Qualification of non code material for Pressure vessels as per ASME code: A Review

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Abstract- *The Superconducting cavities used in particle accelerators require a material which shows low resistance at cryogenic temperature. High-purity niobium is the preferred material for the fabrication of superconducting accelerating cavities. The Superconducting cavities are a type of pressure vessel. In case of pressure vessels the material of construction should meet the exact specifications and metallurgical requirements as described in various codes. The material should provide a level of safety greater than or equal to that specified by the codes. In addition it should be free from flaws (foreign material inclusions or cracks and laminations) that can initiate a thermal breakdown. Since niobium is a non-code material. It is required to qualify the material before being used for the construction of the cavities. Problems with the certification of pressure vessels constructed partially or completely of niobium arise due to the fact that niobium is not listed as an acceptable vessel material in various pressure vessel codes. Within the ASME code, in particular, pure niobium is not approved for use in Division 1 or Division 2 vessels, and there are no mechanical properties available from code sources [2]. Thus, it is required to show a level of safety greater than or equal to that of the applicable standard for qualification of the material. The aim of the paper is to describe the work carried by various laboratories around the world for qualification of a non-code material.*

Keywords- Pure Niobium, Material qualification, ASME code, Qualification of non-code material. Testing of non-code material.

I. INTRODUCTION

The SCRF cavities are key component of Particle accelerators. The material used for the construction of SRF cavity is Niobium. Niobium possesses very intriguing physical and mechanical properties, not only the highest superconducting transition temperature (Tc) of 9.26°K and the highest superheating field among all available superconducting pure metals but also excellent ductility, which enables machining to be done relatively easily, From many years it is now been the preferred metal for the fabrication of superconducting RF cavities [1–8].

Niobium was introduced as material for superconducting accelerating cavities in 1967, replacing the lead-plated copper cavities, which had been used at High Energy Physics Lab (HEPL), Stanford University, Brookhaven National Lab (BNL) and CERN. Niobium and its alloys are the primary materials used to make high energy particle accelerator superconducting cavities and related components. Typically, the superconducting cavities have ultra-high vacuum inside and sub-atmospheric liquid helium (LHe) bath outside. Due to possible overpressure during a loss of vacuum incident, the niobium cavities are specified to withstand 5.0 atm external pressure. This work environment makes niobium cavities virtually pressure vessels. Design of superconducting cavities shall conform to the rules in ASME B&PV code Section VIII, Division 1 or 2. The nominal work temperature ranges from 1.8 K to 300 K.

II. LITERATURE REVIEW

T .J. Peterson et al. have summarized the use of niobium as a pressure vessel material, since the laboratories around the world are developing niobium superconducting radiofrequency (SRF) cavities for use in particle accelerators. These SRF cavities are typically cooled to low temperatures by direct contact with a liquid helium bath, resulting in at least part of the helium container being made from pure niobium. In U.S, the Code of Federal Regulations allows national laboratories to follow national consensus pressure vessel rules or use of alternative rules which provide a level of safety greater than or equal to that afforded by ASME Boiler and Pressure Vessel Code. Thus, while used for its superconducting properties, niobium ends up also being treated as a non-code material. The use of niobium as a pressure vessel material, with a focus on issues for compliance with pressure vessel codes and the result of a literature survey for mechanical properties and tests results, as well as a review of ASME pressure vessel code requirements and issues were discussed [2].

Ganapati Myneni et al. have observed the variation of mechanical properties of high RRR niobium with heat treatments at various temperatures and duration of heat treatment since they vary a lot from vendor to vendor and batch to batch. In addition, to the usual mechanical properties the Vickers hardness measurements on RRR niobium after various heat treatments ranging from 600 to 800 0C for different periods between 1 to 10 hours were discussed. The details of the sample preparation and mechanical properties measurement procedure were described. The effect of heat treatment time and temperature on the mechanical properties of three different batches of SNS prototype niobium WCL (RRR~400), high RRR niobium WC (RRR~400) and RRR niobium TD (RRR~300) were observed [3].

M. G. Rao et al. performed the testing of thermal and mechanical properties of electron beam welded and heat treated high RRR niobium. It was observed that the thermal and mechanical property of the niobium material has an effect on the design accelerating gradient of SRF cavities [4].

R.P Walsh et al. explained a materials test program to support the structural design and analysis of the Accelerator cavity assembly. The materials studied were high purity niobium, commercially pure niobium, commercially pure titanium, and autogenously welds of these three base metals. Tensile tests at 295, 77, and 4 K and fracture toughness tests at 4 K were performed to characterize the mechanical properties of the materials as a function of temperature. The tensile test results are used to evaluate the materials and as input for general design analysis. The fracture toughness test results (some of which represent first time measurements) are used to develop allowable flaw size criteria related to design and fabrication issues [5].

Gary G. Cheng et al. stated that materials used in the construction of a cryomodule typically include stainless steel and steel alloys, copper and copper alloys, aluminum and aluminum alloys, titanium, niobium, etc. Most of these materials are covered in ASME B&PV code Section II. However, niobium is not presently included. In this technical note, investigations on niobium applied in fabrication of Superconducting Radio Frequency (SRF) cavities are summarized with ASME B&PV code requirements for new material as the guideline. As one of the supporting documents for the ongoing project for cryomodule design; a technical note is aimed at recognizing accomplished niobium properties studies that are equivalent to ASME B&PV code rules [6].

G. Wu et al. performed the Mechanical testing of cavity grade niobium samples for the certification of superconducting radiofrequency cavities and cryomodules. Large changes in mechanical properties occurred throughout the cavity fabrication process due to the cold work introduced by forming, the heating introduced by electron beam welding, and the recovery of cold work during the annealing used to degas hydrogen after chemical processing. Data was provided to show the different properties at various stages of fabrication, including both weld regions and samples from the bulk niobium far away from the weld [7].

Karl T. Hartwig et al. stated that the mechanical properties of commercial pure niobium sheet used for superconducting radiofrequency cavities are known to provide inconsistent yield, spring back and surface smoothness characteristics when plastically formed into a radiofrequency cavity. These inconsistent properties lead to significant variations in cavity geometry and thus superconducting cavity performance. One approach to reduce these problems is to refine the microstructure so that its properties are more uniform. The material was rolled to 4 mm thick sheet and recrystallized. Measurements of hardness, spring back, texture, and micro structural uniformity were reported and compared to those of commercial RRR Grade Nb sheet [8].

M.G.Rao et al. carried out a detailed investigation of the mechanical properties of the high RRR niobium. The mechanical properties, yield strength, ultimate tensile strength and percent of elongation of Nb are routinely measured in the temperature range 300 K to 4.2 K as a quality assurance measure. The mechanical properties of high purity niobium from Fansteel and Teledyne are presented as a function of temperature between 300 K and 4.2 K. It was found that the yield and tensile properties improve with a decrease in temperature. However, a dip in the elongation versus temperature curve was observed at about 100 K [9].

H. Jiang et al. estimated the effects of Electron Beam Welding on microstructure, texture; micro hardness and mechanical properties in high purity Niobium weld specimens. The welds have an equiaxied microstructure with a 1 mm grain size in the fusion zone, 100 μm in the heat affected zone (HAZ) and 50 μm in the parent metal. The fusion zone had slightly higher micro hardness values despite having a large grain size, while the unaffected material had the lowest micro hardness. Tensile tests of specimens were carried out; the properties and microstructure of the weld were discussed in terms of optimizing the SRF cavity [10].

K. Ishio et al. discussed the results of fracture toughness and mechanical tests of pure niobium (RRR200) plates (3-mm-thick) welded joints for superconducting cavities at 4 K. Several mechanical properties of pure niobium (Nb) at low temperatures have been investigated. But, fracture toughness data that enable the quantitative evaluation of the fracture behavior under the presence of a flaw are not available. The detailed results of fracture toughness tests at the liquid helium temperature of 4 K and microscopic analysis were described, including the summary of the basic tensile and impact test results [11].

G. Myneni optimized mechanical and physical properties of high purity niobium are crucial for obtaining high performance SRF particle beam accelerator structures consistently. He summarizes these important material properties for both high purity polycrystalline and single crystal niobium [12].

G. Ciovati et al. observed that the mechanical stability of bulk niobium cavity is an important aspect to be considered in relation to cavity material, geometry and treatments. Mechanical properties of niobium are typically obtained from uniaxial tensile tests of small samples. The experimental results indicate that the yield strength of medium-purity ingot niobium cavities is higher than that of fine-grain, high purity niobium [13].

Defa Li et al. investigated the effect of tempering temperature on microstructures and mechanical properties of niobium and titanium. The results indicate that the mechanical properties change is mainly controlled by the structure evolution, and as the structure evolution during tempering is complex, the mechanical properties do not monotonously increase or decrease with the increasing of tempering temperature [14].

W. Singer discussed the technological and metallurgical requirements of material for high-gradient superconducting cavities. High-purity niobium, as the preferred metal for the fabrication of superconducting accelerating cavities, should meet exact specifications. The material should be free of flaws (foreign material inclusions or cracks and laminations) that can initiate a thermal breakdown. Traditional and alternative cavity mechanical fabrication methods are reviewed. Conventionally, niobium cavities are fabricated from sheet niobium by the formation of half-cells by deep drawing, followed by trim machining and electron beam welding. The welding of half-cells is a delicate procedure, requiring intermediate cleaning steps and a careful choice of weld parameters to achieve full penetration of the joints. A challenge for a welded construction is the tight mechanical and electrical tolerances. The cavity fabrication approach is slicing discs from the ingot and producing cavities by deep drawing and electron beam welding. High accelerating gradients can be achieved by applying electrochemical polishing treatment [15].

III. CONCLUSION

The pressure systems are required to be designed in conformity as per the American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel Code , ASME B31 (code for pressure piping) standards, other applicable state and local codes. But when the codes are not applicable, the contractors must implement measures to provide equivalent protection and ensure a level of safety greater than or equal to the level of protection afforded by the ASME or applicable state or local code. The investigation on niobium applied in fabrication of Superconducting Radio Frequency (SRF) cavities are summarized with various code requirements for new material. The aim is to accomplished niobium properties equivalent to ASME B&PV code rules.

According to ASTM B393-05, the RRR grade pure niobium is specifically used in superconducting applications that require ultra-high purity. The materials shall be made from ASTM B391-03 ingots produced by vacuum or plasma arc welding, vacuum electron-beam melting, or a combination of these three methods. Mechanical and chemical requirements, permissible variations in dimensions and weight, quality and surface finish, mechanical/chemical tests, inspection, certification, etc. are described in details in the B393-05 specification. Tension tests that the material suppliers shall perform are described in ASTM E8/E8M-08 “Standard Test Methods for Tension Testing of Metallic Materials” [16]. Specification ASTM B392-03 “Standard Specification for Niobium and Niobium Alloy Bar, Rod, and Wire” [17] covers niobium rods and bars that are occasionally used to make parts in cryomodule assembly.

Mechanical, thermal, and physical properties of niobium from room to cryogenic temperatures have been investigated in the past [2-15] for various superconducting accelerator projects: CEBAF, SNS, TESLA, ILC, RIA, etc. None of the experimental work was targeted at certifying niobium as a new material to be incorporated by ASME B&PV code. However, nearly all the properties required by ASME B&PV code were reported at various temperatures for satisfying niobium as a material for pressure vessel.

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