Temperature dependence of the critical current near T_c of superconductors containing twins

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The change in the temperature dependence of the critical current near T_c during deformational twinning of niobium single crystals is evidence of the appearance of narrow superconducting channels in the twin region. Data which are evidence of a corresponding feature on the $I_c(T)$ curve in high-temperature superconductors are also discussed.

An increase in T_c in bicrystals of superconductors with a boundary orientation approximately of a twinning nature was reported in Refs. 1–3. A more significant increase in T_c and H_c is observed during deformational twinning.[4–6] The degree of localization of the superconducting state is an important point in reaching an understanding of the nature of this state in the region of twins of various origins. This problem has been discussed in several papers (see, for example, the review by Khlyustikov and Buzdin[7]). One way to obtain such information might be to work from data on the temperature dependence of the critical current I_c in the vicinity of T_c (Refs. 8 and 9). In the present letter we report results of corresponding studies during low-temperature deformation of niobium. We also report data on the $I_c(T)$ dependence in Y–Ba–Cu–O ceramic samples.

Single-crystal niobium samples ($2 \times 3 \times 30$ mm) with long axes oriented approximately along $\langle 100 \rangle$ and $\langle 110 \rangle$ were deformed by four-point bending at $T \lesssim 8$ K. Under these conditions, the abrupt changes in the load associated with twinning were observed against the background of dislocation glide, and the twinning component of the total strain ϵ did not exceed 50% in any of the samples studied. At each abrupt change in the load, a group of intersecting twin interlayers ~ 0.1–$10\ \mu$m thick appeared in the crystals. The distance between these interlayers was[4] $\sim 100\ \mu$m.

The superconducting transitions near T_c were inferred from the change in the resistance R, measured by a four-contact method, and, as in Ref. 5, from the appearance of a signal U in a measurement coil upon the penetration of a weak ($\sim$1-Oe) alternating (37-Hz) magnetic field into the samples. The critical current was determined at the level of a voltage drop of $0.1\ \mu$V and at a current sweep rate of 0.025 A/s. Measurements were carried out during a slow heating (at $\sim 10^{-2}$ K/s) of the samples to $T \lesssim 15$ K just after the deformation. We also carried out some experiments which included an intermediate heating of the deformed samples to 300 K (Ref. 5).

Figure 1 shows some illustrative curves of $R(T)$ and $U(T)$ for one of the $\langle 100 \rangle$ samples, deformed to various levels ϵ. The defects which arise during the low-temperature dislocation glide have only a slight effect on these curves. A significant increase in T_c is observed only after the beginning of twinning. The shape of these curves depends

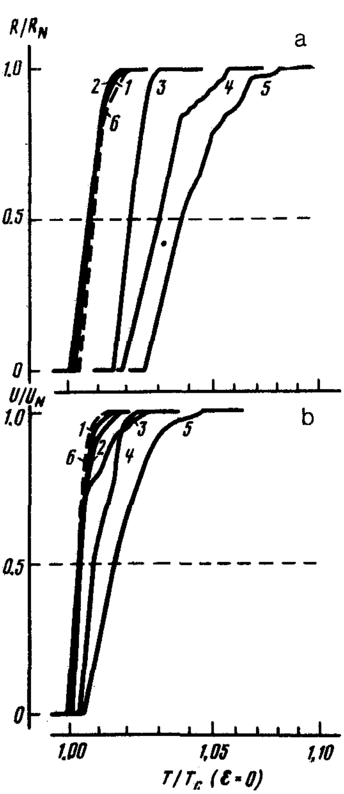

FIG. 1. Temperature dependence of the resistance R (a) and of the signal accompanying the penetration of an alternating magnetic field, U (b), detected during the heating of one of the niobium samples with a ⟨100⟩ orientation. 1—Original sample; 2—dislocation glide before the occurrence of twinning ($\epsilon \approx 1.1\%$); 3–5—after the fifth, twelfth, and twentieth abrupt changes in the load during twinning (ϵ is in the interval 1.8—3%); 6—after a deformed sample is heated to 300 K.

on the particular way in which the samples are filled with the twinning interlayers and the orientation of these interlayers. The shape of the curves also reflects the depletion of the superconducting phase as T is raised. At a given value of ϵ, the $R(T)$ curves are usually shifted up the temperature scale from the $U(T)$ curves. When the deformed samples become essentially "transparent" to the alternating magnetic field, the shunting superconducting channels are retained in them.

Below the temperature $T_{c1}(\epsilon)$, which corresponds to the beginning of the transitions of crystals with twins to a normal state, according to the data on $R(T)$, continuous superconducting channels exist in the crystals. In the interval $T_{c1}(\epsilon = 0) < T < T_{c1}(\epsilon)$ we observe the critical current associated with these channels. Figure 2 shows the results measured for $I_c(T)$ for two samples, differing in orientation, in the initial state and after deformation to $\epsilon \approx 3\%$ and 4% ($\epsilon_{\rm tw} \approx 0.3\%$ and 2%) for the ⟨100⟩ and ⟨110⟩ orientations, respectively. In contrast with the twinning, the dislocation glide has only a slight effect on the $I_c(T)$ dependence. Furthermore, the well-developed dislocation glide during bending reduces the effect of the increase in T_c upon twinning in comparison with experiments involving compression. A heating of the deformed samples to 300 K is accompanied by an "annealing out" of this effect and of the corresponding regions on the $I_c(T)$ curves (Figs 1 and 2) [5]. This result is evidence that structural factors play a role in forming the superconducting channels in the twin region.

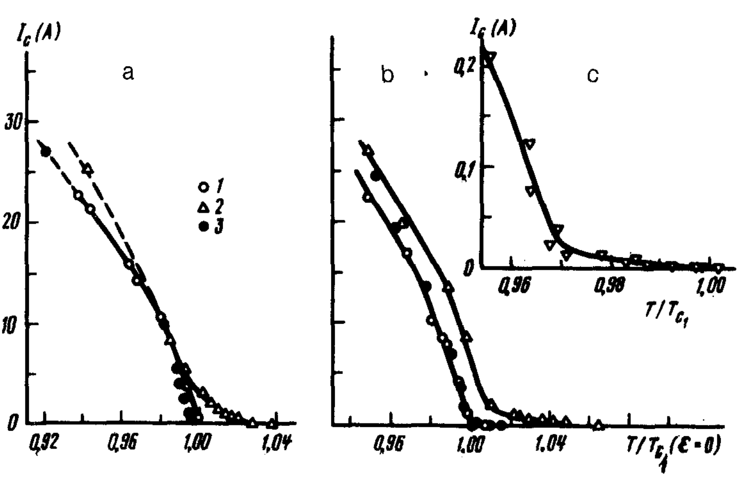

FIG. 2. Temperature dependence of the critical current I_c for two niobium samples (a and b), with ⟨100⟩ and ⟨110⟩ orientations. 1—Original samples; 2—deformational twinning; 3—deformed samples after heating to 300 K. c: Results for one of the ceramic Y–Ba–Cu–O samples.

At $T \gg T_{c1}(\epsilon)$, the superconductivity is destroyed in the weakest links of the system of superconducting channels, associated with the twins. It may be that near $T_{c1}(\epsilon)$ these regions determine the nature of the $I_c(T)$ dependence. In analyzing the data in Fig. 2 in logarithmic scale (the results are shown in Fig. 3), we accordingly normalized T to the corresponding values $T_{c1}(\epsilon = 0)$ and $T_{c1}(\epsilon)$. Curves of this sort (Fig. 3) for the various samples containing twins support this normalization procedure. In the

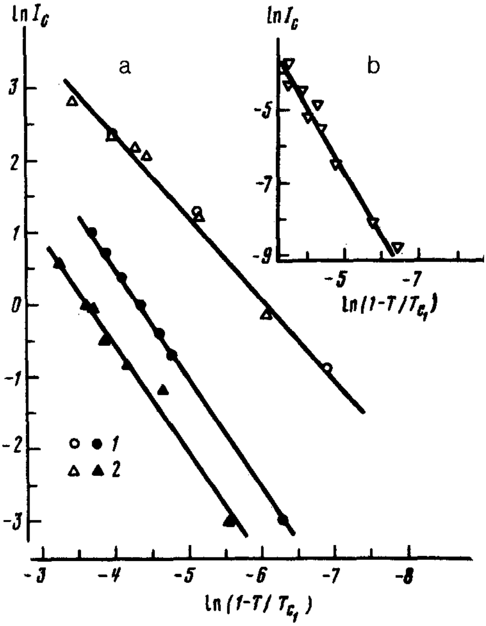

FIG. 3. a: Temperature dependence of I_c near T_c in logarithmic scale, for two niobium samples. 1—⟨100⟩; 2—⟨110⟩. Open symbols) Original samples; filled symbols) low-temperature twinning. b: Results for a ceramic Y–Ba–Cu–O sample.

estimates of T_{c1} we checked for an effect of the magnitude of the measurement current. The $R(T)$ curves in Fig. 1 were measured at currents $I = 50$ mA through the sample. A reduction of I in the case of the deformed samples resulted in a slight shift of the curves up the T scale. We accordingly measured T_{c1} at $I \lesssim 10$ mA; the corresponding error of the estimate is $\sim 10^{-2}$ K. The values found for T_{c1} agree within this error with the temperature below which we detected a nonvanishing critical current in the measurements of $I_c(T)$.

It can be seen from the results in Fig. 3 that the $I_c(T)$ curves near T_c are of the form

$$I_c = I_{c0}(1 - T/T_c)^m \,. \qquad (1)$$

For the initial samples we have $m = 1.11^{+0.04}_{-0.12}$; after twinning, this exponent takes on the following values above T_{c1} ($\epsilon = 0$): $m = 1.51^{+0.05}_{-0.06}$ and $1.48^{+0.08}_{-0.07}$ for the $\langle 100 \rangle$ and $\langle 110 \rangle$ samples, respectively. The error in the estimates stems from the mean-square deviations of the data and the error in the determination of T_{c1}. For the initial samples, expression (1) satisfies Silsbee's rule[9]: $I_c \sim H_{c1}(T) \sim (1 - T/T_c)$. This conclusion was verified by the results of quantitative estimates of H_{c1} on the basis of the data reported here, with allowance for geometric factors. After the twinning, the nature of this dependence ($m = 3/2$) is evidence of the formation of narrow superconducting channels (films or wires) in the crystals, with typical dimensions[1)] $d < \lambda(T)$ (Refs. 8 and 9). The penetration depth λ is $\sim 10^{-5}$ cm in this temperature range (the "clean" limit). If the superconducting channels are sufficiently narrow, or if pinning and self-screening effects suppress the influence of vortex states which appear at the edges of the superconducting layers,[9,10] the critical current density in these channels can reach values corresponding to the depairing current[8,9]: $j_p = \alpha H_c(T)/\lambda(T)$ where H_c is the thermodynamic critical field, and the numerical coefficient is $\alpha \sim 1$ (SI). Pursuing these arguments, we can generate a lower estimate of the dimensions of the current channels: $d \gtrsim I_c / j_p N L$. Estimating the number of twinning boundaries in cross sections of the samples ($N \approx 15$–20), and adopting the estimate $L \sim 0.1$ cm for the total width of the channels associated with an individual twin, allowing for the nonuniformity of the properties, we find $d \gtrsim 10^{-7}$–10^{-6} cm.

In connection with these results and their analysis, we should point out that the superconducting regions associated with twins are near metal with lower values of T_c, which can influence these regions to the extent that the proximity effect is operating[8,9] and result in a suppression of the superconductivity and a change in the nature of the $I_c(T)$ dependence. Analysis of the Ginzburg–Landau equations shows that the proximity effect will not be important if $d \gg \xi(0)$, where ξ is the coherence length. The proximity effect will again be suppressed if the electron subsystem in the region of the twins is separated from the electrons of the surrounding metal by an energy barrier (Ref. 11, for example).

High-temperature superconductors have recently attracted acute interest among researchers. These entities contain large numbers of polysynthetic twins.[12,13] There are papers in which twins have been regarded as a factor which gives rise to high-temperature superconductivity (e.g., Ref. 14). It would be difficult to expect twins to play a decisive role here. For example, Emel'chenko *et al.*[15] conclude that the superconductivity in Y–Ba–Cu–O single crystals is of an exchange nature. The results of that study provide evidence that according to resistance measurements, the superconductivity sets in at temperatures T higher than would follow from data on the Meissner effect. As in ordinary superconductors, one cannot rule out the possibility that twins do participate in shaping the properties of high-temperature superconductors in a certain T region near T_c. Figures 2c and 3b show results of control measurements of the dependence $I_c(T)$ for one of the ceramic Y–Ba–Cu–O samples ($T_c \approx 95$ K). We see that these results ($m = 1.71^{+0.05}_{-0.11}$) are qualitatively similar to the results on niobium. A ceramic is a complex entity. Interfaces and intergrain boundaries could play a definite role in shaping its properties. Consequently, the results are presently being refined on the basis of single crystals of high-temperature superconductors.

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(1) A similar behavior is discussed in Ref. 7 on the basis of a representation of a superconductivity induced near a twinning plane.

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