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FOR ITER FIRST WALL/BLANKET STRUCTURES***

David J. Alexander, Janet E. Pawel, Martin L. Grossbeck,
Arthur F. Rowcliffe, and Kiyoyuki Shibata†

Metals and Ceramics Division
OAK RIDGE NATIONAL LABORATORY
P.O. Box 2008
Oak Ridge, TN 37831-6151

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†Japan Atomic Energy Research Institute, Tokai-Mura, Japan.

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David J. Alexander,¹ Janet E. Pawel,¹ Martin L. Grossbeck,¹ Arthur F. Rowcliffe,¹ and Kiyoyuki Shiba²

FRACTURE TOUGHNESS OF IRRADIATED CANDIDATE MATERIALS FOR ITER FIRST WALL/BLANKET STRUCTURES

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ABSTRACT: Disk compact specimens of candidate materials for first wall/blanket structures in ITER have been irradiated to damage levels of about 3 dpa at nominal irradiation temperatures of either 90 or 250°C. These specimens have been tested over a temperature range from 20 to 250°C to determine J-integral values and tearing moduli. The results show that irradiation at these temperatures reduces the fracture toughness of austenitic stainless steels, but the toughness remains quite high. The toughness decreases as the test temperature increases. Irradiation at 250°C is more damaging than at 90°C, causing larger decreases in the fracture toughness. Ferritic-martensitic steels are embrittled by the irradiation, and show the lowest toughness at room temperature.

KEYWORDS: fracture toughness, austenitic stainless steels, disk compact, ferritic stainless steels, first wall/blanket structure, embrittlement, tearing modulus

Work is under way at Oak Ridge National Laboratory (ORNL) to evaluate the fracture toughness of candidate materials for first wall/blanket structure applications in the International Thermonuclear Experimental Reactor (ITER). A variety of austenitic stainless steels are being examined, as well as several additional materials. Specimens were fabricated from material in several different conditions, including annealed or cold

¹Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6151.

²Japan Atomic Energy Research Institute, Tokai-Mura, Japan.

worked, as well as weldments. These specimens have been irradiated in the High Flux Isotope Reactor (HFIR) at ORNL. To date, three capsules have been designed, fabricated, and irradiated to dose levels of approximately 3 dpa; this approaches the expected accumulated dose at the end of the Basic Performance Phase of operation of ITER. The helium concentration generated as a result of transmutation of nickel was about 50 appm; this is in the range expected for the ITER first wall blanket and shield structure after a neutron exposure of about 3 dpa. These capsules were designed for irradiation temperatures of either 60 to 125°C (capsules HFIR-MFE-JP-18 and -19) or 250 to 300°C (HFIR-MFE-JP-17) [1-3]. These temperatures covered the expected range of operating temperatures for stainless steel components in different ITER designs. All of the capsules have been successfully irradiated and disassembled. Some of the results of earlier testing have already been reported [4,5]. This paper presents the final results for all of the fracture toughness tests.

EXPERIMENTAL PROCEDURE

Four major alloy types were included in this experiment: American and Japanese type 316 steels (designated US316 and J316, respectively), a European type 316L steel (EC316L), and the JPCA alloy. The compositions of the alloys are given in Table 1. Specimens were in solution annealed (SA), cold-worked (CW), or welded conditions. The J316 material was also tested after a thermomechanical treatment in which it was strained, aged, and recrystallized (SAR). There were a total of 12 variants of the austenitic materials in composition and thermomechanical treatment. The EC316L was welded using 16-8-2 filler metal (see Table 1) and gas tungsten arc (GTA) welding with argon cover gas. Both the plate and the filler wire were provided by Joint Research Centre-Ispra from the European Fusion Stockpile. The JPCA and J316 plate material were supplied by the Japan Atomic Energy Research Institute. The JPCA specimens were welded with filler wire with a composition similar to the base metal (see Table 1) for the GTA welding. The US316 material was an air-melted heat from the U.S. fusion program, reference heat X15893. Two ferritic-martensitic steels were also included in this experiment, HT-9 and F82H.

In order to utilize the HFIR target region for the irradiations, the specimen size was severely limited. Therefore, a small disk compact specimen was selected for the fracture toughness experiments. Techniques were developed for generating the J-integral resistance (J-R) curve using either unloading compliance (UC) or potential drop (PD) to monitor crack extension [6,7]. Initial trials showed that either method could be used to develop useful fracture toughness data from these small specimens [6-8]. As a result of the success of the laboratory trials, it was decided to use the unloading compliance technique for testing the irradiated specimens.

The disk compact specimens [designated 0.18T DC(T)] were 12.5 mm in diameter by 4.63 mm thick. All specimens were fabricated from the middle of the thickness of the parent plates of material, with the notch oriented so that crack growth would occur parallel

TABLE 1--Specimen alloy compositions and processing

Alloy	Composition (wt %)											
	Fe	Ni	Cr	Ti	Mo	Mn	Si	C	N	V	W	Ta
JPCA	Bal	15.95	14.3	0.21	2.4	1.6	0.54	0.064	0.003	--	--	--
US316	Bal	12.4	17.3	--	2.1	1.7	0.67	0.061	--	--	--	--
EC316L	Bal	12.3	17.4	--	2.3	1.8	0.46	0.024	0.06	--	--	--
J316	Bal	13.95	16.77	--	2.31	0.23	0.04	0.038	0.011	--	--	--
16-8-2 weld wire	Bal	8.98	16.28	--	2.16	1.82	0.060	0.036	0.029	--	--	--
JPCA weld wire	Bal	16.06	14.39	0.23	2.44	1.77	0.35	0.057	0.0095	--	--	--
HT-9	Bal	0.51	12.1	--	1.04	0.57	0.17	0.20	0.027	0.28	0.45	--
F82H	Bal	0.05	7.65	--	--	0.49	0.09	0.093	0.0018	0.18	1.98	0.038

JPCA Annealed: Solution annealed (1120°C/1 h/water quench).
JPCA Cold Worked: Annealed + cold worked 20%.
J316 Annealed: Solution annealed (1060°C/15 min/water quench).
J316 Cold Worked: Annealed + cold worked 20%.
J316 Strained, Aged, Recrystallized: 1150°C/1 h + 60% cold work + 650°C/15 h + 800°C/15 h.
EC316L Annealed: Solution annealed.
US316 Annealed: Cold worked 50% + annealed (1050°C/1 h).
US316 Cold Worked: Annealed + 20% cold work.
HT-9: 1050°C/1 h/air cooled + 780°C/2.5 h/air cooled.
F82H: 1040°C/0.5 h + 740°C/1.5 h/air cooled.

to the rolling direction (T-L orientation). The specimens were fatigue precracked at room temperature to a crack length to specimen width ratio (a/W) of roughly 0.5 and then side grooved 10% of their thickness on each side, prior to irradiation. Filler pieces were inserted in the loading holes and in the notches to reduce disturbances in the flow of cooling water over the specimens in the capsule and to improve the uniformity of heat transfer across the specimens.

The low-temperature capsules (HFIR-MFE-JP-18 and -19) [2] were shrouded type capsules with the fracture toughness specimens directly cooled on their flat faces by reactor cooling water. Predicted temperatures over the crack-tip region of the fracture toughness specimens ranged from approximately 60 to 85°C near the ends of the capsule to 65 to 125°C near the middle. For convenience, specimens from these capsules are referred to as 90°C specimens. The higher temperature capsule (HFIR-MFE-JP-17) [3] was of the shrouded type cooled by reactor cooling water flowing between a cladding tube that contained the specimens in a helium atmosphere and a shroud tube. This capsule featured a unique thermal design in that, over the middle portion of the test length, aluminum cooling spacers of varying thicknesses were employed between the fracture toughness specimens to achieve predicted specimen temperatures for the crack region between 250 and 300°C. For convenience, specimens from this capsule are referred to as 250°C specimens. Capsules JP-18 and -19 completed their irradiations in October 1991, and capsule JP-17 completed its irradiation in February 1992 [3]. After disassembly of the capsules, the inserts in the individual specimens were pushed out of the loading holes using an arbor press and punch. The filler in the notch was removed with the aid of a hammer and a thinned screwdriver blade.

Tests were conducted in general accordance with American Society for Testing and Materials standards E 813-89, Standard Test Method for J_k , A Measure of Fracture Toughness, and E 1152-87, Standard Test Method for Determining J-R Curves. The equations in E 1152-87 were used for the J calculations. The specimens were tested with a computer-controlled testing and data acquisition system [9]. Tests in the laboratory used an 89-kN capacity servohydraulic test machine. In the hot cell, a 445-kN capacity servohydraulic testing machine with a 22-kN load cell was used. All tests were run in strain control. The displacements were measured with an "outboard" clip gage that seated in grooves machined on the outer edge of the specimen along the load line [6,7]. This arrangement provided very good load-displacement and UC results. Test temperatures from 90 to 250°C were maintained within $\pm 2^\circ\text{C}$ of the desired temperature with a split-box furnace that enclosed the specimen and the grips during the test. Temperature was monitored throughout the testing with a thermocouple that was held in contact with the specimen by a spring-loaded clip. Tensile data from specimens included in the capsules were used for calculations in the J-R analyses.¹ Estimated values were taken from literature data when necessary.

¹Pawel, J. E., unpublished research, Oak Ridge National Laboratory, 1994.

After testing, the specimens were heat tinted by placing them on a hot plate and heating them until a noticeable color change had occurred. The specimens were cooled to room temperature and then broken open. The initial and final crack lengths for the unirradiated specimens were measured with an optical measuring microscope. For the irradiated specimens, photographs of the fracture surfaces were fastened to a digitizing tablet to measure the crack lengths.

Materials with very high toughness and low yield strength, such as the annealed austenitic stainless steels, proved to be more difficult to test than material with lower toughness such as HT-9. The soft, tough materials showed enormous crack-tip blunting before stable crack growth began. This resulted in gross changes in the specimen geometry, and so the crack length predictions were not very accurate. The *J*-*R* curve was much steeper than the calculated blunting line. In these cases, the data were used to calculate a blunting line. A straight line was fit by eye through the initial portion of the data points, and a second line was drawn parallel to the first but offset by an amount corresponding to a crack extension of 0.2 mm following ASTM E 813-89. The candidate toughness value J_Q was then determined from the intersection of the data with this offset line. In cases where the data rose very steeply, the test was terminated before there was enough crack growth to cross the second exclusion line (drawn corresponding to a crack extension of 1.5 mm as defined in ASTM E 813-89). As a result, no tearing modulus value could be calculated. Materials with lower toughness, such as the cold-worked austenitic stainless steels, behaved in a much more conventional manner. For these materials, the data followed the calculated blunting line quite closely, so no additional construction was required. These specimens also showed very good agreement between the measured and predicted final crack lengths.

RESULTS AND DISCUSSION

The results of the testing are given in Tables 2 to 6. These tables also include the tensile values used in the analyses. Radiation increases the yield and ultimate tensile strengths, with irradiation at 250°C causing a greater increase than at 90°C. The yield and tensile strengths decrease as the test temperature increases. The critical stress intensities calculated from the candidate *J* values for the various alloys are summarized in Figs. 1 to 8 as a function of test temperature. These figures show that the toughness of the austenitic steels is very high. In general, the toughness decreases as the test temperature increases, but remains very high.

Both before and after irradiation, the fracture toughnesses of the solution annealed materials, as shown in Figs. 1, 3, and 5, are very high ($K_{Ic} > 150 \text{ MPa}\sqrt{\text{m}}$) in the test temperature range. The toughness decreases slightly as the temperature increases, but remains very high, even after irradiation and testing at 250°C. The EC316L and J316 annealed steels show only a slight decrease in toughness (50 to 100 $\text{MPa}\sqrt{\text{m}}$) after irradiation. The JPCA annealed material undergoes a larger decrease in toughness (100 to 200 $\text{MPa}\sqrt{\text{m}}$) after irradiation (Fig. 5). Even in this case, the toughness is still high,

TABLE 2--Fracture toughness and tensile properties of EC316L

Material	Specimen	Irradiation temperature (°C)	Test temperature (°C)	J_Q (kJ/m ²)	K_J^a (MPa√m)	T	σ_y (MPa)	σ_u (MPa)	E (GPa)
EC316L Annealed	FA14	Unirradiated	22	847	404	NA	296 ^b	579	193
	FA22	Unirradiated	100	889	407	NA	283 ^b	517	186
	FA5	Unirradiated	200	697	353	NA	214 ^b	448	179
EC316L Annealed	FA16	90	25	781	388	107	625	700	193
	FA3	90	25	800	393	93	625	700	193
	FA21	90	25	634	350	135	625	700	193
	FA6	90	100	671	353	129	607 ^b	676	186
	FA11	90	100	574	327	92	607 ^b	676	186
	FA17	90	200	548	314	221	525	600	179
EC316L Annealed	FA2	250	25	417	284	39	850	860	193
	FA10	250	100	387	268	38	800	810	186
	FA9	250	250	257	214	47	741 ^b	748	179
	FA18	250	250	353	252	42	741 ^b	748	179
EC316L PERP ^c	FS4	Unirradiated	90	831	393	NA	283	517	186
EC316L PERP ^c	FS1	90	90	512	309	102	607	676	186
EC316L Weld	FB3	Unirradiated	22	772	386	NA	310 ^b	614	193
	FB14	Unirradiated	90	710	363	NA	221 ^b	476	186
	FB17	Unirradiated	250	610	331	NA	241 ^b	448	179
EC316L Weld	FB4	90	90	341	252	109	627 ^b	703	186
EC316L Weld	FB5	250	250	160	170	29	741	748	179
	FB13	250	250	152	165	23	741	748	179

^a $K_J^2 = J_Q E$.

^bData from tensile test from these experiments.

^cPERP = Specimens oriented so that crack growth was perpendicular to the rolling direction.

TABLE 3--Fracture toughness and tensile properties of J316

Material	Specimen	Irradiation temperature (°C)	Test temperature (°C)	J_Q (kJ/m ²)	K_J^a (MPa√m)	T	σ_y (MPa)	σ_u (MPa)	E (GPa)
J316 Annealed	FC8	Unirradiated	22	790	391	NA	100	450	193
	FC24	Unirradiated	90	959	423	NA	90 ^b	427	186
	FC21	Unirradiated	250	843	388	NA	62 ^b	372	179
J316 Annealed	FC12	90	90	737	370	100	689 ^b	696	186
	FC16	90	250	620	333	99	600	625	179
J316 Annealed	FC10	250	90	453	291	59	825	850	186
	FC2	250	250	333	244	55	750	775	179
J316 SAR ^c	FM5	Unirradiated	22	595	339	103	525	650	193
	FM8	Unirradiated	90	548	319	63	517 ^b	634	186
	FM9	Unirradiated	250	392	265	107	455	559	179
J316 SAR ^c	FM11	90	90	263	221	36	690	696	186
J316 SAR ^c	FM2	250	250	170	175	28	750	775	179
J316 CW ^d	FD7	Unirradiated	22	870	410	71	717 ^b	765	193
	FD5	Unirradiated	90	591	332	101	593 ^b	641	186
	FD1	Unirradiated	250	328	243	89	572 ^b	607	179
J316 CW ^d	FD12	90	90	479	299	46	827 ^b	841	186
	FD8	90	250	302	233	40	725	750	179
J316 CW ^d	FD10	250	90	271	225	40	889 ^b	938	186
	FD11	250	250	138	157	18	821 ^b	827	179

^a $K_J^2 = J_Q E$.
^bData from tensile test from this experiment.
^cSAR = Strained, aged, and recrystallized.
^dCW = Cold worked 20%.

TABLE 4--Fracture toughness and tensile properties of JPCA

Material	Specimen	Irradiation temperature (°C)	Test temperature (°C)	J_Q (kJ/m ²)	K_J^a (MPa√m)	T	σ_y (MPa)	σ_u (MPa)	E (GPa)
JPCA Annealed	FF10	Unirradiated	22	616	345	NA	331 ^b	600	193
	FF13	Unirradiated	100	706	363	158	269 ^b	510	186
	FF20	Unirradiated	200	498	299	82	269 ^b	483	179
JPCA Annealed	FF6	90	25	349	260	23	750	770	193
	FF5	90	25	355	262	41	750	770	193
	FF16	90	100	310	240	34	717 ^b	738	186
	FF15	90	100	312	241	31	717 ^b	738	186
	FF2	90	200	225	201	46	614 ^b	634	179
JPCA Annealed	FF3	250	25	271	229	18	900	950	193
	FF11	250	100	133	157	13	862 ^b	910	186
	FF18	250	250	123	148	14	779 ^b	827	179
JPCA EBW ^c	FR7	Unirradiated	250	619	333	NA	269	483	179
JPCA EBW ^c	FR11	90	90	885	406	101	717	738	186
JPCA EBW ^c	FR12	250	250	315	238	52	779	827	179
JPCA CW ^d	FE6	Unirradiated	22	365	266	45	625	650	193
	FE3	Unirradiated	90	306	239	55	600 ^b	627	186
	FE1	Unirradiated	250	181	180	82	524 ^b	572	179
JPCA CW ^d	FE8	90	90	167	176	24	931 ^b	952	186
JPCA CW ^d	FE7	250	250	124	149	8	868 ^b	896	179
JPCA Weld	FG10	Unirradiated	22	655	356	NA	331	600	193
	FG13	Unirradiated	90	1020	436	NA	269	510	186
	FG1	Unirradiated	250	959	415	NA	269	483	179
JPCA Weld	FG8	90	90	316	242	46	717	738	186
JPCA Weld	FG12	250	250	234	205	27	779	827	179

^a $K_J^2 = J_Q E$.^bData from tensile test from these experiments.^cEBW = Electron beam weld.^dCW = Cold worked 20%.

TABLE 5--Fracture toughness and tensile properties of US316

Material	Specimen	Irradiation temperature (°C)	Test temperature (°C)	J_Q (kJ/m ²)	K_J^a (MPa√m)	T	σ_y (MPa)	σ_u (MPa)	E (GPa)
US316 Annealed	FK16	Unirradiated	22	234	213	79	262 ^b	607	193
	FK6	Unirradiated	90	235	209	76	186 ^b	510	186
	FK8	Unirradiated	250	213	195	88	152 ^b	462	179
US316 Annealed	FK7	90	90	156	171	17	500	550	186
US316 Annealed	FK10	250	250	36	80	6	650	700	179
US316 CW ^c	FL13	Unirradiated	22	35	82	4	683 ^b	793	193
	FL8	Unirradiated	90	34	80	0	662 ^b	724	186
	FL9	Unirradiated	250	28	71	-	572 ^b	648	179
US316 CW ^c	FL15	90	90	22	64	0	848 ^b	862	186
US316 CW ^c	FL5	250	250	15	52	0	825	850	179

^a $K_J^2 = J_Q E$.
^bData from tensile test from these experiments.
^cCW = Cold worked 20%.

TABLE 6--Fracture toughness and tensile properties of ferritic-martensitic alloys

Material	Specimen	Irradiation temperature (°C)	Test temperature (°C)	J_Q (kJ/m ²)	K_J^a (MPa√m)	T	σ_y (MPa)	σ_u (MPa)	E (GPa)
HT-9	FH11	Unirradiated	22	484	316	104	476 ^b	696	207
	FH3	Unirradiated	90	470	307	91	414 ^b	621	200
	FH4	Unirradiated	250	415	283	131	427 ^b	627	193
HT-9	FH1	90	90	283	238	41	903 ^b	917	200
HT-9	FH5	250	25	5	31	-	950	1000	207
	FH6	250	250	140	164	17	876 ^b	931	193
F82H	FI3	Unirradiated	250	334	254	122	448 ^b	531	193
F82H	FI4	250	25	117	156	-	950	975	207
	FI1	250	250	197	195	22	855 ^b	855	193

^a $K_J^2 = J_Q E$.

^bData from tensile specimen from these experiments.

FIG. 1--Fracture toughness values for annealed EC316L. Also shown are data (solid symbols) for two specimens oriented perpendicular to the rolling direction (PERP).

FIG. 2--Fracture toughness values for the gas tungsten-arc (GTA) weldment in EC316L base metal.

FIG. 3--Fracture toughness values for J316 in the annealed condition (open symbols) and the strained, aged, and recrystallized (SAR) condition (solid symbols).

FIG. 4--Fracture toughness values for cold-worked J316.

FIG. 5--Fracture toughness values for JPCA in the annealed condition (open symbols) and after 20% cold work (solid symbols).

FIG. 6--Fracture toughness for the gas tungsten-arc (GTA) weldment (open symbols) and electron-beam weldments (solid symbols) in JPCA.

FIG. 7--Fracture toughness for US316 in the annealed condition (open symbols) and after 20% cold work (solid symbols).

FIG. 8--Fracture toughness for ferritic-martensitic steels HT-9 (open symbols) and F82H (solid symbols).

with a K_I value of 150 MPa $\sqrt{m}$ (Table 4). The US316 material has the lowest toughness both before and after irradiation (Fig. 7). This heat of material was air melted and contains an unusually high volume fraction of nonmetallic inclusions which are likely to promote rapid microvoid growth and coalescence.

The fracture toughness of the cold-worked material is generally lower than that of the annealed material, typically by about 75 to 100 MPa $\sqrt{m}$, both before and after irradiation. One exception is the JPCA material irradiated and tested at 250°C, for which the annealed and cold-worked materials had almost identical toughnesses (see Table 4). In all cases, the fracture toughnesses of the cold-worked JPCA and J316 materials remain high. The US316 material, which had the lowest toughness of the austenitic steels in the solution annealed condition, also had by far the lowest toughness values of the cold-worked materials, about 65 MPa $\sqrt{m}$. This material also had very low values of tearing modulus (Table 5).

Electron beam welds of JPCA (Table 4, Fig. 6) and GTA welds of JPCA (Table 4, Fig. 6) and EC316L (Table 2, Fig. 2) proved to be very tough, both before and after irradiation. The JPCA GTA welded material had approximately the same toughness as the JPCA SA material ($K_I \approx 240$ MPa $\sqrt{m}$) after irradiation and testing at 90°C, while the JPCA EB-welded material had an even higher toughness.

The EC316L material contained a small volume fraction (~3%) of ferrite stringers running along the rolling direction of the plate. However, it was found that specimens with the crack propagation direction parallel to the direction of the delta ferrite stringers had essentially the same toughness as specimens with the crack propagation perpendicular to the stringer direction. These specimens are identified as "PERP" (since they were oriented perpendicular to the rolling direction) in Table 2 and Fig. 1.

The J-R curves for specimens of EC316L, J316, and JPCA, all in the annealed condition, are shown in Figs. 9 to 11. The J316 material shows the smallest degradation in toughness and the JPCA alloy shows the greatest decrease. After irradiation, the J-R curves have a lower slope, which reflects the lower values of tearing modulus given in Tables 2 to 4. The toughness level decreases with increasing test temperature.

The fracture toughness of the ferritic materials is also reduced by these irradiations. The F82H alloy is more resistant to damage than the HT-9 material. Both of these alloys show high toughness at high test temperatures (250°C) with lower toughness at 25°C (Fig. 8). The HT-9 specimen irradiated at 250°C fractured in a brittle manner when tested at room temperature. The load-displacement trace was linear, and the value of the fracture toughness (31 MPa $\sqrt{m}$) is so low that it satisfies the specimen thickness validity criteria for plane strain fracture toughness, despite the very small specimen size. The F82H specimen irradiated at 250°C and tested at 25°C also showed a lower toughness than when tested at 250°C, but the load-displacement curve showed considerable nonlinearity and the final fracture, although unstable, occurred at a high toughness level of 156 MPa $\sqrt{m}$.

FIG. 9--J-R curves for annealed EC316L material in the unirradiated condition (top), and after irradiation at 90°C (middle) and 250°C (bottom).

FIG. 10--J-R curves for annealed J316 material in the unirradiated condition (top), and after irradiation at 90°C (middle) and 250°C (bottom).

FIG. 11--J-R curves for annealed JPCA material in the unirradiated condition (top), and after irradiation at 90°C (middle) and 250°C (bottom).

Comparison with Literature Data

There are surprisingly little data available for comparison with these results. These stainless steel alloys are very tough, and so the fracture toughness is not usually a concern. Odette and Lucas [10-12], Tavassoli [13], and Boutard [14] have recently surveyed the available data for the effects of low temperature irradiation ($< 400^{\circ}\text{C}$) on the mechanical properties, including the fracture toughness, of austenitic stainless steels. There are very little data that are directly comparable to the present work, but the overall trend of the data shows that although irradiation reduces the fracture toughness, it still remains high, in agreement with the present results.

Several researchers have reported fracture toughness tests of unirradiated austenitic stainless steels, including 304 and several variants of 316 and similar steels [15-21]. At room temperature, the fracture toughness values reported for 316L range from about 200 to 400 kJ/m^2 [15,16] to well over 1000 kJ/m^2 [17-19]. Toughnesses of 304 are generally greater [15,20]. The fracture toughness decreases at higher test temperatures [18,19,21]. Irradiation to low doses has little effect on the toughness [16,20,21] but does degrade the toughness at higher doses [15,19,20].

A trend line of toughness versus irradiation dose is shown in Fig. 12, adapted from the review article by Lucas [22]. This represents data for a variety of wrought materials irradiated at temperatures from 290 to 430 $^{\circ}\text{C}$, slightly higher temperatures than in the present work. After a rapid initial decrease, the minimum toughness values (note that K_{I} values are shown) approach 50 $\text{MPa}\sqrt{\text{m}}$ for doses beyond 10 dpa. Also shown are data from Sindelar et al. [20] for a 1950s-vintage type 304 stainless steel irradiated at 100 to 155 $^{\circ}\text{C}$ to doses up to 2 dpa. The data from the present work fall into two groups. Results from the higher irradiation temperature (250 to 300 $^{\circ}\text{C}$) are consistent with the published data represented by the trend line which indicates toughness values in the range of 200 to 250 $\text{MPa}\sqrt{\text{m}}$ for doses up to 3 dpa. For the lower irradiation temperature (60 to 125 $^{\circ}\text{C}$) the reduction in fracture toughness is significantly less with the data falling well above the trend line. This is likely the result of a different microstructural response to irradiation, and a reduced level of irradiation hardening for the same dose as compared to higher temperature irradiation. The data of Sindelar et al. [20] fall well below the present data for low temperature irradiation, likely reflecting the greater sensitivity to irradiation damage of the 1950s-vintage heat of type 304 stainless steel.

The fracture toughness of welds in austenitic stainless steels has also been examined [15,16,18-20,23,24]. In general, the welds show lower initial toughnesses and a greater response to irradiation than do the base metals.

Jitsukawa has reported fracture toughness measurements on the JPCA material [25]. In the solution-annealed condition the toughness ranged from 770 to 1000 kJ/m^2 . It decreased to 300 to 340 kJ/m^2 after 15% cold work and to 165 to 175 kJ/m^2 after 40% cold work. These values are similar to the present results.

FIG. 12--Trend line of fracture toughness versus irradiation dose in dpa, adapted from Lucas [22], for a range of austenitic stainless steels, irradiation temperatures, and test temperatures. Also shown are data from the present work and results from Sindelar et al. [20] for comparison.

Huang and Hamilton [26] have summarized their work on the effects of irradiation on the toughness of HT-9. The limited results for unirradiated material show toughness values that decrease from 100 to about 50 kJ/m^2 as the test temperature increases from 24 to 316°C. After irradiation at 55°C to 5 dpa, the toughness decreases to about 50 kJ/m^2 for test temperatures from 25 to 205°C. This is very different from the present results, which show fracture toughnesses of over 400 kJ/m^2 for unirradiated material tested from 25 to 250°C. The apparent reason for the difference is the different heat treatments used in the two investigations, as reflected in the very different yield strengths. The material tested by Huang was tempered at 750°C for 1 h, while the present work used 780°C for 2.5 h. As a result, the yield strength at room temperature for Huang's material was 621 MPa as compared to the present 476 MPa (see Table 6). The lower yield strength agrees with the higher toughnesses. After irradiation at 90°C to 3 dpa, the yield strength at 90°C for the material in the present work rises to 903 MPa, similar to the value reported by Huang of 954 MPa for material irradiated to 5 dpa at 55°C and tested at 93°C, but the toughness of the present material is still much higher (283 kJ/m^2) than Huang observed (52 kJ/m^2 at 93°C).

The toughnesses for unirradiated HT-9 reported by Huang are similar to data from Hawthorne [27]. Other data from Hawthorne et al. [28] generated with precracked Charpy specimens show higher toughnesses of about 230 MPa√m for specimens in the upper-shelf (i.e. higher toughness) regime. These latter data also show that irradiation at 93°C is much more damaging than irradiation at 288 or 300°C. The present work shows that irradiation at 250°C is more damaging than irradiation at 90°C for austenitic alloys. The present results suggest this is also true for the ferritic alloys in this study, but the data are too sparse to provide a definitive answer.

The fracture toughness of F82H has been measured by Li et al. [29]. They reported a value of about 430 kJ/m² at room temperature. This specimen had a narrow slit rather than a fatigue precrack. With a conventional precrack, the fracture toughness was lower, about 280 kJ/m² [30]. Although the heat treatments are slightly different, these values are similar to the limited data from the present work.

Comparison of Results with ASTM Validity Requirements

It should be pointed out that nearly all of the J-R data generated with this small disk compact specimen do not satisfy all of the validity requirements of the ASTM standards, and so, these data are not valid. ASTM E 1152-87 sets three limits based on the specimen size. The maximum J-integral measurement capacity is given by the smaller of

$$J_{\max} = b \sigma_y / 20, \text{ or} \quad (1)$$

$$J_{\max} = B \sigma_y / 20, \quad (2)$$

where b = initial ligament size,
 B = specimen thickness, and
 σ_y = flow stress (average of yield and ultimate tensile stresses).

If the crack length to specimen width ratio (a/W) is 0.5, these limits are identical, as b will equal B for this specimen, in this case. For nearly all of the data, the measured J-integral values greatly exceed this limit. Only the lowest toughness materials have J-integral values low enough to satisfy these conditions. However, there is another even more limiting condition. The maximum allowable crack extension is limited to $0.1b$. For an initial a/W value of 0.5, which was the intent, the resultant maximum allowable crack extension is only 0.46 mm, well short of the second exclusion line at 1.5 mm of crack extension. If the initial crack length is longer, as was nearly always the case, even less crack extension is allowed. Examination of the J-R curves in Figs. 9 to 11 shows that, for tough materials, these crack extensions are still on the blunting line, and stable tearing has not even begun to occur. Even for lower toughness conditions, i.e. annealed JPCA material

irradiated at 250°C (bottom of Fig. 11), only a few of the data points are valid, and the bulk of the J-R curve is beyond the limit of validity. The values given in Tables 2 to 6 have been generated by using all the data between the first and second exclusion lines to determine the curve fit for calculation of J_Q , even though these data are not valid according to ASTM E 1152-87.

It must be emphasized that the J-R data, despite being invalid according to ASTM E 1152, are not incorrect. The size limitations imposed are conservative, and the J-integral values are quite likely still true measures of the materials' toughness, as long as the limits are not exceeded by too great a margin. Previous work [7] has shown that the 0.18T DC(T) specimens gave results similar to data from 12.7-mm-thick compact [0.5T C(T)] specimens for the US316 material, and Jitsukawa [25] found good agreement between data generated with the 0.18T DC(T) specimen and 10-mm-thick compact [0.4T C(T)] specimens for 15% cold-worked JPCA material. The J-R curves are applicable to structures of the same thickness as the specimens. Additional work is needed to provide more information about specimen size effects for these tough materials.

The J-R curves are of great value in elucidating the materials' responses to irradiation. The J-R curves show how these materials are embrittled by irradiation as a function of irradiation temperature and damage level. They also show which materials are most resistant to embrittlement, and give an indication of the rate at which embrittlement will occur for the present irradiation and material conditions. These are very useful pieces of information for evaluating candidate structural materials for ITER applications.

CONCLUSIONS

Specimens of several austenitic stainless steels and two ferritic-martensitic steels have been irradiated in HFIR to about 3 dpa at nominal irradiation temperatures of 90 or 250°C. For the austenitic stainless steels, irradiation reduces the fracture toughness, and irradiation at 250°C is more damaging than irradiation at 90°C. The fracture toughness decreases with increasing test temperature, for all the austenitic materials. The annealed materials have higher toughnesses than the cold-worked materials. The toughness of the cold-worked materials is still high, with the exception of the US316 material. The welds also have high toughnesses. For the ferritic-martensitic materials, the specimens irradiated at 250°C and tested at room temperature fail in an unstable manner. The F82H has a higher toughness than the HT-9 alloy.

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