Magnetoresistance effect in ferromagnetic metal foil

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Abstract. The paper presents the results of investigating how electric current and a permanent external magnetic field affect the magnitude of magnetoresistance effect (MRE) in polycrystalline nickel foils. For a current density of $j = 2.5 \cdot 10^8$ A/m$^2$ the maximum MRE we obtained for our foil samples (25x2x0.005 mm strips) was 11.6%. We studied the effect of external magnetic fields, when $H_0 = (0.5...6) \cdot 10^5$ A/m, on the MRE magnitude in polycrystalline nickel foils through which we simultaneously passed electric current with densities in the $j = (1...4) \cdot 10^8$ A/m$^2$ range. We found that the maximum MRE value (10.7 %) results from increasing the external magnetic field $H_0$ up to $6 \cdot 10^5$ A/m when the current in the sample is fixed at $j = 3 \cdot 10^8$ A/m². These results may stem from the fact that the electric current may cause electroplastic softening of the foil material, which leads to additional magnetization. The current value is the threshold for starting the dislocation motion and restructuring the conductive material. Varying the external magnetic field controls the decrease in magnetization dispersion in nickel foils.

Keywords: electric current, magnetic field, ferromagnetic metal, foil, magnetization, magnetoresistance effect

1. Introduction
A high density electric current $j \geq 10^7$ A/m$^2$ in a metal does not only contribute to its heating, but also impacts its mechanical stress state. This stress state has anisotropic properties. Experiments [1-3] confirmed this: among the phenomena observed there were movement of dislocations along the current, oriented recrystallization and dynamic texturing of metals and alloys of arbitrary crystal structure, which may lead to changes in the electrical resistance of a conductor.

Using ferromagnetic materials as magnetoresistive transducer elements requires detailed information about the properties of such a material when it is exposed to external pressure or magnetic fields [4]. It is necessary to consider both the amplitude of the external effect and its direction. In this regard, we carried out a study of magnetoresistance of a polycrystalline ferromagnetic metal sample subjected to high current densities. We took the direction of the external factors into account in the first place.

2. Experiments and results
We conducted two series of experiments. In the first series we varied the current flowing through the sample in the $I = (0.1...10)$ A range, and varied the orientation of the DC external magnetic field. In the second series of experiments we varied the magnitude of the DC external magnetic field in the $H_0$
= (0.5...6) \times 10^5 \text{ A/m range and its orientation relative to the current, keeping the electric current passed through the sample constant. We used polycrystalline nickel foil in the form of 25x2x0.005 mm strips as samples. We used an electromagnet to create a constant external magnetic field, which we measured both with a magnetometer and independently by measuring the electric current passing through the windings of the electromagnet. We employed a standard four-probe method to measure } R(j) \text{ and } R(H) \text{ magnetoresistance. Figure 1 schematically shows the factors we exposed our samples to: } \mathbf{H}_o \text{ and } \mathbf{j}, \text{ while } \theta \text{ is the angle between the external field } \mathbf{H}_o \text{ and the current density vector } \mathbf{j} \text{ in the sample. In both series of our experiments we obtained current-voltage characteristics (CVC) as well.}

\begin{align*}
\Delta R (j) &= \frac{R_{||}(j) - R_{\perp}(j)}{R_o(\theta = 0^\circ) + R_o(\theta = 90^\circ)}
\end{align*}

This dependence is shown in figure 3.
Figure 3. The dependence of MRE on current density in nickel foil for an external magnetic field $H_0 = 3 \cdot 10^5$ A/m.

Figure 4 shows how the MRE in nickel foils depends on the external magnetic field $H_0 = (0.5...6) \cdot 10^5$ A/m at various fixed current densities ($j = (1...4) \cdot 10^8$ A/m$^2$) passed through the foil.

Figure 4. The dependence of the MRE on the external magnetic field at a fixed current in the sample: $j = 10^8$, $3 \cdot 10^8$, $4 \cdot 10^8$ A/m$^2$ in curves 1-3 respectively.

3. Discussion

It is evident that the dependence of $R_{\parallel}(j)$, $R_{\perp}(j)$ (figure 2) and the dependence $\frac{\Delta R(j)}{R_0}$ (figure 3) have three characteristic areas. In the $j = (0...0.5) \cdot 10^8$ A/m$^2$ range the magnetoresistance is almost independent of the current, and the MRE takes on a value of 1.8%. Then, the magnetoresistance increases in the $0.5 \cdot 10^8 < j < 2.5 \cdot 10^8$ A/m$^2$ range of the electric current, and when the current is equal to the value of $j = 2.5 \cdot 10^8$ A/m$^2$, the value of the MRE reaches an abnormal value of 11.6%. The magnetoresistance $R_{\parallel}$ does not depend on $j$ anymore when $j > 2.5 \cdot 10^8$ A/m$^2$, while $R_{\perp}$ continues to grow until $j = 4.5 \cdot 10^8$ A/m$^2$. The value of $R_{\perp}$ does not depend on the electric current density $j$ for $j > 4.5 \cdot 10^8$ A/m$^2$. Thus, there is a dramatic decrease in the MRE value for $j > 2.5 \cdot 10^8$ A/m$^2$. Then, when $j = (6...10) \cdot 10^8$ A/m$^2$, the magnetoresistance effect magnitude depends weakly on the current density and drops to approximately 1.2%.
Previous publications [5] state that the maximum MRE value in nickel is 2.5 %, which is consistent with the results of the experiment in the region of small currents $j < 0.5 \times 10^8$ A/m$^2$ (figure 1, curve 3). However, the results of the experiment indicate an increase in MRE (11.6 %) for $j = 2.5 \times 10^8$ A/m$^2$ by 6.4 times in comparison to the MRE value (1.8 %) for the case of low currents when $j = 0.5 \times 10^8$ A/m$^2$.

Considering that the MRE magnitude is proportional to magnetization squared, namely $\frac{\Delta R}{R_0} \sim M^2$ [5], it is logical to assume that the effective magnetization of the sample should increase by 2.5 times. Therefore, the appearance of additional magnetization can explain the abnormally high MRE value (11.6 %) that is achieved when the current in the foil is $j = 2.5 \times 10^8$ A/m$^2$.

On the other hand, the influence of Joule-Lenz heat cannot explain the experimental dependence of the MRE in Ni foil on the electric current density $j$, since we know [5] that MRE will decrease with increasing sample temperature. The decrease in MRE when $j > 2.5 \times 10^8$ A/m$^2$ is not associated with the heating of the sample either as the experiment was conducted in conditions similar to isothermal. Solving the stationary equation of thermal conductivity for nickel foil allowed us to estimate the drop in temperature across the thickness $d$ of the sample, which is $\Delta T \approx 6$ K if $j = 10 \times 10^8$ A/m$^2$. The following sample parameters were used to calculate the temperature difference: thickness $d = 5 \times 10^{-6}$ m, specific conductivity $\rho = 7.0 \times 10^{-8}$ $\Omega \cdot$m, coefficient of thermal conductivity $\lambda = 92$ W/(m$^\circ$K), heat transfer coefficient $\alpha = 3 \times 10^4$ W/(m$^2$·K), initial sample temperature $T_0 = 293$ K. It means that we can neglect the sample temperature dependence on electric current density if our thin-film metallic conductor is subjected to intensive cooling.

The decrease in MRE for $j > 2.5 \times 10^8$ A/m$^2$ can be explained by an increase in the internal magnetic field $H_o = \frac{3\lambda_\sigma}{M}$ due to the magnetostriction effect, which leads to a change in the orientation of the magnetization vector $M$ relative to the external magnetic field $H_e$. However, we should bear in mind that the effects of a high-density electric current ($j = (0...12) \times 10^8$ A/m$^2$) in thin metallic magnetic films (TMF) have a threshold character as regards current, and yet they always decrease [6]. The exception is the case of a strong external magnetic field $H_e > 4 \times 10^5$ A/m, when the value of MRE does not depend on the electric current density in TMF.

When studying the influence of a constant external magnetic field $H_e = (0.5...6) \times 10^5$ A/m on the magnitude of magnetoresistance and MRE (1) in polycrystalline nickel foil samples, we were able to identify the value of the current that maximises the effect that the magnetic field has on the MRE magnitude (figure 4). The MRE increases from $\approx 1\%$ to $\approx 6\%$, i.e. by 6 times (curve 1, figure 4) for a fixed current density in the sample $j = 1 \times 10^8$ A/m$^2$ when the external magnetic field $H_e$ increases from $0.5 \times 10^4$ A/m to $6 \times 10^4$ A/m. The maximum MRE value (10.7 %) is achieved by increasing the external magnetic field $H_e$ up to $6 \times 10^5$ A/m when the current in the sample is fixed at $j = 3 \times 10^8$ A/m$^2$ (curve 2, figure 4). Increasing the external magnetic field leads to a decrease in MRE from a value of $\approx 5 \%$ to a common tabulated value of approximately 2.5% (curve 3, figure 4) which we can observe when the current density in the sample is $j = 4 \times 10^8$ A/m$^2$.

The results of our experiments can be explained by the state that the sample structure is in. For instance, applying an external magnetic field and increasing it further leads to a decrease in magnetization dispersion and an increase in the MRE [6], which is observed at low currents ($j = 1 \times 10^8$ A/m$^2$). Electroplastic softening process in the sample material leads to the appearance of additional magnetization; an increase in $H_e$ then reduces the scatter of the magnetization vector $M$ in the foil. Consequently, the MRE increases (curve 2, figure 4). We observe this when $j = (2.5...3) \times 10^8$ A/m$^2$. As the plastic softening process approaches its final stage, the MRE is reduced to tabulated values; we observe this when $j = 4 \times 10^8$ A/m$^2$. In this range of currents, magnetic field has virtually no effect on the MRE magnitude (curve 3, figure 4).

4. Conclusion
The dependence of the MRE on the electric current density and a constant external magnetic field, as well as its anomalous value of 11.6% at $j = 2.5 \times 10^8$ A/m$^2$, can be attributed to structural changes in the sample caused by the current accompanied by plastic deformations. Namely, the electronic subsystem causes additional directional movement of atoms, affecting the crystal lattice of the conductor. This lattice possesses structural inhomogeneity, which in turn causes the movement of defects. As a result, the process affects the physical properties of the material. Increasing the external magnetic field when the currents in the sample are above the threshold causes additional magnetization, which leads to a decrease in magnetization dispersion. This anomalous dependence of magnetoresistance on current density in nickel foils when the conducting sample is positioned differently with respect to the external uniform magnetic field may be used to increase the sensitivity of electromagnetic signal sensors based on MRE in particular.

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