

## Structure and properties of soft magnetic alloy 2HCP subjected to short-term annealing

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of thermomagnetic treatment in an elastic stress field (ESF) are characterized by a stable tendency to increase saturation magnetization. When studying the 2HCP alloy with small additions of Nb ( $\sim 0.8$  at.%) and Cu ( $\sim 0.3$  at.%) at room temperature, an increase in saturation magnetization was found due to the effect of elastic loading during cooling. The increase in magnetization was  $\sim 15\%$  after TUO at  $540^\circ\text{C}$  for 5 min, and  $\sim 20\%$  after TUO at  $540^\circ\text{C}$  for 7 min, respectively. It can be assumed that such a change in fundamental characteristics, namely, the anomalous growth of saturation magnetization, is associated with the state of the amorphous structure in the pre-crystallization stage, and with the appearance of finely dispersed precipitates of the crystalline phase as a result of the decomposition of the amorphous matrix.

**Keywords:** amorphous alloys, thermo-magnetic treatment, magnetization, elastic load.

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A considerable improvement of the soft magnetic properties of amorphous alloys has been achieved in recent years, driven by the need to develop soft magnetic materials with higher saturation magnetization, lower coercivity, and high magnetic permeability levels. This rapid progress is attributable to the fact that these materials offer energy saving, efficiency, and miniaturization advantages in fabrication of electron-magnetic devices [1]. It is known that amorphous alloys combine high hysteresis magnetic characteristics with high plasticity and a relatively simple production process (quenching from melt) [2]. The examination of magnetic properties of a number of high-entropy alloys revealed the prospects for development of soft magnetic materials with their magnetic properties controlled by doping and annealing.

Iron-based amorphous alloys are characterized by relatively high values of saturation induction  $B_s$  and magnetostriction  $\lambda_s$  and fine hysteresis magnetic properties; most importantly, they offer low magnetization reversal losses, which may be 5 or more times lower than the ones in traditional electrical steels [1].

It was established that the saturation magnetization of Fe–Ni–Si–B amorphous alloys (type 2NSR) tends to increase consistently under certain thermomagnetic treatment conditions in an elastic stress field (ESF). The saturation magnetization in the 2NSR alloy with small additions of Nb and Cu ( $< 1\%$ ) increased by more than 20% with an increase in elastic load during cooling both in the as-prepared state and after thermal treatment [3,4]. Spectroscopy data revealed that regions with different values

of saturation magnetization were formed in tape samples after spinning. It can be assumed that the increase in magnetization is associated with the amorphous material state at the recrystallization stage with the emergence of finely dispersed precipitates of the crystalline phase as a result of decomposition of the amorphous matrix [5]. Such a change in magnetic characteristics may be caused by the intensification of effective magnetic field at iron nuclei and a change in the number of electronic states  $t_{2g}$ .

Thermal treatment leads to relaxation of atomic positions in the bulk of the material, making the initial amorphous state less „loose“ and enhancing magnetization [6,7]. The degree of ordering of the atomic and electronic systems of the 2NSR alloy was found to increase (relative to its state immediately after spinning) after combined thermal treatment in a magnetic field and ESF treatment, which may lead to an enhancement of tape magnetization in comparison with its magnetization in the as-prepared state.

The aim of the present study is to investigate the magnetic properties of the 2NSR alloy in the as-prepared state and after 5 and 7 min of thermomagnetic treatment at  $540^\circ\text{C}$ .

The 2NSR alloy of the following composition (at.%) was examined: Fe — 78, Ni — 1, Si — 8, B — 13, and small additions of Nb ( $\sim 0.8$  at.%) and Cu ( $\sim 0.3$  at.%).

A VSM-250 vibration magnetometer was used to determine the saturation induction. The recorded magnetization curves are the dependences of specific magnetization  $\sigma$  [ $\text{A} \cdot \text{m}^2/\text{kg}$ ] on field strength  $H$  [Oe]. The vibration magnetometer data were processed using the Model DJAW2000 [8,9] code.

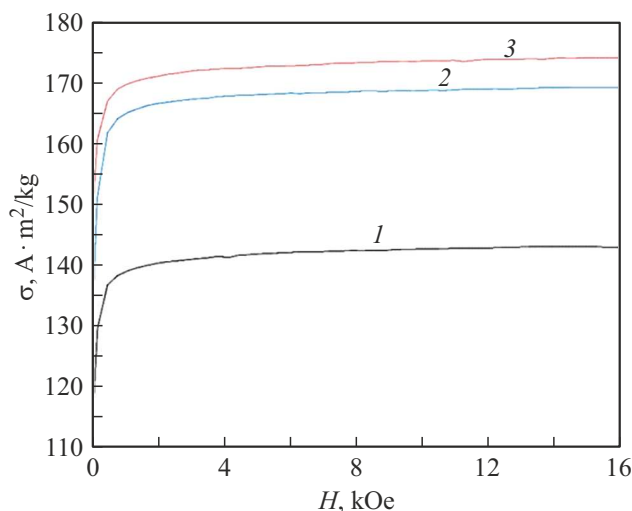
The structure and phase composition of the 2NSR tape were studied using transmission electron diffraction microscopy (JEOL JEM-2100F device). Foils studied with this microscope were produced by ion thinning with argon ions (Ion Slicer EM-091001S setup) of plates cut normally to the modification surface from bulk samples using an Isomet Low Speed Saw cutter. This made it possible to trace the changes in structure of the elemental and phase composition of the material with distance from the sample surface (coating surface).

The saturation magnetization of iron-based amorphous alloys tends to increase consistently under certain ESF treatment conditions. The 2NSR alloy doped with Nb was subjected in [3] to ESF treatment in a transverse magnetic field with simultaneous application of an elastic load codirectional with the magnetic field, and the saturation magnetization was found to increase by more than 20% (the measurements were carried out at liquid nitrogen temperature).

In the present study, room-temperature measurements for the 2NSR alloy with small additions of Nb ( $\sim 0.8$  at.%) and Cu ( $\sim 0.3$  at.%) revealed an increase in saturation magnetization achieved due to elastic loading during cooling, which is evident from the data presented in Fig. 1. The magnetization increased by  $\sim 15\%$  after 5 min of ESF treatment at  $540^\circ\text{C}$  and by  $\sim 20\%$  after 7 min of ESF treatment at  $540^\circ\text{C}$ .

It can be assumed that this change in fundamental parameters, namely the anomalous growth of saturation magnetization [4,5], is associated with the state of the amorphous structure at the pre-crystallization stage with the emergence of finely dispersed precipitates of the crystalline phase as a result of decomposition of the amorphous matrix.

The electron microscopic images of the 2NSR alloy structure shown in Fig. 2 indicate that the material under



**Figure 1.** Variation of saturation magnetization with magnitude of the external magnetic field for the 2NSR alloy samples. 1 — As-prepared state; 2, 3 — ESF treatment for 5 and 7 min, respectively.

study is amorphous. This is made clear by the structure of the electron microdiffraction pattern, which features two diffuse halos (Fig. 2, *b*). A more detailed examination of the tape structure revealed rounded inclusions distributed in a chaotic manner. The small size (1.5–2.5 nm) and low concentration of such inclusions preclude us from recording their microdiffraction pattern, which could potentially lead to a conclusion regarding the formation of second-phase inclusions and result in determination of their phase composition.

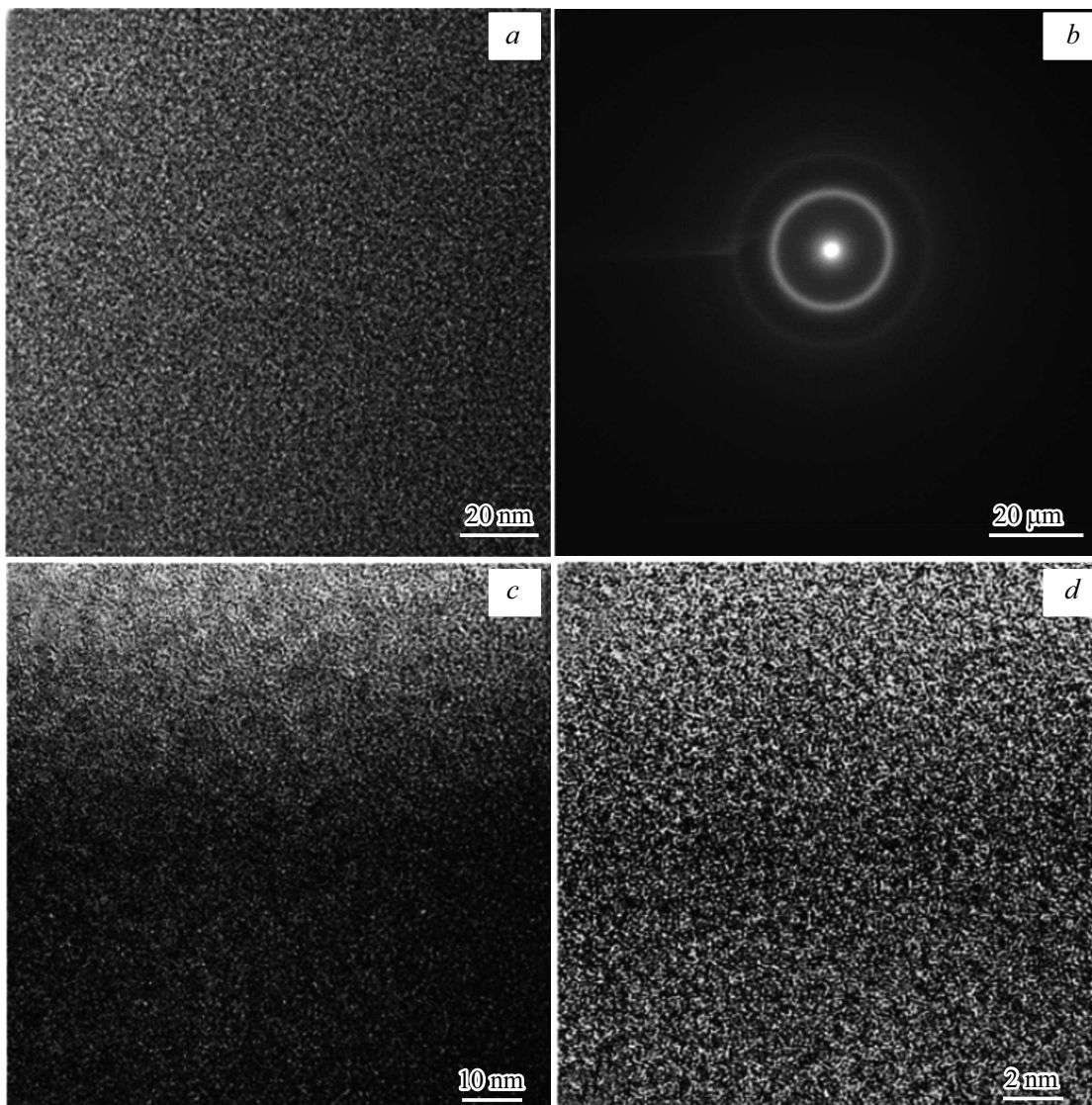
In certain cases, regions 1.5–3 nm in size with an ordered arrangement of electron-beam scattering centers are revealed in the structure of the studied tape. This is indicative of the initial stage of crystallization of the amorphous material state. According to the results of mechanical testing with an Instron 5582 machine, uniaxial tension failure was of a brittle nature and occurred at low degrees of deformation ( $\sim 0.6\%$ ), which is quite consistent with the amorphous state of the alloy under study [10–12].

Room-temperature measurements for the 2NSR alloy with small additions of Nb ( $\sim 0.8$  at.%) and Cu ( $\sim 0.3$  at.%) revealed an increase in saturation magnetization achieved due to elastic loading during cooling. It was demonstrated that the anomalous growth of saturation magnetization is associated with the state of the amorphous structure at the pre-crystallization stage with the emergence of nanosized (1.5–2.5 nm) precipitates of the crystalline phase as a result of decomposition of the amorphous matrix and the formation of nanosized (1.5–3 nm) regions with an ordered arrangement of atoms (Figs. 3, 4).

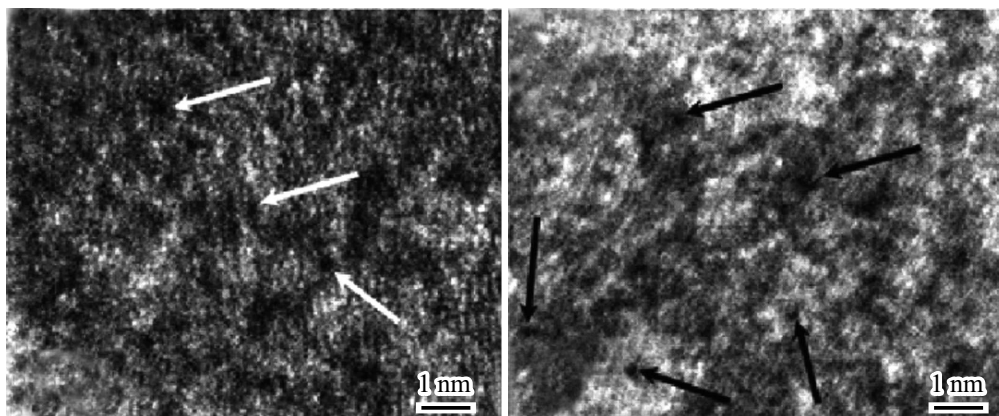
Further research should reveal the effect of production parameters of a tape with this composition on the size, topology, and number of nanoscale precipitates in the initial quenched state. The influence of heating and cooling rates, magnitude and direction of the magnetic field, and magnitude and sign of the specific load on the structural parameters and magnetic properties of the amorphous tape after treatment needs to be studied. It is also necessary to investigate the crystal structure and crystallographic parameters of nanoscale cluster precursors and their magnetic characteristics. In the near future, we plan to examine the possibility of synthesis of soft magnetic amorphous and nanocrystalline Fe–Si–B–P, Fe–Si–Nb–B, and Fe–Ni–Nb–B alloys with nanosized ultradispersed clusters and study their properties. The results reported above may help produce electronic devices with an extended frequency range, high magnetic induction, and low coercive force.

### Conflict of interest

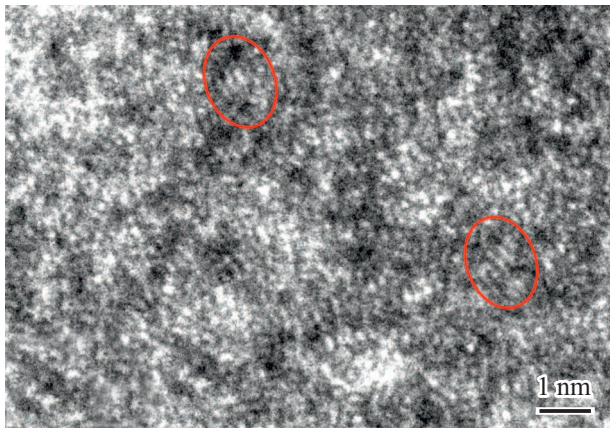
The authors declare that they have no conflict of interest.



**Figure 2.** Electron microscopic images of the structure of the 2NSR tape after 7 min of thermomagnetic treatment at 540 °C. *a, c, d* — Bright-field images with different magnifications; *b* — electron microdiffraction pattern of the region shown in panel *a*.



**Figure 3.** Electron microscopic images of the structure of the 2NSR tape after 7 min of thermomagnetic treatment at 540 °C. Arrows indicate particles of (presumably) the second phase.



**Figure 4.** Electron microscopic image of the structure of the 2NSR tape after 7 min of thermomagnetic treatment at 540 °C. Regions with a quasi-ordered arrangement of scattering centers are highlighted.

## References

- [1] I.B. Kekalo, *Protsessy strukturnoi relaksatsii i fizicheskie svoistva amorfnykh splavov* (Izd. Dom MISiS, M., 2016), Vol. 2 (in Russian).
- [2] A.P. Semin, V.E. Gromov, Yu.F. Ivanov, S.V. Panin, V.V. Sosnin, P.S. Mogil'nikov, I.S. Litovchenko, I.D. Selivanov, *Probl. Chern. Metall. Materialoved.*, No. 4, 64 (2024) (in Russian). DOI: 10.52351/00260827\_2024\_4\_64
- [3] B.A. Kornienkov, E.B. Artamonov, *Steel Transl.*, **39** (6), 518 (2009).
- [4] B.A. Kornienkov, M.A. Libman, B.V. Molotilov, D.I. Kadyshchev, *Stal'*, № 3, 90 (2015).
- [5] V.V. Vavilova, V.P. Korneev, B.A. Kornienkov, M.A. Libman, B.V. Molotilov, D.I. Kadyshchev, *Steel Transl.*, **46** (8), 606 (2016).
- [6] E. Matsubara, S. Sato, M. Imafuku, T. Nakamura, H. Koshiba, A. Inoue, Y. Waseda, *Mater. Sci. Eng. A*, **312**, 136 (2001). DOI: 10.1016/S0921-5093(00)01903-1
- [7] W. Yang, H. Liu, Y. Zhao, A. Inoue, K. Jiang, J. Huo, H. Ling, Q. Li, B. Shen, *Mech. Sci. Rep.*, **4**, 6233 (2014). DOI: 10.1038/srep06233
- [8] R.E. Hummel, *Understanding materials science: history, properties, applications* (Springer, N.Y., 1998).
- [9] J.W. Yeh, Y.L. Chen, S.K. Chen, *Mater. Sci. Forum*, **560**, 1 (2007). DOI: 10.4028/www.scientific.net/MSF.560.1
- [10] A.M. Glezer, B.V. Molotilov, *Struktura i mekhanicheskie svoistva amorfnykh splavov* (Metallurgiya, M., 1997) (in Russian).
- [11] F.E. Lyuborskii, *Amorfnye metallicheskie splavy* (Metallurgiya, M., 1987) (in Russian).
- [12] K. Suzuki, H. Fujimori, K. Hashimoto, *Amorfnye metally* (Metallurgiya, M., 1987) (in Russian).

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