Current state of studies of shock-wave action on the structure and properties of superconductors

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Abstract: The article presents the results of the action of shock waves generated by the Plasma Focus setup on the structure and critical current \( J_c(B) \) of MgB\(_2\) and Bi-2223-based superconductors. The structure of the tapes was studied in the transverse and longitudinal sections using different impact energy intensities (due to a change in the distance from the plasma anode from 20 to 50 mm for the same number of plasma pulses (\( n = 5 \))). The studies showed the possibility of increasing the critical current (\( J_c \)) up to 50% in transverse and longitudinal magnetic fields to 2-3 T after plasma impact due to changes in the microstructure of the superconducting phase, including: grain refinement, interlayer compaction, microdeformations and crystal lattice defects allowing to increase the number of pinning centers of magnetic vortices.

1. Introduction

The first experiments on the influence of shock waves (SW) with a pressure of \( 10^{10}-10^{11} \text{ Pa} \) were used to increase the current carrying capacity of the commercial composite HTSC YBCO-tape (123) in [1,2]. To implement the submicrosecond shock wave action, the effect of the formation of SW arising from the interaction of high-speed cumulative plasma jet with a solid target is used. The basis of experimental studies of shock-wave action is the fact of the formation of point defects - vacancies and interstitial atoms (collective Frenkel pairs) at the front of SW as they pass through metallic and semiconductor materials. In this case, the concentration of emerging vacancies upon impact of plasma jet can be many times higher than the concentration of thermal vacancies in the initial material [3].

The formation of point defects in nickel under the influence of giant laser pulses and the effect of laser irradiation of niobium-based superconducting materials on the nature of critical temperature changes were shown in [4].

Taking into account the effect of the formation of point defects in metal and semiconductor materials at the front of shock waves [4,5] the laser influence on the temperature of the transition to the superconducting state (\( T_c \)) of niobium-based alloys was studied. These experiments showed a noticeable effect of shock waves influence on \( T_c \). The observed effect was explained by the acceleration of diffusion processes due to the excess thermodynamically nonequilibrium defects arising during the passage of shock waves, as well as the role of dislocation interstitial loops. The results of these studies suggest that shock waves, depending on the power, can lead to significant
changes in the superconducting characteristics and structure of HTSC tapes due to the creation of more equilibrium structural phase states and the formation of dislocation interstitial loops and vacancy pores. Studies of the physical processes occurring in superconductors in the state of contact with shock waves are in significant interest and open up wide possibilities for controlling the processes of structural, chemical, and phase transformations. Shock-wave action during the formation of micro and macrostructure can be selective and lead to different results. The action of a shock wave can cause high-speed crushing and mixing of particles and initiate ultrafast chemical reactions, contribute to the compaction of the microstructure, and lead to the appearance of various gradient defects.

The use of shock waves (SW) generated by various sources, including plasma pulses, dosed mechanical shocks, etc. attracts an interest to increase the superconducting parameters of a number of superconductors [4-15], including commercial tapes that are already ready for use.

The article presents some results of studies of shock effects produced by using a plasma focus type setup on the structure, grain morphology, phase composition, texture, and superconducting parameters Tc, Jc, Jc (B) of various superconducting compounds (wires and strips) based on Bi-2223 and MgB2 [4-16].

2. Materials and Experimental Methods
The experiments were performed on the carved from industrial multicore wires and multilayer tapes samples based on Bi-2223, multifilament MgB2 tapes and composite wires (D=0.9 mm) containing a stoichiometric mixture of magnesium and boron powders and on the tapes coated with superconducting powder, obtained using pressing and rolling.

To implement submicrosecond shock-wave action, a phenomenon of SW generation under the interaction of high-speed cumulative plasma jet with a solid target was used. A plasma jet was generated in a PF-4 plasma focus device (Lebedev Physical Institute, Russian Academy of Sciences) with a maximum energy stored in a capacitor bank of 4 kJ and a plasma jet velocity of 107 cm/s. The energy flux density in a jet impinging against the target surface reaches ~2 x 109 W/cm2. The working chamber was filled with an inert gas (argon) at a pressure of 1.5Torr. The surface of the target (superconducting tape) was shielded from direct influence of plasma pulse with strips of metals with different electrical and thermal characteristics (Mo, Fe, Cu, Ti, and Al). The zone of SW action was 10 mm along the length of the tape, the distance from the anode to the tape surface was changed from 20 to 50 mm, and the number of plasma impacts was varied from 1 to 20. All plasma impacts were delivered on one side of the sample.

After the shock, the critical current value Tc was measured and the structure of superconducting interlayers was investigated. The critical current was measured in magnetic fields from 0.3 to 5.0 T at a temperature of 4.2 K.

X-ray diffraction phase analysis (XRD) was carried out by means of Rigaku Ultima IV at CuKα radiation using crystallographic database ICDD PDF-2 and software PDXL. Microstructure analysis was carried out using the optical microscope and scanning electron microscope EVA-40 (ZEISS).

3. Experimental Results
Studies of the samples microstructure before and after plasma shock exposure allows you to get the visual picture of the changes that occur when applying SW. Figure 1 shows the microstructure of the cross section of multilayer Bi-2223 tapes in the initial state before impact (a) and after plasma SW (b).
Figure 1. The cross section microstructure of Bi-2223 multilayer tapes in the initial state – before the impact (a) and after the plasma SW (b).

When comparing these structures, a significant compaction of the microstructure, the disappearance of the cracks, and decrease in the number of point pores in the microstructure core after SW exposure are noticeable.

Figure 2 shows with more magnification, the microstructure of the MgB$_2$ tape cross section in the initial state (a) and after the SW (b). After SW crushing and grinding of grains were observed, as well as the formation of a denser skeleton in MgB$_2$ core microstructure to compare with the sample before processing, which has a loose friable microstructure.

Figure 2. The cross section microstructure of MgB$_2$ core in the initial state (a) and after SW (b).

The change in the microstructure of the superconducting core after SW is also consistent with the XRD data. In a number of samples from MgB$_2$, Bi-2223, and Y-123 after SW, compared with the peaks in the X-ray diffraction patterns obtained before exposure, broadening of the X-ray peaks was established, and in some cases, with an increase of SW intensity, the formation of an amorphous phase has been established (5-10 wt.%).

The broadening of the peaks indicates the processes associated with a decrease in grain size and, consequently, size reduction of the coherent scattering regions (CSR) blocks. The broadening value is also depending of the microdeformations intensity in the structure of superconductors. On figure 3a. the X-ray diffraction pattern of the initial MgB$_2$ powder (Sp. Gr. P6 / mmm) is shown. The quantitative x-ray phase analysis was shown that the powder consists mainly of the MgB$_2$ compound - 94.4 wt% with an admixture of MgO ~ 5.6 wt% . The sizes of CSR (D) calculated in the PDXL...
(Rigaku) program by the Williamson – Hall method for the initial powder were \(-1000\) Å and the magnitude of microstresses \(-\varepsilon=0\%\). Such values of these quantities are typical, as a rule, for annealed powders consisting of large crystallites. The \(\text{MgB}_2\) lattice constants after refinement in the \textit{Celref} program were \(a = b = 3.0859(7)\) Å, \(c = 3.5214(3)\) Å.

![X-ray diffraction pattern of the initial \(\text{MgB}_2\) powder (a) and X-ray diffraction pattern after rolling on aluminum substrate and SW action (b).](image)

\textbf{Figure 3.} X-ray diffraction pattern of the initial \(\text{MgB}_2\) powder (a) and X-ray diffraction pattern after rolling on aluminum substrate and SW action (b).

Further X-ray phase studies showed that the \(\text{MgB}_2\) powders after treatment (Figure 3.b) remain almost single-phase and their phase composition does not change after processing by SW action of plasma - \(95.6\) wt\% \(\text{MgB}_2\) and \(4.4\) wt\% \(\text{MgO}\). However, the diffraction lines are noticeably broadened due to a change in the microstructure of the powder and grain grinding. The calculation of CSR (D) on the samples after SW action (5-10 strokes and 25-35 mm distance) showed that the CSR (D) decreases noticeably (to \(230-300\) Å) from sample to sample. The values of microstrains \((\varepsilon)\) are also slightly increase to \(0.01-0.02\%\). In the range of \(2\theta\) (9°-35°), a small amorphous halo appears (Figure 3b), which is apparently due to the small part of the powder goes into an amorphous state after a plasma shock. The refinement of \(\text{MgB}_2\) lattice constants after SW showed that periods \(a\) and \(b\) after treatment are practically unchanged \((3.0853(3)\) Å\). However, the \(c = 3.5184\) (3) Å, which may be due to the appearance of defects in the crystal structure of \(\text{MgB}_2\) under the influence of plasma shock waves. The formation of additional defects can contribute to an increase of the pinning force of magnetic vortices, which, according to the accepted theory of superconductivity upon application of a field, begin to attach to them and, as a result, prevent the penetration of an external magnetic field into the bulk of the superconductor.

\(\text{Bi-2223}\) based samples were studied in more detail using the Rietveld structure refinement method in the MAUD software package. Figure 4 shows the x-ray spectrum of the initial \(\text{Bi-2223}\) powder (Sp. Gr. A2aa), after refinement of the structure in the MAUD software package. In the refinement, background parameters, profile parameters, zero point position, peak asymmetry, lattice periods, the amount of each of the phases that make up the powder, texture parameters, atomic coordinate values, thermal corrections, and fill factors of atomic positions are taken into account.

The phase content in the initial sample was: \(\text{Bi-2223} - 67.6\) wt\% and \(\text{Bi-2212} - 32.4\) wt\%. The lattice periods of the main phase of \(\text{Bi-2223}\): \(a = 5.419\) (5) Å, \(b = 5.418\) (6) Å, \(c = 37.195\) (9) Å. The sizes of the CSR blocks (D) and microstresses \((\varepsilon)\) were specified. They respectively amounted to \(D \approx 800\) Å, \(\varepsilon \approx 0.05\%\) for the main phase of \(\text{Bi-2223}\).
Figure 4. The results of the refinement of the structure according to the Rietveld method for the initial powder Bi-2223. The calculated spectrum is marked in red, black is the experimental one, the difference picture is shown under the figure. The divergence factors between the experimental and calculated profiles were: Rwp = 5.5, Rb = 4.3, Rexp = 1.9.

Next, we studied samples of coatings from HTSC ceramics based on Bi-2223 obtained by pressing and rolling on substrates made of copper and aluminum before and after treatment with a plasma focus. The distance between the anode and the sample was L = 35 mm, the number of strokes n = 5. Figure 5 shows the XRD results for such a sample.

Figure 5. The XRD results of Bi-2223 ceramics sample after the shock wave action from the side of the plasma source.

The refinement by the Rietveld method showed that after SW decomposition of the superconducting Bi-2223 phase and degradation into simpler homologous phases was not observed. The number of Bi-2212 and Bi-2223 phases remains at the level of the initial sample: Bi-2223 - 68.2 wt% and Bi-2212 - 31.8 wt%.

This indicates, first of all, that the use of a plasma effect under the selected conditions (L = 35 mm, the number of strokes n = 5) made it possible to prevent overheating of the sample and its subsequent
melting. When comparing the X-ray spectra for the initial powder and after SW action (Figure 5), it can be noted that the intensity of the lines of the sample after processing decreases, and the lines are very blurred, including reflections of the (001) type, which are characterized by a higher intensity due to the formation of texture rolling. At the same time, the preferential orientation of the grains is retained after SW processing. As in the case of MgB$_2$, the appearance of the peak broadening effect is noticeable, which indicates a strong grain refinement upon SW exposure, a decrease in the CSR (D), and the occurrence of microdeformations. The total visible effect after SW action of plasma exposure is expressed in obtaining more dense uniform microstructure of an ordered type. In macrovolume, annihilation of such defects as pores, cracks, loose fragments, and grain crushing can be observed. At the same time, microdeformations and microstresses appear in the structure of superconducting compounds.

![Figure 6. Comparison of fragments of powder diffraction spectra after SW action (1) and initial powder (2).](image)

According to the calculations by the Rietveld method, the factors of divergence between the experimental and calculated profiles were: Rwp = 10.01, Rb = 6.54, Rexp = 1.98. These indicators are significantly higher than for the initial powder and after rolling.

This is due to the change in the microstructure and structure of the samples as a result of pressing, rolling and SW processing and, accordingly, a change of X-ray spectrum, including description by mathematical functions. The sizes of the CSR blocks and microdeformations for the sample after SW processing – for the Bi-2223 compound – were D ≈ 580Å, ε ≈ 0.05%. It can be seen that the size of the CSR is noticeably smaller than for the initial powder. The lattice periods were Bi-2223 - a = 5.386 (5) Å, b = 5.423 (4) Å, c = 37.188 (9) Å. Changes in the lattice periods can be associated with the cyclical SW influence (in this case, n = 5) as a result of which the sample alternately experienced rapid heating and then gradually cooled. This could lead to disordering in the structure, as well as the appearance of defects and a change of lattice constants. To study such effects, it is necessary to eliminate the reflections of the second impurity phase (Bi-2212) from the spectrum, to exclude the contribution from the influence of texture and substructure, since these features of the sample very much distort the X-ray picture, and do not make it possible to refine a lot of parameters. As can be seen from the results of X-ray powder diffraction and microstructure studies on the examples of three superconducting compounds: MgB$_2$, Y-123 and Bi-2223, after processing by shock waves using a plasma source, grain
size grinding, powder compaction, and better adhesion between grains were observed in all samples. The phase composition of the samples did not change, but the appearance of defects was observed in the structure, which expresses itself in a decrease of the lattice periods, and the size of the CSR blocks (D). Microdeformations became more noticeable. A certain amount of powder (1-10% - depending on the conditions of striking) acquired an amorphous structure. Similar changes in the structure and microstructure can explain an increasing of the critical current after SW treatment. Firstly, defects occur at the micro level, which leads to an increase in pinning force, and secondly, the powder is compacted by grinding and core compaction in the bulk of the cores themselves; moreover, grain boundaries are melted, which also improves contact between grains. Also, in the case of manufacturing samples using rolling and pressing, a texture is formed in the direction of the current flow, which remains after SW treatment. The material of the protective shield covering the sample from direct plasma exposure during SW processing also has a significant effect on the structure of the samples the critical current. The experiments with using screens of various metals with a thickness (100 μm) at the same distance from the PF anode (35 mm) showed the highest critical currents in the case of using titanium foil (850 A) in a magnetic field of 1.0 T at helium temperatures.

Depending on the exposure conditions: the distance between the tapes and the anode, and the number of pulses, as well as the type of protective gaskets used, all these effects can express themselves in different degree and lead to different results, basically in case of the critical current magnitude.

4. Conclusion
1. The possibility of the critical current increasing of superconducting tapes to 50% in 3–4 T magnetic fields due to shock-wave and temperature effects has been shown in a number of published works.
2. The increase in the critical current of the tapes can be explained by an increase in the density and hardness of superconducting layers, grain refinement, and an increase in the number of effective pinning centers.
3. The possibility of increasing the critical current MgB$_2$ tapes in the case of SW action using protective gaskets of various metals has been established.

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