LOW TEMPERATURE MECHANICAL PROPERTIES OF TITANIUM AND WELD JOINTS (Ti/Ti, Ti/Nb) FOR HELIUM VESSELS

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Abstract

The joint project for high-intensity proton accelerators in KEK and JAERI has been proposed with the superconducting (SC) proton linac. Mechanical properties of commercially pure titanium (Ti) and weld (EB (Electron Beam) and TIG) joints were tested at 4 K in order to verify a possibility of usage of titanium to a helium vessel material of a 400-600 MeV SC linac. Tensile tests, Charpy impact tests, bending tests and fracture toughness tests were conducted at room temperature (RT), 77 K and 4 K mainly for the JIS Class 2 commercially pure titanium (0.1 - 0.12% oxygen) and weld joints (Ti/Ti, Ti/Nb (niobium)). Typical data of the fracture toughness at 4 K were 66 MPa·m$^{1/2}$ (KIC(J)) for JIS Class2 Ti base metal, 210 MPa·m$^{1/2}$ (KQ(J)) for Ti/Ti EB weld and 87 MPa·m$^{1/2}$ (KIC(J)) for Ti/Nb EB weld.

1 INTRODUCTION

Superconducting cavities are usually made using commercially available high purity niobium. Titanium is a desirable candidate for the material for liquid helium vessels, because Ti and Nb have almost same thermal expansion coefficients, and negligible thermal stresses may be caused during a cooldown, and because of the good weldability of Ti/Nb. However, very little has been reported about mechanical properties of pure titanium and Ti/Nb welded joints at cryogenic temperatures [1]. Therefore mechanical properties of commercially pure titanium (Ti) and weld (Electron Beam (EB) and TIG) joints were tested at 4 K in order to verify a possibility of usage of titanium to a helium vessel material. Especially, low temperature fracture toughness data that enable the design based on the fracture mechanics were obtained.

2 MATERIALS

For this investigation, commercially pure titanium (JIS Class 1 and JIS Class 2) from Kobe Steel, LTD and high purity niobium with residual resistivity ratios RRR ≥ 200 from Tokyo Denkai LTD were prepared.

2.1 Base Metal Test

Table 1 shows the impurity levels of the materials used for base metal tests. These Ti materials were forged and rolled at 850 ºC, then annealed at 700 ºC.

Table 1: Materials for base metal tests (μg/g)

Material \ Element	O	N	H	Fe
Titanium JIS Class 1	330	20	28	270
Titanium JIS Class 2	1200	40	59	510

2.2 Weld Joint Test

Table 2 shows the impurity levels of the materials used for weld tests. Weld butt joints for the tests were fabricated using 5 mm-thick materials by EBW and TIG. Only Ti/Nb welded joints were heated up to 750 ºC for 3 hrs.

Table 2: Materials for weld tests (μg/g)

Material \ Element	O	N	H	Fe
Titanium JIS Class 2	1000	100	30	600
Niobium (RRR>200)	14	9	4	
Filler metal for TIG (Titanium JIS Class 1)	700	100	10	300

3 TEST PROCEDURES

3.1 Tensile Test

Tensile tests were conducted according to Japanese Industrial Standards (JIS) Z2241 (method) and Z2201 (Test pieces) at RT, 77 K and 4 K.

3.2 Charpy Impact Test

Charpy impact tests were conducted according to JIS Z2242 (method) and Z2202 (Test pieces) at RT, 77 K and 4 K.

3.3 Fracture Toughness Test

Fracture toughness tests were conducted according to JIS Z2284 (Method of elastic-plastic fracture toughness J_{IC} testing for metallic materials in liquid helium) at 77 K and 4 K.

Ti and Nb are so soft at RT that fatigue pre-cracks were initiated in liquid nitrogen in order to enable the test results valid.

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Figure 2 ~ figure 4 show a fracture toughness specimen (1/2 CT), a schematic drawing of a test apparatus and photos of test equipments. Since the specimen sizes are small and might exhibit elastic-plastic behaviour, J_{IC} tests were conducted. These J_{IC} values were converted to $K_{IC}(J)$ using the following equation.

$$K_{IC}(J)=\left\{\frac{J_{IC}E}{(1-\nu^2)}\right\}^{1/2} \qquad (1)$$

Where, E : Young's modulus, ν : Poisson's ratio.

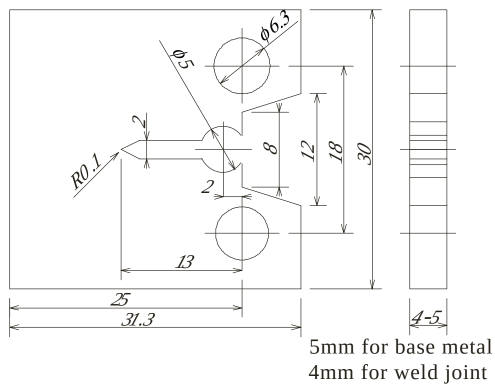

Figure 2: Fracture toughness specimen (1/2 CT)..

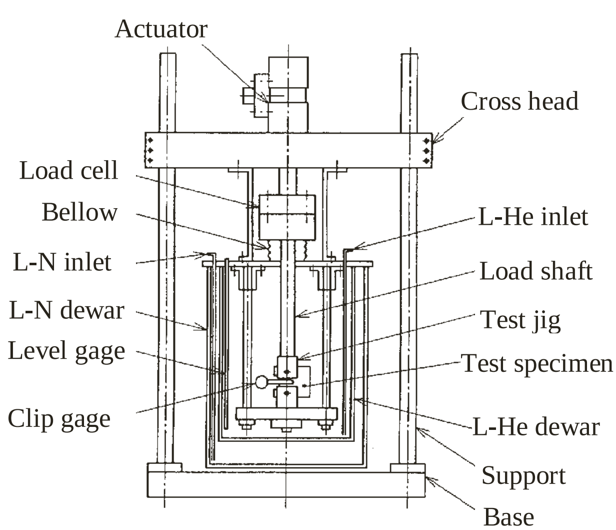

Figure 3: Schematic drawing of a test apparatus. (JIS Z2284)

Fatigue pre-crack at 77 K   Fracture toughness test at 4 K

Figure 4: Test apparatus.

4 RESULTS AND DISCUSSION

4.1 Tensile Test

Mechanical properties, 0.2% yield strength (YS) and ultimate tensile strength (TS) of Ti base metal and weld joints were measured at 4 K, 77 K and RT. Figure 4 and figure 5 summarize the tensile strength properties as a function of temperature. Figure 6 summarizes the yield strength properties. In case of Ti/Nb joints, rupture positions were located at Nb base metal potions, showing the stronger Ti/Nb weld bead in comparison with the Nb base metal. These strengths increase greatly at cryogenic temperatures. The Ti/Ti weld strengths are approximately the same as JIS class 1 Ti or class 2 Ti. The Ti/Nb weld tensile strengths (ruptured at Nb base metal) are approximately the same as JIS class 1 Ti, and yield strengths same as JIS class 2 Ti at cryogenic temperatures, but softer at RT. These tendencies of Ti base metal and Ti/Ti weld are almost similar to previously reported LANL data [1].

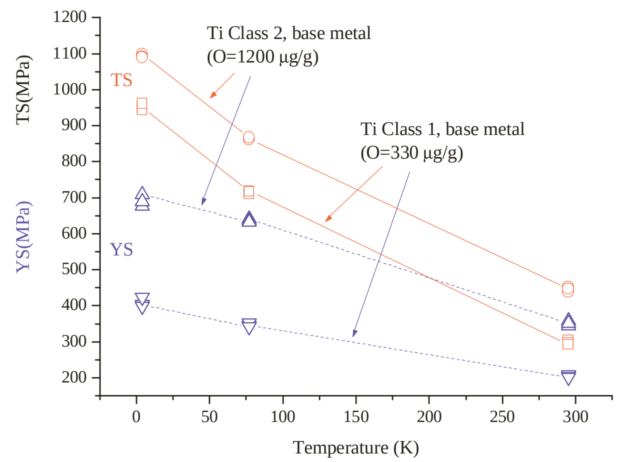

Figure 4: Tensile and yield strength versus temperature of Ti base metal (Class 1, Class 2).

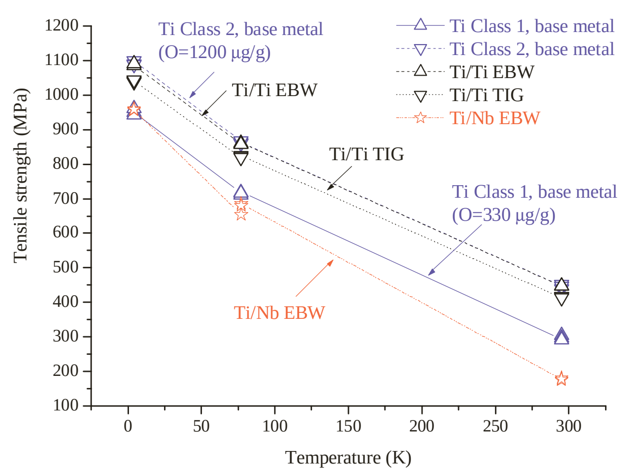

Figure 5: Tensile strength versus temperature of Ti base metal (Class 1, Class 2) and weld joints (Ti/Ti EBW, Ti/Ti TIG, Ti/Nb EBW (ruptured at Nb base metal)).

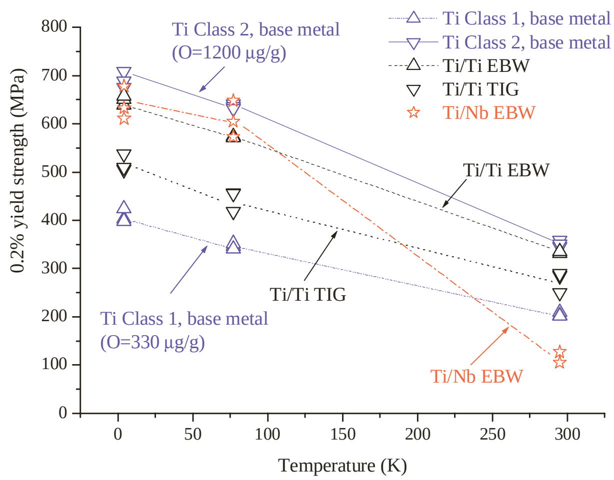

Figure 6: Yield strength versus temperature of Ti base metal (Class 1, Class 2) and weld joints (Ti/Ti EBW, Ti/Ti TIG, Ti/Nb EBW (ruptured at Nb base metal)).

4.2 Charpy Impact Test

The results of V-notch Charpy impact tests at 4 K, 77 K and RT are summarized in figure 7. The thickness for base metal is 10 mm, for weld joints 4 mm. The data of weld joints are 2.5 times multiplied and converted to 10 mm thickness. No indications of brittleness of Ti/Ti and Ti/Nb welds are observed. All the data of welds are greater than those of JIS class 2 Ti.

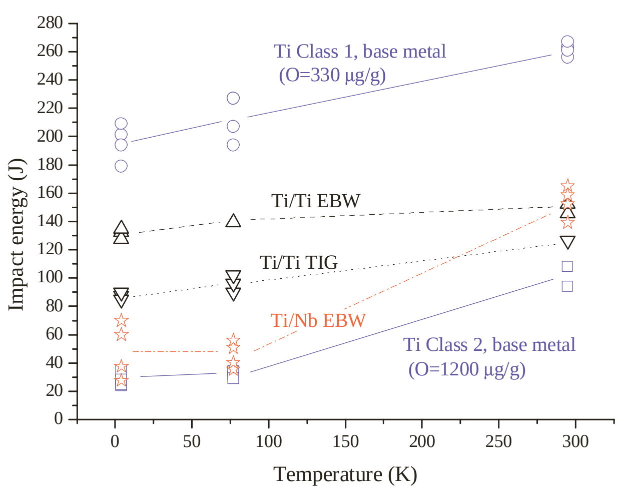

Figure 7: Charpy impact energy versus temperature of Ti base metal (Class 1, Class 2) and weld joints (Ti/Ti EBW, Ti/Ti TIG, Ti/Nb EBW).

4.3 Fracture Toughness Test

Table 2 shows the results of elastic-plastic fracture toughness tests of Ti base metal (Class 2) and weld joints (Ti/Ti EBW, Ti/Ti TIG, Ti/Nb EBW). Figure 8 shows the fractured appearances. In case of Ti/Nb weld joints, effective yield strengths at cryogenic temperatures were so high and difficult to be measured that (ruptured at Nb base metal in tensile tests) Ti-50Nb alloy data [2] was used. Fracture toughness data of Ti base metal are almost similar to previously reported data [1]. But, the Ti/Ti weld data are much greater (almost double). The Ti/Nb weld data 87 MPa·m$^{1/2}$ is considerably large in comparison with Nb base metal of 46 MPa·m$^{1/2}$ and Nb/Nb welds of 34 MPa·m$^{1/2}$ [3].

Table 2: Summary of fracture toughness tests.

Material	Temperature (K)	JIC (kN/m)	KIC(J) (MPam$^{0.5}$)	Av. KIC(J) (MPam$^{0.5}$)
Ti Base metal	4	27	64	66
Class 2	4	29	67	
O : 1200 mg/g	4	30	68	
N : 40 mg/g	77	65	100	100
	77	65	100	
	77	67	101	
Ti/Ti EBW	4	J_Q: 384	K_QJ: 215	K_QJ: 210
Class 2	4	J_Q: 358	K_QJ: 207	
O : 1000 mg/g	4	J_Q: 361	K_QJ: 208	
N : 100 mg/g	77	J_Q: 451	K_QJ: 233	K_QJ: 221
	77	J_Q: 441	K_QJ: 230	
	77	J_Q: 332	K_QJ: 200	
Ti/Ti TIG	4	J_Q: 368	K_QJ: 216	K_QJ: 205
Class 2	4	J_Q: 301	K_QJ: 196	
O : 1000 mg/g	4	J_Q: 326	K_QJ: 203	
N : 100 mg/g	77	J_Q: 429	K_QJ: 227	K_QJ: 246
	77	J_Q: 454	K_QJ: 233	
	77	J_Q: 646	K_QJ: 278	
Ti/Nb EBW	4	58	87	87
Class 2	4	54	84	
O : 1000 mg/g	4	61	90	
N : 100 mg/g	77	79	95	107
	77	106	111	
Nb RRR>200	77	113	114	

J_Q : judged to be invalid JIC test. They can be used only for the plates under the thickness of 4 mm.

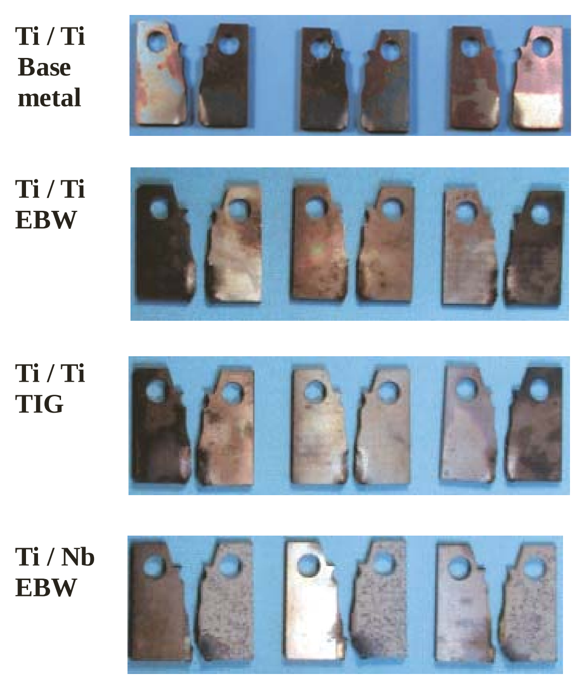

Figure 8: Fractured test specimens of Ti base metal (Class 2) and weld joints (Ti/Ti EBW, Ti/Ti TIG, Ti/Nb EBW).

Figure 9 and figure 10 show the typical load and load-line displacement and J integral and crack propagation of Ti base metal Class 2, respectively.

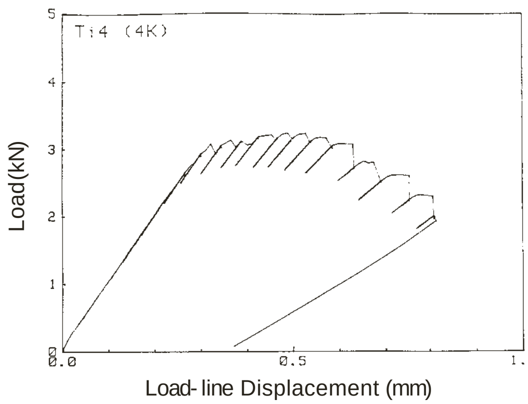

Figure 9: Typical load and load-line displacement. (Ti base metal Class 2)

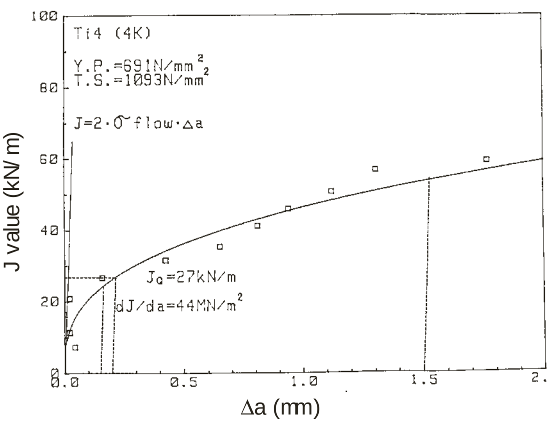

Figure 10: Typical J integral and crack propagation. (Ti base metal Class 2)

4.4 Bending Test

Bending tests of butt joints of Ti/Ti EB & TIG welded and Ti/Nb EB welded were conducted. All the weld qualities were good, and no surface crack of the weld beads was observed.

5 ACKNOWLEDGEMENT

We would like to thank Dr. A. Kiuchi of KOBELCO Research Institute, Inc for his cooperation in mechanical tests and discussions.

6 CONCLUSIONS

Basic mechanical properties (Tensile test, Charpy impact test, Bending test) of JIS Class2 Ti base metal and weld joints (Ti/Ti, Ti/Nb) were tested at RT, 77 K and 4K and will be used for structural designs.

Typical data of the fracture toughness at 4 K were 66 MPa·$m^{1/2}$ (KIC(J)) for Ti base metal, 210 MPa·$m^{1/2}$ (KQ(J)) for Ti/Ti EB weld and 87 MPa·$m^{1/2}$ (KIC(J)) for Ti/Nb EB weld. These data provide the information needed to assess structural reliability on the basis of fracture mechanics procedures at cryogenic temperatures.

7 REFERENCES

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