

Mechanical Characteristics of Austenitic Stainless Steel 316LN Weldments at Cryogenic Temperature

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1. Introduction

Austenitic stainless steel 316LN has been used for structural material of fusion device as commercial grade due to its excellent physical and mechanical properties at cryogenic temperature. Korea Superconducting Tokamak Advanced Research (KSTAR) also has chosen this grade for magnet support structure. Magnet structure should be designed and manufactured with heavy and thick weld section to endure operating high magnetic force. Thus weld properties are very important to ensure the structural soundness. The design criteria of the KSTAR magnet structure follow as[1];

- (1) Yield strength (σ_{YS}) : more than 750 MPa for base metal and 90% of base metal for weld metal.
- (2) Fracture toughness (K_{IC}) : more than 150 MPa $m^{1/2}$ for base metal and 130 MPa $m^{1/2}$ for weld metal.

The applied welding processes are GTAW(Gas Tungsten Arc Welding) and EBW(Electron Beam Welding), which are good welding for parts with thick section. In this study, mechanical tests are performed for verifying and qualifying weld properties for two weld methods including base metal.

2. Experiments

2.1 Material and Test Specimen

Table 1 shows the chemical composition for base metal and weld filler metal. Base metal has nitrogen of 0.13 wt% and carbon less than 0.03 wt%. The filler metal has higher carbon, manganese, nickel content than base metal for good weldability and low magnetic permeability. Especially, nickel content has been known as element which stabilizes austenitic stability and increase toughness at low temperature[2].

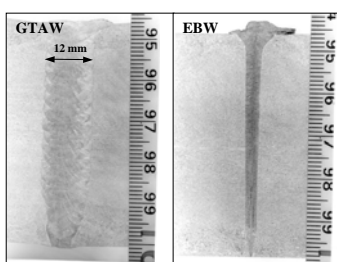


Figure 1. The cross-section of GTA weld(left), EB weld(right)

Table 1. Chemical composition of base metal and filler metal

Material	C	Mn	Si	Ni	Cr	Mo	N
Base	0.022	1.14	0.69	10.1	17.7	2.01	0.13
Filler	0.06	6.5	0.34	16.5	17.6	2.3	-

Auto GTA weld and EB welds are prepared by 55 mm thickness of 316LN plate. Figure 1 shows the cross section of welds. The width of each weld metal is very small about 12 mm and 3 mm, respectively.

2.2 Test Method

Tensile test is performed at room temperature, liquid nitrogen, and liquid helium by using ASTM E1450-92. Unfortunately, there is no standard for elastic-plastic fracture toughness test at cryogenic temperature. So ASTM E813 has been used at cryogenic temperature. Especially, unloading compliance method using single specimen technique is used for cost effectiveness rather than multi-specimen technique.

3. Results and Discussion

3.1 Tensile Test

Stress versus strain curves of three type specimens at 4 K are shown in Figure 2. All of them displayed the conventional serration resulting in pop-ins due to adiabatic heating during plastic deformation[3]. Also both base and EB weld specimen experience small strain hardening after uniform deformation due to martensite transformation at low temperature. It's well known that this transformation will increase the strength and decrease the fracture toughness[4].

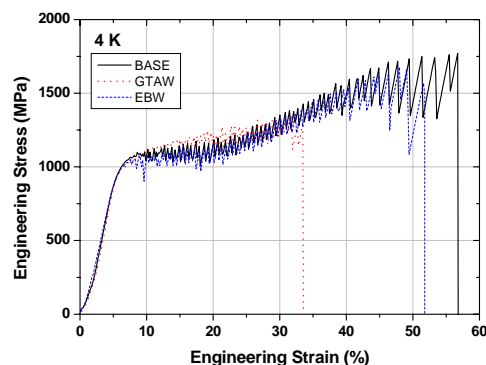


Figure 2. Engineering stress and strain curve at 4 K

The tensile test results of the base and two welded joints are summarized in Table 2. All tensile properties depend on temperature strongly. Here yield strength, elongation, and reduction of area for weld metals can't be directly compared by base metal because weld specimen includes HAZ(Heat Affected Zone) which is weakest part in weld. Temperature dependence of yield strength and ultimate strength is shown in Figure 3. One can see that GTA weld with HAZ has lower ultimate strength as discussed before.

Table 2. Tensile properties of base and weld metal

Material	Temp. K	σ_{YS} (MPa)	σ_{UTS} (MPa)	$\delta(\%)$	RA(%)
Base	293K	329	653	59.3	79.6
	77K	726	1532	52.2	61.8
	4.2K	862	1759	50.8	59.9
Weld (GTAW)	293K	430	549.2	20.7	73.1
	77K	713	1086	32.6	55.3
	4.2K	885	1308	28.1	45.1
Weld (EBW)	293K	328	619	34.3	81.9
	77K	755	1506	50.7	60.7
	4.2K	994	1718	43.4	44.6

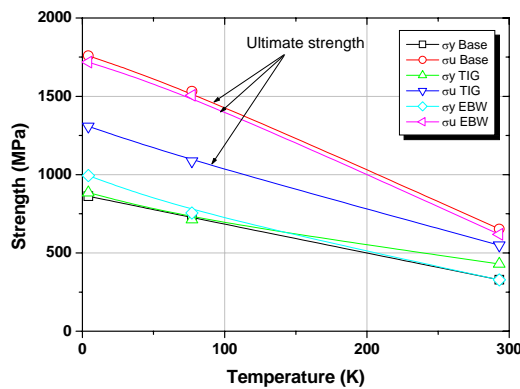


Figure 3. Yield and tensile strengths as a function of temperature for 316LN base and weld metals

3.2 Fracture Toughness Test

Figure 4 shows the effect of decreasing temperature on critical J-integral, J_Q for base and two welds. Fracture toughness decrease linearly from 293 K to 4 K. Results show a peculiarity that GTA weld indicates the highest toughness at low temperature. Reed et al.[2] showed that there is strong dependence of fracture toughness on nickel content. Thus, it is thought that main reason for higher toughness of GTA weld comes from the fact that filler metal contains more nickel than base.

Figure 5 shows the reverse relation of fracture toughness and yield strength for results with various nickel contents. Material containing low nickel like that in this study is less than $200 \text{ MPa m}^{1/2}$. These values located below NIST trend-line of stainless steel 316. Materials with higher nickel content show the fracture toughness of about $400 \text{ MPa m}^{1/2}$. However, tested results are satisfying KSTAR design criteria.

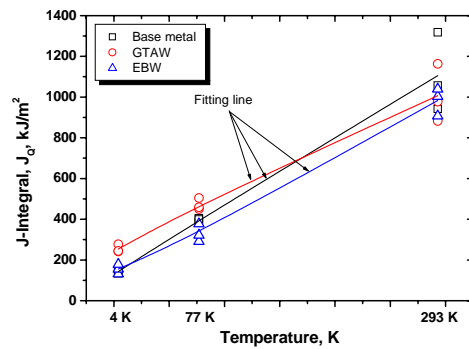


Figure 4. Fracture toughness as a function of temperature

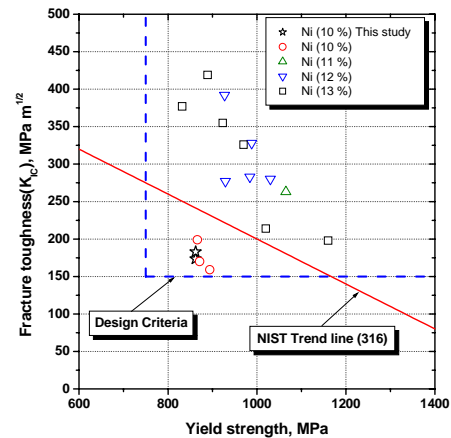


Figure 5. Relation of fracture toughness and yield strength[5]

4. Conclusion

Mechanical tests are carried out from room temperature to cryogenic temperature for weld qualification of stainless steel 316LN for KSTAR magnet structure. The yield strength and fracture toughness of base metal, auto GTA weld, and EB weld satisfy the structural design criteria. Especially, GTA weld has good toughness due to high nickel content.

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