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INVESTIGATION OF
THERMAL-STRESS-FATIGUE BEHAVIOR
OF STAINLESS STEELS

Prepared under
AEC Contract AT(04-3)-250
Project Agreement No. 11
for the
Joint U. S. -Euratom Research and Development Board

Mountain View, California

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Joint U. S. -Euratom Research
and Development Report
Special Distribution

INVESTIGATION OF
THERMAL-STRESS-FATIGUE BEHAVIOR
OF STAINLESS STEELS

Quarterly Progress Report No. 4

ATL Job 121200

October-December 1962

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Prepared under
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Joint U. S. -Euratom Research and Development Board

INTRODUCTION

The United States and the European Atomic Energy Community (Euratom), on May 29, and June 18, 1958, signed an agreement which provides a basis for cooperation in programs for the advancement of the peaceful applications of atomic energy. This agreement, in part, provides for the establishment of the Joint U. S. -Euratom research and development program which is aimed at reactors to be constructed in Europe under the Joint Program.

The work described in this report represents the Joint U. S. -Euratom effort which is in keeping with the spirit of cooperation in contributing to the common good by the sharing of scientific and technical information and minimizing the duplication of effort by the limited pool of technical talent available in western Europe and the United States.

SUMMARY

The program to date has been concerned with the thermal-stress-fatigue (TSF) and strain-cycling-fatigue (SC) testing of Types 304 and 304-L stainless steels. The test variables included atmospheric surroundings, hold time, specimen size, and mean temperature. Results indicate a significant difference in fatigue life between annealed and cold-worked material. No significant difference in fatigue life results from testing in argon as opposed to air. Metallographic structural analysis has shown the effects of strain softening as well as various modes of plastic deformation.

The program has now reached the state where it will soon be necessary to decide upon the next material for testing. In connection with the remainder of the program, consideration should be given to using a new specimen design that will permit more accurate measurement of plastic strain.

As was stated in the last quarterly progress report, emphasis is still being placed on the metallographic examination of fatigued specimens.

PRINCIPAL INVESTIGATORS

Investigators on the project include K. E. Horton, Project Leader, and R. S. Stewart, Section Supervisor.

STATEMENT OF PROBLEM

The thermal-stress-fatigue behavior of reactor materials, in particular stainless steels, cannot be predicted by extrapolation of known data such as conventional fatigue data. Because thermal fatigue may be a major consideration in reactor core and vessel design, suitable engineering data are needed. The objective of this program is to obtain thermal-stress-fatigue data on various types of stainless steels for the conditions that may be encountered in reactor operation and if possible to separate the effects of the various environmental and metallurgical variables. The isolation of variables should allow a theoretical treatment of data that would eventually lead to the formalization of generalized equations for predicting thermal-stress-fatigue life for any reactor conditions.

PROGRESS OCTOBER-DECEMBER 1962

A. Test Results (Mechanical)

1. Conventional Specimens

During the quarter, tests were conducted primarily on Type 304-L stainless steel, using the specimen design shown in Figure 1. This design can be considered "conventional" since it has been used by Coffin,¹ Mehringer and Felgar² at General Electric, Carden and Sodergren³ at the University of Alabama, Majors⁴ at the University of Seattle, and Horton and Stewart⁵ at Advanced Technology Laboratories. As mentioned in the last quarterly report,⁶ the measurement of plastic strain in this design is somewhat uncertain. Further discussion on this matter is presented in a later section of this report in association with the results of a theoretical stress analysis on a new specimen design.

1. Superscripts indicate list of references, page 13.

The tests conducted during the quarter are listed in Table I. A summary of the results of tests on annealed and cold-worked 304-L stainless steel at three different mean temperatures, showing the plastic strain per cycle ($\Delta\epsilon_p$) versus cycles to failure (N), is presented in Figure 2. There is definitely a band within which most of the tests lie. The horizontal bandwidth represents the scatter in data for a variety of test conditions. The fact that the band is comparatively narrow supports the choice of $\Delta\epsilon_p$ as the dependent variable.

The decision to use log-log graph paper to plot $\Delta\epsilon_p$ versus N stems from previous knowledge of the empirical relation found for TSF test results^{1,5}:

$$N^K \Delta\epsilon_p = C, \quad (1)$$

where $K = \text{constant} \cong \frac{1}{2}$, and $C = \text{material constant}$. Equation 1 becomes

$$K \ln N + \ln \Delta\epsilon_p = C',$$

and the log-log relationship is clearly evident.

The testing of 304-L stainless steel is still in progress. Because the test conditions are chosen to keep the machines operating and to use the available machined specimens, a strictly ordered sequential study of variables is not being performed. Thus, the data plotted in Figure 2 are not complete in regard to any particular set of test conditions. For instance, the graph shown in Figure 3 is drawn for the purpose of comparing the TSF lives in air of cold-worked and annealed 304-L stainless steel. However, a similar graph for argon cannot be drawn as yet, since the data are still incomplete. The two curves shown in Figure 3 indicate a crossover in the abilities of the specimens to absorb damage (plastic strain). This conclusion is consistent with similar tests performed on zirconium by Horton and Stewart⁵ and on 347 stainless steel by Coffin.¹

The effect of hold time has been partially investigated, and the results are shown in Figure 4. There does not appear to be an "independent" effect other than its influence on the quantity $\Delta\epsilon_p$. This, of course, is in contrast to the effect of cold work as shown in Figure 3. No noticeable effect of hold time in curves of $\Delta\epsilon_p$ versus N has been obtained by Carden⁷ from his tests of Hastalloy N. On the other hand, Coffin¹ obtained an effect when N was plotted versus hold time for 347 stainless steel; however, an effect would be expected in this type of presentation.

The effect of the surrounding atmosphere on fatigue life is shown in Figure 5. Again, no noticeable effect is detected when data are plotted on $\Delta\epsilon_p$ versus N coordinates. It should be mentioned that although oxidation was greatly retarded, it was not completely arrested in argon tests. These results indicate that stress corrosion was probably not influencing the behavior. Had stress corrosion been significant, the data points would lie outside the band of normal data on $\ln \Delta\epsilon_p$ versus $\ln N$ curves, since $\Delta\epsilon_p$ makes no allowance for this type of behavior per se.

From Figures 3, 4, and 5, it may be argued that a fundamental expression should be chosen for the abscissa such that temperature can be treated as an independent variable. Following are examples of such fundamental expressions.

a) The Larson-Miller Parameter⁸:

$$K = T(C + \log t) , \quad (2)$$

where T = temperature,

C = constant $\cong 20$,

t = stress-rupture time.

b) The Feltner-Morrow Relationship⁹:

$$\log \sigma_a = K - (n/1 + n) \log N, \quad (3)$$

where $K = \log [U(1 + n)/2k] n/n + 1$,

U = area of stress-strain hysteresis loop,

k = proportionality constant between stress and plastic strain $= \epsilon_p / \sigma^{1/n}$,

n = slope of plastic strain versus stress on logarithmic coordinates,

N = cycles to failure,

σ_a = one-half of total stress change during fatigue life.

c) The Goldfein Parameter¹⁰ for a Second-Order Reaction:

$$K = \frac{T T_o}{T_o - T} (22.78 + \log \frac{at}{2}) , \quad (4)$$

where T, T_o = temperature,

a = product of concentration of reactant or square of concentration of one reactant (moles per liter),

t = stress-rupture time.

The first and last parameters are easily derived starting from the Arrhenius rate equation. Thus,

$$\text{Rate} = A \exp(-Q/RT), \quad (5)$$

where A = constant,

Q = activation energy,

R = gas constant.

Either by substituting $1/t$ for rate or by having rate in the form of a reaction velocity constant, equations 2 and 4 are developed. Such a development has not been previously applied to thermal-stress fatigue. It is a simple matter to do so, however, by assuming that rate is inversely proportional to $\Delta\epsilon_p N$ (total plastic strain to failure). The result of differentiating the Arrhenius rate equation with regard to temperature is

$$d \left[\ln \left(\frac{1}{\Delta\epsilon_p N} \right) \right] = \frac{Q}{RT^2}, \quad (6)$$

from which it is seen that

$$K = \frac{Q}{R} = T_m \left[\frac{T_2}{T_2 - T_m} \right] \left[\ln (\alpha \Delta T_1 N_1) - \ln (\Delta\epsilon_{p2} N_2) \right], \quad (7)$$

where T_m = mean temperature of cycling, and α = coefficient of thermal expansion.

The limits at boundary 2 are subject to debate, and the procedure for handling equation 7 is presently uncertain. Therefore, Coffin's equation can still be considered as yielding "master fatigue curves" under general conditions. When comparison between test conditions is desired, however, it becomes necessary to determine the different values of K and C .⁵

2. New Specimen Design

It was noted in the last quarterly progress report⁶ that a discrepancy existed between the results of TSF testing at ATL and at the University of Alabama on 304 stainless steel. The ATL data gave more conservative results (see Figure 7 of ATL-A-133), since plastic strain was measured over a 2-inch gage length. The University of Alabama $\Delta\epsilon_p$ results were accurately determined (by optical means) over a 1-inch gage length,

and recently Majors⁴ has used a $\frac{1}{2}$ -inch gage length for determining $\Delta\epsilon_p$. Gage length has an effect on $\Delta\epsilon_p$ primarily because of the axial temperature gradient. Realizing this, ATL has been obtaining simultaneous values of $\Delta\epsilon_p$ for both 2-inch and ~ 0.4 -inch gage lengths in order to assure maximum utility of program results. It has been found that plastic strain over a 0.4-inch gage length is $2\frac{1}{2}$ to 4 times greater than that occurring over a 2-inch gage length in a given test. More complete results of gage length-temperature gradient effects will be published at a later date.

The obvious desire to have uniform temperature in the gage length, and to have the instrumentation present in the exact region of failure, has led ATL to investigate the possibility of using a new specimen design. A particular design that immediately suggests that there would be no temperature gradient in the gage length, since the axial gage length approximates zero, and that the instrumentation can be placed in the exact region of failure is shown in Figure 6. In this TSF specimen, an axial, cylindrical hole is present which results in a 0.020-inch wall thickness at the minimum cross-sectional area. The elongation-contraction movements would be measured radially (herein called diametral strain) at the minimum diameter. There was some doubt about the state of stress at the minimum diameter, and also as to whether strain could be calculated from outside radial-movement measurements. Therefore, the services of the Engineering Mechanics Department at Stanford University were contracted for a theoretical stress analysis. The pertinent findings from this analysis are given below.

A general solution of the stresses present was attempted, using equilibrium equations in association with the well-known biharmonic equation $\nabla^4 \phi = 0$. (In tensor notation, these stresses are σ_{rr} , $\sigma_{\theta\theta}$, σ_{zz} , σ_{rz} , where z is the axial direction.) It was found that solutions to the resulting equations would involve an immense amount of labor. Therefore, a numerical solution was attempted with the assumption that $\sigma_{zz} = f(z)$ only. This assumption can be proved experimentally valid. The numerical solution yielded the following maximum values for the various stresses in terms of σ_{zz} (at $z = 0$, i. e., at the minimum cross-sectional area):

$$\sigma_{rr} = 0.056\% \text{ of } \sigma_{zz},$$

$$\sigma_{\theta\theta_1} = 2.6\% \text{ of } \sigma_{zz},$$

$$\sigma_{\theta\theta_2} = 2.5\% \text{ of } \sigma_{zz},$$

$$\sigma_{\theta\theta_3} = 2.3\% \text{ of } \sigma_{zz},$$

where subscript 1 refers to the inner radius,

subscript 2 refers to the mean radius,

subscript 3 refers to the outer radius.

Thus, the assumption that uniaxial stress exists in the new specimen geometry is in maximum error by 4% in the elastic region of stress and 1.5% in the plastic region.

The foregoing analysis and the following facts support the use of the new specimen geometry:

- a) Strain is maximum at $z = 0$.
- b) Failure will occur at $z = 0$.
- c) Instrumentation to measure $\Delta\epsilon_p$ can be placed at $z = 0$.

Therefore, it will be strongly recommended that the new specimen geometry be used in the future. Results obtained on previous specimens can be extrapolated by performing a few comparative tests; hence, all data reported to date will still be useful.

B. Structural Analysis

Every test specimen is sectioned and mounted for metallographic examination after failure, since this procedure should allow the effects of test variables on failure to be ascertained. As a base for comparison, the as-received (cold-worked) and annealed (2 hours at 1900°F) structures of 304-L stainless steel are shown in Figures 7 and 8, respectively. The extensive slip traces in the cold-worked specimen are more clearly shown in Figure 9. It is noticed that cross-slip is common in this steel. The conventional annealing treatment destroys the slip traces, as seen in Figure 10.

The effect of cyclic thermal stress on the cold-worked structure is made evident by examination of Figures 11, 12, 13, and 14.* The gross difference in grain structure

* See Appendix for explanation of test parameters.

between Figures 12 and 14 is indicative of an "annealing" treatment caused by time at cyclic temperature. Although the specimen shown in Figure 14 was heated to a higher temperature (900°C) than that shown in Figure 12 (800°C), it was held at the higher temperature for a shorter period of time (the cycle ratio, or relative time at temperature, was 900°C/800°C : : 42/370). Failure was initiated in this series of tests by the propagation of surface cracks inward via both intercrystalline and transcrystalline paths. Even with a 60-second hold time at the temperature extremes, the 900°C maximum-temperature test did not "anneal", as shown in Figure 15. While slip traces are not commonly seen in the non-failure regions of these tests, such markings occur near the propagating cracks due to the high strain that takes place in these regions. These slip traces are shown in Figure 16. There is some difficulty in distinguishing between narrow twin boundaries and broad slip traces as outlined by Hempel;¹¹ consequently, it is possible that some of the markings labeled slip could actually be twin boundaries. In face-centered-cubic structures, the phenomenon of mechanical twinning does not take place at elevated temperatures because of energy considerations.¹² This is borne out by present test results, since no noticeable increase in twin density is found after thermal-stress cycling.

TSF testing at a lower mean temperature (400°C) also causes an "annealing" action to occur on cold-worked specimens, as shown in Figures 17 and 18. The specimen in Figure 18 reached the maximum temperature of only 700°C, whereas the specimen of Figure 14 reached 900°C (both cycling through the same ΔT). The cycle ratio is 700°C/900°C : : 288/42, which again emphasizes the importance of time at temperature. A similar comparison is also shown by Figures 19 and 15, where the cycle ratio is 700°C/900°C : : 94/32.

The effect of stress on structure (or vice versa) is illustrated in Figure 20, where it is seen that the structure "annealed" during TSF testing (specimens 66 and 87) and underwent strain softening; however, the structures that were relatively unaffected by TSF testing (specimens 68 and 89) were strain hardened.

Testing of previously annealed specimens evidently results in some further grain growth, as seen in Figures 21 and 22. Longer hold time did not change the structure, as evidenced by comparing Figures 21 and 23. Pure transcrystalline fracture is also shown in Figure 23. (It should be mentioned that the two cracks emanating from the remains of the spot-welded thermocouple were not noticed in other specimens.) Testing at a higher mean temperature (600°C) again caused less "annealing", i. e., grain growth, as seen by comparing Figures 24 and 23.

It was mentioned in the last quarterly progress report⁶ that TSF-cycled specimens appeared to have broader grain boundaries than both as-received (cold-worked) and annealed materials. This difference was also observed between cold-worked specimens which "annealed" during testing and those which did not (see Figures 18 and 14, respectively). An enlargement of Figure 18 is shown in Figure 25. It is apparent that carbide precipitation is the cause of some of the gross etching of grain boundaries. Also, it appears that carbide precipitation takes place at twin boundaries; however, the etch pits at the twin ends are no doubt merely an energy-accelerated process. It is not certain whether the twins actually stop at these points or whether their angle relative to the surface is such that they submerge below the surface. An even clearer indication of carbide precipitation, and perhaps grain-boundary migration, is shown in Figure 26 (the region shown here was also seen in Figure 24).

The concurrent tests of strain cycling at constant temperature have resulted in predictable structures. For example, in Figure 27, both the "annealed" and the cold-worked structures appear to exist; whereas in a specimen undergoing greater plastic strain per cycle at a higher temperature (Figure 28) the "annealed" appearance is everywhere evident. The total time at temperature was approximately 5 times greater in Figure 27 than in Figure 28; thus, it was noted that the 400°C temperature was too low to effect "annealing". The cold-worked structure is still present in specimens that were held for long lengths of time (60-second hold time) at temperatures of 400°C; however, a relatively small amount of plastic strain per cycle resulted (see Figure 29).

Strain cycling the annealed 304-L stainless steel has no doubt resulted in the slip whose traces are seen in Figures 30 and 31. Cross-slip is clearly evident in both these photomicrographs, as is grain-boundary carbide precipitation.

Various investigators^{13,14} have reported that twin boundaries are sites for fatigue cracks in face-centered-cubic metals. Such cracking has not been observed in the structures examined to date by ATL. Another reported phenomenon is the creation of voids, especially in grain boundaries, as a result of fatigue testing.¹¹ There are two causes for void formation: grain-boundary sliding (or grain rotation), and dislocation climb followed by vacancy migration condensation. Void formation has been generally observed in the tests at ATL as evidenced by Figures 14, 24, 31, and 32. As yet, a study has not been performed on the test criteria for void formations; hence, this subject cannot be elaborated on further. It is worthwhile to mention, however, that it is troublesome to distinguish between grain-boundary carbides and voids. Clearly, it is possible for carbides to become unbonded during polishing, leaving a cavity that can be mistaken for a void formed by vacancy agglomeration.

PLANS FOR FUTURE WORK

Both TSF and SC testing will continue on 304-L stainless steel. The next major variable to be studied will be the effect of very large grain size as compared to the as-received and annealed grain sizes. It is expected that the smaller grain-boundary area will weaken the specimens at higher temperatures.

A meeting will be held with the U. S. Atomic Energy Commission to decide upon the next material for testing and whether major emphasis will be placed on the proposed new specimen design.

CONCLUSIONS

1) The effect of cold work is manifested in a longer fatigue life than shown by annealed material at low-cycle-fatigue conditions and a shorter fatigue life at high-cycle-fatigue conditions. The cause for this is probably the lack of strain softening of as-received material at low-cycle-fatigue test conditions.

2) An effect of hold time at temperature extremes is not evident on graphs of $\Delta\epsilon_p$ versus N, whereas an effect is evident on graphs of hold time versus N. The reason for the former is the dependence of the $\Delta\epsilon_p$ variable, since increasing hold time increases $\Delta\epsilon_p$ (per cycle).

3) Atmospheric effects have not been seen to date. It is not certain if this is a valid general conclusion because the study is still incomplete.

4) The variable $\Delta\epsilon_p$ has been shown to be dependent on extraneous conditions. This implies that any parameter that attempts to predict fatigue life should include $\Delta\epsilon_p$ directly.

5) The "annealing" that takes place during TSF testing merely distinguishes between two obviously different structures. The primary differences between the two structures are: a) widths of the grain boundaries, b) presence of voids at grain boundaries, and c) difference in the grain shape (rounded as compared to irregular). It is highly possible that dislocation motion toward grain boundaries by both slip and climb mechanisms is responsible for the first two differences and that grain rotation and boundary migration are responsible for the third difference.

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TABLE I

TSF AND SC TEST CONDUCTED DURING QUARTER
(See Appendix for explanation of test parameters.)

<u>Specimen No.</u>	<u>Test</u>	<u>Specimen No.</u>	<u>Test</u>
59	I. A. 1. a. <u>1</u> . a)-1d	50	I. A. 1. b. <u>1</u> . c)-3b
38	I. A. 1. b. <u>1</u> . a)-2b	54	I. A. 1. a. <u>1</u> . a)-1c
61	I. A. 1. a. <u>1</u> . a)-3d	56	I. A. 1. a. <u>1</u> . c)-3b
69	I. A. 1. b. <u>1</u> . a)-3a	57	I. A. 1. a. <u>1</u> . c)-3c
70	I. A. 1. b. <u>1</u> . a)-3b	58	I. A. 1. a. <u>1</u> . a)-3a
71	I. A. 1. b. <u>1</u> . a)-2c	74	I. A. 1. a. <u>1</u> . f)-1c
72	I. A. 1. b. <u>1</u> . a)-1d	81	I. A. 3. a. <u>1</u> . e)-1a
73	I. A. 1. b. <u>1</u> . a)-3c	82	I. A. 3. a. <u>1</u> . f)-1c
62, 52	I. A. 1. a. <u>1</u> . f)-1a	83	I. A. 3. a. <u>1</u> . f)-1a
63	I. A. 1. a. <u>1</u> . e)-1a	85	I. A. 3. a. <u>1</u> . e)-3b
64	I. A. 3. a. <u>1</u> . c)-3b	88	I. A. 3. a. <u>1</u> . e)-1c
65	I. A. 3. a. <u>1</u> . c)-3c	80	I. A. 3. a. <u>1</u> . a)-3b
66	I. A. 3. a. <u>1</u> . c)-1d	84	I. A. 3. a. <u>1</u> . a)-3c
67	I. A. 3. a. <u>1</u> . c)-1c	86, 94	I. A. 3. a. <u>1</u> . a)-1c
68	I. A. 3. a. <u>1</u> . c)-3d	87	I. A. 3. a. <u>1</u> . a)-1d
35	I. A. 1. a. <u>1</u> . f)-3b	89	I. A. 3. a. <u>1</u> . a)-3d
37, 41	I. A. 1. b. <u>1</u> . c)-1d	91	I. A. 3. a. <u>1</u> . a)-3a
38	I. A. 1. b. <u>1</u> . a)-1b	92	I. A. 3. b. <u>1</u> . a)-1c
39	I. A. 1. a. <u>1</u> . a)-3b	93	I. A. 3. a. <u>1</u> . a)-1b
40	I. A. 1. a. <u>1</u> . a)-3c	42	I. B. 1. b. <u>1</u> . c)-3c
49	I. A. 1. a. <u>1</u> . a)-1b	43	I. B. 1. a. <u>1</u> . c)-3a

DASH NO.	DIMENSION A
-1	0.020"
-2	0.030"

CONVENTIONAL TSF TEST SPECIMEN

FIGURE 1

SUMMARY OF RESULTS OF TESTS ON ANNEALED AND
COLD-WORKED 304-L STAINLESS STEEL, SHOWING
PLASTIC STRAIN PER CYCLE VERSUS CYCLES TO FAILURE

FIGURE 2

PLASTIC STRAIN PER CYCLE VERSUS CYCLES TO FAILURE FOR
ANNEALED AND COLD-WORKED 304-L STAINLESS STEEL TESTED IN AIR,
SHOWING EFFECT OF COLD WORK

FIGURE 3

PLASTIC STRAIN PER CYCLE VERSUS CYCLES TO FAILURE FOR
ANNEALED AND COLD-WORKED 304-L STAINLESS STEEL TESTED IN AIR,
SHOWING EFFECT OF HOLD TIME

FIGURE 4

PLASTIC STRAIN PER CYCLE VERSUS CYCLES TO FAILURE FOR
 ANNEALED 304-L STAINLESS STEEL
 SHOWING EFFECT OF SURROUNDING ATMOSPHERE
 ($T_m = 600^\circ\text{C}$)

FIGURE 5

Neg. #4495

PROPOSED NEW SPECIMEN DESIGN
(An axial, cylindrical hole runs entirely through the specimen.)

FIGURE 6

100×

Neg. #4363

AS-RECEIVED (COLD-WORKED) TYPE 304-L STAINLESS STEEL
Electrolytic Etch: 10% Oxalic Acid

FIGURE 7

100×

Neg. #4377

TYPE 304-L STAINLESS STEEL
ANNEALED 2 HOURS AT 1900°F
Electrolytic Etch: 10% Oxalic Acid

FIGURE 8

750×

Neg. #4640

COLD-WORKED TYPE 304-L STAINLESS STEEL
SHOWING SLIP STRACES
Electrolytic Etch: 10% Oxalic Acid

FIGURE 9

750×

Neg. #4661

COLD-WORKED TYPE 304-L STAINLESS STEEL
SHOWING DESTRUCTION OF SLIP TRACES
BY 2-HOUR ANNEAL AT 1900°F
Electrolytic Etch: 10% Oxalic Acid

FIGURE 10

100×

Neg. #4635

SPECIMEN 91. TEST I. A. 3. a. 1. a)-3a

$T_m = 600^\circ\text{C}$, $\Delta T = 200^\circ\text{C}$

Electrolytic Etch: 10% Oxalic Acid

FIGURE 11

100×

Neg. #4636

SPECIMEN 80. TEST I. A. 3. a. 1. a)-3b

$T_m = 600^\circ\text{C}$, $\Delta T = 400^\circ\text{C}$

Electrolytic Etch: 10% Oxalic Acid

FIGURE 12

100×

Neg. #4638

SPECIMEN 84. TEST I. A. 3. a. 1. a)-3c
 $T_m = 600^\circ\text{C}$, $\Delta T = 500^\circ\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 13

100×

Neg. #4619

SPECIMEN 89. TEST I. A. 3. a. 1. a)-3d
 $T_m = 600^\circ\text{C}$, $\Delta T = 600^\circ\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 14

100×

Neg. #4631

SPECIMEN 68. TEST I. A. 3. a. 1. c)-3d
 $T_m = 600^\circ\text{C}$, $\Delta T = 600^\circ\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 15

750×

Neg. #4639

SPECIMEN 68. TEST I. A. 3. a. 1. c)-3d
 SHOWING SLIP TRACES
 $T_m = 600^\circ\text{C}$, $\Delta T = 600^\circ\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 16

100×

Neg. #4628

SPECIMEN 86. TEST I. A. 3. a. 1. a)-1c
 $T_m = 400^\circ\text{C}$, $\Delta T = 400^\circ\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 17

100×

Neg. #4633

SPECIMEN 87. TEST I. A. 3. a. 1. a)-1d
 $T_m = 400^\circ\text{C}$, $\Delta T = 600^\circ\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 18

100×

Neg. #4620

SPECIMEN 66. TEST I. A. 3. a. 1. c) -1d

$T_m = 400^{\circ}\text{C}$, $\Delta T = 600^{\circ}\text{C}$

Electrolytic Etch: 10% Oxalic Acid

FIGURE 19

CYCLIC STRESS DURING FATIGUE TESTS

FIGURE 20

100×

Neg. #4629

SPECIMEN 54. TEST I. A. 1. a. 1. a)-1c
 $T_m = 400^\circ\text{C}$, $\Delta T = 400^\circ\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 21

100×

Neg. #4622

SPECIMEN 61. TEST I. A. 1. a. 1. a)-3d
 $T_m = 600^\circ\text{C}$, $\Delta T = 600^\circ\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 22

100×

Neg. #4630

SPECIMEN 34. TEST I. A. 1. a. 1. c)-1c
 $T_m = 400^{\circ}\text{C}$, $\Delta T = 400^{\circ}\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 23

100×

Neg. #4643

SPECIMEN 57. TEST I. A. 1. a. 1. c)-3c
 $T_m = 600^{\circ}\text{C}$, $\Delta T = 500^{\circ}\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 24

500×

Neg. #4634

SPECIMEN 87. TEST I. A. 3. a. 1. a)-1d
 $T_m = 400^\circ\text{C}$, $\Delta T = 600^\circ\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 25

500×

Neg. #4642

SPECIMEN 57. TEST I. A. 1. a. 1. c)-3c
 $T_m = 600^\circ\text{C}$, $\Delta T = 500^\circ\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 26

100×

Neg. #4623

SPECIMEN 81. TEST I. A. 3. a. 1. e)-1a
 $T = 400^{\circ}\text{C}$, $\Delta T \cong 400^{\circ}\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 27

100×

Neg. #4621

SPECIMEN 88. TEST I. A. 3. a. 1. e)-1c
 $T = 600^{\circ}\text{C}$, $\Delta T \cong 400^{\circ}\text{C}$
 Electrolytic Etch: 10% Oxalic Acid

FIGURE 28

100×

Neg. #4632

SPECIMEN 83. TEST I. A. 3. a. 1. f)-1a

$T = 400^{\circ}\text{C}$, $\Delta T = 400^{\circ}\text{C}$

Electrolytic Etch: 10% Oxalic Acid

FIGURE 29

250×

Neg. #4645

SPECIMEN 62. TEST I. A. 1. a. 1. f)-1a

$T = 400^{\circ}\text{C}$, $\Delta T \cong 400^{\circ}\text{C}$

Electrolytic Etch: 10% Oxalic Acid

FIGURE 30

250×

Neg. #4644

SPECIMEN 63. TEST I. A. 1. a. 1. e)-1a

$T = 400^{\circ}\text{C}$, $\Delta T \cong 400^{\circ}\text{C}$

Electrolytic Etch: 10% Oxalic Acid

FIGURE 31

750×

Neg. #4658

SPECIMEN 40. TEST I. A. 1. a. 1. a)-3c
 $T_m = 600^{\circ}\text{C}$, $\Delta T = 500^{\circ}\text{C}$
Unetched

FIGURE 32

APPENDIX

VARIABLES TO BE INVESTIGATED

The investigation of the thermal-stress-fatigue variables listed below is believed necessary because: 1) data obtained should provide a thorough explanation of thermal-stress-fatigue theory, and 2) such data should be applicable to actual design conditions and, hence, be useful as "handbook" data.

Structure-Sensitive Variables

1. Sensitization
2. Grain size
3. Degree of cold work

Structure-Insensitive Variables

1. Strain rate
2. Hold time
3. Atmosphere
4. Specimen size
5. Temperature
6. Loading factors (e. g. ,
 prestraining, reverse
 loading)
7. Stress-corrosion cracking

The testing program outlined on the following page is designed to allow investigation of all of the listed variables and to establish their interdependence. An accurate prediction of the time necessary to perform this experimental program is not possible; however, the detail of the investigation will be a function of available time and all data points indicated may not be involved. A reduction in the number of data points is possible without a reduction in the number of variables to be investigated.

PROPOSED TESTING PROGRAM

DESCRIPTION OF TESTS
(Experimental Temperatures, Temperature Changes, and Strains)

Thermal-Stress Fatigue

	<u>1</u>		<u>2</u>		<u>3</u>	
	$T_e^* = 400$		$T_e = 500$		$T_e = 600$	
	ΔT	$T_2 - T_1$	ΔT	$T_2 - T_1$	ΔT	$T_2 - T_1$
a.	200	500-300	200	600-400	200	700-500
b.	300	550-250	400	700-300	400	800-400
c.	400	600-200	600	800-200	500	850-350
d.	600	700-100	800	900-100	600	900-300

$$* T_e = \frac{T_2 + T_1}{2}$$

Strain-Cycle Fatigue
at Constant Temperature

		<u>Strain ($=\alpha\Delta T$)</u>		
<u>Temperature of Tests</u>		<u>1</u>	<u>2</u>	<u>3</u>
		<u>$\Delta T = 400$</u>	<u>$\Delta T = 600$</u>	<u>$\Delta T = 800$</u>
a.	400	X	X	
b.	500		X	X
c.	600	X	X	

Notes: 1) All temperatures in °C.

2) Test conditions will be reported as two series of numbers and letters separated by a dash. The first series is referenced to page A-2 and the second series to page A-3.

EXAMPLE	<u>1st series</u>					<u>2nd series</u>
	I.	B.	1.	a.	2.	c)- 3d.
	<u>Austenitic stainless steel</u>					
	<u>Type 304 stainless steel</u>					
	<u>Annealed, small grain</u>					
	<u>Tested in air</u>					
	<u>30-mil wall</u>					
	<u>TSF, 60-sec hold time,</u>					
	<u>0.0005 in./in.-sec</u>					
	<u>strain rate</u>					
	<u>Temperature cycling</u>					
	<u>of 900-300°C</u>					

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25