Journal of Physics: Conference Series

**PAPER** • **OPEN ACCESS**

# Influence of mechanical and plasma shockwaves on the structure and properties of superconductors

To cite this article: B P Mihailov *et al* 2020 *J. Phys.: Conf. Ser.* **1582** 012037

# Influence of mechanical and plasma shockwaves on the structure and properties of superconductors

**B P Mihailov[1], S Ya Alibekov[1], N A Krutskih[1], A V Egorov[1], A I Pavlov[1], A V Lysyannikov[2], Yu F Kaizer[2] and A V Kuznetsov[3]**

[1] Volga State University of Technology, 3, Lenina Square, Yoshkar–Ola, 424000, Russia
[2] Siberian Federal University, 82/6, Svobodny ave., Krasnoyarsk, 660041, Russia
[3] Krasnoyarsk State Agrarian University, 2, Kirenskogo str., Krasnoyarsk, 660074, Russia

E–mail: kaiser171074@mail.ru

**Abstract**. The article presents the results of studying the critical temperature, critical current, and field dependencies of superconducting Bi-2223 and $MgB_2$ multilayer tapes after them being subjected to the influence of shock waves generated at the Plasma Focus test bench and mechanical impacts of various intensities. The influence of the specific energy, the number of impacts, the distance of the samples from the plasma anode, the energy of the falling shock mechanism, and the step of moving the impacts was studied. Studies have shown that the critical current *Jc* can be increased by 50 % in magnetic fields of 2–3 *T*. In this case, the grains are crushed, compacted, homogenized, and the impurity content changes. The results of microanalysis of superconducting interlayers in the initial state and after influence of shock-wave of plasma show an improvement in the homogeneity of the distribution of the main components (Mg and B) and impurities (C and O).

## 1. Introduction
Current-carrying properties, field-dependent critical current *Jc***,** critical temperature and critical magnetic field of superconducting materials are structurally sensitive parameters and to a large extent change during deformation by metal rolling, being drawn through a roller die, extrusion and heat treatment.

Dimensions play a big role in this and grain morphology, phase composition, texture, the presence and dimensions of structural defects, admixture, dislocation, vacancies, etc. [1]. Along with this, all these structural factors can also experience significant changes under the influence of shock-waves, generated by shock pulses of high-temperature plasma, mechanical shocks, explosive actions [2–5].

Influence of shock waves of high-temperature argon plasma and mechanical shocks of varying intensity to increase current-carrying properties and critical temperature used in a number of works on composite high-temperature superconducting (HTS) Bi-2223 tapes and on multilayer $MgB_2$ tapes [6–10]. A submicrosecond shock-wave action occurs when a high-speed cumulative plasma jet interacts with the surface of a superconducting tape. The basis of this study is the influence of the formation of point defects – vacancies and interstitial atoms (Frenkel pairs) at the front of shock waves as they pass through metal targets [11].

The aim of the research is to study the influence of the energy of plasma and mechanical shocks, distances from the plasma anode and the number influence of shock on the critical current in magnetic fields in the interval 2.0–9.0 *T*, at the macro – and microstructure, homogeneity and chemical composition of the superconducting layers.

## 2. Materials and experimental methods

The research was carried out on 14-core composite tapes containing layers of $MgB_2$ compound. Tape thickness – 0.65 mm., width – 3.75 mm. and sample length 35–40 *mm*. Superconducting $MgB_2$ interlayers are enclosed in a composite shell, containing iron and nickel. Copper was introduced into the core of the tape to stabilize the superconducting state in an unintentional transition to the normal state.

Plasma shock was carried out at the test bench «Plasma focus. The test bench diagram and photographs of the plasma jet in the discharge space are shown in Figures 1 and 2. Shockwaves in the samples are generated upon impact of a plasma pinch on the target material. The maximum stored energy in a capacitor bank reaches 4 *kJ*, and in a plasma stream striking a target, about 100 *J*. The impact time on the target is 10–7 seconds. The energy flow density on the target reaches ~2–109 $W/cm^2$, and the plasma jet's spread rate is ~107 *cm/s*.

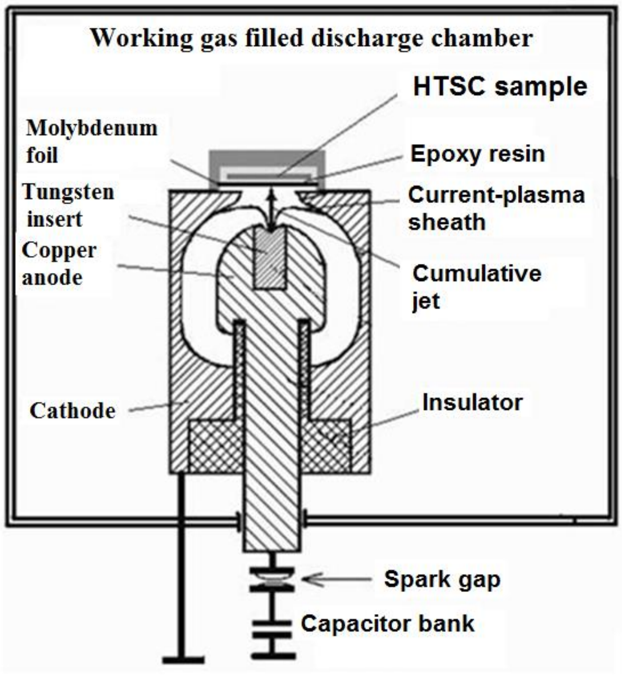


**Figure 1.** Diagram of a test bench for cumulative plasma influence.

The working chamber was filled with argon at a pressure of 1.5 Torr. The surface of the studied samples of tapes was protected from direct thermal influence of a plasma pulse by a molybdenum shield with a thickness 0.2 *mm*. In addition, to align the energy on the surface of the sample, non-linear shock waves generated by plasma impact passed through a two-millimeter layer of epoxy, applied to the surface of superconducting tapes. To prevent bias, the samples were fixed in a steel cuvette in which there was a hole with a diameter of 10 *mm*; a plasma jet was directed through it to the sample. This design allows you to evenly transfer pressure and heat into the sample volume.

In the case of $MgB_2$ tapes, the shock zone was 10 mm along the length of the tape. The distance from the anode to the surface of the tapes was varied within 25, 30, 35, and 40 *mm*, and the number of strikes was from 3 to 5. All strikes were perpendicular to the surface of the tape on only one side. The time interval between the shock pulses was 1.5 *min*.

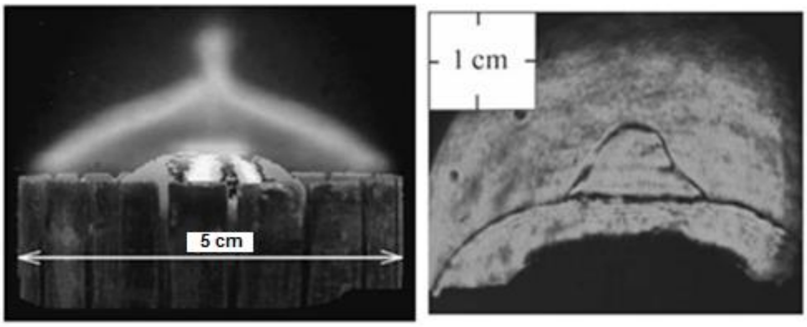


**Figure 2.** Plasma jet: a) Plasma jet in discharge space; b) Shadow image of a plasma jet.

Mechanical shock was applied at room temperature on the test bench shown in (Figure 3a, 3b). Shocks with heating tapes to 500 *°C* were carried out on the test bench shown in figure 3c.

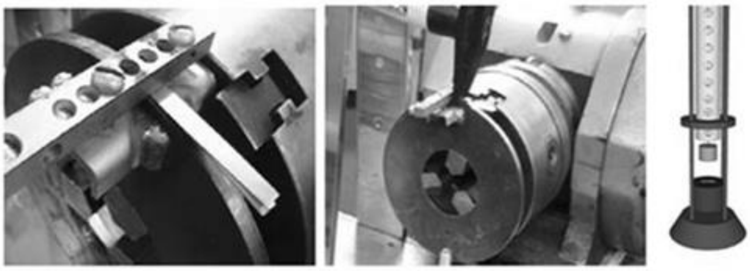


**Figure 3.** Devices for applying dosed mechanical shocks: a – disk with a fixed HTS tape, b – a device for moving HTSC tape after applying mechanical shocks, c – a test bench for applying mechanical shocks when heating HTS tapes to 500 *ºC*.

The specific energy of mechanical shocks at these test benches varied from 0.5 to 100 $J/cm^2$, due to the change in mass of the shock mechanism (from 0.5 to 0.8 *kg*), the heights of the shock mechanism fall within 10-40 *mm*, number of shock, tape widths, shock areas and etc. The impact with heating up to 500 *°C* in relation to Bi-2223-tapes was carried out at the specific energy of single mechanical shocks in the range from 0.5 to 5.0 $j/cm^2$. The sample was placed on the surface of the electric furnace; the temperature in the sample area was controlled by a thermocouple.

The impact areas overlapped by 0.05–0.1 *mm*. The dimensions of the shock mechanism were greater than the width of the tape. The area of mechanical shock on the surface of the HTS tapes was 1.6 $mm^2$ in the case of Bi-2223 tape and 1.46 $mm^2$ in the case of $MgB_2$ tapes.

After a series of mechanical shocks, samples of Bi-2223 tape were annealed in air in a muffle furnace at temperatures of 830–835 *°C* for 5–30 hours, $MgB_2$ tapes were annealed in quartz ampoules filled with argon at temperatures of 750–800 *°C* for 5 hours.

Critical currents and current-voltage characteristics (CVC) were measured on tapes in the initial state and after influence of shock in the International laboratory of high magnetic fields and low temperatures (Wroclaw, Poland) in magnetic fields in the range from 2 to 9 T at a temperature of 4.2 K and in National Research Center Kurchatov Institute. The temperature of the superconducting transition of the Ts is determined on the test bench of measuring the magnetic susceptibility in variable magnetic fields.

Microstructure of tapes in the initial state and after influence of shock, the elemental composition of the superconducting layers in the volume and on the borders of the partition with the metal shell, they were studied in cross and longitudinal sections at various magnifications using a scanning electron microscope. X-ray phase analysis was performed using a diffractometer.

## 3. Results and discussion

Figure 4 shows the macrostructure of the cross-section of a multi-stranded $MgB_2$ tape in the initial state before shock (a) and after influence of shock-wave of plasma (b).

After influence of shock on the layers of $MgB_2$ become more durable and denser (Figure 4b, 4c.). Microstructural studies in the cross section of the initial tapes and after plasma shock (Figure 4a, 4c) show noticeable differences.

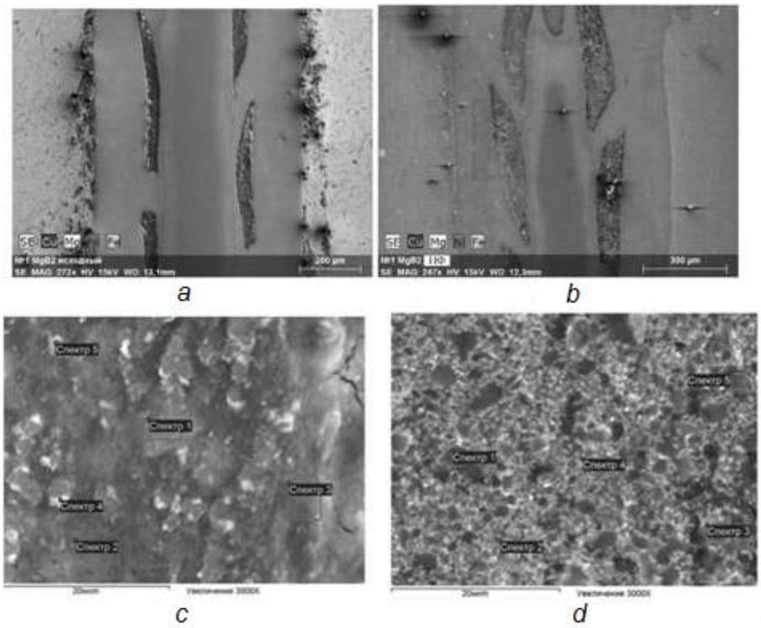

**Figure 4.** Macro-and microstructure of the cross-section of the $MgB_2$ layer: a, b) in initial state; c, d) and after plasma shock-wave action.

In the layers of the original tape, larger grains and cracks are observed. After plasma shocks, the aggregates of the structure become smaller and the cracks disappear. These structural transformations after shocks are the reason for increasing the critical current. In Figure 5, photos of the surface of the superconducting tape are $MgB_2$ presented in initial state (a) and after mechanical shock with specific energy (0.11 $J/cm^2$) (b, c).

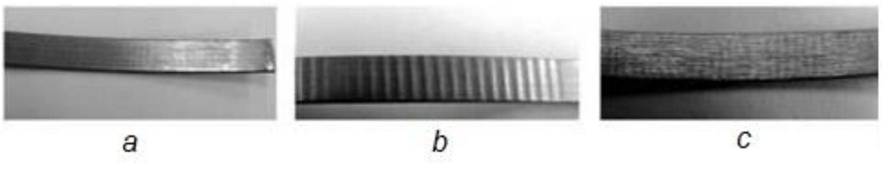

**Figure 5.** Surface relief of the $MgB_2$ tape: a) in initial state; b) after applying mechanical shocks with an energy of 0.11 $j/cm^2$ and a step of 0.4 *mm*. on the shock side; c) after applying mechanical shocks with an energy of 0.11 $j/cm^2$ and a step of 0.4 *mm*. from the opposite side.

The shocks were applied at room temperature on one side of the tape with a 0.4 mm. displacement step after each shock. The structure of the surface was studied as from the side of the applied shocks (b), so on the opposite side (c). When comparing the presented images (b, c), the difference in the surface relief of the tapes is clearly visible. On the side of the shock, there are clearly marked transverse traces of the shocks inflicted. At the same time, on the opposite side (c), the surface of the tape becomes striped along the length of the tape, and the transverse traces of blows become barely noticeable.

As the step of shocks increases to 0.8 *mm*, the relief pattern of the surface of the tape changes (figure 6). On the surface of the tape from the side of the strikes, the transverse tracks from the striker become deeper and more pronounced. Longitudinal stripes appear on the opposite side of the tape. With a further increase in the step of shocks to 1.0 *mm*. these transformations become more obvious (Figure 5). The obtained results testify the necessity of optimization of shock spacing, the energy density, the influence area of the shocks and the area overlap of shocks zones.

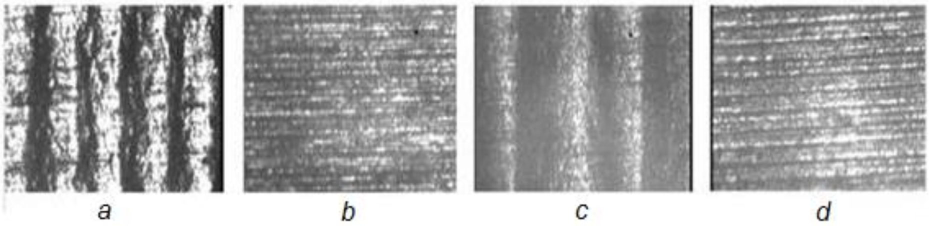


**Figure 6.** Surface relief of the $MgB_2$ tape: a) after applying mechanical shocks with an energy of 0.11 $j/cm^2$ and a step of 0.4 *mm* on the shock side; b) after applying mechanical shocks with an energy of 0.11 $j/cm^2$ and a step of 0.4 *mm* from the opposite side; c) and 1.0 *mm* step on the shock side.

The macro-and microstructure of the tapes in the cross-section and longitudinal section of the tapes in the initial state are shown in Figure 7, the superconducting phase is colored black. After the shock-wave influence of the plasma, the density increases noticeably.

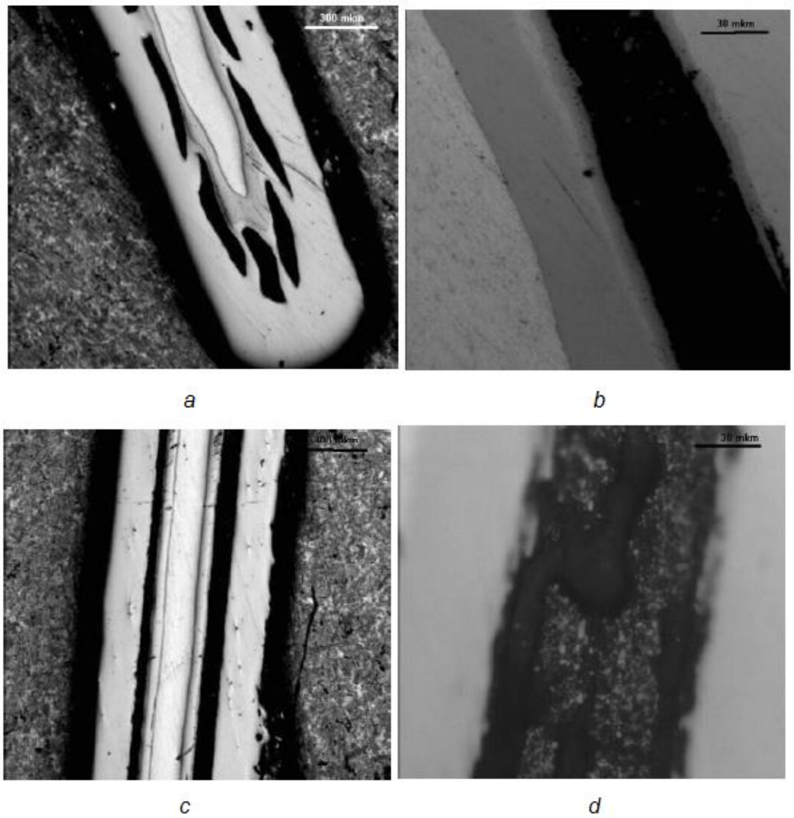


**Figure 7.** Macrostructure and microstructure of the transverse (a, b, c) and longitudinal (d) section of the tape $MgB_2$ in the initial state at different magnifications.

The Influence of specific energy of mechanical shocks on the critical current of $MgB_2$ tapes in various magnetic fields is shown in Figure 8a. It is evident that with an increase in the shocks energy from 14 to 21 *j/cm²*, the critical current in the zero field and fields in the 0.5 and 1.0 *T* decreases. The results obtained show the need to reduce the shocks energy to small values (from 0.1 to 0.5 *j/cm²*). In this case, we should expect an increase in the critical current to 250-300 *A* in the zero magnetic field.

The dependences of the critical current on the strength of the external magnetic field are shown in Figure 8b. It can be seen that with increasing magnetic field, the critical current of the tapes decreases after mechanical shocks. This is due to grain crushing and violation of grain border ties. During subsequent heat treatment at 750 *°C*, the value of $J_c$ is restored and increased in these samples.

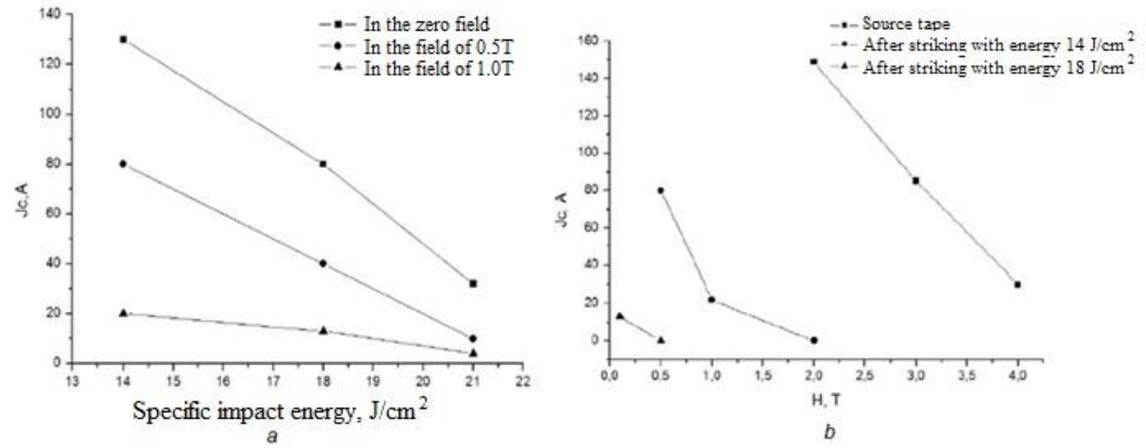


**Figure 8.** Influence of the specific energy of mechanical shocks on the critical current of the $MgB_2$ tape; in magnetic fields (0; 0.5 and 1.0 *T*): a) in the initial state; b) after applying mechanical shocks with an energy of 14 and 18 *j/cm*.

In the case of applying single mechanical shocks from a height of 3 cm (a) and 9 cm (b), the surface of the tape Bi-2223 heated to 500 *°C* changes. With an increase in the specific impact energy to 0.91 *j/cm²*, the shocks zone becomes more noticeable, and the thickness of the tape decreases by 2–3 microns (figure 9a, 9b).

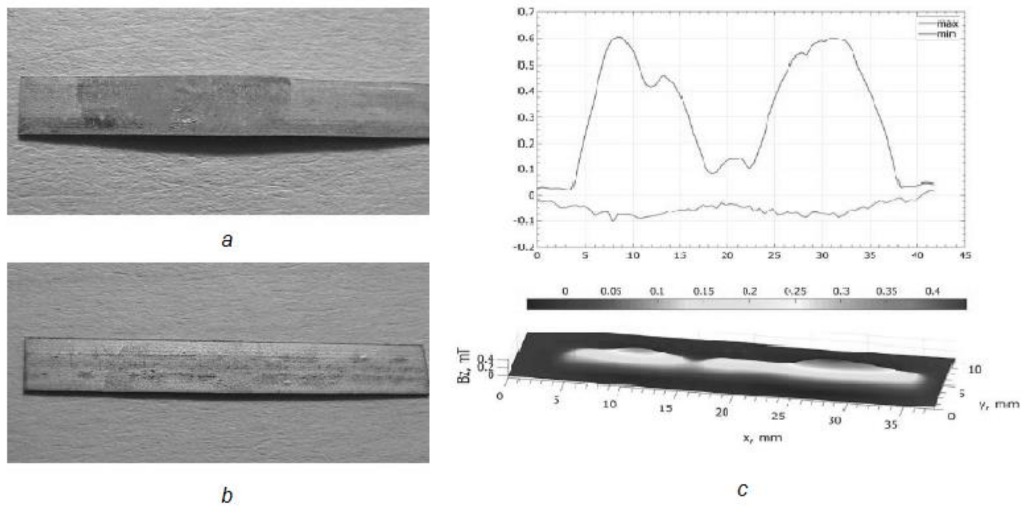


**Figure 9.** The surface of the Bi-2223 tapes after mechanical shocks with different energies: a) 0.91 *j/cm²*; b) 0.32 *j/cm²*; c) distribution of the frozen-in-field at a temperature of 77 K after influence of shock with a specific energy of 0.32 *j/cm²* when the tape is heated to 500 *°C*.

Investigation of the value of the frozen-in-field on a sample heated to 500 *°C* (Figure 8b), shows a decrease in the magnetic field in the shock zone. However, this decrease is noticeably lower than in the sample after influence shock without heating. Subsequent heat treatment at 835 *°C* for 5 hours leads to a complete restoration of $T_c$.

When applying mechanical shocks with the same energy (0.1 $j/cm^2$), the surface of the Bi-2223 tapes when you change the spacing of strokes from 0.4 to 1.0 *mm* undergoes a transformation (figure 10a-d). At a small step (0.4 *mm*) in the shock zone, there are strictly defined stripes outlined along the surface of the tape, and the traces of transverse shocks are hardly noticeable. When increasing the pitch to 0.6 mm, the number of longitudinal strips is preserved, but at the same time the transverse traces of shocks become more noticeable, and with a larger shock step (0.8 and 1.0 *mm*), the surface relief changes completely, only transverse shock traces remain visible.

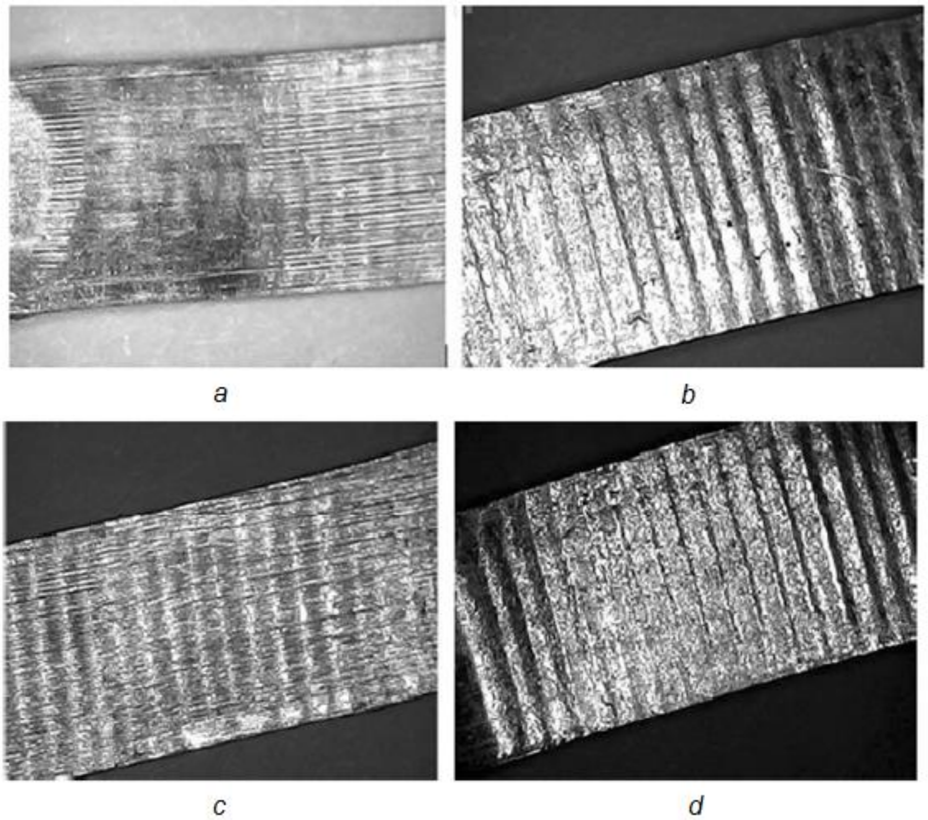


**Figure 10.** The surface of the Bi-2223 tape after mechanical shocks with a specific energy of 0.1 $j/cm^2$, with a step of movement along the tape: *a)* – 0.4 *mm*; *b)* – 0.6 *mm*; *c)* – 0.8 *mm*.; *d)* – 1.0 *mm*.

In contrast to mechanical shock, plasma shock waves at a distance of 40 and 45 *mm* from the plasma anode they lead to a significant increase in the critical current of tapes $MgB_2$ in magnetic fields of 1.5-3.0 *T* (figure 11). It can be seen that in a magnetic field of 2 *T*, the critical current of the original tape is 150 *A*, and in the tape after 3 shocks at a distance of 45 *mm* from the plasma anode the critical current increases to 225 *A*, and at a distance of 40 *mm* (5 shocks) - about 200 *A*. Noticeable differences in the course of the curves are related to the different number of shocks and the distance between the sample and the plasma anode.

Results of microanalysis of the layer $MgB_2$ after plasma shock processing and in the original tape are shown in Table 1. When comparing the results in 5 sections of the microstructure, it can be seen that after exposure to plasma shocks, the content of the components changes. The content of magnesium and boron increases, and the content of carbon and oxygen decreases in comparison with the original sample.

The highest content of boron was found in individual secretions with dimensions of the order of 5 microns (spectrum 1). The magnesium content of these particles is about 33 wt.%, and boron 46.39 wt.%. After plasma shocks, the homogeneity of the distribution is improved.

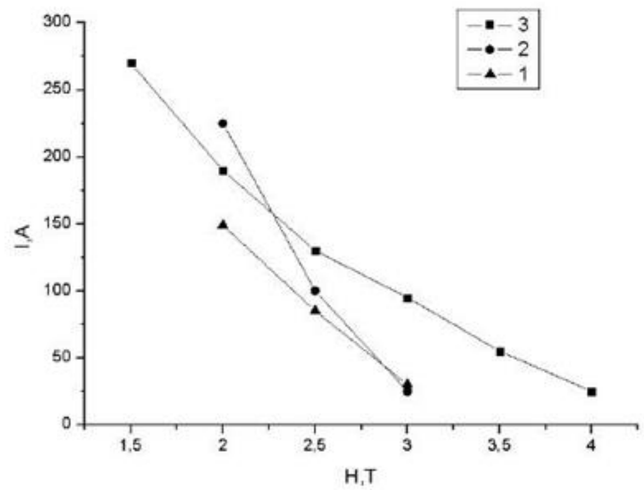


**Figure 11.** Dependences $J_c$ of tapes $MgB_2$, in the initial state (1) and after plasma shocks at a distance of 45 *mm* (2) and 40 *mm* (3) from the anode.

**Table 1.** Chemical composition of the interlayer $MgB_2$ in the initial tape and after plasma shocks based on averaged data in mass and atomic samples %.

| The composition of the interlayer | B | Mg | C | O |
|---|---|---|---|---|
| In initial state | 13.06/17.67 | 24.78/14.92 | 36.27/43.92 | 25.87/23.48 |
| After plasma shocks | 37.32/48.82 | 27.32/13.69 | 26.26/30.44 | 9.09/7.44 |

## 4. Conclusion

1. The possibility of increasing the critical current of the $MgB_2$ tapes from 150 to 225 *A* in a transverse magnetic field of 2.0 *T* under the shock-wave influence of plasma at distances of 40-45 *mm* from the surface of the tape has been established.

2. Study of the effect of mechanical shocks with specific energy from 14 to 21 $j/cm^2$ on the surface of the $MgB_2$ tape showed a decrease in the critical current with an increase in the impact energy. In this case, the superconducting layers of $MgB_2$ are grain crushing and the electrical conductivity at the grain boundaries is broken, and subsequent heat treatment restores the critical current.

3. The surface relief of the superconducting $MgB_2$ and Bi-2223 tapes on the side of the shock influence and on the opposite side changes noticeably with increase in the shock spacing from 0.4 to 1.2 *mm*. With an increase in the shock spacing of more than 0.4 *mm*, sharply defined transverse impact traces are formed on the surface of the tapes.

4. Results of microanalysis of superconducting layers in the initial state and after plasma shock-wave influence, show an improvement in the homogeneity of the distribution of the main (Mg and B) and admixture (C and O) components.

## References

[1] Jin H S, Tiefel R S, Sherwood et al 1988 *Melt-textured growth of polycrystalline YBa2Cu307-x with high transport Jc at 77 K. Phys. RPV. B* **37(13)** 7850–3
[2] Dremin A N and Breusov O N 1968 Processes Occurring in Solids Under the Action of Powerful Shock Waves *Russian Chemical Reviews* **37(5)** 392–402

[3] Avvakumov A V 2009 *Fundamental Bases of Mechanical Activation, Mechanosynthesis and Mechanochemical Technologies* (Novosibirsk: Siberian branch of the Russian Academy of Sciences) p 344
[4] Pruemmer R and Ziegler G 1981 Influence of pressure during explosive and isostatic compaction on microstructure of molybdenum, tungsten, titanium and alumina *Proceedings – Int. Conf. on High Energy Rate Fabrication* pp 274–80
[5] Lin E E, Novikov S A, Kuropatkin V G, Medvedkin V A and Sukharenko V I 1995 Dynamic compaction of ultradisperse diamonds *Combustion, Explosion and Shock Waves* [in Russian – Fizika Goreniya i Vzryva] **31(5)** 136–8
[6] Antonova I Kh, Borovitskaya P V, Gorshkov et al 2009 Effect of shock waves on the current-carrying properties of HTSC YBCO(123) tape *Doklady Physics* **54(10)** 463–5
[7] Mikhailov B P, Ivanov L I, Shamrai V F, Nikulin V Y, Mikhailova G N, Nizhankovskii V I, Rudnev I A and Gorshkov P V 2010 The effect of pulse high-density plasma on superconducting properties of bi-2223 multilayered tape *Inorganic Materials: Applied Research* **1(2)** 92–4
[8] Antonova L Kh, Borovitskaya I V and Gorshkov P V 2011 Application of shock waves for the improvement of current-carrying properties of YBCO(123) and Bi(2223) HTSC tapes in magnetic fields *Physics of Metals and Metallography* **111(2)** 158–64
[9] Mikhailov B P, Mikhailova A B and Borovitskaya I V 2017 Impact of shock waves on the conductive properties and structure of $MgB_2$ tapes *EPJ Applied Physics* **80(2)** 20601
[10] Polukhin S N, Dzhamankulov A M, Gurei A E, Nikulin V Ya, Peregudova E N and Silin P V 2016 Laser-optical measurements of the velocities of the plasma jets formed from different gases in a kilojoule-range plasma focus facility *Plasma Physics Reports* **42(12)** 1127–33
[11] Mesokh Z I, Yanushkevich V Ya and Ivanov L I 1971 The formation of point defects in nickel under the influence of giant pulses of laser *Physics and chemistry of material processing* [in Russian – Fizika i khimiya obrabotki metallov] **4** 163–5