A COMPARISON OF COMBINED TEMPERATURE AND MECHANICAL STRAIN CYCLING DATA WITH ISOTHERMAL FATIGUE RESULTS

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ABSTRACT

Special control circuits have been developed to permit the evaluation of materials under combined temperature and mechanical strain cycling. This technique involves the separation of the thermal expansion component from the mechanical strain component which is caused by the applied load. Independent programming and control of each component is obtained through the use of separate closed-loop systems. Hourglass-shaped specimens, diametral strain measurements and axial force measurements are employed to accurately identify maximum strains and to minimize thermal gradient problems. The precision closed-loop systems contain built-in analog computers to provide axial strain control using diametral strain measurements.

Combined temperature and mechanical strain cycling tests were performed using annealed AISI 304 stainless steel specimens. The total strain range employed was 2.0 percent and the test temperature was cycled between 800° and 1200°F. Hold periods of 4.75 minutes duration were imposed in either the tension or compression portions of the cycle and the effect of temperature phasing was also studied. It was found that when the highest temperature occurred at the peak tensile strain the fatigue life was considerably reduced in comparison to isothermal data at the peak temperature. When the lowest temperature (800°F in these tests) was caused to coincide with the peak tensile strain the difference between tension and compression hold periods was negligible.

A correlation between isothermal and combined temperature and mechanical strain cycling data is presented to allow estimates to be made of the fatigue behavior to be expected under various conditions.

1. INTRODUCTION

In some recent low-cycle fatigue studies [1, 2, 3, 4] of annealed AISI 304 stainless steel, closed-loop, servo-controlled, hydraulically-actuated testing machines were employed in evaluating strain-rate and hold-time effects at 1200°F. It was found that hold periods in tension were much more detrimental than hold periods in compression and that the decrease in the cyclic fatigue life was a function of the length of the hold period. These data were employed to develop an interesting correlation between strain rates and hold periods in tension-hold-only tests in that for a given strain range a plot of time to fracture versus cycle time appeared to be linear on logarithmic coordinates. While this correlation is of value in the analysis of isothermal fatigue data there is no basis for assuming that this concept can be applied to data obtained under conditions which involve a varying temperature throughout the strain cycle. It was felt desirable therefore to extend the range of application of the above analysis by performing some non-isothermal tests. In these studies it was decided to program the temperature and mechanical strain independently and to evaluate the effect of having the peak temperature occur at peak tensile strain in one case and at peak compressive strain in another case. It was also considered pertinent to evaluate the effect of hold periods in the tension and compressive portions of the cycle. It is these test results which form the basis for this paper and these data, obtained using annealed AISI 304 stainless steel, are compared with previously reported isothermal fatigue results for this material.

2. EXPERIMENTAL

Specially-developed, hydraulically-actuated, servo-controlled, closed-loop fatigue testing machines were employed in conjunction with hourglass-shaped test specimens which were heated inductively to obtain the desired test temperatures. A diametral extensometer functioned to measure the diametral strain at the point of minimum diameter while a precision load cell was used to measure the applied force. These values were fed into an analog computer which calculated the corresponding value of axial strain. This approach allowed the axial strain rate to be monitored and controlled and also allowed any selected value of axial strain to be used as the control point. This technique is well established in isothermal fatigue testing and has been described in detail elsewhere [5].

In a recent development a technique was identified to allow controlled temperature cycling to be incorporated in a mechanical strain cycling test. In such testing the electronic signal from the extensometer consists of a component which represents the mechanical deflection of the specimen and another component which represents the combined thermal expansion and/or contraction of the specimen and extensometer. While these same components are present in an isothermal test, the temperature change is encountered only in the initial heating of the specimen to test temperature and this effect is easily accommodated. However, when the temperature is varying continuously the thermally induced signal is not constant with time and must be accounted for in a special manner. In the present approach a circuit has been devised which accepts a thermocouple signal and then generates a correction signal of the same amplitude and wave form as the thermally induced component present in the signal from the extensometer. The correction signal is subtracted from the total extensometer signal to obtain a signal representing only the deflection of the specimen corresponding to the mechanical load. Once this signal is obtained the testing system uses it in exactly the same manner as in an isothermal test. The mechanical strain can then be programmed and controlled independent of the temperature. This separation of thermal and mechanical components allows the effect of various parameters to be studied in detail and a more reliable assessment of material response to certain variables is made possible.

In these tests the strain computer was calibrated using the specimen cross-sectional area and material constants evaluated at the maximum test temperature. This resulted in a slightly incorrect computer output in the other regions of the temperature cycle, the largest error existing at the minimum temperature. A simple calculation shows the magnitude of this error; for example, in the equation:

$$\epsilon = \frac{-2\Delta d}{d} + \frac{F}{EA}(1 - 2\nu_e) \tag{1}$$

where ϵ = total axial strain
d = original specimen diameter
Δd = change in the specimen diameter
F = axial force
E = Young's modulus
A = specimen area
ν_e = Poisson's ratio (elastic)

the amount of axial strain present in a specimen is defined for a given axial force F which results in a diametral deformation Δd. It is this equation that the computer solves, accepting values of F and Δ d and combining them with calibrated values of d, E, A and ν_e to produce an electrical analog of axial strain. The values for these quantities used in the present study are shown in Table I for 800° and 1200°F. At 1200°F the output of the computer was correct. At 800°F the computer still used the 1200°F values and under actual operating conditions at this temperature, where the force was 1900 pounds and the diametral deflection was 1.18×10^{-3} in., the indicated axial strain was 9.98×10^{-3} in/in. If the 800°F data are used from Table I, however, along with the same force

Table I - Specimen Data For Annealed AISI 304 Stainless Steel

Temp. °F	d, inch	E, psi	A, in^2	ν_e
1200	0.253	21.6×10^6	0.0503	0.315
800	0.251	23.4×10^6	0.0495	0.282

and Δd values, it can be shown that the correct axial strain was 10.1×10^{-3} in/in. This indicates an error of only about 1 percent at this strain level.

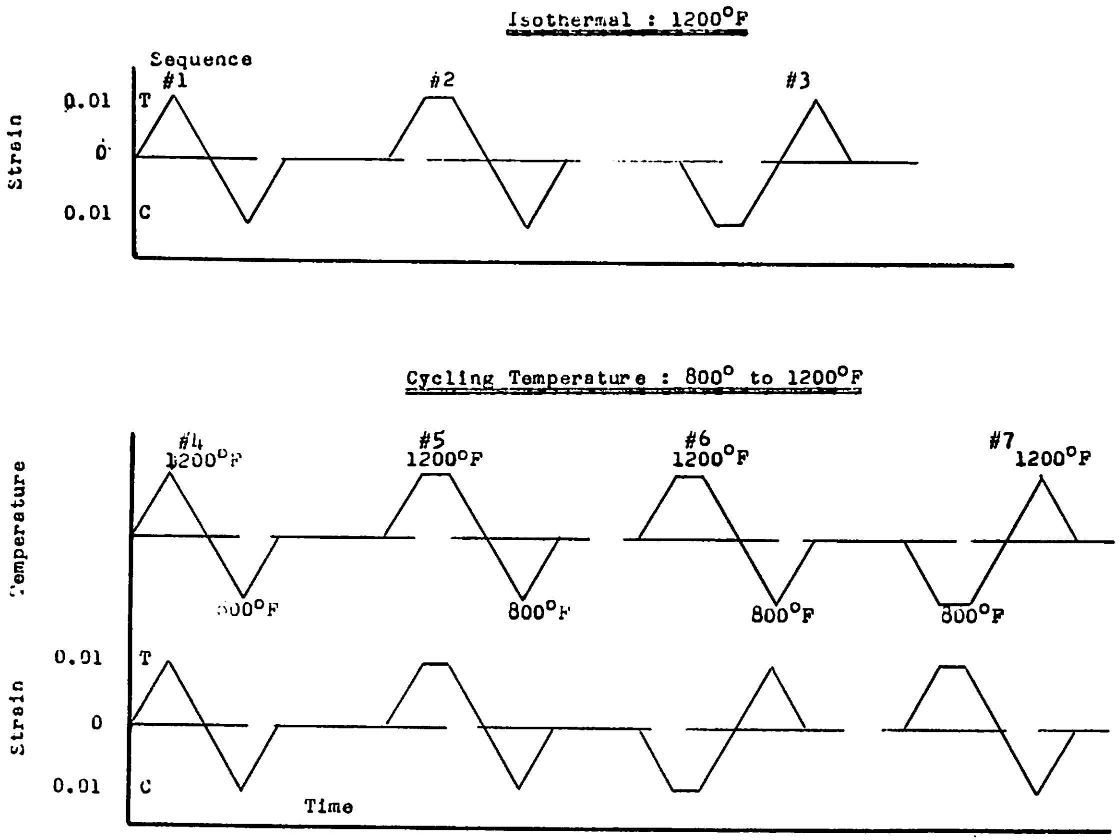
It is possible, of course, to dynamically compensate for changing specimen area and material constants by employing function generators in combination with the strain computer. However this refinement would not be considered necessary except at much lower strain ranges.

3. RESULTS AND DISCUSSION

Schematics of the strain and temperature wave forms applicable to this study are presented in Figure 1. Sequences #1, #2 and #3 apply to isothermal testing for continuous cycling, a hold period in tension and a hold period in compression respectively. Sequence #4 involves continuous cycling of both temperature and strain with the maximum temperature occurring at the peak tensile strain; sequence #5 involves a hold period at peak tensile strain with a hold on peak temperature as well; sequence #6 involves a hold period at peak compressive strain with the maximum temperature occurring in this portion of the cycle (temperature is maintained constant during the hold period); and sequence #7 involves a hold period at peak tensile strain with the minimum temperature occurring in this portion of the cycle (temperature is maintained constant during the hold period).

Corresponding steady-state hysteresis loops are shown schematically in Figure 2. Three different strain rates corresponding to different cycle times are shown in sequence #1; in sequences #2 and #3 the cycle time was 7 minutes with a 4.75 minute hold period and a 2.25 minute cycling period. Two different strain rates (cycle times) are illustrated for sequence #4 and one each for sequences #5, #6 and #7. In these latter three cases the total cycle period was 7 minutes which involved a 4.75 minute hold period and a 2.25 minute cycling period. Of special significance in these loops are the effects of cycle time on the stress range and the relative shapes of the loops in the isothermal and non-isothermal tests.

Data obtained in this study are presented in Table II along with previously reported [2, 3, 6] data for AISI 304 stainless steel.


Isothermal : 1200°F

Cycling Temperature : 800° to 1200°F

Figure 1- Strain and Temperature Waveforms.

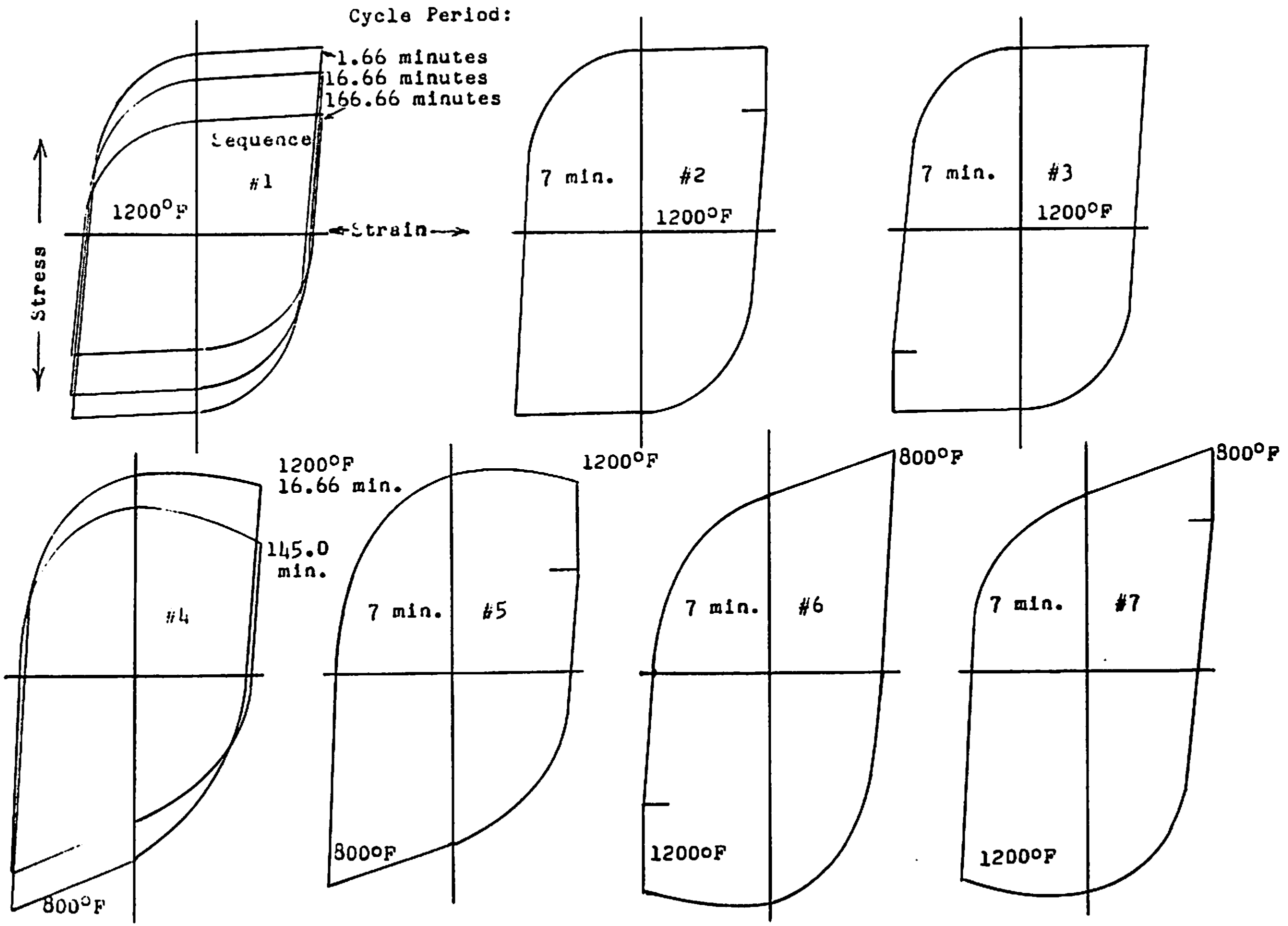


Figure 2- Schematic Hysteresis Loops for Sequences Shown in Figure 1.

TABLE II

Low-Cycle Fatigue Data for 304 Stainless Steel Obtained in Isothermal and Cyclic Temperature Tests

Test No.	Temp. -Strain Sequence	Temperature, °F		Hold Period, minutes		Ramp			Axial Strain Range at $N_f/2$, %			Fatigue Life	
		Tens. Peak	Comp. Peak	T	C	cps	Period, minutes	$\dot{\epsilon}_t$, sec.$^{-1}$	$\Delta\epsilon_t$	$\Delta\epsilon_p$	$\Delta\epsilon_e$	Cycles	Hours
1	1	1200	1200	0	0	0.0001	166.66	4×10^{-6}	1.98	1.76	0.22	307	855
2	4	1200	800	0	0	0.000115	145.0	4.6×10^{-6}	2.00	1.71	0.29	106	253.5
3	1	1200	1200	0	0	0.001	16.66	4×10^{-5}	1.98	1.68	0.29	315	87.5
4	4	1200	800	0	0	0.001	16.66	4×10^{-5}	2.00	1.63	0.37	116	33.1
5	2	1200	1200	4.75	0	0.0075	2.24	3×10^{-4}	2.00	1.72	0.28	173	20.2
6	5	1200	800	4.75	0	0.0075	2.24	3×10^{-4}	2.00	1.73	0.27	180	21.0
7	3	1200	1200	0	4.75	0.0075	2.24	3×10^{-4}	2.00	1.72	0.28	367	42.8
8	6	800	1200	0	4.75	0.0075	2.24	3×10^{-4}	2.00	1.70	0.30	355	41.4
9	7	800	1200	4.75	0	0.0075	2.24	3×10^{-4}	2.00	1.62	0.38	399	46.5
10	1	1200	1200	0	0	0.01	1.66	4×10^{-4}	2.10	1.76	0.34	310	8.61

In the isothermal tests with no hold period: $\Delta\epsilon_p = \Delta\epsilon_t - \Delta\sigma/E$

In the isothermal tests with hold periods: $\Delta\epsilon_p = \Delta\epsilon_t - \Delta\sigma_r/E$

In the temperature cycling tests with no hold period: $\Delta\epsilon_p = \Delta\epsilon_t - (\sigma_{t\,max}/E_t + \sigma_{c\,max}/E_t')$

In the temperature cycling tests with hold periods: $\Delta\epsilon_p = \Delta\epsilon_t - (\sigma_{tr}/E_t + \sigma_{c\,max}/E_t')$

$\text{or} = \Delta\epsilon_t - (\sigma_{t\,max}/E_t + \sigma_{cr}/E_t')$

(E_t is the modulus of elasticity at the temperature existing at peak tensile strain and E_t' is the modulus value at the temperature existing at peak compressive strain).

These results should be viewed in terms of the wave forms presented in Figure 1. In this presentation the possibility of hold periods in both tension and compression was not studied and is not included.

Sequences #6 and #7 represent inverted-phase cycling in that the longitudinal strain and temperature wave forms are the inverse of one another (this has been referred to as negative stress-temperature cycling by Carden [7]). This relationship between temperature and strain will be seen to be identical to that encountered in the temperature cycling of completely restrained material. Sequences #4 and #5 identify a direct phase cycling (positive stress-temperature cycling) with the maximum temperature occurring at the peak tensile strain.

Some additional data obtained in the tests reported in Table II are presented in Table III. This information relates to the stress range at $N_f/2$, the relaxed stress range at the end of the hold period and several other stress components. Of particular interest in the Table III compilation is the effect of strain rate and temperature on the stress range and stress amplitude. For example, the effect of strain rate on stress range in the isothermal tests at 1200°F is evident in test Nos. 1, 3 and 10. As the strain rate is increased from 4×10^{-6} to 4×10^{-4} sec^{-1} at a total strain range of about 2.0 percent the stress range is also increased. The first effect of temperature cycling is shown in the comparison between test Nos. 1 and 2; the increased stress range at the same strain range and strain rate is due to a time-temperature effect as is the difference between the values for maximum tensile stress. Had the period in test No.2 been extended just slightly (compare hysteresis loops in Figure 2) it is felt that this would have led to a tensile stress identical to that observed in test No. 1. The larger compressive stress in Test No. 2 is a result of the same effect; but here the peak compressive stress is attempting to approach a stress comparable to steady state 800°F data.

Another illustration of the time-temperature effect is provided by the data in test Nos. 3 and 4 and follows the pattern discussed in Test Nos. 1 and 2. It is important to note, however, that as the cycle time is decreased to about two minutes in these cycling temperature

TABLE III

Stress Relaxation Data ** Obtained For Annealed AISI 304 Stainless Steel

Spec. No.	Stress Range at $N_f/2$, $\Delta\sigma$, psi	Relaxed Stress Range at $N_f/2$, $\Delta\sigma_r$, psi	Maximum Tensile Stress at $N_f/2$, $\sigma_{t\,max}$, psi	Minimum Tensile Stress at $N_f/2$, $\sigma_{t\,min}$, psi	Maximum Comp. Stress at $N_f/2$, $\sigma_{c\,max}$, psi	Minimum Comp. Stress at $N_f/2$, $\sigma_{c\,min}$, psi	$\sigma_{t\,max} - \sigma_{t\,min}$ psi	$\sigma_{c\,max} - \sigma_{c\,min}$ psi
1	47, 300	--	23, 650	--	23, 650	--	--	--
2	64, 800	--	26, 400*	--	38, 400*	--	--	--
3	63, 460	--	31, 730	--	31, 730	--	--	--
4	84, 000	--	37, 500*	--	46, 500*	--	--	--
5	72, 500	60, 300	35, 700	23, 500	36, 800	--	12, 200	--
6	78, 900	61, 000	37, 900*	20, 000	41, 000*	--	17, 900	--
7	72, 000	59, 900	35, 900	--	36, 100	24, 000	--	12, 100
8	87, 000	68, 500	43, 100*	--	43, 900*	25, 400	--	18, 500
9	84, 950	82, 750	43, 200*	41, 000	41, 750*	--	2, 200	--
10	73, 600	--	36, 800	--	36, 800	--	--	--

* Maximum stress at peak or minimum temperature

** All stresses are based on nominal area of 0. 05 square inch tests the tensile and compressive stresses become identical and the difference between the maximum tensile stress in the isothermal and cyclic tests reaches a maximum value. These conditions have an important influence in affecting material behavior and must be acknowledged in a proper interpretation of fatigue resistance.

The data obtained in test Nos. 5 and 10 represent a consistent behavior as has been previously reported [2] ; this same comment applies to the stress range observed in test No. 7. The stress range data in test Nos. 6, 8 and 9 define a behavior pattern which is explainable in terms of the time-temperature effects described above.

A concluding remark relating to the stress information in Table III concerns relaxation behavior during the hold period. The lower value obtained in test No. 9 is due to a temperature effect since in this case relaxation is occurring at 800°F. Relaxation is essentially identical in test Nos. 5 and 7 as would be expected. The larger relaxation in test Nos. 6 and 8 is due to the larger initial stress values in these two evaluations.

An analysis of the cyclic fatigue lives reported in Table II is made more meaningful by referencing some data [6] describing strain-rate and hold-time effects. This information is shown in Figure 3 to define two important regions. When the strain rate is high (short cycle times) the time to fracture data define a slope of unity to indicate a regime in which N_f is independent of strain rate. Above a certain cycle time a creep effect is evidenced and the cyclic fatigue life is reduced below that predicted by an extension of the line of unit slope. This behavior defines the second region which is indicated by the segments in Figure 3 with slopes lower than unity. These segments appear to develop a slight curvature and seem to once again approach a slope of unity in the regime of long cycle times. This latter behavior might well define a third important region of this plot. This behavior will be seen to apply to all the strain ranges studied [6] .

An important aspect of interpretation should be understood in evaluating Figure 3. Lines of constant N_f are lines of unit slope and the cyclic fatigue life for any point can be compared by making note of this

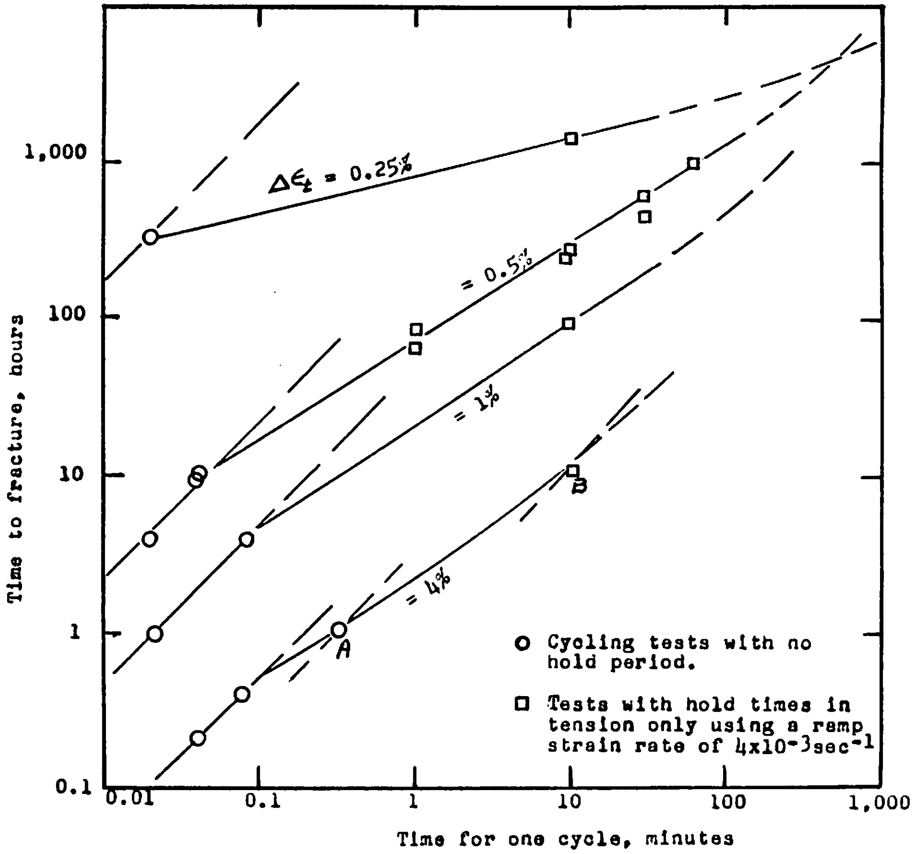


Figure 3- Effects of Strain Rate and Hold Time in Tension Only on the Fatigue Life of AISI 304 Stainless Steel Tested at 1200°F Using Various Strain Ranges(6).

characteristic. For example, in Figure 3, point A represents a higher N_f value than point B simply because the lines of unit slope represent lines of lower N_f values as they are moved to the right in this type of diagram.

Since the data in Table II are limited to a strain range of about 2.0 percent the use of the concept in Figure 3 will focus on just this one segment of strain behavior. Such a plot is shown in Figure 4 based on test results reported in previous studies [4, 6]. In triangular wave-form tests (i.e. no hold period) the fatigue life, expressed as cycles to failure, is independent of strain rate at cycle times below 0.1 minute. This behavior is shown in Figure 4 to define line A with a slope of unity. Above a cycle time of 0.1 minute the triangular wave-form data deviate from line A to reflect a certain amount of creep damage as the strain rate is decreased (cycle time is increased). This behavior is represented by curve C. For cycle times above about 10 minutes it appears that curve C once again becomes linear to exhibit a slope of unity. This, of course, represents another regime in which the fatigue life, measured in cycles to failure, is independent of strain rate.

Curve D in Figure 4 corresponds to cyclic fatigue behavior [4, 6] when a hold period in tension only is involved and the detrimental effect of this mode of operation is evident. It is to be noted that curves C and D are essentially coincident in the region of cycle times from about 0.1 to 1.0 minute. Above this range the two curves separate to indicate different fatigue characteristics. This divergence is due to the different wave forms involved and is seen to become fairly sizeable as the cycle times increase to 100 minutes and beyond. This behavior pattern has now been well substantiated in the light of recent data [6] and Figure 4 is viewed as a more representative form of the fracture-time/cycle-time plot reported previously [1, 3, 4]. In curve D, the slope also seems to approach unity as the cycle times increase. This, of course, means that the fatigue life, measured in terms of cycles to fracture, becomes constant and is independent of cycle time. This is an important observation for it identifies a region in which increasing the hold period beyond a certain value will have no significant effect on the cycles to failure.

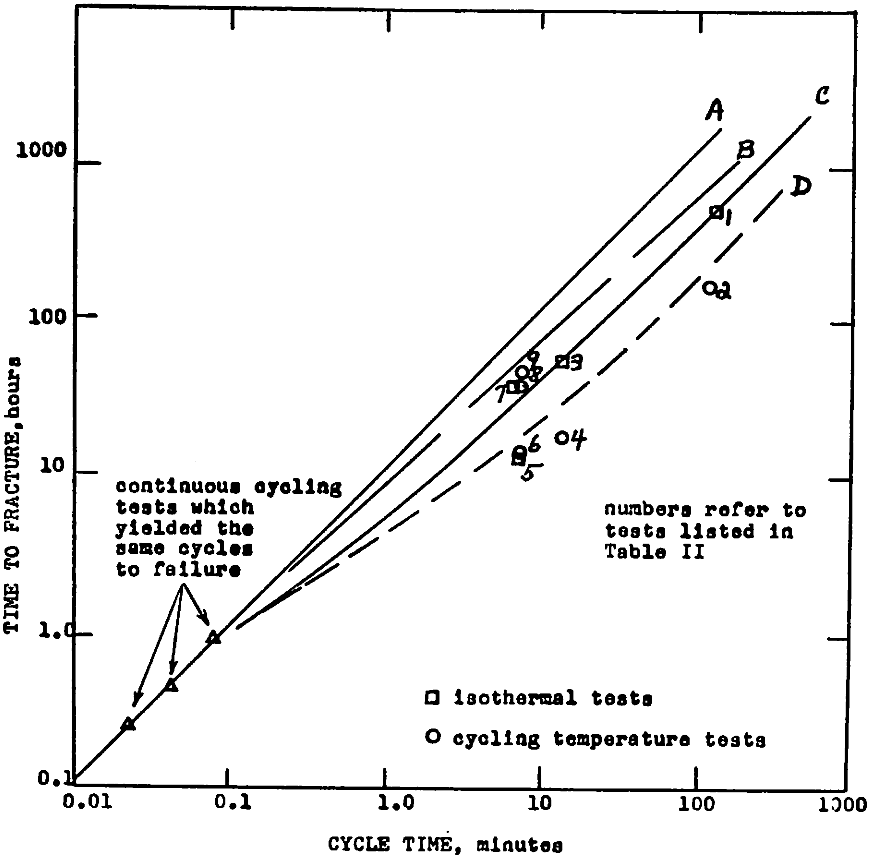


Figure 4- Time to Failure versus Cycle Time for AISI 304 Stainless Steel Tested Under Constant and Cyclic Temperatures at a Strain Range of 2.0 Percent.

The difference between curves C and D is not difficult to understand when stress amplitude and time periods are considered. In curve C, equal time periods of tension and compression exposure are involved and, for the material studied, the stress amplitudes in tension and compression were equal. However when tension hold periods were introduced the time period in tension became greater than in compression and the creep damage due to tension was not fully recovered [2] by the relatively brief compression exposure.

Some comment should also be made to explain the return to unit slope in curves C and D in the region of long cycle times. For triangular wave-forms this appears to be due to the continual decrease in tensile stress amplitude as the strain rate is decreased (this amplitude is 23,650 psi at 4×10^{-6} sec^{-1}). As a result an upper limit or saturation on creep damage is reached at a certain cycle time and beyond this the fatigue life (in cycles) remains constant independent of the cycle period.

An explanation of tension-hold-only behavior is similar to that offered for triangular wave-form results. Longer hold periods lead to increased stress relaxation and eventually the relaxed stress is so low that no further creep damage is associated with the tensile force.

Curve B represents data similar to that which defines curve D but is for cases when a hold period in compression only is employed or when hold periods in both tension and compression are encountered. This curve along with curves C and D provide an interesting assessment of the relative severity of the various modes of operation. For a given strain rate and hold period the longer fatigue life for curve B compared to curve D is due to the larger creep damage recovery which is obtained when hold periods in compression are involved.

Using the comparison plot of Figure 4 the data of Table II define several important patterns. Test Nos.2 and 4 emphasize the detrimental effect of the lower temperature occurring in the compression portion of the cycle. Obviously the creep damage recovery usually associated with the compressive stress is seriously reduced with a significant decrease in fatigue life. These points, of course, should be compared to curve C and identify a fatigue life of something like 30 percent of that measured in the isothermal tests at 1200°F. This observation is an important one for it questions the practice of using isothermal data at the peak cyclic temperature to represent what has been termed "pessimistic" (that is, actual fatigue life will be higher than this) fatigue lives for cyclic temperature evaluations. These data indicate quite definitely, at least for the material in question, that the fatigue life for a cyclic temperature condition can be significantly lower than that observed in isothermal tests at the peak cycle temperature.

Test Nos. 5 and 6 revealed identical behavior even though one test involved a cycling temperature and the other was performed isothermally. Based on this one available data point the effect of a cycling temperature (minimum temperature in compression) seems unimportant at the period involved insofar as tension-hold-only data are concerned. In other words, while a temperature of 800°F in the compression cycle has a marked effect in reducing the fatigue life in continuous cycling tests having cycle times from 16.6 to 150 minutes, it has little to no effect in tension-hold-only tests when the time period is short. This observation can be made even more general for it is clear that had tests similar to Nos. 1 and 2 been performed with a cycle time close to a few minutes the fatigue lives would have been comparable. It is felt that the relatively short exposure to a compressive force provides very little creep recovery in the isothermal test (No. 5) and since this exposure is short the effect of introducing a lower temperature into this portion of the cycle in test No. 6 is not noticeable. This represents an important observation and suggests a more detailed study of this effect.

Test No. 7 yielded an expected result and one which is consistent with previously reported observations [2, 3]. These data reveal a fatigue life greater than that given by curve C and this is due to the hold period in compression and the short period associated with the tension portion of the cycle. Actually it was thought that this data point should be closer to Curve B but apparently some slight material differences caused a lower fatigue life than that corresponding to curve B. This same effect seems responsible for test No.5 leading to a fatigue life just slightly below curve D.

Test No. 8 identifies a very interesting effect. Since the tensile period involves the lower temperature portion of the cycle the creep damage in this lower temperature exposure should be small and the fatigue life would be expected to be greater than that experienced in test No. 7. This effect, however, was not observed. Instead the fatigue lives were identical. The explanation for this effect involves the fact that the primary damage mechanism for the waveform imposed is pure fatigue. In test No. 7 the tensile period is relatively short and the small creep damage is recovered during the compression hold period. In test No. 8 the lower temperature in the tension portion of the cycle leads to very little creep damage just due to the temperature effect and hence there is no need for any recovery inthe hold period. The plastic strain ranges in the two tests are essentially identical and this is consistent with the fact that in test No. 8 the specimen is exposed to 1200°F for a large percentage of the cycle period. This observation suggests that when the creep effect is small the fatigue lives in isothermal and cyclic temperature tests will be comparable. This is obviously another effect which warrants further study.

In test No. 9 the creep damage occurring in tension is small but because of the hold period it must be slightly greater than that associated with the tension portion of the cycle in test No. 8. Some of this damage is recovered due to the exposure to the higher temperature in the compression portion of the cycle. Since the relaxation occurs at 800°F in test No. 9 and at 1200°F in test No. 8 different plastic strain ranges are to be expected. This is seen to be the case and a slightly longer fatigue life is observed in test No. 9 compared to test Nos. 7 and 8 to suggest that the failure mechanism is essentially pure fatigue.

A final comment on Figure 4 relates to test Nos. 2 and 4. Although the data are limited it is expected that had other tests been performed the data would describe another curve just below curve D and it would be concave upward and tend toward a slope of unity as the cycle time is increased. It is interesting and probably significant that the curve D behavior can be used to yield a fairly good estimate of the behavior to be expected in the type of tests corresponding to test Nos. 2 and 4.

4. CONCLUDING REMARKS

The use of isothermal fatigue data obtained at a temperature equal to the peak temperature of a cyclic temperature exposure can yield a serious overestimation of the fatigue life for the cyclic condition. In tests of 304 stainless steel a very significant thermal cycling effect was observed in continuous cycling evaluations when the cycling time was in excess of 16 minutes. When the lower temperature occurs in the compression portion of the cycle in such tests the fatigue life is some 30 percent of that corresponding to an isothermal test at peak cyclic temperature. These test results also identify a cycling frequency below which the temperature cycling effect is negligible. Also identified in these tests are:1) a cycle period below which the tensile and compressive stress components(measured at the peak strain points) are identical even though the temperatures at the two end points differ by 400°F;and2) a cycle period at which the maximum tensile stress can be either much greater than or much less than the maximum compressive stress depending on the phasing of temperature and strain. The isothermal data obtained in this study support earlier observations and indicate the important effect of wave form on fatigue life.

Special attention must be given to temperature phasing,hold periods and stress amplitude in combined temperature and mechanical strain cycling tests for these have a pronounced effect on material behavior. And once these factors are taken into account it is felt that this will do much to resolve many of the contradictory observations which have been made in the area of combined thermal and mechanical strain cycling.

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DISCUSSION

Q J. J. KANTER, U. S. A.

It would be of considerable interest to know to what extent the various strain cycles studies affect the degree of "sigma phase" formations at the failure points.

A E. KREMPL, U. S. A.

No metallurgical evaluations were performed using the specimens tested in this program. However, it is felt that sigma phase formation was not an important factor in any of the material behavior patterns observed in this study.

Q H. R. JHANSALE, Canada

Was the technique of separating the thermal expansion component from mechanical strain component to control the cycling condition maintained throughout the cycle or was it used only to control the limits ?

A E. KREMPL, U. S. A.

It was applied continuously.

Q S. KRISHNASAMY, Canada

I am involved in predicting fatigue like of di-electric materials to be used in high-voltage transmission cables. At present we are running (at Research Laboratories, Ontario Hydro, Toronto, Canada) only isothermal tests. I am wondering whether the behaviour of di-electric materials under high temperature will be similar to that of metals.

A E. KREMPL, U. S. A.

Since the observations in this paper are basically concerned with wave-form, flow stress and creep-relaxation characteristics it is reasonable to assume that similar behavior would result for dielectric materials.

Q S. BUNTING, U. K.

Would the author please tell us how many specimens were tested at each type of loading (as listed in his final slide) ?

A E. KREMPL, U. S. A.

The number of specimens are listed in Table II of the paper.

Q D. G. HAVARD, Canada

The results shown in your paper are all for a high level of strain compared to strains normally used in design. Could you comment on how these conclusions might apply to fatigue behaviour at lower strain levels ?

A E. KREMPL, U. S. A.

We have not performed any low strain range tests using the combined thermal and mechanical strain cycling procedure. However, because of the relative amounts of creep and fatigue damage associated with low strain rate testing we would expect that the difference between isothermal and combined thermal-mechanical results would be more extensive at the lower strain ranges.