Fatigue Properties Of Modified 316LN Stainless Steel At 4 K For High Field Cable-In-Conduit Applications

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ABSTRACT

Cable-In-Conduit-Conductor (CICC) alloys, exposed to Nb3Sn reaction heat-treatments, such as modified 316LN require a design specific database. A lack of fatigue life data (S-n curves) that could be applied in the design of the ITER CS and the NHMFL Series Connected Hybrid magnets is the impetus for the research presented here. Tension-tension load control axial fatigue tests have good applicability to CICC solenoid magnet design, thus a series of 4 K strength versus fatigue life curves have been generated. The more than 30 fatigue tests show good grouping on the fatigue life curve and allow discretionary 4 K fatigue life predictions for conduit made with modified 316LN.

MATERIAL

Table 1 below shows the chemical composition of 316LN compared with the tested modified 316LN. The round tube is shaped into rectangular (13.8 mm x 16.2 mm x 1.6 mm wall) conduit using the NHMFL shaping mill. The shaping introduces 16 to 20% cold as estimated from room temperature yield and tensile strength measurements. In-situ samples of modified 316LN base metal, seam welded, butt welded and seam plus butt welded are removed directly from the conduit.

TABLE 1. Chemical Composition (Weight %)

Alloy	C	N	Mn	Si	Cr	Ni	Mo	Fe
316 LN	0.03	0.1	2	1	16-18	10-14	2-4	Bal
Mod. 316 LN	0.01	0.15	1.58	0.36	17.6	13.1	2.2	Bal

Samples were then removed from the conduit and exposed to an abbreviated Nb3Sn reaction heat treatment (650°C for 48 hours in an argon atmosphere). Later samples such as the seam/butt welded and butt welded samples were exposed to a more conventional heat treatment: 210°C for 48 hours, 400°C for 48 hours followed by 640°C for 50 hours. Additional samples were heat treated at 650°C for 65 hours. Figure 1 shows specimen configuration.

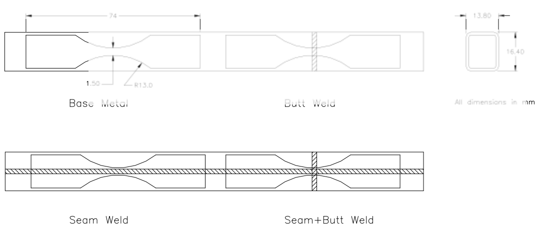

FIGURE 1. Specimen Configurations

TEST PROCEDURE

Fatigue tests are conducted according to the guidelines given in ASTM E 466. All testing is done with a 100 kN capacity servo-hydraulic MTS test machine equipped with a cryostat. The fatigue specimens used have a constant radius geometry test section as shown in Figures 2. Testing was performed at either 5 Hz or 20 Hz in force control with a load ratio R = 0.1. The nominal elastic strain rate in the 5 Hz and 20 Hz tests are 6x10-2 strain/sec and 2.4x10-1 strain/sec respectively.

A one-inch clip-on extensometer was used to record strain allowing confirmation of the previously published yield strength (1200 MPa). A ring gage recorded lateral displacement on several samples to record elastic-plastic behavior of the metal through it's cycle life.

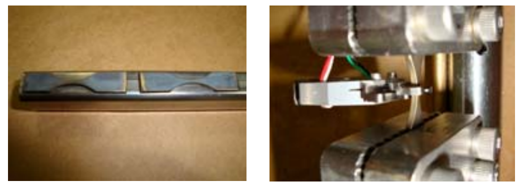

FIGURE 2. Specimen removed from conduit (left) and in test fixture with ring gage attached. (right).

RESULTS AND DISCUSSION

Typical fatigue requirements for CICC magnets place factors of safety of 20 times on the service-life number of cycles or 2 times on the maximum service stress, which ever is more conservative. Here we evaluate the material performance based on design requirements of a service-life of 20,000 cycles and a maximum applied stress of 400 MPa. Based on previous tensile testing, the 4 K yield strength values of modified 316LN stainless steel after heat treatment were about 1200 MPa or base metal and 1120 MPa for the seam welded metals. Figure 3 shows a comparison of stress-strain curves from fatigue tests of two tensile samples for the first ten cycles during cyclic loading with the same conditions (both base metals).

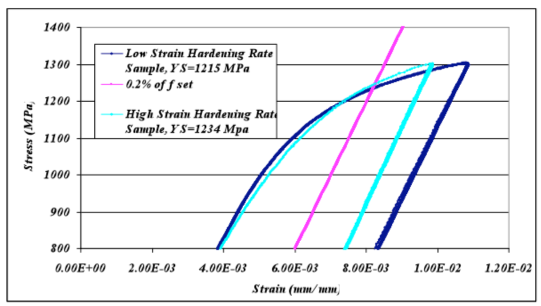

FIGURE 3. Stress-strain curves in the first ten cycles of loading.

Even when the maximum stress (1300 MPa) is higher than the yield stress, the stress-strain curves show almost no plastic deformation after the first cycle. At maximum stress (1300 MPa) and R =0.1 in load-control fatigue tests, the sample with high strain hardening rate shows higher yield stress and low maximum strain.

Figure 4 shows a strain vs. cycles curve for both a base and seam weld. Typically, it can be seen that the maximum strain and minimum strains remain constant after the first 1000 cycles. This indicates that the sample length is stabilized for a large number of cycles after 1000 cycles. Such an observation indicates that the deformation occurs by dislocation slip without changing the sample geometry.

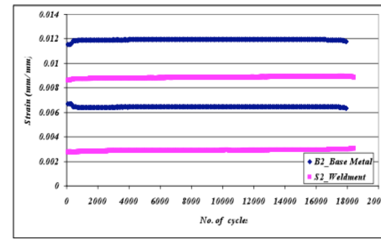

FIGURE 4. Strain vs. No. of cycles

The fatigue test results are summarized by an S-n graph in Figure 5. The data appears to show that the base metal and seam weld metal have slightly longer fatigue life than the butt weld and seam+butt weld. The experiments were conducted by two different frequencies (5 Hz and 20 Hz). At the start of the program, 5 Hz was used for Butt Weld and Seam + Butt Weld samples. The slower rate may yield more conservative results since flow stress is strain rate dependant.

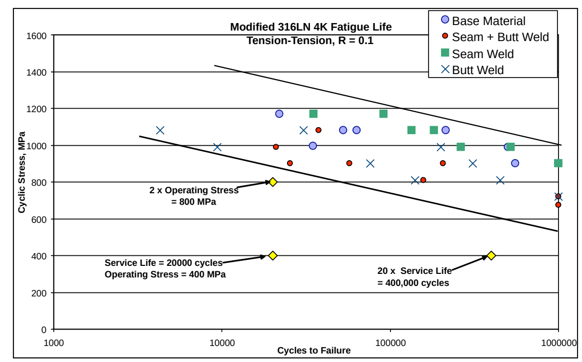

FIGURE 5. Fatigue life of the modified 316 LN at 4K.

SUMMARY

The 4K fatigue life of a 316LN modified alloy intended for use in CICC magnets are estimated by generating S-n fatigue life curves. After the first cycle, the samples show almost no hysteresis loops during the cyclic loading. In stress controlled mode, higher strain hardening rates appears to introduce smaller initial strain amplitudes and longer fatigue life. Using the abbreviated and regular reaction heat treatment schedules does not appear to have affected the fatigue life of the material or conditions.

ACKNOWLEDGMENTS

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