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Influence of minimum temperature on the thermomechanical fatigue of a directionally-solidified Ni-base superalloy

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Abstract

It is well understood that thermomechanical fatigue (TMF) lives are significantly influenced by the maximum temperature of the cycle since increasing temperature accelerates both creep and the coupled fatigue-oxidation effects, usually exponentially with increasing temperature. Hence, most TMF experiments focus on the impact of the maximum temperature of the cycle along with the phasing of the temperature and strain. Very little focus has been placed on the role of the minimum temperature of the TMF cycle. Usually the minimum temperature is chosen for experimental expediency and is not based on minimum temperature experienced in actual components. For example, in a gas turbine, the minimum temperature for an extended shutdown is near room temperature. This paper shows that out-of-phase TMF with lower minimum temperature while maintaining the same mechanical strain results in lower life. Possible explanations for the reduction in life include the increase in inelastic strain range due to the increase in elastic modulus at lower temperatures and microstructural changes that occur at elevated temperature, reducing the lower temperature yield strength. Both experiments and simulations using crystal viscoplasticity modeling show that the increase in elastic modulus with decreasing temperature leads to greater inelastic strain range and a commensurate reduction in fatigue life. This effect is just as important to consider as the influence of microstructure changes occurring at the elevated temperatures of the cycle.

Keywords: Thermomechanical fatigue; creep; rafting; Ni-base superalloy

1. Introduction

Thermomechanical fatigue (TMF) testing has become the preferred method for compiling material characterization data used in analytical life models, since it simulates the most damaging transient periods of turbine operation and potentially captures degradation mechanisms missed in isothermal tests. Even though the most significant thermal cycle experienced in the hot section of gas turbines is usually a complete shut-down, cooling to

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room temperature, the typical minimum temperature T_{min} selected for TMF testing is in the range of 400°C-600°C, well above the minimum temperature that is experienced in service. The simple reason for selecting a higher T_{min} is experimental expeditiousness, since a higher T_{min} considerably shortens cycle times compared with a lower T_{min}. It is generally assumed the influence of T_{min} on life is small because the yield strength and isothermal LCF lives do not vary much from room temperature to 500°C [1]. However, limited experimental evidence on a single-crystal Ni-base superalloy suggests that reducing the T_{min} to 100°C from 400°C, while maintaining the same maximum temperature T_{max} and mechanical strain range $\Delta\varepsilon_{mech}$, the out-of-phase (OP) TMF lives are reduced by a factor of three [2].

Increasing requirements for material capabilities over the operating temperature ranges of gas turbines have led to a high degree of optimization in the processing and microstructural characteristics of precipitation-hardened Ni-base superalloys. This is especially true of the composition, and the volume fraction, distribution, and lattice mismatch of the matrix and γ' precipitate phases [3]. The highly optimized heat treatment typically provides excellent room temperature strength for the virgin alloy due to the fine secondary γ' precipitates that form [4]. This optimization, however, is inherently thermodynamically unstable at typical peak operating temperatures. Diffusion-controlled coarsening, with the dissolving of the fine γ' precipitates and rafting (i.e., directional coarsening) of the γ' precipitates, occurs during extended exposures to elevated temperatures and low stresses. Rafts form parallel to the stress axis under compression loading in alloys with negative γ/γ' lattice mismatch, defined as

$$\delta = \frac{2\left(a_{\gamma'} - a_{\gamma}\right)}{a_{\gamma'} + a_{\gamma}} \tag{1}$$

where $a_{\gamma'}$ and a_{γ} are the lattice parameters of the γ' phase and γ matrix, respectively. The phenomenon of rafting is related to the coherency stresses that arise from the lattice mismatch [3]. Rafting perpendicular to the stress axis occurs under tension loading.

In addition to microstructural changes that may affect the lower temperature strength and fatigue properties, the elastic modulus and coefficient of thermal expansion are also temperature dependent. For example, the elastic modulus in the ⟨001⟩ direction decreases from 130 *GPa* at room temperature to 113 *GPa* at 500°C [5]. The coefficient of thermal expansion in the ⟨001⟩ direction is also weakly temperature dependent ranging from 13.5×10^{-6} 1/°C at room temperature to 16.2×10^{-6} 1/°C at 500°C [5]. The temperature-dependence of the CTE is usually compensated for in mechanical strain controlled TMF tests, though it certainly plays an important role in the analysis of the TMF behavior of components. The elastic property variation affects the partition of the mechanical strain range into its elastic and inelastic components.

In a study on the single-crystal Ni-base superalloy CMSX-4 exploring the T_{min} effect, it was concluded that this decrease in life when T_{min} is reduced was due to a degraded microstructure resulting from rafting at the higher temperature in the TMF cycle [2]. In the virgin material, the strengths at 100°C and 400°C were comparable, but after rafting the strength at 100°C was less than that at 400°C [2]. The yielding behavior at these lower temperatures tended to exhibit the anomalous strength increase with increasing temperature, typical of the pure γ' phase, as shown in Fig. 1 [1]. The reduced yield strength at lower temperatures resulted in an increase in the inelastic strain range and hence reduced life.

Precipitate coarsening due to long-term aging at high temperatures prior to fatigue or tensile testing has also been shown to have an undesirable effect on the material's low temperature fatigue resistance. This effect was demonstrated through OP TMF tests conducted on polycrystalline IN 738LC with temperature cycling between 100°C - 950°C after the test specimen had been exposed to 25 TMF cycles to set up realistic microstructure conditions and then 4000 *hrs* of aging at T_{max} in a furnace [4]. This procedure was devised to simulate the microstructural characteristics similar to those of turbine components at mid-life, in which the smaller, secondary precipitates will have dissolved into the matrix and contributed to the growth of the larger, primary precipitates. The subsequent OP TMF testing showed that, when compared to the baseline stress-strain response without the extended aging, yielding occurred at much lower stress values for the same temperature upon resumption of TMF cycling. As a result, the stabilized inelastic strain range was consistently higher in tests with extended aging. Consequently, fatigue life was substantially reduced.

In this paper, the influence of T_{min} is explored through both OP TMF experiments and crystal viscoplasticity simulations. In particular, the influence of microstructure change on strength properties and the influence of the temperature-dependent elastic properties on the inelastic strain range are studied.

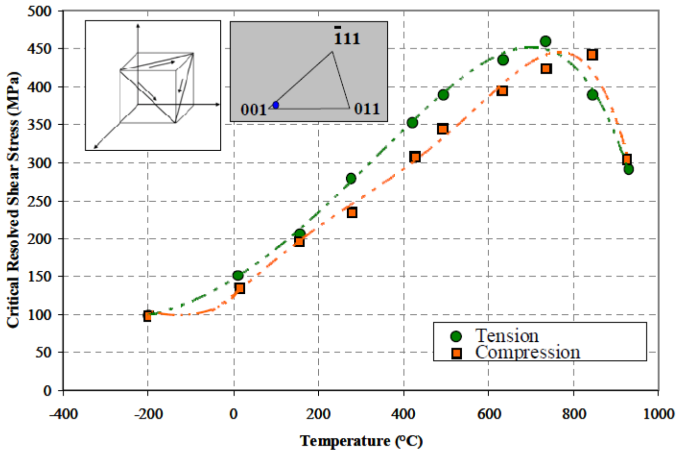

Fig. 1. Variation in critical resolved shear stress for slip as a function of temperature for pure γ' (Ni_3Al) single crystals in the [001] orientation measured in tension and compression [1].

2. Material Microstructure and Composition

The material considered in this study is the directionally-solidified (DS) Ni-base superalloy CM247LC, receiving a conventional heat treatment for gas turbine hot section components. The matrix-precipitate structure of the alloy is depicted in Fig. 2, and consists of γ' precipitates dispersed in an FCC matrix (γ). All specimens were machined as cylindrical round bars that satisfy the ASTM standard for LCF testing (ASTM E606-04) [6]. The axis of all specimens in the current study was in the [001] longitudinal (L), grain growth orientation.

The composition by weight percent of CM247LC DS is shown in Table 1. Large columnar grains result from the slow cooling process during solidification. Although their size can vary to a degree, they are typically on the order of 500 μm (0.5 mm) in diameter. The dendritic structure that forms within grains during solidification is also shown in Fig. 2. The primary dendrite stems are parallel to the solidification direction, with secondary branches in the ⟨010⟩ directions.

Table 1. Average nominal chemical composition of CM247LC (wt %)

Al	B	C	Co	Cr	Hf	Mo	Ta	Ti	W	Zr	Ni
5.6	0.015	0.07	9.2	8.1	1.4	0.5	3.2	0.7	9.5	0.015	Bal.

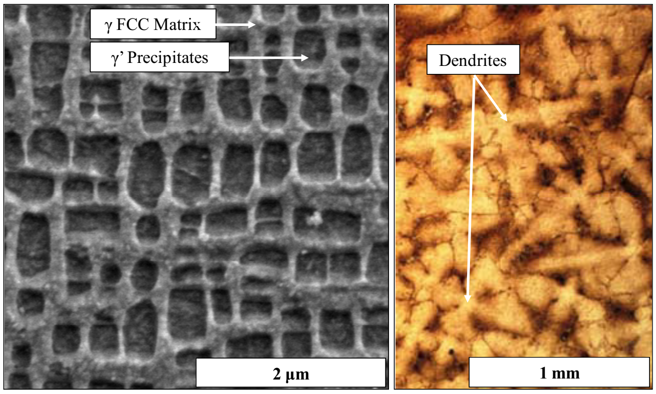

Fig. 2. Images of (left) the microsturcture and (right) the dendritic structure of CM247LC DS.

3. Experimental Method

The TMF tests were performed on a servo-hydraulic test system using MTS Testware SX 4.0D control software. Specimens were heated by induction and cooled through conduction into both the water-cooled collet grips (MTS 646) and the ambient atmosphere surrounding the gage section. No forced air cooling was used to prevent gradients and false readings of thermocouples, which were spot welded to the specimen just outside of the gage section. All tests were conducted in mechanical strain control on smooth specimens. A high temperature extensometer with 12.7 *mm* gage section was used to measure the total strain. Before beginning the TMF cycling, stress-free thermal cycling was conducted to determine the thermal strain response, which was then fit to a polynomial function for calculated-variable thermal strain compensation. Additional experimental details can be found in Refs. [5, 7].

The baseline TMF tests were conducted with a temperature range from 500°C to 950°C and total cycle time of 180 *s*. To determine the influence of T_{min} on the resulting response and life under OP TMF conditions, a test was conducted with T_{min}=100°C while maintaining the same T_{max} and mechanical strain range of a baseline test. Even for this low T_{min}, forced-cooling was not used, as it often results in unwanted radial temperature gradients which influence the material deformation response. As a result, the TMF cycle was extended to allow for the slower natural cooling rates as the temperature difference between ambient and test temperature becomes smaller. Therefore, the total cycle time for the 100°C to 950°C TMF tests was increased to 1700 *s*.

Some specimens were aged at 950°C for 144 *hr* in laboratory air under a mechanical stress of 112.5 *MPa*, either in tension or compression. This stress is sufficient to cause stress-induced rafting, while limiting inelastic creep strain to less than 0.16%. After aging, the surface oxide and γ'-depleted layers were removed by mechanical polishing. These specimens were used to study the role of the rafted microstructure on yield strength and TMF behavior.

4. Modeling Method

Crystal viscoplasticity simulations of a directionally-solidified Ni-base superalloy undergoing TMF were conducted using the model described in Shenoy et al. [8]. This model captures the deformation on the octahedral and cubic slip systems in the FCC microstructure, though the cubic slip systems are only activated at the elevated temperatures. The model captures both isotropic and kinematic hardening effects as well as rate dependence due to dwells and creep. Since material parameters for CM247LC were not available, simulations were conducted using the parameters for GTD-111 [8], which is also a DS Ni-base superalloy used in gas turbine hot section components. The parameters were calibrated to the behavior of the initial virgin microstructure. Since room temperature strength properties for GTD-111 were not available, for the purposes of this exercise, the inelastic response at room temperature to 427°C, which was the lowest temperature calibrated to data, was assumed to be the same. Yield strength experiments on CM247LC over this lower temperature range suggest that this is a reasonable assumption, at least in the virgin condition [5]. The elastic response is temperature-dependent over the entire range of temperatures.

5. Results and Discussion

The effect of reducing T_{min} on life is shown in Fig. 3. For the same mechanical strain amplitude, fatigue life was reduced by a factor of 3.4 when compared with the baseline temperature range and reduced by a factor of 10 when compared to isothermal tests conducted at T_{max}. This is comparable to the magnitude of the life reduction observed in the single crystal CMSX-4 when T_{min} was reduced to 100°C [2]. The hysteresis response and evolution of maximum and minimum stress for tests conducted with the same mechanical strain amplitude but different T_{min} are shown in Fig. 4. The increase in elastic modulus at temperatures less than the baseline minimum of 500°C resulted in the onset of yielding occurring earlier upon cooling. As a result, the increase in the inelastic strain range was nearly three times that of the baseline cycle. The width of the hysteresis loop continued to increase over the duration of the test, as shown Fig. 5. Also evident is the significant cyclic softening, which resulted in a 14% reduction in peak tensile stress between the first cycle and stabilized half-life, as shown in Fig. 4(b). There was not a notable change in the high temperature response. As a result, the stabilized tensile mean stress was 1.4 times lower than the comparable baseline test.

Initial yielding occurred at nearly the same stress level as with the baseline test (Fig. 4(a)), indicating not only that strength was similar at the two minimum temperatures in the near virgin condition, but also that rate effects did not contribute notably to the deformation response. This lends validity to the life comparison between the two tests, as the strain rate with T_{min}=100°C was 9.4 times slower than that with T_{min}=500°C. This, coupled with the similar stresses reached at peak compressive strain, indicated that the reduction in the minimum temperature of the TMF cycle was primarily responsible for the reduction in fatigue life.

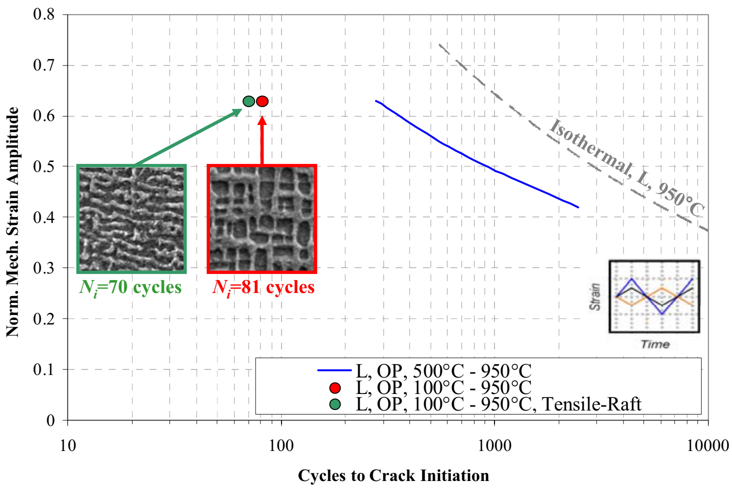

Fig. 3. Effect of reducing T_{min} to 100°C on the life of a smooth specimen subjected to OP TMF with norm. $\Delta\varepsilon_{mech}$=1.26%.

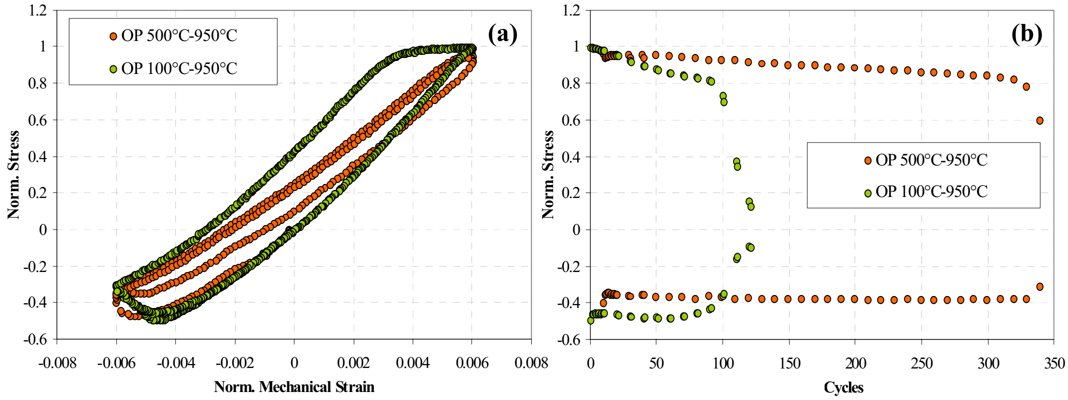

Fig. 4. (a) Hysteresis loops for first three reversals and (b) evolution of peak values of stress for longitudinal CM247LC DS subjected to OP TMF with normalized. $\Delta\varepsilon_{mech}$=1.26%.

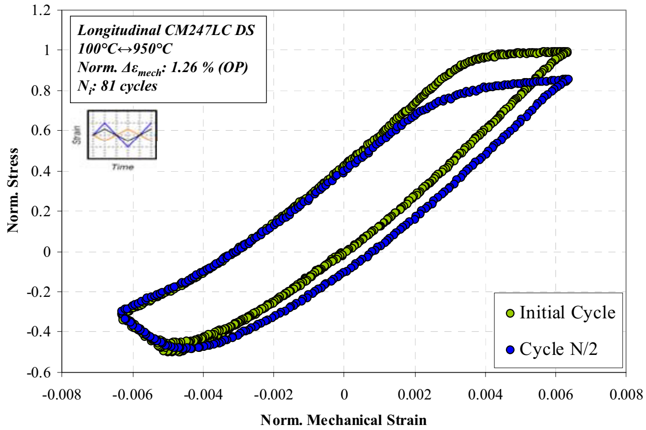

Fig. 5. Stress-mechanical strain hysteresis of longitudinal CM247LC DS subjected to OP TMF with $\Delta\varepsilon_{mech}$=1.26% and T=100°C↔950°C.

TMF tests conducted on L-oriented DS CM247LC with T_{max} = 950°C exhibit rafting as shown in Fig. 6. This indicated that this temperature is sufficient to induce the thermodynamic change in microstructure. The γ' platelets align parallel to the stress axis in OP cycling for which the specimen is in compression at T_{max}, typical of alloys with negative γ/γ' lattice mismatch. Under in-phase (IP) TMF, the γ' rafts are perpendicular to the stress axis. The influence of the rafted microstructure on tensile yield strength is shown in Fig. 7. When the rafts formed in tension, the lower temperature yield strength increased compared to the virgin yield strength. But when the rafts formed in compression, which occurs in OP TMF, the yield strength for temperatures below 700°C decreased. When these rafted microstructures were exposed to OP TMF, the cyclic response was stable, whereas the virgin microstructure exhibited cyclic softening [4, 5]. For temperatures above 800°C, the yield strength is not as sensitive to the character of the rafted microstructure, particularly those formed in compression typical of OP TMF. In fact, rafts formed in compression have been shown to enhance high temperature creep and isothermal fatigue strengths [3, 9] as well as enhance OP TMF when T_{min} is relatively high (T_{min} = 600°C) [10]. However, rafting in compression will result in a reduced tensile yield strength at lower temperatures resulting in wider hysteresis loops as T_{min} is reduced under OP TMF conditions. Hence, rafting in compression will not be beneficial for OP TMF conditions with low T_{min}.

TMF tests on the rafted microstructure were carried out. The OP TMF life of the tensile-rafted microstructure was slighted reduced compared to beginning with the virgin condition as seen in Fig. 3. Unfortunately, an unexpected power outage pre-maturely interrupted an OP TMF test with a compressive-rafted microstructure under the same T_{min} = 100°C conditions. The yield strength at the lower temperature end of the compressive raft microstructure was smaller and the inelastic strain greater as shown in Fig. 8. Hence, the accumulation of cyclic inelastic strain is greater in the compressive raft case with lower T_{min}. The increase in fatigue resistance for the compressive raft case (i.e., rafts parallel to the stress axis) reported in the literature [3, 9, 10] has been attributed to the large cutting resistance of the γ' since cracks cannot avoid cutting γ' with this morphology [9, 10]. This cutting resistance results in crack branching that hinders propagation. But as the temperature is reduced, the cutting resistance of γ' is reduced and hence less effective in promoting crack branching, and consequently resistance to crack propagation is reduced.

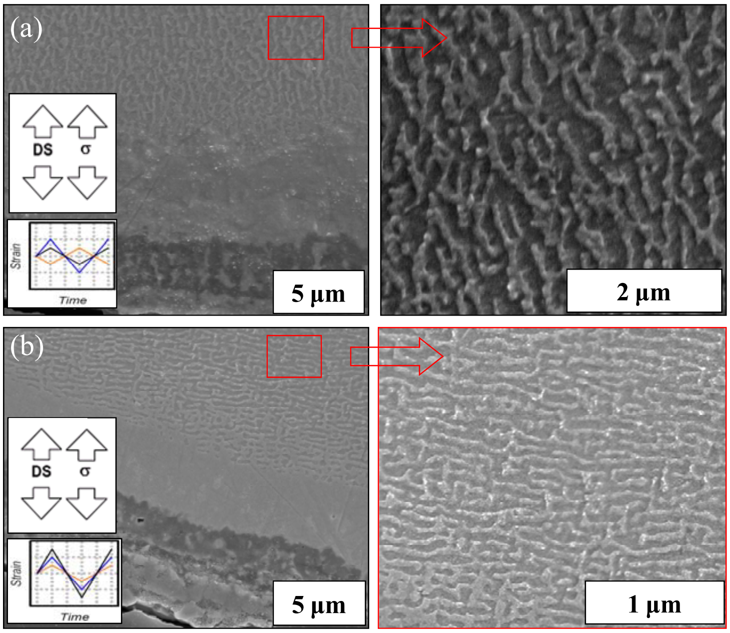

Fig. 6. SEM images of γ' precipate rafting resulting from (a) OP and (b) IP TMF cycling with T_{max} = 950°C.

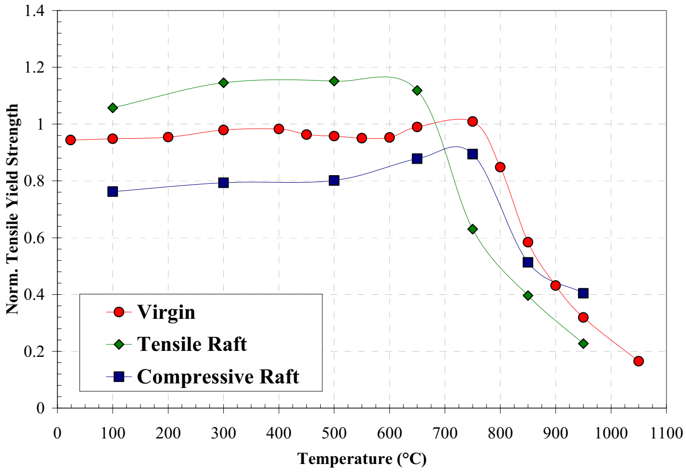

Fig. 7. Yield strength (0.02% offset) of L-oriented DS CM247LC in the virgin, tensile-rafted, and compressive-rafted condition.

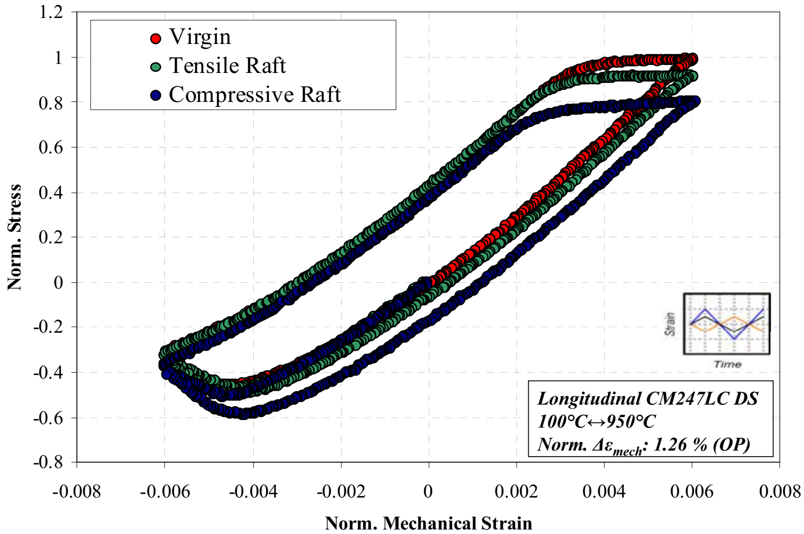

Fig. 8. First cycle hysteresis loops for L-oriented DS CM247LC comparing the response of the virgin with the rafted microstructures.

These experimental results also suggest that the reduction in life due to a reduction in T_{min} may occur even if there is no reduction in strength at the lower temperatures due to microstructural changes when operating in mechanical strain control conditions. To demonstrate this, crystal viscoplasticity simulations were conducted. In these simulations, the inelastic response for temperatures less than 427°C were assumed to be invariant with temperature. Hence, only the elastic properties varied with temperature below 427°C. The responses are shown in Fig. 9. It is clear that reducing T_{min} results in a greater inelastic strain range. This effect may even be magnified when T_{max} is reduced as shown in Fig. 10. This suggests that the T_{min} effect should still be observed under conditions when microstructural change is negligible. A critical test program to isolate the source of the T_{min} effect, whether it is primarily controlled by the elastic response under mechanical strain control conditions or whether it is primarily controlled by microstructural change, would involve experiments in which the microstructure change is active and not active. This can be accomplished by varying T_{max}. For the alloy considered here, the microstructure is stable when T_{max} is 750°C. Based on our simulations and experiments and those reported in the literature [2], it is likely that the reduction in life when T_{min} is reduced is a combination of both effects. Presently, experiments are planned to further examine the role of T_{min} so that it can be correctly captured in life models of hot section components.

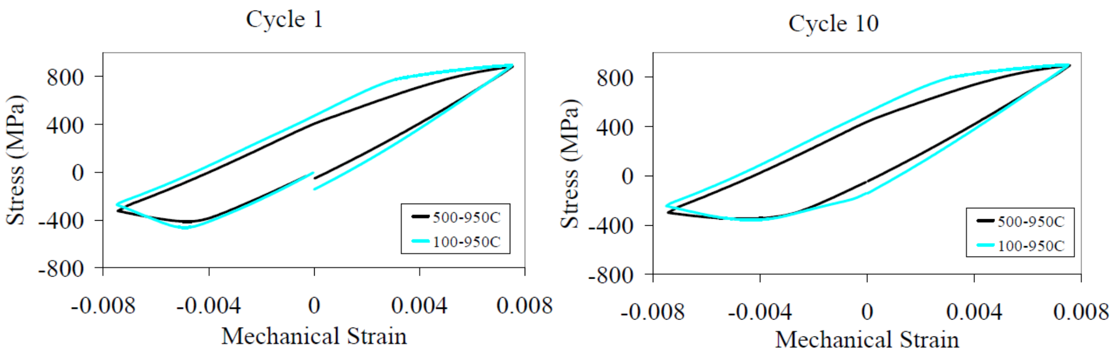

Fig. 9. Predicted OP TMF response varying T_{min} for T_{max} = 950°C.

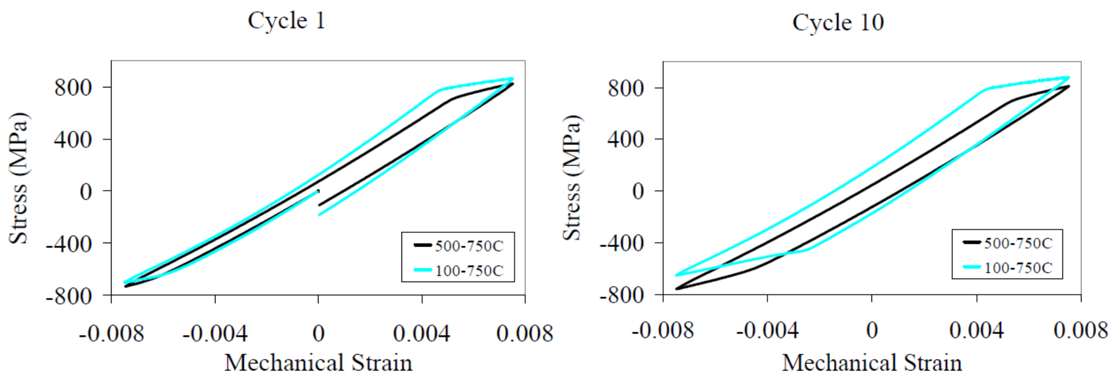

Fig. 10. Predicted OP TMF response varying T_{min} for T_{max} = 750°C.

6. Summary

To date, little attention has been given to the effect of the minimum temperature of a TMF cycle on the life of Ni-base superalloys due to the assumption that strength and isothermal fatigue properties are nearly independent of temperature below 500°C. However, the effect of the increase in elastic modulus as temperature is reduced is shown to be significant. Additionally, directional coarsening (i.e., rafting) of the γ' resulting from high temperature exposure and stress will have an impact on the mechanical properties at these low temperatures and may further enhance this reduction in life. In particular, the yield strength at temperatures less than 650°C decreases with exposures to compressive dwells at 950°C. In the current study, the effect of reducing the minimum temperature of an OP TMF cycle from 500°C to 100°C was investigated through experimentation and modeling. Even in cases when yielding occurs at roughly the same stress level at these lower temperatures, the increase in elastic modulus at lower temperatures meant that the specimen subjected to a lower T_{min} reached the onset of yielding sooner, which led to a significant increase in cyclic inelastic strain over the baseline cycle with higher minimum temperature. The resulting increase in accumulated inelastic strain per cycle reduced the number of cycles to crack initiation by a factor of 3.4 for the particular case examined. Modeling suggests that this effect will be observed even in cases where the maximum temperature is sufficiently low such that thermodynamically unstable microstructural changes including coarsening and rafting do not occur. Therefore, the elastic response when evaluating life of TMF in mechanical strain controlled conditions needs to be carefully considered.

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