DEFECT STRUCTURE AND PHYSICO-MECHANICAL PROPERTIES OF CERAMIC HIGH TEMPERATURE SUPERCONDUCTORS

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ABSTRACT

The present work is a review of the investigations of the physico-mechanical properties of the ceramic high temperature superconductors with various structures which were performed at the A.F.Ioffe Physico-Technical Institute. The inelastic deformation rate $\dot{\epsilon}$ of the ceramics under the constant mechanical stress was studied in the temperature range $T=77-300$ K, using the laser interferometer technique. In all cases the dependence $\dot{\epsilon}(T)$ shows a few maxima. Changes in the inelastic strain rate at the superconductive transition, caused by the action of transport current or magnetic field were found. Stress effect on voltage-current (V-I) characteristics of the ceramics under tension and compression was observed. The effect of stress on V-I curves depends on the value of the magnetic field. The conclusion has been made that critical temperature of superconductive transition and its change at mechanical loading are attributed to the internal grain structure and current characteristics depend on grain boundary state.

1. INTRODUCTION

Since the discovery of high temperature superconductors (HTSC) intensive studies of their various properties, including the physico-mechanical ones, have been undertaken [1]. The term "physico-mechanical properties" represents the phenomena manifesting the influence of physical characteristics on mechanical properties and the reverse effects when a mechanical stress alters physical characteristics. An example of such phenomenon in superconductors is a change in the critical temperature under the hydrostatic pressure [2,3]. The studies of physico-mechanical effects in high temperature superconductors are important not only from the fundamental aspects of superconductivity and material science, but also from the practical viewpoint as well.

In Ioffe Physico-Technical Institute (Sankt-Petersburg) investigations of the physico-mechanical properties of HTSC began nearly four years ago. The studies were carried out by the uniaxial compression tests of superconducting ceramics with different microstructure. The

structure of ceramics has been changed by technology of their preparing, by deviation from the stoichiometric composition and also due to silver addition into the compound. The present paper is mainly the review of those investigations.

The following questions will be presented and discussed in the paper:

1. The rate of inelastic deformation of the superconducting ceramics under the small constant stress in the temperature range 77-300 K.
2. Effect of the superconductive transition on this strain rate.
3. Effect of the stress on high temperature superconductivity and voltage-current characteristics.

2. EXPERIMENTAL

Main results have been obtained on yttrium ceramics of the 123 system. Some tests were performed on Bi-based compound of 2223 system.

The samples were prepared by standard powder sintering method. They were of rectangular shape with cross section about $2 \times 2 \text{ mm}^2$ and 6 mm in length.

The critical temperature of samples was determined by the dc electrical resistivity measurement using four-probe method.

The samples were loaded by uniaxial compression. The measurements of their strain and strain rate were performed in a special installation representing Michelson's interferometer with a laser source [4]. The strain rate $\dot{\epsilon}$ was determined from the recorded interference pattern. Practically the strain rate value can be measured basing on linear shifts of about $0.15 \text{ }\mu\text{m}$.

The measurements of the strain rate at various temperatures were performed in the following manner [5]. At first the sample was loaded with constant stress σ at some given temperature, stress value being nearly 20% of the sample's strength at room temperature. After reaching the strain value necessary for determining the strain rate the sample was unloaded and then heated to another temperature and loaded again, etc. The strain rate was determined from interference pattern recorded at every temperature under identical conditions, namely after decrease in the sample's length during the loading on the constant value.

3. RESULTS AND DISCUSSION

3.1. Low-temperature inelastic deformation.

Fig. 1 demonstrates the general view of the strain rate versus temperature dependences for some yttrium ceramics [5]. It can be seen that in all cases the dependence of the strain rate on temperature shows a few maxima in the temperature range 77-300 K. One of the peaks occurs at 90 K, which is close to critical temperature. The most high temperature of the maxima observed occurs in the range 250-270 K. The position of the middle peak varies within broader limits. In the ceramics 1, 2,

and 3 the superconducting transition was clearly observed on the temperature dependences of the resistivity with T in the range 90-95 K and it was confirmed Meissner effect. For ceramics 4 the resistivity drop till 77 K does not occur but it displays a noticeable Meissner effect.

Similar temperature dependences $\dot{\epsilon}(T)$ were obtained in [6] on ceramics with various content of oxygen and were also observed in [7]. It should be noted that the similar maxima have been observed for HTSC ceramics when studying the temperature dependences of internal friction [8,9].

Fig. 1. Temperature spectra of the inelastic strain rate of YBaCuO ceramics under compression stress $\sigma=10$ MPa. 1 - fine-grained

sample; 2,3 - coarse-grained single phase samples of 5.5 and 5.9 g/cm³ density, respectively; 4 - coarse-grained multiphase sample.

The question of what is the possible mechanism behind the observed maxima arises. Obviously these maxima are related to change in mobility of defects responsible for the strain in the temperature range of T_{max} . The nature of these defects as well as that of the processes influencing their mobility could be of various kind. In particular, the maximum of the strain rate in vicinity of critical temperature can be accounted for by the acceleration of the dislocation movement at the transition into the superconducting state due to the disappearance of the electron contribution to the dislocation drag [10].

3.2. Effect of superconductive transition.

The possibility of a change in the inelastic strain rate at the sample transition from superconducting into normal state has been considered in [11-13]. The experiments were made at 77 K. Superconductivity was destroyed by passing a supercritical current through the samples or by a magnetic field. At 77 K the critical currents for different ceramics varied from 15 to 300 A/cm².

Changes in the inelastic strain rate due to switching of supercritical current once on and off are shown in Fig. 2. It is seen that strain rate decreases strongly (practically till zero) at the moment when

Fig. 2. Changes of rate $\dot{\epsilon}$ of microplastic deformation under the switching on and off of a 30 A/cm²

current. S is the superconducting state, N is the normal state; $\sigma = 12$ MPa, $T = 77$ K.

the current is switched on. The subsequent deformation occurs at a lower rate than before the flow of the current. The opposite effect is observed when the current is switched off. In this case the strain rate increases abruptly and the subsequent deformation occurs at the same rate as before the switching of the current on. It should be noted that the noticeable effect is observed in the case when the current is higher than the critical value. It is also possible to destroy the superconductivity by means of the magnetic field at some current smaller than critical one. The effect of magnetic field on the inelastic strain rate is demonstrated in Fig. 3. It is seen that in this case the strain rate changes gradually at S-N and N-S transitions.

Thus, we can conclude that in the superconducting ceramics, like in metallic superconductors [10], the S-N transition leads to a decrease in the inelastic strain rate, whereas the N-S transition leads to its increase. From these observations it could be supposed that the maximum of inelastic strain rate in the vicinity of critical temperature is related to the superconductive transition.

Other effect was observed in the case of repeated switching of the current on and off [12]. The experiments were carried out by the same method as told before. The only difference was that the current was switched on and off at frequency of 1 Hz. The experimental results are

Fig. 3. Changes of inelastic strain rate of the loaded YBaCuO ceramics at S-N transitions due to switching of the magnetic field H

on and off in the presence of the current I (a) or due to switching of the current I on and off in the presence of H (b). $T=77$ K, $\sigma=26$ MPa, $I=80$ A/cm², $H=50$ Oe.

presented in Fig. 4. We can clearly see an acceleration of deformation during the current cycling. As in the previous series of experiments, the noticeable effect increases with increase in the current value and is observed for supercritical currents. We have called this phenomenon as "current fatigue" on the analogy of mechanical and thermal fatigue.

The observed effects of inelastic strain rate change under destruction of superconducting state by the transport current or by the magnetic field can be explained by the change of grain boundary strength for moving defects responsible for this strain [13].

3.3. Stress-induced effects

Now we shall consider briefly results on the effect of the mechanical stress on high temperature superconductivity and voltage-current characteristics.

To analyze the compression effect the current contacts were applied to the sample ends while the voltage ones were located in the central part along the axis, as shown schematically in Fig. 5(a) [13]. In this case the current was parallel to the load. To study the tension effect the contacts were located across the sample axis, as shown in Fig. 5(b), and the current was normal to the load.

Fig. 6 shows the temperature dependences of the resistivity near critical temperature for a sample without load and for one under compressive stress of 100 MPa. It is seen that the compression causes the increase of critical temperature, the shift effect being approximately 5 K/GPa. The critical temperature increases also for ceramics with small silver addition [14]. In this case the observed critical temperature change can be explained by local internal strain caused by silver atoms.

Fig. 4. Increase of microplastic deformation rate $\dot{\epsilon}$ under the cyclic switching on and off of 175

A/cm² current. S is the superconducting state, N is the normal state; $\sigma=40$ MPa, $I_c=120$ A/cm², $T=77$ K.

Fig. 5. Configuration of current contacts (1) and potential contacts (2) on a sample for studying

the effect of compressive (a) and tensile (b) deformation; P is the load and I is the current.

Fig. 6. Temperature dependences of the resistivity of the YBaCuO

ceramics without load (1) and under compression $\sigma=100$ MPa (2).

Fig. 7 demonstrates the V-I curves for both the nonloaded sample and the sample under compressive stress. The current is parallel to the load. It is seen that the compression shifts the V-I curves to the right and the effect increases with the stress. The critical current increases also, but the slope of the curves decreases. The dependence of the shift ΔI on the stress is nonlinear. The value of $\Delta I/\Delta \sigma$ decreases with increasing stress, being approximately 4 GPa^{-1} . Similar effect is also observed in Bi-based compounds [15].

Now, if we compare the effect of stress on the V-I curves for various ceramics of the 123 system we can see that the shift is more pronounced at a higher critical current [7,14] (Fig.8). The same relation is observed for ceramics with silver additions and with deviations from the stoichiometric composition [16]. In other words, usually a correlation between the critical current value and the stress-induced shift of curves exists.

Mechanical effect on superconductive transition is usually studied under hydrostatic pressure [2,3]. It is natural, since it allows to avoid fracture and to achieve higher stress. But applying hydrostatic pressure it is impossible to understand the role of stress as tensor and to obtain tensile strain.

We tried to find the effect of the deformation sign on the V-I curves by means of current passing along and across the compression axis.

Fig. 9 gives the V-I curves for the sample without load and with compressive stress at current passing both parallel and normal to load. It is seen that the sign of curve shift is different while spherical component of the stress tensor are the same for both current directions.

Fig. 7. Effect of a compression on the V-I characteristics of the

YBaCuO ceramics with various critical currents; σ , MPa: 0 (1), 10 (2), 40 (3).

Fig. 8. Effect of the strain sign on the V-I characteristics of the

YBaCuO ceramics; σ , MPa: 0 (1), 50 (2-compression, 3-tension).

Fig. 9 (left). Influence of magnetic field on the V-I characteristics of YBaCuO ceramics under load;

σ , MPa: 0 (1,2,3); 20 (1',2',3');
 H , Oe: 0 (1,1'); 25 (2,2');
 50 (3,3').

Obviously, it is related not with the stress but with the elastic strain in the current direction. The compressive strain shifts V-I curves to the right, but if the strain is tensile the shift is directed to the left. The value of curve shift appeared to be proportional to that of the strain. The shift under compressive strain is nearly 4 times greater than under tensile one, which is in agreement with the elastic strain ratio. Theoretical consideration of problem on value and sign of stress-induced effects in tensile and compressive strains was represented in [17].

As showed before, for ceramics with various defect structure the higher the critical current value the larger the stress-induced effect. It was naturally of interest to check this correlation using specimens with the same structure. For this purpose we used the effect of magnetic field on the critical current value.

In order to measure the V-I characteristics the sample together with loading device was placed in solenoid with the magnetic field parallel to the transport current. Fig. 10 presents the V-I curves which were obtained on the same specimen under different stress and in different magnetic fields [18]. It is seen that the stress-induced effect decreases with increasing magnetic field, that is with decreasing the critical current value. Thus, the correlation between the stress-induced effect and critical current value is valid in the case of magnetic field as well.

The stress-induced shift of V-I curves can be explained on the basis of a model where the critical current behaviour in the polycrystalline superconducting materials is consistent with weak links at the grain boundaries and contacts between granules forming the ceramics. Since compression reduces the thickness of grain boundaries and increases square of contacts between granules, normal to both the current and the load, this can result in a higher critical current and, hence, in a shift of the V-I curve to the right. Some changes in a state of grain boundaries under the load are possible too. Thus, the value of stress-induced effect is determined by a quality of grain boundaries and contacts between granules.

4. CONCLUSION

In summary, the present study allows the following conclusions:

(i) In high temperature superconducting ceramics, like in metallic superconductors, the superconductive transition leads to an increase in the inelastic strain rate under the load. Effect is connected with the difference in mobility of the defects responsible for strain mechanisms in normal and superconducting states.

(ii) The effect of stress on the critical temperature and the V-I characteristics of the ceramics is observed. Compression leads to an increase in critical temperature and causes the shift of the V-I curves. This shift is determined by the elastic strain along the electric current. The direction of shift depends on sign of strain. The correlation between the stress-induced effect and critical current value exists. These effects are associated with weak links at the grain boundaries.

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