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## DETERMINATION OF POWER LOSS IN Fe-BASED SOFT MAGNETIC COMPOSITES

## WYZNACZANIE STRAT MOCY W KOMPOZYTACH MAGNETYCZNE MIĘKKICH NA BAZIE ŻELAZA

The magnetic properties of Fe-based composite materials with different particle sizes were investigated. The results of energy loss density were obtained from measurements of the static (DC) hysteresis cycles ranging from 0,2 to 1,4 T. In turn, the results of power loss density were obtained from measurements of the dynamic (AC) hysteresis cycles ranging from 20 to 400 Hz and at the maximum flux density 0,3; 0,9 and 1,3 T. Two sets of specimens was analyzed in the investigation: the specimens compacted under pressure of 800 MPa and hardened at 500°C and the specimens compacted under different pressure and hardened at 500°C. Specimens of the second set had the same density. The study confirmed the influence of particle size distribution on magnetic properties of Fe-based soft magnetic composites.

*Keywords*: magnetic materials, power losses, soft magnetic composites

## 1. Introduction

Powder metallurgy has recently attracted the interest of the scientific and engineering community interested in the development of electric machines. This fact is closely related to the application possibilities for made of powder in electric devices. Furthermore, powder metallurgy is characterized by low production costs, low powder waste and ease of recycling. There are two basic techniques for the preparation of magnetic elements made of powders: sintering and bonding by a dielectric agent [1-3]. Sintered parts have low resistivity; therefore, they are used only in devices with constant or low-frequency magnetic fields. On the other hand, magnetic composites compared with sintered elements achieve a lower magnetic flux density, however, owing to relative high resistivity and are applied in devices with a power and higher frequency of up to about 100 kHz.

The expanding interest in the introduction of Fe-based composite materials in electrical devices, such as electrical motors, is obviously connected with their properties. The main feature of these materials is that iron particles are insulated by a thin organic or inorganic coating. SMCs offer several advantages over laminated steel sheets, for example isotropic magnetic properties, the opportunity to tailor their physical properties to requirements, very low eddy current loss, relatively high resistivity and high magnetic permeability [4, 5].

The aim of this study is to determine the influence of particle sizes on the power loss density in Fe-based soft magnetic materials. The paper consider the effect of the magnetic properties of SMC cores made of powders with different particle size 63, 124 and 188 $\mu$m.

## 2. Loss determination

In the magnetic circuit during the magnetization process occurs the energy dissipation. Total power loss $P_{tot}$ (W kg$^{-1}$) are divided into three main parts: hysteresis loss $P_h$, eddy current loss $P_e$ and excess loss $P_{ex}$ [6, 7].

Hysteresis loss are proportional to the area of the static hysteresis loop which depends on the material and include the structural aspects affecting domain wall pinning and magnetization reversal reflecting into coercive field. Eddy current loss are caused by an alternating magnetic field. In the case of soft magnetic composites there are two different paths for eddy current: only inside particles (intra-particles eddy current loss) and currents between neighboring particles (inter-particles eddy current loss) [8]. In turn excess loss are caused mainly by domain wall branching and bowing.

In order to ensure penetration of magnetic particles in the entire volume, the maximum frequency $f_{max}$ was limited to 400 Hz. This assumption allows one to reduce the power loss density to the two components, i.e. the hysteresis loss and eddy-current loss. Thus, the power loss density may be described by Eq. (1), where $k_1$ and $k_2$ are coefficient that de-

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scribed physical properties of magnetic materials such as e.g. resistivity.

$$P_{tot} = f(k_1 + f \cdot k_2) \qquad (1)$$

## 3. Experimental details

Specimens investigated in this study were produced from commercially available pure iron powder Somaloy 500 produced by water atomization techniques, with a special surface coating on each and every particle. The research has examined magnetic properties of soft magnetic composites made of powders with a different particle size distribution. The mean particle size of powders were respectively equal to 63, 124 and 188 $\mu$m. Two sets of specimens was analyzed in the investigation. The first set of measurements covered the specimens compacted under pressure of 800 MPa and hardened at 500°C. In turn the second set covered the specimens compacted under different pressure and hardened at 500°C. Specimens of the second set had the same density.

The energy loss (volume) density $w$, expressed in joules per cubic meter (J m$^{-3}$), were obtained from measurements of the DC hysteresis cycle according to IEC Standards 60404-4 using the system AMH-20K-HS produced by Laboratorio Elettrofisico Walker LDJ Scientific. The magnetic energy losses were measured at maximum flux density $B_m = 0.2...1.4$ T. Measurements of power losses and magnetic energy losses were taken by recording individual points and the integration of the area of the hysteresis loop.

Total power loss density $P_{tot}$, expressed in watts per kilogram (W kg$^{-1}$), were obtained from measurements of the AC hysteresis cycle according to IEC Standards 60404-6 using the same measuring system. Total power losses $P_{tot}$ were measured at maximum flux density $B_m = (0.3$ T; $0.9$ T; $1.3$ T), over a frequency range from 50 to 400 Hz. During measurements of the total power losses $P_{tot}$, the shape factor of the secondary voltage was equal to 1.111 ±1.5%. Maximum measurement error of the total energy losses was equal to 3%.

The particle-size distribution was obtained by laser diffraction technology using Horiba LA-950 particle size analyzer.

## 4. Results and discussion

The dependence between total energy loss density and maximum flux density was fitted to the Steinmetz equation $w = kB^{\beta}$. Figure 1 shows the measured data and fitting lines. In turn, Figure 2 depicts the Steinmetz exponent $\beta$ and their estimation error bounds for the magnetic composites made of particle with different size.

Figure 3 depicts the dependencies of the power loss density of specimens prepared under constant compaction pressure on the median particle size for three levels of frequencies. In turn, Figure 4 depicts the dependencies between the power loss density of specimens with the same densities on the median particle size. Maximum induction in both cases were equal to 1,3 T.
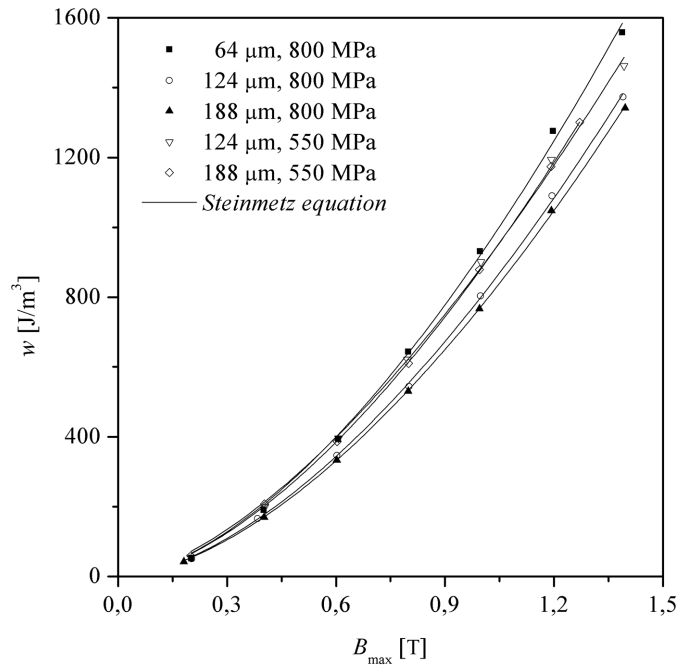


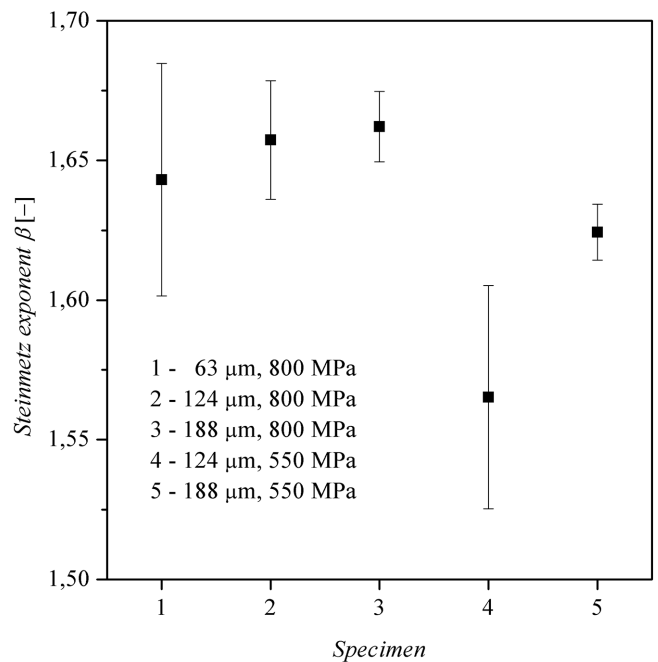Fig. 1. The dependence of energy loss density $w$ on maximum induction



Fig. 2. The values of Steinmetz exponent $\beta$ for curves from Fig. 1

Measurements of the power loss density of specimens prepared under constant pressure of 800 MPa exhibit local minimum (Fig. 3). Which means that it is possible to find the optimal particle size with the lowest power loss density. In a wide frequency range from 50 to 300 Hz, the median particle size of 124 $\mu$m is close to the global minimum of the power loss density. This median particle size provides a balance the participation of hysteresis loss and eddy-current loss. The mentioned effect is readily observable at frequencies of 150 and 300 Hz in Figure 3.
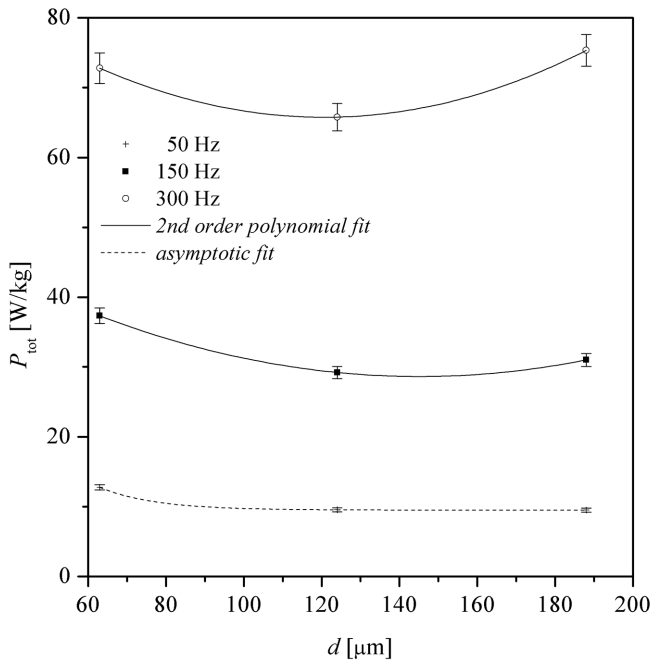
Fig. 3. The dependence of power loss density $P_{tot}$ on median particle size $d$ at $f = 50$ Hz and $B_m = 1,3$ T. Specimens prepared under pressure of 800 MPa
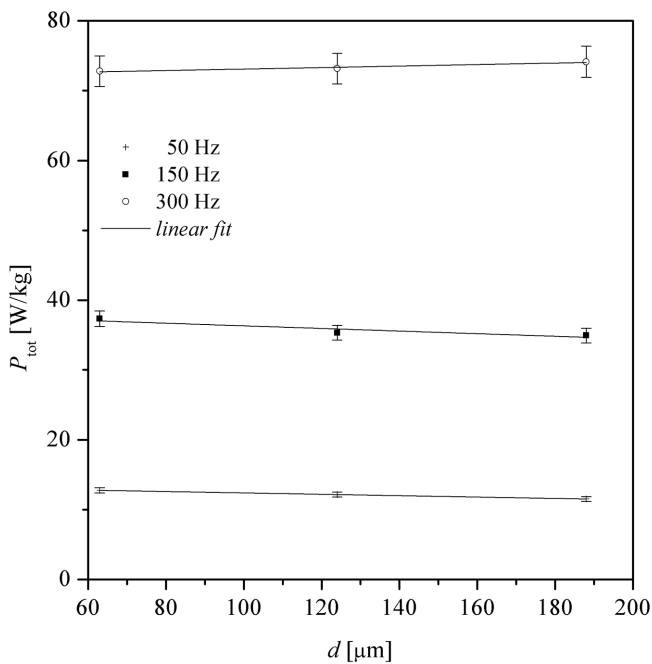


Fig. 5. Power loss density $P_{tot}$ vs. excitation frequency $f$. Specimen made of powder with the median particle size $d = 188$ $\mu$m. Compaction pressure of 550 MPa



Fig. 4. The dependence of power loss density $P_{tot}$ on median particle size $d$ at $f = 50$ Hz and $B_m = 1,3$ T. Specimens with the same density



Fig. 6. Power loss density $P_{tot}$ vs. excitation frequency $f$. Specimen made of powder with the median particle size $d = 63$ $\mu$m. Compaction pressure of 800 MPa

Measurements of the power loss density of spiecimens with the same density are depicted in Figure 4. The increases in the median particle size leads to decrease of the hysteresis loss which is visible for frequencies of 50 and 150 Hz. Note, however, that increasing the particle size leads consequently to an increase in eddy-current loss.

Figure 5 and 6 depicts curves of power loss density $P_{tot}$ vs. frequency $f$ for spiecimens with the same density of 7,18 ±0,07 g/cm$^3$. The spiecimens were made of powder with the median particle size equal to 63 and 188 $\mu$m, respectively. Solid lines represent fitting to Eq. (1).
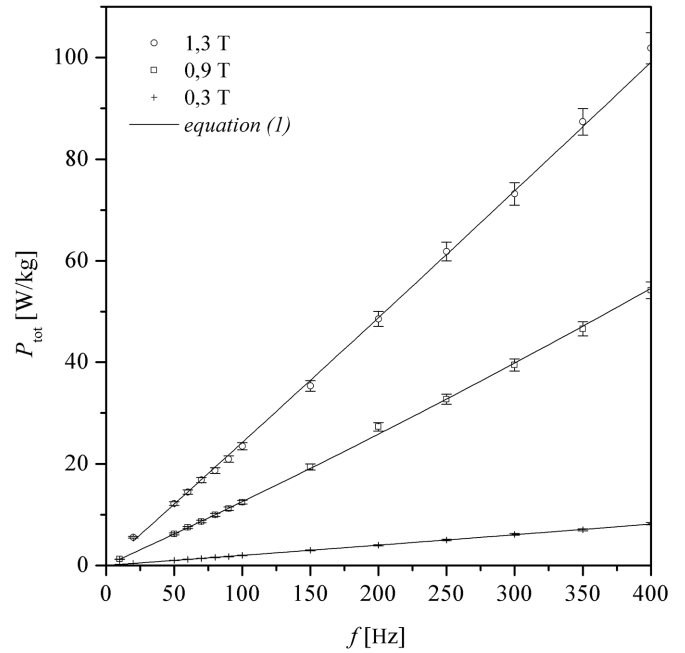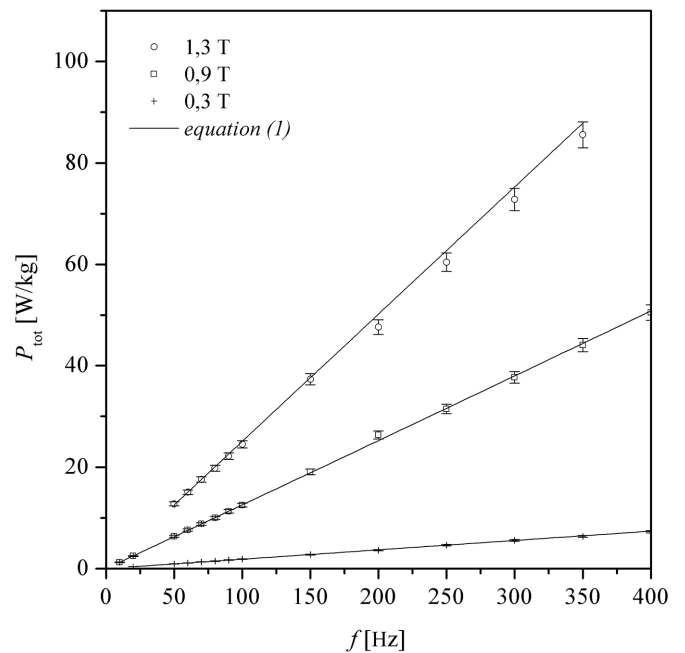
In order to identify the changes in power loss density, caused by different sources of energy dissipation, Eq. (1) has been used. According to Eq. (1), the energy dissipation process in magnetic materials is associated with the occurrence of the so-called hysteresis loss and eddy-current loss. Occuring in Eq. (1) coeffcent $k_1$ and $k_2$ are proportional to hysteresis loss and eddy-current loss, respectively. Based on the power loss density modelling in soft magnetic composite made of the powder with different particle size and compacted at different pressures, the dependencies $k_1(d)$ and $k_2(d)$ have been constructed (Fig. 7 and Fig. 6). According to the results depicted

in Figures 7 and 8, in the considered range of the median particle size $d \in <63; 188>$, two general conclusions may be drawn:
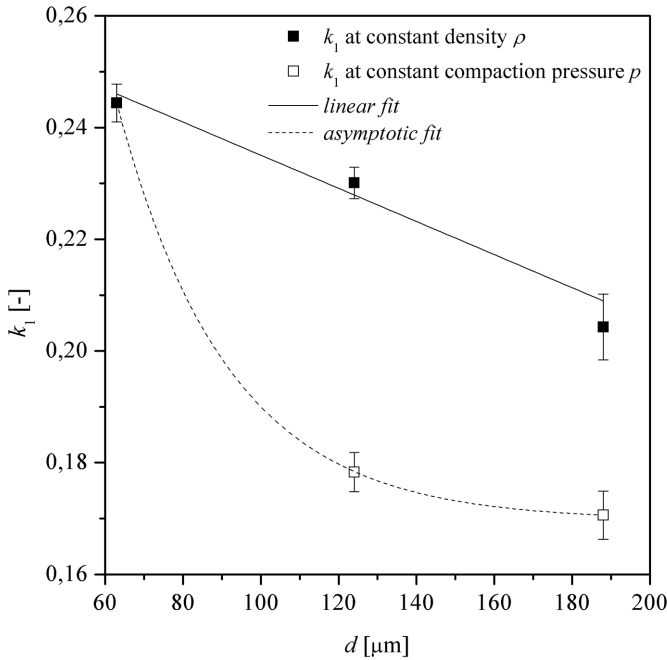


Fig. 7. The dependence of $k_1$ coefficient on median particle size $d$ at $f = 50$ Hz and $B_m = 1,3$ T
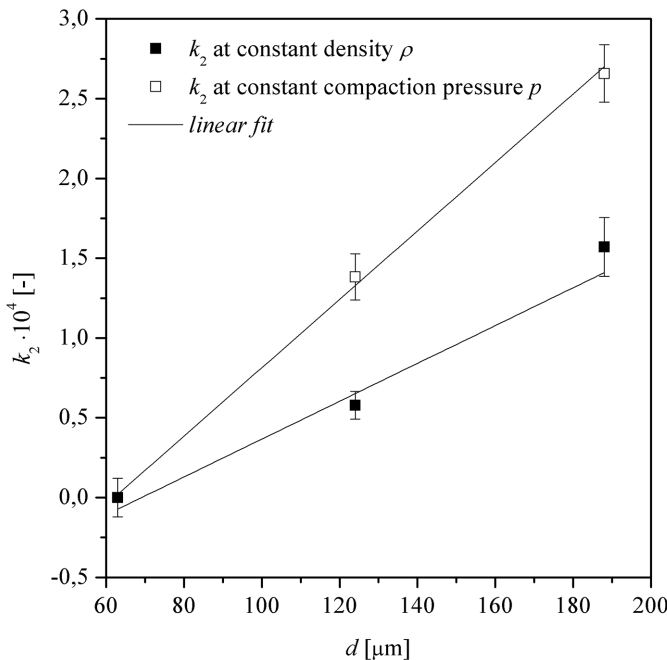


Fig. 8. The dependence of $k_2$ coefficient on median particle size $d$ at $f = 50$ Hz and $B_m = 1,3$ T

a) the hystersis losses are linearly proportional to the particle size $P_{hys}(d) \sim \gamma \cdot d + \delta$,
b) the eddy current losses are linearly proportional to the particle size $P_{eddy}(d) \sim \varepsilon \cdot d$,

for spiecimens with the same density but compacted at different pressure, where $\gamma$, $\delta$ and $\varepsilon$ are coefficients related to material properties. Application spiecimens with fixed densities but compacted at different pressures allows one to avoid the effect of worse compressibility in case of powder with the smaller particle size. This procedure also allows one to reduce an influence of smooth air-gap on magnetic properties made of powder with different particle size.

## 5. Conclusion

In the paper the influence of the particle size distribution on the power loss density of Fe-based soft magnetic composites has been studied. Results of study indicate that the choice of the particle size has a significant influence on magnetic properties of Fe-based magnetic composites.

According to the results of measurements and modelling some general remark may be drawn. The hysteresis loss and eddy-current loss depend linearly on the particle size in considered range from 63 to 188 $\mu$m. It should be noted that the hysteresis loss decreased with increasing of the median particle size which results from the fact that hysteresis loss depends greatly on the domain structure. Materials with a large particle size (larger than 100 $\mu$m) have a complex structure of magnetic domains. The magnetization process in these materials takes place through the motion of magnetic walls and the rotation of the magnetization vector. It is, however, dominated by the first component which contributes to reducing the hysteresis loss. On the other hand, in the materials with a small particle size (smaller than 100 $\mu$m) the rotation of the magnetization vector plays a dominant role [9].

The non-linear relationship between the coefficient $k_1$ and the median particle size $d$ in Figure 7 (*at constant compaction pressure p*) owing to significant differences in the compressibility of powders with different particle sizes. Specimens made of the powder with median particle size of 63 $\mu$m had the density equal to $7,18 \pm 0,07$ g/cm$^3$, while, specimens made of powder with median particle size of 124 and 188 $\mu$m had densities equal to $7,30 \pm 0,07$ g/cm$^3$ and $7,32 \pm 0,07$ g/cm$^3$, respectively. Therefore, this effect causes disturbances in the correct analysis of the hysteresis loss.

In contrast to the hysteresis loss, the eddy-current loss increased with increasing of the median particle size that is connected with possibility of current flow path inside particles. It should be noted that in the case of the fixed compaction pressure of 800 MPa the eddy-current losses are higher compared to the case of specimens with fixed densities (Fig. 8). The reason for this may be the fact that in specimens compacted at a pressure of 800 MPa the insulation layer is destroyed.

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