1997

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Repository Citation

Goswami, T., Halford, G. R., & Hoeppner, D. W. (1997). Dwell Sensitivity Fatigue Behaviour of High Temperature Materials. *High Temperature Materials and Processes, 16* (2), 87-96.
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Dwell Sensitivity Fatigue Behavior of High Temperature Materials

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ABSTRACT

The dwell sensitivity fatigue behavior of six high temperature materials is examined in this paper: two stainless steels, 304L and 304, two tantalum alloys, T-111 and ASTAR 811C, pure nickel Ni 201 and a single crystal nickel-base superalloy, PWA 1480. The stainless steel alloys were found to be tensile dwell sensitive; however, a saturation in dwell sensitivity was found with the increase in strain range for all materials examined. At lower strain ranges the dwell cycles were producing lower lives than at higher strains, as found in the case of AISI SS 304 and two tantalum based alloys, T-111 and ASTAR 811C. Trends in various normalized life curves were found to be strain dependent for ASTAR 811C, in which below 0.2% inelastic strain range, dwell effects were more deleterious than above it. Mechanistic aspects under different test conditions were summarized.

KEY WORDS:

dwell sensitivity, plastic and total strain ranges, cycles to failure, normalized cycle ratio, isothermal and thermo-mechanical fatigue

1. INTRODUCTION

Cyclic strain fatigue curves of materials are frequently used in the design of critical components of high performance equipment such as: aeronautical gas turbines, ground based turbines, nuclear reactors, rocket motors, the space shuttle main engine, earth-to-orbit propulsion and other systems. These applications require a component to operate under near-steady conditions for a duration of time (hundreds of seconds to hundreds of hours) once peak operating conditions have been achieved. Therefore, under such conditions the materials of construction suffer not only the rapidly induced damage of start-up and shut-down, but also creep damage under sustained load and strain during the steady periods. The extent of the creep damage depends upon the operating parameters of temperature, stress, and loading waveform, and material parameters. Such steady loading periods are simulated in the laboratory in terms of dwell periods applied at peak stress or strain conditions /1-6/. Some components experience tensile stress-strain dwells while others experience compressive dwells.

Effects of dwells under tension or compression loading conditions can be different from material to material. These effects are not fully understood /7-11/ since tension and compression creep mechanisms are not the same. Therefore, a material can be either tensile or compressive dwell sensitive, both, or a combination respectively. A material in an alloy group, low alloy steels for example, 1Cr-Mo-V steel is tensile dwell sensitive /12/, whereas 2.25Cr-Mo steel is compressive dwell sensitive /13/. In the former, material creep damage is due to cavitation /12/, whereas in the latter, oxidation and strain aging mechanisms compete with one another at specific temperatures. Parameters such as homologous test temperature, strain rate, strain range, thermal expansion, hold time, microstructure and others are important in governing cyclic lives under dwell conditions. This paper describes the dwell sensitivity for six materials in a range of alloy systems. The data are from the open literature. A brief discussion on dwell sensitivity fatigue behavior with respect to mechanistic aspects under different test conditions is presented in this paper. Mapping of dwell sensitivity fatigue behavior, a procedure proposed in Reference /10/, has been used in this paper.

2. MATERIALS

The dwell sensitivity behavior of the six materials /1-4/ summarized in Table 1 is investigated in this paper. Table 1 describes the materials, their conditions, proposed use and references. These materials have been considered for applications involving space or aerospace propulsion systems. Low cycle isothermal fatigue (IF) and thermal-mechanical fatigue (TMF) are predominating failure modes in such applications, so laboratory data of this nature were generated and reported in the literature.

Table 1
Summary of materials investigated

Materials	Form	Usage	Reference
Stainless Steel of type SS 304L	round bar stock (mill annealed and water quenched)	Proposed material for nozzle of an advanced design orbital manoeuvrable system (OMS)	(1)
AISI 304 stainless steel	rolled rods, annealed and water quenched	In the nuclear systems and power industry	(2)
Commercially pure nickel (Ni 201)	Annealed thick wall pipe	Proposed material for nozzle of an advanced design orbital manoeuvrable system (OMS)	(1)
Tantalum based alloy T-111	Plate, cold rolled and recrystallized	Proposed use in space electric power systems	(3)
Tantalum base alloy ASTAR 811C	Plate, cold rolled and recrystallized	Proposed use in space electric power systems	(3)
Superalloy PWA 1480	Single crystal	Gas turbine blade material	(4)

2.1. Low Cycle Fatigue Data

Two groups of tests in the low cycle regime were conducted /1-4/ for the materials summarized in Table 1. Isothermal and thermo-mechanical tests were conducted with total strain control with the application of hold times in tension and/or compression directions. Complete details of the test parameters and data can be found in references /1-4/.

The features of IF and TMF tests with hold times are summarized in Table 2. Dwell periods (t) were applied in tension (t/0) or in compression (0/t). In some instances dwells were applied in both tension and compression. When the same dwell time is applied in tension and compression the resulting cycle is known as a balanced cycle (t/t); however, when the time of dwell and compression is different, the resulting cycle is known as an unbalanced cycle (t_1/t_2).

In all cases (except for PWA 1480) inelastic strain range and corresponding cycles to failure data were available. The Coffin-Manson equations were determined for the data. Such equations had a slope (m) and an intercept (c) for each data set. These data were used to extrapolate life. The dwell sensitivity behavior of these six materials is discussed below.

3. DWELL SENSITIVE BEHAVIOR

The dwell sensitivity of a material under different hold-times conditions is examined for the following types: t/0, 0/t, t/t and t1/t2. These data are compared against a "datum" to establish whether a material is sensitive to dwell or otherwise. The continuous fatigue data with no dwells are considered as a representative "datum". Therefore, the dwell effects data are compared with respect to no dwell cycles. This comparison is conducted in terms of normalized cycle ratio (NCR) as defined below:

3.1. Normalized Cycle Ratio

The normalized cycle ratio is the ratio of the number of cycles to failure of a dwell-time test to the cycles to failure under continuous fatigue conditions under the same test parameters /10/. If the value of NCR exceeds unity, the behavior of a material is beneficial. In general, dwell-time sensitivity is more deleterious in one direction than the other, i.e. tensile or compressive dwell sensitive. Strain controlled IF and TMF data were analyzed to determine the material parameters of the Coffin-Manson equation. These parameters were used to generate an extrapolated IF or TMF response. For PWA 1480, the extrapolation equation was derived for the total strain range and cycles to failure, data fitting by using a least square, best fit equation.

3.2. Dwell-time Sensitivity Map

Dwell-time sensitivity maps are used in this paper to display creep-fatigue behaviors. Using the strain range and NCR, such a map can be constructed /10/. This map describes the dwell effects in terms of fractions of continuous fatigue response and associated life reductions with the application of dwell cycles. Dwell sensitivity maps are constructed for the six materials tabulated in Tables 1-2 that are discussed below.

3.2.1. Type 304L Stainless Steel

Dwell sensitive behavior of SS 304L is shown in Fig. 1. Though the data available were limited, a distinct trend was shown where with an increase in inelastic strain range the compressive dwell data of 120 sec were found to be beneficial. The NCR values were more than unity with inelastic strain range of around 0.2% for three temperatures ranging from 650 to 870°C. Below 0.2% inelastic strain range the test temperature had an influence on the dwell sensitivity.

3.2.2. Type 304 Stainless Steel

A number of dwell tests were performed /2/ for this particular steel. Dwell sensitivity behavior of this material is shown in Fig. 2. Most of the data were either at 0.3-0.35 and 1.8% inelastic strain levels, with fewer tests at intermediate levels. The tensile dwell cycles were most damaging at lower strain levels, where a 30 min dwell condition produced the maximum damage at 0.3% inelastic strain level. In general, an increase in the tensile dwell time decreased the NCR, which implies that this material is tensile dwell sensitive.

In one case, that associated a t/0 of 10 min dwell, as

Table 2
Features of IF and TMF tests

Materials	Test Conditions	Temperature	Others
SS 304L	High rate strain cycle (0.2 Hz) and 0/t of 120 sec.	650, 760 and 870° C	IF tests
SS 304	Continuous fatigue tests, t/0 tests with 1 min. to 600 min, 0/t tests with 1 min. to 30 min, t/t tests with 1 to 30 min. and t_1/t_2 tests.	650°C and strain rates of $4x10^{-3}$ per sec.	IF tests
Ni 201	High rate strain cycle, t/0 and 0/t tests with 120 sec.	483, 594 and 760°C	IF tests
T-111	Continuous fatigue IF and TMF cycles and t/0 cycles with 60 min.	IF temperature range was 1149°C and TMF cycles were 205-1149°C, 205-482°C and 1149-205°C.	IF and TMF tests comprising of in-phase (IP), max. strains at max. temperature and out of phase (OP), with max. strains at min. temperature.
ASTAR 811C	Continuous fatigue IF and TMF cycles and t/0 cycles with 60 min.	IF temperature ranges were 871 to 1149°C and TMF cycles were 205-1149°C, 205-482°C and 1149-205°C	IF and TMF tests comprising of max. strains at max. temperature (IP) and (OP) with max. strains at min. temperature.
PWA 1480	Continuous fatigue, t/0 and 0/t cycles with 60 sec. hold and TMF cycles.	1038°C for IF and 427 to 1038°C for TMF.	IF and TMF tests

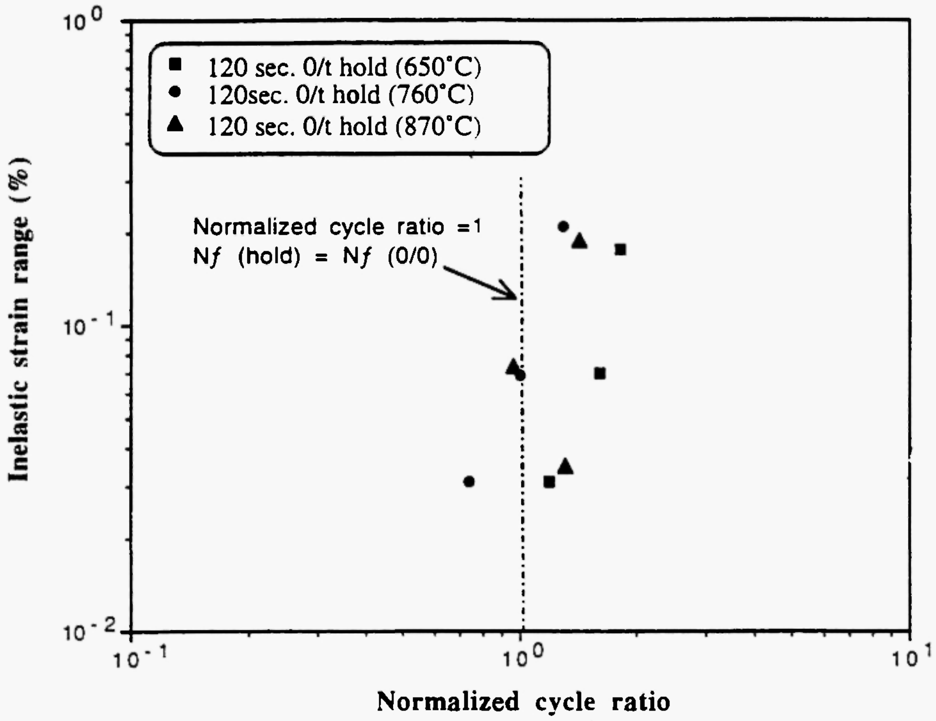

Fig. 1: Dwell sensitivity behavior of type SS 304L stainless steel.

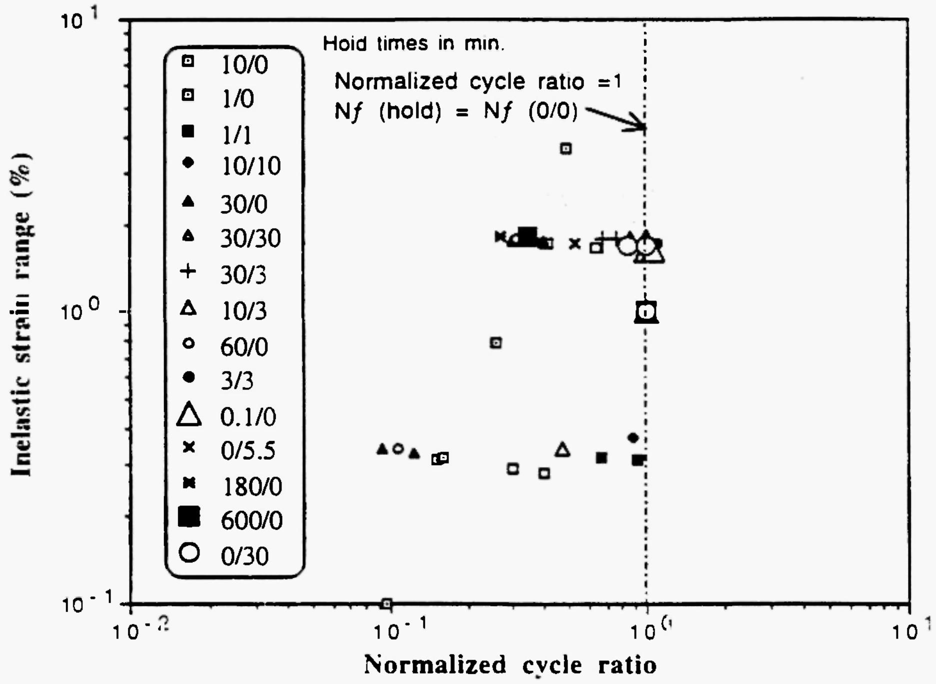

Fig. 2: Dwell sensitivity behavior of type 304 stainless steel at 650°C.

the inelastic strain range increased by an order of magnitude from 0.3 to 3%, the NCR increased one-half an order of magnitude from 0.1 to 0.5. This particular behavior produces a positive slope in Fig. 2. The total strain range in such cases may vary from 0.5 to 4%. The higher strain levels are not practical simulations of plant operating conditions and hence more data at or near the operating conditions needs to be generated to study dwell effects.

Other data such as compressive dwells, balanced and unbalanced dwells were found to be less sensitive to dwells than t/0 of 30 min. It may be noted from Fig. 2 that as the strain range increases (both inelastic as well as total) a saturation in the strain range and life occurs. This saturation effect is predominant in the case of other tensile dwells with more than 60 min dwell, e.g., 180 and 600 min. A combination of temperature, strain range, and dwell time determine the materials' sensitivity against dwells.

3.3.3. Commercial Pure Nickel, Ni 201

Figure 3 shows the dwell sensitive behavior of Ni 201 at two temperatures under either 0/t or t/0 dwells of 120 sec. This material is found to be tensile dwell sensitive at 760°C in Fig. 3. The dwell effects were a little more deleterious in this case as the inelastic strain range was lower than other materials discussed above. Such an effect is well described at 0.007 to 0.008% inelastic strain range. However, as the strain range is enhanced from 0.07 to 0.4%, a saturation in the dwell effect was observed. Compressive dwell cycles were found to produce a NCR very close to unity. One data point at 483°C and other 0/t cycles at 760°C show that similar values of NCR were associated with similar strain ranges and cause least dwell sensitivity.

3.3.4. Tantalum Based Alloy T-111

A dwell sensitive map for the tantalum based alloy T-111 is constructed in Fig. 4. Since this was a proposed material for space electric power systems, the types of data that were generated were both isothermal fatigue (IF) and thermo-mechanical fatigue (TMF) at proposed operating conditions. Therefore, IF tests were conducted at the maximum temperature of 1149°C and other TMF tests were conducted with IP, OP and a hold in IP (IPH).

Normalized cycle ratio was determined from a number of comparisons which involved TMF (IP and OP) with IF at the maximum test temperature of TMF cycle, TMF IPH with TMF IP cycle and ratio of smooth and notch life under IF conditions.

Figure 4 shows the NCR and inelastic strain range distributions under different conditions. It is evident that when the TMF IP was normalized by IF, a sensitivity was observed. However, this trend had a positive slope, where, with the increase in inelastic strain range, the NCR increased. Under such normalization, this combination was found to be more sensitive.

When the TMF OP was normalized with IF, it was found in Fig. 4 that with a decrease in inelastic strain range the NCR increased. In the case of TMF IPH normalized by TMF IP at the same temperature and strain range, the NCR values were found to increase with the increase in inelastic strain range. An order of magnitude increase in the inelastic strain range caused NCR to increase from 0.4 to 0.9.

An interesting behavior can be found in Fig. 4 which shows that the notch effects were the same at all strain levels. Over an order of magnitude change in inelastic strain range the NCR values were the same. This implies that the smooth specimen fatigue lives were nearly 3.2 times those of the notched specimens under inelastic strains from 0.1 to over 1%. Therefore, notch effects were the same, which contributed equally to the damage development and failure at all strain levels in Fig. 4.

3.3.5. Tantalum Based Alloy ASTAR 811C

A dwell sensitive map for ASTAR 811C is shown in Fig. 5. Various normalizations used in Fig. 5 show that the sensitivity is inelastic strain range dependent. Three behaviors that correspond to TMF IP and IF, TMF OP and IF, and TMF IPH and TMF IP normalizations respectively show that sensitivity is greater below the inelastic strain range of 0.2%. Figure 5 shows that with the increase in inelastic strain range from 0.2% to 1.0%, the NCR values change only from 0.1 to 0.2, whereas, within the 0.2 - 0.04% inelastic strain range the NCR values were from 0.03 to 0.2 respectively. The TMF IP normalized by IF show the most sensitivity and

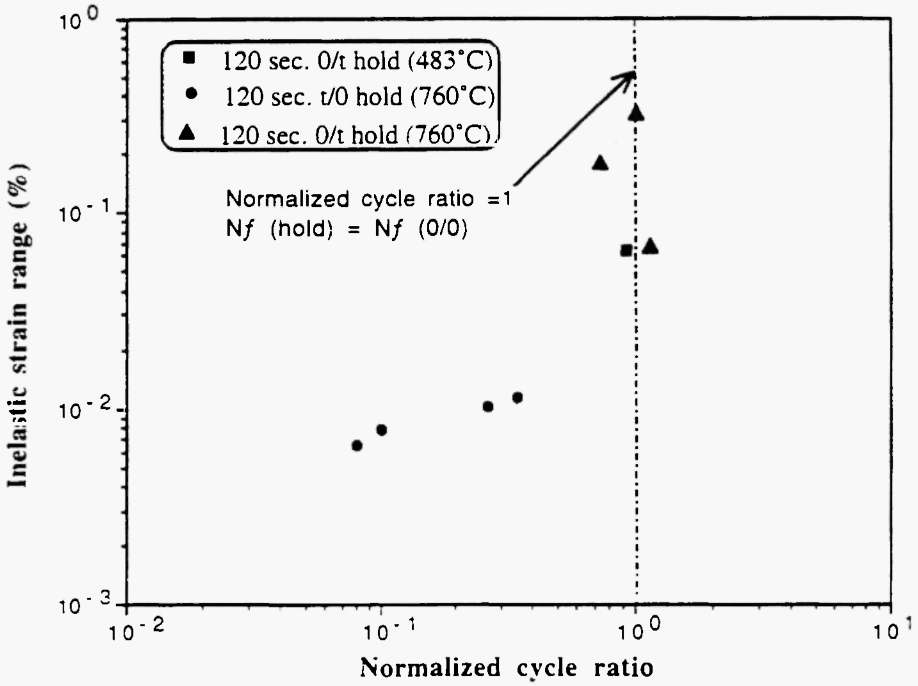

Fig. 3: Dwell sensitivity behavior of commercially pure nickel, Ni 201.

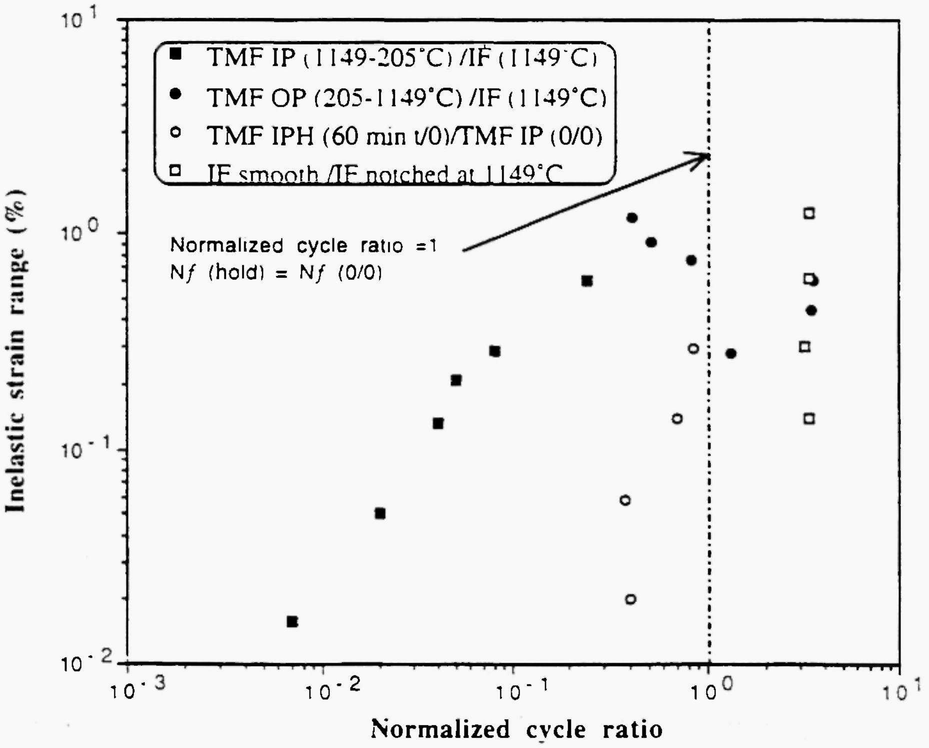

Fig. 4: Dwell sensitivity behavior of tantalum based alloy T-111.

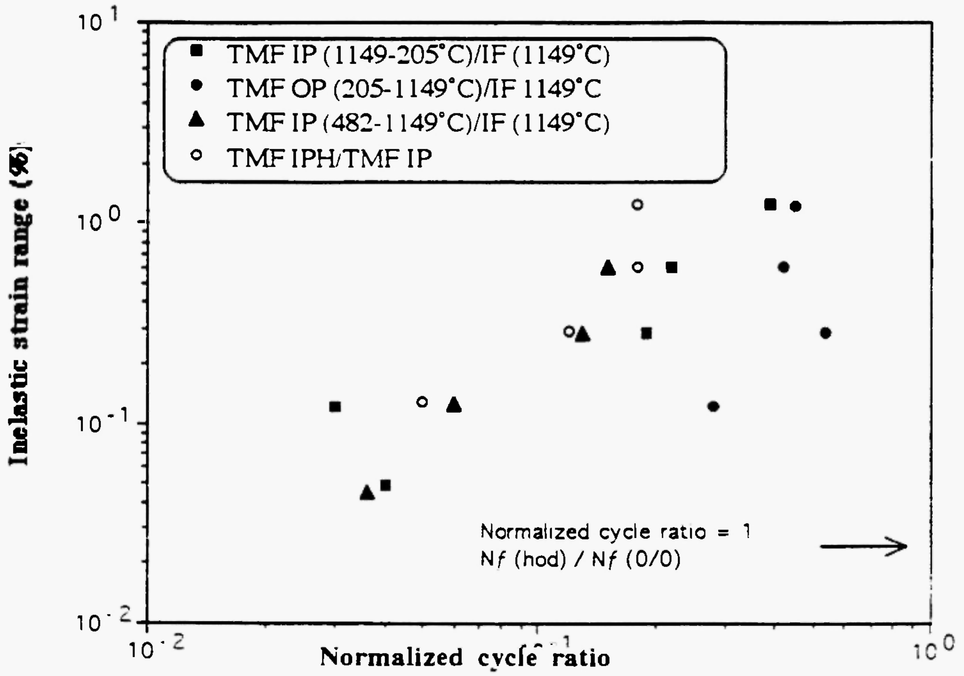

Fig. 5: Dwell sensitivity behavior of a tantalum base alloy ASTAR 811C.

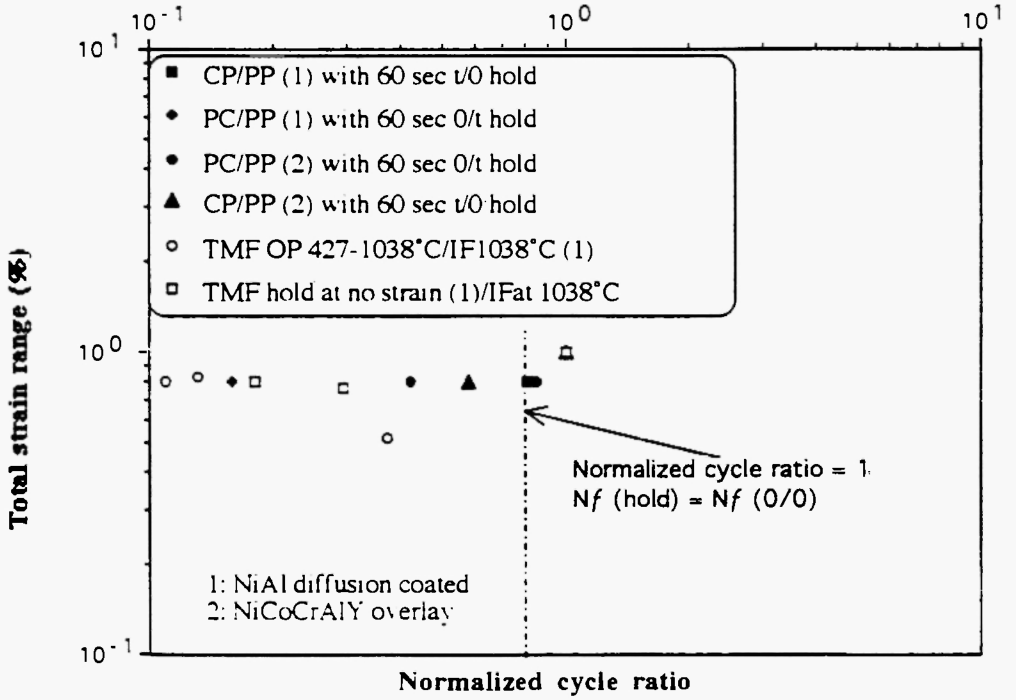

Fig. 6: Dwell sensitivity behavior of single crystal nickel-based superalloy PWA 1480 under isothermal and thermomechanical fatigue.

TMF IPH normalized by TMF IP show an intermediate effect between the TMF IP and IF normalizations in Fig. 5.

3.3.6. Superalloy PWA 1480

Dwell sensitive behavior of PWA 1480 is shown in Fig. 6. The data generated in /4/ were both IF and TMF; other parameters included different orientations and coating types. Therefore, this discussion also will involve consideration of two coatings that influenced life. The IF normalized curve with 60 sec hold in compression was found to be more dwell sensitive with the NiAl diffusion coating than with the overlay coating.

TMF OP cycles (when normalized by IF) show the greatest dwell sensitivity. It is not possible to conclude whether PWA under <001> orientation is more dwell sensitive to tensile, compressive, TMF IP, or TMF OP conditions as the data contained numerous variables.

4. MECHANISTIC ASPECTS

The mechanistic aspects by which damage develops under dwell and non-dwell conditions are not understood well enough that a correlation can be established among six materials studied in this paper. Nevertheless, some individual features are worthy of note. Features observed in the case of AISI SS 304 /2/ relate to the growth of transgranular and/or intergranular cracks above a critical stress range and strain rate. In some materials tensile strain rates are more deleterious than compressive because compressive strain rates required to cause the equivalent cavitation damage to that of tensile are found to be several times lower. Therefore, if type 304 stainless steel undergoes intergranular damage at 816°C at 0.5% strain range with $4x10^{-5}$ /sec strain rate, for the same damage to occur in the compression direction may require much lower strain rates. Some of these aspects where intergranular damage occurs were modeled by Halford and Manson /15/ who assessed data over a range of test conditions for thirty materials.

In tantalum-based alloys T-111 and ASTAR 811C, the former alloy was found to be susceptible to intergranular attack with R type of voids /3/; however, the latter alloy was strengthened by grain boundary precipitates which enhanced its creep-fatigue resistance. The ASTAR 811C was found to involve both transgranular as well as intergranular fracture. Under TMF conditions massive decohesion was observed /3/ for both the materials under IP as well as OP cycles. For OP cycles T-111 underwent more intergranular damage than ASTAR 811C which associated mixed damage modes. Under TMF, in most cases, geometric factors of the test specimens contributed more to the failure mechanisms than other factors /3/. Hoeppner /7/ proposed a weakest link mechanism that contributes to dwell sensitivity; this was found consistent with the geometric factors observed in /3/ and used in the assessment of gas turbine disk components /8/.

The IF damage for PWA 1480 under the orientations specified produced cyclic softening, whereas TMF under both IP and OP produced hardening. Cracking occurred from the outside surface in TMF IP and OP tests. With the increase in the number of cycles greater γ' agglomerations were observed /4/. High exposure times resulted in the higher oxidation damage. At the same strain range the TMF IP cycle produced higher life than TMF OP with higher γ' agglomerations and oxidation. Mean stresses developed for TMF IP cycles were negative which in the case of TMF OP cycles were positive /4/, which caused lower life under TMF OP conditions. Stress relaxations occurred amounting to nearly 30% of initial stress range for the TMF IP cycles, whereas a similar extent of tensile stresses developed for the TMF OP cycles. The exact interactive mechanisms that occur under IF and TMF are not very well characterized to address dwell sensitivity for PWA 1480. More research is needed so that various boundaries of mechanistic aspects in terms of test parameter and material conditions be constructed.

The mechanistic features under individual test conditions were not investigated for these materials /1-4/. Therefore, dwell and non-dwell mechanistic features cannot be compared. The general features summarized above indicate that tensile dwell cycles caused more intergranular damage as well as grain boundary sliding. These aspects need more research in order to understand dwell sensitivity.

5. CONCLUSIONS

A new approach to address dwell sensitivity of high temperature materials is used in this paper. A dwell sensitive map was developed which shows the effects of dwell times in a fraction of its continuous fatigue response. Dwell effects were found to be deleterious as well as beneficial since materials are sensitive under a specific combination of test parameters.

A saturation effect in dwell sensitivity with the increase in strain range was observed for all the materials investigated in this paper. Dwell effects were deleterious only below a critical strain range. The NCR values were less than unity under tensile dwells for types SS 304 and SS 304L produced tensile dwell sensitivity. Various normalized cycle ratio curves for ASTAR 811C under different test conditions exhibited that dwell sensitivity depends upon a critical value of strain range below which dwell sensitivity is more deleterious. A saturation in the NCR values observed with the increase in strain range for the materials examined. However, trends in the NCR and strain range were different when TMF IP and OP normalized by IF behavior were plotted. More study needs to be undertaken to determine such trends in the material behavior since it will prove to be a very important practical for the materials in order that they can be recommended for use in high temperature applications.

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