Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **65**, *3–4*, pp. 153–156, Bucarest, 2020

QUASI-STATIONARY MAGNETIC BEHAVIOUR OF IRON NICKEL BASED ALLOYS MACHINED THROUGH MECHANICAL CUTTING

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Key words: Nickel based alloys, Energy losses, Static magnetic properties, Hysteresis loss analysis, Normal magnetization curves, Strain-hardening phenomena.

A quasi-static analysis on 0.30 mm thick Permimphy material has been performed. The samples were mechanically cut as strips with a length of 300 mm and variable widths between 5 mm and 30 mm. The experimental measurements of the normal magnetization curves in quasi-static condition and of the total energy losses as a function of the frequency were made by means of an industrial Brockhaus single strip tester (SST). A hyperbolic model, previously applied in the case of silicon iron steels, was extended for the investigated material and the width of the damaged zone due to cutting procedure was estimated.

1. INTRODUCTION

The iron nickel (Fe-Ni) alloys were discovered and used in special applications since 1920 [1–7]. Usually, these types of materials crystalize in face-centered cubic (fcc) structures (> 30 % by weight nickel) of the Fe-Ni group, to which different elements are added in low amount. Nowadays, permalloy materials have 80 % Ni and exhibit important magnetic properties, such as a low coercive magnetic field strength (that can be adjusted from low level of almost 0.2 A/m to high level of 100 kA/m), good hysteresis shape shifter from linear to rectangular, very low energy losses, and a high magnetic permeability obtained by some special treatments [8].

Mumetal, Permimphy and Superpermimphy are crystalline soft magnetic alloys with 80 % Ni, (4.5 – 6) % Mo, (0.05 – 0.4) % Si, (0 – 0.5) % Mn, 0.01 % C and Fe balance. Permimphy is an ideal industrial grade, which has good magnetic properties and mechanical characteristics, suitable for mechanical cutting of complicated profiles. The saturation magnetic flux density of Permimphy is 0.75 T and the coercive force is 0.65 A/m. In order to achieve the highest magnetic permeability state, standardized thermal treatments under vacuum at 1050°C, or a 4 hours heat treatment at 1170°C in controlled H_2 atmosphere have to be applied [9]. Permimphy is delivered in cold rolled state with no applied thermal treatments. An important disadvantage of thermal treatments is an increased ductility of the material, fact that makes more difficult the mechanical cutting procedure.

The Fe-Ni alloys could have different magnetic properties as a function of nickel content. The 80% Ni grades has zero magnetostriction, being suitable for current sensors due to the fact that they have a particular crystalline structure with one Fe atom and three Ni atoms. Another important application of Permimphy is the shielding domain, which consists of devices' protection against electromagnetic interference. The volume that can be protected could be in the order of quite large dimensions. Nowadays, shielded zones are used in the medical field, in order to sense very low magnetic flux densities ($10^{-15} \div 10^{-14}$ T), *i.e.* magnetoencephalography [8]. In binary iron-nickel alloys it was demonstrated a relationship relating high magnetic permeability, obtained after heat treatments, and low magnetostriction. By taking into account the domain wall theory, it is noticed that the crystalline anisotropy is negligible when magnetization rotations are present, and thus permeability could increase. Also, at the moment when the material magnetostriction is zero, the magnetic domain walls' movements are almost free, because in these binary alloys the impurity content is carefully controlled and kept very low. This fact leads to an increased magnetic permeability.

When a heat treatment is applied after the material was cut, it results a relief of the induced magneto-strictive constraints and the effect of mechanical cutting on the static magnetic properties is annulated [10].

One commercially available material Permimphy was investigated in the paper. The static magnetic properties such as normal magnetization curves and hysteresis energy losses were analyzed and computed. Based on the model developed in [11–15] the depth of the damaged zone was estimated and used in a hyperbolic model to predetermine the hysteresis energy losses.

2. MATERIALS AND METHODS

Industrial grade Permimphy (Fe-Ni 80 %) from Aperam Alloys Imphy, with a thickness of 0.3 mm, was mechanically cut parallel to the rolling direction (RD) from delivered sheets, in cold rolled state with no applied thermal treatment. The width of the strips was variated between 5 mm and 30 mm. To reconstruct the Epstein standard width sample of 30 mm, there were placed together 6, 5, 4, 3, 2, 1 strip(s). The length of all the samples was set at 300 mm.

Table 1

Physical properties of Permimphy [3]

Property	Value
Density δ	8700 [kg/m^3]
Melting temperature T	1450 [°C]
Curie temperature T_C	420 [°C]
Thermal expansion α	12×10^{-6} [1/K]
Resistivity ρ	60×10^{-8} [Ωm]
Thermal conduction k	19 [W/K/m]
Specific heat c	460 [J/kg/K]
Hardness	160 [HV]
Grain size	8 [µm]
Tensile strength	650 [MPa]
Yield strength	280 [MPa]

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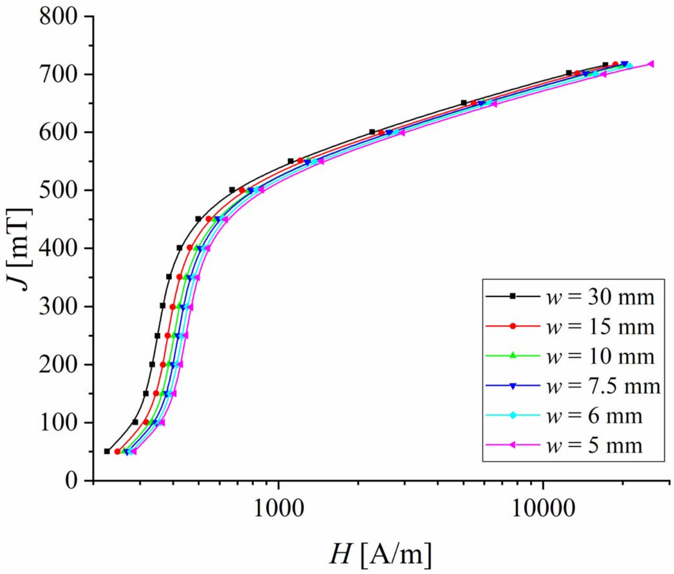

Fig. 1 – Normal magnetization curves as a function of the strip width w in mechanical cut 0.3 mm thick Permimphy material in cold rolled state.

The physical properties of the material are provided in Table 1.

The Permimphy samples were cut by using a Trumpf Trumatic 500 Machines that is based on a computer program, which permits the user to automatically execute the cutting steps.

The magnetic measurements were done using a Brockhaus industrial single strip tester (SST) that permits testing of samples with a given geometry as it follows: length of 300 mm and width of 30 mm. The measurements were made according to standard IEC 60404-3 [16]. The normal magnetization curves were done at a frequency *f* of 10 Hz, variating the peak magnetic polarization J_p from 50 mT to 750 mT with a step of 50 mT. The total energy losses were made at J_p of 500 mT as a function of frequency between 10 Hz and 100 Hz. The energy loss separation was performed as in [17–19] and the hysteresis loss component was computed by extrapolating in zero the total energy losses.

3. RESULTS AND DISSCUSSIONS

Figure 1 shows the mechanical cutting effect on normal magnetization curve, measured from demagnetized state to saturation at a frequency of 10 Hz. The physical quantities maximum peak couple (peak magnetic field strength H_p and peak magnetic polarization J_p) was extracted from each measured hysteresis cycles that were centered at the origin point. The normal magnetization curves, in the case of different strip widths were constructed, by taking into consideration the above-mentioned peak couples. The maximum applied magnetic field strength was $H_p = 17.2$ kA/m and the saturation magnetic polarization J_s was considered to be equal to 750 mT. Given the evolution of the magnetization curves as a function of strip width, we can estimate quite accurately the depth of the damaged zone ($2L_c$) (see Figs. 2 and 3).

When the cutting perimeter is increased (Fig. 1), *i.e.* the strip width *w* is decreased, the saturation magnetic polarization becomes harder to be achieved. This is due to the fact that a magnetic strain hardening phenomenon is present when Permimphy material is mechanically cut. The strain hardening makes the sample magnetization process to become more difficult in FeNi alloys. These phenomena are present also in the case of other types of soft magnetic alloys [11–14].

In order to estimate the depth of the zone damaged by cutting, the sample is considered to be divided into two regions: one undamaged core in the middle of the strip (with a length of $300 - 2L_c$) and two strain-hardened affected lateral zones, each with a width of L_c (Fig. 2).

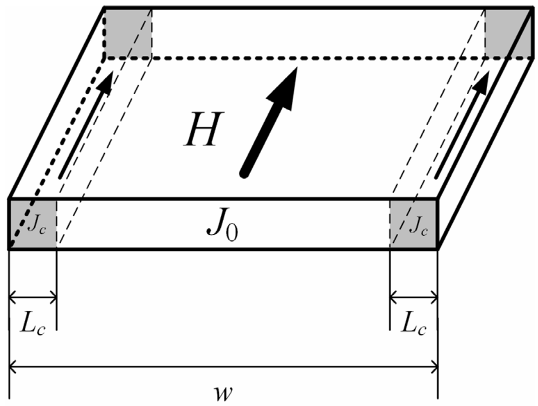

Fig. 2 – Schematic representation of the magnetic polarization distribution within the strip width.

It could be considered a hyperbolic law variation of the peak magnetic polarization as a function of the strip width *w* [11–13]:

$$J_p(w) = J_{p0} - \left(J_{p0} - J_{pc}\right)\frac{2L_c}{w}, w \geq 2L_c, \tag{1}$$

where J_{pc} is the magnetic polarization that corresponds to the damaged zones and J_{p0} is the magnetic polarization, which is linked to the undamaged core of the sample [6–9]. In the case of $w \leq 2L_c$ it can be considered that $J_p = J_{pc}$.

In order to mathematically compute the parameters of (1) there were set the following values for the magnetic field strength *H*: 400 A/m, 500 A/m, 1 kA/m, 2 kA/m, 5 kA/m, 10 kA/m, 12 kA/m, and 17 kA/m. Then, using interpolated experimental normal magnetization curves for two strip widths (w = 30 mm and w = 5 mm), we succeeded to exactly compute the J_{p0} parameter. Knowing this value and estimating as in [11–14] the depth of the damaged zone, the J_{pc} physical quantity was determined.

In the case of 0.3 mm thick Aperam Permimphy alloy the depth of the damaged zone was considered ($2L_c$ = 3.8 mm); the values of the J_{p0} and J_{pc} parameters are listed in Table 2.

Table 2

Computed polarization parameters for $J(w)$ dependence

H [A/m]	J_{p0} [mT]	J_{pc} [mT]
400	411.2	58.8
500	470	318.56
1000	542.07	502.927
2000	592.8	560.44
5000	654.2	619
10000	688.23	658.76
12000	702.7	667.16
17000	717.9	694.88

Figure 3 shows the dependencies of the experimentally measured (symbols) and computed using (1) (solid lines) magnetic polarization for different field strengths *versus* strip width. It can be noticed that (1) gives a very accurate estimate of the experimental results. It can be also concluded that by increasing the strip width beyond 50 – 60 mm the effect of mechanical cutting becomes negligible, but in the case of 30 mm wide strip it is still important [12].

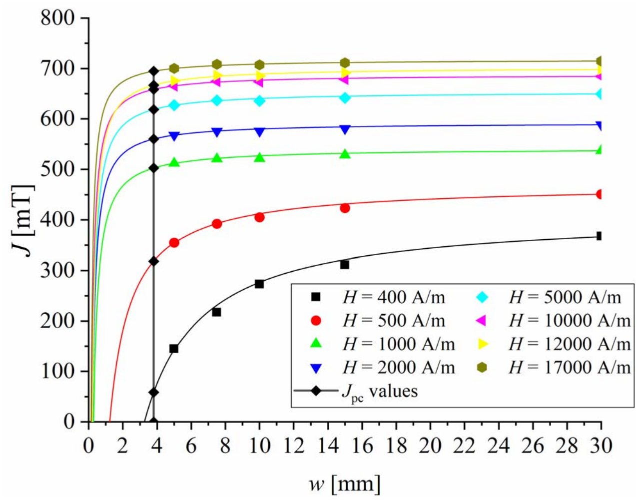

Fig. 3 – Experimentally determined magnetic polarizations J (represented with symbols) for the 0.30 mm Permimphy in cold rolled state *versus* strip width w. The solid lines are computed according to (1). The vertical line was set for $w = 2L_c$ and the diamond symbols represent the intersection between hyperbolic dependencies and the width of the entire damaged strip and correspond to parameter J_{pc}.

A complete quasi-static analysis of a given material includes the behavior of the hysteresis energy losses W_h, which can be considered as a function of the strip width w. We have used a similar phenomenological model, as in the case of normal magnetization curves. The limit values of W_h for the pristine and completely damaged strips are estimated and presented in the paper.

Mechanical cutting has a strong influence on the total energy losses. It can be observed that by decreasing the strip width the total energy losses W_{tot} increase. The strain hardening phenomena is put in evidence when the total losses are plotted *versus* frequency as in Fig. 4.

The classical energy losses are computed with a standard formula [13, 15], by considering that the magnetic flux density is uniform in the cross-sectional area of the samples:

$$W_{cl} = \frac{\pi^2}{6} \cdot \frac{d^2 J_p^2 f}{\rho \cdot \delta}, \tag{2}$$

where δ is the Permimphy material density, ρ is the electrical resistivity and d is the material thickness

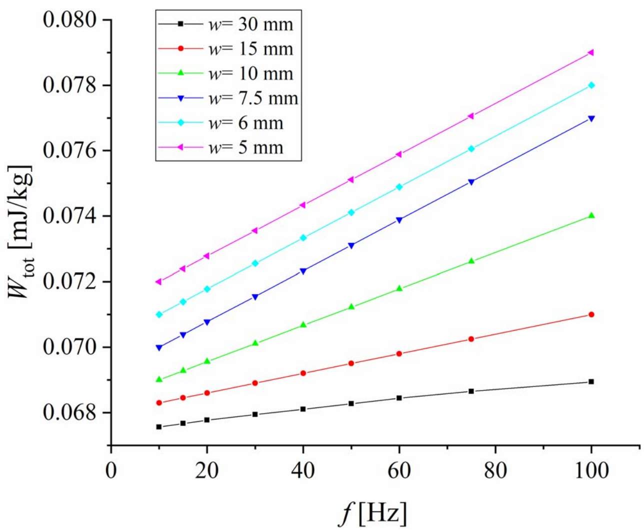

Fig. 4 – Total energy losses W_{tot} measured as a function of the frequency at J_p = 500 mT for the 0.30 mm Permimphy in cold rolled state. The strip width was variated between 5 mm and 30 mm. An increase of the total energy losses, directly proportional with the frequency and inversely proportional with the strip width, can be noticed.

The use of (2) is perfectly justified, the measuring frequency being variated in the range of 10 Hz to 100 Hz, below the critical frequency at which the skin effect appears. The lowest value of the strip width w is much higher than the strip thickness d, hence the approximation of boundless extended sheet could be applied [12, 13, 15].

The hysteresis energy losses were computed by extrapolating in zero the difference between W_{tot} and W_{cl}, which is always related to the macroscopic eddy currents. The hysteresis losses are an important quasi-static parameter being associated with the energy of the Barkhausen jumps [11].

As we have applied in [11, 12, 14], a simple phenomenological model can be used to predict the hysteresis energy behavior, as a hyperbolic function of the width w, according to (3):

$$W_h(w) = W_{h0} + \left(W_{hc} - W_{h0}\right)\frac{2L_c}{w}, w \geq 2L_c, \tag{3}$$

where W_{h0} and W_{hc} are the hysteresis losses associated with the strain-hardened and undamaged regions of the samples. In order to compute parameters W_{h0} and W_{hc}, we have considered the values of the hysteresis losses in the case of two strip widths w = 5 mm (W_h = 73.6 mJ/kg) and w = 30 mm (W_h = 67.16 mJ/kg) for the same magnetic field strength value. It was obtained W_{h0} = 65.32 mJ/kg and W_{hc} = 76.212 mJ/kg. The strain hardening phenomena is again put in evidence by a higher value of the hysteresis losses in the damaged region.

A very good agreement between mathematical model and experimentally computed data is shown in Fig. 5. It can be concluded that the simple scheme developed for the Fe-Si materials could be also successfully applied in the case of Fe-Ni alloys.

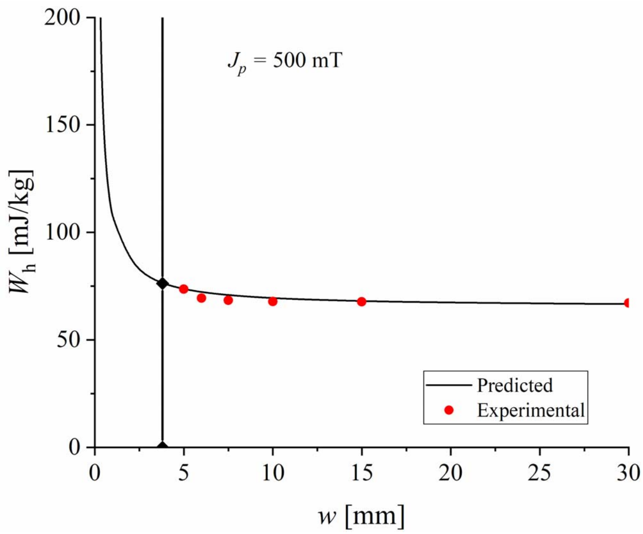

Fig. 5 – Hysteresis losses W_h as a function of the cut strip width w at J_p = 500 mT for the 0.30 mm Permimphy in cold rolled state. The values computed by (3) are represented with solid lines and the experimentally computed losses are marked using the circle symbols. The black vertical line was set for $w = 2L_c$ and the diamond symbol represent the intersection between the hyperbolic dependency and the width of the entire damaged strip (W_{hc} parameter).

4. CONCLUSIONS

Industrial Fe-Ni Aperam Permimphy material cut through mechanical punching was investigated in the paper. A simple scheme, which was initially proposed for standard Fe-Si alloys, was applied in the case of Permimphy to analyze the quasi-static behavior of the material; it proves also a perfect fit in the case of this material. The effect of mechanical punching was put in evidence, by using simple analytical expression. The depth of the damaged zone was estimated to be $2L_c$ = 3.8 mm. Based on this assumption it can be computed a hyperbolic dependence of hysteresis losses and their components in the damaged and undamaged zones.

The quasi-static analysis presented in the paper is a full one, because it includes the analysis of the normal magnetization curves and hysteresis energy losses and the accurately estimation of an important parameter, the width of the cutting zone.

ACKNOWLEDGEMENT

Dr. Fausto Fiorillo and Dr. Enzo Ferrara are acknowledged for developing and extending the model presented in the paper, working constantly with authors Veronica Manescu (Paltanea) and Gheorghe Paltanea.

The work was supported by a grant of the Romanian Ministry of Education and Research, CCCDI - UEFISCDI, project number PN-III-P2-2.1-PTE-2019-0423 (47PTE/2020), within PNCDI III.

Received on July 6, 2020

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