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THE EFFECTS OF IRRADIATION AT ELEVATED
TEMPERATURES ON THE MECHANICAL PROPERTIES
OF A TYPE 347 STAINLESS STEEL PRESSURE TUBE

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The Effects of Irradiation At Elevated
Temperatures on the Mechanical Properties
of a Type 347 Stainless Steel Pressure Tube^(a)

F. R. Shober^(b), C. D. Sellers^(c), and W. E. Murr^(d)

Introduction

The effects of fast neutron irradiation on the mechanical properties of Type 347 stainless steel have been studied by a number of investigators^(e). In most cases, the properties were determined at room temperature after reactor irradiations at process water temperatures (about 120°F) and the results show generally that exposure to fast neutrons causes increases in hardness, ultimate and yield strength, and a decrease in ductility. Data are available⁽³⁾ which show that, under the above-mentioned conditions of irradiation and post-irradiation testing, increases of 40 to 50 per cent in yield strength, increases of 18 to 22 per cent in tensile strength, and decreases of about 40 per cent in

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- C

elongation may be expected in Type 347 stainless steel. Based upon design experience with the material in question, these data indicate that sufficient ductility is maintained to withstand predicted strains without fracture. The increase in yield strength which occurs as a result of such an exposure has no deleterious effect.

However, in actual reactor operation the stainless steel may be subjected to temperatures as high as 650-750°F. On the basis of data from elevated temperature post-irradiation tests⁽⁵⁾ the assumption has been made that material irradiated at elevated temperatures would undergo a smaller change in mechanical properties than material irradiated at lower temperatures. In essence, it was thought that "anneal out" of damage would occur during the time that damage was produced and that damage to a stainless steel structural component maintained in-pile at elevated temperature would be less severe than damage to a component maintained at the lower process water temperature.

Recent results obtained from 347 stainless steel irradiated to a maximum exposure of about 7.1×10^{21} nvt (greater than 1 Mev energies) at temperatures up to 710°F, indicate that damage imparted to the material at elevated temperature may be greater than that imparted at lower temperature. Since this is contrary to previous concepts, in which the amount of irradiation damage was believed to decrease as the temperature of irradiation increased, the experiment which produced this information is discussed in the following paragraphs.

Experimental Materials

A pressure test loop removed from the Engineering Test Reactor (ETR) provided material for preparation of the necessary test samples. This loop had achieved a maximum fast neutron (> 1 Mev) exposure of about 7.1×10^{21} nvt during 14 operating cycles in the ETR J-10 position. The test loop was composed of two basic components, (1) an inner pressurized tube 2.20 inches in outside diameter x 0.187 inches thick, and (2) an outer gas jacket or shroud, which was 2.450 inches in outside diameter x 0.087 inches thick. Both tubes were constructed of Type 347 stainless steel, with the compositions shown in Table I.

The pressure tube was fabricated by Thompson Products (Jet Division) from a forging produced by McInnes Steel Company. The initial billet, which was 6 inches in diameter, was heated to 2250°F and reduced by forging to 3 inches in diameter and air cooled. The forging was then rough machined, stress-relief annealed for 1 hr at 1000°F, and water quenched. The core section of the pressure tube was milled from the billet at this point. Tensile properties of specimens removed from opposite ends of the billet are given in Table I.

The gas jacket forging furnished by Ladish was heat treated for 1 hour at 1950°F and water quenched, then reheated to 1000°F for 1 hour and water quenched. Tensile properties of the gas jacket, as determined by tests of material removed from opposite

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ends of the gas jacket, are given in Table 1. The similarity of composition and tensile properties, shown in this table, indicate some similarity of the fabrication conditions, although it appears from the lower yield strength that the gas jacket was finished at a higher temperature. The tensile strength of the pressure tube was slightly higher, and the 0.2 per cent offset yield strength was appreciably higher than that of the gas jacket. Ductility, as indicated by the total elongation and reduction of area of both loop sections, was approximately equal in the pre-irradiation condition.

Details of the in-pile section of the test loop are shown in Figure 1. The presence of the outer tube, with the gas annulus between it and the inner tube, permitted the inner tube to reach temperatures up to 710°F during reactor operation while the outer tube was maintained at a maximum temperature of 180°F. Both tubes however, were subjected to cyclic stress conditions during irradiation exposure as a result of the ETR operating sequence. The inner tube, which was subjected only to a pressure stress of about 12,400 psi in tension when the reactor was shut down, had imposed upon it a maximum thermal stress of 48,000 psi when the reactor was operating. Similarly, the outer tube was subjected to a pressure stress of 3,100 psi in compression with an imposed maximum thermal stress of about 13,000 psi during reactor operation.

Experimental Procedure

The pressure tube and gas jacket material used to provide post-irradiation specimens was obtained from those lengths extending through the ETR active core region. The outer and inner loop components were slit into strips approximately 1.15 inches wide (circumferential measurement). These strips were subsequently inspected with a gamma ray spectrometer to determine the relative fast neutron flux profile. The Mn^{54} isotope, whose energy peak occurs at 0.835 Mev, was selected for making the gamma ray scans as this isotope was produced in stainless steels by the nuclear reaction $\text{Fe}^{54}(n, p)\text{Mn}^{54}$. A typical gamma ray activity scan of a top and bottom strip of the inner pressure tube which supplied material for five of the specimens tested is shown in Figure 2. Although the scans measured only the relative gamma intensity of the loop strips, the scans were useful for selecting areas from which specimens of low, intermediate, and high levels of fast neutron flux exposure could be machined.

The geometry of the tensile specimens prepared from the inner pressure tube and the outer gas jacket was dictated somewhat by the radius of the inner and outer sections. The size and geometry of the test specimens were also influenced by the limited amount of irradiated loop material available and, hence, the gage width selected was somewhat substandard for a sheet-type tensile specimen. Dimensions of the test specimens are shown in Figure 3.

A total of 18 irradiated specimens were tested at room temperature (75°F) and either 600°F or 750°F, the approximate maximum operating temperature of the inner pressure tube. Six of the 18 specimens tested were machined from the outer loop or gas jacket and 12 specimens were machined from the inner loop or pressure tube. Those specimens tested at 750°F were heated in a 3-inch diameter resistance wire wound furnace, which was sufficiently long to enclose the specimen grips and thereby minimize the temperature gradient to $\pm 5^\circ\text{F}$ throughout the gage section.

Specimens tested above room temperature were brought to temperature in a period of approximately 30 minutes and maintained at this temperature for another 30 minutes prior to testing. The temperature was monitored and controlled by a chromel-alumel thermocouple strapped to the center of the gage section of each specimen. Specimens were maintained at the selected test temperature until fracture occurred.

The specimens were tested on a Riehle tensile tester, Model PH 30, using a strain rate of 0.005 inch per inch from approximate 0.2% offset yield to specimen fracture. Cross-head travel was measured by the use of a Riehle compressometer, Model DC-10.

Experimental Results

The results of tensile tests upon six specimens machined from the outer gas jacket and 12 specimens machined from the inner pressure loop are given in Table 2. For comparison, values

obtained from both tubes prior to irradiation are also listed. All specimens fractured within the gage section, and exhibited various degrees of necking in the area of fracture as shown by representative photomacrographs, Figure 4.

The data from Table 2 is rearranged graphically in Figures 5 and 6 to show the degree of change produced by the irradiation exposure. Examination of the data in Table 1 and the two graphs showed that large changes in mechanical properties, particularly yield strength and total elongation, were produced both in material from the pressure tube (maximum temperature of operation, 710°F) and the gas jacket operation (at approximately reactor coolant temperature). However, changes were greater in specimens from the pressure tube, which showed maximum increases of about 140 and 60 per cent in yield and ultimate strength, respectively, and a decrease of about 90 per cent in elongation under room temperature testing conditions. Irradiated gas jacket specimens tested at room temperature displayed maximum increases of about 120 and 8 per cent for yield and ultimate strength values and decreases of about 50 per cent in total elongation. The changes in properties noted at the 750°F test temperature were less marked for both inner and outer loop components.

Metallographic examinations and microhardness tests were performed upon the grip ends of several sections of the pressure tube and outer gas jacket, along with unirradiated control sections of

both loop components. In general, the microstructure of both components was unchanged by the fast neutron exposure. Representative microstructures of the two components is shown in Figures 8 and 9.

Hardness values were obtained upon the grip ends of several tested specimens. Both components showed hardness increases following irradiation. Differences of 10 to 15 Rockwell "B" numbers were noted between the two components, with the higher hardness being exhibited by the inner pressure tube.

Conclusions

The data obtained from examination of the two J-10 loop components are of considerable importance since they indicate changes which have been effected under the temperature, pressure and neutron flux exposure conditions of an actual test loop. The properties of specimens machined from the low-operating temperature, nominal pressure, gas jacket were similar to those reported previously^(1,3) from capsule irradiation tests of type 347 stainless steel.

The specimens machined from the inner loop material which had operated at higher temperatures and pressures showed larger hardness and mechanical property changes than the gas jacket specimens and possessed higher ultimate and yield values and lower ductility at similar neutron flux exposures.

Since it would be expected that material irradiated at the lower temperature should exhibit the greatest change in properties, the fact that the material irradiated at the higher temperature showed the greatest changes of properties is of considerable interest. Radio-chemical analysis has shown that the neutron exposure was approximately the same in each case and therefore did not contribute to the observed difference. Although it might be concluded that small property differences found in the fabrication history may have had some effect it was concluded that this factor was minor and could not account for the entire difference observed. A possible cause of the difference may be the higher stresses which were present in the inner tube during irradiation at elevated temperatures. The mechanism for this phenomenon cannot be suggested because available data on the effect of irradiation on stressed members are non-existent or unavailable at the present time.

The results of this study indicate that the real effect of neutron irradiation on materials should be determined where possible from materials which have been irradiated under design conditions of stress and temperature. Data obtained for a given material irradiated under conditions differing from those sustained in actual operation may not be representative of actual performance.

Acknowledgments

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TABLE 1. Composition and Properties of J-10
Gas Jacket and Pressure Tube

Composition, w/o	<u>Outer Loop or Gas Jacket(a)</u>	<u>Inner Loop or Pressure Tube(b)</u>
Carbon	0.035	0.045
Manganese	1.59	1.60
Phosphorus	0.013	0.025
Sulfur	0.018	0.015
Silicon	0.56	0.42
Nickel	10.76	10.30
Chromium	18.66	19.85
Niobium	0.84	.81
Tantalum	0.10	--
Tensile Strength, psi	84,500 - 87,400	91,300 - 93,000
0.2 Per Cent Offset Yield Strength, psi	36,300 - 43,300	53,500 - 60,700
Elongation, per cent	53.0 - 57.0	53.0 - 61.4
Reduction in Area, per cent	73.0 - 75.0	68.0 - 72.1

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- (a) Composition furnished by Ladish of the billet which supplied the gas jacket. Mechanical properties were obtained on billets from opposite ends of the forging following 1000°F stress-relief heat treatment.
- (b) Composition furnished by Thompson-Ramo-Wooldridge on finished component. Mechanical properties were obtained on billets from large and small ends of forging following rough machining and 1000°F stress-relief hot treatment.

TABLE 2. Test Results Obtained on Irradiated Tensile Specimens Machined from Sections of the J-10 Loop

Specimen Designation	Approximate Irradiation Temp., F	Neutron Flux, (a)		Temp. of Test, F	0.2% Offset Yield Strength, 10 ³ psi	Ultimate Tensile Strength, 10 ³ psi	Total Elongation, per cent	Reduction of Area, per cent
		(>1 Mev)						
		Instantaneous, 10 ¹⁴ NV	Total, 10 ²¹ NVT					
Inner Loop, Initial Tests								
ST-3-L	540	1.0	1.9	75	132.0	135.0	4.3	53.5
ST-2-I	590	2.0	3.9	75	143.0	145.0	6.5	54.5
ST-2-H	680	3.7	7.1	75	143.0	149.0	10.3	58.2
ST-2-L	540	1.1	2.1	750	103.0	103.0	4.5	42.7
SB-2-I	680	2.7	5.1	750	115.0	115.0	1.5	40.8
SB-2-H	710	3.6	6.9	750	120.0	120.0	3.5	52.5
Control(b)	--	--	--	70	52.5-60.7	91.3-93.0	53-61	68-72
Handbook Data(c)	--	--	--	750	40-50	70-80	45-50	--
Inner Loop, Duplicate Tests								
ST-7-L	540	0.87	1.7	75	130.0	134.0	6.5	59.1
ST-7-I	630	2.9	5.6	75	139.5	144.8	10.6	59.8
ST-7-H(d)	680	1.7	3.3	75	143.0	147.0	9.4	61.5
SB-7-L	660	1.2	2.3	750	115.3	115.3	4.2	64.0
SB-7-I	700	1.9	3.7	750	123.0	123.5	4.2	45.5
SB-7-H	710	3.4	6.5	750	123.6	125.8	4.1	40.5
Outer Loop								
LT-4-L	180	0.91	1.8	75	100.0	103.5	31.0	54.6
LT-4-I	180	1.8	3.5	75	95.2	101.3	26.0	57.0
LB-3-H	180	3.4	6.5	75	102.5	108.0	25.0	60.5
LT-3-L	180	3.1	2.0	750	62.5	66.7	13.5	54.0
LT-3-I	180	2.4	4.5	750	65.4	69.3	11.5	54.6
LT-3-H(e)	180	2.7	5.1	600	71.8	73.3	12.5	48.3
Control No. 1(f)	--	--	--	75	46.8	99.7	50.4	61.8
Control No. 2(f)	--	--	--	750	36.5	67.6	26.2	62.9

(a) Exposure based on Fe/Mn⁵⁴ ratio determined on filings from individual specimens at the fractured surface.

(b) From McInnes Company, Reports on samples cut from J-10 pressure tube forging.

(c) Metals Handbook, Vol. 1, Eighth Edition, p. 508.

(d) Less than 1 mg of sample was submitted for analysis, therefore, the analysis may be inaccurate due to presence of small weighing errors. Specimen should duplicate SB-7-H since it came from adjacent position.

(e) Only 1.5 mg of sample was analyzed. Small weighing errors could have caused significant errors in analysis. It is believed that the actual value would duplicate LB-3-H since the specimen came from adjacent position.

(f) Samples cut from portion of J-10 gas jacket above reactor core.

Figure 1. Schematic Section of J-10 Pressure Tube and Jacket

Top of Reactor Core Section

Bottom of Reactor Core Section

Longitudinal Distance, In.

Figure 2. Longitudinal Gamma-Ray Activity Scan of Top and Bottom Strips of Inner Loop Section 2. Five specimens were tested from the sections represented by this scan. The specimens were ST-2-L, -I, -H, and SB-2-L and -I. The scan is of the Mn^{54} isotope whose energy peak occurs at 0.835 Mev.

Figure 3. Curved Tensile Specimens Machined from J-10 Loop

Outer Loop is 2.625" O.D.; 2.450" I.D.

Inner Loop is 2.200" O.D.; 1.824" I.D.

Figure 4A. A maximum exposure specimen machined from the inner pressure tube. Note the necking in region of fracture. Ductility is shown in this area by the elongated hardness impression near the fracture. Specimen was maintained near 710°F during in-pile exposure, and tested at room temperature. Mag. 4X.

Figure 4B. A maximum exposure specimen machined from the outer gas jacket. Specimen was maintained at about 180°F by reactor cooling water during in-pile exposure and tested at room temperature. Mag. 4X.

Figure 4. Appearance of Fractured Specimens From Inner and Outer Loop Sections

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MAXIMUM CHANGES IN INDICATED PROPERTIES UPON IRRADIATION FOR OUTER GAS JACKET SAMPLES

Figure 5

MAXIMUM CHANGES IN INDICATED PROPERTIES FOLLOWING IRRADIATION FOR INNER PRESSURE LOOP

Figure 6

Figure 7. Microstructure of high exposure specimen from inner pressure loop. Maximum operating temperature of this component was about 710°F. Mag. 125X - Etched.

Figure 8. Microstructure of high exposure specimen from outer gas jacket. This component operated at a temperature of about 180°F. Note the duplex grain size which was also present in the unirradiated control specimens. Mag. 125X - Etched