

The second critical magnetic field of multilayered conductors with nano-layers of superconducting Nb–Ti alloys

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Multilayer tapes containing Nb–Ti (30 and 31 wt. %) alloy layers separated by niobium layers has been investigated. The thickness of layers was from ~140 to 10 nm. The tapes were produced by the 3-cycle rolling of the multilayered packets. The effective pinning of the vortice threads was occurred at the interlayer Nb/NbTi boundaries. The second critical magnetic field has been found to decrease with decreasing thickness of the layers. At small layer thickness, its value depended on the tape rolling plane orientation with respect to external magnetic field. The results are explained by the proximity effect.

Исследованы многослойные ленты, содержащие слои из сверхпроводящих сплавов ниобия с 30 и 31 масс.% Ti, разделенных слоями ниобия. Толщина слоев — от ~140 до ~10 нм. Ленты получали 3-этапной прокаткой многослойных пакетов. Эффективное зацепление сверхпроводящих вихревых нитей происходило на межслойных границах Nb–NbTi. Установлено, что второе критическое магнитное поле уменьшалось с уменьшением толщины слоев. При малой толщине слоев его величина зависела от ориентации плоскости прокатки ленты относительно внешнего магнитного поля. Результаты объясняются эффектом близости.

1. Introduction

In the mixed state of type II superconductors, a magnetic field can penetrate into a sample as quantum vortice threads. The vortices have a normal core with a radius about coherence length ξ and extend along the magnetic field direction. Around the vortices, a superconducting current flows in area with a radius about the magnetic field penetration depth λ which can exceed ξ considerably.

A Lorentz force acts on the vortices when an electric current flows through superconductor. The vortices should start to move at an indefinitely small Lorentz force in a superconductor free of structural defects that results in energy dissipation, so the superconductor loses the possibility to conduct the electric current. However, there are structural defects in any real superconductors at which the vortices are pinned. The pinning efficiency depends on the size and character of defects. The most effective pinning centers capable to provide a high critical current density j_c in a superconductor are normal metal inclusions of the size about ξ. Smaller defects, such as vacancies, single atom defects et al., are not the efficient pinning centers.

Theoretical consideration of the interaction between the vortices and the superconductor surface has shown that the borders of superconductor layers are the effective pinning centers [1]. Therefore, a layered structure where superconducting layers al-

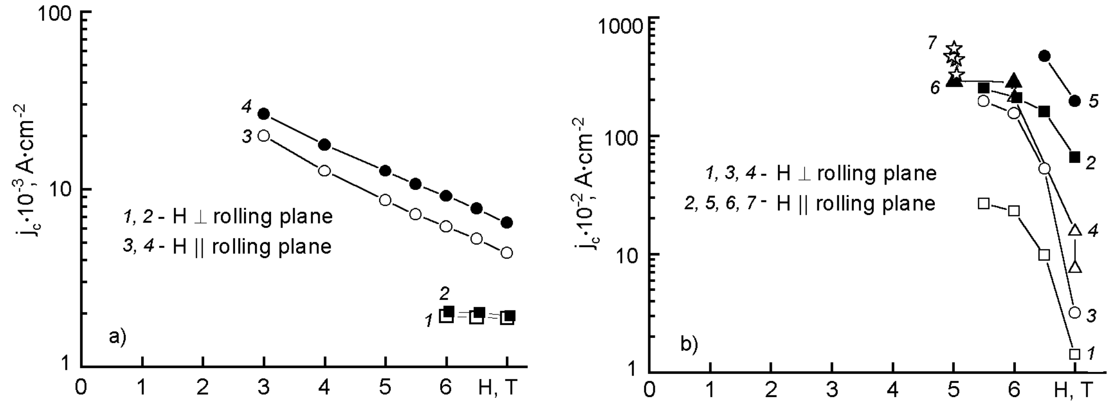


Fig. 1. Dependences $j_c(H)$ for Cu/Nb/Nb31Ti composites at 4.2 K: *a* and *b*, the Nb and alloy layer thickness ~91 and ~138 nm, ~8 and ~12 nm, respectively.

ternate with those of a dielectric or a normal metal are capable to carry a rather high superconducting current of about 10^5 A/cm^2.

In our previous work [2], such a layered structure has been realized in multilayered Cu/Nb composites where niobium layers alternate with copper ones. Measurements in 0.5–0.6 T magnetic fields have shown that in case of parallel orientation of the magnetic field and the layer plane, j_c is 410 times higher than at the perpendicular orientation [2]. The large anisotropy of critical current density testifies to the vortex pinning on extended flat copper/niobium bundaries. Further similar results have been obtained in multilayered tapes with superconducting niobium-titanium alloy layers [3, 4].

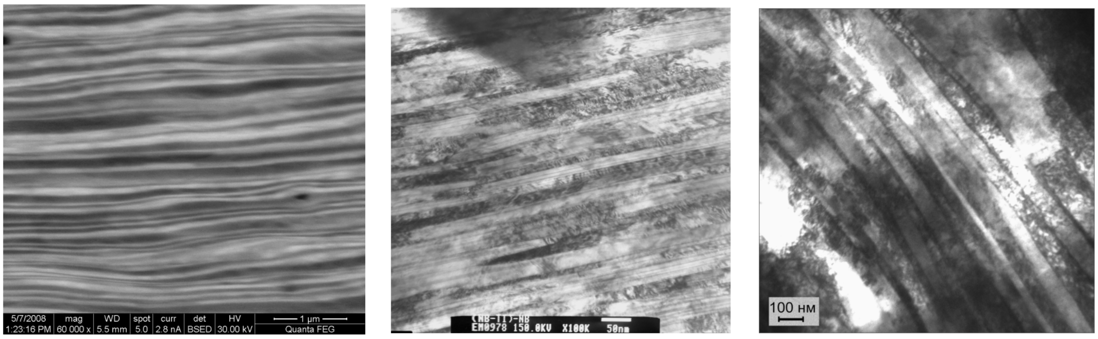
The critical current density j_c increases with the layer thickness reduction because of increasing density of boundaries being the pinning centers. However, in the multilayered tapes with very small layer thickness ($d \le 12$ nm), j_c exceeded that in those of a greater thickness only in rather small magnetic fields $H < 6$ T. In higher fields $H > 6$ T, the j_c value for the multilayered tapes with $d \le 12$ nm decreases sharply (Fig. 1,b) and becomes lower than that in the multilayered tapes with thicker layers of $d \approx 80-140$ nm (Fig. 1,a). The sharp j_c reduction in the high fields $H > 6$ T may be connected with the reduction of second critical magnetic field H_{c2} of the multilayered tapes with thin layers $d \approx 12$ nm. In order to verify this assumption, we have measured the second critical field H_{c2} of the multilayered tapes containing the minimal and maximal number of layers.

2. The study object

Studied were multilayered Cu/Nb/NbTi tapes where the layers of Nb-30 and 31 wt. % Ti alloys of nano-dimensional thickness alternate with niobium layers. Copper was contained in the composite as two external layers.

The tapes were prepared using stage-by-stage rolling [5]. Each stage included the assembling of a multilayered packet, its hot rolling and following rolling at room temperature. At the first stage, the packet was collected from niobium and an alloy foils. To obtain a set of multilayered tapes with various thickness of separate layers, the initial packets are formed of various numbers of niobium and a niobium-titanium alloy foils. For example, for composite Cu/Nb/Nb31Ti with the minimal number of layers (675 niobium, 540 the alloy) thus, with their maximal thickness, the number of Nb foils was 5, the number of alloy ones, 4. For a tape with the maximal number of layers (7440 — Nb, 6975 — an alloy) and their minimal thickness, the initial number of Nb foils was 16, the number of alloy foils, 15. At the second stage, the packet was collected from 9 and 31 multilayered foils of of 0.3 mm thickness obtained after the first stage. At the third stage, the packets consisted of 15 multilayered tapes obtained after the second stage, and copper foils for both composites. To finish the thickness of niobium and alloy layers to ~5 and ~2.5 nm, respectively, the Cu/Nb/Nb31Ti composite with the maximal number of layers was rolled additionally down to 0.15 and 0.075 mm thickness.

Fig. 2,a shows the cross-section microstructure of the multilayered tape containing 2730 niobium layers and 2340 Nb-



a b c

Fig. 2. Cross-section microstructure of multilayered Cu/Nb/Nb31Ti tapes: *a*, raster electronic microscopy, unannealed; *b* and *c*, transmission electron microscopy after annealing at 360°C for 3 h.

31 wt.% Ti ones. The section is arranged along the rolling direction. Under raster electron microscope, the niobium layers look as light strips, the alloy ones are dark. The microstructure photo (Fig. 2, b and c) obtained using transmission electron microscopy shows that the layers are not intermixed after cold deformation and low-temperature annealing. The estimated thickness of layers in this tape did not exceed 100 nm, and in most cases amounted 50–60 nm that corresponded well to the calculated thickness of niobium and alloy layers.

3. Measurement of the second critical magnetic field

The second critical magnetic field H_{c2} was determined experimentally by measuring H_{c2} near the critical temperature T_c [6], that is, at fixed values of magnetic field H produced by a superconducting solenoid. The measuring current was about 1 mA. The superconducting transition temperature was measured using positions of the resistive transitions shown in Fig. 3. The $H_{c2}(T)$ dependence was further plotted, being linear near the critical temperature. Then the slope $(-dH_{c2}/dT)_{T=Tc}$ was calculated. The second critical magnetic field was found using the formula $H_{c2}(0) = 0.69T_c (-dH_{c2}/dT)_{T=Tc}$ [6]. The H_{c2} at 4.2 K amounts ~0.95 of the H_{c2} value at 0 K. The second critical field H_{c2}, as well as the critical current (see Fig. 1) was measured both at perpendicular (*1* and *2*) and parallel (*3* and *4*) orientations rolling plane with respect to the magnetic field direction (Fig. 4).

4. Experimental results

The data of measurements as well as the $(-dH_{c2}/dT)_{T=Tc}$ and H_{c2} (4.2 K) values are summarized in the Table. In the three upper

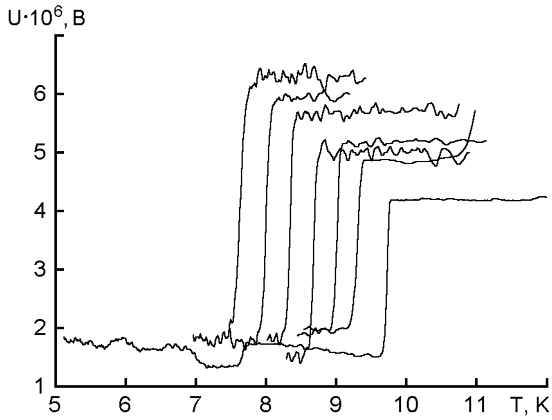


Fig. 3. Superconducting transitions of the Cu/Nb/Nb31Ti composite measured by a resistive method at the measuring current ~1 mA at different values of the magnetic field perpendicular to rolling plane (from right to left): 0; 0.5; 1; 1.5; 2; 2.5 and 3 T. Annealing: 360°C for 3 h.

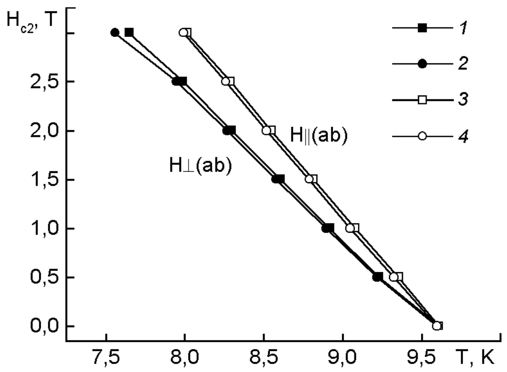


Fig. 4. Dependences $H_{c2}(T)$ for Cu/Nb/Nb30Ti composites at perpendicular (*1* and *2*) and parallel (*3* and *4*) rolling plane orientations relative to magnetic field direction: *1* and *3*, after cold deformation; *2* and *4*, after cold deformation and annealing at 250°C for 295 h. The tape thickness 0.15 mm. See Table, lines 6 and 7.

Table. Results of H_{c2} measurements near T_c

Sample characteristic	$(-dH_{c2}/dT)_{T=Tc}$, T/K		H_{c2}(4.2 K), T	
	$H \perp$ rolling plane	$H \parallel$ rolling plane	$H \perp$ rolling plane	$H \parallel$ rolling plane
1. 9100/91/138 nm Cu/Nb/Nb31Ti annealed at 360°C, 2 h	2.17	2.21	13.8	14.2
2. 9400/8/12 nm Cu/Nb/Nb31Ti unannealed	1.50	1.82	9.7	11.8
3. The same as No.2 but annealed at 360°C, 3 h	1.46	1.78	9.4	11.5
4. 0.3 mm thick tape of Nb-31 %Ti alloy unannealed	2.34	2.27	15.2	14.8
5. ~27800 layers 9.6 nm Cu/Nb31Ti/Nb31Ti Anneal 300°C, 2 h	2.39	2.36	15.4	15.3
6. 8600/3.6/5.4 nm Cu/Nb/Nb30Ti unannealed	1.60	1.88	10.0	11.8
7. The same annealed at 250°C, 295 h	1.54	1.87	9.6	11.8
8. The same annealed at 600°C, 5 h	1.57	1.68	9.9	10.7
9. The same annealed at 600°C, 5 h + 250°C, 295 h	1.57	1.71	9.9	10.9
10. The same annealed at 350°C, 285 h	1.44	1.75	9.0	11.0
11. 8600/7/10.5 nm Cu/Nb/Nb30Ti annealed 350°C, 285 h	1.51	1.75	9.4	10.7

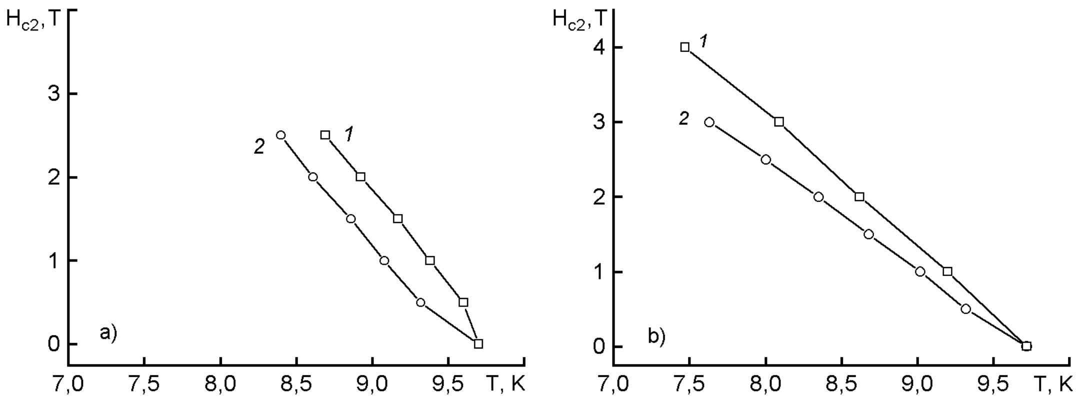


Fig. 5. Dependences $H_{c2}(T)$ for Cu/Nb/Nb31Ti composites with the alloy layer thickness 138 (*a*) and 12 nm (*b*) at parallel (*1*) and perpendicular (*2*) rolling plane orientations relative to magnetic field direction. Annealing: 360°C, 3 h.

lines of the Table, we compare the measurement results for Cu/Nb/Nb31Ti composites having different thickness of layers. The following lines present the data for a "single-layered" tape of Nb-31 %Ti alloy (1), Cu/Nb31Ti/Nb31Ti composite (2) and Cu/Nb/Nb30Ti composites heat treated in various manners (3). The number of 9.6 nm thick Nb-31 %Ti layers in Cu/Nb31Ti/Nb31Ti composite was 27791, thus approximately corresponded to the total number of niobium and alloy layers in Cu/Nb/Nb31Ti composite. The composite Cu/Nb/Nb30Ti are subjected to low temperature annealing after the deformation at the room temperature and after heat treatment at 600°C. All the samples had approximately identical critical temperatures in zero magnetic field. For Cu/Nb/Nb31Ti composite with layers of Nb–Ti alloy of minimal (11.8 nm) thickness, anisotropy of second critical field with respect to the orientation of layers in magnetic field was observed. The slope of $H_{c2}(T)$ dependence and consequently H_{c2}(4.2 T), at the rolling plane orientation perpendicular

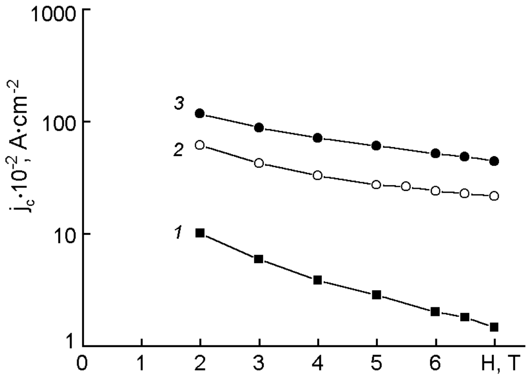


Fig. 6. Dependences $j_c(H)$ at 4.2 K for multilayered tape free of Nb-layers at perpendicular (*1*) and parallel (*2* and *3*) rolling plane orientations relative to magnetic field direction after rolling (*2*) and after rolling and annealing at 300°C for 2 h (*1* and *3*).

to magnetic field direction was appreciably less than for parallel orientation (Fig. 5, b). Such anisotropy was not observed for a composite with maximal (137.6 nm) thickness of layers (Fig. 5, a).

The measurements have confirmed the above-mentioned reduction of the second critical field in composite tapes with thin layers. For the parallel orientation, H_{c2}(4.2 K) = 11.8 T for the tape with the minimum layer thickness $d \approx 12$ nm is appreciably lower than for a "single-layered" (massive) tape of Nb-31 %Ti alloy (14.8 T) and tapes with the Nb-31 %Ti layer thickness $d \approx 138$ nm (14.2 T). The annealing at 360°C resulting in the α-phase segregation in alloy layers practically has not changed the second critical field being 11.5 T. In case of the rolling plane perpendicular to magnetic field, the H_{c2} reduction was even more: H_{c2}(4.2 K) = 13.8 T at $d \approx 138$ nm and 9.7 T at $d \approx 12$ nm.

The critical current density j_c for the Cu/Nb31Ti/Nb31Ti composite in magnetic fields 5–6 T (Fig. 6) was by the order lower than in tapes with Nb-layers (see Fig. 1, b). However, no sharp j_c drop starting from 6.5 T it was not observed. The dependences $H_{c2}(T)$ for the Cu/Nb31Ti/Nb31Ti tape show substantially the same slope $(-dH_{c2}/dT)_{T=Tc}$ = 2.36–2.39 T/K at different tape plane orientations in magnetic field (Fig. 7, a) and thus the same H_{c2} (4.2 K) = 15.3–15.4 T. The values of $(-dH_{c2}/dT)_{T=Tc}$ and H_{c2} (4.2 K) for the Cu/Nb31Ti/Nb31Ti composite do not differ from similar parameters for a 0.3 mm thick "single-layered" alloy Nb-31 %Ti tape (Fig. 7, b).

Thus, our measurements have confirmed that the second critical magnetic field H_{c2} of the Cu/Nb/Nb31Ti composite tapes containing Nb layers decreases at small layer thickness $d \approx 12$ nm comparable with the superconductor coherence length $\xi(T)$ [1]. The measurements have shown also that H_{c2} of the Cu/Nb31Ti/Nb31Ti composite formed only by Nb-31 %Ti alloy, superconducting in the high magnetic fields, coincides with H_{c2} of a massive tape of the same alloy. Therefore, it is obvious that significant decrease of H_{c2} in the Cu/Nb/Nb31Ti composite should be connected with the presence of Nb layers which is in normal (not superconducting) state at high magnetic fields and that decrease can be explained by the proximity effect. The Nb layers having a low second critical field and consequently thus being in the normal state in high magnetic fields, suppress the superconductivity in Nb-31 %Ti layers in the depth about the coher-

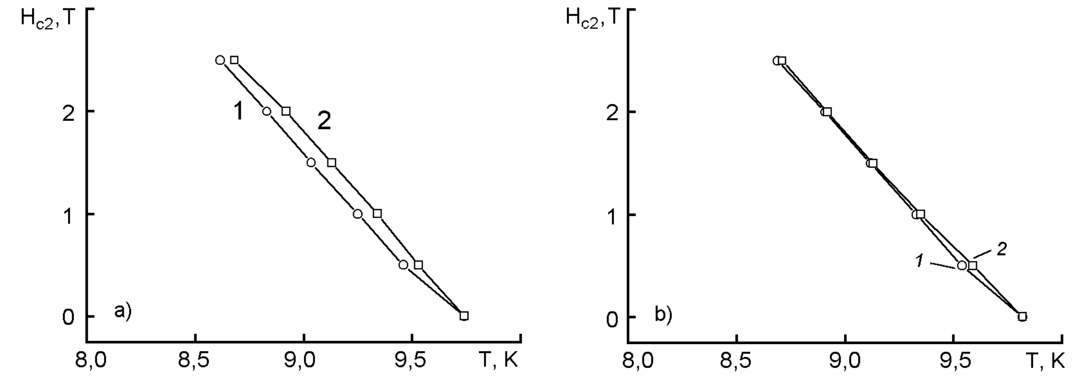


Fig. 7. Dependences $H_{c2}(T)$ at perpendicular (*1*) and parallel (*2*) rolling plane orientations relative to magnetic field direction for the composite free of Nb-layers after cold deformation and annealing at 300°C for 2 h (*a*) and a "single-layered" Nb-31 %Ti alloy tape (*b*).

ence length [1]. This effect cannot result in reduction of the measured H_{c2} value at the layer thickness larger than double coherence length $d >> 2\xi(T)$. In this case, the superconductivity remains unsuppressed inside the layer. But at $d \le 2\xi(T)$, the superconductivity is suppressed in the whole layer and thus, H_{c2} should decrease. The size of $\xi(T)$ at the specified temperature can be calculated from results of H_{c2} measurement using the formula $\xi(T) = (\Phi_0/2\pi H_{c2})^{1/2}$ [1], where $\Phi_0 \approx 2.07 \cdot 10^{-15}$ T·m^2 is the flux quantum. At maximal value $H_{c2} = 4$ T that we were able to measure, the correlation length $\xi(T) \approx 9$ nm at the measurement temperature about 7.5 K. For the Cu/Nb/Nb31Ti composite with the maximal layer thickness $d \approx 138$ nm exceeds considerably $2\xi(T) \approx 18$ nm, while for the composite with the minimum layer thickness, $d \approx 12$ nm $< 2\xi(T) \approx 18$ nm. Thus, the H_{c2} value reduction found for the Cu/Nb/Nb31Ti composites with layer thickness $d \approx 12$ nm can be explained by the suppression of superconductivity because of the proximity effect. The sharp reduction of the critical current density j_c measured at 4.2 K in the fields exceeding 6.5–7.0 T (from high values of 10^5 A/cm^2 at $H = 5$ T down to ~10^3 A/cm^2) observed for the Cu/Nb/Nb31Ti composites with $d \approx 12$ nm is due to the H_{c2} reduction because of the proximity effect. At H_{c2} ~ 11 T determined by us for $T = 4.2$ K, the double coherence length $2\xi(T) \approx 10$ nm is approximately equal to the layer thickness.

At small layer thickness, the H_{c2} value depends on the tape rolling plane orientation with respect to the magnetic field direction. The observed H_{c2} anisotropy can be explained by an increase of the critical field value at the parallel orientation with reduction of plate thickness [1]. While the proximity effect is independent of the orientation.

5. Conclusions

Thus, the measurements of second critical magnetic field H_{c2} near T_c have confirmed the H_{c2} reduction in multilayered Cu/Nb/Nb31Ti tapes containing Nb–Ti nanolayers with decreasing layer thickness. For a tape with the layer thickness $d \approx 12$ nm, the H_{c2} is appreciably lower than for those without Nb layers both for parallel (11.5–11.8 T) and perpendicular orientation (9.4–9.7 T). The reduction of the second critical magnetic field explains a sharp drop of the critical current density in the multilayered tapes containing ~10 nm thick layers in the magnetic fields exceeding 6.5–7 T.

References

1. V.V.Schmidt, Introduction in Physics of Superconductors, Nauka, Moscow (1982) [in Russian].
2. M.I.Karpov, V.P.Korzhov, V.I.Vnukov et al., *Materialovedenie*, No.1, 43 (2005).
3. M.I.Karpov, V.P.Korzhov, V.I.Vnukov et al., *Materialovedenie*, No.6, 35 (2008).
4. M.I.Karpov, V.P.Korzhov, V.N.Zverev et al., *Fiz. Tekhn. Vysok. Davl.*, **18**, 70 (2008).
5. M.I.Karpov, V.P.Korzhov, V.I.Vnukov et al., *Deformatsia i Razrushenie Materialov*, No.6, 18 (2008).
6. R.R.Hake, *Appl. Phys. Lett.*, **10**, 189 (1967).

Друге критичне магнітне поле багатошарових провідників з нанорозмірними шарами з надпровідних сплавів Nb–Ti

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Досліджено багатошарові стрічки, які містять шари з надпровідних сплавів ніобію з (30 та 31 мас.%) титану, розділених шарами ніобію. Товщина шарів від ~140 до ~10 нм. Стрічки одержано триетапним прокатуванням багатошарових пакетів. Ефективне зачеплення надпровідних вихорових ниток відбувалося на міжшарових межах Nb–NbTi. Встановлено, що друге критичне магнітне поле зменшувалося зі зменшенням товщини шарів. При малій товщині шарів його значення залежало від орієнтації площини прокатки стрічки відносно зовнішнього магнітного поля. Результати пояснюються ефектом близькості.