The critical currents of MgB$_2$ tapes after the shock-wave plasma influence through the protective screens with different thermal characteristics

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Abstract: The report presents the researches of the current-carrying characteristics of MgB$_2$ tapes after exposure to shock-wave action through the protective screens with different thermal characteristics. It was used molybdenum, titanium, iron and copper. To implement the shock wave impact, a plasma focus (PF) type setup was used. Current-voltage characteristics (CVC) of the tapes in the initial state and after shock-wave action (SW) through the protective screens are presented. Dependences of critical currents from magnetic field value are measured in the transverse magnetic fields from 0.3 to 6.0 T at the temperature of 4.2 K. The studies performed showed a noticeable change in the critical currents according to the screens material used. The largest increase in $J_c$ (more than 2 times up to 850 A in transverse and longitudinal magnetic fields up to 1 T) was achieved in case of titanium screen.

1. Introduction
Advantages of MgB$_2$ in comparison with known HTSC compounds are associated with simple binary composition, simple hexagonal lattice, low price of ingredients, no problems associated with weak bonds at the grain boundaries, low current anisotropy and, most importantly, with higher current-carrying capacity in external magnetic fields of 0.3 - 4.0 T [1-4]. All these characteristics show the possibility of using this compound in a sufficiently high temperature range of 20–30 K. The superconductivity mechanism in this compound is considered to be electron-phonon [5] and the current-carrying capacity largely depends on the structural phase state (size and morphology of grains, the presence of point defects, effective pinning centers, texture and packing density in superconducting interlayers) [6–8]. Most structural factors can be directionally transformed under the action of shock and temperature waves of the plasma, and as a result, the critical current is expected to increase in magnetic fields to 5.0 T.

2. Experimental
Experiments on shock waves acting were carried out at the Lebedev Physical Institute of Russian Academy of Sciences on the Plasma Focus installation (Tyulpan), which high velocity jets of dense plasma produces. The PF installation consists of capacitor energy storage and a system of coaxial electrodes (anode and cathode) insulated from each other by a cylindrical insulator. The system of electrodes is placed in a chamber filled with working gas up to a pressure of several torr. In our studies,
the chamber was filled with argon to a pressure of 1.5 torr. The energy stored in the capacitor is 4 kJ, the charging voltage of capacitors is 12 kV. Energy of plasma jet, produced by this PF is about 100 J. The time exposure by the jet on target is $10^{-7}$ s. The energy flux density of jet on the target reaches $10^9$ W/cm², and the plasma jet velocity is $10^7$ cm/s. The surface of the test samples was protected from direct plasma exposure by screens made of various materials: molybdenum, titanium, iron and copper with a thickness of 100 μm. In addition, in order to align the impact energy on the surface of a superconducting sample, the shock waves generated in the protective screen as a result of plasma exposure pass through a thin layer of epoxy resin filling the gap between the screen and the superconductor. The samples had the following dimensions: thickness — 0.65 mm; width — 3.75 mm; and a length of 35–40 mm. The superconducting MgB₂ interlayers were enclosed in a shell containing iron, nickel and copper to stabilize the superconducting state. The samples were fixed in a steel cuvette, in which a plasma jet passes through a 10 mm hole. This design allowed the pressure and heating to be evenly transferred to the sample volume and to protect the surface of the test samples from temperature overheating and destruction.

For MgB₂ tapes, the length of the shock-wave zone was 10 mm along the length of the tape. The distance from the anode of PF installation to the surface of the tapes was 30 and 35 mm. The number of shocks for all samples was the same (5 shocks). All shocks were applied perpendicular to the surface of the tape on one side only. The time interval between the shock pulses was 1.5 min.

Critical currents were measured on the samples in the initial state and after shocks in transverse and parallel magnetic fields in the range from 0.3 to 6 T at 4.2 K in the Kurchatov Institute.

Comparative studies of the macro- and microstructure of the initial tapes and tapes after plasma shocks were carried out in transverse and longitudinal section at various magnifications on an EVA-40 scanning electron microscope of the ZEISS Company. The chemical composition of MgB₂ superconducting layer in the volume of the layer and at the interface with the metal shell (iron) was studied on a JSM-35 scanning electron microscope with the Link prefix. X-ray phase analysis was performed in the PDXL software package using the international ICDD database. Diffraction profiles were obtained on Ultima IV Rigaku diffractometer, in CuKα radiation in the 2θ range, from 9° to 100°, with step of 0.02°.

3. Results and discussion.

Figure 1 shows the surface structure of protective screens made of copper (a), iron (b), titanium (c) and molybdenum (d) in the zone of shock-wave plasma exposure under the same conditions. In the lower part of the figures, samples of MgB₂ tapes placed under the protective screens are shown.

![Figure 1](image-url)

Figure 1. The structure of the surface of the screens made of copper - a, iron - b, titanium - c and molybdenum - d and the surface of MgB₂ tapes after treatment with plasma influence of the same power at the distance of 30 mm from the anode (number of shocks = 5).

When comparing these screens, it is possible to notice the different size of the spots. The spot on copper has the smallest diameter and, accordingly, the smallest area. The impact area on an iron screen increases noticeably and the depth of indentation is greater, the grains are also significantly larger. The edge of the stain is less pronounced on the titanium screen and the spot size is smaller than in the case of iron. A sharply defined edge is observed on the molybdenum gasket in the impact zone and the grain
size is not uniform. The surface of the specimens of MgB₂ tapes after shock wave exposure does not suffer any noticeable damage. The physicochemical properties of used protective screens of iron, copper, molybdenum and titanium are given in Table 1. When comparing these properties, there is a noticeable difference in the elastic properties (2 - 3 times) and in the specific heat capacity (from 2.8 to 46 J/kgK). The highest values of the critical current in a transverse magnetic field of 2 T (up to 850A) were achieved in the case of using a protective shield of titanium. In 3T magnetic field, the highest critical current (120A) is achieved in case of using iron shield. It was not possible to establish quantitative correlations of changes in the critical current with the presented physicochemical properties at this stage of research.

Table 1. Physical properties [9] of protective screens and critical currents of MgB₂ tapes after shock-wave plasma exposure

| Material of shields | Plasticity index, % | Young’s modulus E, GPa | Temperature of melting °C | Heat capacity, J/ kg K | Critical currents, A in magnetic fields 2.0 and 3.0 T |
|---------------------|---------------------|------------------------|--------------------------|------------------------|-----------------------------------------------|
| Fe                  | 50                  | 195-205                | 1538                     | 46                     | 120 (3T);                                    |
| Cu                  | 60                  | 110-130                | 1083                     | 7.29                   | 250 (2T) и 25(3T)                            |
| Mo                  | 25                  | 300-330                | 2620                     | 2,8                    | 149(2T) и 85 (3T)                            |
| Ti                  | 30                  | 110                    | 1608                     | 7,0                    | 850(2T) и 110 (3T)                           |

Figure 2 shows the current-voltage characteristics (CVC) of MgB₂ tapes after plasma shock-wave action through a protective shield of titanium.

![CVC of MgB₂ tapes](image)

**Figure 2.** CVC of MgB₂ tapes in magnetic fields from 1 to 3 T after plasma processing through the titanium shield.

The criterion for the superconducting transition was a voltage of 1 mV/cm respectively in magnetic fields of 1.2 and 3 T and critical currents of 110, 360 and 850 A. The dependence of the critical current on the magnetic field is shown in figure 5.

In the case of using a protective shield made of iron, CVC are measured just in high magnetic fields (from 3 to 7 T) (Figure 3).
Figure 3. CVC of MgB$_2$ tape after processing through iron screen.

When using protective screens made of copper and molybdenum, the critical currents in magnetic fields of 2 and 3 T are noticeably reduced (Figure 5) compared with screens made of titanium.

Figure 4. CVC of MgB$_2$ tape in transverse magnetic fields after processing through the protective shields: a- from copper, b- from molybdenum.

Figure 5. The dependences of the critical current of MgB$_2$ tapes in the initial state (1) and after shock-wave action through the protective screens made of molybdenum (2), iron (3), copper (4) and titanium (5).

The diffraction patterns of the initial MgB$_2$ powder and the sample of the powder compacted by rolling on the substrate of aluminum after plasma impact are shown on fig 6. It can be seen that the
phase composition after plasma influence remains almost unchanged, but the diffraction lines corresponding to the MgB$_2$ compound are experiencing broadening after treatment. This effect is associated with the grinding of crystal blocks, as well as with the formation of microdeformations in the crystal structure of MgB$_2$. Due to grinding, the total volume of the superconducting material is compacted, which is noticeable in photographs obtained as a result of studying of microstructure of the samples before plasma treatment and after processing. The appearance of microdeformations leads to the formation of defects in the crystal structure. Both of these effects, apparently, make it possible to achieve an increase in the critical current in external magnetic fields, because of creation of better contacts between the grains and increase in the pinning force of magnetic vortices.

At the same time, on separate diffraction profiles, as well as on Fig. 6b, after the plasma influence a diffraction halo of low intensity appears. It is connected with the formation of an amorphous structure. Apparently, MgB$_2$ powder, which is located closest to the front of the impact of the shock waves arising from the plasma action, suffers too much from deformation effects, leading to the destruction of the crystal lattice. Depending on the type of gaskets used, as well as the substrates, the intensity of the amorphous halo varies. It can be assumed that in case of the absence of a protective screens and a multiple increase in the power of plasma influence, a complete destruction of the MgB$_2$ crystal lattice can occur.

As shown by the experiments, the choice of optimal conditions of plasma influence, including the material of protective shields, can create an optimal compacted microstructure with a uniform distribution of crystallites in the volume of superconductor samples, without destroying the structure.

![Figure 6. X-ray profile](image)

**Figure 6.** X-ray profile: a- an initial MgB$_2$ powder; b- the sample after shock-wave plasma exposure:

1- MgB$_2$, 2- MgO, 3- Mg

4. Conclusions

1. The significant influence of the physicomechanical properties of protective screens made of molybdenum, iron, copper and titanium on the critical current of MgB$_2$ tapes processed by the impact of plasma on their critical current in magnetic fields (1.0 to 6.0 T) has been established.

2. The greatest increase in the critical current of the tapes is achieved when using the titanium screen with a thickness of 100 μm (up to 850A in a 1T field). It is due to the fragmentation of grains, an increase in the density and hardness of superconducting interlayers, increasing of the number of effective pinning centers and a noticeable homogenization of the chemical composition.

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