A Single Crystal Niobium RF Cavity of the TESLA Shape

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Abstract. A fabrication method for single crystal niobium cavities of the TESLA shape was proposed on the basis of metallographic investigations and electron beam welding tests on niobium single crystals. These tests showed that a cavity can be produced without grain boundaries even in the welding area. An appropriate annealing allows the outgassing of hydrogen and stress relaxation of the material without destruction of the single crystal. A prototype single crystal single cell cavity was build. An accelerating gradient of 37.5 MV/m was reached after approximately 110 μm of Buffered Chemical Polishing (BCP) and in situ baking at 120°C for 6 hrs with a quality factor exceeding 2x1010 at 1.8 K. The developed fabrication method can be extended to fabrication of multi cell cavities.

Keywords: Cavity, single crystal, accelerating gradient, material properties.
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INTRODUCTION

There are theoretical and experimental claims that grain boundaries GBs reduce the thermal break down limit of an rf cavity (see for example [1-3]). Some of causes are listed below.

GBs are responsible for magnetic field enhancement (steps on GBs after BCP)

GBs enhance the possibility of penetration of external magnetic field (GBs are planar weak links with reduced critical current density)

GBs add to the RF resistance due to vortices penetrating along the grain boundary (reduce the quality factor Qo)

GBs enhance the possibility of hydrogen absorption and diffusion

GBs are the areas that gathered impurities (reduced RRR)

GBs reduce the thermal conductivity at low temperatures (reduce the phonon contribution)

GBs enhance the surface roughness

A single crystal cavity with no grain boundaries has definitely a potential to improve the cavity performance substantially because by nature it does not contain any

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interruption of the crystal lattice orientation. In addition, one can expect a much easier surface preparation procedure for the superconducting surface. The removal of the surface damage layer from the inner surface - necessary for good cavity performance - can be done by standard BCP 1:1:2, because there is no excessive grain etching or different etching speed of different oriented grains. A very smooth surface can be easily produced.

Very high potential of large grain and single crystal cavities was recently demonstrated at JLab [4-7]. An accelerating gradient of Eacc~46 MV/m was measured on a 2.3 GHz cavity (Low Loss LL shape) fabricated from two single crystal discs of approximately 160 mm diameter.

For an ILC or XFEL cavity shape (TESLA, LL or Reentrant RE) a single crystal disc of 270 mm diameter is required. It seems that in the short term industry will not be in position to produce single crystal niobium of such dimensions.

Therefore, at DESY investigations were conducted to find a method to enlarge smaller single crystal high purity niobium, - available on the market- without breaking-up the single crystal to the desire diameter and a fabrication method for a TESLA like single crystal cavity was proposed.

FABRICATION

The following aspects have been investigated on samples and taken into consideration for the fabrication proposal.

- Definite enlargement of the single crystal disc diameter is possible without destroying the single crystal structure.
- The single crystals keep the crystallographic structure and after forming of the cavity half cell from a disc by deep drawing the orientation perpendicular to the surface remains.
- Appropriate heat treatment will not destroy the deformed single crystal
- Two single crystals will grow together by EB welding, if the orientation of the crystals is matched.

Illustrations of these aspects are shown below in figures 1 to 4, where the dependence of the microstructure on the degree of deformation before and after appropriate heat treatment is depicted.

The aim of the heat treatment is twofold: removing hydrogen from the lattice and to stress relieve the material - required for good cavity performance- without destroying the single crystal. The appropriate heat treatment depends on the degree of deformation. The degree of deformation of available single crystals of high purity niobium is expected to be about 20-70%.

The following heat treatments were applied: annealing at 400-500°C for 2-6 hours as a first step and annealing at 750-850°C for 1-3h as second step. The first step is applied to recover the material (to eliminate possible nuclei, which could create new crystals), the second step provides the outgassing of hydrogen and stress relaxation of the cavity.

The deformation was done by rolling; the degree of deformation was 60-90%. The metallographic analysis of the surface perpendicular to the rolling direction (Fig.1-4) shows that, if the deformation degree is smaller as 70%, the single crystals will not be destroyed; the microstructure of the deformed samples after annealing is similar to to that of the original single crystal. If the critical deformation degree of 70% is exceeded, re-crystallization takes place during annealing. As can be seen in figures 3-4, new small crystals appear and as expected the new crystals become smaller in size as the degree of deformation increases.

As these preliminary investigations show, it seems to be possible to enlarge a smaller niobium single crystal from the inside of an ingot to a disc of the dimensions needed for the deep drawing or spinning of a half cell for a TESLA type cavity. In addition the experiments have shown that the crystallographic structure and the crystal orientation perpendicular to the surface remain after deep drawing of the disc into a half cell as expected due to the rather small degree of deformation (less than 10-15%) produced during deep drawing.

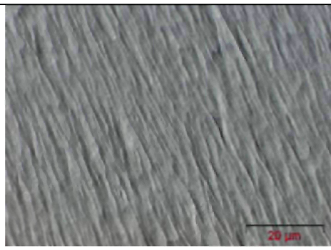

FIGURE 1a. Nb single crystal after deformation degree of 60%.

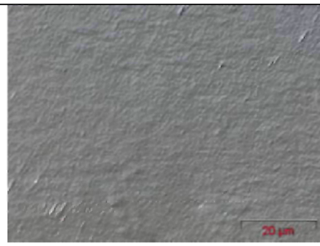

FIGURE 1b. The same Nb single crystal after annealing.

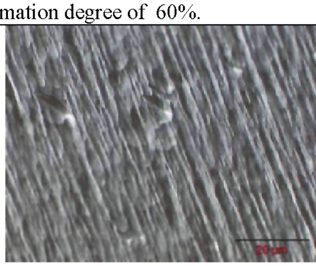

FIGURE 2a. Nb single crystal after deformation degree of 70%.

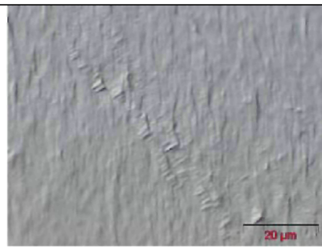

FIGURE 2b. The same Nb single crystal after annealing.

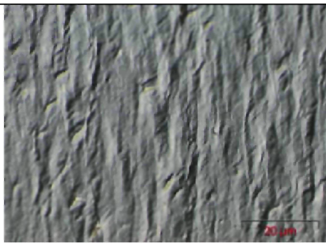

FIGURE 3a. Nb single crystal after deformation degree of 80%.

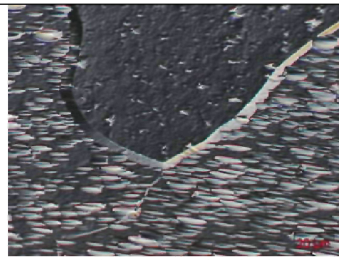

FIGURE 3b. The same Nb single crystal after annealing.

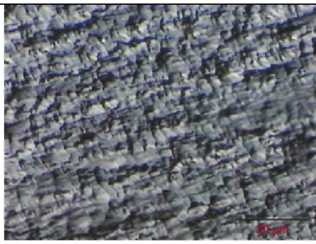

FIGURE 4a. Nb single crystal after deformation degree of 90%.

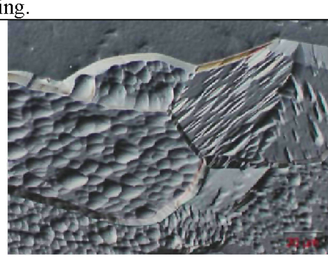

FIGURE 4b. The same Nb single crystal after annealing.

Further investigations focused on the issues of electron beam welding of single crystals. It turned out that two single crystals will grow into one single crystal, if the crystallographic orientations are matched at the EB seam.

The proposed electron beam welding procedure was proven on a single crystal sample. The results of metallographic analysis of the cross section can be seen in fig. 5a, b: whereas unmatched orientations produce a pronounced grain boundary (Fig. 5a), matched orientations of both single crystals grow together without interface (grain boundary free) (Fig. 5b).

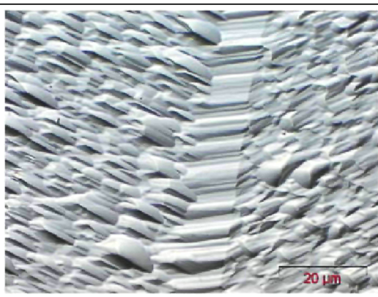

FIGURE 5a. Electron beam welding connection of two single crystals without regarding of crystals orientation (the grain boundary is pronounced).

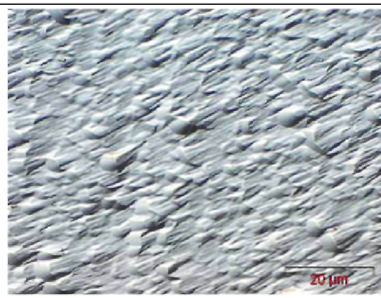

FIGURE 5b. Electron beam welding connection of two single crystals after [assembling in such a way that] matching their orientations [of two single crystals are identical] (the grain boundary is absent).

The orientations of the two single crystal samples before and after EB (Fig. 5b) were determined by means of Laue back scattering. As figure 6 demonstrates, the same crystallographic orientations of both primary samples (left and write) were preserved after EB.

Based on the investigations described above, a prototype single crystal cavity of the TESLA shape was produced. A niobium ingot supplied by W.C. HERAEUS with a single crystal of approximately 150 mm in diameter in its center was used. Two discs cut from the ingot were marked to keep track of the orientation of the single crystals during the production steps to the half cells and of the cavity. The diameters of the discs were increased by rolling at RWTH Aachen. Deep drawing of the half cells and the electron beam welding was done at ACCEL. Prior to electron beam welding the half cells were assembled in such a way that the crystal orientations were identical to the two discs before cutting.

The crystal pattern of the original W.C. HERAEUS ingot with the large central single crystal and the single cell single crystal cavity are shown in Fig. 7 and Fig. 8, respectively. The cell surface is very shiny after only 20 μm of chemical polishing in contrast to the dull appearance of the cut off tubes produced from conventional polycrystalline niobium; no grain boundaries are pronounced at the welding area.

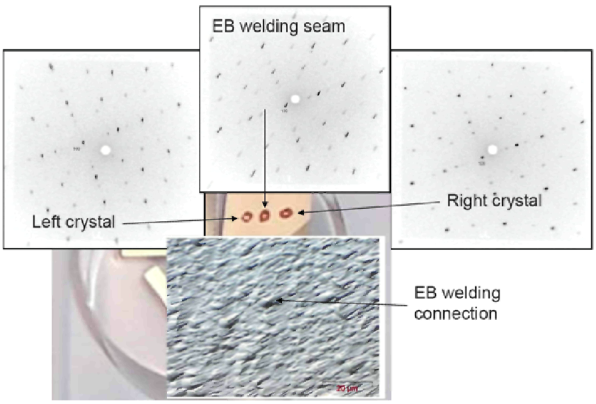

FIGURE 6. Laue back scattering X-Ray reflexes (the same in both welded together crystals and in the welding seam).

FIGURE 7. Grain distribution in the ingot used for fabrication of single crystal cavity.

FIGURE 8. Photo of single crystal cavity

TREATMENT AND RF TESTS

Surface treatment and a series of RF tests after successive material removal with BCP were done at JLab. A best accelerating gradient of 37.5 MV/m was reached after only 112 µm BCP and in situ baking at 120°C for 6 hrs with the quality factor of 2x1010 at 1.8 K (Fig. 9).

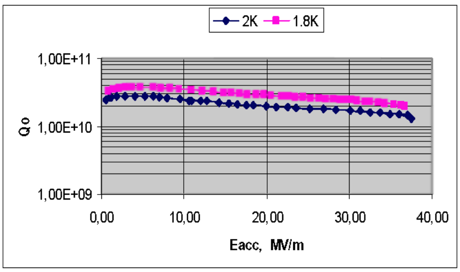

FIGURE 9. Q(Eacc) curve for the single crystal single cell cavity after 112 µm BCP and in situ baking 120°C for 6 hrs.

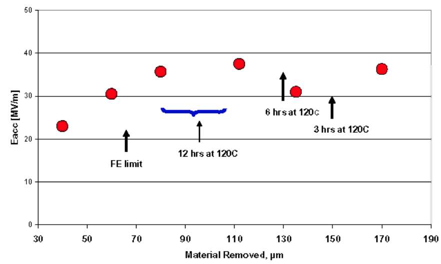

FIGURE 10. Eacc vs. material removal on single crystal single cell cavity.

The limitation was caused by a quench. Fig. 10 shows the quench field as a function of the removed surface layer after each material removal step. It is known from experiments on fine grain material that heat treatment around 800°C provides for hydrogen outgassing and stress relaxation and in many cases an increased accelerating gradient could be obtained. Therefore, as a next step it is planned to anneal the cavity at an appropriate temperature, guided by annealing procedures developed on samples.

OUTLOOK

As shown above the first RF test results obtained with the single crystal single cell cavity are very encouraging. The single crystal option opens the possibility to achieve mirror like inner surfaces of a complete cavity cell by applying standard chemical treatment BCP (1:1:2). This may potentially lead to better superconducting parameters of the niobium and eventually to better cavity performance in terms of achievable accelerating field, quality factor and reproducibility of performance.

The developed method can be extended to fabrication of multi cell single crystal cavities by using the above described assembly method not only for equators but also for the irises welds.

A single crystal applied for cavity fabrication has a crystal orientation close to (100). In this connection appears the question, how the cavity performance can be influenced by the crystal orientation. This issue is not investigated up to now and has a definite potential. Anisotropy of the superconducting energetic gap $2\Delta/Tc$ in the 4d and 5d transition metals including Nb is well known /8/. As one of the main parameters of superconductivity Δ should influence the main physical properties of the material (for example Hc and surface resistance). Therefore, it is not inconceivable that fabrication of single crystal cavities with preferred orientation could lead to further improvement of performance.

Moreover one could speculate that cavities without grain boundaries should produce lower losses; resulting in higher Q-values. The results in fig. 9, were a rather high Qo up to $2x10^{10}$ at maximal gradient and a temperature of 1.8K is shown, seem to support this speculation; however, more statistics is needed.

It is hoped that with single crystal niobium cavities a better understanding of the underlying physics of limitations in RF cavities can be gained, since effects due to the presence of grain boundaries in poly-crystalline niobium such as grain boundary segregation, flux penetration or weak link behaviour are absent. This eventually should lead to simplified treatments and better reproducibility of cavity performances.

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