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FATIGUE AND FRACTURE RESISTANCE OF STAINLESS STEEL WELD DEPOSIT--ETC(U)
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NRL Report 8451

Fatigue and Fracture Resistance of Stainless Steel Weld Deposits After Elevated-Temperature Irradiation

J.R. HAWTHORNE

Thermostructural Materials Branch
Material Science and Technology Division

November 18, 1980

This research was supported by the Department of Energy.

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Report 8451	2. GOVT ACCESSION NO. AD-A093	3. RECIPIENT'S CATALOG NUMBER 090
4. TITLE (and Subtitle) FATIGUE AND FRACTURE RESISTANCE OF STAINLESS STEEL WELD DEPOSITS AFTER ELEVATED-TEMPERATURE IRRADIATION		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. R. Hawthorne		8. CONTRACT OR GRANT NUMBER(s) 28 NOV 80
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, DC 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DOE, EX-76-A-27-2110 NRL Problem 63-1062-0-0
11. CONTROLLING OFFICE NAME AND ADDRESS Department of Energy Division of Reactor Research and Technology Washington, DC 20545		12. REPORT DATE November 18, 1980
		13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) NRL-8451		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This research was supported by the Department of Energy.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Austenitic stainless steel	Fracture toughness	Radiation sensitivity
Charpy V-notch	Notch ductility	Shielded metal arc weldments
Delta ferrite	Nuclear reactors	Type 308-16 welds
Fatigue crack growth	Radiation embrittlement	Weld deposits

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The fatigue crack growth and fracture resistance of Type 308-16 austenitic stainless steel weld deposits were investigated for 427 and 649°C neutron irradiation conditions. The welds (63.5 mm thick) were made by the shielded metal arc process and depicted variations in delta ferrite content from ferrite number 5.2 to 19.0. Specimen irradiations were conducted in the EBR-II reactor in flowing and static sodium environments.

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20. Abstract (Continued)

Fatigue crack growth resistances at 427 and 649°C were determined with single-edge-notch (SEN) cantilever fatigue specimens tested in air with a zero-tension-zero loading cycle. Crack growth rates ~~(da/dN)~~ were related to the stress-intensity-factor range ~~(ΔK)~~. Effects of a tension hold time of 0.5 minute were explored relative to weld behavior under continuous load cycling conditions. Fracture resistance at elevated temperature was investigated through notch ductility and dynamic fracture toughness determinations by Charpy-V and fatigue-precracked Charpy-V test methods respectively.

Neutron fluences in the range 1 to 1.5×10^{22} n/cm^2, $E > 0.1$ MeV, were found to have a large detrimental effect on fatigue crack growth resistance for the 649°C irradiation condition but a beneficial effect for the 427°C irradiated condition. A large detrimental effect of 427°C irradiation on elevated-temperature fracture resistance was observed. The study also revealed that delta ferrite content and fatigue loading patterns can have a major influence on postirradiation fatigue crack growth trends.

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FATIGUE AND FRACTURE RESISTANCE OF STAINLESS STEEL WELD DEPOSITS AFTER ELEVATED-TEMPERATURE IRRADIATION

INTRODUCTION

Proposed designs of advanced nuclear power systems will make extensive use of welded austenitic stainless steels. In support of this application, in-depth studies of elevated-temperature mechanical properties are being made. The temperature range of interest extends to 650°C.

The present study focuses on the influence of delta ferrite content on the fatigue crack growth resistance and fracture resistance of E308-16 stainless steel weld deposits before and after nuclear irradiation. The investigations were prompted not only by the projected need of welding in breeder and fusion reactor systems but also by the early observations of large variations in fatigue and fracture properties among welds in exploratory tests [1,2]. A factor-of-ten difference in fatigue crack growth (FCG) rate, for example, was found between two supposedly identical weld deposits. Likewise, large differences in Charpy-V (C_v) notch ductility between welds and between parent metal (high) and weld metal (low) were noted. The isolation of contributing variables was therefore undertaken to improve weld consistency, thereby assisting the planned material applications. The studies of suspect metallurgical factors have, as a long-term objective, the development of guidelines for optimizing welds for the advanced system requirements.

Delta ferrite content is one of several welding variables having potential for influencing weld metal behavior. This report builds on earlier NRL studies of the as-welded condition in which the influences of delta ferrite content on FCG resistance under continuous fatigue cycling and weld metal notch ductility and strength were assessed [3,4]. The investigations did not reveal a major effect on these properties in the nonirradiated material state; however, positive indications of a delta ferrite contribution to fatigue resistance were recorded in initial tests of the irradiated condition. The present investigation shows more clearly the combined effect of neutron irradiation and delta ferrite content on weld properties. In addition, the study explores the significance of superimposed load hold times to FCG resistance and the significance of notch ductility degradation by irradiation in terms of reduced dynamic fracture toughness.

MATERIALS

The range of delta ferrite content of most interest in reactor applications is approximately from 5 to 15%. Materials employed in this investigation and the predecessor investigations [3,4] were from a series of four 63.5-mm-thick shielded metal arc welds (Type 304 base plate, Type 308-16 filler) which encompassed this range. The welds were obtained from

Manuscript submitted August 13, 1980.

the Arcos Corporation by contract; the electrode composition and coatings used were those developed by Arcos for a prior Metal Properties Council (MPC) project.

Chemical compositions of the weld deposits are listed in Table 1. Welding parameters and conditions are given in Ref. 3. Each weld was a full-thickness weld (19 mm minimum weld width); the root regions were air-arc back gouged and ground to all weld metal after layer seven. Welding was accomplished under full mechanical restraint; however, opposite faces were welded alternately in a sequence designed to minimize unbalanced stresses. Delta ferrite contents of the individual welds as determined by Magne-Gage were ferrite number (FN) 5.2, 10.4, 15.7, and 19.0. The welds were not given a postweld thermal treatment.

SPECIMEN DESIGN AND TESTING

Fatigue Tests

A single-edge-notch (SEN) cantilever specimen of the design shown in Fig. 1 was used for the FCG determinations. The plane of the fatigue crack was oriented parallel to the welding direction and perpendicular to the weldment surface. All specimens were composite specimens made by welding (electron-beam or metal-inert-gas process) end tabs to a center test section 55 X 64 X 13 mm in size. Comparisons of welded vs nonwelded specimens of similar materials (AISI Type 316 plate and welds) have indicated that test results from each are comparable [5].

All tests were conducted in air using a zero-tension-zero loading cycle with and without a 0.5-min tension hold period. Specimen temperatures were provided by induction heating and were monitored continuously by thermocouples. When a high rate of fatigue crack growth became evident, tests normally were interrupted during nonworking hours and were

Table 1 — Chemical Compositions of the Type 308-16 Shielded Metal Arc Weld Series With Variable Delta Ferrite Content

NRL Weld Code	Delta Ferrite Content[a]	Chemical Composition (wt-%)[b]								
		C	Mn	Si	P	S	Cr	Ni	Mo	N
V41[c]	5.2	0.056	1.88	0.32	0.024	0.011	19.71	10.35	0.05	0.068
V42	10.4	0.060	1.54	0.31	0.029	0.009	19.90	9.25	0.05	0.074
V43	15.7	0.060	1.65	0.32	0.029	0.011	20.89	9.11	0.06	0.079
V44	19.0	0.060	1.38	0.43	0.028	0.010	21.08	8.93	0.08	0.084

[a]Weld deposit ferrite number (avg); Magne-Gage determination.
[b]Composition based on standard WRC weld test pad (courtesy Arcos Corporation); core wire for all electrodes from same steel melt.
[c]0.07% Cu in weld deposit.

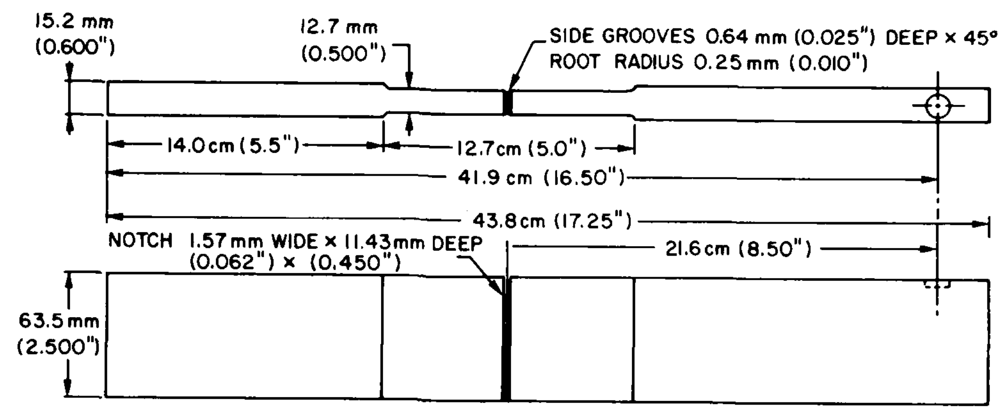

Fig. 1 — Design of the single-edge-notch (SEN) cantilever fatigue test specimen

resumed only after the specimens had again reached temperature. No noticeable effect of this procedure was seen in the data.

Crack length measurements were accomplished by means of a traveling microscope at a magnification of X35 or by means of a high-resolution, closed-circuit television system. The television system was used for those tests conducted remotely in the NRL hot-cell facility. Rates of crack growth were established from plots of crack length vs number of cycles by the ASTM-recommended incremental polynomial method. The method basically involves computer fitting, by least-squares criteria, seven consecutive data points (N_{i-3} to N_{i+3}) to a second order polynomial. The polynomial in turn is differentiated to yield da/dN to the N_ith point.

The SEN specimen crack growth rates (da/dN) were related to stress-intensity-factor range (ΔK) using the expression for K for pure bending developed by Gross and Srawley [6]:

$$K = \frac{6PL}{(BB_n)^{1/2} W^{3/2}} Y , \qquad (1)$$

where $Y = 1.99\,(a/W)^{1/2} - 2.47\,(a/W)^{3/2} + 12.97\,(a/W)^{5/2} - 23.17\,(a/W)^{7/2} + 24.80\,(a/W)^{9/2}$, and where P is the cyclic load, L is the distance from the crack plane to the point of load application, a is the total length of notch and crack, W is the specimen width, B is the specimen thickness, and B_n is the net thickness between the specimen side grooves. A correction for plasticity at the crack tip was not made. Tests normally were terminated when the total flaw length a reached about 38 mm.

Fracture-Resistance Tests

Standard Charpy V-notch (C_v) specimens, ASTM Type A, were used for the notch ductility determinations. Tests were conducted in accordance with ASTM Recommended

Practice E-23. Fatigue precracked Charpy-V (PCC_v) specimens were used for the dynamic fracture toughness (K_J) determinations. Specifications for fatigue precracking called for a specimen crack length-to-width ratio (a/W) of 0.5; the maximum allowable stress intensity (K_1) during the last increment (0.76 mm) of fatigue crack growth was 22 $MPa\sqrt{m}$ or 20 $ksi\sqrt{in}$. The PCC_v testing was in conformance with standard procedures developed by the Electric Power Research Institute (EPRI) for K_J determinations [7]. All K_J determinations given in this report are based on energy absorbed to maximum load, corrected for specimen and test-machine compliance. In this regard, K_J values as computed would tend to overestimate the K_J at crack initiation if some stable, i.e., rising load, crack extension takes place before the attainment of maximum load.

MATERIAL IRRADIATION

Material irradiations were conducted in the EBR-II reactor in two experiments. One experiment, number H-8, used a controlled-temperature heat pipe irradiation assembly in which the specimens were immersed during irradiation in static sodium at ~649°C. This temperature condition, as noted above, lies at the upper end of the temperature range of interest. The second experiment, H-11, was not of a controlled-temperature design but placed the specimens in direct contact with the flowing sodium reactor coolant at ~427°C. Radiation-effects processes at this nominal temperature are significantly different from those at 649°C [8]. Target neutron fluences were 1×10^{22} $n/cm^2 (E > 0.1$ MeV) at 649°C and 1.5×10^{22} n/cm^2 at 427°C. Other experiment details are provided in Table 2.

FATIGUE CRACK GROWTH INVESTIGATIONS

Test Matrix

The test matrix employed for the current FCG investigations is outlined in Table 3. Test temperatures are observed to match the nominal irradiation temperatures. In the case of unirradiated condition assessments, the earlier investigations included tests at 260°C in addition to 427° and 649°C for broad-range temperature comparisons. A tendency toward lower FCG rates at this temperature compared to 427° or 649°C was discerned in the data.

Reference tests are those conducted with continuous cycling at 10 cycles/min (0.17 Hz) in a tension-zero-tension sawtooth mode. Hold-time tests used the same loading and unloading rates as the reference tests but included a 0.5-min hold in tension for a 2 cycles/min (0.03 Hz) cycling rate.

Results

Data developed by tests at 649° and 427°C are presented in Figs. 2 to 4 and Figs. 5 to 7, respectively. For reference, delta ferrite content variations within the range investigated did not result in a major difference in FCG rates in the unirradiated condition at

Table 2 — Material Irradiation Experiments

Exp. No.	EBR-II Subassembly	Subassembly Design	Specimen Types	Irrad. Temp. (°C)[a]	Fluence Target (10^{22} n/cm^2)[b]	Period of Irradn(h)	Period in Reactor(h)
H-8	X-266 (8F5)[c]	Heat Pipe	SEN, PCC_v	649	1.0	3110	~6000
H-11	X-322 (3E2 + 2D1)[c]	Open	SEN, PCC_v C_v, Tensile	427	1.5	2100	~2500

[a]Nominal irradiation temperature.
[b]$E > 0.1$ MeV.
[c]Fuel core position.

Table 3 — Experimental Test Matrix (SEN Specimens)

Weld Code	Ferrite Number	427°C Test		649°C Test	
		0.0-min Hold[a]	0.5 min Hold	0.0 min Hold[a]	0.5 min Hold
Unirradiated Condition					
V41	5.2	6[d]	5	7	—
V42	10.4	6	8	3	7
V43	15.7	5	—	6	—
V44	19.0	6	7	3	12
Irradiated Condition[b,c]					
V41	5.2	—	4	—	—
V42	10.4	5	4	2	1
V44	19.0	4	5	1	2

[a]Prior test series, continuous cycling mode.
[b]427°C tests for experiment H-11.
[c]649°C tests for experiment H-8.
[d]Specimen identification number.

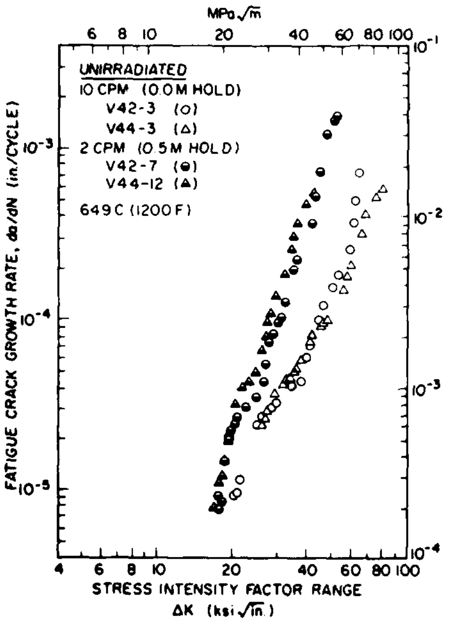

Fig. 2 — Fatigue crack growth rates of the welds V42 and V44 at 649°C in unirradiated (as-welded) condition. Data for continuous cycling (10 cpm) and cycling with a 0.5-min (M) tension hold time (2 cpm) are shown.

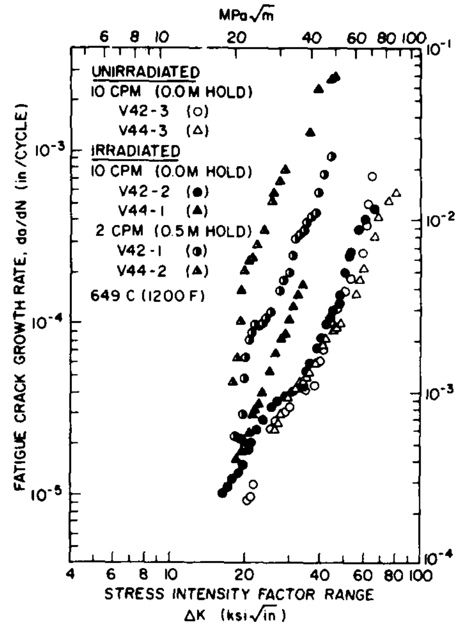

Fig. 3 — Fatigue crack growth rates of the welds V42 and V44 at 649°C in the unirradiated and 649°C irradiated conditions. Data for the irradiated condition are for continuous cycling and for cycling with a 0.5-min tension hold time; the data for the unirradiated condition are for the continuous cycling mode.

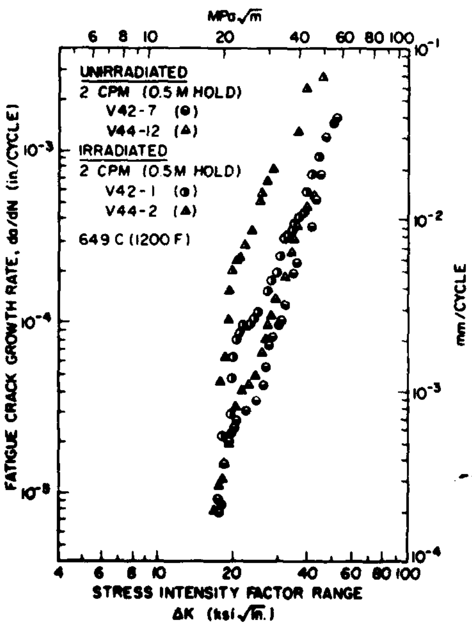

Fig. 4 — Fatigue crack growth rates of the welds V42 and V44 at 649°C in the unirradiated and 649°C irradiated conditions for the case of fatigue cycling with a 0.5-min tension hold time only.

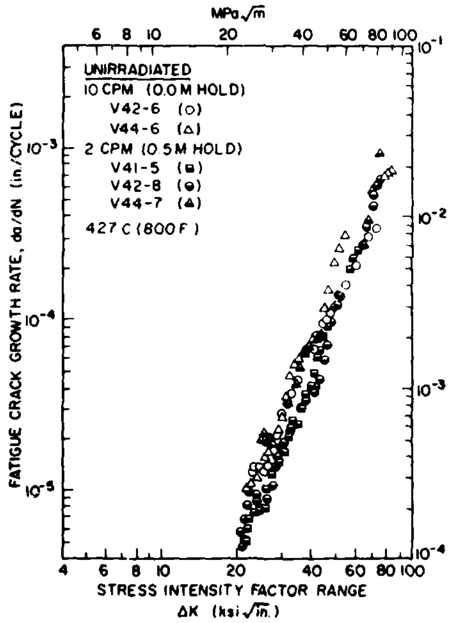

Fig. 5 — Fatigue crack growth rates of the welds V41, V42, and V44 at 427°C in the unirradiated condition. Data for continuous cycling and cycling with a 0.5-min tension hold time are shown. (Reference condition data for weld V41 fell within the data scatter band and have been omitted for clarity.)

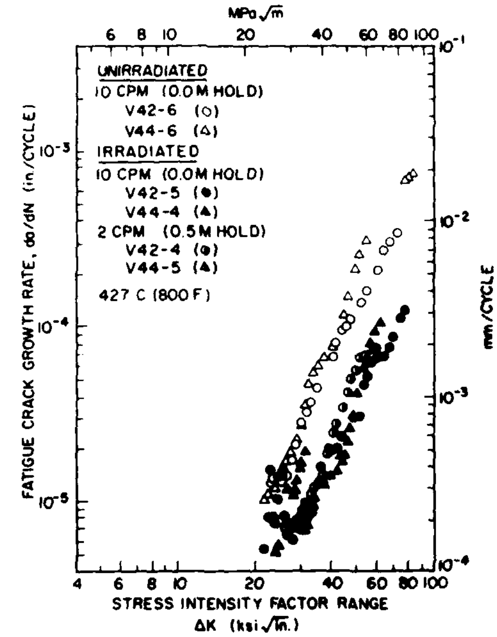

Fig. 6 — Fatigue crack growth rates of the welds V42 and V44 at 427°C in the unirradiated and 427°C irradiated conditions. Data for the irradiated condition are for continuous cycling and for cycling with a 0.5-min tension hold time; the data for the unirradiated condition are for the continuous cycling mode.

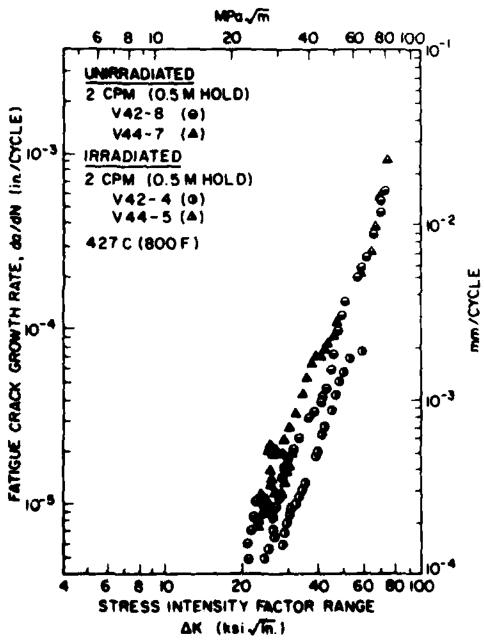

Fig. 7 — Fatigue crack growth rates of the welds V42 and V44 at 427°C in the unirradiated and 427°C irradiated conditions for the case of fatigue cycling with a 0.5-min tension hold time only.

either 260°, 427°, or 649°C when cycling was continuous at 10 cycles/min (cpm), i.e., without a tension hold period [4] (see Figs. 2 and 5).

Comparisons of the new data against the reference data provide these additional observations:

Tension hold time: A 0.5-min tension hold time produces a detrimental effect on FCG resistance at 649°C but not at 427°C in the unirradiated condition (see Figs. 2 and 5, respectively). For the irradiated condition, a detrimental effect is observed for the tension hold time in 649° and 427°C tests (see Figs. 3 and 6), the magnitude of which at the higher temperature is clearly dependent on delta ferrite content.

Neutron exposure: Neutron irradiation at 649°C produced an increase in FCG rate at 649°C both for the continuous cycling mode and for cycling with the 0.5-min tension hold time (Figs. 3 and 4). Compared to reference-condition tests, an elevation in FCG rates on the order of a factor of 15 was induced by the 649°C radiation exposure in combination with the tension hold time. In direct contrast to this observation, neutron irradiation at 427°C produced a reduction in FCG rate (i.e., improvement) for the continuous cycling mode. The data for weld V44, however, suggest that this benefit may be reduced or fully lost if a tension hold time is applied (Fig. 7). These observations, of course, are made for the specific fluence levels investigated.

Delta ferrite content: An increase in delta ferrite content from FN 10.4 to FN 19.0 is shown to be detrimental to FCG resistance at 649°C for the unirradiated condition for cycling with a tension hold time, but not for continuous cycling at 10 cpm. In the 649°C irradiated condition, delta ferrite content is seen to be a significant factor in FCG resistance at 649°C in either cycling mode. On the other hand, the 427°C FCG trends, with one possible exception, do not indicate an effect of ferrite level on FCG properities for either unirradiated, irradiated, continuous cycling, or tension hold time conditions. The possible exception noted is postirradiation testing with a tension hold time. Specifically, a detrimental effect of the higher delta ferrite level is suggested by the data comparisons for weld V44; however, the data obtained with specimen V44-5 are very limited. This particular test was terminated early because the advancing crack developed a small curvature away from the normal (straight) crack path.

FRACTURE-RESISTANCE INVESTIGATIONS

Test Matrix

The test matrix for the C_v and PCC_v tests is shown in Table 4. Postirradiation C_v test temperatures for experiment H-11 were selected to bracket the prior irradiation temperature because reference condition tests indicated a general independence of C_v energy absorption on temperature in the range of 260° to 593°C. (A lower C_v energy absorption was found at 24°C.) Reference condition PCC_v tests showed a similar independence of behavior in this temperature range. Postirradiation PCC_v tests of experiment H-11 were conducted at the prior irradiation temperature of 427°C; however, tests for experiment H-8 were conducted at temperatures somewhat below the exposure temperature of 649°C because of equipment limitations.

Table 4 — Experimental Test Matrix (C_v and PCC_v Specimens)

Exp. No.	Irrad. Temp. (°C)	Weld Code	Specimen Type	Test Temperature (°C)			
				371	427	482	566
H-11	427	V41, V42, V44	C_v	X		X	
		V41, V42, V44	PCC_v		X		
H-8	649	V42, V44	PCC_v				X

Results

Experiment H-11: The C_v data for the preirradiation and postirradiation conditions are presented in Fig. 8 and are summarized in Table 5. The results clearly show a very large detrimental effect on notch ductility produced by the 427°C irradiation exposure. Indicated reductions in C_v energy absorption range from 73% to 82%. The PCC_v test data for the same conditions are given in Table 6 and show large reductions in K_J ranging from 70% to 79%. Equally important, several of the PCC_v specimens fractured before attaining a condition of general yielding, i.e., elastic fracture behavior was exhibited. Table 7 reports postirradiation strength values for the welds V42 and V44. Here, a doubling of the yield strength and a 50% increase in tensile strength are indicated. These increases would be reasonable projections of the strength elevation for weld V41 also. (Limited irradiation space precluded inclusion of a tensile specimen of this weld.) In comparison with the irradiation effect on strength, thermal conditioning at a somewhat higher temperature of 482°C for 2500 h in the absence of irradiation produced a small reduction in yield strength and a somewhat larger reduction in tensile strength (Table 7). From the ratio of postirradiation fracture toughness and yield strength, it would appear that all of the welds after irradiation at 427°C would exhibit elastic fracture behavior in relatively thin section sizes, i.e., less than 25.4-mm thickness.

On balance, the data indicate a slightly greater irradiation effect (percentage property change) with increasing ferrite content. However, the spread among all postirradiation C_v (and K_J) values is relatively low. In turn, the percentage variations become of less significance for the fluence condition evaluated.

Experiment H-8: Postirradiation PCC_v test results have been included in Table 6. Within the data scatter for individual welds, an effect of delta ferrite content is not discerned. Although a reduction in fracture toughness with irradiation is evident, the K_J values in general are much higher than those observed for the welds with 427°C irradiation. Changes in strength with irradiation were very small for the materials based on postirradiation hardness determinations (V42: RB 94.5; V44: RB 96.0). The postirradiation K_J values of 150 MPa$\sqrt{m}$ thus signify high fracture-resistance retention.

DISCUSSION

The data secured in this investigation clearly indicate a need for more detailed studies of fatigue and fracture resistance behavior of Type E308-16 welds for the full range of projected applications in nuclear power systems. For one, the investigations revealed a shift

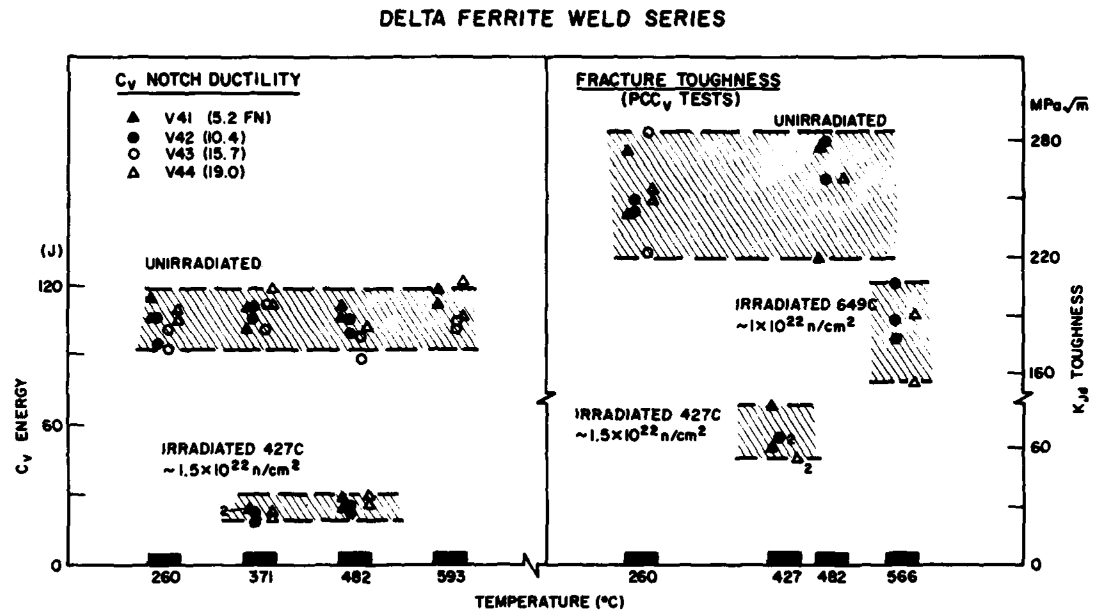

Fig. 8 — Notch ductility and fracture toughness properties of the weld series before and after irradiation

Table 5 — Charpy-V Notch Ductility of the Weld Series in Unirradiated and Irradiated Conditions

Weld Code	Ferrite Number	C_v Energy Absorption (J)[a]					
		Unirradiated Condition				427°C Irradiated Condition[b]	
		260°C	371°C	482°C	593°C	371°C	482°C
V41	5.2	106	100	106	111	24	24
		114	110	111	118	24	30
V42	10.4	95	104	99	—[c]	19	23
		106	110	104	—[c]	23	26
V43	15.7	92	100	87	102	—	—
		100	111	98	104	—	—
V44	19.0	104	111	102	106	20	26
		108	118	—[c]	122	23	30

[a]1 J = 0.738 ft-lb.
[b]~ 1.5×10^{22} n/cm², $E > 0.1$ MeV.
[c]Not determined.

Table 6 — Dynamic Fracture Toughness of the Welds V41, V42, and V44 in Unirradiated and Irradiated Conditions (PCC_v Test, J-Integral Analysis)

Weld Code	Ferrite Number	Dynamic Fracture Toughness K_J (MPa$\sqrt{m}$)[a]			
		Unirradiated Condition		427°C Irradiated Condition[b]	649°C Irradiated Condition[c]
		260°C	482°C	427°C	566°C
V41	5.2	242	211	62[d]	—
		274	278	85	—
V42	10.4	243	259	65	185
		249	279	68	207
					177[e]
V44	19.0	248	257	54[d]	152
		255	—	56[d]	189

[a]1 MPa$\sqrt{m}$ = 0.91 ksi$\sqrt{in.}$
[b]~ 1.5×10^{22} n/cm², $E > 0.1$ MeV.
[c]~ 1.0×10^{22} n/cm², $E > 0.1$ MeV.
[d]Specimen fractured before general yielding.
[e]482°C test.

Table 7 -- Tensile Properties of the Weld Series in Unirradiated, Irradiated, and Thermally Aged Conditions

Weld Code	Ferrite Number	Unirradiated Condition[a]						427°C Irradiated Condition[b]			
		Yield Strength (MPa)			Tensile Strength (MPa)			Yield Strength	Tensile Strength	Elongation (%)[c]	Hardness (Rc)[d]
		260°C	371°C	482°C	260°C	371°C	482°C	427°C	427°C	427°C	24°C
V41	5.2	382 (365)[e]	350	325 (310)[f]	473 (485)[e]	476	430 (412)[f]	—	—	—	30.4
V42	10.4	420 (403)[e]	394	358 (329)[f]	521 (519)[e]	514	478 (425)[f]	679	703	7.1	32.9
V43	15.7	415 (415)[e]	378	362 (342)[f]	520 (522)[e]	494	482 (447)[f]	—	—	—	—
V44	19.0	447 (416)[e]	378	376 (362)[f]	563 (564)[e]	535	517 (475)[f]	811	811	5.8	33.9

[a]1 MPa = 0.145 ksi.
[b]~ 1.5×10^{22} n/cm^2, $E > 0.1$ MeV (5.74-mm gage diameter specimens).
[c]Elongation in 25.4 mm.
[d]Average of duplicate specimens.
[e]Thermally conditioned at 260° C for 2500 h.
[f]Thermally conditioned at 482° C for 2500 h.

from "improvement" in FCG resistance to "impairment" with irradiation, depending on irradiation and test-temperature conditions. Equally important, a clearer understanding of the detrimental effect of the 0.5-min tension hold time on FCG resistance is needed. From the standpoint of fracture resistance, the low C_v energy absorption and the low K_J values found in PCC_v tests after 427°C irradiation can be a cause for concern. Tests with larger size specimens for determination of *J-R* curve characteristics are needed to confirm and assess the engineering significance of the elastic fracture trend indications.

Studies of the mechanisms underlying the observed property changes have been initiated [9], using TEM and SEM procedures. For the unirradiated state and continuous cycling conditions, clear differences among the welds were not found for either 427° or 649°C tests. Also, sigma phase was not observed in the microstructure of the one weld (FN 15.7) examined thus far in the reference condition (649°C FCG tests of the unirradiated condition at 10 cpm, however, were completed in a cycling time of 115 h or less). Selected area diffraction analyses did reveal that small precipitates were formed during fatigue cycling; these were $M_{23}C_6$ carbide particles. TEM and SEM investigations of irradiated samples are just getting underway. For the irradiation conditions used here, only limited void formation is normally expected and should have a negligible effect on fatigue and fracture resistance properties.

Long-term thermal exposure in the range of 500° to 900°C can cause the transformation of ferrite (ductile) to sigma phase (brittle) in addition to the carbide precipitation reported in Ref. 9. Accordingly, the total time at temperature, i.e., the residence time in the reactor plus the total time of cycling, can be quite important in property trend assessments. The effect of 482°C thermal conditioning on tensile properties was shown in Table 7. Comparison tests of fracture resistance, using dynamic tear test samples aged at 482°C for 2400 h, gave indications of reduced energy absorption for welds with FN $\geqslant$ 10.4, but the changes were small. In-depth studies of the effects of long-term (up to 10,000-h) 593°C thermal conditioning on delta ferrite content and weld metallographic features have been made in the MPC study [10]. The study used material from multilayer weld test pads prepared with the same welding electrode/electrode-coating compositions used here. However, the MPC test pads had lower ferrite levels than the thick-section NRL welds, an unexpected occurrence at that time. Weld-pad ferrite contents were on the order of FN 2, 4, 9, and 16. The effect of aging on microstructure was found to differ depending on the ferrite level. Specifically, in the two higher ferrite content materials, the measured decrease in ferrite content with aging resulted primarily from a transformation to sigma phase. In the two lower ferrite content materials, the decrease in ferrite content resulted primarily from a formation of carbides and, possibly, additional austenite; little of the ferrite transformed to sigma in these materials. In all cases, some ferrite was observed after 10,000 h at 593°C.

The following interpretations of the FCG data trends, in terms of probable mechanisms and radiation effects on the mechanisms, can be made with the aid of the MPC observations:

- The equal, detrimental effects of the tension hold time on the FCG resistance at 649°C of welds V42 and V44 in the unirradiated condition may be due to sigma phase formation if the percent of sigma formed (or its contribution) is independent of ferrite content in the range of FN 10.4 to 19.0.

• The unequal detrimental effects of irradiation on FCG resistance at 649°C of welds V42 and V44 under continuous cycling may indicate radiation-enhanced sigma phase formation in weld V44 or possibly a change in mechanisms in weld V42.

• For the 649°C irradiation condition, the equal increases in FCG rates for tension hold time tests over continuous cycling tests for welds V42 and V44 suggests a direct effect of the tension hold component rather than a time-at-temperature effect. That is, the increase in time at temperature with hold-time testing (<100 h) was only a small fraction of the prior time at temperature during irradiation (3110 h).

• The negligible effect of the tension hold time on the FCG resistance at 427°C of the welds V41, V42, and V44 in the unirradiated condition may indicate the absence of sigma phase formation for all ferrite levels at this temperature. The maximum duration of these tests was ~525 h.

• The beneficial and equal effects of 427°C irradiation on the FCG resistance of the welds V42 and V44 under continuous cycling may indicate radiation-enhanced carbide precipitation.

• For the 427°C irradiation condition, the unequal increase in FCG rates for tension hold time tests over continuous cycling tests for welds V42 and V44 may indicate two competing mechanisms dependent on ferrite level.

It is expected that the Magne-Gage and fatigue tests of thermally conditioned SEN specimens now in progress will help clarify the separate roles of thermal conditioning and irradiation exposure in FCG trends.

As for postirradiation fracture resistance, the elevation in yield strength is believed to be largely responsible for the reduction in C_v energy absorption observed with 427°C irradiation. Carbide formation may have contributed to this elevation. The relatively small effect on PCC_v fracture toughness by 649°C irradiation, on the other hand, would be considered inconsistent with a significant transformation of delta ferrite to sigma phase. However, K_J values relate to crack initiation rather than crack propagation. Crack propagation resistance assessments would require *J-R* curve test determinations.

CONCLUSIONS

In summary, the following general conclusions and primary observations were drawn from the experimental data and analyses presented here:

• Delta ferrite content can have an appreciable influence on elevated-temperature FCG resistance at 427° or 649°C irradiation, depending on fatigue cycling conditions. This welding variable, however, does not appear to affect FCG resistance in the unirradiated condition under continuous cycling conditions or cycling with a tension hold time.

• Delta ferrite content has only a small or negligible effect on elevated-temperature fracture resistance after 427° or 649°C irradiation to fluences on the order of 1 to 1.5×10^{22} n/cm^2, $E > 0.1$ MeV.

- Irradiation at 649°C to ~1 × 10^{22} n/cm^2, in general, is detrimental to 649°C FCG resistance. Irradiation at 427°C to ~1.5 × 10^{22} n/cm^2, in contrast, proved beneficial to 427°C FCG resistance, but had a large detrimental effect on fracture resistance.

- Postirradiation FCG resistance trends at 427°C indicate two competing mechanisms which individually may stem from carbide precipitation vs sigma phase formation.

- A 0.5-min tension hold time, with one exception noted, appeared to be detrimental to FCG resistance after 427° or 649°C irradiation.

- Postirradiation FCG resistance, on balance, is greater for a delta ferrite content of FN 10.4 than for a delta ferrite content of FN 19.0.

ACKNOWLEDGMENTS

The investigation of weld properties in the unirradiated and irradiated conditions was conducted for the Department of Energy (Division of Reactor Research and Technology). The investigation of weld properties in the unirradiated, thermally aged condition was conducted for the U.S. Army Engineer Nuclear Power Group (Engineering Division). The support of both agencies is sincerely appreciated.

The author expresses his appreciation to H. E. Watson, W. E. Hagel, and E. Woodall for their assistance and participation in the experimental phases of the investigations.

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