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Dwell Sensitivity Behavior and Modeling

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ABSTRACT

Since engineering materials are exposed to dwell-times in service, it is important to understand the effects of dwell times on the fatigue life. The mechanisms controlling deformation and failure under dwell conditions are in terms of metallographic damage namely; transgranular fracture, intergranular fracture, mixed intergranular transgranular fracture modes, surface striated damage, creep damage and oxidation. These mechanisms are very difficult to include in a quantitative model to predict the dwell sensitivity behavior of high temperature materials. Published creep-fatigue data were compiled from various sources for a number of materials such as copper alloys (NARloy-Z, AMZIRC), steel alloys (9Cr-1Mo), and nickel based alloys(IN 100, Rene 95, Waspaloy). In general, dwell-times were found to be detrimental to the fatigue life of materials, but the exact extent of the effect varies depending on the material, duration of the dwell, and the direction in which a dwell was applied.

In this research an attempt has been made to further develop the models of the senior author and include such concepts as stress relaxation with respect to a particular dwell time. Very limited data sets are available in the literature showing all the test details needed for developing a model for this research. However, the initial trials show stress relaxation as a result of a dwell cycle may exhibit an effect that may describe dwell. A dwell sensitivity damage mechanistic map and a new dwell sensitivity damage parameter were developed.

1. INTRODUCTION

Due to the market influences on price, weight considerations, and design constraints, modern engineering designs border on the thresholds of material durability. Modern innovations such as jet engines and rocket motors used in space exploration typically experience high temperatures, very high loads, and aggressive environments. Under these conditions materials fail due to high-temperature, low-cycle fatigue (HTLCF) and component lifetimes at temperature can often be measured in just a few hours. With small margins of error, it becomes increasingly important that life prediction models properly account for all the factors leading to the failure of a component.

One important consideration in the fatigue life of a component is the duration of time during which peak loading is maintained, known as dwell time. This prolonged period at peak loading can have a number of effects on the expected fatigue life of these components depending on such factors as the material, direction and duration of the hold, temperature, and the strain range at which the dwell is applied. In the laboratory dwell times are simulated by applying a hold at a specified strain level for a period of time. Usually it ranges from a few seconds to a few minutes for gas turbine components and several hours or days for power equipment components.

Figure 1 illustrates a typical hysteresis loop for a strain controlled hold cycle. Starting at point A and proceeding in a clockwise fashion, tensile load is applied to the specimen until the desired strain level is achieved. That strain level is then held for some interval of time during which stress relaxes ($\delta\sigma_t$) as shown in Figure 1. The strain (and stress) is then reversed and the steps are in the compression direction with another hold time applied at peak compressive strain.

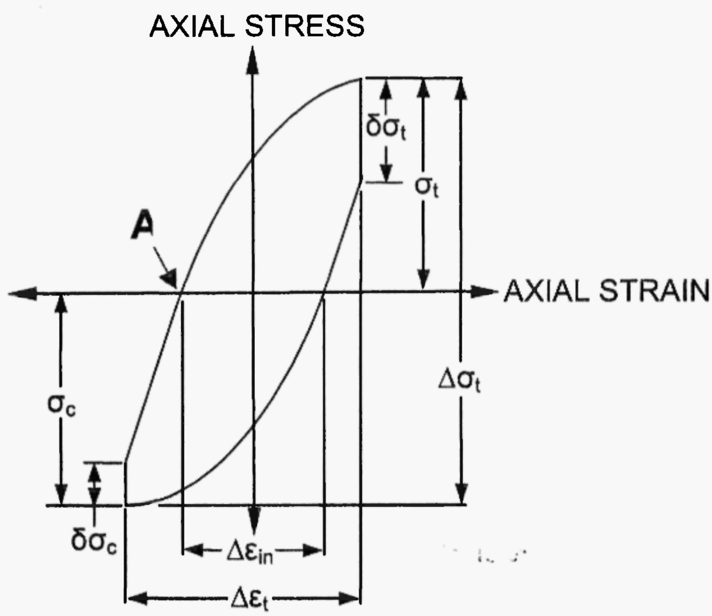

Fig. 1: Typical strain controlled hysteresis loop showing stress relaxation.

When a dwell time (t) is applied in tension only the cycle is identified as a tensile dwell cycle and is denoted by (t/0). Dwell times in the compressive direction only constitute a compressive dwell cycle denoted by (0/t). Unbalanced dwell cycles having a dwell time in both directions (t_1/ t_2), and balanced cycles with equal hold times in both directions (t/t) are similarly designated. Figure 2 illustrates the waveform types studied in this paper.

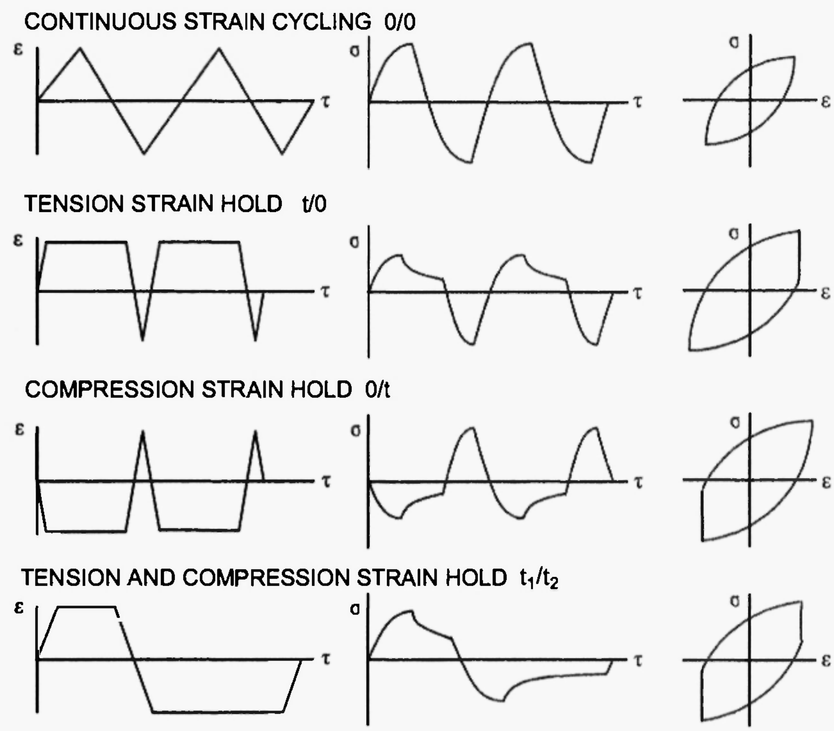

Fig. 2: Typical Low-cycle fatigue testing waveforms.

In a previous paper, Goswami /1/ proposed a new map of dwell sensitivity behavior of high-temperature materials. This map presented data in terms of the inelastic or total strain range and normalized cycle ratio (NCR). The NCR is the ratio of the fatigue life with dwell time to the expected life under continuous fatigue loading (no dwell) when all other parameters are constant. This ratio denotes dwell sensitivity when its value is less than one. NCR values higher than one indicate that the dwell time had a beneficial effect on the fatigue life of the material. The majority of the materials studied exhibited dwell sensitivity in both tensile hold cycles and compressive hold cycles, denoted by (t/0) and (0/t) respectively. A few materials, however, exhibited longer lives under dwell conditions than could be expected under continuous fatigue or (0/0) cycles.

2. DATA COMPILATION

The HTLCF data compiled are from a number of published sources. Table 1 summarizes the materials studied and pertinent testing conditions. In order to generate the NCR plots it was necessary to extrapolate some data points as continuous fatigue data and dwell cycle data were rarely available for the same strain range. Continuous fatigue data ($\Delta\varepsilon_t$ - N_f) were fitted with a least square best-fit equation of the following form:

$$\Delta\varepsilon_t = A(N_f)^b \tag{1}$$

where A and b are material parameters. This equation is a simplified version of the total strain verses life equation that, although not applicable to the entire total strain versus cycles to failure curve, provides a good approximation when cycles are below the transition value from plastic to elastic dominated strain. These parameters for the materials studied are listed in Table 2 along with a measure of the degree of correlation (R^2) between experiment and analytic representation.

Table 1

Summary of materials studied

Materials	Dwell Times	Temperature	Reference
Copper alloys			
NARloy-Z	300s t/0, 0/t	538°C	2
AMZIRC	56s, 200s, 300s, t/0, 0/t, t/t	538°C	2
Superalloys			
IN 100	30s, 300s, 330s, 0/t, t/0	900°C, 1000°C	2
Rene 95	60s, 600s, 0/t, t/0, t/t	650°C	3
Waspaloy	30/0, 0/30, 30/30, 100/10	750°C	2
Low-alloy steel			
9Cr-1Mo Steel	600s, 3600s, t/0, 0/t, t/t	550°C	4

Table 2

Slope and intercept of total strain as a function of cycles to failure

Material	b	log A %	R^2
NARloy-Z (538 °C)	-0.457	1.475	0.972
AMZIRC (538 °C)	-0.517	2.019	0.893
IN 100 (900°C)	-0.185	0.401	0.988
IN 100 (1000°C)	-0.174	0.226	0.998
Rene 95 (650°C)	-0.169	0.672	0.955
Waspaloy (750°C)	-0.439	1.088	0.996
9Cr-1Mo Steel (550°C)	-0.511	1.751	0.966

3. DWELL SENSITIVITY BEHAVIOR

NARloy-Z at 538 °C

NARloy-Z tested at 538 °C is tensile dwell sensitive. As noted earlier, the NCR appears to increase with an increase in total strain range, indicating that at higher strain ranges strain saturation occurs. Compressive hold times increased the NCR. Higher compressive strain rates appeared to further increase the NCR.

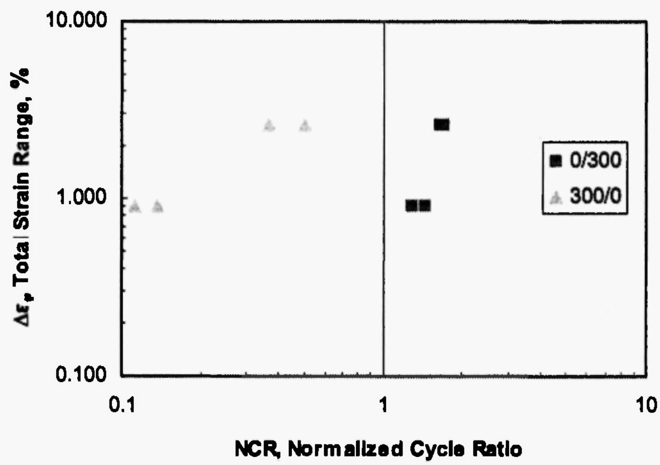

Fig. 3: Dwell Sensitivity Map of NARloy-Z at 538 C

AMZIRC at 538 °C

AMZIRC specimens tested at 538 °C were found to be tensile dwell sensitive at lower strain ranges (1.4%) with the NCR trending toward unity at higher strain ranges. Compressive dwells appeared to transition from damaging to beneficial between 1.4% and 5% strain range. Balanced hold cycles have an NCR greater than tensile dwell cycles and less than compressive dwell cycles indicating that some healing action occurred in the compressive portion of the balanced cycle.

IN-100, Coated at 900°C and 1000 °C

The tests for Coated In-100 were conducted under a wide variety of hold times and temperatures. Compressive dwells at 900°C appeared to be more damaging than compressive dwells of equal length at 1000°C. This can possibly be explained by an increase in ductility with increasing temperature as more ductile materials tend not to be as compressive dwell sensitive as explained in the latter sections. This is further supported by the increase in damage caused by the tensile hold cycles at 3% total strain range for 900°C and 1000°C.

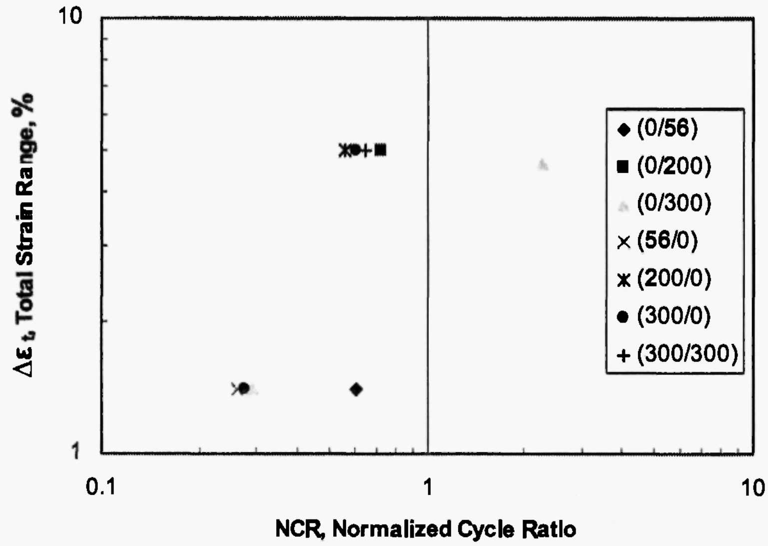

Fig. 4: Dwell Sensitivity Map of AMZIRC at 538 C

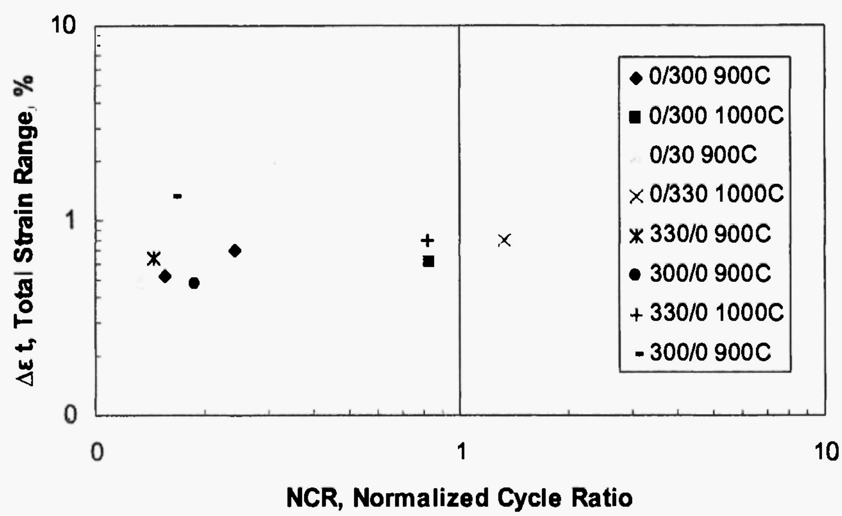

Fig. 5: Dwell Sensitivity Map of Coated IN-100

Rene 95 at 650°C

This data is in accord with earlier results by Goswami and Hänninen. Rene 95 is both tensile and compressive dwell sensitive with compressive dwell cycles being among the most damaging ones. Unlike other materials, where balanced hold cycles tended to have an NCR between that of their component compressive and tensile hold cycles, balanced hold cycles for Rene 95 were among the most damaging. At equal strain ranges, the NCR for a balanced hold cycle was almost a linear sum of the two component tensile and compressive cycles, indicating that little or no healing occurred during the strain reversal. Of the materials surveyed for this study, this behavior was unique to Rene 95.

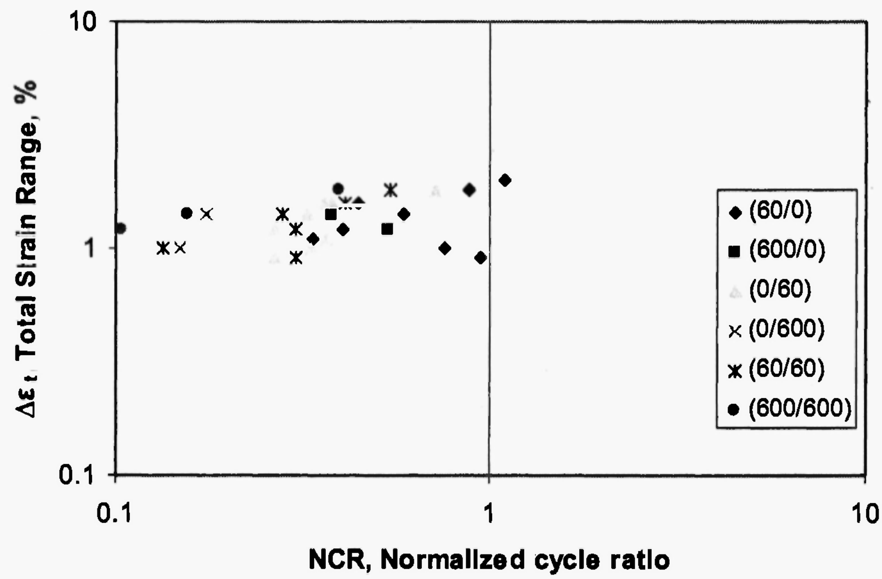

Fig. 6: Dwell Sensitivity Map of Rene '95 at 650C

Waspaloy at 750°C

Waspaloy was found to be both tensile and compressive dwell sensitive. For compressive and balanced hold cycles, the NCR appears to increase linearly with total strain range. Data plotted in Figure 7 illustrates that at higher strain ranges strain saturation occurred and hold times above that strain range were no more damaging than continuous fatigue at that strain range. The balanced (30/30) cycles have an NCR between that of the compressive (0/30) and tensile (30/0) dwell cycles indicating that the stress reversal had a healing effect.

9Cr-1Mo Steel at 550°C

The data set was extracted from a report filed by Ruggles and Ogata /4/. The plot (Figure 8) shows virtually no sensitivity to tensile dwells. At 3600 seconds tensile dwell time and 1% strain range, fatigue life values were still 70% percent of expected life. Compressive dwell cycles caused the largest decrease in NCR. The NCR for balanced hold cycles (600/600 and 3600/3600) was approximately 10% higher than the NCR for a compressive cycle at that dwell time (0/600 and 0/3600) at all strain ranges.

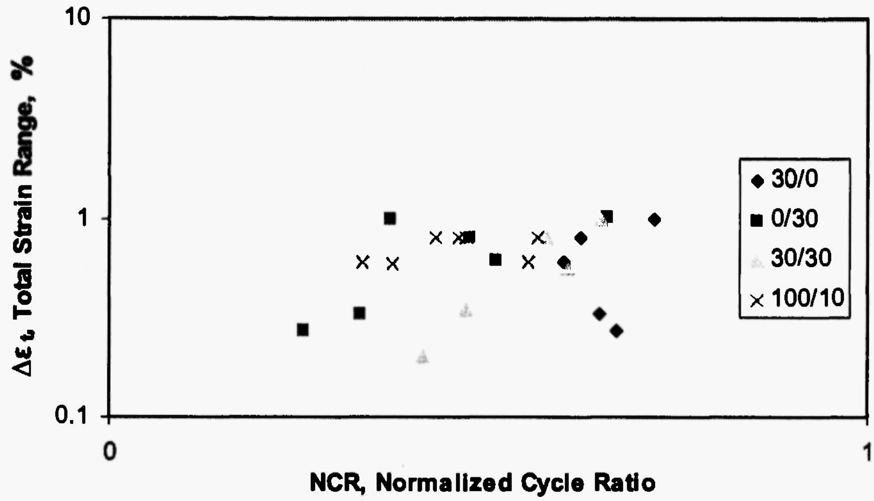

Fig. 7: Dwell Sensitivity Map of Waspaloy at 750 C

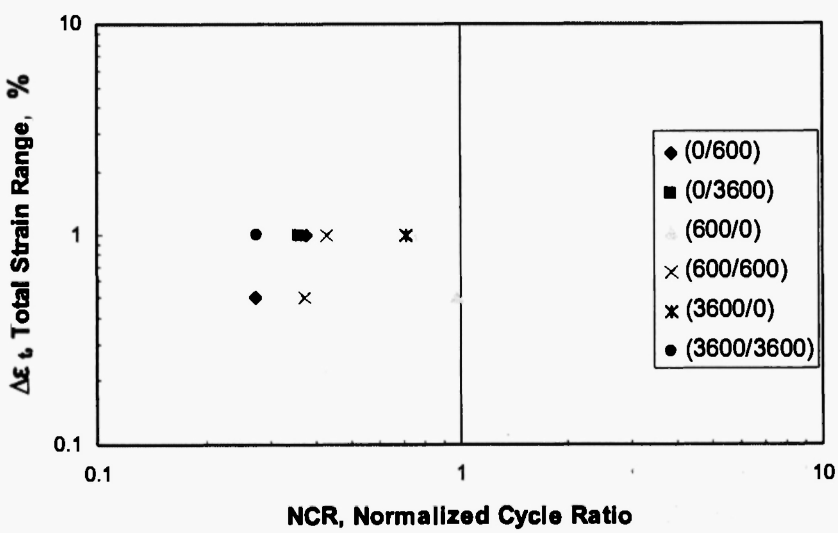

Fig. 8: Dwell Sensitivity Map of 9Cr-1Mo Steel at 550 C

4. DISCUSSION - MODELING DWELL SENSITIVITY

Using tensile strength properties, Goswami /1/ developed an empirical relationship to predict dwell sensitivity. The relationship compares the strength ratios, yield-to-tensile strength of the materials at test temperature and room temperature, and correlates with compressive dwell sensitivity at equal strength ratios. Equal strength ratios correlate with the compressive dwell sensitive materials indicated by the NCR plots. Table 3 summarizes the tensile properties of the materials studied.

Table 3

Summary of tensile properties of materials studied

Materials	Temperature	σ_y / σ_u (room temp.)	σ_y / σ_u (high temp.)	Reduction in Area at test Temp. (%)
NARloy-Z	538°C	0.63	0.85	41.5
AMZIRC	538°C	0.89	0.98	84.0
IN 100	900°C	0.87	0.77	4.0-20.0
Rene 95	650°C	0.82	0.83	12.4
Waspaloy	750°C	0.76	0.76	37.7
9Cr-1Mo Steel	550°C	0.73	0.81	83.0

In a dwell cycle several mechanisms interact with each other such as creep and fatigue. Relaxation is a phenomenon related to creep that occurs under constant strain. That is, the stress that is required to maintain a particular state of constant strain will decrease with time as elastic strain is converted to inelastic strain via relaxation. The rate at which relaxation occurs is dependent on the applied strain, temperature, dwell time and to a certain extent, the immediately prior strain history. In general, relaxation begins at a rate proportional to the applied strain and decays exponentially with time. Hold cycles provide the time component needed for relaxation to occur. Figure 9 illustrates the typical behavior of the stress relaxation rate with respect to time.

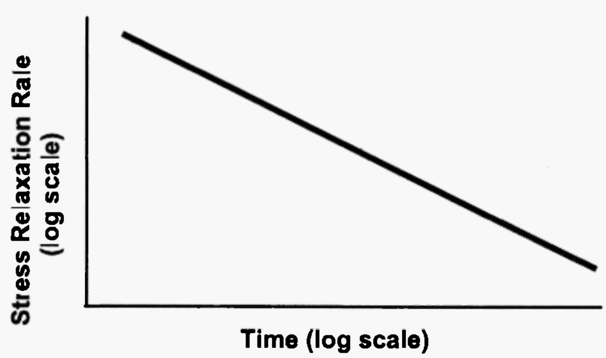

Fig. 9: Typical relation of Stress Relaxation Rate with time

Yang *et al.* /5/ studied the effects of time dependant deformation on a solder alloy at high homologous temperature and concluded that for strain controlled cycles with hold times, an increase in dwell time leads to a decrease in fatigue life if inelastic strain range and inelastic strain rate remain constant. Rapid relaxation of stress was recorded in the initial seconds, becoming gradual as time increased. A study of the NCR plot of 9Cr-1Mo Steel at 550 C (Figure 8) where tensile and compressive dwell times of 600 and 3600 seconds at a strain range of 1% show virtually no change in NCR, seems to indicate that for dwell cycles in one direction only most of the damage is caused in the initial seconds of the dwell time. Balanced hold cycles, however, exhibit large changes in NCR with the addition of more hold time.

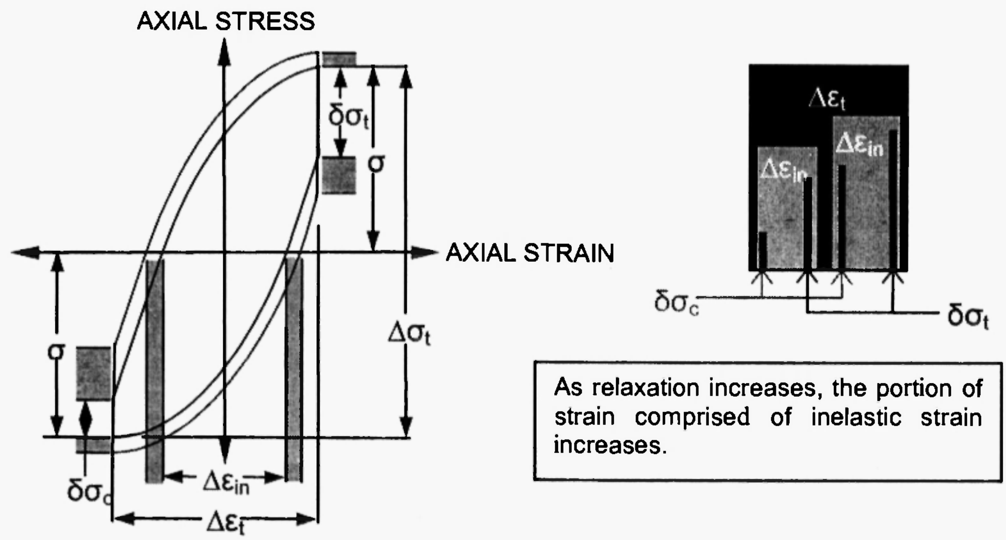

Fig. 10: Typical hysteresis loop showing the effects of relaxation

Since there are no models in the literature to predict dwell sensitivity, a conceptual model is developed below, which needs to be validated with experimental data and its applicability determined for high temperature materials. A dwell time damage parameter (DTDP) was evolved to predict the dwell sensitivity behavior in terms of the following:

$$DTDP = \sigma_r \cdot t_h \cdot \dot{\varepsilon} \cdot \Delta\varepsilon_{in} \quad (2)$$

$$DTDP = \sigma_{sdh} \cdot t_h \cdot \dot{\varepsilon} \cdot \Delta\varepsilon_{in} \quad (3)$$

$$DTDP = \sigma_{tsr} \cdot t_h \cdot \dot{\varepsilon} \cdot \Delta\varepsilon_{in} \quad (4)$$

where

$\sigma_{r;sdh;tsr}$	r- relaxed stress ($\delta\sigma_t$ for tensile hold components and $\delta\sigma_c$ for compressive components)
	tsr- total stress range of dwell cycle ($\sigma_{Max} - \sigma_{Min}$)
	sdh- stress range in the direction of dwell
t_h	dwell time in seconds
$\dot{\varepsilon}$	strain rate
$\Delta\varepsilon_{in}$	inelastic strain range

The new parameter shows a linear relationship with cycles to failure data under dwell fatigue tests. Figures 11 through 13 with various versions of DTDP, namely relaxed stress, stress in the direction of hold, and total stress range, show that as the damage parameter increases the fatigue life decreases. The proposed DTDP can be used as a parameter to characterize the dwell sensitivity behavior of materials.

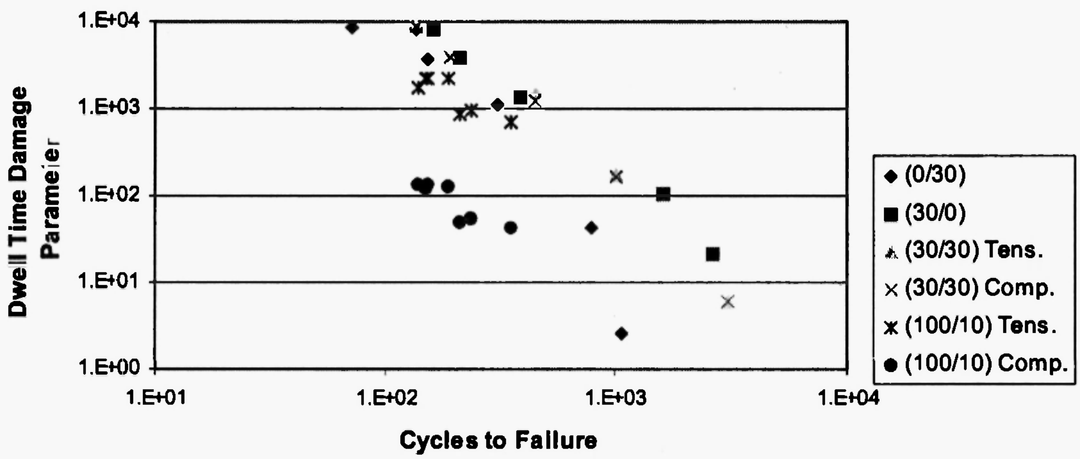

Fig. 11: Dwell time damage parameter vs. Cycles to Failure (relaxed stress version)

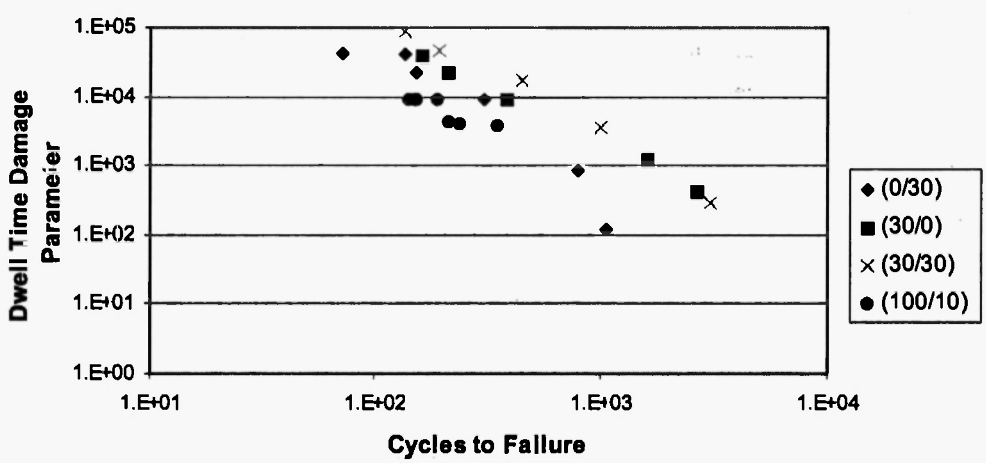

Fig. 12: Dwell time damage parameter vs. Cycles to Failure (total stress range version; dwell time= t_t+t_c))

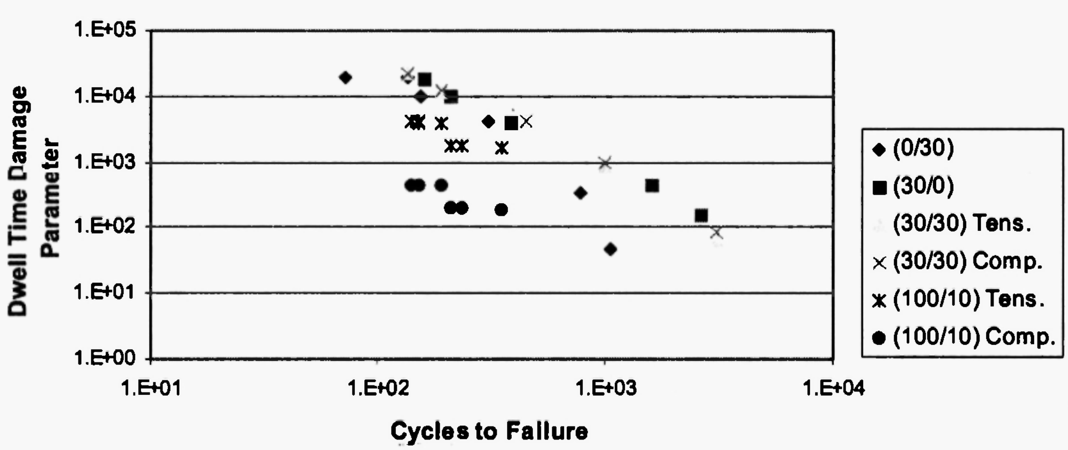

Fig. 13: Dwell time damage parameter vs. Cycles to Failure (stress in direction of hold version)

A dwell sensitivity damage mechanistic map, Figure 14, was developed from an extensive review of damage mechanisms under dwell cycles /6/. This map shows the boundaries in fracture modes above and below the test line 0.5 T_h. Once these lines reach the left hand side of NCR = 0.1 or less creep occurs. To the right of the NCR = 1 line, fracture is thought to be of predominately fatigue mode. The three possible modes in which damage develop are:

1. Transgranular
2. Mixed transgranular and intergranular
3. Intergranular

Transgranular damage occurs in cycles with faster strain rates, lower strain range (<1%), lower temperature ($T_t \leq 0.5T_h$), and moderate dwell time combinations. Mixed transgranular and intergranular damage occurs in cycles with slower strain rates, intermediate strain range (<1.5%), higher temperatures ($T_t > 0.5T_h$), and longer dwell times (dwell times > 1 - 10 minutes). Intergranular damage occurs in cycles experiencing the slowest strain rates, higher strain ranges (>1.5%), higher temperatures ($T_t > 0.5T_h$), and longer dwell times. It is likely that these combinations may not apply for compressive dwell sensitive materials and therefore cannot be generalized.

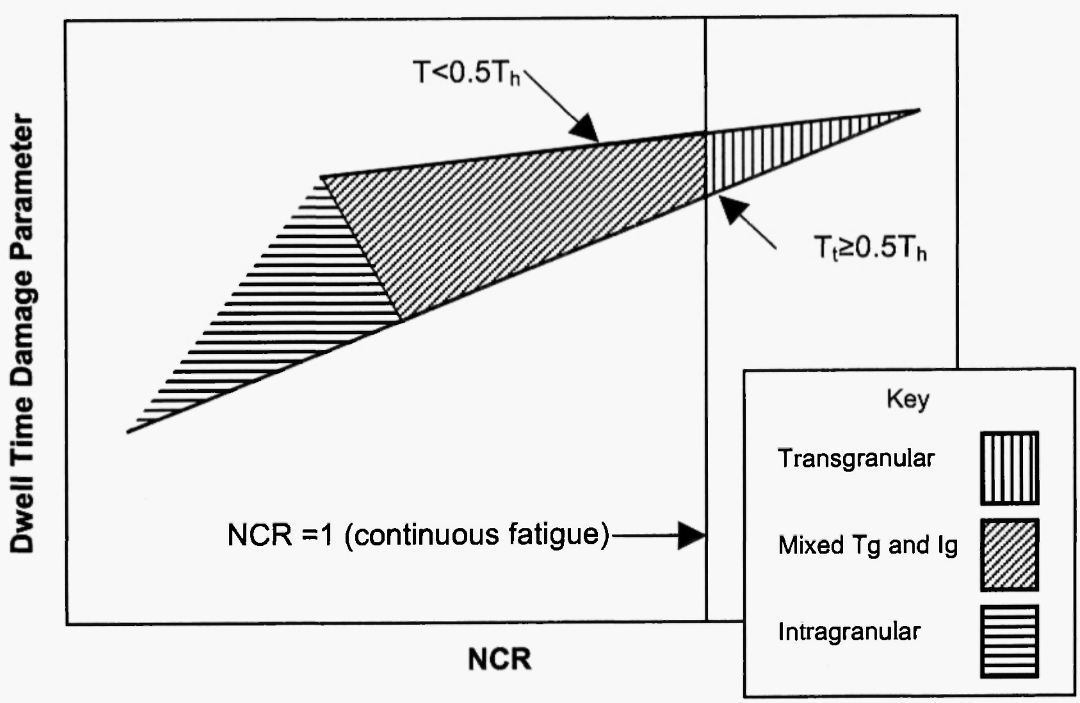

Fig. 14: Conceptual Model of Dwell Sensitivity Mechanistic Map

5. CONCLUSIONS

1) Dwell sensitivity was mapped in terms of normalized cycle ratio (NCR) and strain range plot for a number of high temperature materials. As the strain range increased, the dwell sensitivity was found to saturate. Dwell sensitivity was more pronounced only at lower strain ranges.
2) The empirical model developed to predict dwell sensitivity using tensile properties, strength ratios, was examined for the materials and found to be an indicator of dwell sensitivity in most of the materials studied in this paper.
3) A dwell time damage parameter was proposed which exhibits linear relationships with cycle to failure data and may be an indicator of damage produced by dwell cycles.
4) A conceptual damage mechanistic map of dwell sensitivity was proposed which establishes the combinations of test parameters producing different damage features such as transgranular, mixed transgranular + intergranular, and intergranular damage.

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