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Steel 110G13L. Thermomagnetic and Galvanomagnetic Effects in its Films

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Abstract. The article shows the ability to control magnetic properties due to modulation of phases in the film with varying temperature of growth. So, at low growth temperatures, a film is formed with an axis of easy magnetization in plane. An increase in temperature leads to a change in the phase composition of the film. It is shown that the presence of even a small component of the magnetization vector in the perpendicular direction leads to the appearance of a thermomagnetic effect of a large magnitude with respect to thermal noise.

Keywords: Hadfield steel, films, thermomagnetic effect, magnetization, semiconductor properties, Hall resistances, Nernst-Ettingshausen stresses.

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Environmental problems associated primarily with the inefficient use of fuel resources, the question of the development of alternative sources of electric energy, in particular, autonomous low-power energy sources. It is interesting to consider magnetic materials as transformers of thermomagnetic energy [1]. The principle of operation of thermomagnetic converters is based on the Nernst-Ettingshausen effect [2]. By analogy with the Hall effect [3], in which the transverse voltage arises when an electric current passes through the antenna, the voltage between two components: ordinary, different "hot" and "cold" carriers, and abnormal ones associated with spin-dependent carrier scattering in magnetic centers in [4]. This may be due to the large mobility of charge carriers due to intersections in electronic bands. To improve the thermoelectric characteristics of a particular material (power factor), it is necessary to increase the electrical

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conductivity and reduce the thermal conductivity $\lambda = \lambda_e + \lambda_{ph}$ (λ_e and λ_{ph} mean electronic and background inlays in λ, respectively) [5], it has been theoretically and experimentally shown that steel from Hadfield has metal and semiconductor properties. This combination allows us to expect large values of thermoelectric figure of merit in such materials [6].

The mathematical expressions describing the effects of Hall and Nernst-Ettingshausen in magnetic systems have the following form:

$$\begin{aligned} U_{NE} &= Q_0 B \Delta T + Q_M M(B) \Delta T, \\ U_H &= R_0 B I + R_M M(B) I, \end{aligned} \tag{1}$$

where Q_0 is the ordinary Nernst-Ettingshausen constant, Q_M is the anomalous Nernst-Ettingshausen constant, ΔT is the temperature gradient, M is the magnetization of the structure, B is the induction of an external magnetic field, I is the induction of an external magnetic field, I is the electric current passing through sample, R_0 is the ordinary Hall constant, R_M is the anomalous Hall constant. The constants R_0 and Q_0 do not have magnetic properties and mobile vehicles (mobility, concentration, resistance, scattering coefficient, etc.). Anomalous constant oscillations in the magnetic system.

The magnitude of the ordinary Nernst-Ettingshausen component is small and amounts to several tens of microvolts, while the anomalous component can reach gigantic values in compared to the usual effect due to strong spin-dependent scattering. Thin-film thermomagnetic, in which the magnetization is oriented perpendicular to a flat film, are of the greatest practical interest. A similar situation can be realized in a system with strong magnetic anisotropy, for example, in [7].

Hadfield steel is a composition having a mixture of magnetic and non-magnetic phases. As objects of study, we used two-layer films formed on sapphire substrates as a result of pulsed laser deposition in a vacuum of 10–6 Torr. Dimensions 1 × 1 cm and a thickness of 2 mm. Structures 1 and 2 differ in substrate temperatures during spraying of 250 and 400°C, respectively. The spraying time was 60 minutes, which corresponds to a thickness of 50 nm.

Perhaps this is due to the fact that the alloy is an antiferromagnetic invar, in which the appearance of localized magnetization in the sample occurs under shock loading. The latter is due to the fact that the structural features of $\mathrm{Fe_{86}Mn_{13}C}$ are different types of magnetic ordering in the same sample. In Fig. 1, you can see the image of the surface of a bulk $\mathrm{Fe_{86}Mn_{13}C}$ sample after shock loading obtained by scanning electron microscopy. Individual grains are visible. Dark bands in some grains turn into dark bands of neighboring grains. X-ray diffraction studies take place after the appearance of martensite deformation. This phase is localized in the shear strain bands of austenitic grains [10].

According to the Zhurkov equation [12]:

$$\tau = \tau_0 \cdot e^{\frac{u_0 - \gamma \cdot \sigma}{k \cdot T}}, \tag{2}$$

where τ is durability at a given voltage (s); τ_0 is period of thermal fluctuations of vibrations (s); u_0 is the activation energy of destruction (kJ/mol); γ is the structurally sensitive coefficient (cm^3/mol); σ is the stress in the localized volume equal to γ, (MPa); k is the gas constant (kJ/mol. · deg. K); T is the temperature (degree K).

Fig. 2 shows an image of the structure of a thinned foil based on Hadfield steel. Comparing Fig. 1 and Fig. 2, we can conclude that the structure of bulk samples of Hadfield steel is large-scale, which indicates the alternation of the bands of ferrimagnetic deformation martensite and non-magnetic austenite.

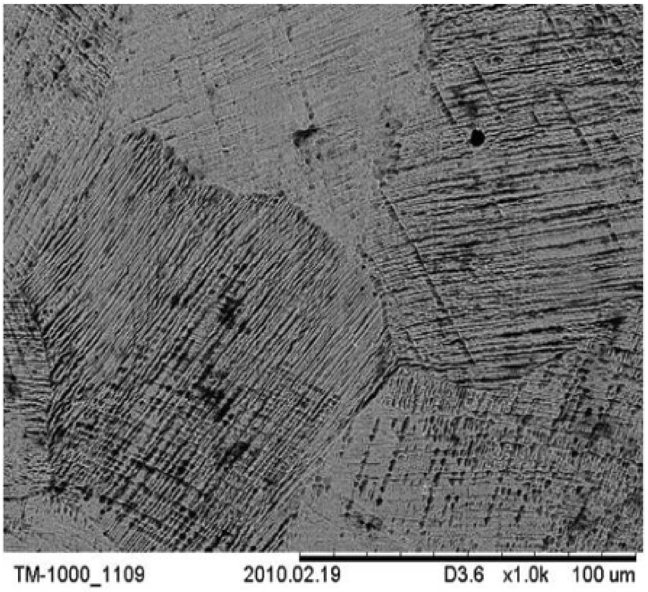


Fig. 1. Image of the structure of Hadfield steel samples of the surface of a massive sample in a scanning microscope

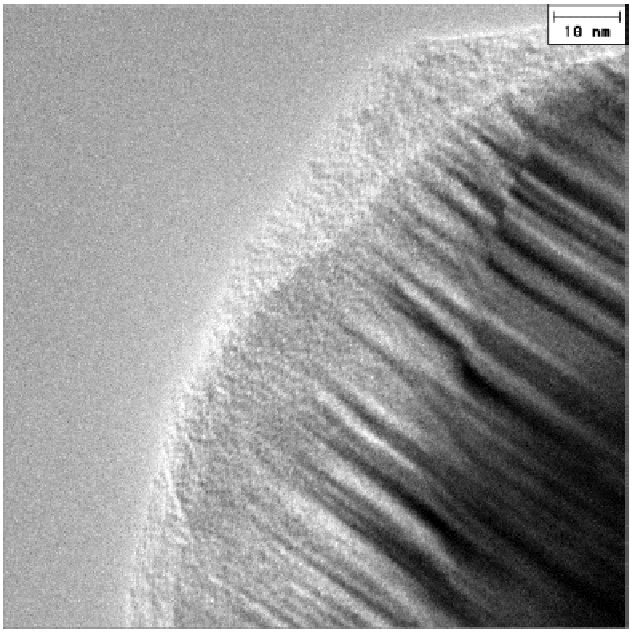


Fig. 2. Image of the structure of a thinned foil of a Hadfield steel sample in a transmission electron microscope

Thus, it can be assumed that it is precisely the different state of the magnetic structure that can determine the sign of the thermo-EMF in experiments. The thermo-EMF observed in the experiment may be due to the longitudinal or transverse Nernst-Ettingshausen (NE) effects —

these are the thermomagnetic effects observed when a semiconductor with a temperature gradient is placed in an external magnetic field [11].

The research methods consisted in measuring the dependence of the Hall and planar Hall resistances on the magnetic field, the Nernst-Ettingshausen voltage, the Seebeck effect, and registration of the structure magnetization in the planar direction using magnetometry with a variable gradient field.

To record the dependences of the Hall resistance and Nernst-Ettingshausen voltage on the magnetic field, 6 ohmic contacts were formed on the surface of the structure. The sample was mounted on a holder, the schematic diagram of which is shown in Fig. 3. The holder is equipped with a resistor-heater and radiator, which provides heat removal from one of the faces of the structure to form a temperature gradient.

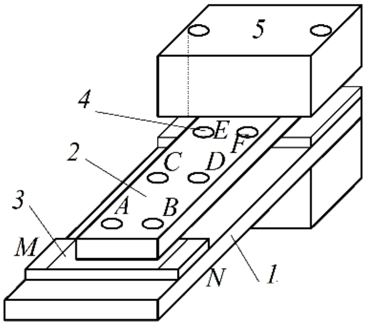


Fig. 3. Schematic representation of the installation of the sample on six contact holders for recording thermal effects, as well as the Hall effect. Heat flow spreads along the structure. 1 — substrate holder, 2 — sample, 3 — resistor-heater, 4 — contact pads, 5 — radiator

The technique allows us to consistently conduct experiments to study the effects of Hall (RH) and Nernst-Ettingshausen (Q):

$$(I_{MN}U_{CD}) - Q. \tag{3}$$

Fig. 4 shows the experimentally obtained dependences of the Hall resistances of the magnetic fields of the structures under study according to the method described above:

It can be seen from the obtained experimental curves that structure 1, formed at a temperature of 250°C, has a linear dependence of the Hall resistance on the magnetic field, which indicates that the magnetization vector lies in the plane of the structure, which does not allow magnetizing the structure in this region of the magnetic field. An increase in the sputtering temperature (structure 2) leads to the formation of a magnetic structure with a small perpendicular component of the magnetization vector, which is expressed in the appearance of nonlinearity in the dependence of the Hall resistance on the magnetic field (Fig. 4, black curve). The presence of oriented magnetization in the plane for both films is confirmed by an analysis of the nature of the magnetic field dependences of the magnetization vector, recorded by magnetometry with a variable field gradient. The obtained experimental curves are shown in Fig. 5.

The obtained curves show that the dependence of magnetization on the magnetic field has the form of a hysteresis loop, which indicates the presence of a ferromagnetic order in the structures under study. It is important to note that the loop width of structure 2 is smaller than that of structure 1, which further confirms the thesis that the second structure has a perpendicular component of magnetization.

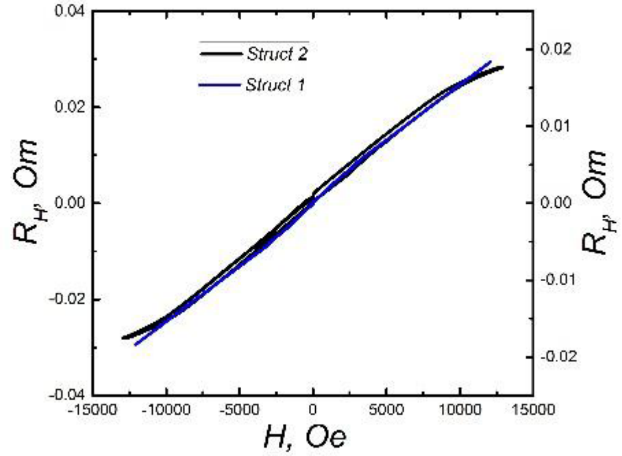


Fig. 4. Dependences of the Hall resistances of the magnetic fields of the structures under study: blue curve — structure 1, black curve — structure 2

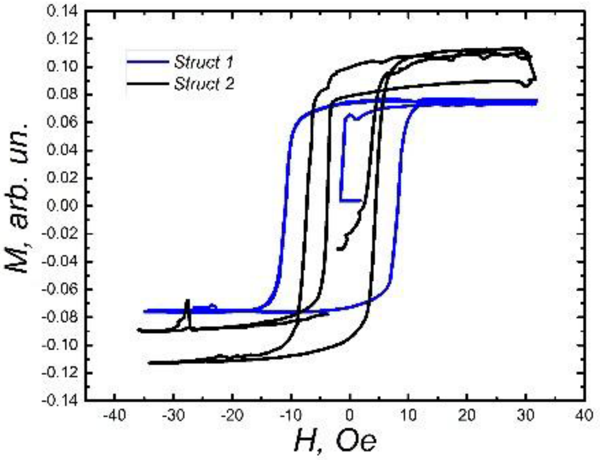


Fig. 5. Dependences of the magnetization of the studied structures on the magnetic field: blue curve — structure 1, black curve — structure 2

The absence of a perpendicular component of magnetization in structure 1 leads to the absence of the Nernst-Ettingshausen effect, while in structure 2 the effect was more than 40 μV with a temperature gradient of 10 degrees (Fig. 6).

It is important to note the presence of anisotropic magnetoresistance in the studied structures, expressed in the characteristic form of the dependence of the magnetic field on the plane Hall resistance (Fig. 7).

The paper shows the ability to control magnetic properties due to modulation of phases in the film at various rising temperatures. Thus, at low growth temperatures, a film with a flat axis of easy magnetization is formed. An increase in temperature leads to a change in the phase composition of the film, which is probably the reason for the rotation of the easy magnetization axis by an angle relative to the plane. This is manifested in the appearance of a hysteresis loop in the magnetic field dependences of the magnetization, the Hall effect, and the Nernst-Ettingshausen effect, and also leads to an increase in the thermomagnetic properties.

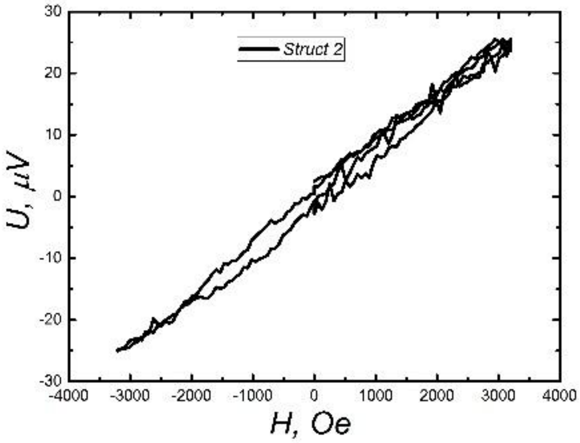
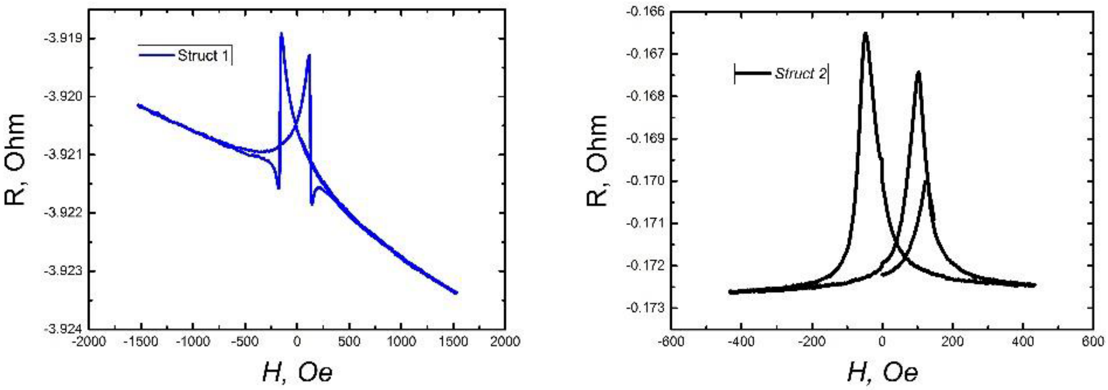


Fig. 6. Magnetic field dependence of the Nernst-Ettingshausen voltage of structure 2



a) б)

Fig. 7. Dependences of the magnetic field on the flat Hall resistance of structures: a – 1, b – 2

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Сталь 110Г13Л. Термомагнитные и гальваномагнитные эффекты в ее пленках

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Аннотация. В статье показана возможность управления магнитными свойствами за счет модуляции фаз в пленке при варьировании температуры роста структуры. Так, при низких температурах формируется пленка с осью легкого намагничивания в плоскости. Повышение температуры приводит к изменению фазового состава пленки. Показано, что наличие даже небольшой компоненты вектора намагниченности в перпендикулярном направлении приводит к возникновению термомагнитного эффекта большой относительно тепловых шумов величины.

Ключевые слова: сталь Гадфильда, пленки, термомагнитный эффект, намагниченность, полупроводниковые свойства, сопротивление Холла, напряжение Нернста-Эттингсгаузена.