Growth Rate and Morphology of Nb$_3$Sn Layers in ITER-type Bronze-Processed Wires under Different Diffusion Annealing Regimes

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Introduction

The Nb$_3$Sn-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, Nb$_3$Sn 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 Nb$_3$Sn layers formed under various regimes of the diffusion annealing.

Samples

Table 1. The annealing regimes of the samples.

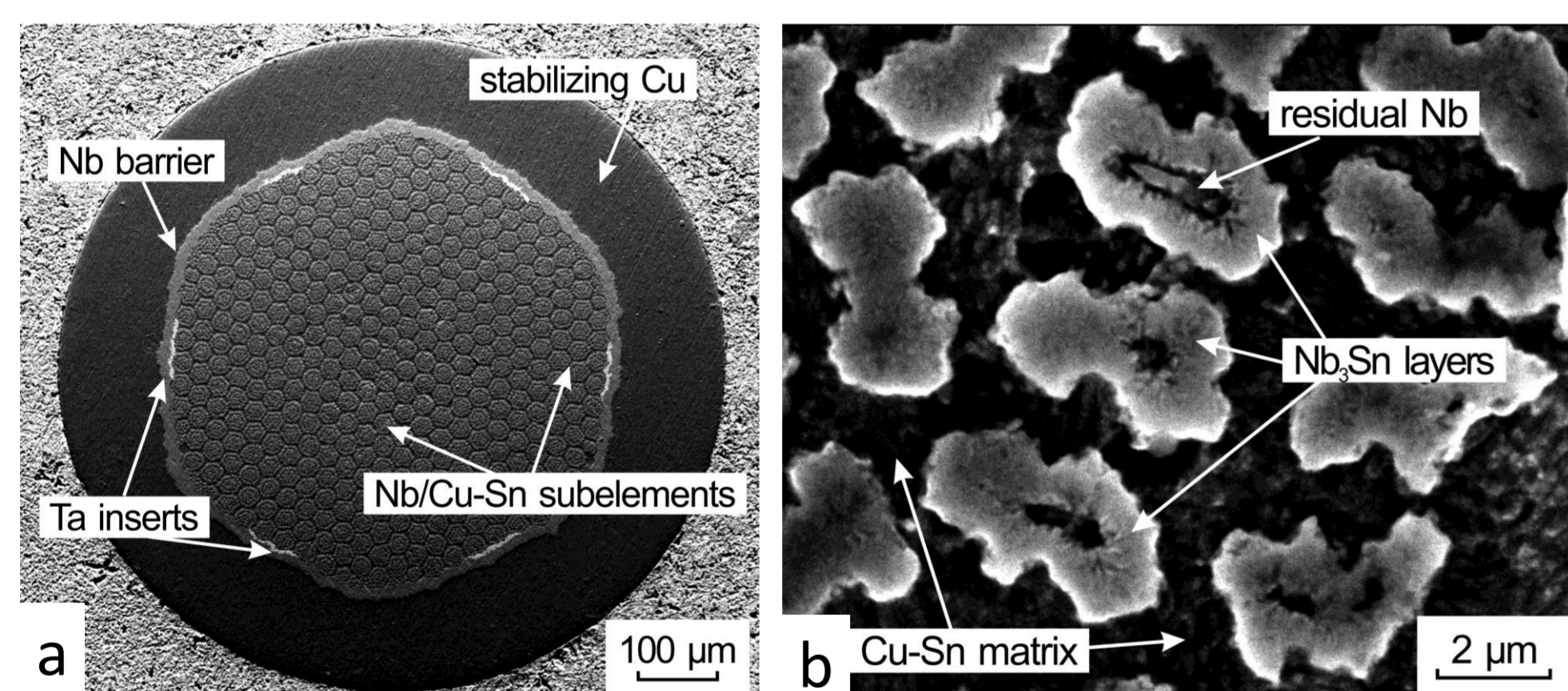| Temperature, °C	Annealing time, h		
	10	**50**	**100**
575	sample 1	sample 2	sample 3
650	sample 4	sample 5	sample 6
750	sample 7	sample 8	–

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 Nb$_3$Sn.
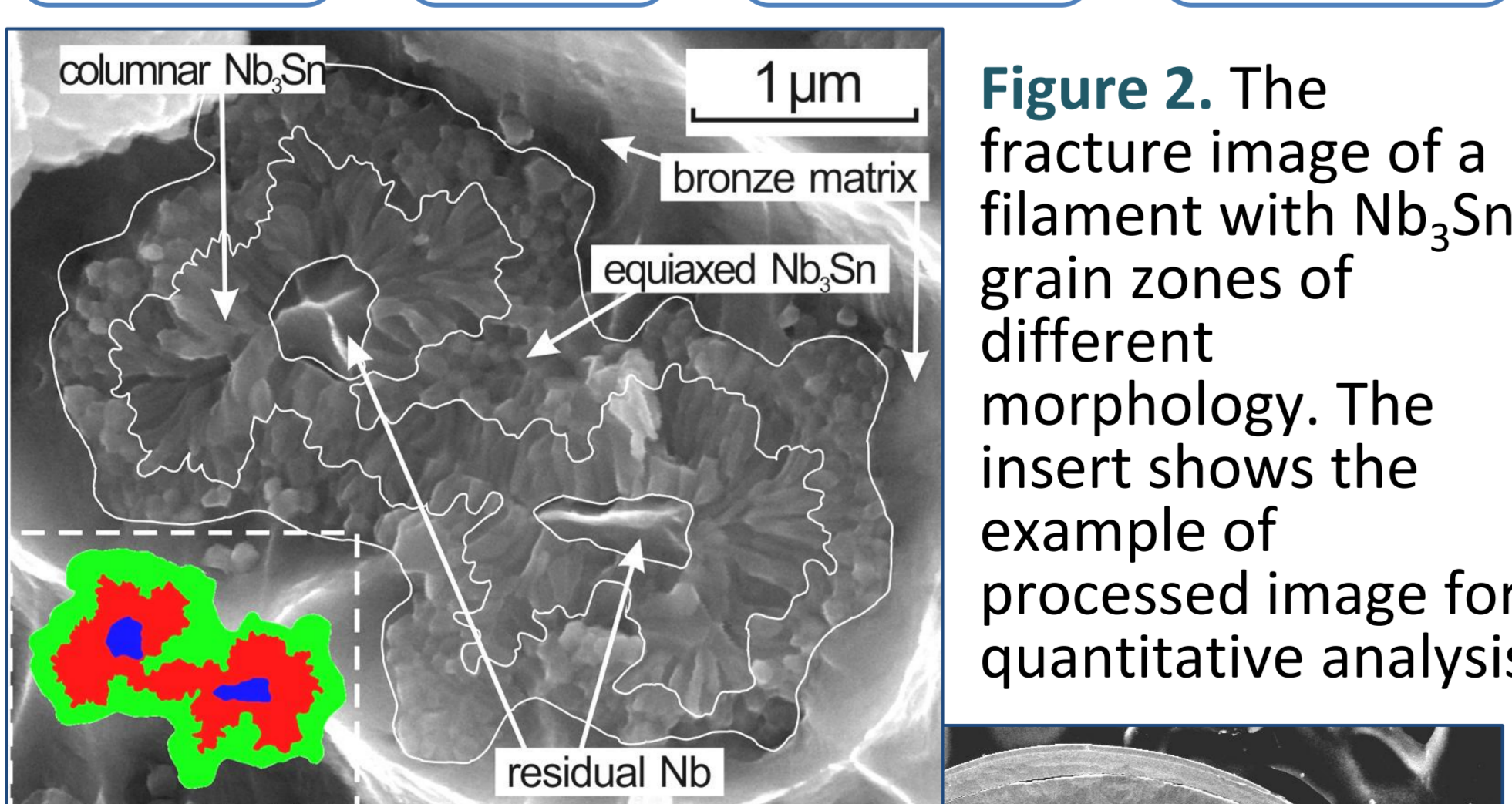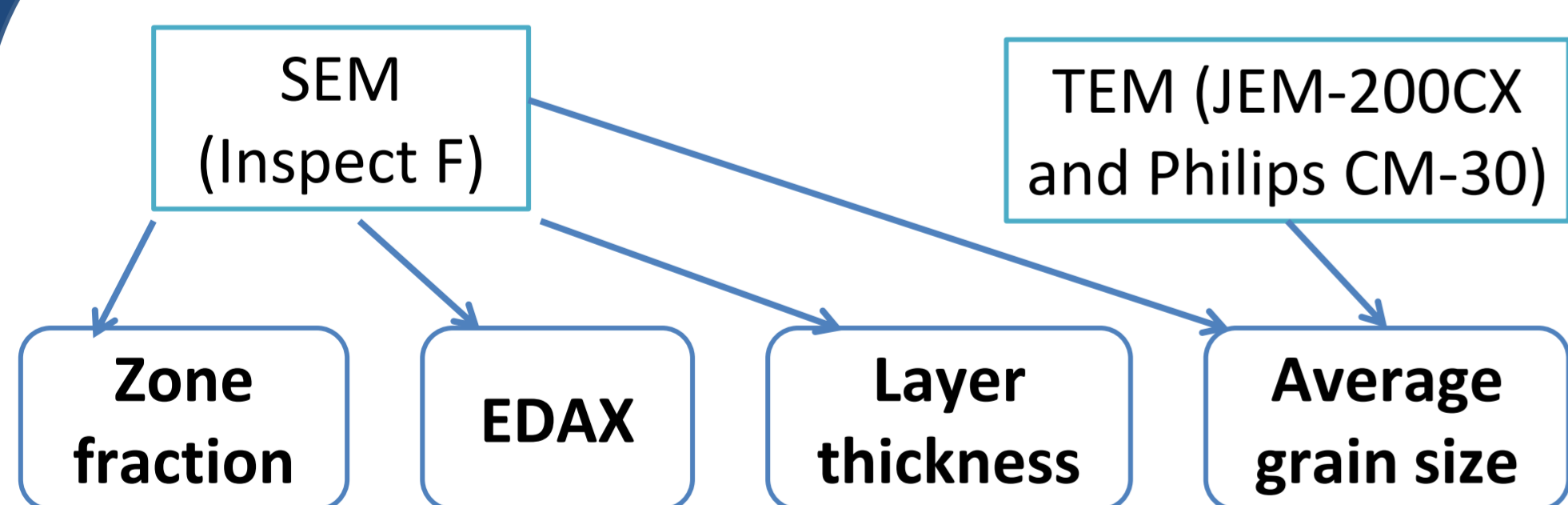
Methods

Figure 2. The fracture image of a filament with Nb$_3$Sn grain zones of different morphology. The insert shows the example of processed image for quantitative analysis.
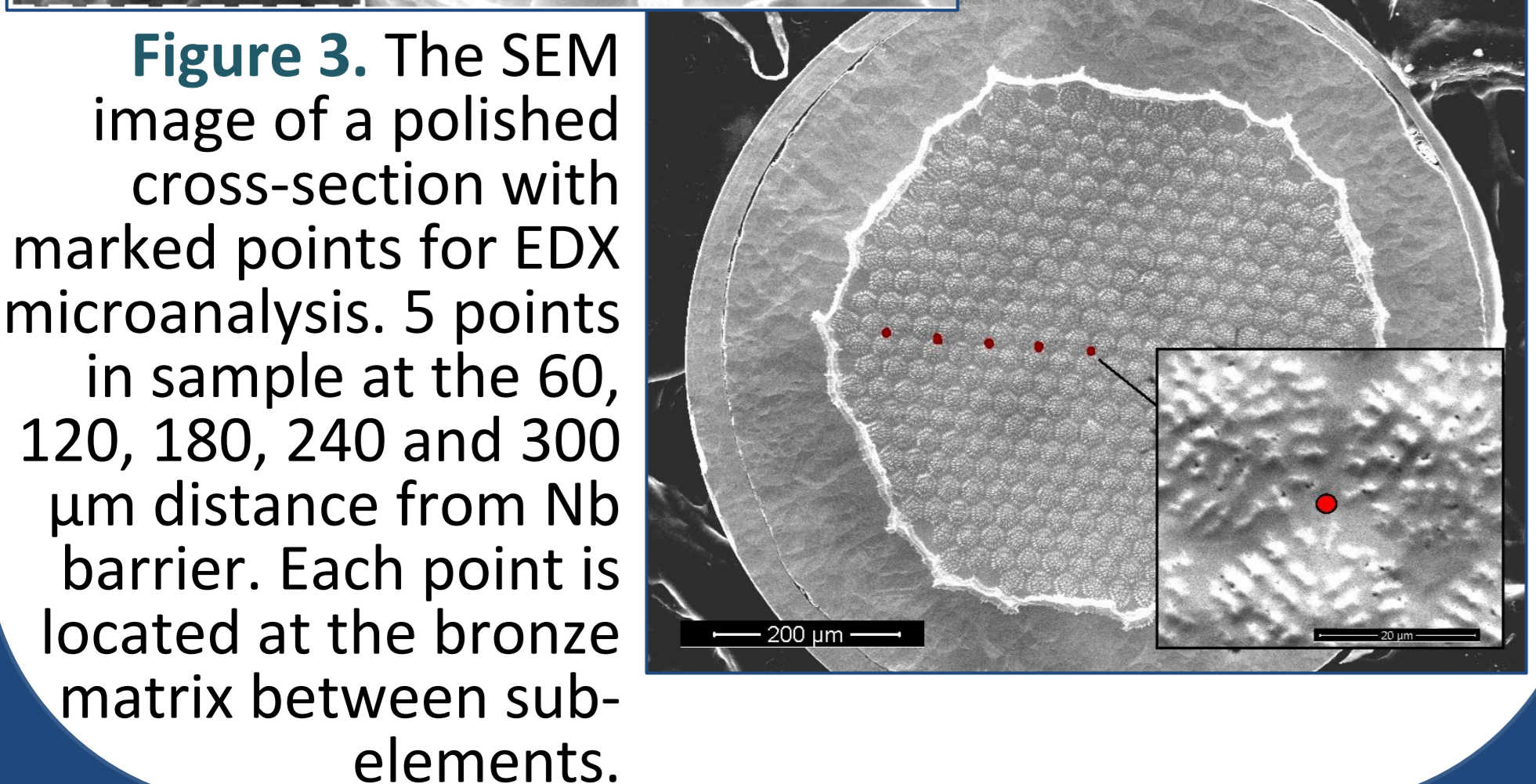

Figure 3. The SEM image of a polished cross-section with marked points for EDX microanalysis. 5 points in sample at the 60, 120, 180, 240 and 300 µm distance from Nb barrier. Each point is located at the bronze matrix between sub-elements.
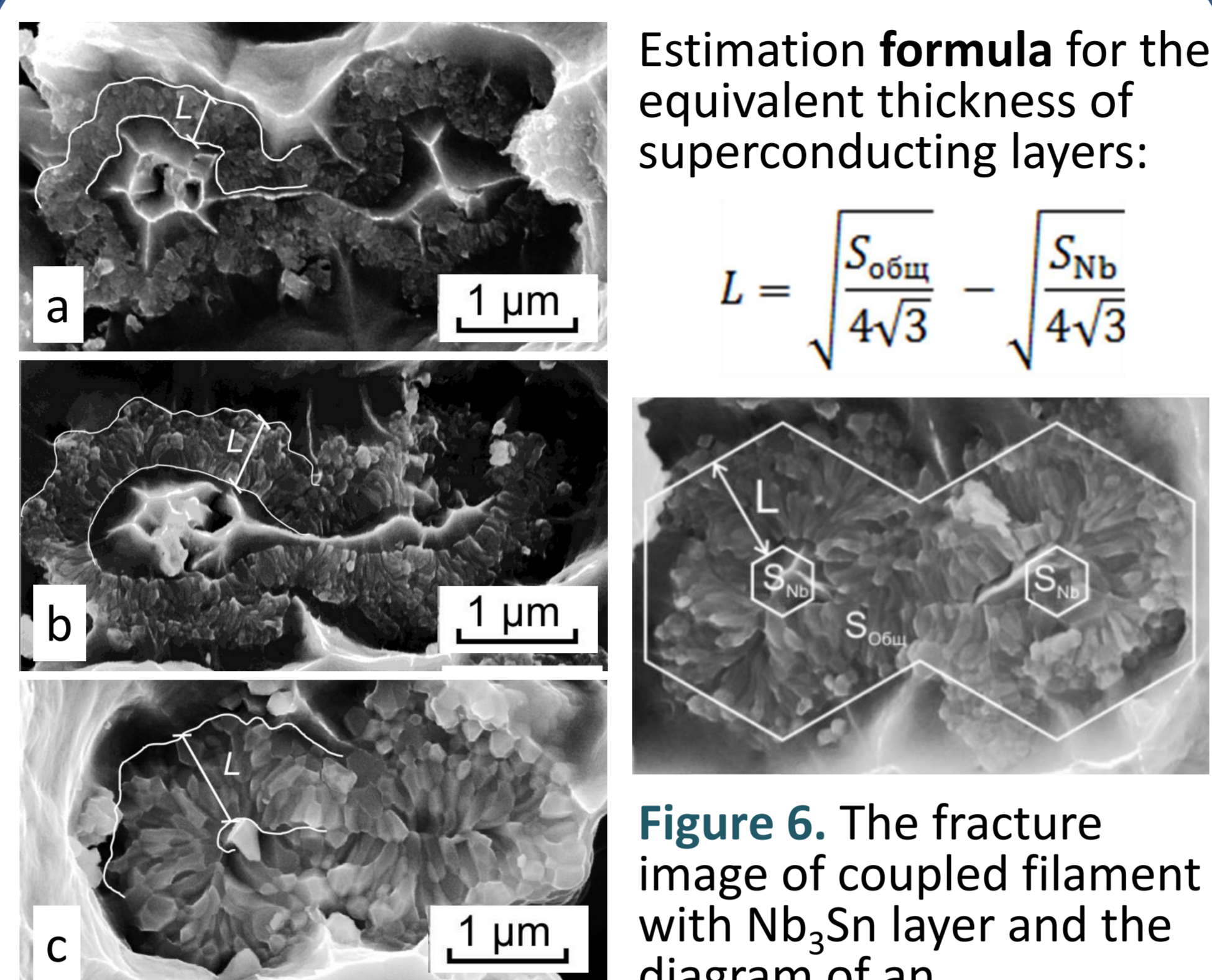
Results

Figure 5. SEM images of fractures of Nb filaments with Nb$_3$Sn layers after the annealing at 575 °C (a), 650°C (b) and 750 °C (c) for 10 hours.

Estimation **formula** for the equivalent thickness of superconducting layers:

$$L = \sqrt{\frac{S_{общ}}{4\sqrt{3}}} - \sqrt{\frac{S_{Nb}}{4\sqrt{3}}}$$

Figure 6. The fracture image of coupled filament with Nb$_3$Sn layer and the diagram of an approximating figure.

Table 2. The calculated equivalent Nb$_3$Sn layer thickness, nm.

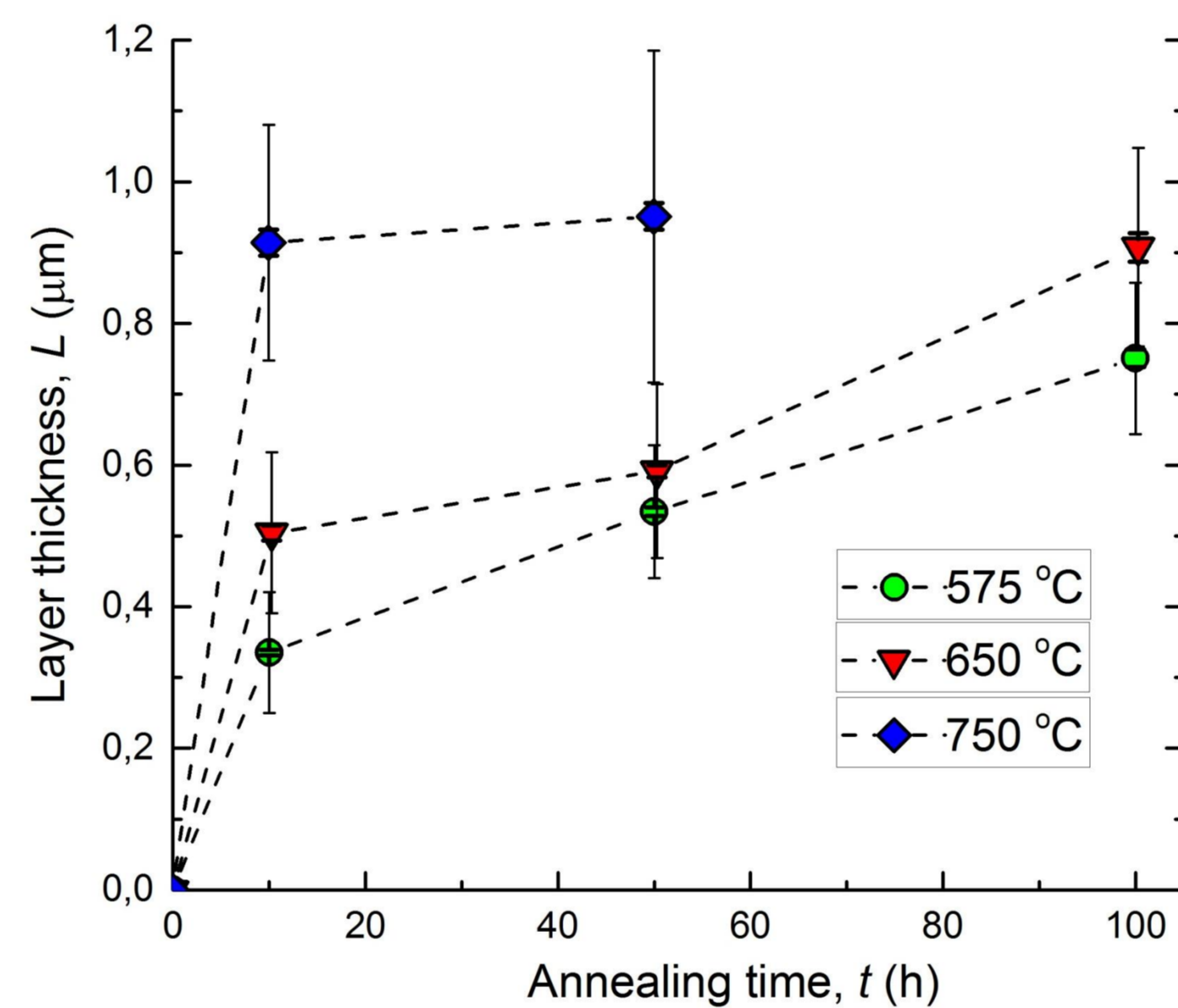| Temperature, °C	Annealing time, h					
	10		50		100	
575	1	**330**	2	**520**	3	**750**
650	4	**470**	5	**590**	6	**910**
750	7	**905**	8	**950**	–	–

Figure 7. Growth rate of Nb$_3$Sn layers. Layer thickness (µm) vs. the annealing time (h). Wide bars show standard deviation of values obtained, narrow bars mark standard error of mean.
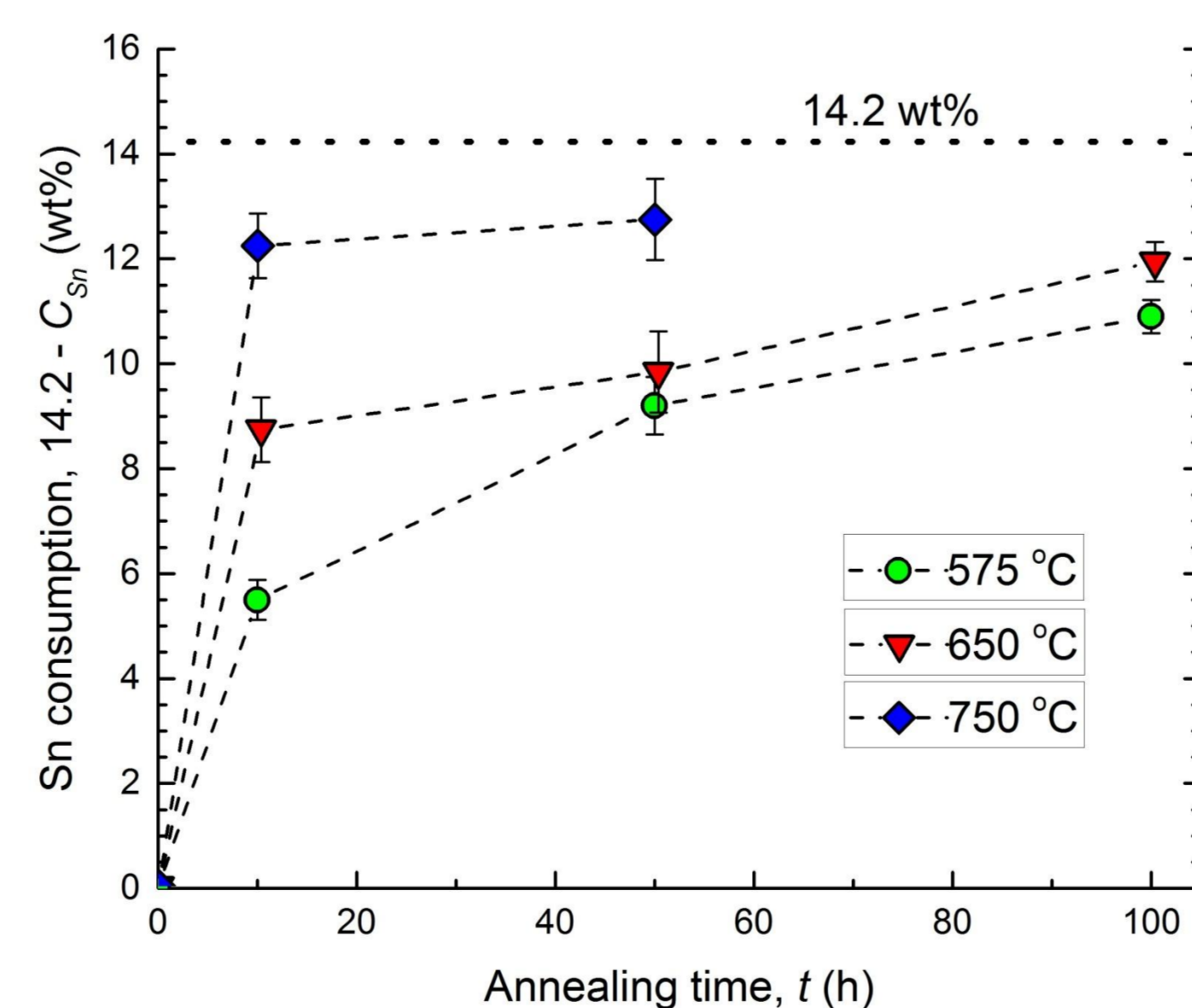

Figure 8. The consumption of tin from the matrix during diffusion annealing, as the difference between the initial and final concentration of tin in the matrix for samples with different annealing times and temperatures. The values obtained are averaged over the points indicated in Fig. 3. The bars indicate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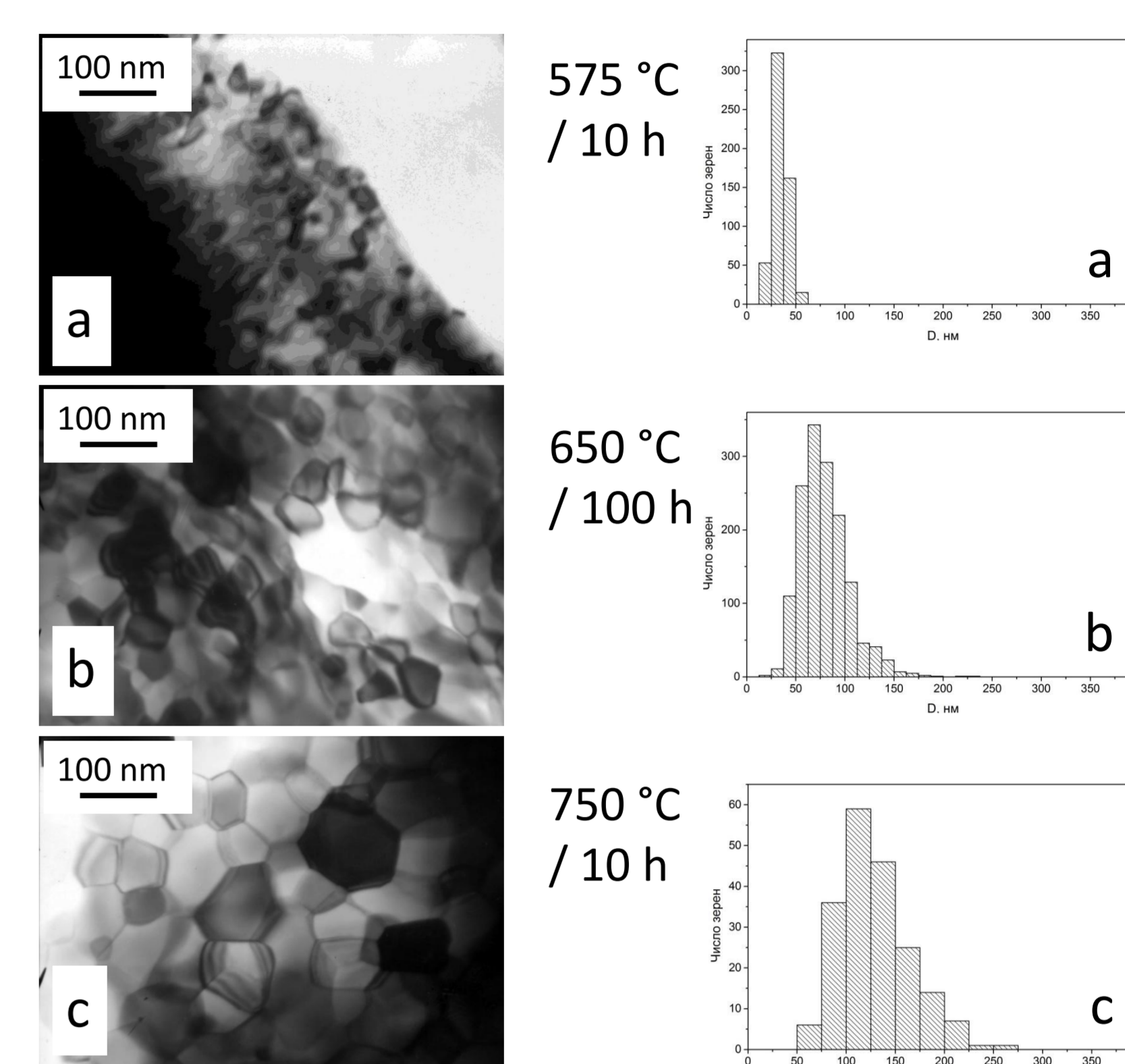
Results

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).
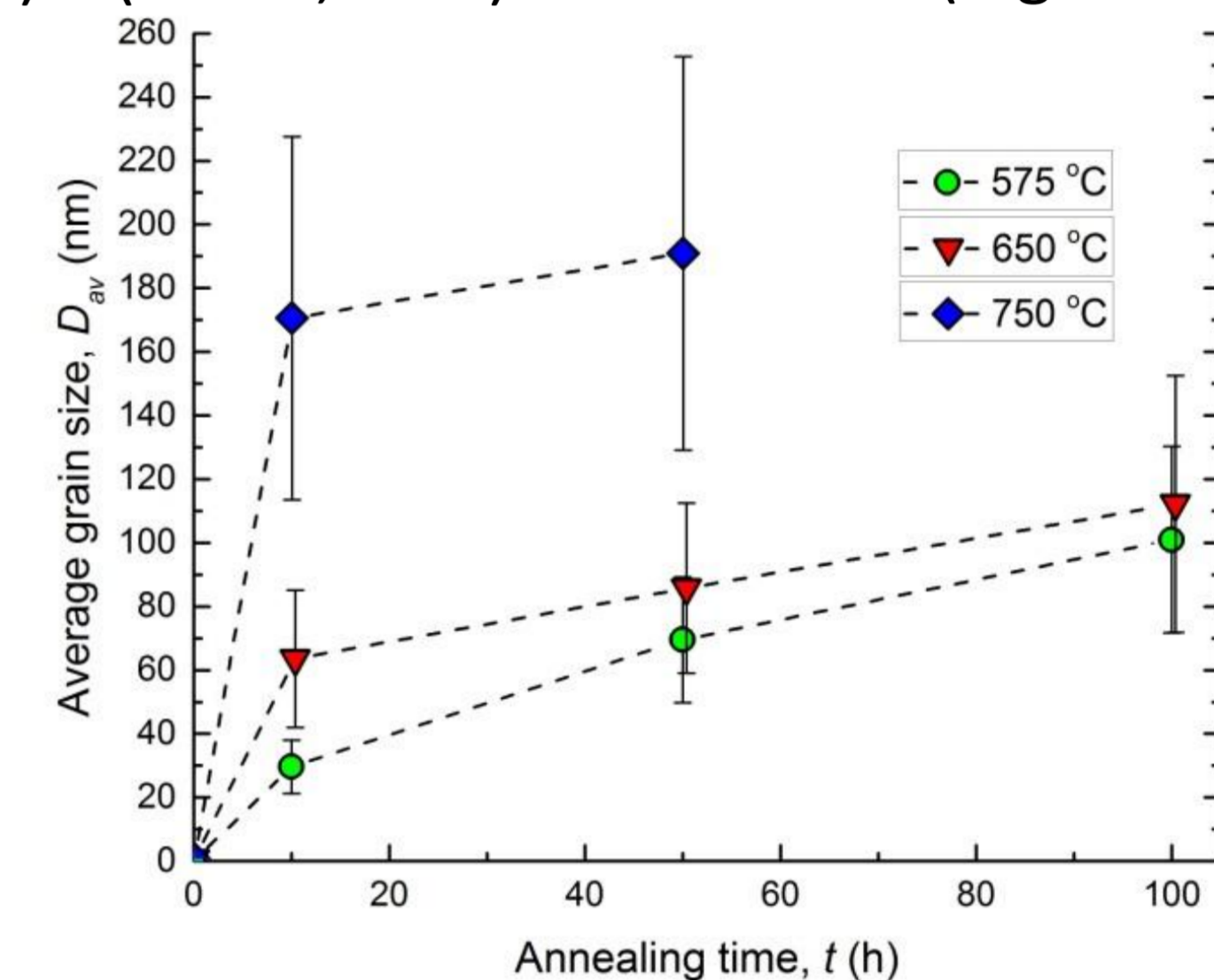

Figure 12. Average size of equiaxed grains of the Nb$_3$Sn phase as a function of the annealing time at different temperatures (according to SEM). Vertical bars indicate the standard deviation of the grain size distribution.

Summary

- Composition, morphology and grain sizes of Nb$_3$Sn 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 also almost completely transformed into the Nb$_3$Sn 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 in high magnetic fields composition of the Nb$_3$Sn phase is of greatest importance, whereas in intermediate fields the role of the pinning force is great, one can find a reasonable compromise for optimal regimes of the diffusion annealing based on the data obtained in this study.

References

1. Dietderich D.R., Godeke A. Cryogenics 2008. V. 48. P. 331–340.
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