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MASTER

Quarterly Technical Progress Report
INVESTIGATION OF
THERMAL-STRESS-FATIGUE BEHAVIOR
OF STAINLESS STEELS

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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.

SUMMARY OF PROGRESS TO DATE

1. The three ATL testing machines have been reconditioned.
2. Material for the Phase I testing (austenitic stainless steel) has been ordered, and a partial shipment obtained to enable early testing.
3. Strain rates in the range of 0.001 to 0.0005 in./in.-sec have been selected for the experimental program, based on preliminary work with Type 304 stainless steel. Tensile tests have been initiated.
4. The variables to be examined initially have been selected jointly with the San Francisco Operations Office of the AEC. The proposed Phase I testing was substantiated by utilizing results of previous research on 347 stainless steel obtained at ATL and General Electric Company under similar conditions. However, the steels were from different heats. A review of this previous work is presented in this report.

PROGRESS APRIL-JUNE 1962

A. Equipment

All ordered electronic instruments have been received, as well as the parts for the new thermal-stress-fatigue tester. Work on rewiring of the controls, assembly of the new fatigue tester, and installation of the electronic instruments is underway and approximately 30 to 40% complete.

B. Material

The preliminary investigation of the mechanical properties (including thermal-stress-fatigue-life) of specimens of austenitic Type 304-L stainless steel machined from cold-drawn tube and cold-forged bar was completed. This investigation led to the conclusion that either form of starting material (i. e. , tube or bar) would give satisfactory results in the testing program. Consequently, to maintain the greatest flexibility in the program, it was decided to order Type 304-L stainless steel bar stock in the annealed condition.

The initial order for Type 304-L stainless steel in the annealed condition was canceled when samples from the intended supply showed a secondary recrystallization structure upon metallographic examination. Since a fine grain size (ASTM 5-8) is desirable when thin material is to be tested, to prevent erratic data caused by single grains traversing an entire cross section of gage length, an order was placed for as-rolled Type 304-L stainless steel, which will subsequently be carefully annealed by ATL after machining.

A small quantity of Type 304 stainless steel was ordered and received to provide material for early testing, since results of this testing will be useful for interpreting the effects of carbon content on grain-boundary sensitization during thermal-stress fatiguing. The certified chemical analysis of this material listed carbon as 0.05%, which is approximately twice that expected in the Type 304-L heat.

C. Initial Testing

1. Strain Rate

An 0.030-inch-wall specimen of Type 304 stainless steel was cycled (unrestrained) to determine the maximum practical strain rate (rate of temperature change) obtainable with the recirculating argon cooling system. The rate, determined for a temperature change from 900 to 100°C, averaged out at 0.0005 in./in.-sec. It must be emphasized that the strain rate in this experiment is a function of temperature, being most rapid at high temperatures on cooling and at low temperatures on heating. Thus it is easily possible to increase the strain rate by an order of magnitude merely by changing the cycling conditions from 900 → 100°C to 700 → 300°C. The new thermal-stress-fatigue testing machine will allow constant, programmed strain rates to be applied; however,

the existing machines lack this ability. With the above experimentation completed, it has been decided to use strain rates in the range of 0.001 to 0.0005 in./in.-sec for the testing program.

2. Tensile Tests

Tensile testing of standard ASTM, $\frac{1}{2}$ -inch-diameter bars (Type 304 stainless steel), is underway. These tests will be used to measure Young's modulus and the coefficient of thermal expansion as a function of temperature and also to predict fatigue life under the assumption of both constant total strain to failure and increasing total strain to failure with decreasing strain per cycle.

D. Comparative Study of Earlier Research Work

A comparative study was made of the research previously conducted on 347 austenitic stainless steel. The sources of data were the work performed by ATL and by General Electric Company.^{1,2} While the attempt to obtain chemical analysis of the steel used by GE was unsuccessful, it was learned that their material fell within accepted standards for this columbium-stabilized stainless steel. The specimens used for testing in both programs were essentially identical; however, there were minor differences in the test apparatus, notably in the degree of constraint applied by the apparatus. The cause of the differences in constraint was the manner in which load (therefore stress) on the specimens was recorded. ATL used load cells in series with the specimen, whereas GE used strain gages in parallel with the specimen, resulting in greater constraint. This apparatus difference leads to the predictable observance of earlier failure of ATL specimens when total strain change per cycle is plotted versus cycles to failure, as shown in Figure 1. The shorter ATL fatigue life at a given strain change is, of course, brought about by the greater temperature change necessary to give that strain. The spread in the GE data resulted from normal data scatter and the fact that more than one heat of steel was used in their tests.

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1. L. F. Coffin, "Design Aspects of High Temperature Fatigue with Particular Reference to Thermal Stress," ASME Preprint No. 54-A-252, 1954.
 2. L. F. Coffin, "A Study of the Effects of Cyclic Thermal Stress on a Ductile Metal," Trans. ASME, August, 1954.

STRAIN CHANGE PER CYCLE VERSUS CYCLES TO FAILURE FOR
ANNEALED 347 STAINLESS STEEL

FIGURE 1

From Figure 1 it would be expected that the result of plotting stress change per cycle versus cycles to failure would be that ATL tests would also indicate a shorter fatigue life at a given stress change, since this stress is being applied at a greater temperature change (ΔT); therefore a higher temperature. Such was not the case, however, since in Figure 2 it is seen that at the same mean temperature of cycling, the stainless steel used by ATL had a greater load-carrying capability. Figures 1 and 2 may at first appear contradictory but could be a result of, for instance, the greater strength of cold-worked materials. That is, the structure of the annealed 347 stainless steel used by ATL was equivalent to a cold-worked structure of the steel used by GE. Hence, the combination of a stronger steel and a less restraining testing fixture results in a shorter fatigue life at equivalent strain changes per cycle and a longer fatigue life at equivalent stress changes per cycle. It naturally follows that a graph of stress versus strain during thermal cycling would indicate a higher yield stress for the ATL material, as confirmed by Figure 3. It should be pointed out that the ATL values for stress were taken at half life, whereas it is not certain at what time during fatigue testing the GE data were recorded.

From the preceding discussion, it is evident that the presentation of thermal-stress-fatigue data can lead to erroneous conclusions. The kinetics of thermal stress are such that strain is the independent variable and thus strain change (and in particular plastic strain) is the important consideration. This is not to say that temperature is unimportant. Temperature derives its importance by its effect on the yield strength and Young's modulus. As shown in Figure 1, although both laboratories were cycling 347 stainless through equivalent total strain changes and at the same average temperature, ATL was using a higher temperature and consequently was inducing a greater plastic strain per cycle than GE.

A final comparison of the programs conducted on 347 stainless is the total plastic strain to failure* versus cycles to failure. This information is graphed in Figure 4 and reveals that at equivalent cycles at failure the ATL material was incapable of sustaining as great a plastic strain per cycle. This, naturally, substantiates the data

* Total plastic strain to failure = plastic strain per cycle $\times$ cycles to failure.

AVERAGE STRESS CHANGE PER CYCLE VERSUS CYCLES TO FAILURE FOR
ANNEALED 347 STAINLESS STEEL

FIGURE 2

STRESS CHANGE PER CYCLE VERSUS STRAIN CHANGE PER CYCLE FOR
THERMALLY CYCLED 347 STAINLESS STEEL

FIGURE 3

TOTAL PLASTIC STRAIN TO FAILURE VERSUS CYCLES TO FAILURE FOR
ANNEALED 347 STAINLESS STEEL

FIGURE 4

plotted in Figure 1. Figures 2 and 4 are somewhat contradictory in that at equivalent cycles at failure Figure 4 indicates that ATL's material is incapable of as large a plastic strain per cycle, yet Figure 2 indicates that ATL's material is capable of sustaining larger stress. This apparent anomaly arises from the differences in test apparatus and materials, as does the confusing relationship between Figures 1 and 2.

The curves of Figure 4 suggest an exponential relationship between strain and fatigue life of the form

$$N^k \epsilon_p = C,$$

where N = cycles to failure,

ϵ_p = plastic strain per cycle (algebraic sum of + and - strain), and

k and C = material constants.

GE has suggested that $k = 0.5$ and their curve for Figure 4 gives

$$N^{0.5} \epsilon_p = 0.36;$$

whereas, the ATL curve implies

$$N^{0.59} \epsilon_p = 0.59.$$

Thus, it is evident that the metallurgical history and chemical composition of different heats of steel will affect the thermal-stress-fatigue life. (It is for this reason that the present program is utilizing material from only one heat of 304-L.) Since the structure (other than that the grain size was ASTM 6-7) of the GE material is unknown, a comparison of the materials in question is impossible. It is known that carbide precipitation occurred in the 347 used at ATL, and this precipitation could be the strengthening mechanism noted in Figure 2. Carbide precipitation in the sensitization temperature range was expected to occur, and it is rather odd that this phenomenon was not noted in the GE work. In the present program 18-8 stainless steels of different carbon content are being studied to note if a cutoff carbon content exists for carbide precipitation under thermal stress.

With the realization of the complicated nature of thermal-stress fatigue, it is necessary to investigate a fairly large number of variables for complete elucidation of the subject. Such basic material variables as composition, grain size, and

metallurgical history are important, as are the external variables of temperature, temperature change, rate of temperature change, hold time at temperature, specimen size, and surrounding atmosphere. The importance of these variables can be illustrated, as in Figure 5,³ where it is seen that increasing strain rate increases fatigue life. While direct comparison to the ATL and GE work on 347 stainless is questionable, it is feasible to explain Figure 1 by stating that the strain rate (rate of temperature change) used by ATL was less than that used by GE, resulting in a lower yield strength, hence a greater plastic strain per cycle and a shorter life.

In any design work, a material factor of safety is employed to allow for, among other things, the variations in the properties of the material. A safety factor of 3 would be inadequate if fatigue-life data were taken from Figure 5 for fast strain-rate tests and if the material used were under cyclic conditions at the slow strain rate. If the equation deduced from the ATL curve in Figure 4 were used, it would be an overestimate of fatigue life by a factor of 2 according to the GE data. Clearly, the designer tries to use test data gathered under conditions identical with those a proposed design will experience, and then computes the necessary geometry required for a safe design. It is therefore impossible to decide without testing which variables have no effect on thermal-stress-fatigue life, and the proposed testing program presented in the last quarterly report⁴ was evolved to obviate the questionable extrapolation of data and, of course, to elucidate completely the nature of thermal-stress-fatigue damage to stainless steels.

CONCLUSIONS

The subject research program is proceeding according to the schedule originally presented in the proposal. An orderly experimental program is being initiated, utilizing what is probably an unequalled thermal-stress-fatigue measurement capability.

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3. K. E. Horton and R. S. Stewart, "Thermal-Stress-Fatigue Behavior of Zirconium and Zirconium Alloys," ATL-A-127, 31 October 1961.
 4. "Investigation of Thermal-Stress-Fatigue Behavior of Stainless Steels," Advanced Technology Laboratories, a Division of American-Standard, Quarterly Technical Progress Report, January-March 1962.

EFFECT OF STRAIN RATE IN FATIGUE TESTING OF
ZIRCONIUM AND ZIRCALOY-2

FIGURE 5

PLANS FOR FUTURE WORK

Thermal-stress-fatigue testing will get fully underway during the next quarter, as will the strain-cycling research. The field of immediate research is Phase I testing (austenitic stainless steel), I. A. 1. a. and I. B. 1. A. of Proposed Testing Program.⁴

PRINCIPAL INVESTIGATORS

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

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