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ELEVATED-TEMPERATURE TENSILE AND CREEP PROPERTIES OF SEVERAL FERRITIC STAINLESS STEELS

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16. Abstract

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SUMMARY

The elevated-temperature mechanical properties of several ferritic stainless steels have been determined. The alloys evaluated included Armco 18SR, GE 1541, and NASA-18T-A. Tensile and creep strength properties at 1073 and 1273 K and residual room-temperature tensile properties after creep testing were measured. In addition, 1273 K tensile and creep tests and residual property testing were conducted with Armco 18SR and GE 1541 which had been exposed for 200 hours to a severe oxidizing environment in automotive thermal reactors. Aside from the residual tensile properties for Armco 18SR, prior exposure did not affect the mechanical properties of either alloy. The 1273 K creep strength parallel to the sheet-rolling direction was similar for all three alloys. At 1073 K, NASA-18T-A had better creep strength than either Armco 18SR or GE 1541. NASA-18T-A possesses better residual properties after creep testing than either Armco 18SR or GE 1541.

INTRODUCTION

Recent work (ref. 1) has shown that several ferritic stainless steels have potential for use in severe oxidizing environments such as automotive thermal reactors. In such environments, candidate alloys must possess excellent high temperature oxidation and corrosion resistance; in addition, moderate elevated temperature strength is required to prevent severe distortion. The elevated temperature stress rupture, tensile, and oxidation data of several ferritic stainless steels and alloy modifications which performed well in severe environments have been reported (ref. 2). This work presents additional mechanical properties of two of the most promising ferritic stainless steels, GE 1541 and Armco 18SR, and one alloy modification, NASA-18T-A. The latter alloy was evaluated in place of the somewhat more desirable alloy modification NASA-18T (ref. 2) because the supply of NASA-18T was exhausted during thermal reactor tests (ref. 1). However, it should be noted that NASA-18T-A is only slightly weaker than NASA-18T (ref. 2) and yet both possessed equivalent oxidation resistance. Also, NASA-18T-A contains much less (0.45 wt. percent) tantalum, an expensive alloying element, than NASA-18T (1.25 wt. percent).

The mechanical properties evaluated in this study included 1273 K tensile and creep properties. Creep testing was conducted for a maximum of 150 hours, and most unfailed creep test specimens were tensile tested at room temperature to determine if any serious microstructural damage occurred during creep testing. A few 1073 K tensile and creep tests were also conducted, and the unfailed creep specimens were tensile tested at room temperature. All alloys were tested in the as-received condition; in addition, GE 1541 and Armco 18SR were tested after being exposed for 200 hours in a severe oxidizing environment as actual thermal reactor cores (ref. 1). The latter testing was conducted in an effort to assess the effects of the strenuous environment on mechanical properties.

EXPERIMENTAL PROCEDURE

All the alloys used in this study were purchased in the form of nominally 0.3 meter wide by 1 meter long and 0.16 centimeter thick sheets. The specific melting and rolling practice for each alloy can be found in references 2 and 3. The compositions and average grain size as determined by linear analysis of the as-received sheet alloys are shown in table I. None of the alloys possessed a crystallographic texture. All the alloys were tested in the as-received condition. In addition, GE 1541 and Armco 18SR were tested after 200 hours exposure as thermal reactor cores (ref. 1). These cores were subjected to 80 cycles where each cycle consisted of 2 hours at ~1315 K; forced air cooling to ~345 K; and return to ~1315 K. Specific information concerning reactor performance and photomicrographs of exposed alloys can be found in reference 1. In general, the cores were in good condition and exhibited only minor surface oxidation. After 200 hours exposure, the average grain size of GE 1541 increased to 165 μm while Armco 18SR increased to 125 μm.

Pin grip tensile type specimens, 3.18 centimeter gage length by 0.95 centimeter gage width, were blanked from the as-received alloys. Specimens with gage lengths both parallel and perpendicular to the final sheet rolling direction were punched from Armco 18SR and GE 1541 while only specimens with the gage length parallel to the final sheet rolling direction were punched from NASA-18T-A. Identical tensile specimens were also blanked from the exposed thermal reactor cores which had been split open and flattened at room temperature. Specimens were carefully punched from regions which had not undergone severe changes (for example, welding) during core fabrication. The gage lengths of all the test specimens punched from reactor cores were perpendicular to the final sheet rolling direction. In this report, test specimens punched from thermal reactor cores are noted by the designation (TRC) following the alloy name. All specimens were tested in the as-punched condition.

Short-term tensile tests and creep tests were conducted at 1273 K on all possible alloy-exposure-direction combinations: total of seven combinations. In addition, short-term tensile tests and a few creep tests were carried out at 1073 K on as-received alloys. All testing at 1073 K was conducted on specimens with the gage length parallel to the final sheet rolling direction. All elevated temperature testing was conducted to ASTM

Specifications E21-70 and E139-70 by Spectrum Laboratories, Inc., Piscataway, New Jersey. Strains for both elevated temperature tensile and creep tests were measured by an extensometer mechanically attached to the gage section. Differential motion of the extensometer was measured by a linear variable differential transformer and its output was continuously recorded. Creep tests were generally conducted for 150 hours unless failure occurred. Most unfailed creep test specimens were tensile tested at room temperature to determine if microstructural damage occurred during creep exposure. Room temperature tensile testing was conducted at a constant cross head speed of 0.002 centimeter per second on a screw driven test machine. Since many creep test specimens underwent significant creep deformation, residual tensile properties were calculated on the basis of the gage dimensions after creep testing. Additionally, because of necking in many unfailed creep test specimens, extensometry was not used to measure room temperature yield strengths. Instead, approximate yield strengths were estimated from load-cross head motion charts and cross sectional area of necked specimens.

Selected tensile test, failed creep test, and residual property specimens were metallographically examined. In addition, the fracture surfaces of selected residual property specimens were studied with aid of the scanning electron microscope (SEM).

RESULTS

Elevated Temperature Tensile Testing

The elevated temperature tensile data for tests conducted at 1273 and 1073 K are given in table II. With regards to ultimate tensile strengths at 1273 K, Armco 18SR seems to be slightly stronger in the longitudinal (parallel to the rolling direction) direction than the transverse (perpendicular to the rolling direction) direction. The opposite appears to be true for GE 1541. In general, the ultimate tensile strengths of all three alloys are equivalent; however, the yield strength of GE 1541 is about twice that of the other alloys. Additionally, it appears that 200-hour exposure in a thermal reactor did not affect the strength of either Armco 18SR or GE 1541. At 1073 K, NASA-18T-A has a small (approximately 15 percent) strength advantage over the other alloys. All alloys possess high ductility at both test temperatures. Metallography of tensile tested specimens did not indicate anything unusual such as intergranular cracking.

Creep Testing

The tabular elevated temperature creep data are presented in table III. The data includes time to 0.5, 1.0, 2.0, and 5.0 percent creep strain, steady state creep rate, time to rupture, and elongation at the end of test or rupture, if it occurred. The steady state creep rate data as a function of applied stress are presented in figures 1 and 2. These figures also contain relative steady state creep data (determined by interrupting stress rupture tests and measuring actual gage length elongation) for several alloys from reference 2. This relative creep data appears to agree well with that determined in this study. In addition, figures 1 and 2 contain creep data determined for several simple ferritic iron base alloys. As can be seen in these figures, all the ferritic stainless steels evaluated in this study are much stronger than simple single phase alloys.

Data for the various alloy-direction-exposure combinations and pooled (over direction and/or exposure) combinations were fitted to the normal power law creep equation by means of a linear regression program. Additionally, the creep rate data for Armco 18SR and GE 1541 were fitted to a linear regression equation involving a power law stress dependency and two dummy variables representing test direction and exposure condition. The latter results combined with the Extra Sum of Squares Principle (ref. 6) were used to determine if test direction and/or exposure condition were important variables in the description of the creep behavior.

Analysis of the linear regression results indicate that thermal reactor core exposure had little effect on creep strength of Armco 18SR. However, it appears that the strength of this alloy is dependent on testing direction where the longitudinal direction is about 30 percent stronger than the transverse direction. The regression results for GE 1541 indicate that creep strength for all testing conditions can be well described by a single curve; thus, the creep resistance of GE 1541 is apparently not dependent on testing direction or exposure condition. At 1273 K, the stress exponents for creep for Armco 18SR are about 6.5 and 4.3 for testing in the longitudinal and transverse direction, respectively. The stress exponents for GE 1541 and NASA-18T-A at 1273 K are approximately 4.6. At 1073 K, the stress exponents for creep are about 8.1 for NASA-18T-A and 6.7 for GE 1541. A creep exponent for Armco 18SR at 1073 K could not be calculated because of the scatter in the data. Decreasing values for the stress exponents with increasing test temperature have been previously observed (ref. 4) in simple ferritic iron alloys; thus, this behavior is not unusual. No attempt was made to determine activation energies for creep.

Consideration of the creep data in figure 1 indicates that the creep strengths of all three alloys are similar when tested parallel to the rolling direction at 1273 K. On the other hand, the data in figure 2 show that NASA-18T-A has better 1073 K creep strength than either Armco 18SR or GE 1541. Additionally, the creep data in figures 1 and 2 indicate that the creep strengths of NASA-18T-A and NASA-18T are quite similar at 1073 K and probably 1273 K.

Metallography of failed creep test specimens indicated a few grain boundary cracks in several Armco 18SR specimens tested at 1273 K. Additionally, one Armco 18SR (TRC) specimen appeared to be undergoing uniform oxidation attack (fig. 3(a)). No cracks were seen in failed GE 1541 specimens; however, several localized oxidation attack regions were seen (fig. 3(b)). No obvious microstructural changes were seen in failed NASA-18T-A specimens.

Residual Property Testing

After creep testing at 1273 or 1073 K, the majority of the unfailed specimens were tensile tested at room temperature in order to assess the effects of prior creep. The results of the residual property testing are tabulated in table IV. Typical examples of fracture surfaces are presented in figure 4.

As can be seen in table IV, there are differences between the residual properties of the evaluated alloys after creep testing at 1273 K. Comparison of specimens tested parallel to the final rolling direction indicates that NASA-18T-A possess better residual properties than either Armco 18SR or GE 1541. Additionally, the residual properties of NASA-18T-A are not influenced by the amount of prior creep strain up to 1.5 percent (maximum strain achieved) since the strength and ductility properties are equivalent to those specimens not subjected to prior creep strain. SEM fractography and metallography revealed that the NASA-18T-A residual property specimen which had low properties partially failed by cleavage in a region which had undergone abnormal grain growth such that one grain traversed the sheet thickness. Tensile failure in the other NASA-18T-A specimens occurred exclusively by ductile mechanisms. The behavior of the single NASA-18T specimen was identical to that of NASA-18T-A.

The residual tensile property results in table IV for Armco 18SR after creep testing at 1273 K indicate differences in behavior for the various exposure conditions and test directions. Residual testing of Armco 18SR in the transverse direction yielded higher strengths and ductilities than those obtained for testing in the parallel direction. The tensile properties measured in the transverse direction are similar to the as-received room temperature properties reported in table IV of reference 2 for the longitudinal direction. On the basis of the transverse testing, it appears that prior creep at 1273 K has little effect on residual properties. On the other hand, thermal reactor exposure followed by creep testing at 1273 K reduces the residual tensile properties, particularly the ductility. In all cases, residual tensile fracture involved cleavage type failure, regardless of the final tensile elongation. Metallography of residual property specimens indicated that precipitation occurred on the original grain boundaries (fig. 5) and significant grain growth occurred in Armco 18SR creep tested at 1273 K; on the other hand, Armco 18SR (TRC) did not undergo as much grain growth nor as much precipitation as the unexposed alloy. The composition of the precipitates formed in Armco 18SR could not be determined by SEM techniques.

The residual tensile strength properties in table IV for GE 1541 indicate that the strength perpendicular to the rolling direction is not dependent on prior creep at 1273 K or thermal reactor exposure. However, the residual ultimate tensile strength is somewhat reduced (approximately 10 percent) by prior creep exposure at 1273 K for GE 1541 tested parallel to the rolling direction. The residual tensile strength properties are nearly equal to those measured for the as-received alloy in this study and those reported elsewhere (ref. 3). But, the tensile ductilities, particularly those measured for the parallel test direction, are lower than the 25 percent tensile elongation determined by Bartos, Perkins, and Robertshaw (ref. 3). Examination of the fracture surfaces and microstructures indicated that cleavage is an important failure mode for this material; only GE 1541 (TRC) residual property specimens exhibited extensive regions of ductile fracture.

After creep testing at 1073 K, all the evaluated alloys possessed tensile properties equivalent to those measured for as-received materials (ref. 2). Tensile failure in Armco 18SR occurred by ductile mechanisms while GE 1541 failed by cleavage. NASA 18T-A subjected to prior creep at 1073 K exhibited a partially intergranular ductile fracture with scatter regions where cleavage occurred (fig. 4). Metallography of the failed residual property specimens confirmed that the fracture was partially intergranular. Such behavior seems to be the result of precipitation which took place during creep testing (fig. 6). Attempts on the SEM to determine the composition of the intergranular precipitate were not successful. No unusual microstructural features were seen in GE 1541 or Armco 18SR residual property test specimens.

DISCUSSION

Consideration of the tensile and creep properties in the longitudinal direction reveals that the strength of all three alloys are similar at 1273 K at strain rates ranging from 10^{-9} to 10^{-6}/s. Equivalence of the creep strength is somewhat surprising as GE 1541 has better 1273 K rupture strength than either Armco 18SR or NASA-18T-A (ref. 2). At 1073 K, NASA-18T-A has better tensile and creep strength in the longitudinal direction than the other two alloys; these results are in agreement with the 1073 K stress rupture data in reference 2. While the residual properties of all three alloys in the longitudinal direction are nominally equal after 1073 K creep testing, NASA-18T-A has better residual tensile properties, particularly ductility, after 1273 K creep testing than either Armco 18SR or GE 1541. Therefore, it appears that NASA-18T-A possesses some strength advantages over the other two alloys.

While the work in reference 2 indicates some stress rupture strength advantage for NASA-18T (nominally Fe-18Cr-2Al-1.25Ta) over NASA-18T-A (nominally Fe-18Cr-2Al-0.45Ta), this study indicates that both alloys possess similar creep strengths at 1073 K and possibly at 1273 K. This behavior should be studied in greater detail. If this is correct, an effective Ta-strengthened Fe-18Cr-2Al alloy could be produced at a much lower cost than originally thought since less Ta would be required.

The test results indicate that the ferritic stainless steel NASA-18T-A has potential for use in situations that require a moderate strength, oxidation resistant alloy. Previous work (ref. 2) has shown that NASA-18T-A has better oxidation and corrosion resistance than best existing commercial and semicommercial ferritic stainless steels. This work indicates that the effective elevated temperature tensile and creep properties and residual tensile properties after creep testing of NASA-18T-A are equal to or better than best existing wrought ferritic stainless steels.

Finally, it should be noted that the 1273 K tensile and creep strength of Armco 18SR and GE 1541 were not affected by 200 hour exposure in a thermal reactor. Thus, these alloys possess excellent resistance to a severe thermal, oxidizing environment and are capable of much longer lives in such applications.

CONCLUSIONS

Based on the results of this study of the elevated-temperature tensile and creep properties and residual room-temperature properties after creep testing, the following conclusions are made:

1. The developmental Ta-modified ferritic stainless steel NASA-18T-A has good potential for use in situations that require moderate strength as well as good oxidation and corrosion resistance at elevated temperature.

2. Two-hundred-hour exposure to severe oxidizing conditions has essentially no effect on the 1273 K tensile and creep properties of Armco 18SR and GE 1541 ferritic stainless steels.

REFERENCES

1. Blankenship, Charles P.; and Oldrieve, Robert E.: An Evaluation of Alloys and Coatings for Use in Automobile Thermal Reactors. SAE Paper 740091, Feb. 1974.

2. Oldrieve, Robert E.: Modified Ferritic Iron Alloys with Improved High-Temperature Mechanical Properties and Oxidation Resistance. NASA TN D-7966, June 1975.

3. Bartos, J. L.; Perkins, R. J.; and Robertshaw, F. C.: Mechanical Properties of Fe-Cr-Al-Y Alloys. GEMP-711, General Electric Co., 1969.

4. Stang, R. G.; Nix, W. D.; and Barrett, C. R.: High Temperature Creep in Fe-3 Pct Si. Metall. Trans., vol. 4, no. 7, July 1973, pp. 1695-1699.

5. Watanabe, Tadao; and Karashima, Seiichi: Stress Dependence of High-Temperature Creep in Fe-Mo and Fe-Co Alloys. Metall. Trans., vol. 2, no. 5, May 1971, pp. 1359-1365.

6. Draper, Norman R.; and Smith H.: Applied Regression Analysis. John Wiley & Sons, Inc., 1966, p. 67.

TABLE I. - COMPOSITIONS AND GRAIN SIZE OF FERRITIC IRON ALLOYS EVALUATED

Alloy	Heat	Composition, wt percent											Average grain size, μm
		C	Mn	Si	Cr	Ni	Ta	Al	Ti	P	S	Y	
Armco 18SR	490578	0.031	0.27	1.14	17.90	0.37	----	2.16	0.54	[a]0.015	[a]0.015	---	13
GE 1541	M-287	.012	<0.01	.07	15.20	----	----	4.95	----	.003	.001	0.7	96
NASA-18T-A	32	.038	.37	1.14	17.74	0.17	0.45	2.10	0.44	.008	.012	---	60

[a]Expected or nominal.

TABLE II. - ELEVATED TEMPERATURE TENSILE PROPERTIES OF SEVERAL FERRITIC STAINLESS STEELS

Material	Test direction relative to final rolling direction	Tensile properties		
		0.2 percent yield stress, MPa	Ultimate tensile strength, MPa	Elongation, percent
		1273 K		
Armco 18SR	Parallel	5.5	22.5	83.2
	Parallel	6.5	27.4	91.2
	Perpendicular	6.5	21.4	118.4
Armco 18SR (TRC)	Perpendicular	7.2	19.9	72.8
	Perpendicular	7.5	20.4	85.6
GE 1541	Parallel	(a)	19.5	78.4
	Parallel	15.1	15.3	75.2
	Perpendicular	12.3	23.4	72.8
	Perpendicular	12.6	26.0	75.2
GE 1541 (TRC)	Perpendicular	12.7	27.0	72.0
	Perpendicular	8.8	22.7	71.2
NASA-18T-A	Parallel	4.8	24.3	70.4
	Parallel	5.0	25.5	116.8
		1073 K		
Armco 18SR	Parallel	44.6	64.2	51.2
	Parallel	22.9	64.8	46.4
GE 1541	Parallel	36.3	64.2	51.2
	Parallel	22.9	64.8	46.4
NASA-18T-A	Parallel	44.6	74.3	62.4
	Parallel	45.2	76.7	61.6

[a]Anomalously low value of 2.2 MPa measured.

TABLE III. - CREEP STRENGTHS OF SEVERAL FERRITIC STAINLESS STEELS

MATERIAL	TEST DIRECTION RELATIVE TO FINAL ROLLING DIRECTION	STRESS, MPA	TIME IN HOURS TO INDICATED CREEP STRAIN (PERCENT) 0.5	1.0	2.0	5.0	STEADY STATE CREEP RATE, S**-1	ELONGATION AT END OF TEST, PERCENT	LENGTH OF TEST IF SPECIMEN FAILED, HOURS (A)
			1273 K						
ARMCO 18 SR	PARALLEL	3.45					3.3E-09	0.2	
		3.45	66.8	92.4	135.		1.8E-08	2.3	
		6.9	.2	.3	.6	1.2	1.2E-05	131.	9.35
		6.9	.8	1.9	3.9	7.7	2.1E-06	81.	23.16
		10.4	.1	.2	.3	.9	1.0E-05	110.	3.3
		10.4	.2	.6	.8	2.0	5.1E-06	80.	21.37
	TRANSVERSE	2.1	108.9	150.			9.4E-09	1.	
		3.45	9.6	15.7	26.9	59.6	2.5E-07	15.8	
		3.45	17.5	33.6	79.3		7.5E-08	4.3	
ARMCO 18 SR(TRC)	TRANSVERSE	2.1	2.9	9.5	34.7		7.0E-08	8.9	
		2.1	27.3	30.0	36.3		3.3E-08	4.8	
		3.45	.6	2.0	6.3	21.0	5.9E-07	53.	71.5
		3.45	.9	2.5	17.5	90.0	1.1E-07	9.5	
		6.9	.6	.7	1.1	2.7	5.5E-05	24.	9.85 (B)
GE 1541	PARALLEL	2.1	128.0				2.4E-09	.5	
		2.1	112.8				6.4E-09	.5	
		3.45	65.6				6.4E-09	.6	
		3.45	127.0				2.9E-09	.5	
		6.9	.5	1.8	6.7	38.	2.6E-07	86.	162.
		6.9	1.8	4.7	15.1	75.7	7.3E-08	8.9	
		10.4	.1	.8	.9	3.3	3.1E-06	59.	36.05
		10.4	.2	.4	1.3	4.5	2.8E-06	52.	25.27
	TRANSVERSE	2.1					3.4E-10	.03	
		2.1					6.4E-10	.03	
		3.45	38.3	143.3			1.6E-08	1.1	
		3.45					5.8E-09	.4	
		6.9	1.9	5.4	13.3	42.2	3.2E-07	45.	130.3
		6.9	1.7	4.0	10.2	46.9	2.2E-07	49.	114.1
		10.4	.3	.7	1.6	4.1	1.3E-06	20.	15.0 (B)
GE 1541(TRC)	TRANSVERSE	2.1	129.				2.0E-09	.3	
		2.1	57.	150.			3.5E-09	1.	
		3.45	15.9	60.			2.3E-08	1.6	
		3.45					6.6E-09	.3	
		6.9	1.3	4.4	33.8	71.7	1.1E-07	53.	108.5

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TABLE III. - CONCLUDED.

MATERIAL	TEST DIRECTION RELATIVE TO FINAL ROLLING DIRECTION	STRESS, MPA	TIME IN HOURS TO INDICATED CREEP STRAIN (PERCENT) 0.5	1.0	2.0	5.0	STEADY STATE CREEP RATE, S**-1	ELONGATION AT END OF TEST, PERCENT	LENGTH OF TEST IF SPECIMEN FAILED, HOURS (A)
			1273 K						
NASA-18T-A	PARALLEL	2.1	128.4				1.1E-09	.6	
		2.1					4.6E-10	.1	
		3.45					2.5E-09	.1	
		3.45	58.4	95.2			3.2E-08	1.5	
		6.9	4.5	7.5	12.5	23.9	3.9E-07	31.	57.3 (B)
		6.9	1.7	3.7	6.1	12.3	9.8E-07	54.	42.5 (B)
		10.4	1.2	1.6	2.9		2.0E-06	3.7	5.5 (B)
		10.4	.4	.8	1.5	3.7	4.6E-06	(C)	3.2
NASA-18T	PARALLEL	3.45					6.0E-09	.4	
			1073 K						
ARMCO 18 SR	PARALLEL	13.8	12.2	24.5	45.3	129.8	1.1E-07	5.5	
		13.8	10.6	22.1	40.	93.6	1.5E-07	7.5	
		20.7	8.7	15.	44.8	68.9	2.1E-07	16.3	
		20.7	65.4	101.9			3.1E-08	1.5	
GE 1541	PARALLEL	13.8	2.6	10.8	55.9		3.8E-08	3.1	
		13.8	1.6	5.7	20.8	98.5	1.0E-07	5.9	
		20.7	.5	1.5	4.7	18.3	1.1E-06	34.	63.7 (B)
		20.7	.4	1.3	6.2	15.7	7.7E-07	34.	50.0 (B)
NASA-18T-A	PARALLEL	13.8					9.0E-10	.05	
		13.8					2.9E-09	.1	
		20.7	14.5	19.1	24.9	35.9	6.7E-08	31.2	
		20.7	32.5	61.	94.3		2.8E-08	4.4	

(A) UNLESS NOTED, TEST CONDUCTED FOR 150 HOURS AND THEN UNLOADED
(B) ELONGATION AT TIME SHOWN; FURTHER TIME DEPENDENT DEFORMATION NOT RECORDED
(C) OUT OF GAGE FAILURE

TABLE IV. - RESIDUAL ROOM TEMPERATURE TENSILE PROPERTIES OF SEVERAL FERRITIC STAINLESS STEELS

MATERIAL	TEST DIRECTION RELATIVE TO FINAL ROLLING DIRECTION	PRIOR CREEP HISTORY, 150 HOURS OF TESTING: STRESS, MPA	PRIOR CREEP HISTORY, 150 HOURS OF TESTING: ELONGATION, PERCENT	RESIDUAL ROOM TEMPERATURE TENSILE PROPERTIES: 0.2 PERCENT YIELD STRESS, MPA	RESIDUAL ROOM TEMPERATURE TENSILE PROPERTIES: ULTIMATE TENSILE STRENGTH, MPA	RESIDUAL ROOM TEMPERATURE TENSILE PROPERTIES: ELONGATION, PERCENT	TENSILE FRACTURE APPEARANCE
1273 K CREEP TESTING							
ARMCO 18 SR	PARALLEL	3.45	.2	381.7	480.7	4.8	MPC (A)
		3.45	2.3	368.6	460.5	7.4	MPC
	TRANSVERSE	2.1	1.	378.7	541.7	13.9	MPC
		3.45	16.4	402.9	517.2	14.9	MPC
		3.45	4.3	416.8	546.3	17.8	MPC
ARMCO 18 SR(TRC)	TRANSVERSE	2.1	4.9	351.3	335.6	3.	CLEAVAGE
		2.1	8.4	393.9	359.2	1.1	CLEAVAGE
		3.45	8.5	346.3	385.4	3.5	MPC
GE 1541	PARALLEL	NOT CREEP TESTED		405.6	516.7	8.	MPC
		NOT CREEP TESTED		392.5	501.6	6.	MPC
		2.1	.5	347.3	438.9	4.8	MPC
		2.1	.5	384.8	472.2	10.	MPC
		3.45	.6	343.2	449.3	5. (B)	MPC
		3.45	.5	338.4	430.5	5.6	MPC
		6.89	6.9	417.6	550.1	6.9	MPC
	TRANSVERSE	2.1	.03	354.3	509.5	13.6	MPC
		2.1	.03	345.9	501.4	14.4	MPC
		3.45	1.1	356.	507.8	15.2	MPC
		3.45	.3	369.7	512.2	15.6	MPC
GE 1541(TRC)	TRANSVERSE	2.1	1.	330.6	494.3	20.	D+CE (C)
		2.1	.3	348.9	490.2	19.2	D+CE
		3.45	1.6	333.6	433.2	20.8	D+CE
		3.45	.3	332.6	452.1	10.8	MPC
NASA-18T-A	PARALLEL	NOT CREEP TESTED		426.6	593.9	27.2	DUCTILE
		NOT CREEP TESTED		420.9	596.8	25.6	DUCTILE
		2.1	.1	383.4	498.9	14.	PC (D)
		2.1	.6	399.	574.8	28.	DUCTILE
		3.45	1.5	409.	574.7	29.2	DUCTILE
		3.45	.1	400.4	573.6	31.6	DUCTILE
NASA-18T	PARALLEL	3.45	.4	443.5	639.9	25.6	DUCTILE

TABLE IV. - CONCLUDED.

MATERIAL	TEST DIRECTION RELATIVE TO FINAL ROLLING DIRECTION	PRIOR CREEP HISTORY, 150 HOURS OF TESTING STRESS, MPA	PRIOR CREEP HISTORY, 150 HOURS OF TESTING ELONGATION, PERCENT	RESIDUAL ROOM TEMPERATURE TENSILE PROPERTIES 0.2 PERCENT YIELD STRESS, MPA	RESIDUAL ROOM TEMPERATURE TENSILE PROPERTIES ULTIMATE TENSILE STRENGTH, MPA	RESIDUAL ROOM TEMPERATURE TENSILE PROPERTIES ELONGATION, PERCENT	TENSILE FRACTURE APPEARANCE
1073 K CREEP TESTING							
ARMCO 18 SR	PARALLEL	13.8	5.5	465.9	641.1	28.1	DUCTILE
		13.8	7.5	471.9	639.7	27.6	DUCTILE
		20.7	16.3	468.7	636.9	21.7	DUCTILE
		20.7	1.5	478.1	644.5	23.8	DUCTILE
GE 1541	PARALLEL	13.8	3.1	353.	478.8	20.3	MFC
		13.8	6.9	338.1	481.5	20.6	MFC
NASA-18T-A	PARALLEL	13.8	.1	424.3	618.3	27.2	DI+C (E)
		13.8	.05	418.9	618.4	27.2	DI+C
		20.7	4.8	427.	597.7	19.2	DI+C
		20.7	31.2	425.2	575.	13.1	DI+C

(A) MULTIFACETED CLEAVAGE
(B) OUT OF GAGE FAILURE
(C) DUCTILE WITH CLEAVAGE AT EDGES
(D) PARTIAL CLEAVAGE - SEPARATE REGIONS OF CLEAVAGE AND DUCTILE FRACTURE
(E) DUCTILE INTERGRANULAR MIXED WITH CLEAVAGE

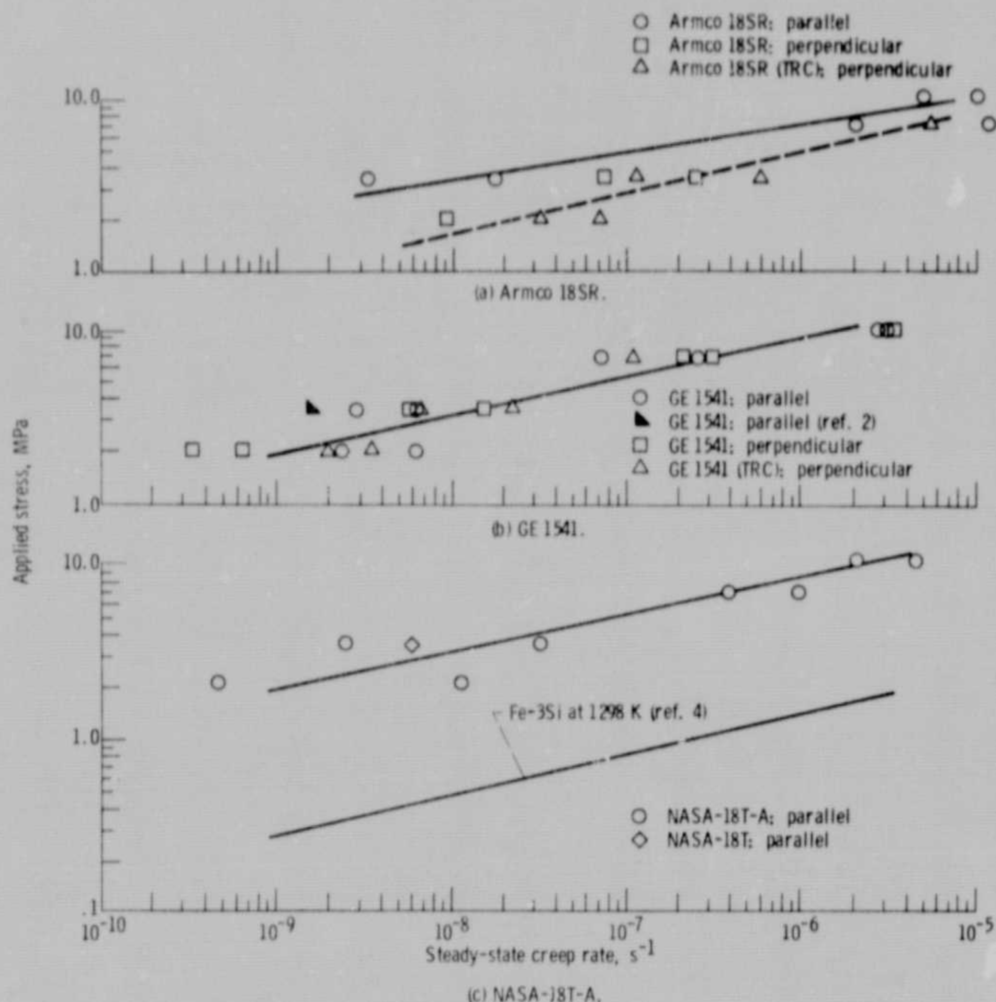

Figure 1. - Steady state creep rate as a function of applied stress for several ferritic stainless steels tested at 1273 K.

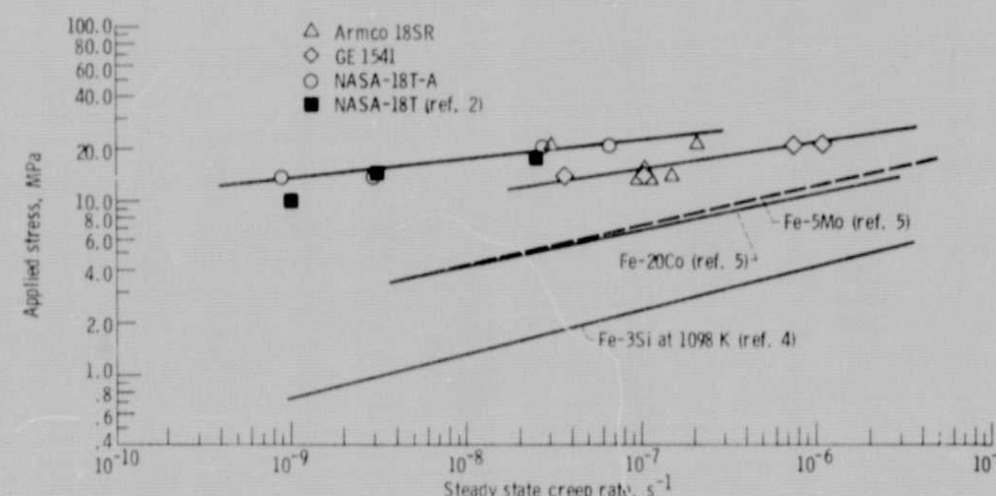

Figure 2. - Steady state creep rate as a function of applied stress for several ferritic stainless steels tested parallel to the final rolling direction at 1073 K.

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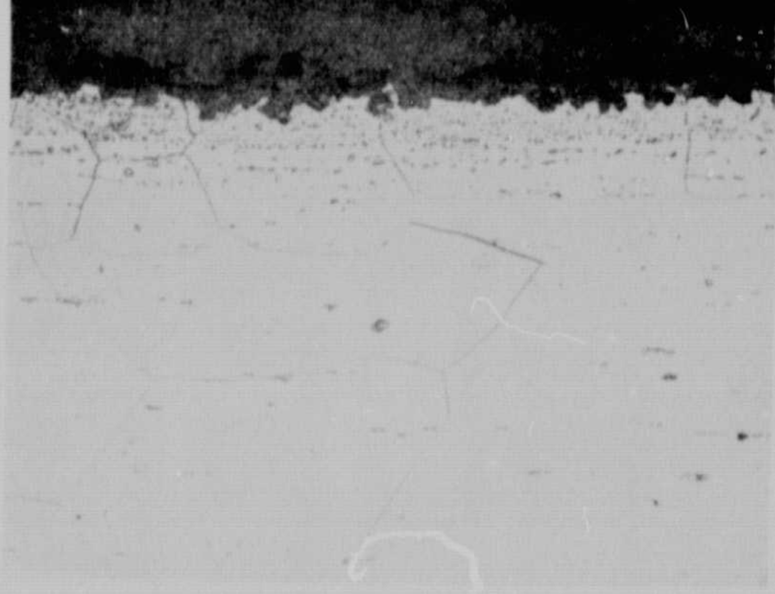
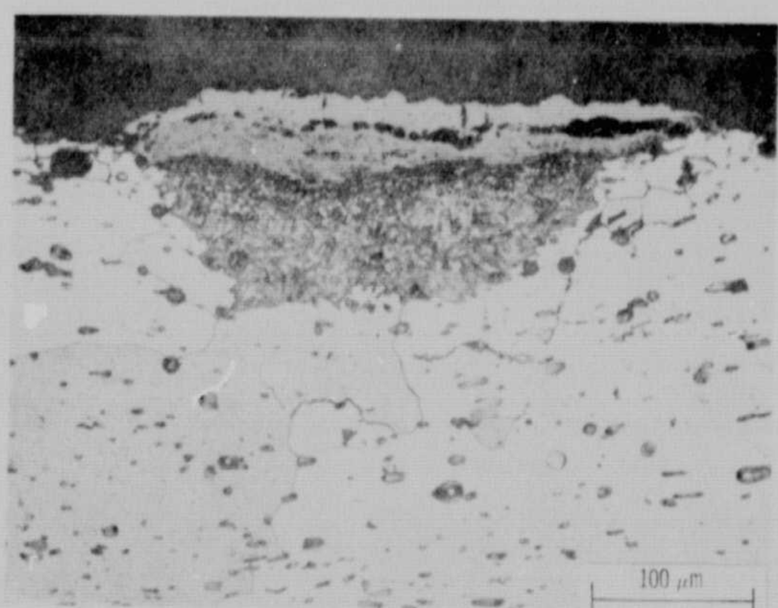
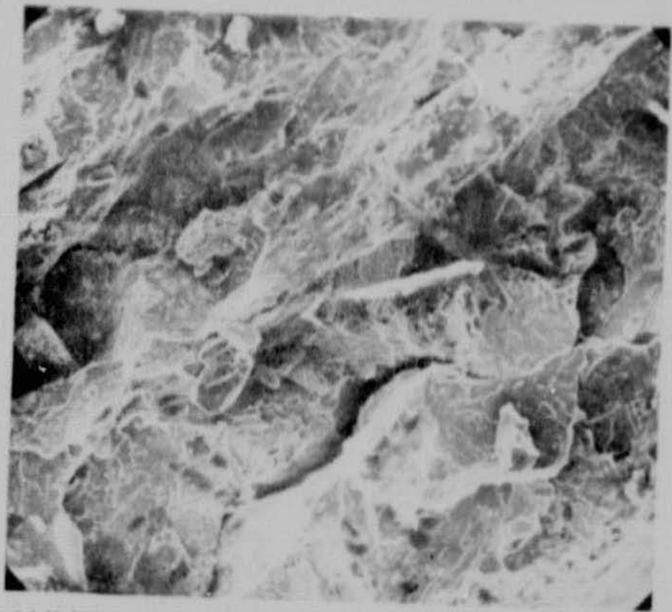


(a) Armco 18 SR(TRC) tested at 3.45MPa for 71.5 hours; 53 percent elongation at failure.



(b) GE 1541 tested at 6.9MPa for 142 hours; 46 percent elongation at failure.

Figure 3. - Examples of oxidation attack observed on failed specimens of several ferritic stainless steels tested at 1273 K.



(a) Multifaceted cleavage in GE 1541 tested parallel to final rolling direction. Prior creep exposure; 6.9MPa at 1273 K to 8.9 percent strain.

(b) Cleavage in Armco 18 SR (TRC) tested prependicular to final rolling direction. Prior creep exposure 2.1MPa at 1273 K to 4.9 percent strain.

Figure 4. - Typical fracture surfaces observed on residual property specimens.

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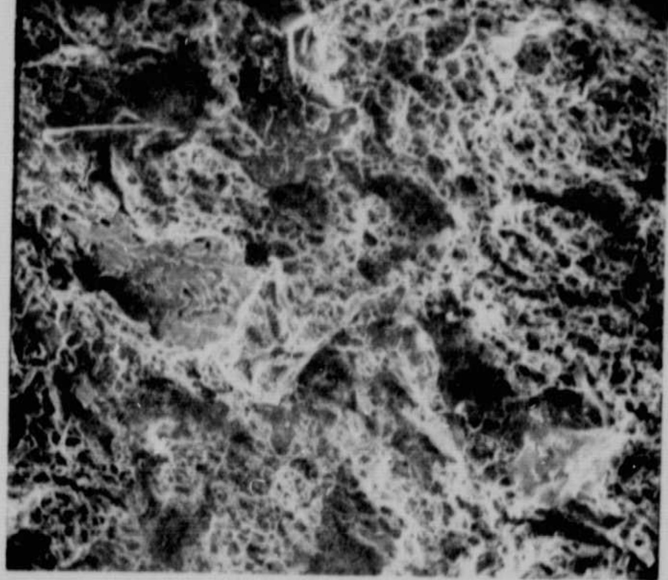
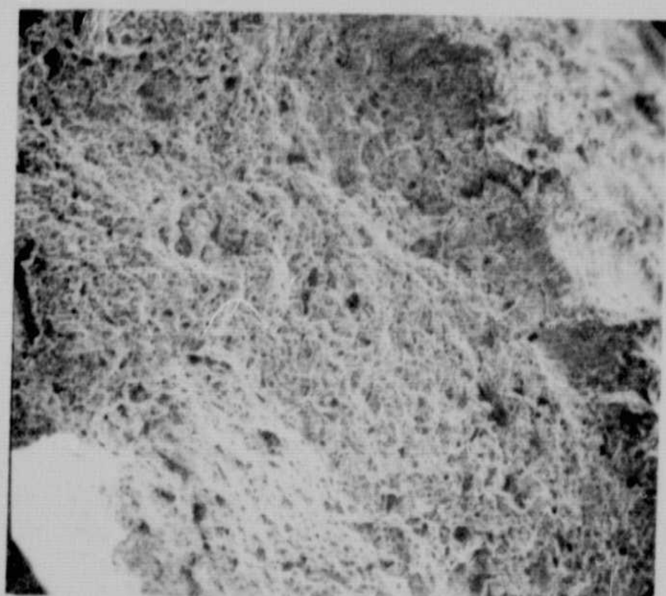


(c) Ductile plus cleavage at edges in GE 1541 (TRC) tested transverse to final rolling direction. Prior creep exposure; 3.45MPa at 1273 K to 1.6 percent strain.



(d) Ductile in NASA-18T-A tested parallel to final rolling direction. Prior creep exposure; 3.45MPa at 1273 K to 1.5 percent strain.

Figure 4. - Continued.

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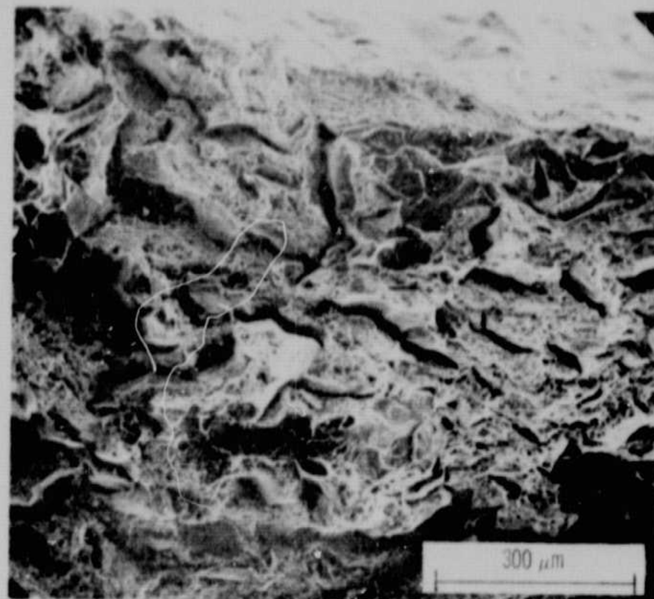

(e) Ductile intergranular plus cleavage in NASA-18T-A tested parallel to final rolling direction. Prior creep exposure; 20.7MPa at 1073 K to 4.4 percent strain.

Figure 4. - Concluded.

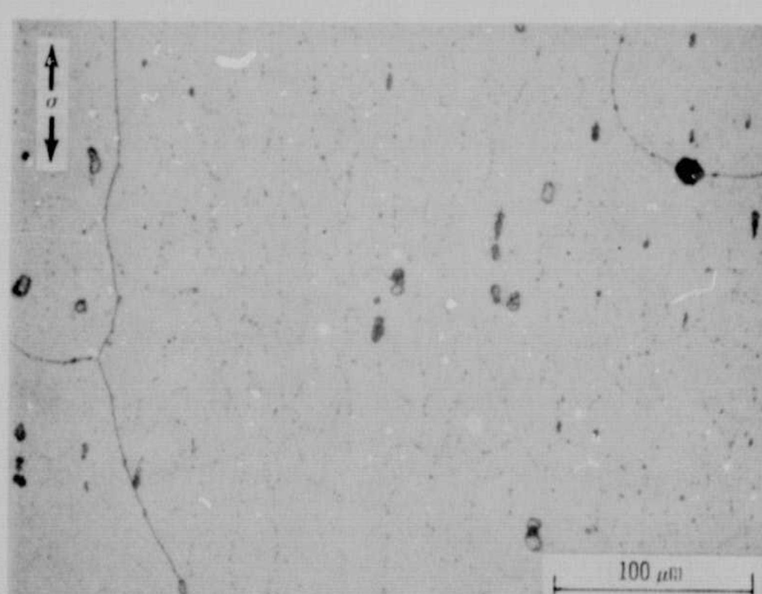

Figure 5. - Typical example of the precipitation on prior grain boundaries in Armco 18 SR during creep testing at 1273 K and 3.45MPa for 150 hours to 2.3 percent strain.

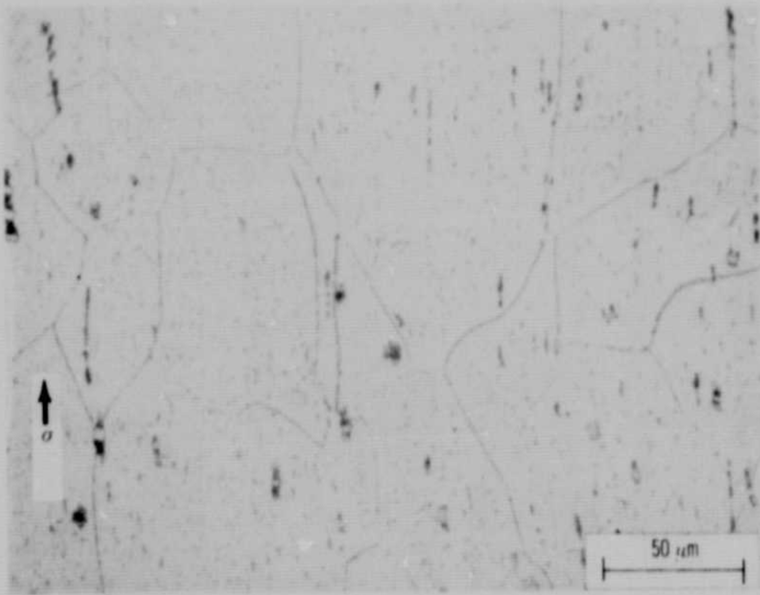

Figure 6. - Precipitates formed in NASA-18T-A during creep testing at 1073 K at 13.8MPa for 150 hours to 0.1 percent strain.

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