LARGE-GRAIN SUPERCONDUCTING RF CAVITIES AT DESY

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Abstract

The DESY R&D program on cavities fabricated from large-grain niobium explores the potential of this material for the production of approximately 1000 nine-cell cavities for the European XFEL. The program investigates both basic material properties, comparing large grain material to standard sheet niobium, and material availability, production, and preparation aspects. Several single-cell cavities of TESLA shape have been fabricated from large grain niobium. A gradient up to 41 MV/m at $Q_0 = 1.4\cdot10^{10}$ (T_B = 2K) was measured after EP (electropolishing). Recently, the first three large-grain nine-cell cavities worldwide have been produced under a contract of DESY with ACCEL Instruments Co. The first cavity has already been tested with an accelerating gradient of 29 MV/m after BCP (Buffered Chemical Polishing) treatment.

INTRODUCTION

The power of niobium melting equipment is growing steadily in the industry. Ingots of high-purity niobium with diameters of 300-500 mm can be produced today. Such a large diameter allows, in principle, simply discs of appropriate thickness to simply be sliced from the ingot and cavities to be produced by common deep drawing and electron-beam welding. This production method was proposed at JLab, and it can potentially be considered as a cost-effective option. Several single cell cavities produced at JLab from high-purity niobium sliced directly from EB-melted large-grain ingots demonstrated very good performance [1-4].

The main aim of the DESY R&D program is to check whether the large-grain option is reasonable for the production of approximately 1000 nine-cell cavities for the European XFEL [5]. Two aspects have been pursued: on the one hand, material availability on the market and the production and preparation procedure, and on the other hand, basic understanding of the difference between large grains and small grains. Some mostly preliminary results are presented below.

MATERIAL AND CAVITY PRODUCTION

All companies producing high-purity niobium were invited to participate in the DESY large-grain R&D program. The cost item has great significance. At first glance, the large-grain option seems to be cost-effective, because the long production chain from ingot to fine-grain sheet (forging, cleaning, rolling, cleaning, intermediate annealing, rolling, cleaning, final annealing) will be replaced by one step (cutting the discs from ingots). However it is a challenge to cut the discs cost- effectively while keeping tight thickness tolerances, purity and high surface quality. Applying EDM (electric-discharge machining) or sawing with subsequent machining can not withstand competition with conventional sheet production. The HERAEUS company has put a lot of effort into developing a cost-effective cutting procedure for large- grain discs and (as it seems) solved this problem. A special machine for cutting many discs simultaneously by wire sawing was adapted. The cutting conditions have been developed so far that disc-slicing can be done now without polluting the material /6/. The surface roughness of the delivered discs met the specification, and the thickness tolerances (within ±50 μ) were even better than the DESY specification required /7/.

Niobium discs with RRR=300-500 for 10 single cells and three 9-cell cavities of TESLA shape were purchased by the HERAEUS company. The discs for cavities 1AC3-1AC5, 1DE20, 1DE21, AC112 were annealed at the company at 1200 °C for 6 hours with titanium, and thereafter a layer of half a mm was removed by machining from each site. The discs for the remaining cavities were cut from ingots without additional treatment. Material for 3 single-cell cavities (RRR=400) was supplied by the NINGXIA company. In addition, JLab and NPC (Niobium Products Company, Germany) kindly provided us with some large-grain disks of CBMM (RRR=200-250).

It is to be expected, that the disc material from ingots is less susceptible to foreign material inclusion and another types of defects, because several sources of material pollution, such as forging or rolling, are not present in this case, compared to fine-grain sheets. The discs used for cavity production were scanned by an eddy-current device available at DESY. No indications of localized defects in the crystals were observed. The grain boundaries were seen distinctly, caused rather by steps on grain boundaries after BCP etching than by impurities.

Single-cell cavity production was done in two ways. Cavities 1AC3, 1AC4, 1AC5, and 1AC7 were produced under a contract of DESY with ACCEL Instruments Co., cavities 1DE20-1DE26 are planned to be welded on DESY electron-beam equipment. Cavities 1AC6 and 1AC8 were produced from single- crystal material. This item will be discussed elsewhere. Deep drawing of the half cell was done in the same way as for fine-grain material (instead of female tool, a rubberized material was used). All half cells were leak- tight, but the grain boundaries were noticeably pronounced, with steps up to 0.5 mm. It turned out that the steps on grain boundaries can be reduced by applying spinning during half-cell production. Half cells for cavities 1AC5 and 1AC6 were been produced by this means. The steps on the grain boundaries were less pronounced, but nevertheless clearly visible. Three nine-cell cavities AC112-AC114 (first large-grain multicell cavities worldwide) were produced from the HERAEUS material at ACCEL.

Optical-coordinate measurement and creation of a 3D image were applied to estimate shape accuracy. Measurements were done at DECOM company on half cells, on dumb bells with welded stiffening rings, and on end half-cell units with welded connecting flanges.

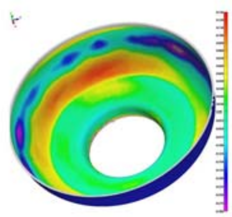

Figure 1. 3D image of the fine-grain long half cell. Shape accuracy: +0.13/-0.30 mm

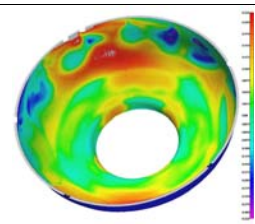

Figure 2. 3D image of the large-grain long half cell. Shape accuracy +0.22/-0.32 mm

An example of the half-cell shape in comparison with a standard fine-grain niobium can be seen in Figs. 1-2. The large grains are fractionally pronounced (Fig. 2). The variation of the large-grain half cell shape is somewhat larger.

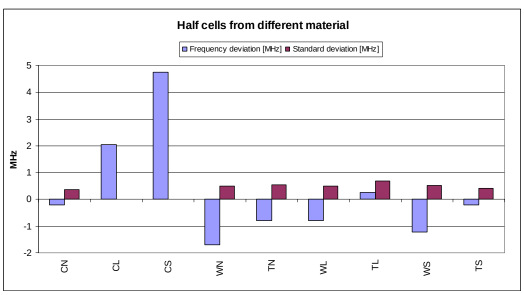

Figure 3: Frequency measurement of 6 end half cells (L and S) and 48 middle half cells (N) for cavities AC112-114. C = large crystal, W = Wah Chang, T = Tokyo Denkai,

RF frequency measurement showed a large deviation from the expected frequency in large-grain niobium parts as well as for the fine grain (Fig. 3). Nevertheless, the correct cavity length and frequency of the fundamental mode in nine-cell cavities AC112-AC114 could be achieved with appropriate trimming. At the same time, the scattering (standard deviation) in the shape of large-grain half cells is smaller than for conventional material. This means that the deep-drawing behavior for large-grain is different compared to fine-grain sheets (different spring back), but it is more stable and allows production of more uniform half cells. Better conformity in shape to the specification requirements could be achieved by correcting the deep drawing tools. It should be mentioned that having a large central crystal is essential for large-grain discs; otherwise, forming of the iris can be critical (necking of the material in the iris area is possible).

PREPARATION AND RF TESTS

The following aspects should be taken into consideration in order to define the preparation recipe for large-grain cavities (BCP, as a less challenging treatment, or EP). On the one hand, after BCP, the surface of the large grains becomes very shiny and the surface roughness is even smaller than after EP [2, 8]. On the other hand, the influence of grain boundaries on cavity performance is not completely understood. After EP, the steps on grain boundaries are decreased, in contrast, then increase after BCP [8]. Both treatments are planned to be applied in the DESY R&D program. For some cavities, EP should be done first and BCP after that, for some cavities, vice versa.

The treatment applied and first RF test results are summarized in the table. The best accelerating gradient of 41 MV/m was achieved with the cavity 1AC3 after 150 µm EP, 800 °C 2h, 40 µm EP, baking at 120 °C for 48 h, HPR, and was limited by quenching at the equator. The performance of the cavity with half cells produced by spinning 1AC5 was limited by quenching at a lower accelerating gradient compared to deep-drawn single cells (1AC3, 1AC4), and it is probably related to production issues. At the moment, both treatments (EP and BCP) have been applied only to one large-grain cavity, 1AC3. Surprisingly, about 12 MV/m was lost after BCP treatment.

On one of the nine-cell cavities, AC114, the first RF test done so far was after 100 µm BCP, 800°C, 2h, 20µm BCP, HPR. Unfortunately the performance was restricted by a field emission started at 23 MV/m. Nevertheless an accelerating gradient of 28.7 MV/m was reached.

SUMMARY

Production of cavities from large-grain niobium deserves attention as a potentially cost-effective option. Several companies are working now on developing and optimizing production of the material. At least one vendor is currently in a position to deliver such material in conformity with specification requirements and with reasonable cost conditions.

Table 1: Summary of the First RF Test Results on Large-Grain Cavities

Material from company	No./Type	Treatment	Eacc, MV/m	Qx10^{-10} at max Eacc	Limitation
Heraeus	1AC3/single-cell	150 µm EP, 800 °C, 2h, 40 µm EP, 120 °C 48h, HPR	41.0	1.40	Quench at equator
Heraeus	1AC4/single-cell	150 µm EP, 800 °C, 2h, 40µm EP, 128°C 48h, HPR	37.2	0.63	Quench at equator
Heraeus	1AC5/single-cell	150µmEP, 800°C,2h, 40µm EP, 135 °C 48 h, HPR	29.3	1.30	Quench between equator and iris
Heraeus	AC114/nine-cell	100 µm BCP, 800 °C, 20 µm BCP, HPR	28.7	0.73	Quench probably FE-induced

Production of single-cell and multi-cell cavities from large-grain niobium has shown that no significant problem appeared during deep-drawing and electron-beam welding. Although the shape conformity of deep-drawn half cells from large-grain material is lower compared to conventional fine-grain niobium sheets, (which could be improved by correcting the tools), nevertheless the uniformity of the half cells from large-grain material is better. The grain boundaries in the formed half cells are significantly pronounced (with steps up to half a mm).

The first RF test results have shown that accelerating gradients similar to the best fine grain-cavities can be achieved, especially after EP treatment. A very reasonable performance of about 29 MV/m was achieved on the nine-cell cavity after simple BCP preparation. The steps on grain boundaries were not ground away. Nevertheless, surprisingly, cavity performance seems not to be essentially affected. A detailed analysis of the magnetic-field enhancement in the case of large-grain boundary steps would be very desirable. More statistics are necessary, especially in order to compare the EP and BCP treatments.

Preliminary investigation of the crystallographic structure has shown [8] that despite a similar procedure in principle for ingot production, the difference in the crystal orientation of ingots from different companies is significant. How the crystal orientation can influence the cavity performance has not been investigated up to now. Anisotropy of the superconducting energetic gap $2\Delta/T_c$ in the 4d and 5d transition metals including Nb is well known [9]. As one of the main parameters of superconductivity Δ should influence the physical properties of the material (for example H_c). This means that production of single-crystal cavities with preferred orientation could probably lead to improved performance.

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