Development of an attachment for continuous step-by-step shock-wave irradiation of long-length superconducting tapes in the «Plasma Focus» setup

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Abstract. The article presents the results of the creation of an additional attachment placed on the "Plasma Focus" installation (PF), and designed for uniform movement of superconducting tapes through the working chamber of PF. This device allows step-by-step shock-wave impact at the long superconducting samples and tapes in the "Plasma Focus" installation in order to increase their superconducting and technological characteristics. The worth of this device that the process of irradiation of the tapes can be carried out without interrupting and completely turning the plasma installation off, which is usually necessary to displace the tape and make the strike to the next section of the tape. The use of attachment also allows to get an additional data integrated over the length of the processed tape and to study the effect of plasma shock-wave action to the physical and structural properties of tapes. The experiments carried out will make it possible to select and test the optimal plasma strike models and recommend further conditions of shock-wave treatment, which would make it possible to use this method for long tapes with the aim of using them in various devices.

1. Introduction
The task of improving the functional characteristics (Tc, Ic, Jc (B)) of superconducting cables and tapes and the creation of new optimized and efficient methods for their manufacture based on ceramic powders, including MgB2, Bi-HTSC, Y-123, etc., is in the area of the series interests of leading companies, including the field of creating modern resource-saving technologies.

As shown by numerous works, the process of manufacturing current-carrying elements (wires, tapes and cables) based on ceramic compounds is much more laborious and complicated, compared to the manufacture of metal superconductors. In addition to superconducting properties, important parameters are density, strength, dimensional stability, compatibility with various metals, alloys and ceramics.

The value of the critical current of ceramics-based superconductors is a structure-sensitive parameter. It is determined by the combination of the influence of the cation and anion composition, the perfection of the crystal lattice, the grain size, texture, the presence of nano-sized non-superconducting precipitates, the structure of their segregation in the volume, the presence or absence of pores, vacancies, dislocations, thickness of coatings, films, the microstructure of veins and interlayers.

Conditions for improving the properties arise when the optimal stoichiometric composition of the main superconducting phase, homogeneity of the volume distribution, optimal orientation, density, and
microstructure of grains in the inner volume of superconductors are achieved, as well as the presence of uniformly distributed pinning centers of nano and ultra-sizes [1-5].

Studies [6-8] by various authors indicated that shock waves (SW) generated in the bulk of compounds or during their subsequent processing, can be effectively used to form the given structural states for various materials. This is possible as a result of high-voltage fields and mechanical activation influence and the formation of ionic and atomic vacancies, nanoscale defects, dislocations. Such a structure can stimulate subsequent chemical interactions [9-10]. A more significant effect on the properties is possible to observe in case of the shock-wave effects arising from the use of a plasma source with a pressure at the front of the sample up to \(10^{11}\) Pa. The efficiency of impacts with the use of plasma, in contrast to mechanical effects, is associated with a short-term concentration of high pressure and temperature on the surface and in the bulk of the material. In this case, it is possible to initiate additional reactions of interaction of a large number of components, the initiation of SVS processes, quenching and amorphization. In a series of studies performed in our researches [11-15] with using various models of influence, changing the distance from the sample to the source and the number of repeated local strikes, their direction, different gaskets and the conditions of the samples preparation, the possibility of an increasing of \(Y-123\), \(Bi-2223\) and \(MgB_2\) superconducting parameters (\(T_c, I_c\)) was shown. The mechanisms of changes in the structure, microstructure, texture, microhardness, phase composition and homogeneity of the samples were studied depending on the selected plasma strike conditions.

2. Materials and experiment

During the experiments, shock waves were applied to the tape samples using the Plasma Focus setup PF-4 (P.N. Lebedev Physical Institute, RAS). The setup is schematically shown in Figure 1.

![Figure 1. Scheme of the Plasma Focus installation PF-4 and shock-wave treatment of HTSC tapes.](image)

Shock waves were generated when the plasma jet hits the target material. The maximum stored energy in the capacitor storage reaches 4 kJ, and in the plasma jet striking the target - about 100 J. The time of exposure to the target is 100 ns. The energy flux density to the target reaches \(~2 \times 10^9\) W/cm\(^2\), the velocity of the plasma jet is \(~10^7\) cm/s. The working chamber was filled with argon at a pressure of 1.5 Torr. The surface of the tape samples was protected from the direct thermal effect of the plasma with various types of gaskets made of metals and alloys. In addition, to equalize the energy on the sample surface the special scheme was created, in which the nonlinear shock waves generated by the plasma impact were passed through the layer of epoxy resin deposited on the surface of superconducting tapes. To prevent displacement, the samples were fixed in a steel cuvette with a hole (\(D=10\) mm), through which a plasma jet was directed onto the sample. This design made it possible to uniformly transfer the SW effect into the sample volume and protect the surface of the samples under study from thermal overheating and destruction.
The zone of shock waves action along the tapes length depended on the specific of experiments. The distance from the anode to the surface of the tapes also varied from 25 to 40 mm. The number of strokes also varied (from 1 to 10 strokes). All impacts were applied perpendicularly to the surface of the tape both from one side of it and from two sides according to a certain pattern. The time interval between shock pulses was 1.5 min. The scheme of exposure is shown in Figure 2.

As a result of these experiments, it was shown that with short optimized shock-wave impact to Bi-HTSC and Y-123 tapes, it is possible to noticeably improve the density of the microstructure, eliminate pores and loose areas, achieve one-way grain orientation, while maintaining the optimal structure without decomposition of superconducting phases. In this case, the values of the critical parameters (Tc, Jc, Jc (B)) of these tapes increased, including those that were already ready for use. For the tapes on base of MgB2 compound, the critical current was higher by more than 1.5 times compared to a similar sample without treatment [14, 15]. Experiments of additional gaskets using made it possible to achieve a uniform distribution of pressure and thermal front of the shock wave over the sample surface. When using a protective screen made of titanium, the optimal combination of distance and the number of impacts, it becomes possible to increase Jc of MgB2 tapes to 850 A in magnetic fields of 1-2 T.

However, the use of this installation let to carry out experiments only on individual fragments of tapes and samples whose length did not exceed 3 cm. In addition, serious difficulties were appeared when it was required to influence to the sections of the tape with a certain strictly fixed step. Therefore, experiments to study the effect of step-by-step uniform processing of tape samples by shocks wave impacts on longer tape fragments to obtain data for optimization conditions as close as possible to industrial conditions could not be performed. Because of this, the idea of creating an additional special attachment to the PF-4 unit, which could be used for continuous step-by-step tape input was appeared.

2.1. Installation of attachment for long tapes processing
Figure 3 shows a 3D model of the PF-4 setup with an attachment for inserting extended HTSC tapes into the PF-4 chamber. The designed device for the continuous supply of HTSC tapes to the PF-4 installation assumes the supply of the initial superconducting tape in the form of an assembly consisting of the tape itself fastened through an epoxy resin with a metal protective screen (in this case, titanium was used). The assembly is fed through the branch pipe (1) using a mechanical rotary rod (then, it will be possible to use a stepper motor) to a rubber band located inside the branch pipe (1). Further, due to the rotation of the rollers (4), the tape together with the protective screen enters to the PF-4 chamber onto a bridge with sides, located inside the tunnel with a hole (6) from the anode side (irradiation zone of the HTSC tape). After irradiation at a given place according to a given mode, the tape is shifted to the selected step and is irradiated at the next point. Through the branch pipe (7), to which either a feed...
pipe of a similar design or a rod with a length comparable to the size of the HTSC tape is connected, the already processed tape leaves the installation. The length of the supply tube limits the minimum length of the HTSC tape. Namely, from its right edge to the irradiation region above the anode. For aiming shots, hole (6) must be closed with an additional flap, which is fed on a vacuum rod through any free side window in the PF-4 chamber. Construction (5) is made in the form of a tunnel to avoid bending or throwing the HTSC tape upward due to the impact of a shock wave on it. The shape of hole (6) can be changed from round to rectangular in order to change the shape of the irradiated area. Accordingly, the shape of the overlapping between irradiation areas on the HTSC tape will be changed too. Depending on the task, it is possible to irradiate the tape without hitting the next shot on the edge already irradiated area or conversely with overlapping. Using of the manual pulling of the HTSC tape by the long rod located on the left side of the PF-4 chamber allows to avoid the problems of the HTSC tape slipping, when the rod will be rigidly connected to the HTSC tape.

To seal the resulting installation and maintain the vacuum, rubber gaskets and clamping rollers can be used at locations (1) and (7). This design is a pilot scheme of the installation and will be further refined and modified as experiments are carried out.

![Figure 3. Model of the PF-4 installation with a device for inserting extended HTSC tapes in 3D: 1 - a branch pipe for preliminary insertion of an HTSC tape into the supply pipe (shown as transparent); 2 - branch pipe for connecting a stepper motor or a manual rotary rod; 3 – the rubber tape feeding the HTSC tape to the PF chamber; 4 - rotating rollers; 5 - structure above the anode is a tunnel for the HTSC tape with a hole (6) from the anode side (the irradiation zone of the HTSC tape); 7 - outlet pipe, to which either a supply pipe of a similar design or a rod with a length comparable to the size of the HTSC tape is connected; 8 - anode; 9 - cathode; 10 - one of the four capacitors of the capacitor bank.]

3. Experimental result

For testing the attachment, we used superconducting tapes based on 14-strand MgB₂ tape manufactured by Columbus Superconductor (Italy). Samples of tapes had the following dimensions: thickness - 0.65 mm, width - 3.75 mm and length about 70 cm. Superconducting layers of MgB₂ are enclosed in a shell containing iron, nickel and copper to stabilize the superconducting state. Figure 4 shows tapes before and after processing by shock wave action (a, e), the scheme of exposure, and the irradiated fragments of the titanium gasket after striking.

For initial experiments, it was decided to expose limited pieces of tapes (no more than 5 cm) in order to gradually select the optimal exposure modes. The tape with a total length of more than 70 cm was passed through the attachment and processed with a step h = 7 mm in a limited determined section.

In total, 5 strikes were delivered to each of 4 points at a distance of 25 mm from the plasma focus. The impact on all positions and areas was distributed evenly over the area of the fragment directly adjacent to the impact site. It was a result of the use of special titanium and epoxy resin gaskets. In the boundary regions between the points, it is likely that partial overlap from various neighbor points subjected to shock waves could occur.
After exposure, measurements of the superconducting properties were performed at the National Research Center “Kurchatov Institute”. In Figure 4 the dependence of the critical current on the magnetic field for the tape after treatment in comparison with the tape before treatment is presented.

**Figure 4.** Photos of superconducting tapes based on MgB$_2$ before (a) and after impact application using plasma (d). Scheme of the impact (c) and photo of titanium gasket fragments (b).

**Figure 5.** Dependence of the critical current $I$ (A) from the transverse magnetic field $B$ (T) for MgB$_2$ tapes in the initial state (1) and after impact at a distance of 25 mm by 5 impulses to each point at 4 different points located with a step $h = 7$ mm from each other along the tape. The measurements were carried out at a temperature of 4.2K.

From the dependences in Figure 5, it can be seen that the values of the critical current of the tape after treatment with impact on the PF-4 installation using the designed device in the indicated mode in magnetic fields of 2-4 T, agree with the data obtained earlier [11] on the tapes processed according to the scheme in Figure 2, and exceed the current of the original MgB$_2$ tape by almost 2 times in the range of magnetic fields 2-4T.

4. Conclusions
1. A special attachment has been developed for step-by-step impact on the surface of long-length superconducting tapes in order to compact, texturize and increase their current carrying capacity in PF-4 installation.
2. Experiments on the use of this module on limited sections of a tape based on MgB$_2$ have been carried out.

3. As a result of measuring the current-voltage characteristics, it was found that in the tapes after the SW treatment, the values of the critical current increased in comparison with the original untreated tape by almost 2 times in the magnetic field interval 2–4 T.

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