Physical and Mechanical Properties of Niobium for SRF Science and Technology

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Abstract. Optimized mechanical and physical properties of high purity niobium are crucial for obtaining high performance SRF particle beam accelerator structures consistently. This paper summarizes these important material properties for both high purity polycrystalline and single crystal niobium.

Keywords: Niobium, yield stress, tensile stress, ductility, Vickers hardness, thermal conductivity, residual resistance ratio, critical magnetic field, SRF cavity

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INTRODUCTION

High purity niobium is the material of choice for the SRF cavities used in particle accelerators. The SRF cavity grade niobium is either produced from pyrochlore ore (CBMM's Araxá, Brazil mine holds 90% of world's deposits) or columbite/tantalite ore. The Jefferson Lab's CEBAF, the largest solid niobium SRF accelerator in the world, is built with CBMM pyrochlore polycrystalline niobium sheets with RRR > 250 [1, 2, 3]. The Spallation Neutron Source (SNS, Oakridge, Tennessee) SRF cavities are produced with columbite/tantalite polycrystalline niobium sheets. Generally, it is well known that the SRF cavities need to be annealed at high temperatures (up to 900 °C) for degassing the hydrogen in order to maintain high quality factors and to minimize Q-disease problem [4, 5]. During the initial stages of the SNS cavity development, the polycrystalline high purity niobium cavities exhibited micro-yielding issues after annealing at 800 °C even for 1 hour (resulting in deformation and consequent non uniform field flatness of the cells) [6, 7]. Additionally, it was also found difficult to meet the yield strength specifications for high purity niobium sheets once they were fully recrystallized [8].

A Cooperative Research And Development Agreement (CRADA) is initiated by CBMM's subsidiary Reference Metals Company Inc. and Jefferson Lab in August 2004 to study the interstitial (H, C, N, O) interactions in niobium and to develop techniques for accurately determining the interstitial content in high purity niobium. This collaboration is also aimed to optimize the substitutional tantalum (Ta) impurity content in high purity niobium in order to consistently obtain high performance SRF cavities at reduced cost. As part of this CRADA program niobium ingot slices were

received from CBMM. High ductility (100% elongation) was measured during the initial mechanical property evaluation of the material from the ingot slices leading to the novel innovative idea of producing cavities from sliced ingot material [9, 10]. Since then large grain–single crystal niobium technology has evolved very quickly resulting in the organization of this single crystal niobium technology workshop at CBMM’s Araxá mine in Brazil. In the mean time, the CRADA is extended for three more years (2007 - 2010). During this period we are aiming to optimize the physical and mechanical properties of high purity niobium to reduce the cost of SRF particle beam accelerator structures for CW and industrial applications.

In the following, the mechanical (yield strength, tensile strength, hardness and ductility) and physical properties (thermal conductivity–residual resistance ratio and DC critical magnetic field) of polycrystalline and single crystal high purity niobium are summarized.

PHYSICAL AND MECHANICAL PROPERTIES

Polycrystalline Niobium

Figures 1 to 4 show the average mechanical properties yield & tensile strengths, ductility and Vickers hardness of fully recrystallized high purity polycrystalline niobium samples as a function of annealing temperature. The first data point at 20 °C is for as received niobium samples, the 600 °C data point is for the niobium samples annealed at 600 °C for 10 hours, the 800 °C data point relates to the niobium annealed at 800 °C for 6 hours and the 1250 °C data point is for samples annealed at 1250 °C for 6 hours in the presence of Ti solid state getter. All the samples were annealed in an UHV furnace.

FIGURE 1. Yield strength of polycrystalline niobium as a function of annealing temperature

FIGURE 2. Tensile strength of polycrystalline niobium as a function of annealing temperature

FIGURE 3. Vickers hardness of polycrystalline niobium as a function of annealing temperature

FIGURE 4. Ductility of polycrystalline niobium as a function of annealing temperature

The residual resistance ratio (RRR) of the polycrystalline niobium was estimated from the measured thermal conductivity of the samples at 4.2 K with the well known conversion factor of 4 resulting from the Wiedmann-Franz law and is shown in Figure 5 as a function of annealing temperature.

FIGURE 5. RRR of polycrystalline niobium as a function of annealing temperature

Single Crystal Niobium

The mechanical properties of the single crystal niobium for pristine as received, BCPed (~ 200 microns removed) and heat treated with Ti solid state getter at 1250 °C for 3 hours conditions are shown in Figure 6. The figure also presents the Vickers hardness data of the samples. The yield strength of the pristine single crystal niobium is 9.8 KSI, the yield strength of BCP'ed sample reduces to 5.5 KSI and the yield strength of the heat treated sample further drops to 4.5 KSI. This drop in yield strength with BCP can be attributed to softening of the material from the absorbed hydrogen into niobium during the chemical etching. However, it is not clear why the yield strength further reduced with heat treatment at 1250 °C with Ti which can be expected to remove the dissolved hydrogen. It is likely that during the furnace cool down some of the hydrogen (pp of hydrogen in the furnace ~ 10^{-6} Torr) might have been reabsorbed into more energetically favorable sites. As can be expected the tensile strength also reduced in line with the drop in yield strength. The softening effect is also indicated by the reduced Vickers hardness from 85 for the pristine sample to 44 for the BCPed and heat treated samples.

FIGURE 6. Mechanical properties of single crystal niobium with various treatments

Thermal conductivity of polycrystalline (as received & heat treated), heat treated single crystal and two crystal niobium is shown in Figure 7. The phonon peak can be seen only for the annealed single crystal niobium sample due to the elimination of defects by heat treatment. As expected the polycrystalline, two crystal and polycrystalline heat treated niobium samples did not exhibit the phonon peak due to the grain boundaries and defects [11].

FIGURE 7. Thermal conductivity of polycrystalline and single crystal niobium

The most important physical property that has direct bearing on the performance characteristic of the SRF cavities is the critical magnetic field after the surface contamination issues are eliminated. RRCAT, India and JLab are presently investigating how the various treatments affects on the DC critical magnetic fields of polycrystalline and single crystal niobium with varying amounts of tantalum. The preliminary results indicate that at 2 K the pristine polycrystalline niobium's H_{c1} is ~ 180 mT while H_{c1} of the pristine single crystal niobium can be as high as ~ 240 mT. Chemical treatments appear to suppress the critical magnetic field considerably. Hydrogen is the only interstitial that is absorbed into niobium during chemical or heat treatments and may be responsible for the reduced critical magnetic fields. These results will be published in a peer reviewed journal in the very near future [12].

SUMMARY

This paper briefly summarizes the physical and mechanical properties of polycrystalline and single crystal SRF cavity grade niobium. Hydrogen is the main interstitial that changes with various treatments and it is expected to influence the performance of SRF cavities.

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