSi and especially the values of the energy losses – the evolution of the material microstructure in the cut affected areas, which should impose recondition treatments, as well as the total economic cost of the machine.

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