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Magnetorheological polishing of HTSC substrates based on spherical particles obtained by the liquid anode method

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The results of polishing stainless steel substrate of high-temperature superconducting (HTSC) tapes by magnetorheological method using magnetorheological fluid based on spherical particles obtained by liquid anode method are presented. Best surface roughness measured on 10 by 10 μm area was 1.3 nm Sa / 1.9 nm RMS (arithmetical mean height / root mean square height respectively), which is an indicator of the possibility of using this method for polishing HTSC substrates in case of scaling the method.

Keywords: magnetorheological polishing, HTSC, liquid anode, spherical particles.

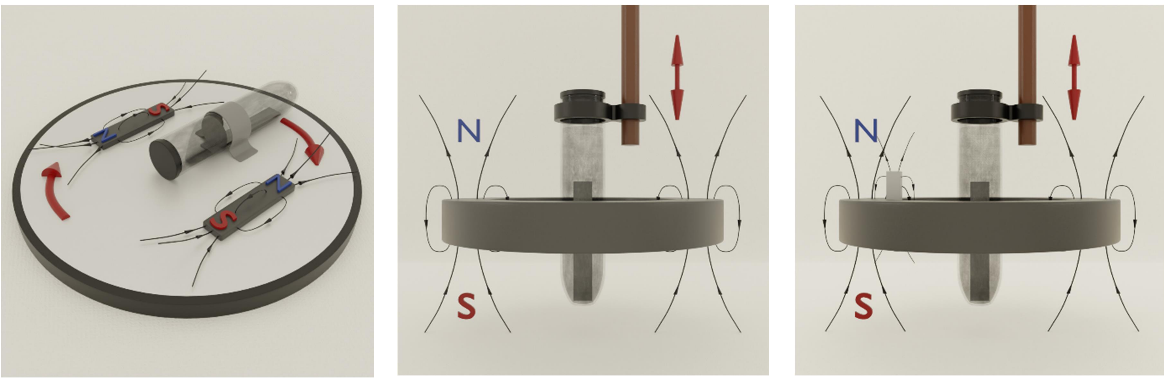
1. Introduction

Industrial production of HTSC tapes is one of the priorities of global technical development, and high-quality substrate polishing with low target roughness is one of the important technological stages for their production. To obtain HTSC tapes, it is necessary to achieve a surface roughness after polishing of less than 5 nm RMS [1] or 5 nm Ra (profile roughness parameter) [2]. In the cited works, the required roughness value was achieved using electrochemical polishing, and measurement of the surface roughness in a scanning area of 5 by 5 μm showed surface roughness values of 2.3 nm Ra [1] and 3.4 nm Ra [2]. The authors of the work [1] conducted a review of studies regarding polishing methods. They concluded that electrochemical polishing is more preferable than mechanical or chemical polishing in terms of ensuring a lower surface roughness, although the electrochemical polishing method has known disadvantages regarding the disposal of acidic electrolytes and harmful vapors. Also, the researchers in [3] reported the possibility of electrochemical polishing of the HTSC tape substrate which allows obtaining a surface roughness of such tapes of less than 1 nm RMS on a scanning area of 5x5 μm. The magnetorheological polishing method, on the other hand, does not have issues with chemical waste disposal. The method using magnetorheological fluid for polishing surfaces has been widely studied by researchers from the A.V. Lykov Institute of Heat and Mass Transfer of the National Academy of Sciences of Belarus [4, 5], and these researchers achieved a surface roughness of stainless steel of 3.9 Sa on a scanning area of 10 by 10 μm. It is also known that roughness values of 16 nm Ra [6], 23.8 nm Ra [7], 50 nm Ra [8] have been achieved by other researchers while studying magnetorheological polishing of stainless steel. A detailed review of the methods of using magnetorheological polishing in various technical applications is given in [9], without mentioning the possibility of using the method directly for HTSC tapes.

This study presents the results of magnetorheological polishing of stainless substrates of HTSC tapes using a magnetic fluid, which included a diamond suspension with a diamond fraction of 1 μm and spherical particles obtained by the liquid anode method during plasma spraying of low-carbon steel. The method for obtaining such spherical particles is presented in [10].

2. Study description

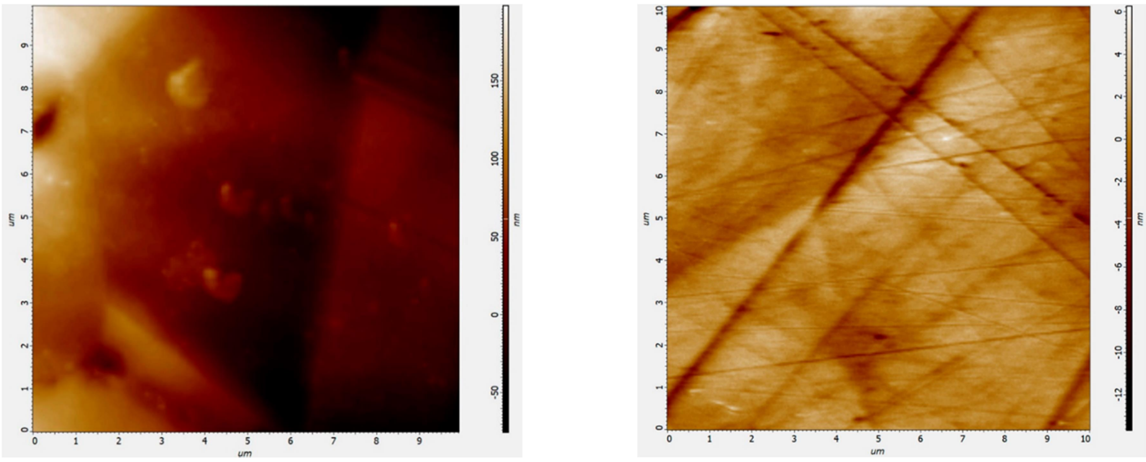
For polishing HTSC stainless steel substrates, a setup was manufactured that had three design variants (Fig. 1): in one case (variant 1), a magnetic field with an induction of 50 mT rotated, creating a flow of magnetorheological fluid in a test tube with a HTSC tape substrate fixed to it (Fig. 1a); in another case (variant 2), the test tube moved back and forth in a magnetic field created by a ring-shaped permanent magnet with a maximum magnetic induction of 25 mT (Fig. 1b); variant 3 was a variation of variant 2 (Fig. 1c), when a rectangular neodymium magnet of 400 mT was installed on the inner circumference of the ring magnet. The magnetic field was measured with a teslameter "Universal 43205".



(a) (b) (c)

Fig. 1. Schematic representation of the experimental system for polishing the substrate of a stainless steel HTS tape using a rotating magnetic field, variant 1 – (a), the red arrows show the direction of rotation of the magnetic field, and using reciprocating motion in the magnetic field, variant 2 – (b) and variant 3 – (c), the red arrows show the direction of reciprocating motion of the sample in the magnetic field.

The initial roughness of the stainless steel samples before magnetorheological polishing was 24.8 nm Sa on a scanning area of 10 by 10 μm for variants 1 and 2 (Fig. 1a, b); this initial roughness was obtained by electrolytic-plasma polishing (Fig. 2a). For variant 3 (Fig. 1c) it was 3.4 nm Sa on a scanning area of 10 by 10 μm; this initial roughness was obtained by mechanical polishing (Fig. 2b).



(a) (b)

Fig. 2. (a)-Surface topography of the HTSC stainless steel tape substrate before magnetorheological polishing after electrolytic plasma polishing, roughness 24.8 nm Sa on a scanning area of 10 by 10 μm. (b) - Surface topography of the HTSC stainless steel tape substrate before magnetorheological polishing and after mechanical polishing, with a roughness of 3.4 nm Sa over a scanning area of 10 by 10 μm.

The stainless steel tape was also polished using the method of variant 1 (Fig. 1a) with a rough initial roughness of 120-150 nm Ra, but the polishing did not significantly improve the surface. This indicates that the modes presented in the results section are precision polishing.

The roughness of polished stainless steel tapes for HTSC was determined using an Ntegra Aura atomic force microscope (AFM) with an NS15 cantilever in the semi-contact mode on 10 by 10 μm sections. SensHeight was used as the main signal. Roughness was extracted from topographic data in two ways - Sa over the entire area and Ra on the best section of the scan with a length of 8 μm. This approach to choosing scan sections and profile length for Ra was chosen in order to optimize the magnetorheological polishing stage, since at lengths of about 80 μm, disturbances in the topographic data introduce defects that are eliminated by previous polishing stages (mechanical polishing, electrolytic-plasma polishing).

Several HTSC stainless steel substrates of grades 13Cr25Ni18, AISI 304, AISI 310 were used in the experiments (Table 1). To compare the polishing quality, two versions of magnetorheological fluid were used based on the FeO powder we obtained with a particle fraction of up to 50 μm and up to 100 μm. The magnetorheological fluid used for polishing consisted of the obtained spherical iron oxide particles (Fig. 3) diluted in a 1 to 3 ratio with a DiaDuo Struers diamond suspension with an abrasive fraction diameter of 1 μm.

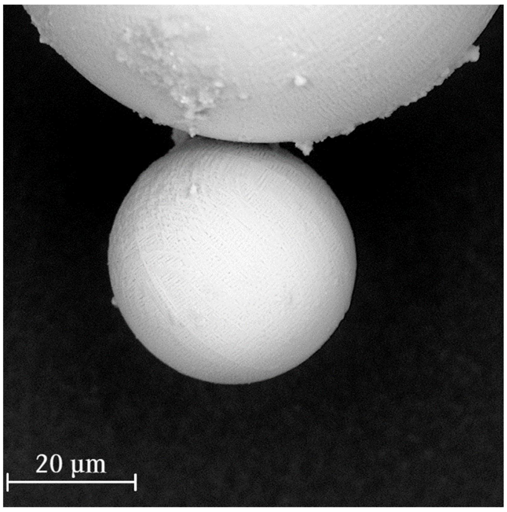


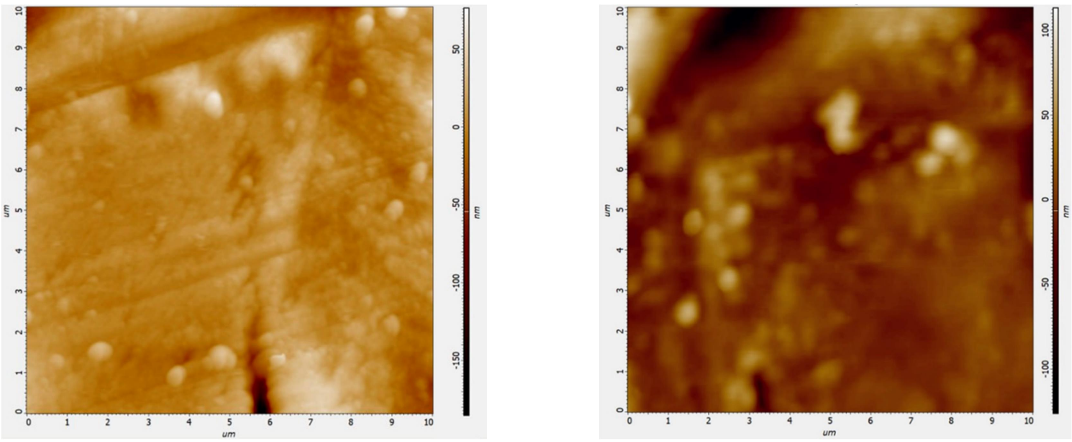
Fig. 3. Photograph of spherical iron oxide powder particles obtained by the liquid anode method.

3. Results

Table 1 Polishing parameters for HTSC substrate samples

Sample №	Polished substrate steel grade	Initial roughness Sa, nm	Type of polishing	Powder fraction used (diameter of spherical particles, μm)
1	AISI 304	24.8	Fig. 1a	10-100
2	13Cr25Ni18	24.8	Fig. 1a	10-100
3	13Cr25Ni18	24.8	Fig. 1b	10-100
4	13Cr25Ni18	24.8	Fig. 1b	10-50
5	AISI 310	3.4	Fig. 1c	10-100

As a result of polishing using the obtained FeO particles, the following values were obtained for the Ra parameter: for sample № 1: 7 nm; for sample №. 2: 2 nm (Fig. 4a); for sample № 3: 6 nm (Fig. 4b); for sample № 4: 8 nm, and for sample № 5: 1.3 nm Sa (1.9 nm RMS) on a 10 by 10 µm area (Fig. 5).



(a) (b)

Fig. 4. (a)- Surface topography of HTSC stainless steel tape substrates after magnetorheological polishing: sample 2, polished using a rotating magnetic field, with a polishing result of (Ra) 2 nm and (Sa) 11 nm. (b) - Surface topography of HTSC stainless steel tape substrates after magnetorheological polishing: sample 3, polishing using reciprocating motion of the sample in a magnetic field, powder fraction diameter up to 100 µm, with a polishing result of (Ra) 6 nm and (Sa) 18 nm.

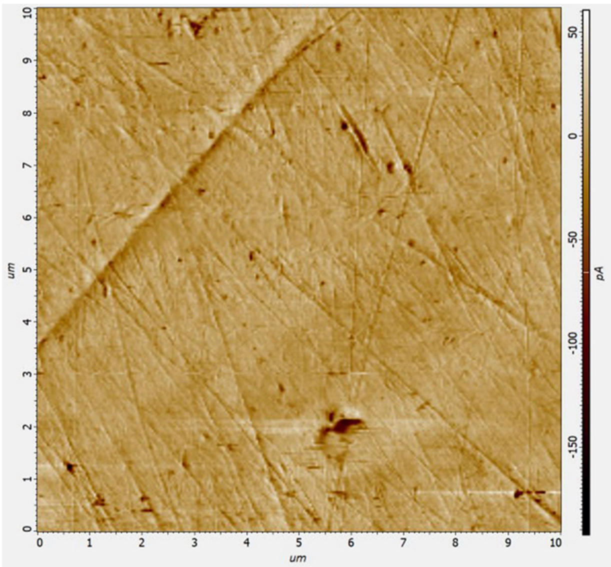


Fig. 5 Surface topography of HTSC stainless steel tape substrates after magnetorheological polishing: sample 5, polishing using reciprocating motion of the sample in a magnetic field, powder fraction diameter up to 100 µm, polishing result 1.3 nm Sa (1.9 nm RMS) scanning area over a 10 by 10 µm section, polishing using reciprocating motion of the sample in a magnetic field, powder fraction diameter up to 100 µm.

The following conclusion can be made based on the polishing results of samples 3 and 4: use of powder with a wider spread of spherical particles by diameters (up to 100 μm) allowed to achieve better roughness after polishing than when utilizing powder with a smaller spread of the spherical particle diameters (up to 50 μm). This is probably explained by the fact that with a wider spread of diameters, the effect of rolling of spherical particles and the entrainment of the tape material by the abrasive occurs more often. This effect is caused by the spherical shape of the powder particles, in which the abrasive seems to stick to the surface of the spherical particles, and when a circulating flow of magnetic fluid is created, the spherical particles with the stuck abrasive roll over the polished surface under the influence of the magnetic field. With the variant of increasing the magnetic induction to 400 mT and improving the quality of preliminary polishing (sample 5), the best polishing quality of 1.3 nm Sa (1.9 nm RMS) was achieved.

4. Conclusion

The application of spherical particles obtained by the liquid anode method as a component of magnetorheological fluid for polishing HTSC tapes was tested. It was shown that as a result of magnetorheological polishing, samples of the original tape substrate for HTSC with an initial surface roughness of 40-50 nm Ra over a profile length of 8 μm were polished to a roughness by Ra in the range from 2 to 8 nm, depending on the selected polishing variant. The lowest roughness of 1.3 nm Sa (1.9 nm RMS) over a scanning area of 10 by 10 μm was achieved on a sample with preliminary mechanical polishing of the surface to 3.4 nm Sa. Thus, magnetorheological polishing using spherical particles obtained by the liquid anode method qualitatively reduces roughness and allows obtaining the required roughness of substrates for use in HTSC tapes. The polishing results can be explained by the influence of the selected composition of the magnetorheological fluid based on spherical FeO particles mixed with a diamond suspension (diamond fraction 1 μm), as well as the selected characteristics of the magnetic field during the experiments. Spherical particles, on the surface of which there was a diamond suspension (upon contact with the HTSC substrate during polishing) due to their spherical shape could roll over the surface of the HTSC substrate, creating a soft polishing effect. Moreover, the polishing results were better for the powder of spherical particles with a particle spread of up to 100 μm than with a particle spread of up to 50 μm. It is possible that this effect occurs because increasing the dispersion of spherical particles provides a better rolling effect and, consequently, polishing. Future studies plan to scale up the method to increase polishing productivity. Our article examined the possibility of final precision polishing using a magnetorheological fluid; for pre-polishing, if performed using a magnetorheological fluid, different conditions will need to be selected. Due to the small spread of 2D surface roughness parameters between randomly selected scan areas and preliminary nature of the study, which focused more on finding promising polishing technique, only visually representative data is demonstrated, and exact roughness error and distribution were not calculated. A more in-depth study of specimen surface is planned to be carried out at the next stages of this research.

Declarations

The authors declare no competing interests.

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