The influence of the shock treatment under heating on the structure and properties of HTS tapes

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Abstract. The influence of shocks of different intensity on the structure and properties of multifilamentary superconducting tapes of Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+x}$ (Bi-2223) and MgB$_2$ compounds was studied. The Plasma Focus setup was used to produce the plasma shock waves, and a specially designed setup was utilized for the mechanical shock treatment. The experiments have shown a possibility to increase the critical current of MgB$_2$ tapes by more than 60% in magnetic fields of 1.5-2.0 T due to the treatment. The critical current increase is caused by homogeneity improvement, densification of superconducting filaments and the pinning enhancement.

1. Introduction

An interest to study an influence of plasma shock-waves and mechanical shocks on the structure and superconducting parameters of high-temperature superconductors (HTS) permanently grows. This interest is caused by a possibility of directional formation of structure of the HTS ceramic filaments enclosed in the metal shell due to increase of density and texture of the filaments, as well as creation of additional effective pinning centers. An increase of both the critical temperature $T_c$ and the critical current $I_c$ in the external magnetic fields was demonstrated in such a study. An increase of $T_c$ by 15 K was observed after ion irradiation of films, consisting of mixture of Bi-2212 and Bi-2223 phases, at the Plasma focus setup [1]. In addition, $I_c$ increase by 15% was observed for Y-123 ceramic based tapes produced by Superpower (USA) [2]. Similar increase by more than 60% in the magnetic field up to 8T was also found for the HTS tapes in [3,4].

The shock-wave impact leads to densification of superconducting filaments due to short-time heating and high pressure in the impact zone, formation of additional nano-sized defects (dislocations) acting as pinning centers, crushing and grinding grains and to a number of other factors. The improvement of pinning characteristics under the shock treatment is explained in [5-9] by formation of vacan-
cies, point defects and interstitial atoms (collective Frenkel pairs) at the shock-wave front. Concentration of vacancies produced by the plasma jet shock is much more than that in virgin material.

This work aims to find new ways and conditions for purposeful formation of microstructure of HTS ceramic filaments, to enhance the critical characteristics and other functional properties of these materials by means of various shock effects.

2. Experiment

The multifilamentary HTS tapes on the base of Bi-2223 or MgB$_2$ ceramics were investigated. Dimensions of the samples were as follows: the cross-section of 0.2×4 mm$^2$ and length of 35-40 mm for Bi-2223 tapes and 0.65×3.65 mm$^2$ MgB$_2$ ones.

Original setups shown in Figure 1 were used for the mechanical shock treatment made at temperatures up to 500°C. Specific energy of mechanical shocks was varied in a wide range from 0.5 to 100 J/cm$^2$ via change of the hummer weight (0.5 and 0.8 kg), height of the hammer's fall (10-40 mm), number of shocks, width of the impact zone, and etc. The hammer width was larger than the tape width. The impact-zone areas were of 1.6 mm$^2$ for Bi-2223 tapes and 1.46 mm$^2$ for MgB$_2$ tapes. The neighboring impact-zones overlapped by about 0.05 -0.1 mm. Single shock with the specific energy from 0.5 to 5.0 J/cm$^2$ was used in experiments on Bi-2223-tapes heated up to 500 °C in an electric furnace. A thermocouple was used to control temperature. After a series of mechanical shocks, the samples were annealed in air at temperature of 830-835°C for 5-30 hours.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Setups for mechanical shock treatment: (a) - the disc with fixed HTS tape; (b) – device producing the tape shift after applying mechanical shocks, (c) - an installation for shock-treatment of heated samples.

To treat tapes with the shock-waves produced by cumulative high-speed plasma streams (CHSPS), the plasma focus setup PF-4 (P.N. Lebedev Physical Institute, RAS) was used [10,11]. The samples were protected from the direct exposition of the plasma, by 0.2 mm thick molybdenum plate used as a target in which shock-waves were created. Sketch of the PF-4 setup and photograph of the plasma jet in the discharge space are shown in Figure 2. The PF-4 parameters are as follows: the energy in the plasma stream hitting the target is about 100 J, the duration of the impact is about 10$^{-7}$ s, the energy flux density is up to 10$^9$ W/cm$^2$. The distance from the PF-4 anode to the tape surface was 25, 30, 35, and 40 mm. Either 3 or 5 shocks were applied to one side of the tape with time interval of 1.5 min.

The surface microstructure of the tapes was examined using the scanning electron microscope EVA-40 (Zeiss). The elemental analysis of Bi-2223 and MgB$_2$ filaments was performed on a scanning electron microscope JSM-35 with a Link attachment. Scanning Hall magnetometry was used to study a magnetic field distribution frozen in the Bi-2223 tapes at 77K. The current-voltage characteristics of the MgB$_2$ tapes before and after treatment were measured at 4.2 K in magnetic fields from 0 to 4 T in NRC “Kurchatov Institute”. The 1 μV/cm criterion was used to obtain the critical current.
3. Results and discussion.
Photographs of the surface of the MgB$_2$ tape before (a) and after mechanical shocks with specific energy of 0.11 J/cm$^2$ (b, c) are shown in Figure 3. The shocks were applied at room temperature and the tape was shifted by 0.4 mm after each shock. The relief of the tape surface was investigated after the shock treatment. Comparing the panels (b) and (c) in Figure 3 we clearly see transverse stripes produced by the shocks on the treated side of the tape (b) The opposite side (c) demonstrates traces of the initial rolling while the stripes are less noticeable.

![Figure 3. Surface of MgB$_2$ tape before (a) and after mechanical shocks with the specific energy of 0.11 J/cm$^2$. (b) - treated side, (c) - the opposite side. After each shock the tape was shifted by 0.4 mm.](image)

Increasing the shift length to 0.8 or 1 mm leads to change of the relief (Figure 4). On the treated side the transverse stripes become more pronounced and deeper, while the longitudinal stripes appear on the opposite side. With all this going on, such transformations are more pronounced for the longer shift (Figure 4 c, d).

![Figure 4. Surface of MgB$_2$ sample after mechanical shocks with energy of 0.11 J/cm$^2$. The tapes were shifted by 0.8 mm (a,b) or 1 mm (c,d) after each shock. Surface of both treated (a,c) and opposite (b,d) sides is shown.](image)

Similar transformations for the similar conditions (specific energy of 0.1 J/cm$^2$) were found for Bi-2223 tapes. Clearly defined strips along the tape appeared when the tape was shifted by 0.4 mm, while the transverse stripes were hard to notice. When the shift was increased to 0.6 mm, the longitudinal strips still remained, but the transverse ones became more noticeable. With increase of the shift up to 0.8 and 1.0 mm the relief completely changed and only transverse stripes were observed.
The obtained results indicate that the specific energy, the shift length, the impact-zone area and overlapping the neighboring zones must be optimized.

The critical current of MgB$_2$ tapes was measured before and after treatment by mechanical shocks. Influence of the shock energy on $I_c$ measured in different magnetic fields is illustrated in Figure 5a. Increase of the shock energy from 14 J/cm$^2$ up to 21 J/cm$^2$ leads to degradation of the critical current. The obtained results have shown the need to reduce the shock energy down to 0.1 - 0.5 J/cm$^2$. In this case we expect an increase of $I_c$ up to 250-300 A in zero magnetic field. $I_c(H)$ dependences are shown in Figure 5b. Decrease of the critical current under mechanical shock treatment is caused by fragmentation of ceramic filaments. $I_c$ has been restored to previous values and even has increased after annealing of the samples.

![Figure 5](image1.png)

**Figure 5.** (a) Influence of energy of mechanical shocks on the critical current of MgB$_2$ tape in different magnetic fields: 1 - 0, 2- 0.5 T, 3 - 1 T. (b) Field dependence of the critical current before (4) and after treatment with mechanical shocks with energies of 14 J/cm$^2$ (5) and 18 J/cm$^2$ (6).

Figures 6(a,b) show the surface of Bi-2223 tapes after single mechanical shocks to the sample heated to 500 °C. The drop height was 3 cm (a) and 9 cm (b) in these experiments. With an increase of shock energy up to 0.91 J/cm$^2$, the impact zone became more noticeable, and the tape thickness decreased for several microns.

![Figure 6](image2.png)

**Figure 6.** Surface of Bi-2223 tapes after mechanical shocks with energies of 0.91 J/cm$^2$ (a) and 0.32 J/cm$^2$ (b). Distribution of the frozen magnetic field measured at 77 K for the tape treated at 500 °C with strokes with energy of 0.32 J/cm$^2$ (c).

Analyzing magnetic field frozen in the tape at 77 K we found that the field decreases in the treated zone (Figure 6c). However, this effect is significantly reduced in comparison with the case when the tape was treated without heating. Annealing at 835 °C for 5 hours led to the complete recovery of $I_c$.  


Unlike mechanical shocks, treatment with the plasma shock-waves (PSW) leads to significant increase of the critical current of MgB$_2$ tapes in the magnetic fields of 1.5-3.0 T. As seen in Figure 7, the critical current in magnetic field of 2T, which was 150 A in virgin tape, has increased up to 200 or 225 A after 5 or 3 impacts respectively, produced by CHSPS generated at the distance of 40 or 45 mm from the plasma anode. Noticeable difference in $I_c(H)$ behavior is caused by both different number of shocks and different distances between the sample and the plasma anode.

Analysis of the cross section of virgin and PSW treated tapes revealed noticeable difference in microstructure of the samples (Figure 8). Larger grains and cracks were observed in MgB$_2$ interlayers in virgin tape. After the PSW treatment the grains became smaller while the cracks disappeared. These structural transformations under PSW treatment cause the critical current increase.

Results of microanalysis of the MgB$_2$ interlayers in the tapes are presented in Table 1. Comparing data for virgin and PSW treated tapes one can see that stoichiometry is changed by the treatment, namely magnesium and boron content increases while carbon and oxygen content decreases. The highest boron content was found in precipitates with dimensions about 5 μm (spectrum 1) contained about 33 wt% of magnesium and 46.39 wt% of boron. The homogeneity has been improved under PSW treatment.

![Figure 7. $I_c(H)$ dependences for MgB$_2$ tapes. (1) – virgin tape, (2) and (3) – the tapes treated with PSW. Number of impacts and distances between the sample and the plasma anode were 3 and 45 mm for (2), 5 and 40 mm for (3).](image)

**Table 1.** Chemical composition of MgB$_2$ interlayers in virgin and PSW treated tapes.

| After PSW impact | B     | C     | O      | Mg    | Virgin state | B     | C     | O      | Mg    |
|------------------|-------|-------|--------|-------|--------------|-------|-------|--------|-------|
| Spectrum 1       | 46.39 | 18.44 | 2.21   | 32.96 | Spectrum 1   | 5.38  | 42.76 | 36.22  | 15.64 |
| Spectrum 2       | 40.02 | 20.04 | 8.22   | 31.72 | Spectrum 2   | 10.70 | 35.92 | 23.21  | 30.17 |
| Spectrum 3       | 40.97 | 26.04 | 10.32  | 22.67 | Spectrum 3   | 8.80  | 42.83 | 31.98  | 16.39 |
| Spectrum 4       | 27.69 | 25.88 | 12.96  | 33.47 | Spectrum 4   | 22.00 | 29.21 | 16.60  | 32.19 |
| Spectrum 5       | 31.54 | 40.93 | 11.74  | 15.79 | Spectrum 5   | 18.43 | 30.67 | 21.38  | 29.51 |

![Figure 8. Macro- and microstructure of the cross-section of the MgB$_2$ interlayer in virgin state (a, b) and after the PSW impact (c, d).](image)
4. Conclusions

1. Critical current increase from 150 to 225 A in the magnetic field of 2.0 T was obtained for MgB$_2$ tapes treated by plasma shock-waves at the distances of 40-45 mm from the surface of the tape to the plasma anode.

2. The study of influence of mechanical shocks on critical current of MgB$_2$ tapes has revealed decrease of $I_c$ with increase of impact energy from 14 to 21 J/cm$^2$. We have observed crushing the grains in the MgB$_2$ interlayers and violation of the electrical conductivity of grain boundaries.

3. It was shown that increase of the shock step from 0.4 to 1.2 mm leads to significant change of the surface relief from both treated and opposite sides of MgB$_2$ and Bi-2223 tapes. Clearly defined transverse traces of impacts were observed on the surface of the tapes when shock step exceeded 0.4 mm.

4. Microanalysis of superconducting layers performed before and after plasma impacts has revealed increase of homogeneity of the superconducting core microstructure.

5. Optimization of the impact treatment allows to improve the functional characteristics of superconducting tapes on the base of MgB$_2$ and Bi-2223.

Acknowledgments
The work was supported by RFBR grants No. 15-08-04045a and No. 15-02-05995a

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