# The Relationship Between Stress Relaxation, Rupture and Effect of Temperature on Type 316 Steel

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The elastic analysis route of Code Case N47 for the calculation of combined creep/fatigue damage when the creep damage is caused by stress relaxation makes use of a single "slow cycling" fatigue curve over the temperature range 538-649°C for Type 316 steel. This situation may appear anomolous in relation to the strong effect of temperature on the forward creep damage of Type 316 steel over this temperature range, and to check the validity of the use of a single fatigue design curve over this temperature range, some tests were performed.

Experiments have been carried out at 550°C and 625°C on Type 316 steel. Continuous strain controlled fatigue cycles were applied to the material at a strain range of 0.7% until cyclic hardening was virtually complete; this required 220 cycles. The specimen was then held at peak tensile strain for a period of 200h during which time the stress was allowed to relax; the stress relaxation curve was accurately measured during this period. The creep damage from each relaxation curve was calculated by sub-dividing the curve into time intervals $\Delta t_1$, $\Delta t_2$ ... $\Delta t_n$ corresponding to stress levels $\sigma_1$, $\sigma_2$ ... $\sigma_n$ which from a knowledge of the stress rupture behaviour give failure in times $T_1$, $T_2$ ... $T_n$. The fractional creep damage per cycle is given by the expression

$$\frac{\Delta t_1}{T_1} + \frac{\Delta t_2}{T_2} + \ldots \frac{\Delta t_n}{T_n}$$

Using this approach it was found that the calculated creep damage at 625°C was about twice the value calculated at 550°C. This difference is relatively small, and confirms that the use of a single slow cycling fatigue curve over the temperature range 538-649°C is a fairly reasonable representation of the situation. This conclusion obviously depends on the assumption made in the Code that creep and fatigue damage can be summated in a linear manner.

The effect of temperature noted on the creep damage from a relaxation situation contrasts strongly with forward creep situations in which a temperature difference of 75°C can lead to a hundred fold change in the creep rupture life of Type 316 steel.

## 1. Introduction

The most comprehensive rules currently available for designing components against failure by the combined effects of creep and fatigue are those given in Code Case N47 of ASME Section III Boiler and Pressure Vessel Code. Two alternative design routes are given in this Code Case, one based on elastic analysis and the other on inelastic analysis. In the situation where the creep damage is caused predominantly by stress relaxation, as may be the case in some fast reactor components, the elastic route requires an assessment against a set of slow cycling fatigue curves which are intended to take creep relaxation effects fully into account. On the other hand, in the inelastic route the creep and fatigue damage are summated separately, the fatigue damage being calculated against a set of fatigue curves derived from rapid cycling tests, and the creep damage calculated from the expression

$$\int_o^t \frac{t}{T_d}$$

where t = time at stress $\sigma$ and $T_d$ = allowable time at stress $\sigma$. One difficulty associated with the inelastic route is the lack of materials data necessary for the fractional creep damage to be calculated. Mechanical tests reported in this document have been performed to investigate the creep damage according to the Code Case N47 inelastic route and, in particular, information relating to the influence of temperature is presented.

A trip in a sodium cooled reactor can result in strain controlled fatigue damage in some components. If plastic straining is produced, subsequent operation may lead to creep relaxation, and this process is repeated after each reactor trip. The creep rupture damage is calculated by summating the fractional damage per cycle. Since however the relaxation behaviour is dependent on the prior straining history it is essential to perform the relaxation tests on cyclically stabilised material. A straining route of this nature has been adopted in the tests performed.

## 2. Material

Solution annealed Type 316 steel was used in this experiment. It was obtained as 39 mm dia bar with a chemical composition of C 0.04, Si 0.65, Mn 1.64, P 0.027, S 0.008, Cr 17.2, Ni 11.7, Mo 2.7, Co 0.163, B 5 ppm, $N_2$ 610 ppm, and with room temperature tensile properties of 0.2% PS 289 N/mm$^2$, UTS 580 N/mm$^2$, elongation (on 5 x dia) 54% and reduction of area 79%.

## 3. Experimental

Fatigue specimens of 7.4 mm dia and 12.4 mm parallel length were machined from the bar stock. Strain controlled elevated temperature tests were performed in a servo-hydraulic fatigue machine. Full details of the specimen and experimental arrangements are described by Williamson and Baldwin [1]. Strain cycling of stainless steel results in a gradual strain hardening of the material until a saturation point is reached (Wareing [2]) after which a sensibly stable and reproducible stress strain loop is obtained. A cyclic strain range of 0.7% was selected for this work as being an upper level of that anticipated in service. Tests were performed at 550$^o$ and 625$^o$; temperature selection was dictated by the availability of stress rupture data on the same cast of steel.

It was found necessary to perform 220 strain cycles at a strain rate of 4%/minute to fully stabilise the material at each temperature. The specimen was then held at peak tensile strain for 200 h during which time it was allowed to relax. The stress relaxation curve was derived from continuous load measurements made on the machine during this period.

## 4. Results

The stress relaxation curves plotted in the form of stress versus time on a log basis are shown in Fig 1. Note that although the initial stress value at 550°C is only slightly higher than that at 625°C the extent of relaxation at 550°C is significantly less throughout the relaxation period and after 200 h the remanent stress is about three times greater.

The stress rupture strengths at temperatures of 550° and 625°C for times ranging from 500 h to 10,000 h are given in Fig 2. Straight lines have been drawn through the points and extrapolated on a linear basis to both higher and lower stress levels to contain the full stress range necessary for a complete analysis of the relaxation curves. The fractional creep rupture damage for one relaxation cycle is obtained by dividing the relaxation curve into time intervals $\Delta t_1$, $\Delta t_2$ ... $\Delta t_n$ for each time interval, evaluating the average stress $\sigma_1$, $\sigma_2$ ... $\sigma_n$ as shown in Fig 1 and then for each stress cycle, determining the rupture time $T_1$, $T_2$ ... $T_n$ from the curves in Fig 2. The fractional damage per cycle is given by

$$\frac{\Delta t_1}{T_1} + \frac{\Delta t_2}{T_2} + \ldots \frac{\Delta t_n}{T_n}$$

The fractional creep rupture damage calculated in this way for the 200 h relaxation cycle is 0.0079 at 625°C and 0.0048 at 550°C.

On completion of the relaxation period, one more fatigue cycle was applied. The stress strain cycles observed for the 1st, 220th and 221st cycles at 550° and 625°C are shown in Figs 3(a) and 3(b) respectively.

## 5. Discussion

The shapes of the relaxation curves in Fig 1 are such that the calculated fractional creep rupture damage will vary in a complex manner with both temperature and time. The creep rupture damage at the two temperatures is shown as a function of time in Fig 4 which indicates that at 625°C most of the damage is done in the first few hours whereas at 550°C the bulk of the damage occurs at times in excess of 20 h. It is difficult to draw strict comparisons of the effect of temperature since in addition to influencing the initial stress values, as indicated below, temperature also affects the extent of strain hardening as shown by Wareing [2] and thermal softening during relaxation. In practice the average relaxation period per cycle is expected to be a few hundred hours. Figure 4 indicates that under these conditions the difference in creep rupture damage within the temperature range 550° to 625°C is likely to be small. This finding contrasts sharply with the forward creep situation (which would apply to primary and secondary stresses) where, as Fig 2 shows, the creep damage at 625°C is about 100 times greater than at 550°C.

It has been shown that the fractional creep damage for a single 200 h relaxation cycle is of the order of 0.005 indicating that if this cycle is typical, unity creep damage would occur in 200 cycles. Adopting the inelastic route of Code Case N47 in all respects it would be necessary to calculate the allowable creep damage against some factor of the rupture strength, and this would result in even fewer numbers of cycles. However, whereas the relaxation behaviour was obtained on cyclically hardened material, the rupture tests were performed on as received material, and hence the assessment is likely to be pessimistic. Furthermore, it is not clear how much hardening might occur in reactor components but it is likely that it will be less than that imposed by 220 rapid cycles at 0.7% strain range. Williamson and Baldwin [1] have shown that a lower strain range will result in less hardening and hence less computed creep damage. Slow cycling will also result in less strain hardening and may in fact produce softening. For instance Fig 3 indicates that significant hardening occurs between the 1st and 220th cycles particularly at 625°C. In addition, the imposition of the 200 h hold period resulted in 10% softening at 625°C and 6% softening at 550°C. The relationship between strain hardening and stress relaxation, and of the effects of temperature and computed stress rupture damage is obviously complex and additional tests under different pre-strain conditions are required to obtain a better indication of the possible bounds to the problem. Tests to date have been performed on material more severely pre-strained than is likely in practice and further stress relaxation tests are now necessary on material less severely pre-strained.

The effect of temperature on the creep damage occurring under relaxation conditions can be indirectly evaluated from observations of the fatigue endurance of specimens subjected to strain controlled fatigue with a hold time in the tension part of the cycle. Information from this type of test was analysed to derive the slow cycling fatigue curves given in Code Case N47 for the elastic analysis route. These curves which are intended to take account of creep relaxation effects, are independent of temperature within the range 1000-1200°F (538-649°C). Further evidence of the small temperature effect is obtained from a recent analysis by Diercks and Raske [3] of the hold time fatigue behaviour of Type 304 steel. They found that in the temperature range 550-650°C a change in temperature of 50°C affected fatigue endurance by only 10%. A complementary fatigue life assessment by Lloyd [4] using a crack growth approach suggests that a change in temperature of 50°C may change the growth rate under relaxation conditions by a factor of two, although the precise value is dependent on the stress intensity value assumed.

From the foregoing, it is clear that under fatigue controlled relaxation conditions, temperature has only a small effect on life, and the present results confirm this view. Obviously the precise effect may vary with the type of stainless steel and cast to cast differences. Nevertheless, in the absence of primary and secondary stresses it is unlikely that temperature changes within the range 538-649°C will have a significant influence on the life of reactor components as calculated by the elastic or inelastic route of Code Case N47.

## 6. Conclusions

1. The 200h relaxation behaviour following a pre-strain introduced by the imposition of 220 rapid fatigue cycles at a strain range of 0.7% has been determined at 625°C and 550°C.
2. The calculated fractional creep rupture damage from these tests using the Code Case N47 inelastic route is high; the high values are attributed to the relatively severe prior strain hardening imposed on the specimens.
3. The calculated creep rupture damage for 200 h relaxation is twice as damaging at 625°C as it is at 550°C. This analysis supported by other information suggests that the long

term behaviour of components subject only to fatigue/relaxation will be little influenced by temperature changes within the range 550-625°C. In contrast, under high primary and secondary stresses a change in temperature of this magnitude could affect the life by up to a factor of 100.

4. The calculated rupture damage from the first few hours relaxation is significantly greater at 625°C than it is at 550°C. This large difference is attributed to the prior severe strain hardening imposed.

5. Further relaxation tests are necessary on material less severely pre-strained.

## References

[1] WILLIAMSON, K and BALDWIN, A. B. Fatigue and plastic deformation data on Type 321 stainless steel at 400°C. TRG Report 3013(R).

[2] WAREING, J. Fatigue crack growth in a Type 316 stainless steel and a 20% Cr/25% Ni/Nb stainless steel at elevated temperature. TRG Report 2525(S).

[3] DIERCKS, D.R and RASKE, D. T. Elevated temperature strain controlled fatigue data on Type 304 steel; a compilation, multiple linear regression model and statistical analysis. ANL-76-95.

[4] LLOYD, G. J. RNL Private communication.

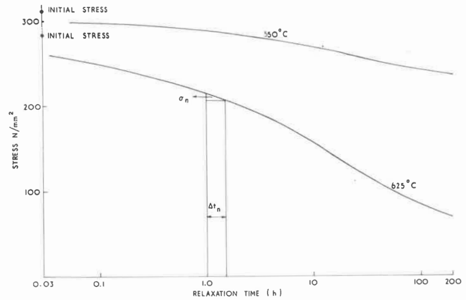

FIG 1 STRESS RELAXATION CURVES

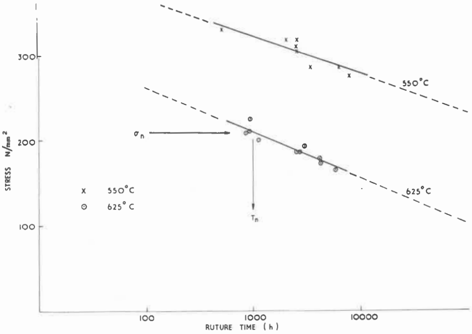

FIG 2 STRESS RUPTURE STRENGTH

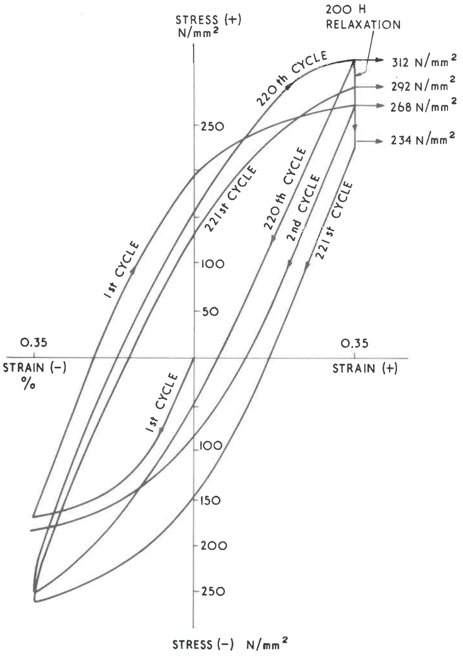

FIG. 3(a) CYCLIC STRESS - STRAIN BEHAVIOUR AT 550° C.

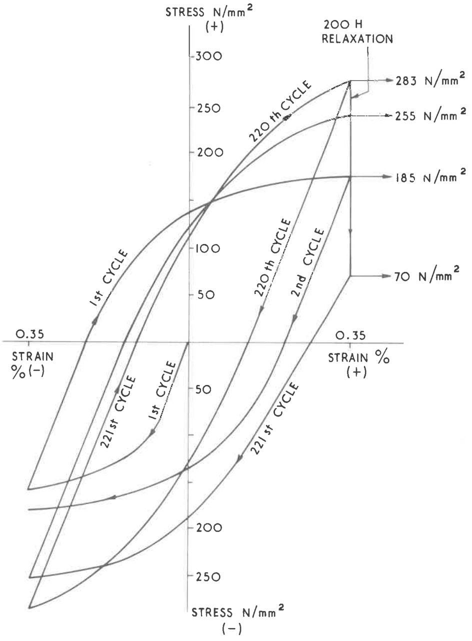

FIG. 3.(b) CYCLIC STRESS - STRAIN BEHAVIOUR AT 625°C.

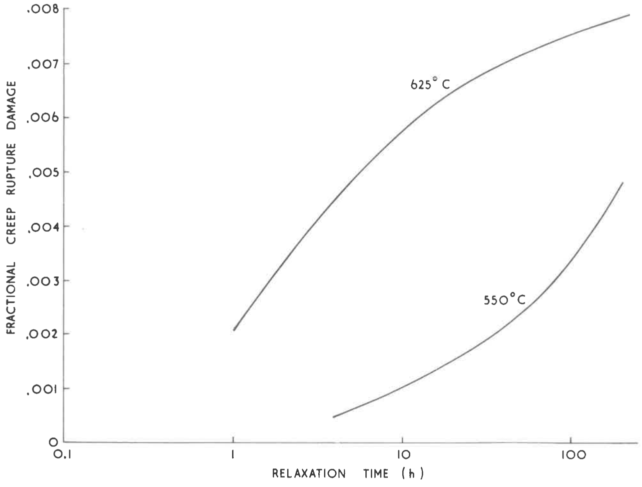

FIG. 4. RELATIONSHIP BETWEEN CREEP RUPTURE DAMAGE AND RELAXATION TIME.