MAGNETIC CHARACTERISTICS OF NON-ORIENTED SILICON IRON STRIPS OBTAINED THROUGH MECHANICAL, LASER, ELECTRICAL DISCHARGE AND WATER JET CUTTING TECHNOLOGIES

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Abstract: The increase of the asynchronous motors efficiency may be usually made by decreasing the total energy losses in the magnetic circuits. Non-oriented silicon iron (NO Fe-Si) sheets are soft magnetic materials with a nearly isotropic grain texture. They are used in the construction of medium and high energy rotating machines, and in order to obtain a higher efficiency, it is necessary to design their magnetic circuits in a new manner, not only to save energy, but also to avoid overheating. There were analyzed samples of non-oriented silicon iron (NO FeSi) grades, M400-65A and M800-65A. The magnetic properties were determined with a single sheet tester in the range of frequency from 10 ÷ 200 Hz at 1 T peak magnetic polarization. The sheet cutting technologies, applied in this article, are mechanical, laser, water-jet and electro-erosion.
Keywords: Non-oriented silicon iron, mechanical cutting, electro-erosion, laser cutting, water cutting, energy losses.

1. INTRODUCTION

Nowadays the need to increase motor system efficiency has never been greater. With the rising costs of energy and the substantial concerns about global CO_2 emissions, achieving the highest possible motor system efficiency has become a critical priority in Europe and in the United States of America. Electric motor-driven systems and motor-driven components in appliances and equipment account for more than 25% of the primary energy consumption in both the residential and industrial sectors.

Motor-driven components used in heating, ventilation, air conditioning and refrigeration are the highest energy consumers in both the residential and commercial sectors. In the residential sector, air conditioning applications account for 63% of motor-driven energy use, and refrigeration accounts for 28%. In the commercial sector, the air conditioning and refrigeration categories account together for 93% of motor-driven energy use [1, 2, 3].

The addition of a variable-speed drive to an electric motor system leads to substantial energy savings, by allowing motor speed and load to be optimized to the system requirements. The efficiency of the variable-speed electronic drive portion of a modern motor system is very high: almost above 95 %, and recent improvements are pushing drive efficiencies to 98 % or higher. These high efficiencies for variable-speed drives can be achieved over a wide range of motor speeds and loads. If an induction motor is used only at its rated speed and torque, then adding a drive will actually reduce the overall system efficiency. However, in real world applications, operation at only one speed and load is rarely, because adding a variable-speed drive usually results in increased system efficiency [2, 4].

Worldwide standards continue to push manufacturers to consider both more efficient motors and variable-speed technologies, among other product design improvements, in order to meet more stringent minimum efficiency requirements. The relatively higher cost of advanced motor technologies compared to traditional technologies remains a significant barrier for applications where first cost is a primary concern. For many types of appliances and equipment, products that just meet the mandatory minimum energy conservation standards represent the majority of overall sales. Typically, these products compete solely on price. Thus, outside of mandatory or voluntary standards programs, efforts to reduce the first cost of advanced motor technologies are essential to accelerate their implementation in both residential and industrial appliances and equipment. In addition to cost constraints, size and weight constraints could also limit the introduction of some higher-efficiency motor technologies that require larger or heavier components than current motor designs. Conversely, some higher-efficiency motor technologies are smaller and lighter than traditional motor designs, in which case the higher upfront cost remains the primary barrier to widespread implementation [1-4].

In order to achieve a high motor efficiency, one must pay attention to all sources of losses. A motor designer should take advantage of any inherent performance characteristics of different motor geometries to achieve the goal of a high efficiency motor with low material and manufacturing costs. Motor efficiency is inversely related to the total amount of power losses in the motor.

The efficiency of motors depends both on their nominal power and their efficiency quality, which is characterized by efficiency classes. For small motors, size is the most important factor in determining efficiency; for large motors, efficiency classes are relatively more important. The International Electrotechnical Commission introduced in 2008 the precisely defined and open-ended international efficiency-classification scheme using Standard Efficiency IE1 (similar in 50 Hz operation with Eff2), High Efficiency IE2 (similar to Eff1) (IEC 60034-30 [5]), Premium Efficiency IE3 and Super Premium Efficiency IE4 (IEC 60034-31 [6]) as classification system. The European Union passed MEPS legislation for electric motors in 2009 as an implementing measure under the Eco-design Directive. Market penetration of different efficiency classes varies considerably between countries. The share of the most efficient class (IE3) has reached 20% in the United States, but it is virtually zero in the European Union [7].

1.1 Cutting Technologies

The punching operation generates localized internal stresses and may affect the energy losses in fully-processed materials. In high power machines a much larger effect on magnetic losses is expected to result from the stresses permanently introduced by stacking and assembling the laminations in the core. Work hardening means the strengthening of the metal by plastic deformation, due to the dislocation movements within the crystal structure of the material.

When a piece undergone a stress and then the stress vanished and size changes of the crystal structure of the material subsist, the sample is in a plastic state due to a non-reversible transformation, and the lengthening will be a plastic transformation. Many alloys like low-carbon steel are submitted to work-hardening hence strain hardening. This action can be desirable or non-desirable. An example of the second situation is when the machining of a piece implies several passes of a cutter that at the first pass inadvertently work-hardens the surface of the piece, the effect of which will be to damage the cutter at its next passes. The work hardening is accompanied by the deformation of the grains and the deterioration of the crystalline lattice. During a recrystallization process, the deformed grains are replaced by non-deformed ones that grow until all the original grains are entirely transformed.

The material absorbs energy during plastic deformation by a growth of the dislocation density. This is the case when shaping the sheets in order to realize the magnetic core of electrical machines and consequently destroy the good magnetic properties of the material. A thermal treatment (annealing) is necessary to recover the original properties of the material [8-12].

The mechanical cutting constitutes the fastest and the cheapest procedure and therefore the most popular. However this method leads to plastic deformation and induces shearing stresses at the cut edges. 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.

The electro-erosion technology (electrical discharge machining EDM) is a controlled metal-removal technology that is used to cut metallic materials by means of electric spark erosion. In this process an electric spark is used as the 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. The method uses a continuous moving vertical wire electrode (Traveling Wire EDM – TW EDM). For that the wire must have a very small diameter and when a metallic material is cut, one can observe different erosion mechanisms like melting, evaporation, sublimation, cooling or solidification, mass transport, convection, diffusion and some chemical reaction. The EDM could also induce in the steels small residual stresses by comparison with the laser cutting [13].

A laser can be used for cutting by exposing the material to the intense heat energy developed by its beam. If this heat could not be reflected, conducted or dispersed by the material the supplementary energy will cause a sudden rise in temperature of the material at that point. If the temperature rise is substantial enough, the input heat is capable of initializing a hole by melting and vaporizing the material. The linear movement of this intense heat energy with respect to the material provides a very accurate cutting action. When a material is cut with a laser beam, it occur multiple physics mechanisms such as: melting, vaporization and chemical degradation. Laser cutting of alloy steels induces thermal stresses, due to temperature gradients, within the cutting area.

The water-jet technology does not have thermal related problems like recast layer and thermal distortion and it exerts a minimal force on the work material. This technology is achieved by producing high velocity stream of water with or without abrasives (sand–garnet, corundum aluminum oxide), which removes material mainly by erosion mechanism [14].

The mechanism of water jet cutting offers basically two possible variants of the separating mechanism: separation through material removal and separation through crack. In electrical steels the separation process are splitting and removal, e.g. about outbreaks, preferably along the grain boundaries. Material removal takes place when the steel is rather hard and brittle and upon impact causes outbreaks which are removed by the water.

1.2 Materials and Methods

The magnetic determinations were made by means of an industrial uniaxial Single Sheet Tester. This measurement device permits one to obtain a fast complete magnetic characterization. There are measured the total power losses within an AC frequency range, the major hysteresis cycle, the relative magnetic permeability, coercivity and remanence values.

Measurements of the total energy losses have been performed on fully processed non-oriented silicon iron sheets NO FeSi M400-65A and M800-65A industrial grades cut through mechanical, laser, electrical discharge and water jet technologies. The physical properties of these steel alloys are presented in Table 1:

Table 1. **Physical and geometrical properties of non-oriented FeSi samples**

Sample Grades	**Mass [g]**	**Density [g/cm^3]**	**Length [mm]**	**Width [mm]**	**Average Thickness [mm]**	**Resistivity [Ωm]**
M400-65A	41.48	7.65	300	30	0.632	47.7×10^{-8}
M800-65A	44.55	7.80	300	30	0.651	30.8×10^{-8}

The samples were investigated between 10 ÷ 200 Hz at peak magnetic polarization J_p = 1 T. The energy loss analysis was applied on the measured data, using the concept of energy loss separation [15, 16], in which the total energy of a magnetic material can be divided into three individual loss components: hysteresis, classical (Foucault) and excess losses.

1.3 Results and Discussions

In Figure 1 is presented the variation of the total energy losses as a function of frequency for M400-65A and M800-65A steel grades. After applying the energy loss separation method, the hysteresis (Fig. 2) and the excess losses (Fig. 3 and Fig. 4) are determined.

The lowest total energy losses are obtained for the water-jetting technology, for both types of alloys. Approximately close to these are the values of the total losses, measured in the case of the electro-erosion cut samples.

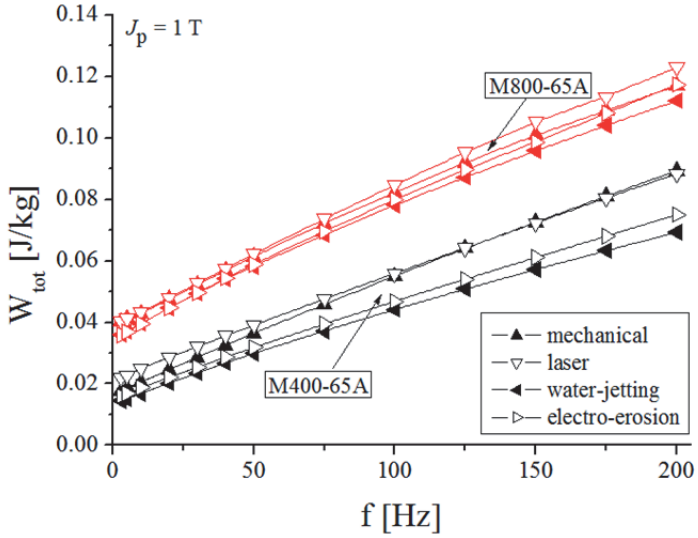

Fig. 1. Total energy losses W_{tot} versus frequency for the two industrial alloys, cut trough mechanical, laser, water-jet and electro-erosion technology for J_p = 1 T.

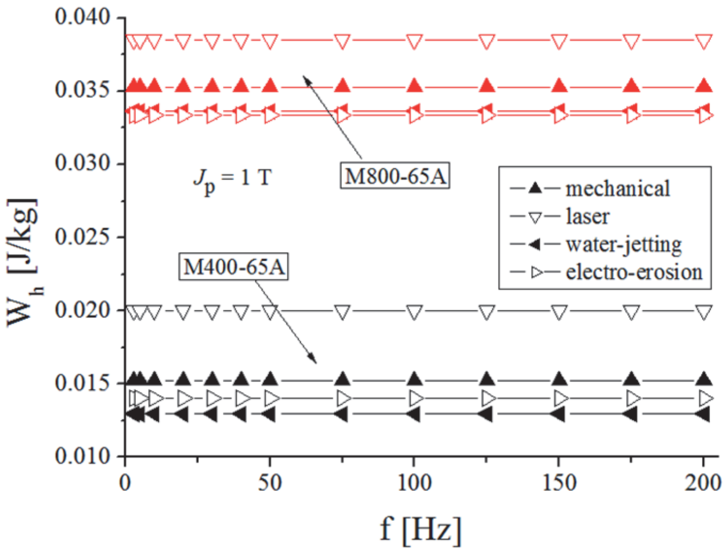

Fig. 2. Hysteresis energy losses W_h in the case of the two industrial alloys, cut trough mechanical, laser, water-jet and electro-erosion technology for J_p = 1 T.

The laser and mechanical cutting technologies lead to higher hysteresis energy losses because the laser cutting method induces thermal stress at the cutting zone and by mechanical cutting it appears plastic deformations in the neighborhood of the cutting line.

The excess energy losses, which are due to the small eddy currents formed in the neighborhood of the domain walls and to the irregularities of the crystalline structure, are higher, for all the frequencies, in the case of mechanical punching and laser technology. Better results are obtained in the case of water-jetting and electro-erosion.

The microstructural changes and the appearance of residual stresses affect the magnetizing behavior in a different way. Local changes of grain size and texture result in local changes of the critical field for domain wall movement, which conduct to an increased value of the hysteresis and excess losses.

The M800-65A alloy is 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. Minimum values of the coercive field are obtained in the case of water-jetting, for both cases of steels (Fig. 5 and Fig. 6).

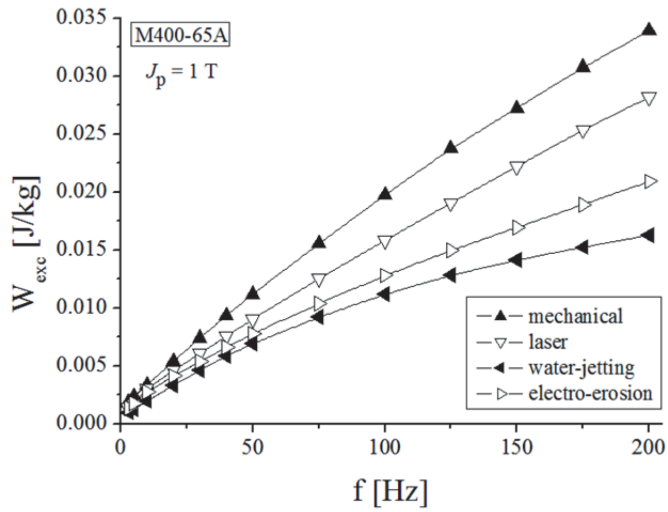

Fig. 3. Excess energy losses W_{exc} in the case of M400-65A grade, cut through mechanical, laser, water-jet and electro-erosion technology for J_p = 1 T.

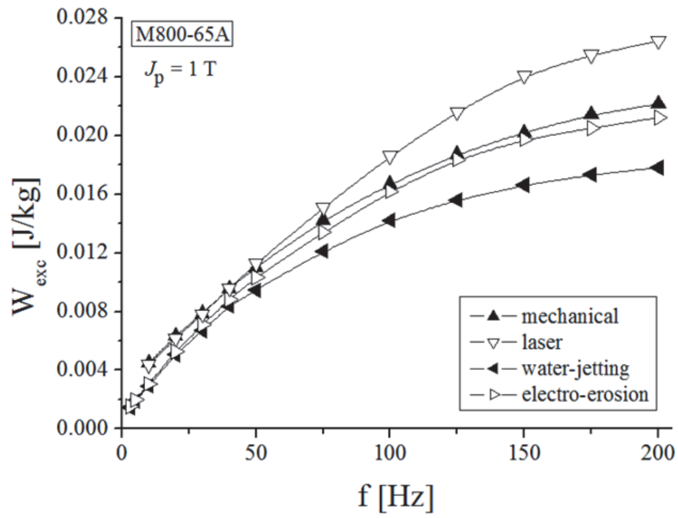

Fig. 4. Excess energy losses W_{exc} in the case of M800-65A grade, cut trough mechanical, laser, water-jet and electro-erosion technology for J_p = 1 T.

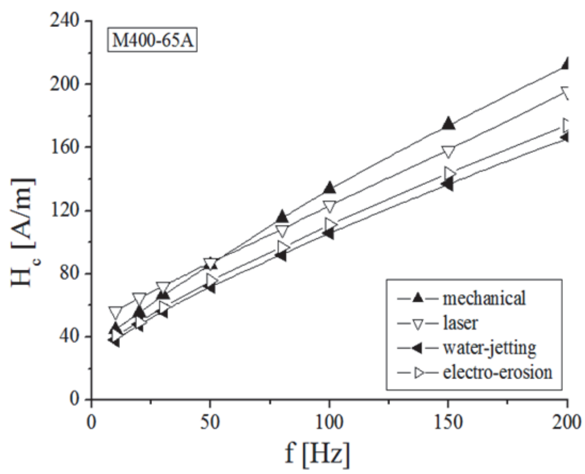

Fig. 5. Coercive field in the case of M400-65A grade, cut trough mechanical, laser, water-jet and electro-erosion technology for J_p = 1 T.

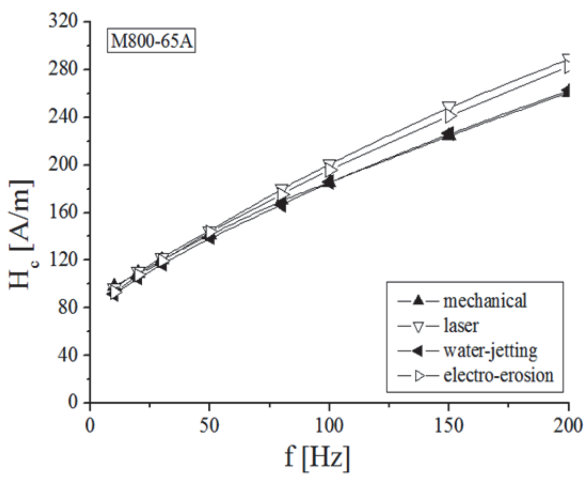

Fig. 6. Coercive field in the case of M800-65A grade, t trough mechanical, laser, water-jet and electro-erosion technology for J_p = 1 T.

2. CONCLUSIONS

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. The fully processed steel sheets are not annealed after being mechanical cut, so that local plastic strains and internal stresses alter their magnetic properties. The area affected by punching is mostly located around critical parts of the magnetic core (teeth, air gap) that having a strong impact on the global behavior of the machine. Even there is no clear indication of a change in the grain morphology for samples obtained by laser technology; the residual stresses due to the thermal gradients may be the origin of the observed changes of the energy losses, respectively, the decrease of the permeability. Both technologies, punching and laser lead to a supplementary stress induced magnetic anisotropy, perpendicular to the rolling direction and proportional to the magnitude of the residual stress. In the case of EDM and water-jet technologies lower values of energy losses and higher values of relative magnetic permeability are obtained, because of the reduced level of interaction between the cutting element and the material.

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ANALIZA PIERDERILOR DE ENERGIE ŞI A PROPRIETĂŢILOR MAGNETICE ALE TOLELOR ELECTROTEHNICE CU GRĂUNŢI NEORIENTAŢI DEBITATE PRIN DIFERITE TEHNOLOGII

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Rezumat: Aliajele fier-siliciu cu grăunţi neorientaţi (NO FeSi) sunt materiale magnetice moi extrem de larg utilizate în construcţia maşinilor electrice rotative de medie şi mare putere. În condiţiile actuale, când a devenit obligatorie creşterea eficienţei energetice a maşinilor electrice produse, atât în vederea economisirii de energie cât şi a protejării mediului, pentru obţinerea unei eficienţe de peste 95% este imperios necesară promovarea unor noi concepte de proiectare a circuitului lor magnetic sau/şi tehnologii alternative de debitare a tolelor. Au fost testate eşantioane de tablă electrotehnică recoaptă ("fully processed") cu grăunţi neorientaţi (NO FeSi) de tipurile M400-65A şi M800-65A, cu dimensiunile standardizate 300 × 30 mm^2. Proprietăţile lor magnetice, în principal pierderile specifice de energie au fost măsurate cu ajutorul unui tester uni-tolă pentru o polarizaţie magnetică de vârf de 1 T, într-un domeniu de frecvenţe 10 ÷ 200 Hz. Tolele au fost debitate utilizând diverse tehnologii: ştanţarea mecanică, tăierea cu laser, tăierea cu jet de apă şi, respectiv, electroeroziunea.