Use of Niobium as a Pressure Vessel Material: A Review

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Abstract: The SCRF cavities are key components used in accelerators for accelerating the charge particles. The SCRF cavities are made of high purity niobium and welded by electron beam welding. The SCRF cavity falls under the category of external pressure vessels. The welded joints of pressure vessels need to qualify the criteria as specified in the applicable codes before being used in the required application. This paper contains the findings of the work carried out in various laboratories on the study of weld joints in the SCRF cavities. This covers the details of work done in order to qualify a non-code material (niobium) as a pressure vessel material. It also discusses the details of testing done for satisfying the level of safety established for the SCRF cavity using a non-code material.

1. Introduction

The material (niobium) of construction of the SCRF cavity is not listed in the ASME code Section II, Subsection I. It requires special condition to qualify as per ASME Section VIII, U-2(g). For such cases, the examination of the weld sample for each joint is required. The SCRF cavities operate at cryogenic temperature of 2K. Cavities containing cryogens pose a potential pressure hazard as they may be subjected to high external pressure arising during accidental condition of vacuum leak, heat leaking, etc. Pressure vessel such as SRF cavities fall within the scope of the ASME Boiler and Pressure Vessel code.

These cavities are made of high purity niobium. However, niobium is used for its superconductivity but it is a non-code material (non-listed material), as per ASME Section II, Part D [1]. The cavity design that satisfies a level of safety, equivalent to that of a pressure vessel code is affected by the use of non-code material (niobium). For such cases, alternative procedures and measures have been established to assure a level of safety equivalent to that afforded by ASME code [2].

2. Literature review

A. Use of niobium as a pressure vessel material

T.J. Peterson et al. have summarized the use of niobium as a pressure vessel material. The pressure vessel should 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 material for pressure vessels. The use of niobium as a pressure vessel material, with a focus on issues for compliance with pressure vessel codes was discussed [3].

C. Astefanous et al. used the 2007 ASME Boiler and Pressure Vessel Code Section VIII, Division 2 to satisfy the DOE pressure safety requirements for a non-code specified material (niobium) pressure vessel. The design criteria of Div. 2 depend in part on the other criteria for materials, fabrication, inspection, and testing. Through the use of Div. 2 requirements and proper engineering judgments provides an equivalent level of safety as per the ASME Boiler and Pressure Vessel Code. The fabrication process and welding qualifications required for the welded niobium material used in the SCRF cavity is discussed. They also successfully developed a frame work required to qualify niobium as per the ASME Boiler and Pressure Vessel Code [5].

Gary G. Cheng et al. discussed the different 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. The investigations of niobium properties with different mechanical testing are carried out with reference to ASME B&PV code. The requirements for qualification of a non-code material (niobium) are also discussed for comparing it with accomplished
niobium properties that are equivalent to ASME B&PV code rules [7].

**B. Effect of EB welding on mechanical properties**

Ganapati Myneni et al. have observed the variation of mechanical properties of high RRR niobium with heat treatments at various temperatures. In addition, the details of the sample preparation and mechanical properties measurement procedure for testing of welded samples 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.

M. Pirinen et al. carried out the experiments to determine the properties of the welded joints for determining the yield strength, elongation and other mechanical properties of an 8 mm thick high-strength steels produced by quenching and tempering and thermo mechanical rolling with accelerated cooling. The dependence of the strength, elongation, hardness, impact energy and crack opening displacement on the heat affected zone was determined. The results show that the dependence of the strength of the welded joints decreases and that of the elongation increases. The heat input has only a slight effect on the impact energy and crack opening displacement in the heat-affected zone. They concluded that the weld strength of the material is more than that of the parent material [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 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 and 4.2 K. It was observed that the yield and tensile properties improve with a decrease in temperature. However, a dip in the elongation versus temperature curve is observed at about 100 K [10].

H. Jiang et al. estimated the effects of electron beam welding on different structural and mechanical properties in high purity Niobium weld specimens. The welds have an equiaxed 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 [11].

**C. Mechanical testing of EB welded niobium joints**

T.J. Peterson et al. have also reported that the ultimate and yield strength for niobium are extremely variable, depending on various steps of forming, welding, and heat treating. The result for analysis of pressure vessels made from niobium as treated for RF cavities has been to use a very low, conservative yield stress estimate of 38 MPa, an ultimate strength of 130 MPa, and an ASME allowable room temperature stress of 25 MPa. They conclude that a low temperature allowable stress of 171 MPa is a very conservative and reasonable value for vessel analysis as shown in figure 2.4 [3].

C. Lusch et al. performed the qualification of welded joints between copper and stainless steel which are commonly applied in cryogenic systems. The electron beam welding is used to combine these materials. The welds need to withstand a temperature range from 300 K down to 4 K, and pressures of several MPa. They conducted a test program in order to qualify the weld joints. The experiments started with the measurement of the hardness in the weld area. To verify the leak-tightness of the joints, integral helium leak tests at operating pressures were carried out at room and at liquid nitrogen temperature. The tests were followed by destructive tensile tests at room temperature, at liquid nitrogen and at liquid helium temperatures, yielding information on the yield strength and the ultimate tensile strength of the welds at these temperatures. Moreover, nondestructive tensile tests up to the yield strength, i.e. the range in which the weld can be stressed during operation, were performed. Also, the behavior of the weld upon temperature fluctuations between room and liquid nitrogen temperature was tested. The results of the qualification indicate that EB welded joints between OFHC copper and 316L stainless steel are reliable [4].

G. Wu et al. performed the Mechanical testing of cavity grade niobium samples for the certification of superconducting radio frequency cavities and cryomodules. Large changes in mechanical properties were observed 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. The testing of welded niobium samples for determining different properties at various stages of fabrication is done as shown in figure 2.5 [9].
K. Ishio et al. discussed the results of mechanical testing carried out on pure niobium (RRR200) plates (3 mm thick) welded joints for superconducting cavities at operating conditions. Several mechanical properties of pure niobium (Nb) at low temperatures have been investigated. The mechanical properties, 0.2 % yield strength (YS), ultimate tensile strength (UTS) and elongation were measured at 4 K, 77 K and room temperature (RT). The detailed results of various tests at the liquid helium temperature of 4 K, including the summary of the basic tensile and impact test results is described as shown in figure 2.6 [12].

R.P Walsh et al. performed the material testing to support the structural design and analysis of the Accelerator cavity assembly. The material studied was high purity niobium, commercially pure niobium, commercially pure titanium, and autogenous welds of these three base metals. Various mechanical tests including tensile test at temperatures 295, 77, and 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. This study also explains about the variation in mechanical properties of the material when heated and welded [13].

3. Conclusion

The literature presents the details of review of the study carried out on the weld joints and also describes the work done in various laboratories on the testing of electron beam weld joints of the SCRF cavities. The study involving the testing and procedure required for qualification of a material as per ASME code, along with the test results and effect of EB welding on the mechanical properties. Niobium is a non-code material as per ASME code. Using a non-code material affects the safety criteria established by the ASME code for listed pressure vessel materials. In the present study, niobium is used for the construction of SCRF cavity. So it is required to qualify the non-code material in order to satisfy the safety criteria specified by ASME before being used for the required application.

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5. References
