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THE EFFECT OF STRAIN RATE,
THERMAL AGING AND IRRADIATION
ON THE TENSILE PROPERTIES
OF A-286

MASTER

EB

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J. M. Steichen

March, 1976

Hanford Engineering Development Laboratory

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THE EFFECT OF STRAIN RATE, THERMAL AGING
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By

J. M. Steichen

ABSTRACT

The effects of test temperature, strain rate, neutron irradiation on the tensile properties of A-286 have been experimentally determined. Irradiation conditions included fluences from 0.9 to 1.5 $\times 10^{21}$ n/cm² ($E > 0.1$ MeV) and an irradiation temperature of $\sim 405^\circ\text{C}$ (760°F). Thermal aging was performed at 538°C (1000°F) for durations to 4,000 hours. Test parameters included strain rates from 3×10^{-5} to 1 sec^{-1} at temperatures from room temperature to 649°C (1200°F). Results of the completed tests show that strength properties and ductility are not greatly influenced by strain rate, thermal exposure, or neutron irradiation for test temperatures to 538°C (1000°F). At 649°C (1200°F) the ultimate and 0.2% yield strengths and uniform elongation of unirradiated material increase with increasing strain rate while total elongation and reduction of area decrease. Neutron irradiation does not alter the strain rate sensitivity of strength properties at a temperature of 649°C (1200°F), however, ductility (total and uniform elongation and reduction of area) is significantly enhanced by increasing strain rate.

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I. INTRODUCTION

A-286 is a precipitation hardenable austenitic stainless steel which is being used extensively as a bolting material in a variety of Fast Flux Test Facility (FFTF) structural components. Anticipated operating conditions for A-286 bolts in these components include temperatures from 200 to 565°C (400 to 1050°F) and total neutron fluences to slightly less than 1×10^{21} n/cm². Safety analyses on these bolts require mechanical properties data representative of anticipated steady-state loadings as well as for postulated accident conditions. Of special significance is the effect of neutron irradiation on mechanical properties.

The tensile and creep-rupture properties of unirradiated A-286 have been extensively characterized ^(1,2), and limited data are available on the effects of neutron irradiation on these properties ^(3,4,5,6,7). Reynolds et al ⁽³⁾ have shown that room temperature tensile properties and toughness are not influenced by neutron irradiation to fluences of $\sim 5 \times 10^{20}$ n/cm² (Total) while Moteff et al ⁽⁴⁾ and Robertshaw et al ⁽⁵⁾ have demonstrated that irradiation to approximately the same fluence significantly reduces the 650°C (1200°F) creep-rupture life and ductility. Unfortunately, these studies were performed on specimens irradiated in thermal reactors and the results are therefore not directly applicable to FFTF.

In the present study the effects of test temperature, strain rate, neutron irradiation, and thermal aging on the tensile properties of A-286 were determined. Irradiation conditions included fluences from 0.9 to 1.5×10^{21} n/cm² ($E > 0.1$ MeV) and a temperature of 405°C (760°F). Thermal aging was performed at 538°C (1000°F) for durations to 4000 hours. Test parameters included strain rates from 3×10^{-5} to 1 sec^{-1} and temperatures from Radiographic Test (RT) to 650°C (1200°F). The results of these tests are presented herein.

II. SUMMARY AND CONCLUSIONS

The tensile properties of unirradiated and irradiated A-286 have been determined. For irradiation and test conditions representative of anticipated operating conditions for A-286 bolts in the FFTF, excellent strength and ductility are observed. Results of the completed study are summarized as follows:

- For temperatures to 538°C (1000°F) the strength and ductility of unirradiated A-286 are not greatly influenced by strain rate or test temperature.
- As the test temperature was increased from 538°C (1000°F) to 649°C (1200°F) strength properties and uniform elongation significantly decreased and total elongation increased. At the highest test temperature 649°C (1200°F), strength properties and uniform elongation significantly increased with strain rate while total elongation and reduction of area were slightly reduced.
- Thermal exposure at 538°C (1000°F) for durations to 4000 hours slightly increased the ultimate and 0.2% yield strengths of A-286 and had little effect on ductility.
- Irradiation to fluences of 1.5×10^{21} n/cm² (E > 0.1 MeV) at 405°C (760°F) did not alter the strength properties or strain rate sensitivity of these properties for all test temperatures. Ductility was significantly reduced at low strain rates at temperatures above 538°C (1000°F) by neutron irradiation. Increasing strain rate at these temperatures significantly enhanced ductility.
- The low ductility observed in irradiated specimens tested at 649°C (1200°F) is believed to result from helium embrittlement.

III. EXPERIMENTAL PROCEDURES

MATERIALS AND SPECIMENS

Two heats of A-286 were used in this study. The first (Heat K-58139) was obtained in the form of 1.27 cm (0.5 in.) thick strip and was subsequently used for the majority of tensile and strain rate tests and for the irradiation experiment and thermal aging. The second (Heat 8790) was obtained in the form of 3.81 cm (1.5 in.) diameter rod and was used to verify that tensile properties of the strip material were consistent with those for prototypic bolting material. Both heats of material were annealed at 982°C (1800°F) for 30 minutes and precipitation heat treated at 718°C (1325°F) for 16 hours prior to testing. Chemical compositions for the two heats of material are given in Table 1.

Miniature buttonhead tensile specimens (Figure 1) were fabricated from the test materials and subsequently used for control testing and for the irradiation experiment. All specimens were fabricated from the longitudinal forming direction of the strip and rod materials.

SPECIMEN IRRADIATION

The Experimental Breeder Reactor-II (EBR-II) at the Idaho National Engineering Laboratory (INEL) was used for the irradiation experiment. This experiment was conducted in a Row 2 core position in structural materials subassembly designated X-195. The test specimens were irradiated in a sodium environment at a temperature of approximately 405°C (760°F) to fluences from 0.9 to 1.5×10^{21} n/cm² ($E > 0.1$ MeV).

TEST PROCEDURE

All tensile and high strain rate tests were performed on hard beam machines. An Instron Tensile Machine was utilized for all tests at nominal strain rates from 3×10^{-5} to 3×10^{-3} sec⁻¹, and an MTS Electro-Hydraulic Test Machine for nominal strain rates for 3×10^{-3} to 1.0 sec⁻¹. Both machines were operated at constant crosshead velocity and strain rate values given here are based on the crosshead velocity and initial specimen gauge length.

Two methods were used to produce engineering stress-strain curves. For the Instron Tensile Machine, the output of a conventional strain-gauge load cell was used for determining specimen load and the crosshead displacement for determining specimen extension. Load and displacement values were recorded on a strip chart from which the tensile properties of interest were determined. The MTS Electro-Hydraulic Test Machine provided load measurement by means of a piezoelectric load cell and crosshead displacement (specimen extension) by a Linear Variable Differential Transformer (LVDT) on the actuator. Voltage outputs from the load cell and LVDT were recorded with a digital data recorder and then translated to load and displacement data. Ductility values reported in this report were obtained from pre- and post-test specimen measurements. All elevated temperature tensile and high strain rate tests were conducted in air within recommended American Society for Testing Materials (ASTM) practice.

IV. RESULTS AND DISCUSSION

UNIRRADIATED BEHAVIOR

Tensile testing of unirradiated A-286 was performed at temperatures from room temperature to 649°C (1200°F) and strain rates from 3×10^{-5} to 1.0 sec^{-1} . Results of these tests provided a complete description of unirradiated tensile properties and also established a basis for ascertaining the effects of neutron irradiation. Tensile property data obtained from each test included the ultimate and 0.2% yield strengths, total and uniform elongations, and reduction of area. These data are tabulated in Tables 2 and 3. In addition, the stress-strain curves for each test are stored in the REM computer program at HEDL and are available per the site sequence numbers in the same tables.

The effect of test temperature on the tensile properties of A-286 is illustrated in Figure 2. Data are included for both heats of test material. As shown, both the ultimate and 0.2% yield strengths of A-286 decrease with increasing temperature. Also, a convergence in strength properties is observed with increasing temperature resulting in essentially identical ultimate and 0.2% yield strengths at the highest test temperature 649°C (1200°F). No significant difference in strength properties was observed between the two heats of material.

The temperature dependence of the A-286 ductility is also shown in Figure 2. For temperatures to ~450°C (850°F) both total and uniform (elongation at maximum load) elongation slightly decrease with increasing temperature. At temperatures above 450°C (850°F) total elongation rapidly increases and uniform elongation decreases with increasing temperature. At the highest temperature 649°C (1200°F), total elongation approaches 30% while uniform elongation is approximately 3%. Although the trends in total and uniform elongation are consistent between the two heats of material, Heat 8790 exhibits slightly greater ductility than Heat K-58139. The reduction of area of A-286 is not greatly influenced by test temperature (Figure 2). Also, little difference in values is observed for the two heats of material.

The effect of strain rate and temperature on the tensile strength and ductility of A-286 is presented in Figures 3 through 7. As shown in Figures 3 and 4, the ultimate and 0.2% yield strengths are not greatly influenced by strain rate to temperatures of 530°C (1000°F). However, at 649°C (1200°F), both strength properties rapidly increase with strain rate to a rate of $\sim 10^{-3} \text{ sec}^{-1}$ and then slowly increase with strain rate above that rate. The rapid increase in strength at this temperature at the low strain rates is consistent with other results reported for austenitic stainless steel⁽⁸⁾ and results because creep controls deformation in this temperature strain rate region.

As with the strength properties, the ductility of A-286 is not greatly influenced by strain rate for temperatures to 538°C (1000°F) (see Figures 5 through 7). At the highest test temperature 649°C (1200°F) total elongation (Figure 5) and reduction of area (Figure 7) slightly decrease and uniform elongation (Figure 6) significantly increases with increasing strain rate. Of significance is the fact that excellent ductility is observed for anticipated FFTF service conditions temperatures from 205 to 565°C (400 to 1050°F).

THERMAL AGING BEHAVIOR

To allow the separation of thermal effects from irradiation effects, limited thermal aging was performed on A-286. Specimens of Heat K-58139 were exposed in sodium at a temperature of 538°C (1000°F) for durations of 1000 and 4000 hours. Results of tests on aged material are listed in Table 4 and presented in Figures 8 through 10.

The room temperature tensile properties of exposed A-286 are presented in Figure 8. As shown, both the ultimate and 0.2% yield strengths slightly increase with exposure time. Also, little effect of exposure time on the A-286 ductility is observed. Similar behavior is observed for the ultimate and 0.2% yield strengths, total elongation, and reduction of area of exposed material when tested at 538°C (1000°F) (Figure 9). The uniform elongation at 538°C (1000°F) appears to decrease with exposures at the same temperature. The effect of strain rate on the tensile properties of exposed

material is shown in Figure 10. Behavior for unaged material is represented by lines. Two items of significance are observed for the ultimate and 0.2% yield strengths of exposed material. First, exposure at 538°C (1000°F) slightly increases strength properties at each strain rate and second, the strain rate dependence of the strength properties of exposed material is identical to unexposed material.

The total elongation of unexposed and exposed A-286 is slightly reduced by increasing strain rate (Figure 10). Also, no distinct difference in total elongation is observed between unexposed and exposed material. Uniform elongation of unaged material remains essentially constant with increasing strain rate. Exposure slightly alters this behavior since the uniform elongation is reduced by exposure at the lowest test rate and is essentially identical at the higher rates. No effect of exposure on the strain rate dependence of reduction of area was observed.

IRRADIATION EFFECTS

The effect of neutron irradiation on the tensile strength and ductility of A-286 is illustrated in Figure 11. Data used to construct this figure are presented in Table 5. For the irradiation condition of this study [fluences of 0.9 to 1.5×10^{21} n/cm² ($E > 0.1$ MeV) at a temperature of 405°C (760°F)] the strength of irradiated A-286 is essentially equal to unirradiated material.

The ductility (total elongation) of A-286 is slightly enhanced by neutron irradiation at test temperatures to 427°C (800°F) (Figure 11). Above 426°C (800°F) the total elongation decreases and approaches 2% at the highest test temperature 640°C (1200°F). Similarly, uniform elongation and reduction of area values of irradiated material are essentially identical to unirradiated values at temperatures to 426°C (800°F) and are significantly reduced at higher test temperatures. Low ductility for irradiated A-286 at 649°C (1200°F) has been previously reported for material irradiated in thermal reactors^(3,4) and results from helium embrittlement⁽⁷⁾.

The strain rate dependence of the ultimate strength of irradiated A-286 is presented in Figure 12. Test results are presented for temperatures of

427 and 649°C (800 and 1200°F). For both temperatures, the ultimate strength of irradiated material is essentially identical to unirradiated material. The 0.2% yield strength of irradiated material exhibits similar strain rate dependence to that of unirradiated material, i.e., increases with strain rate. However, the yield strength may be slightly reduced by the subject irradiation.

Both uniform elongation and reduction of area (Figure 13) are not greatly influenced by irradiation or strain rate for a test temperature of 427°C (800°F). At 649°C (1200°F) the uniform elongation of both irradiated and unirradiated material significantly increases with strain rate. Similar behavior is observed for the reduction of area of irradiated material.

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TABLE 1.
CHEMICAL COMPOSITIONS OF A-286 TEST MATERIALS

Composition - Wt.%*												
<u>Heat No.</u>	<u>C</u>	<u>S</u>	<u>Mn</u>	<u>Si</u>	<u>Cr</u>	<u>Mo</u>	<u>Ti</u>	<u>Al</u>	<u>B</u>	<u>Ni</u>	<u>P</u>	<u>V</u>
K-58139-2	0.044	0.002	1.40	0.53	14.34	1.35	2.28	0.22	0.0047	25.91	0.011	0.21
8790	0.057	0.006	1.51	0.50	14.46	1.37	2.24	0.38	0.005	26.35	0.006	0.33
*Balance - Fe												

TABLE 2.
TENSILE PROPERTIES OF A-286

Heat No.	Strain Rate Sec ⁻¹	Test Temp. - °C	Strength - Ksi			Elongation - %		Reduction of Area - %	Site Sequence
			PEL	0.2% Yld.	Uts	Total	Uniform		
K-58139-2	3 x 10 ⁻⁵	22	87.8	111.4	153.9	17.7	15.2	49.6	H00007
		22	81.3	110.4	156.2	19.0	16.3	47.1	0008
		232	89.4	112.4	151.9	14.6	12.4	43.9	2022
		232	83.2	101.6	141.2	15.2	12.7	42.6	2023
		427	48.8	88.6	125.1	15.3	12.7	44.7	0001
		427	48.8	89.3	126.1	15.2	12.7	44.7	0002
		538	52.0	98.4	126.9	18.0	11.2	52.0	0003
		538	52.0	98.6	127.0	17.5	11.3	50.4	0004
		649	48.8	84.5	86.4	30.7	2.9	49.6	0005
		649	56.9	89.8	91.2	23.6	2.9	52.0	0006
8790	3 x 10 ⁻⁵	22	84.5	104.4	159.5	23.2	20.2	49.6	2021
		232	80.3	102.4	153.3	19.4	17.0	44.2	2048
		427	83.9	102.4	142.7	19.6	16.2	47.5	2049
		538	84.3	102.9	137.2	26.5	14.0	48.4	2050
		649	85.2	91.3	94.5	30.0	1.9	52.0	2051

TABLE 3
HIGH STRAIN RATE TENSILE PROPERTIES OF A-286

Heat No.	Strain Rate Sec ⁻¹	Test Temp.-°C	Strength - Ksi			Elongation - %		Reduction of Area - %	Site Sequence
			PEL	0.2% Yld.	Uts	Total	Uniform		
K-58139-2	3 x 10 ⁻³	22	97.6	114.8	156.5	18.8	15.9	48.0	H02024
		232	86.2	106.3	146.3	15.2	12.7	45.5	2025
		427	82.9	100.0	135.6	14.0	10.9	43.9	2026
		538	85.1	102.4	133.3	12.1	9.3	43.9	2027
		649	82.0	99.2	119.0	17.8	8.6	51.6	2028
	6 x 10 ⁻²	22	86.3	113.1	157.5	19.0	15.9	45.5	2036
		232	89.4	110.4	148.1	16.4	13.4	47.2	2037
		427	85.2	105.6	137.9	12.9	10.2	43.4	2038
		538	78.0	93.5	124.9	12.3	9.7	45.5	2039
		649	81.3	102.4	127.0	10.5	7.3	50.4	2040
	1.0	22	96.5	115.9	161.9	19.4	16.3	43.9	2041
		232	93.5	109.4	146.3	16.0	13.3	45.5	2042
		427	81.3	103.4	136.2	13.0	10.3	45.5	2043
		538	81.3	100.0	130.3	11.9	9.1	48.0	2044
		649	83.5	104.5	133.2	10.8	6.8	42.1	2045
8790	6 x 10 ⁻²	22	96.5	118.5	168.4	20.4	17.2	45.5	2052
		232	84.8	102.0	151.7	18.3	14.3	41.7	2053
		427	85.4	102.6	144.1	15.6	13.4	42.3	2054
		538	78.5	99.2	138.2	17.1	14.6	41.3	2055
		649	79.2	107.3	134.1	14.1	10.5	46.7	2056
	1.0	22	78.6	106.8	167.8	23.5	19.9	47.5	2057
		232	93.5	106.1	151.9	18.2	15.5	40.7	2058
		427	80.6	101.2	141.0	17.0	13.9	42.7	2059
		538	85.4	100.6	135.8	16.2	13.6	43.1	2060
		649	85.4	103.1	133.9	16.0	13.1	45.5	2061

TABLE 4
TENSILE PROPERTIES OF THERMALLY AGED A-286

(HEAT K-58139-2)

Aging Temp.-°C	Conditions Exposure Hr.	Strain Rate-Sec ⁻¹	Test Temp.-°C	Strength - Ksi			Elongation -%		Reduction of Area-%	Site Sequence	
				PEL	0.2% Yld.	Uts.	Total	Uniform			
538	1000	3 x 10 ⁻⁵	22	104.1	119.8	169.4	19.1	16.1	46.3	H02015	
			232	92.7	111.0	151.2	14.8	12.2	61.0	2032	
			538	83.6	109.3	126.5	19.1	5.3	56.5	2016	
		3 x 10 ⁻³	538	100.8	117.2	141.3	11.0	8.0	41.5	2033	
		6 x 10 ⁻²	538	88.7	109.7	140.6	12.8	10.2	41.1	2067	
		1.0	232	108.1	119.5	154.6	16.9	14.0	40.7	2068	
			538	85.4	107.9	141.7	12.7	9.7	43.9	2069	
		4000	3 x 10 ⁻⁵	22	90.2	124.3	169.7	19.1	16.6	44.3	2062
				232	102.4	126.0	162.6	14.0	10.8	47.2	2035
				538	100.8	117.5	141.5	16.3	6.8	52.0	2073
3 x 10 ⁻³	538		98.4	117.6	145.2	11.6	8.7	50.0	2034		
6 x 10 ⁻²	538		92.6	115.4	143.0	10.9	8.0	43.4	2070		
1.0	22		121.9	133.3	175.1	18.8	16.0	43.1	2071		
	232		117.9	131.7	162.4	14.8	12.2	43.1	2072		
	538		91.8	112.7	139.7	11.7	8.9	45.1	2066		

TABLE 5

TENSILE PROPERTIES OF NEUTRON IRRADIATED A-286

(HEAT K-58139-2)

Irrad. Temp.-°C	Fluence -10 ²¹ n/cm ²		$\dot{\epsilon}$ - Sec ⁻¹	Test Temp.-°C	Strength - Ksi			Elongation -%		Reduction of Area-%	Site Sequence
	E>0.1 MeV	Total			PEL	0.2% Yld.	Uts.	Total	Uniform		
405 ↓	0.9	2.0	3 x 10 ⁻⁵	22	69.9	107.9	161.8	21.2	17.8	46.3	H02077
	0.9	2.0		232	71.3	91.8	141.1	17.1	14.7	41.0	2076
	1.3	2.4		427	55.3	86.2	136.2	16.2	13.1	37.4	2074
	1.3	2.4		427	65.6	91.4	136.1	16.3	13.4	32.0	--
	1.3	2.4		538	68.8	90.2	123.2	9.2	8.4	7.4	2075
	1.5	2.9		649	68.3	87.6	90.8	2.1	1.1	6.5	2083
	1.0	2.2	7.4 x 10 ⁻³	232	66.1	94.6	144.5	17.8	16.5	43.1	2078
	1.3	2.4		427	65.6	91.0	137.6	15.8	13.8	43.4	2079
	1.5	2.9	1.0	232	100.2	109.5	151.2	19.1	15.5	33.9	2080
	1.5	2.9		427	94.0	103.3	143.0	15.0	11.8	29.8	2081
	1.3	2.7		538	75.2	92.3	130.9	15.6	12.5	39.8	2082
	1.5	2.9		649	77.9	94.3	128.3	10.9	8.0	28.7	2084

FIGURE 1. Tensile Specimen Geometry (Dimensions in inches).

FIGURE 2. Temperature Dependence of the Tensile Properties of Unirradiated A-286.

FIGURE 3. Strain Rate and Temperature Dependence of the Ultimate Strength of Unirradiated A-286.

FIGURE 4. Strain Rate and Temperature Dependence of the 0.2% Yield Strength of Unirradiated A-286.

FIGURE 5. Strain Rate and Temperature Dependence of the Total Elongation of Unirradiated A-286.

FIGURE 6. Strain Rate and Temperature Dependence of the Uniform Elongation of Unirradiated A-286.

FIGURE 7. Strain Rate and Temperature Dependence of the Reduction of Area of Unirradiated A-286.

A-286 HEAT 58139-2

ROOM TEMPERATURE RESULTS AT $3 \times 10^{-5} \text{ sec}^{-1}$

FIGURE 8. Room Temperature Tensile Properties of Thermally Exposed A-286.

A-286 HEAT 58139-2
 538°C (1000°F) RESULTS AT $3 \times 10^{-5} \text{ sec}^{-1}$

FIGURE 9. Tensile Properties of Thermally Exposed A-286 -- Exposed and Tested at 538°C (1000°F).

FIGURE 10. Effect of Strain Rate on the 538°C (1000°F) Tensile Properties of Thermally Exposed A-286.

FIGURE 11. Tensile Properties of Neutron Irradiation A-286.

FIGURE 12. Effect of Strain Rate on the Ultimate and 0.2% Yield Strength of Neutron Irradiated A-286.

FIGURE 13. Effect of Strain Rate on the Ductility of Neutron Irradiated A-286.

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