Introduction

The Nb₃Sn-based superconducting composites under study were developed and manufactured by bronze technology at the Bochvar Institute of Inorganic Materials (VNIINM, Moscow, Russia) [1]. Superconductors of such design have high critical characteristics in magnetic fields up to 12 T, which allowed them to participate in the ITER project [2]. At present, they are the main candidates for use in the superconducting magnetic systems of future large accelerator projects at CERN and thermonuclear reactors. Particularly, Nb₃Sn superconductors are planned to be used in the Future Circular Collider (FCC) project that considers the creation of magnetic fields up to 16 T [3]. For further increase of critical characteristics in high magnetic fields attention should be paid to studying the growth kinetics of the superconducting layers in industrial conductors manufactured by the up-to-date technologies.

The goal of the present study is to investigate the growth rate and structural parameters of the Nb₃Sn layers formed under various regimes of the diffusion annealing.

Results

Table 1. The annealing regimes of the samples.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Annealing time, h</th>
</tr>
</thead>
<tbody>
<tr>
<td>575</td>
<td>10 50 100</td>
</tr>
<tr>
<td>650</td>
<td>sample 1 sample 2 sample 3</td>
</tr>
<tr>
<td>750</td>
<td>sample 4 sample 5 sample 6</td>
</tr>
</tbody>
</table>

Table 2. The calculated equivalent thickness of superconducting layers.

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<th>Temperature, °C</th>
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<tbody>
<tr>
<td>575</td>
<td>1 330 2 520 3 750</td>
</tr>
<tr>
<td>650</td>
<td>4 470 5 590 6 910</td>
</tr>
<tr>
<td>750</td>
<td>7 905 8 950 – –</td>
</tr>
</tbody>
</table>

Figure 1. SEM images of polished transverse sections, sample 3 (575 °C, 100 h): (a) an overall view of multifilamentary ITER-type composite; (b) a group of filaments with different degree of Nb transformation into Nb₃Sn.

Figure 2. The fracture image of a filament with Nb₃Sn grain zones of different morphology. The insert shows the example of processed image for quantitative analysis.

Figure 3. The SEM image of a polished cross-section with marked points for EDX microanalysis. 5 points in sample at the 60, 120, 180, 240 and 300 μm distance from Nb barrier. Each point is located at the bronze matrix between sub-elements.

Figure 4. The fracture image of coupled filament with Nb₃Sn layer and the diagram of an approximating figure.

Figure 5. SEM images of fractures of Nb filaments with Nb₃Sn layers after the annealing at 575 °C (a), 650 °C (b) and 750 °C (c) for 10 hours.

Figure 6. Estimation formula for the equivalent thickness of superconducting layers:

\[ L = \frac{S_{N} - S_{Sn}}{1 + \sqrt{\frac{S_{N}}{S_{Sn}}}} \]

Figure 7. Growth rate of Nb₃Sn layers. Layer thickness (μm) vs. the annealing time (h). Wide bars show standard deviation of values obtained, narrow bars mark standard error of mean.

Figure 8. The consumption of tin from the matrix during diffusion annealing, as the difference between the initial and final concentration of tin in the matrix for samples with different annealing times and temperatures. The values obtained are averaged over the points indicated in Fig. 3. The bars indicate SDs.

Figure 9. TEM images of grains in samples (a) 1 (575 °C, 10 h), (b) 6 (650 °C, 100 h) and (c) 7 (750 °C, 10 h).

Figure 10. Histograms of grain size distribution of the same samples (log-normal).

Figure 11. Average size of equiaxed grains of the Nb₃Sn phase as a function of the annealing time at different temperatures (according to SEM). Vertical bars indicate the standard deviation of the grain size distribution.

Summary

• Composition, morphology and grain sizes of Nb₃Sn superconducting layers are mainly determined by the diffusion annealing temperature.

• At high annealing temperatures (750 °C) more complete transformation of Nb filaments into the superconducting phase is achievable. However, undesirable grain growth is possible at this temperature.

• At lower annealing temperature (650 °C, 100 h) the filaments are almost completely transformed into the Nb₃Sn phase, but the grain sizes are much smaller, which gives rise to an enhanced pinning force.

• Low annealing temperature (575 °C) can be recommended only for the first step of the diffusion annealing for stabilization of fine-grained structure of superconducting layers.

• Keeping in mind that high magnetic fields composition of the Nb₃Sn phase is of greatest importance, whereas in intermediate fields the role of the pinning force is gain, one can find a reasonable compromise for optimal regimes of the diffusion annealing based on the data obtained in this study.

Acknowledgements

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References