

Effect of deformation by equal-channel multiangle pressing on functional properties of NbTi-based superconductor

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Influence of predeformation by the equal-channel multiangle pressing combined with hydroextrusion, drawing and heat treatment on structure and physico-mechanical properties of superconducting Nb + 60 at.% Ti alloy wire has been investigated. Effect of deformation on pinning force in the alloy has been estimated.

Исследовано влияние величины предварительной деформации методом равноканального многоуглового прессования в сочетании с гидроэкструзией, волочением и термообработкой на структуру и физико-механические свойства сверхпроводящей проволоки на основе сплава Nb + 60 ат.% Ti. Произведена оценка влияния деформации на силу пиннинга в сплаве.

The unconventional plastic deformation methods such as reverse twisting, tension-twisting, alternating bending, equal-channel angular pressing make it possible to deform a metal billet, with no changes in geometrical dimensions, in complex loading conditions with unloading stages and deformation sign (direction) alternation [1–4]. This results in high degrees of deformation, refinement and homogenization of the structure and, finally, in changes of physical and mechanical properties.

The variation regularities of the metal properties typical of the sign-alternating deformation differ considerably from those under a monotonous deformation. It is known [5, 6] that the nonmonotonous cold deformation by equal-channel multiangle pressing (ECMAP) followed by monotonous deformation by hydroextrusion (HE) combined with drawing and heat treatment results in improved functional properties of a NbTi alloy due to a more homogeneous nanostructure with equiaxed β-phase grains and nanodisperse precipitations of the secondary α-phase formed in the alloy.

This paper is aimed at the investigation of the effect of preliminary ECMAP deformation value on phase composition, structure and properties of the NbTi alloy as well as at determining the rational mode of ECMAP deformation.

The bimetallic rods of Nb + 60 at.% Ti alloy in a copper matrix prepared by hot-pressing at 750°C were used as the initial billets. This alloy is a two-phase composition with β-solid solution with bcc lattice, which is the major phase, and a small volume fraction (~ 1 %) of hexagonal α-phase.

Some billets were deformed by HE to a diameter of 3.6 mm with the unit deformation degree $e \le 1.2$, then they were drawn with partial deformations $e \le 0.2$ to form a superconducting wire of 0.3 mm in diameter. The other billets were processed by ECMAP with the accumulated deformation value $e = 3.28$ (4 passes); 6.56 (8 passes), 9.84 (12 passes), and 13.12 (16 passes), then deformed by HE and drawing under the above regimes and routes with the total value of monotonous shape change $e = 7.82$.

The 80 mm long specimens were deformed by ECMAP at a laboratory plant [7]. The ECMAP was done by squeezing a billet through a 3-angle deforming system having four intersecting channels of equal section with the intersection half-angles $\theta_1 = 80°$, $\theta_2 = 70°$, $\theta_3 = 80°$ and deformation degree per pass $e_1 = 0.82$. To form an equiaxial structure of the alloy, the billet, in each subsequent pressing cycle, was rotated through an angle of 180° with respect to the transverse axis and through 90° with respect to the longitudinal axis. The specimens to be investigated were taken past the number of passes multiples of four.

The phase analysis was performed and fine structure parameters (microstress values, $\Delta a/a$, and size of coherent scattering regions, D_{csr}) were determined using an X-ray diffractometer (DRON-YM1) using quantitative and qualitative analysis methods. The measurement errors for secondary α-phase content (n_α) and fine-structure parameters were about 1 % and 10 %, respectively. The copper enclosure was pickled away prior to preparation of samples for X-ray studies. Microhardness, H_μ, was measured by a PMT-3 instrument at a load of 0.5 N with experimental error of 2.5 %. The mechanical properties (yield strength σ_b and elongation δ) of the bimetallic copper-stabilized superconducting wire were estimated under tensile test of 200 mm long specimens using a tensile-testing machine ZM-20, in this case, the relative measurement error was 2.5 %. The critical current density for the wire (length up to 200 mm and diameter 0.3 mm) specimens in the deformed and heat-treated states was measured at 4.2 K in transverse external magnetic fields up to 12 T (the criterion being 0.1 μV/cm). The final heat-treatment (HT) of the deformed specimens was done in vacuum of (10^{-5} mm Hg) at 400°C for 1 h.

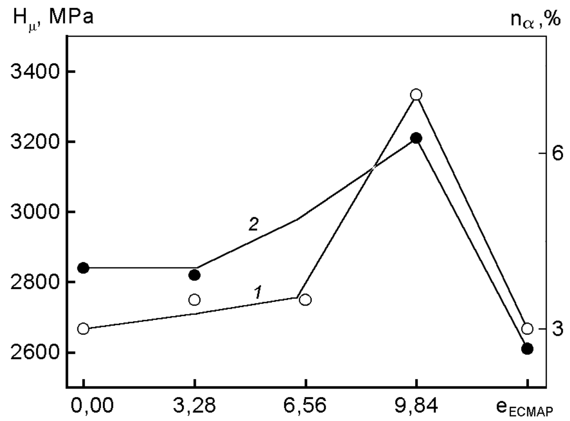

Fig. 1. Dependences of α-phase content (*1*) and microhardness (*2*) of 60T alloy on ECMAP deformation value.

The 60T alloy is known to be within the two-phase region of the NbTi system phase diagram, it may contain the inclusions of secondary phases in β-solid solution. The X-ray diffraction analysis of semifinished items and finished product confirmed the presence of secondary α-phase in the material. The increase of the ECMAP deformation degree to $e = 9.84$ results in a 7 % increase of α-phase volume content (Fig. 1, curve *1*). It is seen that there exists a rather narrow region of the ECMAP deformation degrees ($e = 9.84$) where the volume content of α-phase reaches its maximum. For other deformation degrees, the α-phase content decreases drastically. Such a dependence has been already observed in [8], where the influence of hydropressing parameters was studied. In that case, the dependence was associated with the favorable structure-stressed state formed.

After the combined processing, the alloy is in highly deformed fine-crystalline state. The CSR size decreases with the increase of accumulated strain value resulting from of ECMAP (Fig. 2), it becomes equal to 60 and 55 nm for $e = 9.84$ and 13.12, respectively. The dependence of II order microstresses on the ECMAP deformation degree is not monotonous with $\Delta a/a$ minimum of $1.72 \cdot 10^{-3}$ for $e = 9.84$. The fine structure parameters of alloy samples obtained without ECMAP are: $D_{csr} = 70$ nm, $\Delta a/a = 1.91 \cdot 10^{-3}$.

The character of the microhardness dependence of on ECMAP deformation value (Fig. 2, curve *2*) correlates with the character of changes in α-phase content. Hence, it

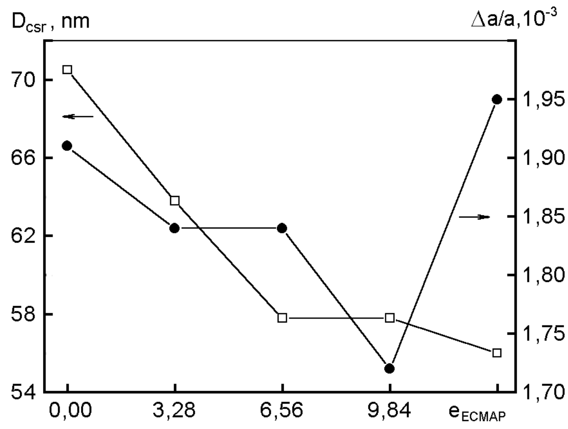

Fig. 2. Dependences of fine-structure parameters for 60T alloy on ECMAP deformation value.

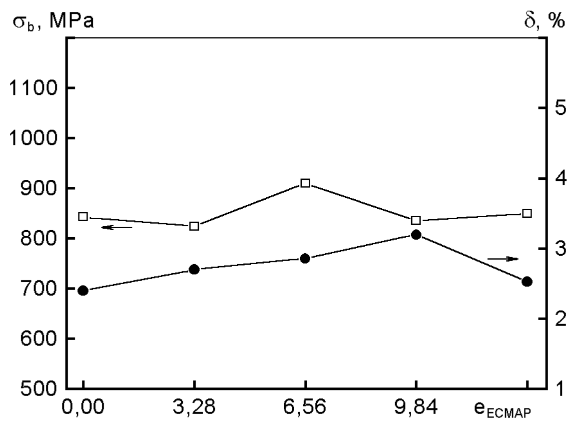

Fig. 3. Dependences of mechanical properties on ECMAP deformation value for a 60T alloy based bimetal superconductor.

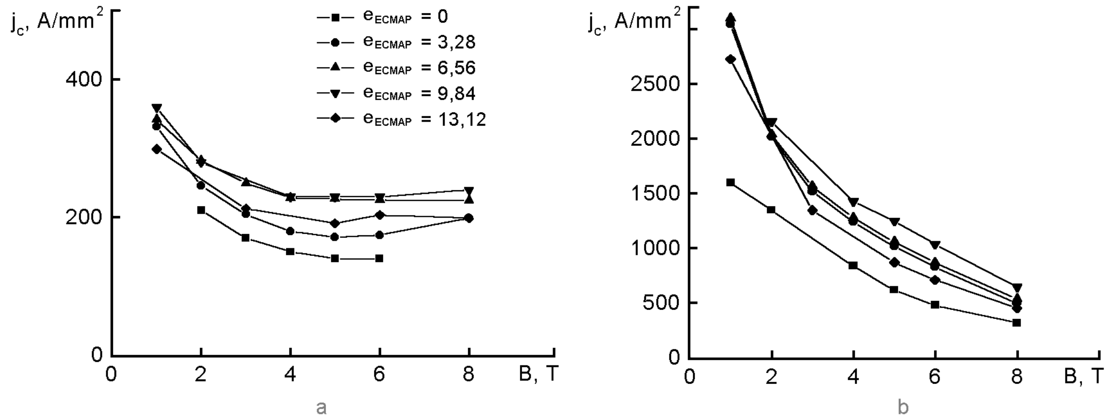

Fig. 4. Dependences of the critical current density for a 60T alloy based bimetal superconductor on magnetic field for different of ECMAP deformation values in deformed (a) and heat-treated (b) states.

can be assumed that the increase in microhardness due to the increase in the quantity of of fine-disperse secondary α-phase precipitations in the volume of ECMAP-created isotropic structure which has been then reorganized by hydroextrusion and drawing.

The tensile tests of the wire specimens show that by varying the ECMAP deformation degree, the highest plastic properties and high enough strength are attained for $e = 9.84$ (Fig. 3). The plasticity decreases in cases of high degrees of deformation. This feature can be explained by the above-mentioned changes in the phase composition and in the structure-stressed state (Figs. *2*, *3*) as well as by the lowering of the isotropic strain hardening effect.

The superconductor specimens obtained using the ECMAP possess higher current characteristics in the whole magnetic field range as compared to the superconductor produced without ECMAP (Fig. 4a, b). The dependences are unmonotonous having a maximum at $e = 9.84$ (Fig. 5). The introduction of ECMAP at $e = 9.84$ into the technology of superconducting wire production gives a 65 % increase of the critical current density for the deformed specimens in the magnetic field of 5 T. The accumulation of deformation by ECMAP to $e = 9.84$ combined with final heat treatment (400°C, 1 h) results in a doubled increase of the critical current density.

Investigation of magnetic field effect on the pinning force F_p (Fig. 6a, b) show that the pinning mechanism is different in low and high magnetic fields. The pinning force was determined as $F_p = J_c \cdot B$, where J_c is the critical current density; B, the corresponding magnetic field. For 60T alloy, the experimentally determined upper critical magnetic field B_{C2} makes 12 T. The maximum of pinning force F_p is at different values of the reduced magnetic induction

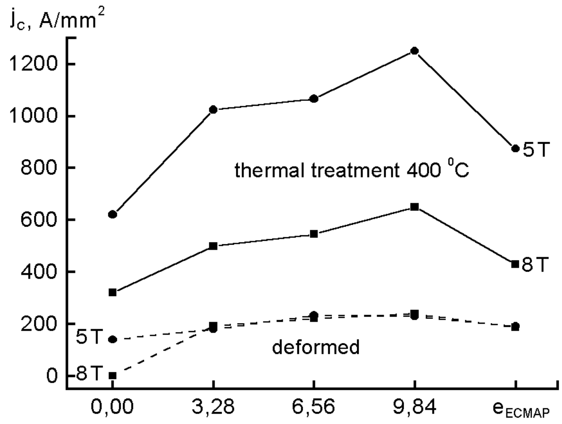

Fig. 5. Dependences of the critical current density for a 60T alloy based bimetal superconductor on ECMAP deformation values.

B/B_{C2} depending on the processing parameters. For alloy specimens deformed using ECMAP at $e = 9.84$, the maximum F_p value is at $B/B_{C2} = 0.65$ (Fig. 6a), whereas after heat treatment, the F_p maximum is at $B/B_{C2} = 0.41$ (Fig. 6b). For specimens obtained without ECMAP, the pinning force absolute values are lower, and for the deformed and heat-treated state, its maxima are at $B/B_{C2} = 0.49$ and 0.33, respectively. The increase of magnetic-flux pinning force, the shift of F_p maximum towards laver magnetic fields, as well as the broadening of the pinning force maximum values region result from refinement and homogenization of the structure under the influence of combined plastic deformation, changes in morphology and volume content of phase precipitations under the heat treatment [5, 9]. For the alloy specimens processed by ECMAP at $e = 9.84$, F_p max is in the wide range of reduced magnetic fields $B/B_{C2}\approx 0.3$ to 0.6 at the level of 6 GN/m^3, being twice as much as the pinning force maximum value for specimens obtained without ECMAP.

These results show the ECMAP to be effective for structure rearrangement. The additional accumulated deformation due to the ECMAP application seem to result in the formation of a structure with effective pinning centers [5, 6], which is favorable for the increase of critical current. Nanograins, grain boundaries and nanodisperse precipitations of α-Ti are in fact the effective pinning centers to equal degree, moreover, the size of structural inhomogeneities formed during deformation and heat treatment are likely comparable with the coherence length [10].

To conclude, the inclusion of ECMAP into the processing scheme of 60T superconducting alloy results in a considerable increase of the critical current density. In the range of deformation values under investigation (e = 0 to 13.12), the maximum of the critical current density due to structural and phase changes is observed. The ECMAP deformation degree ($e = 9.84$) has been determined providing the improvement of such 60T alloy properties as strength, plasticity, microhardness, and critical current density.

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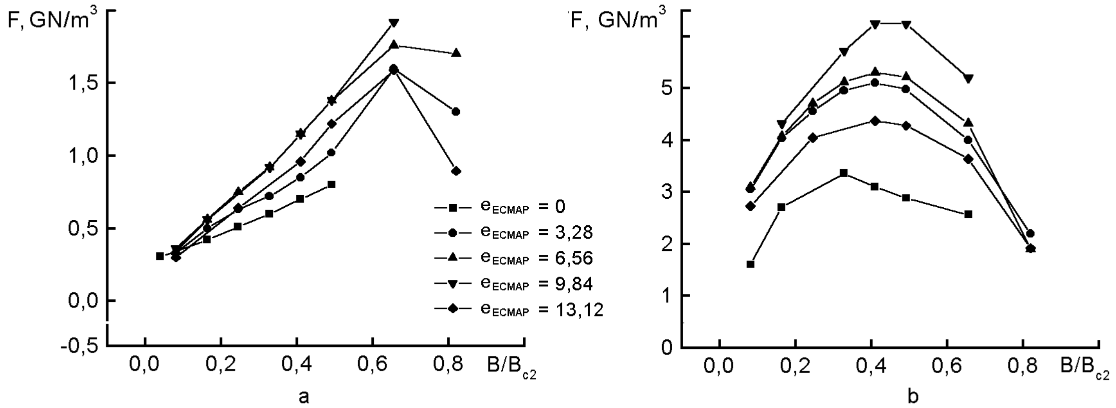

Fig. 6. Dependences of the pinning force for a 60T alloy based bimetal superconductor on reduced magnetic induction for different values of deformation by ECMAP in deformed (a) and heat-treated (b) states.

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Вплив деформації рівноканальним багатокутовим пресуванням на функціональні властивості надпровідника на основі сплаву NbTi

В.О.Білошенко, В.П.Дьяконов, В.В.Чишко, М.І.Матросов, О.М.Миронова, Д.Гайда, А.Залеський, Р.Пужняк

Досліджено вплив величини попередньої деформації методом рівноканального багатокутового пресування у сполученні з гідроекструзією, волочінням і термообробкою на структуру й фізико-механічні властивості надпровідного дроту на основі сплаву Nb + 60 ат. % Ti. Зроблено оцінку впливу деформації на силу пінінгу у сплаві.