A dc superconducting fault current limiter using die-pressed $YBa_2Cu_3O_7$ ceramic

To cite this article: A G Mamalis *et al* 2001 *Supercond. Sci. Technol.* **14** 413

INSTITUTE OF PHYSICS PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY

Supercond. Sci. Technol. **14** (2001) 413–416 www.iop.org/Journals/su PII: S0953-2048(01)17889-9

A dc superconducting fault current limiter using die-pressed $YBa_2Cu_3O_7$ ceramic

A G Mamalis[1], M I Petrov[2], D A Balaev[2], K A Shaihutdinov[2], D M Gohfeld[2], S V Militsyn[3], S G Ovchinnikov[2], V I Kirko[3] and I N Vottea[1]

[1] Manufacturing Technology Division, Mechanical Engineering Department, National Technical University of Athens, Greece

[2] Kirensky Institute of Physics, 660036 Krasnoyarsk, Russia

[3] Research Institute of Physics and Engineering of Krasnoyarsk State University, 660036 Krasnoyarsk, Russia

Received 9 October 2000, in final form 19 March 2001

Abstract

A model of a superconducting fault current limiter on a polycrystalline high-temperature superconductor basis is checked in the dc short circuit regime. Protection of load takes place under the conditions described in this paper. The use of ceramic materials with superconducting–normal metal–superconducting Josephson junction network having an S-type current–voltage characteristic (CVC) is shown to be effective for fault current limiter devices.

1. Introduction

The possibility of application of high-temperature superconductors (HTSC) in fault current limiters has been under intensive investigation since soon after the discovery of the high-temperature superconductivity [1]. At present there are two concepts of superconducting fault current limiters (SCFCL) [2]. The first, so-called 'shielded iron core SCFCL', implies inductive coupling of an HTSC element in a ring form and the load in the line [2, 3]; engineering and creation of large devices are required. In the alternative concept the HTSC is directly connected with the load to be protected [2]; in this case technical problems are associated with the preparation of low-resistance contacts HTSC/current lead. The behaviour of sintered ceramic superconductors as possible elements for SCFCL applications at high pulsed current was also investigated in [4, 5].

In the ideal SCFCL, the ballast resistance (superconductor) is equal to zero for the current I, less than its critical value for the superconductor element, I_c and it 'switches on' when I exceeds I_c, limiting therefore the current to a safe level.

In the present work a prototype of a SCFCL based on $YBa_2Cu_3O_7$ ceramics operating in at liquid nitrogen temperature under dc conditions was constructed, with the aim in mind to examine the behaviour of SCFCL under the short-circuit conditions in the quasi-stationary regime, which is hardly realized in inductive ac devices.

2. Experiment

2.1. HTSC material

HTSC powder of $YBa_2Cu_3O_7$ was synthesized from high-purity Y_2O_3, BaO_2, and CuO by a standard ceramic technique at 880–925 °C for 36 h with three intermediate grindings. The x-ray diffraction pattern of the powder obtained show reflections from 1-2-3 phase only. Then, superconducting $YBa_2Cu_3O_7$ rectangular blocks, with typical dimensions $2 \times 7 \times 44$ mm^3, were die-pressed under stationary conditions (over 5 s up to 10 T, the compaction velocity is about 5×10^{-4} m s^{-1}). The final heat treatment was performed at 925 °C for 10 h, followed by slow cooling within the furnace. The average grain size, measured using a Leica DMRM microscope, was about 2 μm. The sample density was 6.1 g cm^{-3}, which is 93% of the theoretical value. The temperature of the transition into the superconducting state, determined both the resistance and magnetic methods, was 91.5 K ($\Delta T_c \approx 2$ K).

2.2. Contacts HTSC/current lead

Contact islands were formed on the end surfaces of die-pressed samples from silver powder before the final thermal treatment. An optical micrograph of a section of the interface between the HTSC and Ag, obtained using the Leica DMRM microscope, is presented in figure 1; two distinct areas, corresponding to HTSC and silver, are clearly indicated. Note that the diffusion

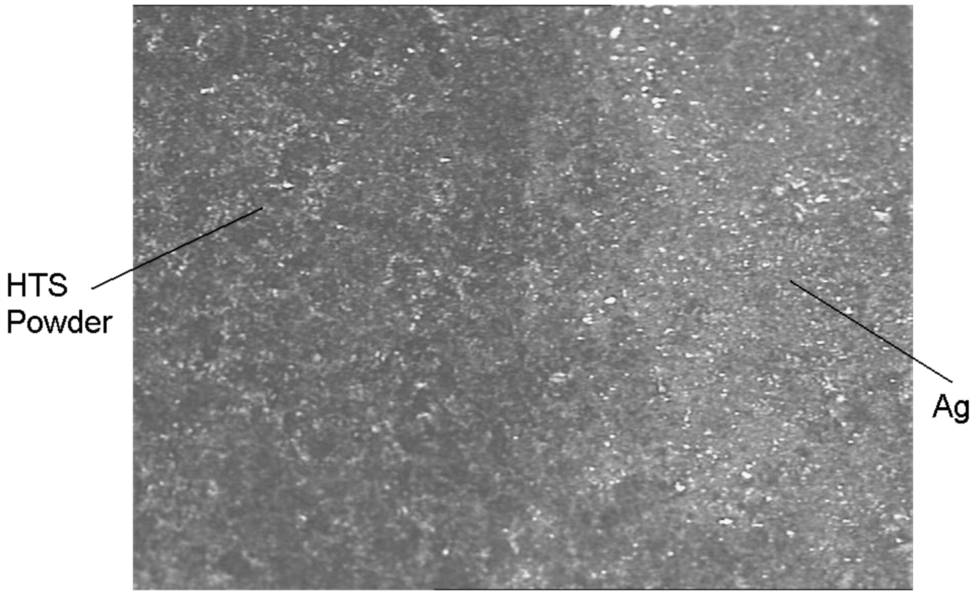

Figure 1. Micrograph of the interface between the HTSC ceramic and the metal (Ag) (×100).

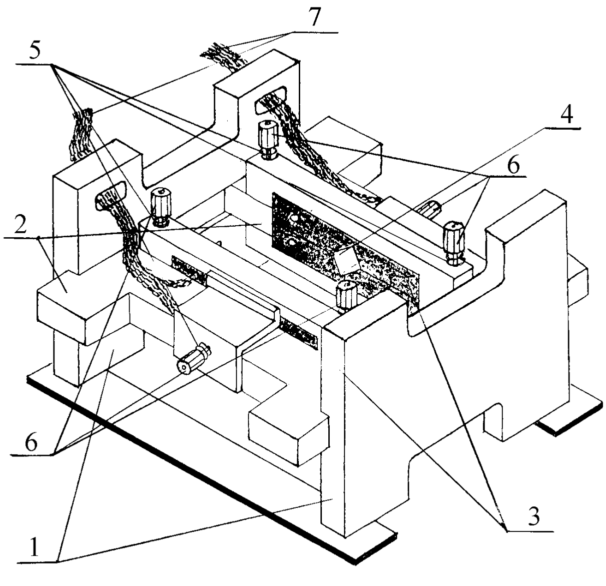

Figure 2. The floating current lead system. 1, insulating plate; 2, floating current lead holders; 3, massive copper current leads; 4, groove in 3 for the active HTSC element; 5, springs securing the holding down of 3 to the active HTSC element; 6, adjusting screws; and 7, flexible output electrodes.

of Ag particles (of 2–10 μm diameter) into the bulk HTSC, to a depth up to about 200 μm, seems to take place, resulting in a low resistance contact between the HTSC and the Ag layers, see below.

After the thermal treatment these contact islands were additionally coated with In–Ga eutectics. The sample prepared in such a manner was inserted between copper floating holders, as shown in figure 2, and put into the liquid nitrogen bath. Due to these actions the typical contact resistance of about 6 $\mu\Omega$ cm^2 at 77 K was obtained, which is the same order of magnitude as given in [6, 7].

2.3. Short-circuit regime modelling

The circuit studied is shown in figure 3. The HTSC element immersed in the liquid nitrogen bath is connected in series as a ballast resistance with the load and voltage sources. The step rheostat was used as a load resistance R_r. The lorry accumulator with six cells in parallel was used as a voltage source, the internal resistance is about 10^{-4} Ω.

3. Results and discussion

Note that for a very low contact resistance the data measured by the two- and four-probe techniques were practically identical, and, therefore in this paper the data measured by the two-probe technique are reported. The two-probe technique was employed because the data obtained are convenient for operating superconducting current limiter (SCL) devices (the SCL voltage drop is the HTSC voltage drop plus contact HTSC/current lead voltage drop).

Figure 4 shows the typical experimental data for a sample measured at the modelling of a short circuit. The current I, the superconductor and the load voltage drops U_{sc} and U_r were fixed under the step-by-step decrease of the load resistance. From figure 4 it is indicated that for $I > 20$ A the I against R_r curve starts to deviate from the hyperbolic law $J = U/R_r$ with decreasing R_r. The current I reaches its maximum, approximately at 60 A, at $R_r = 0.01$ Ω and then drops abruptly to about 35 A. In our opinion this effect is associated with the transition of the current–voltage characteristic (CVC) of the HTSC sample to the branch with higher differential resistance, observed earlier [8]. As it can be seen from figure 3, under minimum load resistance protection takes place, i.e. $U_r < U_{sc}$. The calculated dependences of load and superconductor heat dissipation, P_r and P_{sc}, are also shown in figure 3; it is obvious that, under the minimum load resistance, the P_r equals 20 W, whilst in the absence of HTSC this value would be about 400 W (the value 400 W may be obtained using the relation

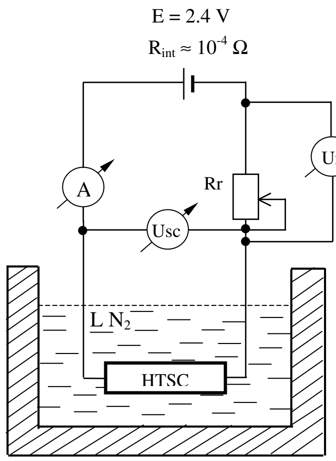

Figure 3. A schematic diagram of the circuit of the high-temperature SCFCL model.

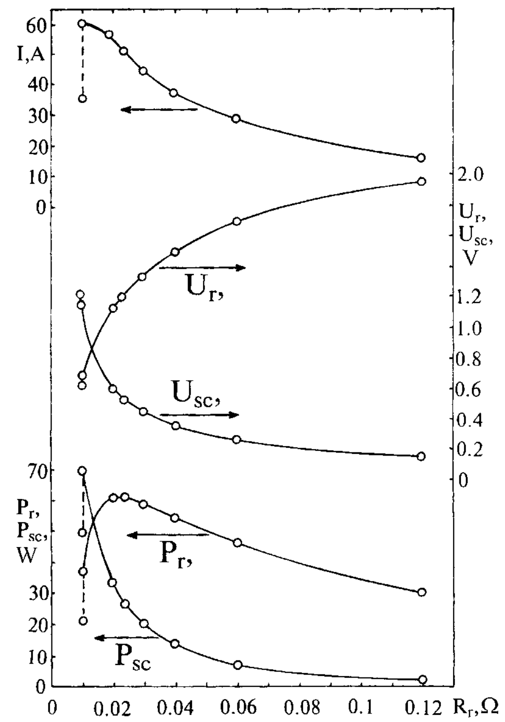

Figure 4. Experimental curves showing the variation with resistance R_r of the (top) current, I; (middle) the superconductor and the load voltage drop, U_{sc} and U_r; and (bottom) superconductor and load heat dissipation, P_{sc} and P_r.

$P_r = U^2/R_r$ under the conditions $U = 2$ V and $R_r = 0.01$ Ω). The value of the superconductor heat released, P_{sc}, which is less than 70 W is effectively removed by liquid nitrogen.

Under fixed current conditions the transition of CVC from the low-resistivity to the high-resistivity branch is usually associated with hysteresis [8, 9]. The hysteresis reflects the branch with negative differential resistance in the CVC of superconductors [10, 11]. The form of the negative differential resistance branch is only observed under fixed voltage conditions. There are at least two physical mechanisms of the negative differential resistance of superconductors appearing on the CVC: (i) self-heating of the superconductor [10]; (ii) Andreev reflection of current carriers on S–N (where S denotes superconductor, N denotes normal metal) interfaces of S–N–S junctions in polycrystalline HTSC [11].

The latter mechanism may take place in polycrystalline HTSC so far as their transport properties are affected mainly by the natural metallic type grain boundaries [12] which constitute the dominant factor to Andreev reflection processes [8, 12, 13]. In our opinion, Andreev reflection gives the main support in the observed effect of spontaneous drop of current in figure 4. The effect of the HTSC–Ag interface is rather negligible, due to the small size of HTSC–Ag–HTSC junctions observed in the specimen (the area of diffusion of Ag particles into the bulk sample is estimated to be about 200 μm, see figure 1, which is much less than the geometric dimensions of the sample). The self-heating mechanism would result in non-stationary resistivity against time behaviour of the sample, while the data presented were repeated many times at any scanning velocity. Moreover, in [8] the temperature behaviour of hysteresis type CVC of polycrystalline YBaCuO system has been under intense study and the Andreev reflection is concluded to be the dominant mechanism, which determines the observed effect. The theory developed for the CVC of S–N–S junctions predicts the sharpest transition from the low- to the high-resistivity branches (the widest hysteresis) for junctions with normal metal layers having highest transparency for current carriers [11]. This explains the observed wide hysteresis on CVC of composite samples HTSC plus normal metal $BaPbO_3$ [9], because $BaPbO_3$, playing the role of artificially created grain boundaries, possesses a long mean free path [9, 13, 14].

Thus, the technological search for superconducting materials with grain boundaries providing the negative differential resistance branch on the CVC is advisable, whereas material having CVC with a hysteresis peculiarity is close to ideal for the fault current limiter because it has the jumpwise transition from low to high resistivity.

4. Concluding remarks

We believe that the detailed study of the hysteresis peculiarity on the CVC of a polycrystalline HTSC with certain additions should allow for the design of the SCFCL possessing parameters needed for practical use.

Acknowledgments

The work was partially supported by the Russian Federal Programme ‘State support for the integration of Higher education and fundamental research’, grant A0019, and by the Greek–Russian bilateral cooperation programme ‘A novel concept of a switchgear combining high-T_c superconductors and silver-free contacts for efficient energy use in electricity and transportation’.

References

[1] Volkov A Yu 1990 *Pis Zh. Tekh. Fiz.* **16** 11–14
[2] Paul W, Lanker M, Rhyner J, Unternahaher P, Baumann Th, Chen M, Widenhorn L and Guerig A 1997 *Proc. EUCAS (Veldhoven, The Netherlands, July, 1997)*
[3] Chen M, Baumann Th, Unternahaher P and Paul W 1997 *Physica* C **235–240** 2639–40

[4] Porcar L, Bourgault D, Noudem J G, Chaud X, Belmount O, Tixador P, Barbut J M, Barrault M and Tournier R 1997 *Physica* C **235–240** 2623–4
[5] Noudem J G, Porcar L, Belmont O, Bourgault D, Barbut J M, Tixador P, Barrault M and Tournier R 1997 *Physica* C **235–240** 2625–6
[6] Ekin J W, Panso A J and Blankeship B A 1988 *Appl. Phys. Lett.* **52** 331–3
[7] Wieck A D 1988 *Appl. Phys. Lett.* **52** 1017–19
[8] Petrov M I, Krivomazov S N, Khrustalev B P and Aleksandrov K S 1992 *Solid State Commun.* **82** 453–6
[9] Petrov M I, Balaev D A, Gohfeld D M, Ospishchev S V, Shaihudtinov K A and Aleksandrov K S 1999 *Physica* C **314** 51–4
[10] Likharev K K 1979 *Rev. Mod. Phys.* **51** 101–59
[11] Kümmel R, Gunsenheimer U and Nicolsky R 1990 *Phys. Rev.* B **42** 3992–4009
[12] Mannhart J, Chaudhari P, Dimos D, Tsuei C C and McGuire T R 1988 *Phys. Rev. Lett.* **61** 2476–9
[13] Petrov M I, Balaev D A, Ospishchev S V, Shaihudtinov K A and Aleksandrov K S 1997 *Phys. Lett.* A **237** 85–9
[14] Kitazava K, Katsui A, Toriumi A and Tanaka S 1984 *Solid State Commun.* **52** 459–62