DWELL TIME EFFECTS ON FATIGUE LIFE AND DAMAGE MECHANISMS

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ABSTRACT: *An overview of dwell sensitivity fatigue behavior of high temperature materials subjected to various creep-fatigue cycles is summarized. Published data from the literature were presented in terms of strain range and normalized cycle ratio and dwell sensitivity behavior mapped for various alloy groups. A summary of dwell sensitivity behavior has been presented summarizing alloy group in terms of dwell sensitivity. It is elucidated that mechanisms controling dwell sensitivity were due to mixed transgranular and intergranular cracking, creep damage by triple point cracking, cavity formation, and oxidation striated surface damage. The transition from transgranular to intergranular damage was from resulting deterioration in tensile properties and other test parameters. It is speculated that dwell cycles evolved mean stresses in tension and compression directions. Mean stress in tension was more deleterious and caused more dwell sensitivity than compressive mean stresses. However, compressive mean stress in steel alloys caused also accelerated cracking and dwell sensitivity. The observations for different materials are summarized.*

INTRODUCTION

The operating conditions of engineering components, such as power plant pressure vessels, turbines, gas turbine engines, and rocket motors are known to be complex. The service loads in such applications change with time in order to meet with a specific demand. Start-up and shut-down cycles impose fatigue damage at localized areas, where material is inhomogeneous or discontinuous, and areas where stresses are concentrated and amplified as a result of geometrical constraints. A major part of applications requires that a component be held at near steady conditions, such as during the period between the shut-downs of a gas turbine engine or power plant turbine. The time during which loads are held near steady conditions is simulated in terms of a dwell time. During a dwell time, creep deformation takes place, if favorable stress and temperature combinations are maintained. This paper presents a summary of the dwell sensitivity behavior and damage mechanisms of various materials from recent work of one of the authors (TG) [1-7].

DAMAGE MECHANISTIC FEATURES

Damage mechanisms of creep-fatigue tests in a range of materials were found to be caused by transgranular (TG), intergranular (IG) or by a mixed TG+IG, oxidation, surface damage by fatigue, creep, and oxidation, dislocation cell structure formation, new precipitates (studied only for IMI-829 and Ti-6Al-4V) and other mechanisms. This section summarizes the dwell sensitivity damage mechanisms of materials in a summary format in Table 1. A detailed description of damage mechanisms has been presented in a separate article [2] and is recommended to interested readers for further information. Materials were selected from the following alloy groups: pure metals, solder alloys, copper alloys, titanium alloys, steel alloys, tantalum alloys and superalloys.

Table 1. Dwell sensitivity damage mechanisms of high temperature materials.

Materials	**Dwell Times**	***Damage Mechanisms***
Solder Alloys		
96.5Pb-3.5Sn	t/0, 10 min	25°C TG/IG cracks, Stage I+II cracking, oxidation, coarsening
37Pb-63Sn		Stage I, fatigue cracking, TG, cyclic softening, coarsening
Copper alloys		
NARloy Z	t/0, 0/t, t/t, 5 min	538°C Creep, oxidation, TG to IG, cyclic strain hardening
AMZIRC	same	same
Low alloy steels		
1Cr-Mo-V	Up to 47 h	540 and 565°C Creep, IG with t/0 dwell, oxidation
1.25Cr-Mo	0/t, t/0, up to 1 h	550-600°C Oxidation, fatigue cracking, cavitation

2.25Cr-Mo	Up to 47 h	540-600°C Oxidation, creep, cavitation and coarsening
9Cr-1Mo	Up to 1 h	550-600°C Cyclic softening, coarsening, IG cavitation above 593°C.
Stainless steel		
SS 316	0/0, t/0, 0/t, t/t, up to 1 h	600 and 700°C TG, striations, IG fracture
SS 316L	IF and TMF, 10 s	250-500°C Ductile striations, fatigue cracking and surface damage and cracking
SS 304	1-60 min	650°C, strain rate of $4x10^{-3}$ 1/s, TG changed to IG with an increase in temperature, cavitation and oxidation
SS 304L	0/t, 120 s	650, 760 and 870°C Cavitation, oxidation and IG corrosion
Titanium alloys		
Ti-6Al-4V	t/0, 0/t, t_1/t_2 up to 3000 s	450°C Fatigue cracking, hydrogen diffusion
IMI 829	t/0, 0/t, t_1/t_2, up to 15 min	600°C TG, IG with cavitation, silicide formation, and other damage
Tantalum alloys		
T-111	IF and TMF cycles t/0 with 60 min	1149°C, TMF cycles 205-1149, 205-482 and 1149-205°C IG cracking, with R type voids
Tantalum alloys		
ASTAR 811C	IF and TMF cycles as well as t/0 cycles, 60 min	871 to 1149°C and TMF cycles 205-1149, 205-482 and 1149-205°C TG, IG, massive decohesion

Pure Nickel		
Ni 201	High strain rate cycle, t/0 and 0/t tests with 120 s	IF 483, 594 and 760°C IG, creep-fatigue at low temps
Superalloys		
MAR M 002	t/0, 0/t and t_1/t_2 of 20 s	750, 850, 950 and 1040°C TG/IG, oxidation, coating cracks, wedge cracks and precipitations
MAR M 002	t/0, 0/t and t/t of 5 min	750, 850, 1000, 1040°C IG cracking predominates above a critical temperature (1000°C)
Waspaloy	t/0, 0/t and t_1/t_2 unequal	750°C Crystallographic facets, striations, micro-twinning, cyclic hardening
Rene 95	t/0, 0/t and t_1/t_2 unequal	650°C Cyclic softening, TG, mixed mode, striation
Rene 80	t/0, 0/t, and t_1/t_2 unequal	871 and 1000°C Coarsening, IG, creep at 1000°C, void nucleation
Inconel 617	t/0, 0/t and t_1/t_2 unequal	650°C TG, IG coarsening, dislocation pileups with no IG
IN 100	unbalanced	925°C TG, TG+IG, oxidation, material discontinuities for powdered samples
PWA 1480	t/0, 0/t & t/t	1015 and 1050°C Pore to pore cracking, surface cracking, oxidation, cyclic softening
PWA 1480	Continuous fatigue, t/0 and 0/t cycles with 60 s hold and TMF cycles	1038°C for IF and 427 to 1038 °C for TMF cyclic hardening

MA 754 L and LT orientations	t/0 and 0/t cycles	850°C Surface decohesion, TG in LT orientation, however, mixed TG/IG in TL orientation

Note: In lack of space references to each of these data are not provided but are supplied elsewhere [1-2].

DWELL SENSITIVITY MAPS

All the test parameters were not given in the literature to determine the parameters of Coffin-Manson equations. Therefore, total strain range ($\Delta\varepsilon_t$) and cycles to failure were fitted with a least square equation and those parameters were used to extrapolate life to determine normalized cycle ratio (NCR). NCR is a ratio of cyclic life under dwell fatigue and continuous fatigue at same test conditions. Only continuous fatigue data were fitted with a least square best-fit equation in the following form:

$$\Delta\varepsilon_t = A\,(N_f)^b, \qquad (1)$$

where A and b are material parameters.

A dwell sensitivity map obtained showed beneficial and/or detrimental effects for dwell cycles. The NCR was proposed to measure the dwell sensitivity when compared against unity [1, 3, 7]. When NCR was higher than 1, dwell times were causing beneficial effects improving thereby the HTLCF resistance and vice versa. Continuous fatigue life was taken as a reference to determine whether or not a material was dwell sensitive mainly because fatigue was thought to be a driving mechanism for damage accumulation. A dwell sensitivity map plots the relationship between the strain range and NCR under a given combination of test parameters. Typical dwell sensitivity maps are presented in Figs 1-2 for a solder alloy and a superalloy.

The dwell sensitivity fatigue behavior of materials, based on the test parameters summarized in Table 1, is discussed in the following.

The following materials were susceptible to tensile dwell sensitivity [1-7]:

- Pure metals, such as titanium, copper and nickel, dwell sensitivity became significant with an increase in temperature.
- Solder alloys (lead-tin) type.
- Copper alloys (AMZIRC and NARloy-Z). AMZIRC showed equal sensitivity to tensile, compressive and balanced dwell cycles.
- Low alloy steels (1Cr-Mo-V, 1.25Cr-Mo and 9Cr-1Mo) were dwell as well as temperature sensitive.

Fig. 1. Dwell sensitive behavior of solder alloy (37Pb-63Sn).

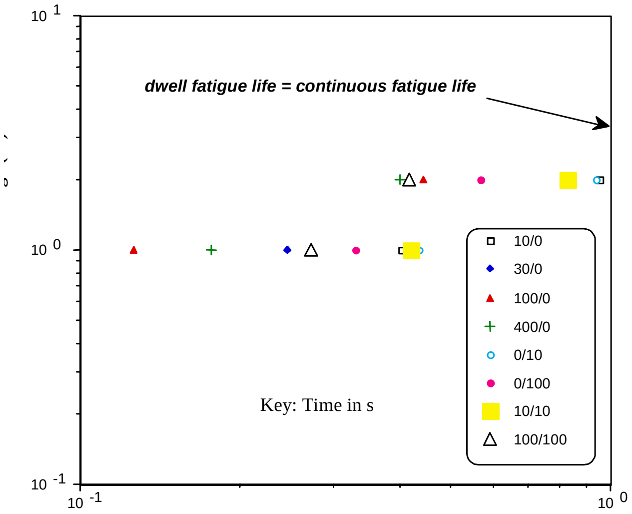
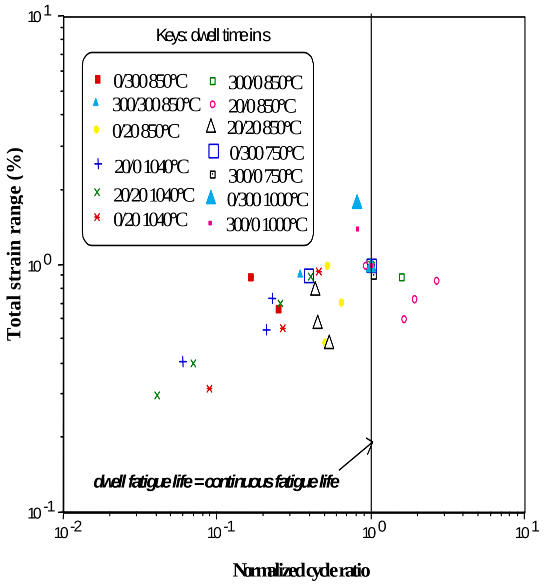


Fig. 2. Dwell sensitive behavior of MARM002 at different temperatures.



- Stainless steels, SS 316, 316L, 304 and 304L are all tensile dwell sensitive under isothermal and thermo-mechanical fatigue.
- Tantalum alloys (T-111, and ASTAR) were sensitive to TMF in-phase dwells but not in other cycle types.
- Superalloys (MAR M 002, Rene 95, Rene 80 at 871 and 1000°C, Inconel 617, IN100, PWA1480, MA754 (ODS) were all found to exhibit tensile dwell sensitivity.

The following materials were susceptible to compressive dwell sensitivity:

- Copper alloy AMZIRC (based on one data point).
- Low alloy steel (2.25Cr-Mo).
- Stainless steel 304L at 760°C (based on one data point).
- Titanium alloys (Ti-6Al-4V and IMI 829).
- Superalloys (MAR M 002 above 1000°C, Waspalloy, Rene 95 and PWA 1480).

Additionally, some materials were also sensitive to balanced and unbalanced dwell cycles.

Concluding Remarks

Dwell sensitivity is an interactive mechanism of processes such as creep, fatigue, oxidation and other mechanisms, but it is not very well characterized for different cycles for all the materials discussed in this paper. A typical dwell sensitivity map, Figs 1-2, shows that dwell cycles in most cases reduced the fatigue resistance, whereas in other cases they enhanced the HTLCF properties. With an increase in temperature, the creep-fatigue resistance improved in the case of Rene 80, PWA 1480 and also in the case of stainless steels.

For low temperature alloy systems, such as solder alloys, the tensile dwell sensitivity is often attributed to the microstructural changes, aging and cyclic hardening. This has been documented based on the fracture surfaces and studies of the gauge area on which cracks are formed. Number of secondary cracks increased with strain range and dwell times and caused dwell sensitivity. This phenomenon, by which multiple cracks form and cause dwell sensitivity, has been documented for titanium alloy IMI 829, where number of secondary cracks increases and reduces the life. Since the interactions with secondary cracks lower the stress intensity of the dominating main crack, a saturation in NCR is observed for a number of materials. This issue has also been documented for titanium alloys by fatigue crack growth studies [8].

The mechanism of dwell sensitivity was conceptualized (1) in terms of following stages:

1) A cyclic hardening stage, in which stresses rise in one direction causing higher strain energy density (area of hysteresis loop) and consequently lower life.
2) A cyclic softening stage, in which elastic strain transforms to plastic strain resulting in reduced life and dwell sensitivity.
3) A combination of these two processes namely, cyclic hardening and softening, produces a positive or negative mean stress that may either lower or enhance the fatigue life. A trend was demonstrated by few materials showing fatigue life improvement.
4) Different cycle types, temperatures, dwell sequences, strain ranges, strain rates and other material and test parameters produce a particular combination and cause accordingly the dwell sensitivity in tension, compression, and mixed dwell conditions.
5) An empirical relationship was developed with the strength factors of different materials. Equal strength ratios, ratio of room temperature (RT) and elevated temperature (HT) yield strength to tensile strength ratios, that occur for low ductility materials, exhibited higher mean stress in tension direction that produced dwell sensitivity.

Item 5 was noted for Ti-6Al-4V, Mar M 002, Waspaloy, Rene 80, and may be interpreted in producing compressive dwell sensitivity.

The dwell sensitivity, as stated earlier, depends on the combinations of test parameters selected. In the case of superalloy MAR M 002 dwell sensitivity was temperature dependent. A threshold value in temperature was observed and exceeding that value caused transition from compressive to tensile dwell sensitivity. The threshold temperature appears to be around 1000°C for MAR M 002. It is also possible that a material may be dwell as well as temperature sensitive, which cannot be separated. Since the waveforms in the literature were randomly used, discussion on dwell sensitivity with respect to temperature requires a closely monitored testing program. The following trends were observed:

- For IMI 829, compressive dwell cycles raised positive mean stress and tensile dwells caused cyclic softening and raised negative mean stress at higher plastic strain ranges.
- For 1Cr-Mo-V steel, cavities formed under tensile dwells at higher strain ranges, but unbalanced dwell cycles enhanced NCR and reduced cavitation.
- For 2.25Cr-Mo steel, compressive dwells caused oxidation damage that interacted with fatigue cracking and accelerated the damage. This mechanism may not apply for other materials.
- Test combinations, such as high temperature, strain range, and dwell times and low strain rates, were conducive to complex environmental interactions. Fracture morphology as a result changed. Along with tunneling, decohesion was associated with both transgranular and intergranular fracture.
- Mechanical properties such as yield strength and ductility began to reach an optimum value with an increase in temperature, and further cyclic action resulted in cyclic softening, and reduced the life. During the cyclic softening, transformation from elastic to plastic strain occurs.

The mechanistic features under individual test conditions are summarized in Table 1, where NCR is correlated with specific damage features, such as oxidation, cavitation, grain boundary sliding, intergranular and transgranular cracking, and other types of damage.

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