On the basis of macroscopic treatment of plastic yield, the values of maximum mechanical stress and maximum superconducting current have been calculated for a superconductor subjected to uniform plastic deformation. The training effect due to strain hardening of the material is discussed. These results are compared with an analogous case when the normal transition is caused by the thermo-magnetomechanical instability. The quenching current is shown to depend on the history of field-current application in the presence of plastic yield.

Quenching stress, quenching current and plastic strain in superconductors

I.L. Maksimov, R.G. Mints and A.L. Rakhmanov

The mechanical stresses which occur in large superconducting magnets may exceed the elastic limit of composite superconductors in certain parts of the winding. Therefore, the energizing of a large superconducting magnet may be accompanied by inelastic deformation of the superconductor at least in certain parts of the winding. As shown in the series of the experimental papers,[1-6] the heat release due to plastic strain may be one of the mechanisms responsible for training and degradation of superconductors.

A normal transition of a plastically deformed short sample with a given value of the transport current I may occur as a result of one of the two following processes.

In the first case, the heat release due to plastic deformation causes the temperature of the conductor to increase slowly up to $T = T_r$. At $T = T_r$ the potential emerges in the sample (here T_r is found from the equation $I = I_c(T_r)$, $I_c = j_c S, j_c$ is the critical current density, S is the cross-sectional area of the conductor). The temperature rises from $T = T_0$ to $T = T_r$ during a time defined by the external stress rate.

In the second case, the superconductor temperature first grows slowly up to $T = T_1 < T_r$. Then, as a result of the thermo-magnetomechanical instability (jointly developing flux jump and strain jerk)[7,8] there occurs a rapid resistive (and then normal) transition. The heating rate in this case is controlled by the increment of the instability increase.

The plastic yieled of the material initially occurs in the vicinity of some weak spot, ie a portion of the material differing from the rest of the sample by a lower elastic limit or higher mechanical stress. If no special measures are taken such weak spots exsist in any sample. The first quench starts in the weakest spot. This process, accompanied by the intensive local heating, leads to the thermal softening of the material and then to an increase of the plastic strain and, as a result, to the strain hardening of the respective weak spot. Therefore, upon the next loading of the sample, plastic yield initiates the vicinity of another weak spot and the whole pattern is repeated. As a result at least the initial part of the training curve is associated with the strain hardening of weak spots in the sample.[6,7]

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After a series of loading-unloading cycles, conditions can develop under which the weak spots have already been trained. Normal transition of the superconductor will then occur as a result of the plastic yield of the material which is homogeneous along the conductor axis.[6,7]

The present paper contains a theoretical study of the normal transition and training of short samples due to the uniform plastic yield in the case of a superconductor which is slowly heated from $T = T_0$ to $T = T_r$.

Quench caused by slow heating

Let us consider the experiment shown in Fig. 1. The mechanical stress σ is applied along the axis and may be produced by the effect of the Lorentz force $\vec{F} = \vec{I} \times \vec{B}$ and/or by an external mechanical force (here $\mathbf{B}$ is the magnetic field). The value of $\sigma = \sigma(t)$ increases monotonically until at $\sigma = \sigma_m$ there occurs the resistive transition of the superconductor ($T = T_r$) owing to the heat release due to plastic deformation. After transition the sample is unloaded fully or in part. Note that in the case of Nb-Ti alloys, the macroscopic plastic yield starts at $\sigma = \sigma_0 \sim 10^9$ Nm^{-2} and in the case of superconducting composites with copper matrix – at $\sigma \sim 10^8$ Nm^{-2}

The time of the resistive transition and the value σ_m can be found with aid of the heat equation:

$$C \frac{\partial T}{\partial t} = \nabla (\kappa \nabla T) + Q \qquad (1)$$

where C and κ denote the specific heat capacity and the thermal conductivity, Q is the specific power of the heat release due to inelastic deformation and Joule heating. In the case of a stable uniform plastic yield the problem can be simplified considerably.

Indeed, the sample heating rate in the case under consideration is controlled by the external stress rate. Correspon-

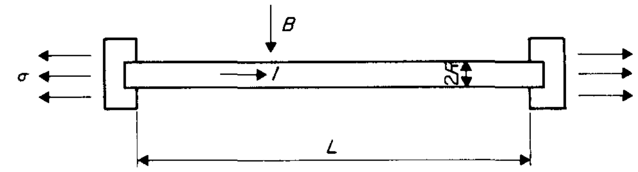

Fig. 1 Schematic representation of problem geometry

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ding time t_0 is usually of the order of $10^{-1} - 10$ s, which is considerably higher than the time of the thermal diffusion over the sample cross section

$$t_1 = CR^2/\kappa \sim 10^{-6} - 10^{-3} \text{ s.}$$

If $t_0 \gg t_1$ and $W = W_0 R/\kappa \ll 1$ (W_0 is the coefficient of the external heat removal and R is the conductor radius), the temperature in the sample cross-section may be regarded as uniform and (1) transforms to

$$C \frac{\partial T}{\partial t} = Q - q \qquad (2)$$

where

$$q = \frac{A}{V} q_w \, (T - T_0)$$

q_w is the heat flux from the surface, A is the area of the cooled surface, and V is the sample volume. For the case of composites the condition $W \ll 1$ is always satisfied. For example, if the sample is cooled by liquid helium where $W_0 \lesssim 10^4$ Wm^{-2} K^{-1}, then assuming $\kappa = 10^2$ Wm^{-1} K^{-1} and $R = 10^{-3}$ m, one can find $W \lesssim 10^{-1}$.

The heat release due to the plastic deformation can be written in the form:

$$Q_\sigma = \gamma \sigma \dot{\epsilon}$$

where $\dot{\epsilon}$ is the rate of plastic deformation, $\sigma\dot{\epsilon}$ is the plastic deformation work per unit time, γ is the coefficient defining the fraction of this work converted into heat.

In the region of plastic yield a mechanical loading occurs according to a definite law:[9]

$$\sigma = \sigma_p(T, \epsilon, \dot{\epsilon}) \text{ where } \sigma_p(T, 0, 0) = \sigma_p(T)$$

which is the elastic limit of the material. In the case which is of interest to us, the mechanical deformation rate is low. This enables one to assume $\dot{\epsilon} = 0$. So, we have $\sigma_p(T, \epsilon, 0) = \sigma_p(T, \epsilon)$. In the case where the external mechanical stress varies according to a given law $\sigma = \sigma(t)$, we find for Q_σ the expression:

$$Q_\sigma = \gamma \, \sigma(t) \left(\frac{\partial \epsilon}{\partial T} \dot{T} + \frac{\partial \epsilon}{\partial \sigma} \dot{\sigma} \right) \qquad (3)$$

where $\epsilon = \epsilon(T, \sigma)$.

The calculation of the Joule heating Q_J represents a rather complicated problem. The appropriate expression can not be written in a sufficiently general form. However, since we are mainly interested in the effect of plastic strain on the normal transition we shall assume that $Q_\sigma \gg Q_J$. The value of Q_σ can be estimated as $Q_\sigma \sim 10 - 10^2$ W cm^{-3}. For the critical current density $j_c \sim 10^5$ A cm^{-2} the equality $Q_\sigma = Q_J$ is attained at the electric fields $E \sim 10^{-5} - 10^{-4}$ V cm^{-1}. This corresponds (at $I < I_c$) to the external magnetic field variation rate $\dot{B} \sim 1 - 10$ T s^{-1} or to the transport current variation rate $\dot{I} \sim 10^4$ A s^{-1} if the characteristic dimension of the sample R is of the order of 1 mm.

Therefore, to find the value σ_m one should solve (2) with $Q = Q_\sigma$ and the initial conditions of $T(0) = T_0$ and $\sigma(0) = \sigma_p(T_0) = \sigma_0$. In this case training can only be associated with the strain hardening of the material whose value is the greater the higher the plastic strain increement $\Delta\epsilon$ in a given loading cycle. Hence, the training effect due to this mechanism will be substantial only if σ_m exceeds appreciably the elastic limit in each loading cycle.

Assume that the sample is strained with a constant stress rate: $\sigma(t) = \dot{\sigma} t$ (where $\dot{\sigma}$ = const) and the heat removal from the surface, heat capacity and the critical current density can be approximated as:

$$q_w(T - T_0) = W_0 (T - T_0),$$

$$C(T) = C_0 \cdot \left(\frac{T}{T_0}\right)^3, j_c(T) = j \left(1 - \frac{T}{T_c}\right)$$

where T_c is the superconductor critical temperature. In this case

$$T_r = T_0 + (1 - i) \cdot (T_c - T_0) \qquad (4)$$

where $i = I/I_c(T_0)$.

To obtain quantitative results for σ_m and to describe the training process one has to formulate a model of plastic yield, ie to define the function $\sigma_p = \sigma_p(T, \epsilon)$ explicitly. As it may be shown,[9-11] the stress-strain curve may be approximated in many cases by the expression:[11]

$$\sigma_p = \sigma_0 - b \cdot (T - T_0) + K \epsilon^{1/p} \qquad (5)$$

where $\sigma_0 = \sigma_p(T_0)$, $p > 1$ and the difference $T - T_0$ is assumed to be not too large ($T - T_0 < T_0$). The second term in (5) describes the thermal softening of the material and the third one – the strain hardening. The parameters σ_0, b, K usually satisfy the inequality $E \gg K \gtrsim \sigma_0 \gg bT_0$, where E is the Young's modulus. Using the experimental stress-strain curves one can estimate the values p, K and b as follows: $p \simeq 2 - 3$,[6,11] $K \sim 10^9$ Nm^{-2} (Nb-Ti-copper composite[6]), $b \sim 10^6 - 10^7$ Nm^{-2} K^{-1}.[11,12]

Now (2) may be conveniently rewritten in the dimensionless form:

$$(1 + \theta)^3 \frac{d\theta}{d\tau} = \kappa_p \, \tau (\tau - 1 + \beta\theta)^{p-1} \left(1 + \beta \frac{d\theta}{d\tau}\right) - h\theta \qquad (6)$$

where

$$\tau = \frac{\dot{\sigma}}{\sigma_0} t, \; \theta = \frac{T - T_0}{T_0} < \theta_r, \theta_r = (1 - i) \frac{T_c - T_0}{T_0},$$

$$\kappa_p = \gamma p \frac{\sigma_0}{C_0 T_0} \left(\frac{\sigma_0}{K}\right)^p, \beta = \frac{bT_0}{\sigma_0}, \; h = W_0 \frac{A\sigma_0}{C_0 V \dot{\sigma}}$$

To find σ_m one has to determine τ_m at which $\sigma(\tau_m) = \theta_r$, then $\sigma_m = \sigma_0 \tau_m$. Supposing that $\gamma p \sim 1$, $T_0 = 4$ K, $C_0 T_0 \sim 10^{11}$ J m^{-3}, $V/A \sim R \sim 10^{-3}$ m and $\sigma_0 \sim 10^8$ Nm^{-2} one can find the estimations $\kappa_p \sim 1 - 10$, $\beta \sim 10^{-1} - 10^{-2}$, and h from $\sim 10^2$ ($W_0 \sim 10^2$ Wm^{-2} K^{-1}, characteristic for cooling by helium gas, $\dot{\sigma} = 10^8$ Nm^{-2} s^{-1}) to $\sim 10^6$ ($W_0 \sim 10^4$ Wm^{-2} K^{-1}, $\dot{\sigma} = 10^6$ Nm^{-2} s^{-1}).

Over the entire range of parameters the non-linear (6) can only be solved numerically, which will provide the subject of a separate communication. To solve the problem analytically, one should probably linearize (6). As $\theta \leqslant \theta_r$ and

$(T_c - T_0)/T_0 \sim 1$, it follows from (4) that $\theta \ll 1$ if $(1 - i) \ll 1$. Therefore, (6) permits the linearization in the case when the transport current is close enough to the critical value I_c. On the other hand, at the characteristic values of parameters we have $\beta \sim 10^{-2} - 10^{-1} \ll 1$. Neglecting the terms $\beta\theta$ and $\beta\, d\theta/dt$ one finds from the (6):

$$\theta = \kappa_p \int_1^{\tau} \tau' (\tau' - 1)^{p-1} \exp \{h(\tau' - \tau)\}\, d\tau' \qquad (7)$$

Thus, we have obtained the transcendental equation for determining τ_m. An analytical solution for τ_m can be obtained in the two limiting cases, namely, $h(\tau_m - 1) \gg 1$ and $h \ll 1$. As usually $h \gg 1$, the former case seems to be more realistic.

Thus at $h(\tau_m - 1) \gg 1$ (good cooling) we find that:

$$\tau_m (\tau_m - 1)^{p-1} = \frac{h\theta_r}{\kappa_p} \qquad (8)$$

Equation (8) corresponds to the limit $C\, dT/dt \to 0$. At $p = 2$ we obtain from (8):

$$\sigma_m = \frac{\sigma_0}{2} + \left(\frac{\sigma_0^2}{4} + (1 - i)\frac{W_0 \cdot (T_c - T_0) A K^2}{2 \gamma V \dot{\sigma}}\right)^{1/2} \qquad (9)$$

At arbitrary p the value of σ_m can be found in the analytical form if $\tau_m \gg 1$:

$$\sigma_m = \sigma_0 \frac{p - 1}{p} + \left[(1 - i)\frac{W_0 (T_c - T_0) A K^p}{\gamma V p \dot{\sigma}}\right]^{1/p} \qquad (10)$$

Supposing that $p \sim 2 - 3$, $1 - i \sim 0.1$, $\sigma_0 \sim 10^8$ Nm^{-2}, $W_0 \sim 10^3$ Wm^{-2} K^{-1}, $T_c - T_0 \sim 5$K, $V/A \sim R \sim 10^{-3}$m, $K \sim 10^9$ Nm^{-2}, $\dot{\sigma} \sim 10^8$ Nm^{-2} s^{-1}, $\gamma p \sim 1$, one can find from (9) or (10) that $\sigma_m \sim 3 \times 10^8$ Nm^{-2}.

If $\tau_m - 1 \ll 1$ (or $\sigma_m \sim \sigma_0$), then:

$$\sigma_m = \sigma_0 + \left\{(1 - i)\frac{W_0 (T_c - T_0) A K^p}{\gamma p V \dot{\sigma}}\right\}^{1/(p-1)} \qquad (11)$$

The equation is analogous to (10) at $\sigma_0 = 0$, and $p = 3$ was found by Pasztor and Schmidt[6] and they have shown that this equation provides a good qualitative description of their experiments.

The case $h \ll 1$ may be attained only under extremely unfavourable thermal conditions. Assuming $h = 0$ we find from (7):

$$(p\tau_m + 1)(\tau_m - 1)^p = \frac{p(p + 1)}{\kappa_p}\theta_r \qquad (12)$$

As at the characteristic values of the parameters

$$\frac{\theta_r}{\tau_p} \ll 1 \qquad (13)$$

$p > 1$ and $\tau_m > 1$, then $\tau_m - 1 \ll 1$ and from (12) one readily finds

$$\sigma_m = \sigma_0 + \left\{\frac{1 - i}{\gamma \sigma_0} C_0 (T_c - T_0) K^p\right\}^{1/p} \qquad (14)$$

Thus at $h \ll 1$ the normal transition occurs at $\sigma_m \simeq \sigma_0$.

On analysing the obtained results one can see that the quenching stress σ_m decreases with an increase of transport current and stress rate. σ_m increases with an increase of external cooling. These facts are in agreement with the experiments.[16]

Training due to strain hardening

As mentioned, superconducting training under conditions of the uniform plastic yield is associated with the strain hardening of the material. It is clear that in the case where the difference $(\sigma_m^{(n)} - \sigma_0^{(n)})/\sigma_0^{(n)}$ is less than, say, 1% no training is observed. On the contrary, if $(\sigma_m^{(n)} - \sigma_0^{(n)})/\sigma_0^{(n)} \sim 1$, the training is appreciable (here $\sigma_m^{(n)}$ is the quenching stress at n-th step and σ_0^n is the elastic limit attained at the n-th step). The values of $\sigma_m^{(n)}$ and $\sigma_0^{(n)}$ depend on both the number of the training steps n and the experimental conditions. In a general form the variations of the parameters σ_0, K, b can not be determined theoretically upon successive loading and unloading cycles. Therefore, the training curve can only be calculated for some models.

We shall consider here the simplest case assuming that σ_0, K and b do not vary in the course of superconducting training. Thus neglecting the variation of plastic deformation during unloading one can find that the macroscopic plastic yield starts at the n-th training step if $\sigma > \sigma_0^{(n)} = \sigma_0 + K \epsilon_{n-1}^{1/p}$, where ϵ_{n-1} is the plastic strain attained at $(n-1)$-th step.

Let, for the sake of simplicity, $p = 2$, $\theta_r \ll 1$ and $\beta\theta_r \ll \tau_m^{(n+1)} - \tau_m^{(n)}$, then analogous with the (7) one can find the relation between $\tau_m^{(n+1)}$ and $\tau_m^{(n)}$ in the form:

$$\frac{\theta_r}{\kappa_p} = \exp\{-h\tau_m^{(n+1)}\} \int_{\tau_m^{(n)}}^{\tau_m^{(n+1)}} x(x - 1) \exp(hx)\, dx \qquad (15)$$

The difference $\Delta\sigma_m^{(n)} = \sigma_m^{(n)} - \sigma_m^{(n)}$ have a maximum at the first step of the training process. By means of (15) one can find $\Delta\sigma_m^{(1)}$ in the following two cases $h(\tau_m - 1) \gg 1$ and $h \ll 1$.

In the first case we find:

$$\frac{\Delta\sigma_m^{(1)}}{\sigma_m} = \frac{1}{h\tau_m} \ln\left\{\frac{h(\tau_m - 1)}{2}\right\} \qquad (16)$$

It follows from (16) that $\Delta\sigma_m^{(1)}/\sigma_m \ll 1$, ie in the case when $h(\tau_m - 1) \gg 1$ the training under conditions of the uniform plastic yield with the constant σ_0, K, b is small. The realistic value of $h\tau_m$ may be estimated as $h\tau_m \sim 10^3$ and $\Delta\sigma_m^{(1)}/\sigma_m \sim 1\%$. This estimate is in good agreement with the results of the experiments by Pasztor and Schmidt[6] (taking into account that the first 4-5 normal transitions observed by Psztor and Schmidt are due to the local heating of the sample).

In the case of bad cooling ($h \ll 1$, $\sigma_r/\kappa_p \ll 1$) one can obtain:

$$\frac{\Delta\sigma_m^{(1)}}{\sigma_m} \simeq 0.6 \left(\frac{\theta_r}{\kappa_p}\right)^{1/2} \qquad (17)$$

As seen from (17) in this case $\Delta\sigma_m^{(1)} \ll \sigma_m$.

The small value of training under uniform plastic yield results from the fact that under usual experimental conditions the heating due to deformation is high enough. Hence, the quenching occurs rapidly and the value $\sigma_m^{(n)}$ could not exceed $\sigma_0^{(n)}$ appreciably.

Quenching current caused by plastic yield of the material

Let us consider now the case where the mechanical stress is due to the effect of Lorentz force. Here we find the value of the quenching current j_m at which the normal transition occurs. For the geometry shown in the Fig. 1 the expression for σ can be written as:

$$\sigma = \left(\frac{EL^2}{24} j^2 B^2\right)^{1/3} \tag{18}$$

where L is the length of the sample (see Fig. 1). While deriving (18), it was assumed that the plastic strain ϵ was much less than the elastic one σ/E and $jBL/\sigma \ll 1$ or using (18):

$$\left(\frac{jBL}{E}\right)^{1/3} \ll 1$$

By means of (18) one can readily find $\dot{\sigma}$ in the form:

$$\dot{\sigma} = \frac{1}{3}\left(\frac{EL^2}{3jB}\right)^{1/3} \frac{d}{dt}(j \cdot B) \tag{19}$$

Let us assume that $\tau_m \gg 1$ and $p = 2$. Then using (9) we have:

$$j_m B \frac{d}{dt}(j \cdot B)\bigg|_{j=j_m} = a\left(1 - \frac{j_m}{j_c}\right) \tag{20}$$

where

$$a = 18\,\frac{AK^2\, W_0\,(T_c - T_0)}{\gamma E V L^2}$$

With the aid of (20) one can find j_m in the following two cases: One, magnetic field B is increased at the constant value of j, ie $B = B(t)$ and j = const. From (20) one can readily find:

$$j_m = j_c \cdot \left(1 - \frac{j_c^2\, B\dot{B}}{a}\right) \tag{21}$$

In deriving the expression (21) it is assumed that $j_c^2\, B\dot{B} < a$ as with (9) is only true if $j_c - j_m \ll j_c$. Two, the transport current increased at a constant value of B, ie $j = j(t)$, B = const. Then, we obtain from (20):

$$j_m = j_c \cdot \left(1 - \frac{j_c B^2}{a}\frac{dj}{dt}\right) \tag{22}$$

In deriving (22) the inequality $j_c B^2 \cdot dj/dt < a$ was assumed to be realized for the same reason as above.

One can readily see from (21) and (22) that the function $j_m = j_m(B)$ depends upon the history of the current-field application. This effect may be of importance for an interpretation of experimental results. In the case when $j_c - j_m \sim j_c$ the value of j_m can only be calculated numerically.

Discussion

As mentioned above, the normal transition of a plastically deformed superconductor may occur as a result of one of at least two processes. Let us now compare the stress σ_j at which the thermomagnetomechanical instability occurs with the stress a_m obtained in the preceding sections.

To find σ_j explicitly one needs to know the dependence of σ_p on σ, T, ϵ and $\dot{\epsilon}$.[7,8] For the sake of simplicity we shall assume here the linear dependence of σ_p on $\dot{\epsilon}$:

$$\sigma_p = \sigma_p(T, \epsilon) + \eta\dot{\epsilon} \tag{23}$$

where η is a coefficient independent of T and ϵ. Equation (23) may be used to describe the plastic yield regarding the dependence of σ_p on $\dot{\epsilon}$ for superconductors reasonably if the temperature T is not too close to T_c. Equation (23) is valid if the rate of plastic strain is not too low.

Following[7,8] and using (5) and (23) one can readily derive the value σ_j in the form:

$$\sigma_j = \frac{\sigma_0}{2} + \frac{\sigma_0}{2}\left\{1 + \frac{4\sigma_0}{bT_0\,\kappa_2}\left(1 - i^3\,\frac{\mu_0 R^2 j_c}{3C_0}\left|\frac{dj_c}{dT}\right|\right)\right\}^{1/2} \quad W_0 < W_k \tag{24}$$

$$\sigma_j = \max(\sigma_0, \sigma_c),\ W_0 > W_k \tag{25}$$

where

$$W_k = C_0 R \left|\frac{\partial\dot{\epsilon}}{\partial\epsilon}\right|$$

$$\sigma_c = \frac{W_0 \eta}{Rb}\left(1 - \frac{iR\rho}{W_0} j_c \left|\frac{dj_c}{dT}\right|\right) \tag{26}$$

here ρ is the resistivity of the composite, μ_0 is the vacuum magnetic permittivity. For simplicity the plane geometry (plate of the thickness $2R$) is considered.

As it follows from the (24)-(26) and the results of the preceding sections the functions $\sigma_j = \sigma_j(I, W_0)$ and $\sigma_m = \sigma_m(I, W_0)$ have the similar qualitative appearance, but the quantitative discrepancy between σ_j and σ_m may be considerable. For example, the dependence of σ_j on i at $i \to 1$ is not too strong compared with σ_m. However, the considerable uncertainty of the parameters does not allow one to carry out the quantitative comparison of σ_j and σ_m at present. Note further, that (24) and (26) for σ_j do not include the dependence on $\dot{\sigma}$. As it can be shown, this results from the linear relation between σ_p and $\dot{\epsilon}$.

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