CONF-910635--8

DE91 015307



# THICK-SECTION WELDMENTS IN 21-6-9 AND 316LN STAINLESS STEEL FOR FUSION ENERGY APPLICATIONS*

D. J. Alexander and G. M. Goodwin

Metals and Ceramics Division
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6151

## INTRODUCTION

The Burning Plasma Experiment (BPX), formerly known as the Compact Ignition Tokomak, will be a major advance in the design of a fusion reactor. The successful construction of fusion reactors will require extensive welding of thick-section stainless steel plates. Severe service conditions will be experienced by the structure. Operating temperatures will range from room temperature (300 K) to liquid nitrogen temperature (77 K), and perhaps even lower. The structure will be highly stressed, and subject to sudden impact loads if plasma disruptions occur. This demands a combination of high strength and high toughness from the weldments. Significant portions of the welding will be done in the field, so preweld and postweld heat treatments will be difficult. The thick sections to be welded will require a high deposition rate process, and will result in significant residual stresses in the materials. Inspection of these thick sections in complex geometries will be very difficult. All of these constraints make it essential that the welding procedures and alloys be well understood, and the mechanical properties of the welds and their heat-affected zones must be adequately characterized.

The candidate alloy for structural applications in the BPX such as the magnet cases was initially selected as 21-6-9 austenitic stainless steel, and later changed to 316LN stainless steel. This study examined several possible filler materials for thick-section (25 to 50 mm) weldments in these two materials. The tensile and Charpy V-notch properties were measured at room temperature and 77 K. The fracture toughness was measured for promising materials.



## WELDMENT MATERIALS AND PREPARATION

Type 21-6-9 stainless steel [referring to its nominal composition of 21Cr-6Ni-9Mn (wt %)], also known as Nitronic 40, is one of a family of nitrogen-strengthened high-manganese austenitic alloys possessing high yield

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

strengths and usually adequate base metal toughness levels. Modified composition filler metal is suggested for thick-section weldments. The Nitronic "type W" filler metals have reduced nitrogen, and a balanced chromium/nickel ratio, to assure ferrite in the weld deposit to avoid hot cracking. One might anticipate that ferrite in the weld metal would adversely affect cryogenic toughness.

Four different type 21-6-9 base metals and seven weld filler metals were included in the program. Six were added as cold filler wire using the argon shielded gas tungsten arc welding process, and ENiCrFe-3 (Inconel* 182) is a coated electrode for use with the shielded metal arc process. ERNiCrMo-3 (Inconel 625) is the Armco-recommended filler metal to use if 35W or 40W are not appropriate for some reason. ERNiCr-3 (Inconel 82) is a universal filler metal, widely used to join a variety of nickel-based alloys and numerous dissimilar metal combinations, including austenitics to ferritics. Type 21-6-9 filler is essentially a matching composition weld metal for 21-6-9 base plate. Inconel 625 PLUS is a modified Inconel 625 composition recently introduced by Carpenter Technology Corporation.

Seven welds were made for Phase I of this project. All of the base materials were prepared with a double-groove butt-weld geometry. The 25-mm-thick type 21-6-9 plate used a double-V joint design with a 45° included angle, a 1.5-mm root face, and 3-mm root opening. All other base materials used a double-U joint design with 15° included angle, 6-mm radius, 1.5-mm root face, and 3-mm root opening.

The gas tungsten arc welds were made at 10 to 14 V DCEN and 125 to 200 A with pure argon shielding gas using a stringer bead technique. The 25-mm plates required 30 to 40 passes and the 50-mm plates, 90 to 100 passes.

The Inconel 182 shielded metal arc weld in 25-mm plate was made with 3-mm electrodes at 100 A and 23 V DCEP. Eighteen passes completed the weld.

Type 316LN stainless steel does not offer strength levels as high as the 21-6-9 steel, but this steel has been widely used for cryogenic structural applications. The 316LN base plate used in this study was available from a single pedigreed heat in both 25- and 50-mm thicknesses. Four welds were produced. A submerged-arc weld made with type 316L filler was included for comparison purposes, with the presumption that its toughness properties would be low, due to the significant ferrite volume fraction. The remaining welds were produced using the flux-cored arc welding process with various filler metals. With 1.5-mm-diam wire and a current of 200 A, a double-U joint in 50-mm plate required approximately 30 passes, compared to approximately 100 passes for gas tungsten-arc.

Type 316L-T3 is a self-shielded electrode formulation designed to give ferrite contents of greater than 5 (FN). Type 316L-4K-O is a product of Teledyne-McKay that is formulated to give intentionally low ferrite (0-2 FN) for use in cryogenic applications. Inconel 82-O is a flux-cored arc version of the basic Inconel 82 (ERNiCr-3) composition newly introduced by Teledyne-McKay. The "O" designation indicates a self-shielded formulation.

Inspection of all welds was visual only since subsequent sectioning would reveal any possible defects.

---

*Inconel is a registered trademark of Huntington Alloys, Inc., West Virginia.

## EXPERIMENTAL PROCEDURE

Test specimens were oriented transverse to and centered in the weld metal, and located near the top and bottom surfaces of the plates, to avoid the middle of the plate where the welds were thinnest and the dilution would be greatest. Two types of tensile specimens were tested. Oversize tensile specimens [gage length 38.1 mm by 5.1 mm in diameter (1.5 by 0.20 in.)] traversed the entire weld, and thus included base metal, heat-affected zone, and weld metal. Testing of these specimens provided a qualitative demonstration of the relative strengths of these different zones, and identified the weakest link in the compound structure. Miniature tensile specimens [gage length 10.2 mm by 2.5 mm in diameter (0.40 by 0.10 in.)] were machined transverse to the weld. These specimens were small enough so that the reduced diameter gage length was wholly contained in the weld metal.

Tensile testing of duplicate specimens was conducted on a screw-driven electromechanical test machine at a constant crosshead speed of $4.2 \times 10^{-3}$ mm/s (0.01 in./min). This resulted in an initial strain rate of $4.2 \times 10^{-4}$ $s^{-1}$ for the small specimens. Tests at 77 K were performed with the specimens immersed in a bath of liquid nitrogen contained in a vacuum dewar. Load and crosshead displacement were recorded, and the 0.2% offset yield strength was derived from this record after allowance for the test system compliance. Uniform and total elongations were measured from the load-displacement trace.

Charpy specimens were tested at room temperature and at 77 K. The latter specimens were immersed in a bath of liquid nitrogen and then quickly transferred to the test machine with special tongs which centered the specimen. The TL specimens were notched so that the fracture would propagate in the direction of welding, while for the TS specimens the fracture would propagate through the weld thickness.

For those materials that seemed promising based on the tensile and Charpy results, 1/2T compact specimens were tested at room temperature and at 77 K to determine the fracture toughness. The specimens were oriented so that the crack growth was in the direction of welding (TL orientation). Unloading compliance was used to monitor the crack growth during the test. The specimens were fatigue precracked at room temperature, and then side-grooved 10% of the thickness on each side. Testing was conducted in general accordance with ASTM Standards E 813-89 and E 1152-87.

Sections from the welds were metallographically polished and etched to allow the different microstructures to be examined. Selected fracture surfaces were examined in a scanning electron microscope.

## RESULTS

All of the welds appeared to be sound and defect-free upon visual inspection after welding. No evidence of hot cracking was observed.

The tensile data are presented in Table 1. At room temperature all of the filler metals had yield strengths which exceeded the base metal for both series of welds. However, the strength of the base metal increases rapidly as the temperature is decreased. Therefore, for the 21-6-9 series, the Inconel 625, 625 PLUS, 82, and 182 filler metals were significantly weaker than the base metal at 77 K, but the yield strength of the ferrite-containing Nitronic 35W, 40W, and the 21-6-9 filler metals exceeded that of the base metal. The Inconel 82-0 and the 316L-type filler metals have

Table 1. Mechanical properties of filler and base metals

| Filler metal | Welding process[a] | Temperature (K) | Strength (MPa) | | Elongation (%) | | Charpy energy (J) | Fracture toughness | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Yield | Tensile | Uniform | Total | | $J_{Ic}$ ($kJ/m^2$) | $K_J$ ($MPa\sqrt{m}$) |
| | | | 316LN Filler Metals | | | | | | |
| 316L | SA | 300 | 421 | 600 | 25 | 33 | 8 | | |
| | | 77 | 667 | 1240 | 42 | 48 | 27 | | |
| 316L-T3 | FCOA | 300 | 460 | 621 | 23 | 33 | 130 | | |
| | | 77 | 821 | 1248 | 42 | 49 | 20 | | |
| 316L-4K-O | FCOA | 300 | 571 | 702 | 8 | 16 | 117 | 245 | 209 |
| | | 77 | 723 | 1187 | 30 | 31 | 46 | 133 | 157 |
| Inconel 82-O | FCOA | 300 | 413 | 610 | 27 | 37 | 155 | 370 | 277 |
| | | 77 | 567 | 850 | 31 | 38 | 125 | 502 | 330 |
| | | | 21-6-9 Filler Metals | | | | | | |
| 40W | GTA | 300 | 552 | 724 | 18 | 26 | 168 | | |
| | | 77 | 1051 | 1358 | 17 | 17 | 9 | | |
| 35W | GTA | 300 | 593 | 762 | 25 | 39 | 166 | | |
| | | 77 | 979 | 1400 | 25 | 25 | 17 | | |
| 21-6-9 | GTA | 300 | 579 | 793 | 26 | 38 | 202 | | |
| | | 77 | 1182 | 1569 | 27 | 27 | 28 | | |
| Inconel 625 | GTA | 300 | 514 | 814 | 27 | 29 | 36 | | |
| | | 77 | 738 | 1124 | 19 | 19 | 22 | | |
| Inconel 625 Plus | GTA | 300 | 500 | 796 | 31 | 37 | 75 | | |
| | | 77 | 696 | 1110 | 31 | 32 | 55 | | |
| Inconel 82 | GTA | 300 | 486 | 714 | 26 | 33 | 169 | 714 | 384 |
| | | 77 | 690 | 965 | 24 | 30 | 160 | 785 | 413 |
| Inconel 182 | SMA | 300 | 403 | 631 | 26 | 34 | 129 | | |
| | | 77 | 527 | 900 | 31 | 40 | 111 | | |
| | | | Base Metals | | | | | | |
| 316LN | | 300 | 280 | 610 | | 57 | | | |
| | | 77 | 725 | 1215 | | 61 | | | |
| 21-6-9 | | 300 | 345 | 690 | 50 | 65 | >300 | | |
| | | 77 | 970 | 1510 | 35 | 40 | 100 | | |

[a]SA = submerged arc, FCOA = flux-cored open arc, GTA = gas tungsten arc, SMA = shielded metal arc.

higher strengths than the 316LN base metal at room temperature. At 77 K, the 316L-type filler metals are similar in strength to the base metal, but the Inconel 82-O is much weaker.

Close examination of the oversize tensile specimens indicated that the HAZ was stronger than the base metal, at least at room temperature, as the diameter of the specimen in the HAZ area was greater than the base metal further from the weld. At 77 K the deformation was largely limited to the weld metal, and the heat-affected zone and base metal regions were unaltered. Fracture occurred in the weld metal for all of the specimens at either test temperature.

The impact properties are also shown in Table 1. The impact toughness of the base metals is very high at room temperature. Although the toughness of the base metals drops at 77 K, it is still high. All of the filler metals had good impact properties at room temperature except for Inconel 625. However, at 77 K the impact properties were very poor, except for the Inconel 82 and 182 alloys. These alloys had excellent impact properties at both temperatures, particularly Inconel 82 (both the gas tungsten arc and the flux-cored arc weldments). The 316L-4K-O had better impact properties at 77 K than the other ferrite-containing materials, but was still much worse than the Inconel 82 materials.

Only three series of fracture toughness tests were run: the Inconel 82 from the 21-6-9 weldments, and the Inconel 82-O and the 316L-4K-O from the 316LN series. The results of these tests are also in Table 1. The Inconel 82 toughnesses are very high, with the gas tungsten arc weld being much tougher than the flux-cored arc weld. The 316L-4K-O toughness is lower than the Inconel 82, but still quite high. It is intriguing to note that the toughness at 77 K exceeds the room temperature toughness for the Inconel weld materials.

The microstructures of the different weld metals were examined. The 35W, 40W, 21-6-9, 316L, and 316L-T3 filler metals had significant amounts of ferrite present, as expected. The ferrite content of the 316L-4K-O material was much lower. The Inconel-type filler metals did not contain any ferrite.

DISCUSSION

The testing conducted has shown that the filler metals with higher ferrite contents have high strengths, but suffer a severe decrease in impact properties at low temperature. The Inconel alloys are slightly weaker than the Nitronic alloys at room temperature, and much weaker at 77 K. The Inconel 82 and 182 alloys offer good impact properties, with the Inconel 82 alloy being both stronger and tougher at all temperatures. The Inconel 625 PLUS and particularly the Inconel 625 filler metal have poor impact properties regardless of temperature.

The microstructure of the ferrite-containing filler metals offers an explanation for the dramatic decrease in energy absorbed as the temperature is lowered. The welds contain about 5 to 10% ferrite phase, which is also reflected in their slight magnetism. It is believed that this ferrite phase fractures by a low energy cleavage process at low temperatures. The high volume fraction of ferrite permits the crack to move readily to nearby ferrite regions, and so the fracture process requires low energy. Any filler metal which results in a significant volume fraction of ferrite in the weld will probably show a similar low energy level for impact tests at 77 K.

The fractography of the ferrite-containing welds supports this conclusion. Fracture at room temperature occurs by a ductile microvoid coalescence process. This fracture process will be dominated by the austenitic matrix and the inclusions in the weld. However, specimens tested at 77 K display very different fracture features. The fracture surface consists of flat steps which are linked by narrow ridges of ductile tearing. It is believed that the crack preferentially follows the ferrite phase, and jumps from one island of ferrite to another. The flat regions are the result of cleavage fracture of the ferrite phase, whereas the tearing results from the crack joining these areas together by ductile tearing of the austenite matrix between the ferrite.

The Inconel alloys do not produce any ferrite phase in their welds. These alloys create a fully austenitic weldment, as indicated by their total lack of magnetism. The austenitic microstructure is not susceptible to cleavage fracture, and so the fracture process is a ductile one at either test temperature. Welding defects were noted in some of the 21-6-9 weldments, and are possibly related to the high nitrogen content of the base metal. Despite such defects, the impact energy of the Inconel 82 and 182 welds was quite high, whereas it was quite low for the Inconel 625 and 625 PLUS materials.

The absence of ferrite in the Inconel weld materials means that the fracture mode will be ductile microvoid coalescence at both room temperature and 77 K. The growth and joining of the microvoids will be very sensitive to the matrix flow properties. Greater amounts of energy will be required to deform the matrix as the temperature decreases and the flow stress rises. This explains the increase in the fracture toughness with the decrease in temperature observed for the Inconel 82 materials.

The Inconel 82 filler metal is clearly the best of the alloys examined in the 21-6-9 series of weldments. It offers excellent impact properties over the temperature range of interest, and reasonable strength. It exceeds the base metal strength at room temperature, but falls below the base metal at 77 K. It is not clear how severe a restriction this might place on the structural design.

The 316L and 316L-T3 filler metals have fairly high ferrite contents. As expected, they suffer a severe decrease in their impact properties at 77 K. The 316L-4K-0 material has a very low ferrite content. Metallographic examination showed that the ferrite was present in small apparently isolated islands within the austenitic matrix. The reduced size of the ferrite islands makes initiation of cleavage fracture more difficult. The separation of the ferrite islands makes propagation of the crack more difficult also. As a result, at 77 K the impact properties of the 316L-4K-0 material are better than any of the other ferrite-containing materials, although the energies are still much lower than the Inconel 82 material, whether gas tungsten arc or flux-cored arc. However, for applications for which higher strength in the weld material is necessary at cryogenic temperatures, the 316L-4K-0 provides an alternative to the Inconel 82 material. The impact properties will be reduced, but will be better than any of the other ferrite-containing materials.

## CONCLUSIONS

Seven different filler metals have been used to produce thick-section welds in 21-6-9 stainless steel plate. Tensile and Charpy impact tests were performed at room temperature and at 77 K. These tests indicate that the Nitronic-type filler metals, which contain a significant fraction of ferrite, have strengths which exceed the base metal, but have very low impact energies at 77 K. The Inconel-type filler metals, which do not contain ferrite, are somewhat weaker than the base metal. The Inconel 82 and 182 filler metals offer good impact properties at both temperatures, and are only slightly weaker than the base metal at 77 K. The Inconel 625 and 625 PLUS materials have poor impact properties. These tests indicate that the Inconel 82 filler metal is the prime candidate material for welding 21-6-9 stainless steel in thick sections.

Four different filler metals have been used to produce welds in 316LN base metal. The 316L-type filler metals offer strength similar to the base metal, but the Inconel 82-O material is weaker. The high-ferrite weld materials 316L and 316L-T3 suffer drastic decreases in the impact properties at 77 K. The low ferrite 316L-4K-O material also shows a drop in impact properties at 77 K, but the impact energies are higher than any of the other ferrite-containing materials. The Inconel 82-O material offers excellent impact properties but low strength. For applications that demand higher weld metal strength, the 316L-4K-O material offers an alternative, with impact properties that are better than any other ferrite-containing material, but still much lower than the Inconel 82-O.

ACKNOWLEDGMENTS

We would like to acknowledge the support of the Princeton Plasma Physics Laboratory for this work. The welds were fabricated at ORNL in the Materials Joining Group by J. D. McNabb, D. W. Swaney, and D. A. Frederick. The mechanical testing was performed by J. J. Henry, Jr., and R. L. Swain. We would like to thank R. K. Nanstad for numerous useful discussions, and M. L. Santella and D. E. McCabe for helpful reviews of the manuscript, which was prepared by J. L. Bishop.

## DISCLAIMER