Final Status Report: Proton and Neutron Irradiation Effects on Tensile Properties for APT Target/Blanket Assembly Metallic Structural Material Welds

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Abstract:

The effect of proton/neutron irradiation on the tensile properties of a variety of welds, similar to those potentially required for Accelerator Production of Tritium (APT) target/blanket systems and components, was determined. The irradiation was carried out in a high energy, mixed proton/spallation neutron spectrum produced in the Los Alamos Neutron Science Center (LANSCE) accelerator by an 800 MeV, 1 mA proton beam impinging on a solid tungsten target. Exposures of 0.1 to 2.1 dpa were achieved. The irradiation increased the yield and ultimate strengths and decreased the ductility (uniform elongation) of annealed Type 316L stainless steel weld specimens. These changes were similar to those found for non-welded (parent metal) companion specimens. The response of Alloy 718 weld specimens to irradiation was more difficult to compare to non-welded parent material because post-weld heat treatments of Alloy 718 weld specimens did not strengthen the weld fusion zone to the level achieved for the heat-treated base metal. Consequently, the strength of the weld specimens was significantly less than that for age-hardened Alloy 718. However, irradiation increased that strength of the Alloy 718 weld specimens and extrapolation of the data suggests that after a 1 to 2 dpa exposure the weld properties would be similar to those of the non-welded base metal. The non-irradiated and irradiated 4043 alloy-filled 6061-T6 Al weld specimens failed in the weld fusion zone, and thus the strengths were controlled by the weld filler metal. The heat-affected zone in the 5052-0 Al welds controlled the strength of these welds. The strengths of the 6061 Al-to-stainless steel inertia welds and of the Alloy 718-to-Type 304L stainless steel welds were controlled by the behavior of the low strength members of the dissimilar metal couples (i.e., 6061-T6 Al and Type 304L stainless steel, respectively).

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1.0 Introduction

The window and target/blanket components for the Accelerator Production of Tritium (APT) system will require a wide variety of structural welds. The welds must maintain structural integrity during irradiation in a mixed, high-energy proton and neutron environment. Anticipated irradiation conditions include temperatures in the range 333 to 483 K. The atom displacements (per atom or dpa) associated with the end-of-life service will vary with both weld and component and may reach tens of dpa in highly irradiated welds. Large quantities of hydrogen and helium may also be implanted in the welds because of nuclear interactions with the high-energy particles. The combined effects of atom displacement damage and hydrogen and helium accumulation may significantly alter the mechanical properties of the base metal, welds, and weld heat-affected-zones, and limit component serviceability and lifetime.

Design lifetimes for components and structures in the APT target/blanket system range from approximately one year (the window) to forty years (the vessel). Component replacement schedules must be selected to assure continued satisfactory performance based on the APT structural design criteria/design stress allowables, which include provisions for handling irradiation—induced degradation of the mechanical properties. However, experimental data directly applicable to the APT target/blanket materials and welds is minimal, primarily because of the unique exposure conditions anticipated for the APT components. To rectify this situation, a large-scale irradiation and test program was established [1]. Test results from this program have indicated that the tensile properties and fracture toughnesses of age-hardened Alloy 718, annealed Type 304L and 316L stainless steel and Al6061 in the T4 and T6 conditions show a degradation of toughness and a concomitant decrease in uniform elongation with proton and neutron fluence [2]. Evaluation of these data provided a technical basis to conclude that the large database of irradiation effects on the mechanical properties of structural metals exposed to fission reactor environments provides useful indicators of the anticipated trends for property/dose predictions in spallation neutron environments. However, the enhanced gas production associated with the high-energy proton/neutron spectra of spallation neutron sources may cause enhanced degradation at low doses [2]. This report provides the results of tensile tests on welded material samples that were irradiated in the Los Alamos Neutron Science Center (LANSCE) as part of APT Materials Program and subsequently tested at the Oak Ridge National Laboratory (ORNL) Irradiated Materials Examination and Testing Facility (IMET) [3].

The APT System will produce tritium (^3H) through the $^3He(n, p)^3H$ reaction. The ^3He used for ^3H production will be contained, at approximately 0.83 MPa, in 6061-T6 aluminum pressure tubes that will be connected to a $^3H/^3He$-separation facility through a Type 316L stainless steel manifold. This facility will be fabricated using a variety of weld types including gas-tungsten arc (GTA) welds of annealed Type 316L to Type 316L stainless steel, inertia welds of 6061-T6 Al to annealed Type 316L stainless steel and GTA welds of 6061 Al to 6061 Al. Neutrons for the $^3He(n, p)^3H$ reaction will be produced by proton-induced spallation of a tungsten target. Lead blanket assemblies will moderate and, through additional spallation reactions, multiply the number of available neutrons. The high-energy proton beam will transition from the accelerator portion of the APT system into the target/blanket system by passing through an Alloy 718 window before inducing spallation in the tungsten target. Design concepts for the target/blanket system are summarized in Reference 4, and include 1) cladding of the tungsten target elements and containing the target cooling water with Alloy 718, and 2) containing the lead blanket components in 6061-T6 aluminum. Weld types required for the target/blanket components will include GTA and electron beam (EB) welds of Alloy 718 to Alloy 718. The containment vessel will be fabricated from Type 304L stainless steel, and Type 316L stainless steel will be used to fabricate much of the primary cooling water system, the ^3He gas delivery system and the vessel internals. The materials irradiation program developed to support the emerging target/blanket design is outlined in Reference 1 and the weld types investigated include butt, V-groove, step and lap. Autogeneous and filler welding techniques were investigated for several of the weld types. The welds include some of the weld configurations applicable to the present APT target/blanket design and other configurations that were applicable to the APT target/blanket design at earlier stages of the design evolution.

2.0 Test Method

Prototypes of the tungsten neutron source were irradiated with 800 MeV protons at power levels prototypic of that anticipated in the APT target (1 mA) to provide the irradiation environment for the test specimens. The proton beam had a Gaussian-like intensity profile with a diameter of approximately $2\sigma = 30$ mm, where σ is the standard deviation. The beam profile has several basic effects on the specimen/irradiation design:

- each test specimen had to be small to assure reasonable uniformity in dose within a single welded sample;
- each test specimen had to be relatively thin, 0.25 to 2.0 mm range, to assure that the energy deposited by the proton beam and spallation products was properly transferred to the coolant (i.e., specimens were not overheated); and
- placement of nearly identical test specimens near the center and near the end of an irradiation capsule provided the opportunity to determine the effects of dose on a given weld type.

Similar effects influenced the design of the mechanical test samples for the base metal studies; however, the evaluation of welded samples placed an additional specimen constraint. The specimen gage had to be of sufficient length to contain the weld fusion zone, the weld heat affected zone and extend into the base metal. This arrangement was necessary to achieve a single specimen test of the various microstructures in the weld. Test results from a specimen having this configuration can be used to establish the weak link in the various micro-/macro-structures associated with the weld process.

The material/weld combinations discussed in this report are summarized in Table 1. Chemical compositions of the base metals and filler rods used in this study are given in Table 2. The materials for the weldments included Type 316L and Type 304L stainless steels (annealed condition), Alloy 718 (post-weld heat treated condition), 5052-0 (annealed condition) and 6061-T6 (precipitation hardened condition) aluminum alloys. The base metals and weld filler materials (rods) were purchased as commercial stock materials. The currents, voltages, travel speeds and other welding parameters are summarized in Table 3. Test specimens were machined from each of the weld conditions. Prior to machining, the welds were radiographed to reveal weld defects and to locate the high integrity (no observable defects) weld areas. Specimens were then electro-discharge machined (EDMed) from the high integrity areas. A schematic representation of the tensile specimen is shown in Figure 1. Gage dimensions of each specimen were measured with an accuracy of 0.08 mm before testing. The specimens that contained only one weld (V-groove, butt and step) were positioned so that the weld fusion zone was near the center of the gage and the tensile axis was perpendicular to the weld centerline (Figure 2). Examples of the V-groove, butt and step welds are shown in Figure 3. Welding processes used included electron beam, gas-tungsten arc and inertia. The Alloy 718 welds were given post-weld heat treatments.

Specimens obtained from the lap welds contained two welds and were machined to position one of the welds near the center of the specimen gage (Figure 4). Residual stresses developed during welding caused distortion in some of the specimens. These welds were mechanically flattened prior to, and in some cases, after, machining. The necessity for, and the amount of plastic deformation associated with, the flattening operation(s) varied from specimen to specimen. This variation and the concomitant variation in mechanical properties increased the data scatter beyond that normally anticipated for tensile test results. Examples of distortion introduced by welding are shown in Figure 5.

Irradiation of the weld specimens in the LANSCE proton beam facility was part of the 1996-97 irradiation program that exposed materials and components to APT prototypical proton/neutron fluences. This irradiation program, including a description of dose calculation methods and mechanical property measurement techniques, is summarized in References 1 and 2. The insert (irradiation capsule) design for specimen irradiation is shown schematically in Figure 6. The welded tensile specimens were irradiated in three tubes in Insert 18C. Irradiation doses and temperatures, determined for each specimen, are summarized in Table 4.

The irradiated specimens and the unirradiated control specimens were tested at Oak Ridge National Laboratory [3]. The control specimens were tested on a screw driven Inston universal testing machine with a 2224 N (500 lb) load cell. The irradiated specimens were tested in a hot cell on a screw driven Instron universal testing machine with a 4448 N (1000 lb) load cell. The load was applied through pins placed through holes in the tab regions of the specimens. The elongation was determined from crosshead displacement normalized to the 7.62 mm (0.3 inch) gage length. The load was determined from the load cell reading. The room temperature (298K) tensile tests were performed in air at a constant crosshead displacement rate of 0.0508 mm/minute (0.002 inches/minute). This displacement rate corresponds to an initial strain rate of approximately 10-4 sec-1 for a test specimen behaving as a homogeneous isotropic material. However, the microstructures of the weld specimens indicate that the test specimens were not homogeneous. The microstructural inhomogeneity also translates to an inhomogeneity in strength. Thus the actual strain rates may have been greater than 10-4 sec-1 because of localized yielding. This lack of homogeneity confounds both the actual test strain rate and any measurement of elongation. Clearly, neither the elastic nor the plastic strains will be uniform across the specimen gage length, especially for the dissimilar metal and filler welds where the lower modulus materials and weaker microstructure in the sample will receive a larger fraction of the total strain. Therefore, even though both uniform and total elongation were recorded, these values are not necessarily representative of the actual behavior of any given macrostructure. However, the reported values of yield and ultimate strength should represent the actual values of the weakest macrostructure in the test weld.

3.0 Test Results

Tensile test data and tensile curve analyses sheets are given in Appendix A for each specimen tested as part of this program. The tensile test data for the irradiated and non-irradiated weld specimens are summarized in Table 4. Several rather obvious behaviors were observed for the welds:

1) The tensile properties of the dissimilar-metal welds (Type 316L to 6061-T6 Al and Type 304L to Alloy 718) are controlled by the behavior of the weakest metal (i.e., specimen failures occurred in the weakest material, and therefore, properties of the test specimen primarily reflect that of the failed material).
2) The irradiation increased the yield strength and decreased the ductility of most of the weld joints.
3) The irradiation increased the ultimate strength of Type 316L stainless steel welds and had little effect on the ultimate strength of Alloy 718, 5052 aluminum, and 6061 aluminum welds.

Additionally, several more subtle behaviors were observed.

1) The irradiation caused the fracture location in the Type 316L stainless steel weld specimens to change from the fusion zone for the non-irradiated weld specimens to the heat-affected zone for irradiated weld specimens exposed to doses of 0.8 dpa, or higher.
2) The properties of the 6061 Al welds made with 4043 filler were controlled by the behavior of the filler weld metal.
3) The properties of the 5052 Al welds made with a 4043 Al filler were controlled by the behavior of the heat-affected zone.
4) The strength of the 5052 Al welds made with a 5554 Al filler was controlled by the behavior of the filler weld metal while the strengths of the irradiated welds were controlled by the heat-affected zone.

The selected observations summarized above are developed more fully in the companion report APT-MP-00-09 Rev.0 [5].

4.0 Summary

The data and evaluations presented herein have demonstrated the following points:

The effects of irradiation on the strength and ductility of gas-tungsten arc welds, made with and without filler metal, and electron beam welds of Type 316L stainless steel are similar to the effects on base metal. This similarity provides a technical basis for the use of existing data for base metal specimens to extrapolate the weld data to higher exposure levels.

The mechanical behavior of unirradiated and irradiated gas-tungsten arc/filler (4043 aluminum) welds of 6061-T6 Al is controlled by the behavior of the 4043/6061-T6 Al fusion zone and is similar to, and predictable from, the behavior of 6061-T4 Al base metal.

The tensile properties of unirradiated and irradiated gas-tungsten arc/filler (4043 and 5554 aluminum alloys) welds of 5052-0 Al are controlled by the behavior of the 5052-0 Al in the weld heat-affected zone.

Alloy 718 welds may not be responsive to strengthening by post-weld heat treatments, probably because of the inability of the heat treatment to re-solution the hardening elements in areas of solidification-induced segregation. The strengths of the unirradiated welds tested in this study were significantly below those for age-hardened Alloy 718. However, the strength increased during irradiation and extrapolation of test data suggests that after 1 to 2 dpa exposure, the strengths of the welds would approach that of the age-hardened base metal after an exposure of 1 to 2˚dpa.

The strength and ductility of 6061-T6 Al- to-Type 316L stainless steel inertia welds are controlled by the behavior of the 6061 Al, but do not reflect the strength of the -T6 condition. The strength is similar to that for the -T4 condition.

5.0 References

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6.0 Acknowledgement

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Table 1. Weld/Material Combinations Used in Weld Evaluation Study.

Condition	Material A	Thickness A (inches)	Material B	Thickness B (inches)	Joint	Process*	Filler
1	316L SS	0.035	316L SS	0.035	Square Butt	GTAW	316L SS
2	316L SS	0.035	316L SS	0.035	Square Butt	GTAW	None
3	304L SS	0.035	304L SS	0.035	Square Butt	GTAW	308L
4	FeCrMo	0.035	FeCrMo	0.035	Square Butt	GTAW	410 NiMo
5	Alloy 718	0.049	Alloy 718	0.196	Step	EBW	None
6	Alloy 718	0.049	Alloy 718	0.196	Step	GTAW	Alloy 718
7	Alloy 718	0.196	304L SS	0.196	V-Groove	GTAW	Alloy 82
8	Alloy 718	0.196	304L SS	0.196	Modified Lap	EBW	None
9	Alloy 718	0.196	304L SS	0.196	Modified Lap	GTAW	Alloy 82
10	5052 Al	0.032	5052 Al	0.032	Square Butt	GTAW	5554 Al
11	5052 Al	0.032	5052 Al	0.032	Square Butt	GTAW	4043 Al
12	5052 Al	0.080	5052 Al	0.080	Square Butt	GTAW	5554 Al
13	5052 Al	0.080	5052 Al	0.080	Square Butt	GTAW	4043 Al
16	6061 Al	0.032	6061 Al	0.032	Square Butt	GTAW	4043 Al
17	6061 Al	0.080	6061 Al	0.080	Square Butt	GTAW	4043 Al
21	304L SS	1.2	6061 Al	1.6	Square Butt	IW	None
22	316L SS	0.357	5052 Al	0.50	Square Butt	IW	None
23	316L SS	0.625	6061 Al	0.75	Square Butt	IW	None
24	316L SS	0.357	5052 Al	0.50	Square Butt	IW	None

* GTAW = Gas-Tungsten Arc Weld, EBW = Electron Beam Weld, IW = Inertia Weld

Table 2. Chemical analysis of base metals and filler rods used in weld evaluation study.

Material	Exp. Cond. No.*	Position in specimen	Thickness of plate (inches)	Lot	Al	C	Cr	Cu	Fe	Mn	Mo	Ni	P	S	Si	Ti	Others
Al 5052-H32	10 and 11	Side A and B	0.032	87074011	BAL		0.15-0.35	0.10 Max	0.40 Max	0.10 Max					0.25 Max		Mg-(2.20-2.80); Zn-0.10 Max; ASTM B209-90
	12 and 13	Side A and B	0.080	114496	BAL		0.15-0.35	0.10 Max	0.40 Max	0.10 Max					0.25 Max		Mg-(2.20-2.80); Zn-0.10 Max; ASTM B209-90
	22	Side B	0.50	Data unavailable													
	24	Side B	0.50	Data unavailable													
Al 5554	12	filler	wire	816	Bal.		0.10	0.01	0.19	0.50					0.12	0.10	Mg-2.54, Zn-0.01
Al 6061-T6	16	Side A and B	0.032	W032	BAL		0.207	0.252	0.463	0.111			0.003		0.695	0.016	Mg-1.011; V-0.016; Ga-0.014; Ca-0.001; Sn-0.002
	17	Side A and B	0.080	280482	BAL		0.04-0.035	0.15/ 0.4	0.70 Max	0.15 Max					0.40/ 0.80	0.15	Mg-(0.8-1.2); Zn-0.25
	21	Side B	1.6	Data unavailable													
	23	Side B	0.75	Data unavailable													
Al 4043	13 and 17	filler	wire	96045	Bal.		<0.01	>0.01	0.13	<0.01					5.07	<0.01	Zn-0.038, Mg-0.04

*Experiment condition number as defined in Table 1.

Table 2. Chemical analysis of base metals and filler rods used in weld evaluation study (continued).

Material	Exp. Cond. No.*	Position in specimen	Thickness of plate (inches)	Lot	Al	C	Cr	Cu	Fe	Mn	Mo	Ni	P	S	Si	Ti	Others
304L	3	Side A and B	0.035	L 918981		0.021	18.24	0.28	BAL	1.72	0.33	9.62	0.037	0.002	0.32		Co-0.16, N-0.032
	7, 8 and 9	Side B	0.196	L919770		0.018	18.46	0.40	BAL	1.76	0.36	8.28	0.030	0.012	0.43		Co-0.14, N-0.086
	21	Side A	1.2	Data unavailable													
316L	1 and 2	Side A and B	0.035	867149		0.022	16.21			1.82	2.10	10.12	0.027	0.004	0.54		N-0.04
	22	Side A	0.375	Data unavailable													
	23	Side A	0.625	Data unavailable													
	24	Side A	0.375	Data unavailable													
	1	Filler	wire	463543		0.010	18.390	0.130	BAL	1.640	2.510	12.100	0.020	0.013	0.510		N-0.038, Co-0.047, B-0.002
308L	3	Filler	Wire	435911		0.011	20.150	0.071	BAL	1.610	0.100	9.710	0.018	0.015	0.490		N-0.036, Co-0.040, Nb-0.,010, B-0.001

*Experiment condition number as defined in Table 1.

Table 2. Chemical analysis of base metals and filler rods used in weld evaluation study (continued).

Material	Exp. Cond. No.*	Position in specimen	Thickness of plate (inches)	Lot	Al	C	Cr	Cu	Fe	Mn	Mo	Ni	P	S	Si	Ti	Others
Alloy 718	5 and 6	Side A	0.049	HT 5889 EK	0.52	0.03	18.41	0.06	18.02	0.08	3.0	53.50	0.012	0.0007	0.08	1.00	Co-0.18, Nb-5.09, Ta-0.01, B-0.003
	5 and 6	Side B	0.196	HT 5849 EK	0.47	0.03	18.47	0.08	17.59	0.08	3.01	53.81	0.012	0.0004	0.09	1.03	Co-0.15, Nb-5.16, Ta-0.01, B-0.003
	7, 8 and 9	Side A	0.196	HT 5849 EK	0.47	0.03	18.47	0.08	17.59	0.08	3.01	53.81	0.012	0.0004	0.09	1.03	Co-0.15, Nb-5.16, Ta-0.01, B-0.003
	6	filler	wire	5716EY2 2	0.51	0.040	18.37	0.10	18.36	0.070	2.98	53.24	0.012	0.001	0.100	0.94	B-0.003, Nb-5.04, Co-0.22, Ta-0.01
FeCrMo	4	Side A and B	0.035	10148	0.002	0.089	9.24	0.08	BAL	0.47	0.96	0.16	0.021	0.006	0.28	0.002	V-0.21; Nb-0.054; Co-0.019; N-0.035; O-0.008
410 NiMo	4	Filler	wire	5001		0.031	12.10		BAL	0.560	0.520	4.02	0.015	0.017	0.400		
Alloy 82	7 and 9	Filler	wire	NX8798 D		0.047	19.340	0.090	0.690	3.110		73.640	0.008	0.001	0.080	0.370	Co-0.050, Nb-2.530

*Experiment condition number as defined in Table 1.

Table 3. Weld parameters for welds in weld evaluation study.

Condition	Current*	Voltage**	Travel***	Wire Feed***	Gas/Flow Rate****	Electrode	Other*****
1	65 A DCSP	10.0 V	12 ipm	20 ipm	Ar @ 20 cfh	W-1%Th	
2	50 A DCSP	9.5 V	12 ipm	None	Ar @ 20 cfh	W-1%Th	
3	75 A DCSP	10.0 V	12 ipm	20 ipm	Ar @ 20 cfh	W-1%Th	
4	105 A DCSP	10.0 V	12 ipm	20 ipm	Ar @ 20 cfh	W-1%Th	
5	6 mA	120 kV	45 ipm	None	Vacuum	N/A	0.96 kJ/in.
6	110 A DCSP	10.0 V	12 ipm	20 ipm	Ar @ 20 cfh	W-1%Th	
7	135–155 A DCSP	9.0–10.0 V	4–6 ipm	15–25 ipm	Ar @ 20 cfh	W-1%Th	4 passes
8	15 mA	120 kV	40 ipm	None	Vacuum	N/A	2.75 kJ/in.
9	160 A DCSP	10.0 V	6, 8 ipm	15, 36 ipm	Ar @ 20 cfh	W-1%Th	2 passes/side
10	140-180 A AC	14-16 V	4-8 ipm	10-20 ipm	Ar @ 20 cfh	Pure W	
11	140-180 A AC	14-16 V	4-8 ipm	10-20 ipm	Ar @ 20 cfh	Pure W	
12	140–180 A AC	14–16 V	4–8 ipm	10–20 ipm	Ar @ 20 cfh	Pure W	
13	140–180 A AC	14–16 V	4–8 ipm	10–20 ipm	Ar @ 20 cfh	Pure W	
16	140-180 A AC	14-16 V	4-8 ipm	10-20 ipm	Ar @ 20 cfh	Pure W	
17	140–180 A AC	14–16 V	4–8 ipm	10–20 ipm	Ar @ 20 cfh	Pure W	

* DCSP = Direct Current Single Polarity, AC = Alternating Current, A = Amperes, mA = milli-Amperes; ** V = Volts, kV = kilo-Volts; *** ipm = inches per minute, **** Ar = Argon, cfh = cubic feet per hour; ***** kJ/in. = kilo-Joules per inch

Table 4. Irradiation dose and temperature, and tensile test data for each specimen in the test matrix.

set	specimen number	materials	Location in Irradiation Capsule	dose, dpa	Tirr, C	Weld type	filler	YS,* MPa	UTS,* MPa	Eu,* %	Et,* %	FS,* MPa	RA,* %	location of fracture**
Ship E control	1-1	316L/316L	. . .	0	. . .	GTA	316L	319	519	24.6	34.6	280	87	center (FZ)
Ship E control	1-2	316L/316L	. . .	0	. . .	GTA	316L	323	521	24.1	33.6	270	. . .	0.4 gage (FZ)
Ship B irrad	1-1	316L/316L	(neutron furnaces)	0.124	80	GTA	316L	519	605	12.3	20.1	314	. . .	. . .
Ship B irrad	1-2	316L/316L	(neutron furnaces)	0.124	80	GTA	316L	534	626	13.1	20.8	378	. . .	. . .
Ship E irrad	1-5	316L/316L	18A	0.2	35	GTA	316L	490	561	12.0	19.1	339	. . .	center (FZ)
Ship E irrad	1-6	316L/316L	18A	0.32	34	GTA	316L	504	579	13.4	19.7	400	. . .	center (FZ)
Ship E control	2-1	316L/316L	. . .	0	. . .	GTA	none	306	554	37.6	46.3	350	85	center (FZ)
Ship E control	2-2	316L/316L	. . .	0	. . .	GTA	none	299	541	40.1	49.9	356	. . .	0.4 gage (FZ)
Ship E irrad	2-2	316L/316L	18C	0.88	51	GTA	none	579	622	10.4	17.5	329	. . .	2/3 gage (HAZ)
Ship E irrad	2-1	316L/316L	18C	2.1	63	GTA	none	658	690	8.8	15.5	485	. . .	2/3 gage (HAZ)
Ship E control	3-1	304L/304L	. . .	0	. . .	GTA	308L	280	499	26.6	38.2	283	87	0.45 gage
Ship E control	3-2	304L/304L	. . .	0	. . .	GTA	308L	288	498	26.7	38.6	297	. . .	0.4 gage
Ship B control	3-3	304L/304L	. . .	0	. . .	GTA	308L	350	538	23.6	31.8	300	. . .	. . .
Ship B control	3-5	304L/304L	. . .	0	. . .	GTA	308L	260	525	22.9	31.2	330	. . .	. . .
Ship B control	3-6	304L/304L	. . .	0	. . .	GTA	308L	499	528	9.4	18.5	325	. . .	. . .
Ship B irrad	3-1	304L/304L	(neutron furnaces)	0.13	80	GTA	308L	459	549	13.3	18.3	518	. . .	. . .
Ship B irrad	3-2	304L/304L	(neutron furnaces)	0.13	80	GTA	308L	462	549	11.6	18.9	330	. . .	. . .
Ship E control	4-1	FeCrMo/FeCrMo	. . .	0	. . .	GTA	410 NiMo	1117	1276	2.4	5.2	1175	26	.2 gage
Ship E control	4-2	FeCrMo/FeCrMo	. . .	0	. . .	GTA	410 NiMo	1114	1263	2.8	6.8	1065	. . .	.3 gage
Ship B control	4-3	FeCrMo/FeCrMo	. . .	0	. . .	GTA	410 NiMo	1125	1330	2.4	6.7	1055	. . .	. . .
Ship B control	4-4	FeCrMo/FeCrMo	. . .	0	. . .	GTA	410 NiMo	1090	1300	2.3	5.2	1158	. . .	. . .
Ship B control	4-5	FeCrMo/FeCrMo	. . .	0	. . .	GTA	410 NiMo	1100	1305	2.6	5.4	1120	. . .	. . .
Ship B control	4-6	FeCrMo/FeCrMo	. . .	0	. . .	GTA	410 NiMo	1145	1305	2.2	6.2	1045	. . .	. . .
Ship B irrad	4-3	FeCrMo/FeCrMo	(neutron furnaces)	0.132	80	GTA	410 NiMo	819	819	0.3	8.5	450	. . .	. . .
Ship B irrad	4-4	FeCrMo/FeCrMo	(neutron furnaces)	0.132	80	GTA	410 NiMo	815	820	0.3	9.0	445	. . .	. . .
Ship E irrad	4-2	FeCrMo/FeCrMo	18A	0.31	35	GTA	410 NiMo	795	799	0.3	5.9	628	. . .	2/3 gage
Ship E irrad	4-1	FeCrMo/FeCrMo	18A	0.44	36	GTA	410 NiMo	798	805	0.4	6.1	588	. . .	1/5 gage
Ship E control	5-1	Alloy 718/Alloy 718	. . .	0	. . .	EB	none	681	1081	21.8	25.5	1004	39	.25 gage (FZ or HAZ)
Ship E control	5-2	Alloy 718/Alloy 718	. . .	0	. . .	EB	none	687	1083	20.8	24.7	1011	. . .	.25 gage (FZ or HAZ)
Ship B irrad	5-3	Alloy 718/Alloy 718	(neutron furnaces)	0.132	80	EB	none	830	940	8.0	11.7	830	. . .	. . .
Ship B irrad	5-4	Alloy 718/Alloy 718	(neutron furnaces)	0.132	80	EB	none	785	896	7.2	11.1	759	. . .	. . .
Ship E irrad	5-1	Alloy 718/Alloy 718	18A	0.31	35	EB	none	938	1022	3.4	7.4	870	. . .	center (FZ)
Ship E irrad	5-2	Alloy 718/Alloy 718	18A	0.45	36	EB	none	935	1003	4.0	7.7	916	. . .	center (FZ)

Table 4. Irradiation dose and temperature, and tensile test data for each specimen in the test matrix (continued).

set	specimen number	materials	Location in Irradiation Capsule	dose, dpa	Tirr, C	Weld type	filler	YS,* MPa	UTS,* MPa	Eu,* %	Et,* %	FS,* MPa	RA,* %	location of fracture**
Ship E control	6-1	Alloy 718/Alloy 718	. . .	0	. . .	GTA	Alloy 718	649	910	6.5	6.5	910	14	center (FZ)
Ship E control	6-2	Alloy 718/Alloy 718	. . .	0	. . .	GTA	Alloy 718	642	975	10.7	10.7	975	. . .	center (FZ)
Ship B irrad	6-1	Alloy 718/Alloy 718	(neutron furnaces)	0.132	80	GTA	Alloy 718	835	975	5.6	7.3	750	. . .	. . .
Ship B irrad	6-3	Alloy 718/Alloy 718	(neutron furnaces)	0.132	80	GTA	Alloy 718	766	790	0.4	1.6	621	. . .	. . .
Ship E irrad	6-2	Alloy 718/Alloy 718	18A	0.2	36	GTA	Alloy 718	732	738	0.7	2.2	468	. . .	center (FZ)
Ship E irrad	6-5	Alloy 718/Alloy 718	18A	0.3	36	GTA	Alloy 718	850	909	2.9	4.1	747	. . .	2/3 gage (FZ or HAZ)
Ship E control	7-1	Alloy 718/304L	. . .	0	. . .	GTA	Alloy 82	332	615	28.0	33.6	497	62	.15 gage (304L)
Ship E control	7-2	Alloy 718/304L	. . .	0	. . .	GTA	Alloy 82	315	618	31.8	39.4	407	. . .	.15 gage (304L)
Ship B irrad	7-1	Alloy 718/304L	(neutron furnaces)	0.132	80	GTA	Alloy 82	?	413?	1.3?		250	. . .	(very unusual curve)
Ship B irrad	7-2	Alloy 718/304L	(neutron furnaces)	0.132	80	GTA	Alloy 82	494	531	0.9	3.3	241	. . .	. . .
Ship E irrad	7-6	Alloy 718/304L	18A	0.29	36	GTA	Alloy 82	571	711	17.0	21.5	348	. . .	round of shoulder (304L)
Ship E irrad	7-3	Alloy 718/304L	18A	0.41	38	GTA	Alloy 82	593	633	3.2	6.0	251	. . .	2/3 gage (304L)
Ship E control	8-1	Alloy 718/304L	. . .	0	. . .	EB	none	711	1068	21.3	25.1	961	44	center (FZ)
Ship E control	8-2	Alloy 718/304L	. . .	0	. . .	EB	none	705	1044	18.0	20.9	958	. . .	center (FZ)
Ship B irrad	8-1	Alloy 718/304L	(neutron furnaces)	0.132	80	EB	none	918	999	7.9	14.3	800	. . .	. . .
Ship B irrad	8-2	Alloy 718/304L	(neutron furnaces)	0.132	80	EB	none	915	1000	11.0	18.6	870	. . .	. . .
Ship E irrad	8-3	Alloy 718/304L	18A	0.2	36	EB	none	985	1045	2.7	8.4	800	. . .	center (FZ)
Ship E irrad	8-4	Alloy 718/304L	18A	0.3	36	EB	none	1007	1065	2.5	7.6	800	. . .	center (FZ)
Ship E control	9-1	Alloy 718/304L	. . .	0	. . .	GTA	Alloy 82	376	594	10.6	10.6	205	44	0.2 gage (304L)
Ship E control	9-2	Alloy 718/304L	. . .	0	. . .	GTA	Alloy 82	362	616	15.3	19.7	450	. . .	0.3 gage (304L)
Ship B irrad	9-1	Alloy 718/304L	(neutron furnaces)	0.132	80	GTA	Alloy 82	575	738	16.1	19.6	584	. . .	. . .
Ship B irrad	9-2	Alloy 718/304L	(neutron furnaces)	0.132	80	GTA	Alloy 82	570	729	15.2	18.7	550	. . .	. . .
Ship E irrad	9-3	Alloy 718/304L	18A	0.29	36	GTA	Alloy 82	561	665	11.2	15.7	469	. . .	round of shoulder (304L)
Ship E irrad	9-6	Alloy 718/304L	18A	0.41	38	GTA	Alloy 82	605	719	15.4	21.5	102	. . .	3/4 gage (304L)
Ship E control	10-1	Al5052/Al5052	. . .	0	. . .	GTA	Al 5554	95	193	15.4	19.4	168	60	0.15 gage (at notch)
Ship E control	10-2	Al5052/Al5052	. . .	0	. . .	GTA	Al 5554	100	195	17.8	22.6	169	. . .	0.20 gage
Ship B control	10-3	Al5052/Al5052	. . .	0	. . .	GTA	Al 5554	114	211	13.8	17.2	164	. . .	. . .
Ship B control	10-4	Al5052/Al5052	. . .	0	. . .	GTA	Al 5554	181	207	9.4	12.0	164	. . .	. . .
Ship B control	10-5	Al5052/Al5052	. . .	0	. . .	GTA	Al 5554	102	203	14.4	16.4	167	. . .	. . .
Ship B control	10-6	Al5052/Al5052	. . .	0	. . .	GTA	Al 5554	110	198	13.3	17.8	110	. . .	. . .
Ship B irrad	10-1	Al5052/Al5052	(neutron furnaces)	0.136	80	GTA	Al 5554	122	222	17.3	20.2	210	. . .	. . .
Ship B irrad	10-3	Al5052/Al5052	(neutron furnaces)	0.136	80	GTA	Al 5554	120	214	16.7	21.0	176	. . .	. . .

Table 4. Irradiation dose and temperature, and tensile test data for each specimen in the test matrix (continued).

set	specimen number	materials	Location in Irradiation Capsule	dose, dpa	Tirr, C	Weld type	filler	YS,* MPa	UTS,* MPa	Eu,* %	Et,* %	FS,* MPa	RA,* %	location of fracture**
Ship E control	11-1	Al5052/Al5052	. . .	0	. . .	GTA	Al 4043	116	173	6.7	11.3	117	73	0.10 gage
Ship E control	11-2	Al5052/Al5052	. . .	0	. . .	GTA	Al 4043	101	163	6.4	9.8	130	. . .	0.10 gage
Ship B control	11-3	Al5052/Al5052	. . .	0	. . .	GTA	Al 4043	131	181	5.6	8.9	138	. . .	. . .
Ship B control	11-4	Al5052/Al5052	. . .	0	. . .	GTA	Al 4043	100	181	6.3	10.4	110	. . .	. . .
Ship B control	11-5	Al5052/Al5052	. . .	0	. . .	GTA	Al 4043	132	170	5.5	8.3	120	. . .	. . .
Ship B control	11-6	Al5052/Al5052	. . .	0	. . .	GTA	Al 4043	107	171	5.5	10.3	120	. . .	. . .
Ship B irrad	11-2	Al5052/Al5052	(neutron furnaces)	0.136	80	GTA	Al 4043	133	211	6.6	10.3	165	. . .	. . .
Ship B irrad	11-7	Al5052/Al5052	(neutron furnaces)	0.136	80	GTA	Al 4043	140	226	8.4	12.7	174	. . .	. . .
Ship E control	12-1	Al5052/Al5052	. . .	0	. . .	GTA	Al 5554	100	198	17.9	22.6	145	49	center (FZ)
Ship E control	12-2	Al5052/Al5052	. . .	0	. . .	GTA	Al 5554	124	200	16.8	22.8	156	. . .	center (FZ)
Ship B irrad	12-3	Al5052/Al5052	(neutron furnaces)	0.136	80	GTA	Al 5554	104	205	15.7	18.0	177	. . .	. . .
Ship B irrad	12-6	Al5052/Al5052	(neutron furnaces)	0.136	80	GTA	Al 5554	117	207	14.1	16.9	177	. . .	. . .
Ship E irrad	12-4	Al5052/Al5052	18C	0.37	44	GTA	Al 5554	115	220	12.8	17.1	186	. . .	3/4 gage (HAZ)
Ship E irrad	12-1	Al5052/Al5052	18C	0.8	52	GTA	Al 5554	147	173	1.3	4.8	33	. . .	near shoulder (HAZ)
Ship E control	13-1	Al5052/Al5052	. . .	0	. . .	GTA	Al 4043	112	201	11.1	15.9	129	69	at radius (HAZ)
Ship E control	13-2	Al5052/Al5052	. . .	0	. . .	GTA	Al 4043	127	210	12.6	18.0	159	. . .	at radius (HAZ)
Ship B irrad	13-3	Al5052/Al5052	(neutron furnaces)	0.136	80	GTA	Al 4043	134	243	12.3	17.5	195	. . .	. . .
Ship B irrad	13-6	Al5052/Al5052	(neutron furnaces)	0.136	80	GTA	Al 4043	142	239	10.4	16.4	186	. . .	. . .
Ship E irrad	13-7	Al5052/Al5052	18C	0.63	51	GTA	Al 4043	165	250	8.7	12.6	201	. . .	round of shoulder (HAZ)
Ship E irrad	13-4	Al5052/Al5052	18C	1.18	63	GTA	Al 4043	192	276	6.0	8.6	242	. . .	near shoulder (HAZ)
Ship E control	16-1	Al6061/Al6061	. . .	0	. . .	GTA	Al 4043	133	205	6.9	7.9	194	23	0.40 gage
Ship E control	16-2	Al6061/Al6061	. . .	0	. . .	GTA	Al 4043	124	200	6.3	7.5	191	. . .	center
Ship B control	16-3	Al6061/Al6061	. . .	0	. . .	GTA	Al 4043	113	214	9.1	10.0	200	. . .	. . .
Ship B control	16-4	Al6061/Al6061	. . .	0	. . .	GTA	Al 4043	113	205	5.8	7.5	187	. . .	. . .
Ship B control	16-5	Al6061/Al6061	. . .	0	. . .	GTA	Al 4043	151	196	5.0	6.6	175	. . .	. . .
Ship B control	16-6	Al6061/Al6061	. . .	0	. . .	GTA	Al 4043	122	220	6.4	7.8	164	. . .	. . .
Ship B irrad	16-3	Al6061/Al6061	(neutron furnaces)	0.136	80	GTA	Al 4043	172	241	4.7	6.1	230	. . .	. . .
Ship B irrad	16-4	Al6061/Al6061	(neutron furnaces)	0.136	80	GTA	Al 4043	158	209	2.9	3.5	190	. . .	. . .
Ship E control	17-1	Al6061/Al6061	. . .	0	. . .	GTA	Al 4043	136	203	5.6	5.6	189	19	center (FZ)
Ship E control	17-2	Al6061/Al6061	. . .	0	. . .	GTA	Al 4043	147	227	9.2	9.2	221	. . .	center (FZ)
Ship B irrad	17-1	Al6061/Al6061	(neutron furnaces)	0.136	80	GTA	Al 4043	203	275	5.8	6.0	268	. . .	. . .
Ship B irrad	17-3	Al6061/Al6061	(neutron furnaces)	0.136	80	GTA	Al 4043	193	261	4.1	4.7	244	. . .	. . .
Ship E irrad	17-4	Al6061/Al6061	18C	0.37	44	GTA	Al 4043	201	282	7.2	8.1	262	. . .	center (FZ)
Ship E irrad	17-6	Al6061/Al6061	18C	0.8	52	GTA	Al 4043	223	301	6.4	6.6	298	. . .	center (FZ)

Table 4. Irradiation dose and temperature, and tensile test data for each specimen in the test matrix (continued).

set	specimen number	materials	Location in Irradiation Capsule	dose, dpa	Tirr, C	Weld type	filler	YS,* MPa	UTS,* MPa	Eu,* %	Et,* %	FS,* MPa	RA,* %	location of fracture**
Ship E control	21-1	304L/Al6061	. . .	0	. . .	inertia	none	232	261	2.0	7.2	161	55	0.4 gage (Al)
Ship E control	21-2	304L/Al6061	. . .	0	. . .	inertia	none	226	252	1.6	6.4	163	. . .	0.4 gage (Al)
Ship B control	21-3	304L/Al6061	. . .	0	. . .	inertia	none	235	267	1.8	5.4	180	. . .	. . .
Ship B control	21-4	304L/Al6061	. . .	0	. . .	inertia	none	237	276	1.5	6.2	155	. . .	. . .
Ship B control	21-5	304L/Al6061	. . .	0	. . .	inertia	none	239	273	1.7	5.7	188	. . .	. . .
Ship B control	21-6	304L/Al6061	. . .	0	. . .	inertia	none	250	286	2.2	6.2	145	. . .	. . .
Ship B control	21-7	304L/Al6061	. . .	0	. . .	inertia	none	240	276	2.1	6.0	175	. . .	. . .
Ship B irrad	21-1	304L/Al6061	(neutron furnaces)	0.123/0.136	80	inertia	none	281	298	1.5	4.5	216	. . .	. . .
Ship B irrad	21-3	304L/Al6061	(neutron furnaces)	0.123/0.136	80	inertia	none	289	304	1.5	4.5	221	. . .	. . .
Ship E control	22-1	316L/Al5052	. . .	0	. . .	inertia	none	161	203	1.1	9.1	147	66	0.4 gage (Al)
Ship E control	22-2	316L/Al5052	. . .	0	. . .	inertia	none	159	199	4.8	9.4	159	. . .	0.35 gage (Al)
Ship B control	22-3	316L/Al5052	. . .	0	. . .	inertia	none	167	219	3.7	7.5	167	. . .	. . .
Ship B control	22-4	316L/Al5052	. . .	0	. . .	inertia	none	160	160	0.0	0.0	160	. . .	. . .
Ship B control	22-5	316L/Al5052	. . .	0	. . .	inertia	none	167	221	3.1	7.9	135	. . .	. . .
Ship B control	22-6	316L/Al5052	. . .	0	. . .	inertia	none	167	215	3.9	9.5	156	. . .	. . .
Ship B irrad	22-2	316L/Al5052	(neutron furnaces)	0.123/0.136	80	inertia	none	171	224	4.0	9.8	167	. . .	. . .
Ship B irrad	22-3	316L/Al5052	(neutron furnaces)	0.123/0.136	80	inertia	none	161	199	1.8	1.9	186	. . .	. . .
Ship E control	23-1	316L/Al6061	. . .	0	. . .	inertia	none	170	209	2.0	6.5	150	61	0.4 gage (HAZ; Al)
Ship E control	23-2	316L/Al6061	. . .	0	. . .	inertia	none	174	202	2.0	6.2	132	. . .	0.4 gage (HAZ; Al)
Ship B irrad	23-1	316L/Al6061	(neutron furnaces)	0.124/0.136	80	inertia	none	261	280	2.4	7.1	195	. . .	. . .
Ship B irrad	23-2	316L/Al6061	(neutron furnaces)	0.124/0.136	80	inertia	none	257	277	1.9	6.7	129	. . .	. . .
Ship E irrad	23-3	316L/Al6061	18A	0.20/0.29	34	inertia	none	188	222	2.6	7.3	155	. . .	3/4 gage (HAZ)
Ship E irrad	23-5	316L/Al6061	18A	0.32/0.37	35	inertia	none	155	194	2.6	8.1	113	. . .	3/4 gage (HAZ)
Ship E control	24-1	316L/Al5052	. . .	0	. . .	inertia	none	160	202	4.8	9.1	162	47	0.4 gage (Al)
Ship E control	24-2	316L/Al5052	. . .	0	. . .	inertia	none	157	172	0.9	0.9	172	. . .	center
Ship B control	24-3	316L/Al5052	. . .	0	. . .	inertia	none	183	218	4.0	7.9	165	. . .	. . .
Ship B control	24-4	316L/Al5052	. . .	0	. . .	inertia	none	170	220	4.4	7.7	170	. . .	. . .
Ship B control	24-5	316L/Al5052	. . .	0	. . .	inertia	none	202	212	2.9	7.5	145	. . .	. . .
Ship B control	24-6	316L/Al5052	. . .	0	. . .	inertia	none	160	217	4.1	7.9	156	. . .	. . .
Ship B irrad	24-1	316L/Al5052	(neutron furnaces)	0.124/0.136	80	inertia	none	168	225	4.2	9.9	151	. . .	. . .
Ship B irrad	24-2	316L/Al5052	(neutron furnaces)	0.124/0.136	80	inertia	none	173	226	4.4	9.8	155	. . .	. . .

*YS = tensile yield strength; UTS = ultimate tensile strength; Eu = uniform elongation; Et = total elongation; FS = fracture strength; RA = reduction in area

**FZ = fusion zone; HAZ = heat affected zone

7.0 Figures

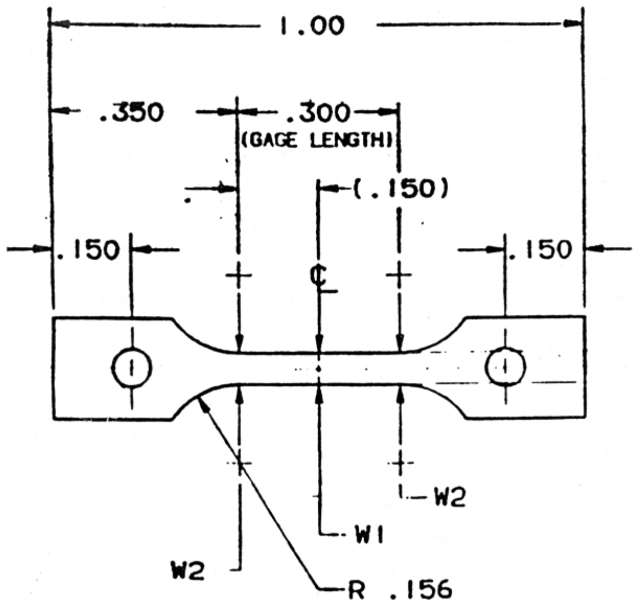


Figure 1. Sketch of the test samples used to determine the effects of irradiation on tensile properties of metal welds.

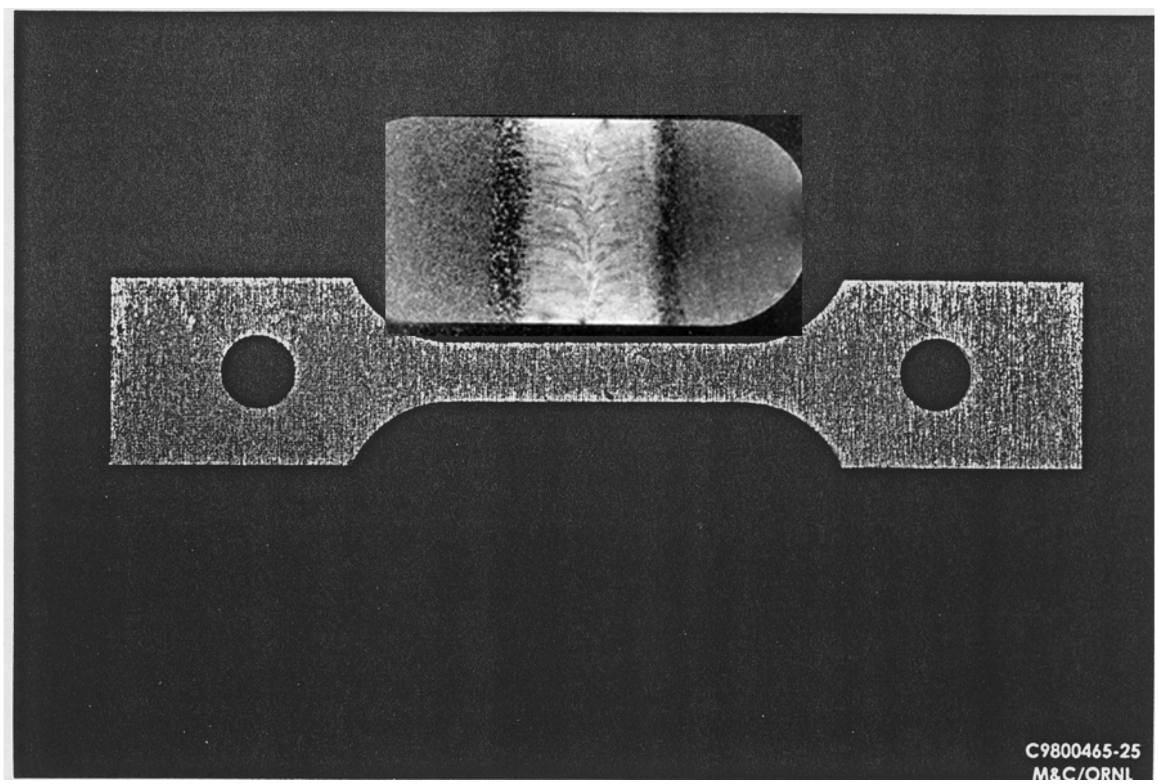
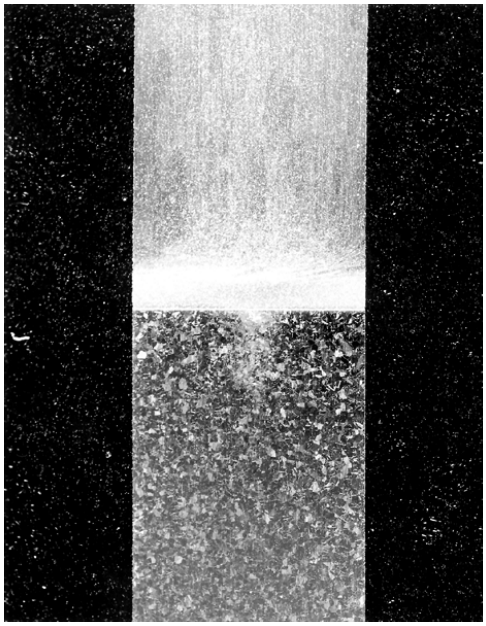
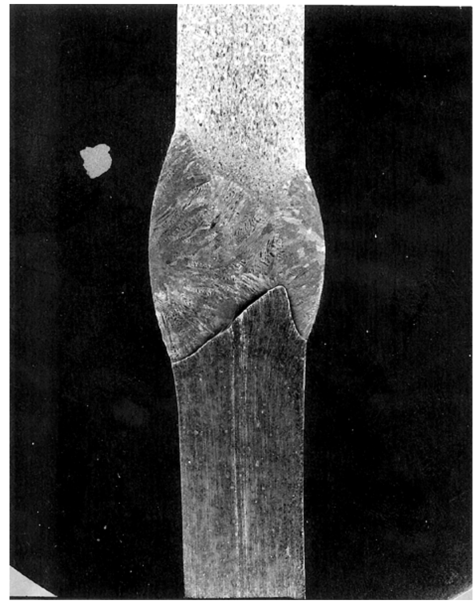


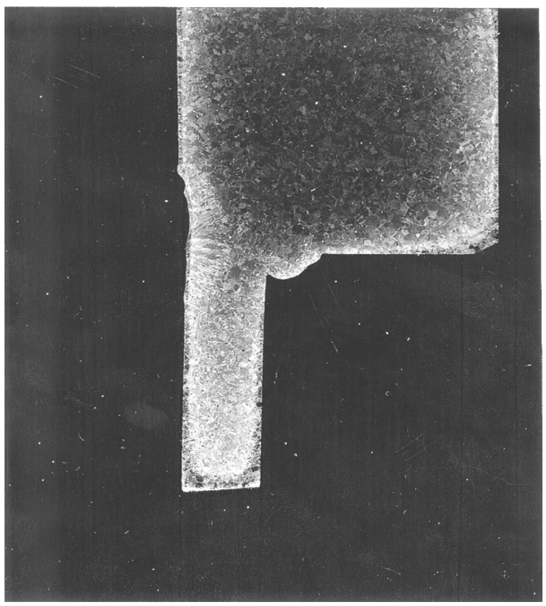
Figure 2. Photographs of tensile specimen and macrostructure of specimen gage, GTA weld joining Type 316L stainless steel to Type 316L stainless steel using a Type 316L filler.

A.



B.





C.

Figure 3. Weld configuration for several test conditions:

Figure 3.a. **Inertia butt weld joining 6061 Al to Type 316L stainless steel**

Figure 3.b. **GTA V-groove weld joining Type 304L stainless steel to Alloy 718 using an Alloy 82 filler**

Figure 3.c. **Electron beam step weld joining Alloy 718 to Alloy 718.**

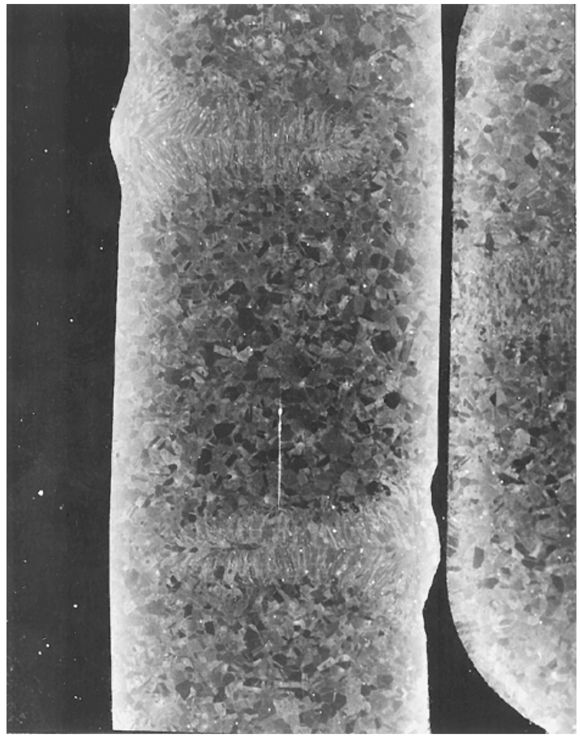
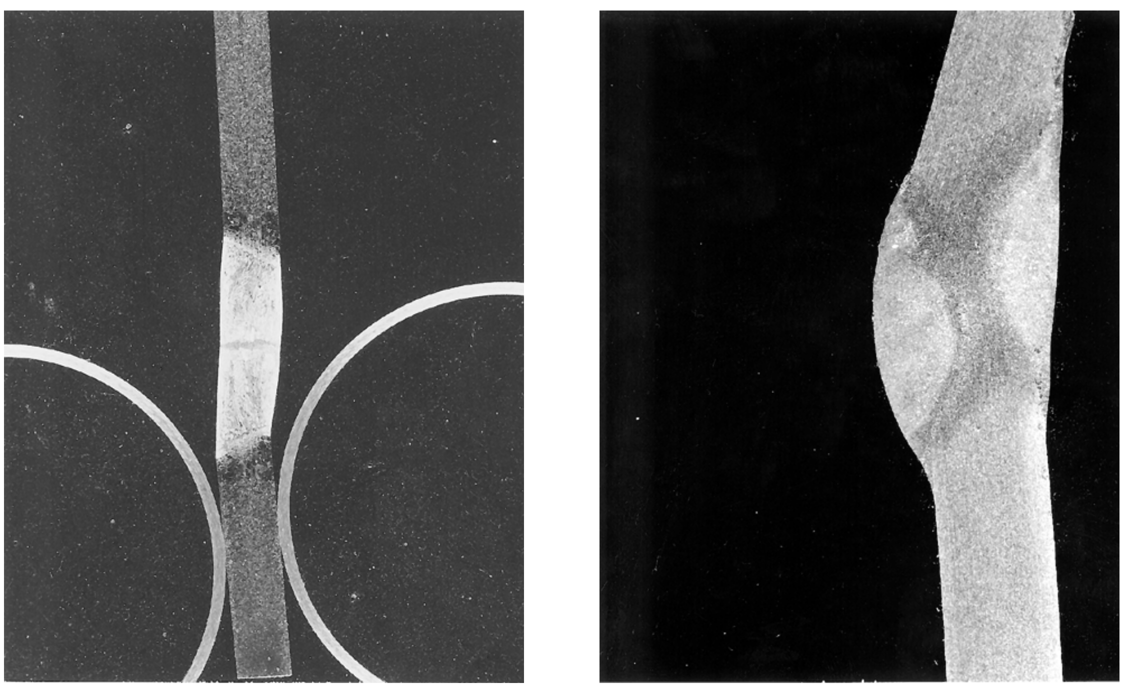


Figure 4. Lap weld configuration and positioning of welds within specimen gage, electron beam weld of Alloy 718 to Alloy 718.



A. B.

Figure 5. Welding induced distortion in butt welds a) autogeneous GTA weld joining Type 316L stainless steel to Type 316L stainless steel b) filler GTA weld joining 6061 Al to 6061 Al.

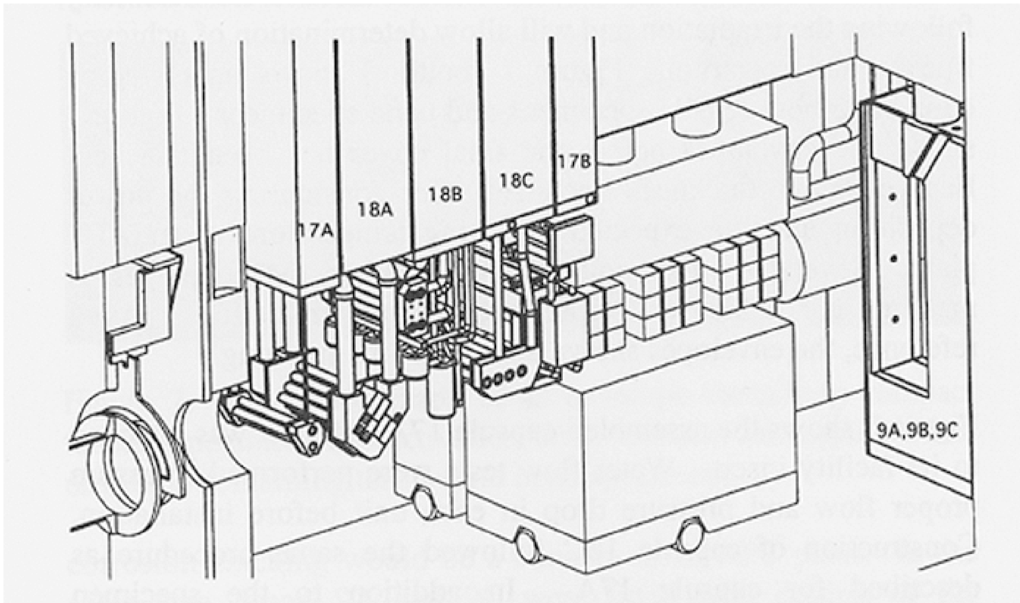


Figure 6. Arrangement of capsules used to expose specimens and components to the radiation environment at LASREF.

This is ORNL part of final project report which has been submitted to Los Alamos National Laboratory (LANL) (Stuart Maloy, LANL author) and will be published by LANL as combined laboratories Final Report.

Please contact Stuart Maloy, LANL or Janet P. Robertson (ORNL author) for additional information.