PROBABILITY OF OCCURRENCE OF LIFE-LIMITING FATIGUE MECHANISM IN P/M NICKEL-BASED ALLOYS (POSTPRINT)

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SPECIAL NOTES

ABSTRACT (Maximum 200 words)
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SUBJECT TERMS
Probability of occurrence, Fatigue life prediction, Life-limiting mechanism, Superalloy

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PROBABILITY OF OCCURRENCE OF LIFE-LIMITING FATIGUE MECHANISM IN P/M NICKEL-BASED SUPERALLOYS

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Keywords: Probability of occurrence, Fatigue life prediction, Life-limiting mechanism, Superalloy

Abstract

The mean and the minimum fatigue lifetimes are often produced by different mechanisms [1, 2]. In this paper, a microstructure-based model of the probability of occurrence of the minimum-lifetime, or the life-limiting, mechanism in powder processed Ni-base superalloys is discussed. The life-limiting mechanism in the stress level and temperature regimes of interest was taken to correspond to surface crack initiation from a non-metallic particle. The model by Tanaka and Mura [3] for crack initiation due to blocking of a slip band at a non-metallic particle was adapted in formulating a microstructural criterion for the life-limiting mechanism. The probability of occurrence was based on a Monte Carlo analysis using random instantiations of microstructural volumes containing combinations of non-metallic particle and grain neighborhoods. The model was exercised to study the probability of occurrence of life-limiting failures with respect to microstructure, temperature, stress level, and volume. The predicted trends are discussed with reference to published results on Ni-based superalloys.

Introduction

Current fatigue-design approaches for fracture-critical components are often based on data-driven methods whereby the lower-limit of fatigue lifetime is determined from distributions with respect to the mean lifetime [4]. An underlying assumption in such an approach is that the mean and the minimum, or the life-limiting, behaviors are due to the same mechanism and follow the same trend with respect to microstructural and loading variables. However, in many cases, the life-limiting mechanism may not be a variation of the mean mechanism and exhibits different sensitivity to microstructure and loading variables than the mean [1, 2]. In particular, it was shown that while the mean behavior is increasingly dominated by the crack initiation lifetime as the stress level is decreased, the life-limiting mechanism, which is attributed to extreme combinations of microstructural features, is largely controlled by the small + long crack growth lifetime [1, 2]. Previously, a model-based approach to predicting the lower limit of fatigue lifetime was proposed, which assumed a population of life-limiting failures due to almost instantaneous crack-initiation from critical microstructural combinations resulting in small + long crack growth lifetime dominated mechanism [1, 2]. Since the life-limiting mechanism is dependent on the concentration of a critical level of fatigue damage in microstructural configurations in very few cycles, the probability of occurrence of the life-limiting condition will vary with microstructure and loading condition, and it is important to account for that probability in a comprehensive model-based fatigue lifeing approach.

Ni-base superalloys have been one of the high temperature materials of choice for fracture-critical aero-engine applications [5]. This is due to the desirable strength, fatigue, and creep properties exhibited by these alloys at elevated temperatures [5]. In a study on a fine grain IN100, it was shown that while lifetimes from multiple fatigue tests could be characterized by a single distribution at higher stress levels, a separation of the mean from the life-limiting population occurred at lower stress levels [1]. Furthermore, while the mean-dominating population was due to cracks that initiated from a mixture of subsurface non-metallic particles (NMPs) and surface pores, the life-limiting failures occurred by surface crack-initiation from NMPs [1]. However, due to the decrease in the rate of occurrence of these failures with decreasing stress level, NMP-initiated surface failures were not captured at the lowest stress level in the given number of tests [1]. The effect of NMP on fatigue lifetime has been studied by other researchers [6, 7, 8]. In studies with seeded NMPs, the fatigue lifetime was shown to significantly decrease when the initiation was forced to occur from NMP in the surface [7, 8], consistent with the IN100 study in [1]. Probabilistic models of the occurrence of NMP-initiated failure have also been proposed, for example [8 – 12]. Huron and Roth [8] used Monte Carlo simulation to determine the size distribution of crack initiating NMP based on the largest size in a specimen volume and used that distribution to calculate fracture mechanics-based lifetimes. Grison and Remy [9] developed a probabilistic model for the distributions in lifetimes due to surface, near-surface, and subsurface NMP crack initiation, based on a stress intensity factor calculation associated with fractured NMPs of different sizes, shapes, and proximity to the surface. Other probabilistic models based on the occurrence of the largest NMP in the surface of the specimen have also been proposed [10, 11, 12].

The model discussed in this paper is focused on the probability of occurrence of life-limiting failure due to NMP-initiated, surface crack. It captures the effect of the matrix microstructure, for example, the grain size distribution and grain properties, NMP parameters such as size and fracture properties, as well as the stress level, temperature, and volume. Secondly, the proposed model is based on the mechanistic understanding that the life-limiting failures occur in a few cycles and are essentially dominated by the crack growth lifetime. To develop the model, the sensitivity of the probability of occurrence to microstructure, applied stress level, temperature, and volume was examined. The predicted trends are discussed with reference to previous reports on Udimet 720 [7] and René88DT [8].

Model Description

As discussed before, the distribution of fatigue lives for mean and life-limiting failures begin to deviate below certain stress levels and that cracks are found to initiate by different mechanisms, as shown
in a fine grain IN100 [1] and René88DT [13]. The same behavior has been studied in some other materials; for example, reference [2] provides a discussion of the mean versus life-limiting mechanism in a titanium alloy. At elevated temperatures, the life-limiting failures in IN100 were found to occur by crack initiation from NMP in the surface of the specimen [1]. Due to a decrease in the probability of occurrence of the critical damage condition at the specimen surface with decreasing stress level, the life-limiting mechanism did not occur at the lowest stress level in the fatigue tests that were undertaken [1]. However, subsurface NMP-initiated failures were commonly observed. This indicated that the NMP crack initiation mechanism was active at the lowest stress level but not sampled in the surface, due to statistically insufficient number of specimens or the volume of surface material that was sampled. It was also shown that at lower stress levels, the majority of the mean fatigue lives was spent in initiating cracks while the life-limiting failures were largely governed by small + long crack growth starting from the initiating NMP size [1]. The model for the probability of occurrence of life-limiting failure is, therefore, based on the probability of occurrence of a critical combination of NMP and the neighboring microstructure, which produces crack initiation in the first fatigue cycle.

A schematic showing the steps and the flow of the model is given in Figure 1. A microstructural metric that correlates with fatigue damage is required in order to define the criterion for life-limiting failure. The crack initiation model by Tanaka and Mura [3] for initiation of fatigue cracks due to slip band pile up at a NMP was adapted for this purpose. Tanaka and Mura’s [3] model accounts for the properties of the NMP, as well as the surrounding matrix, and was suitable in formulating a criterion for life-limiting failure that is sensitive to material parameters, temperature, and stress level. The version of the model applied here assumes crack initiation by fracture across an NMP [3], which is similar to the mechanism observed in IN100 [1] and René88DT [13] at the conditions of interest. As suggested by Chan [14], in order to adapt the model for the case of fracture across NMP, the area of as-initiated crack faces [3] can be taken as the area of NMP faces and the fracture energy can be taken to be that for NMP fracture. Furthermore, slip was assumed to cover the entire grain or the controlling microstructural unit as in homogenous slip, which was invoked by Tanaka and Mura [3] by assuming the slip band width to equal the slip length. This assumption is considered applicable to the multiple slip condition expected in the temperature regime of interest in this study. The crack initiation model by Tanaka and Mura [3] after adapting to the case of crack initiation across a NMP, as suggested by Chan [14], can be expressed as:

$$N_i = \frac{1}{(Δσ - 2Mk)^2} \left[ \frac{μM^2(μ + μ')W_i}{πμ'a} \right]$$

where $N_i$ is the crack initiation lifetime, $Δσ$ is the stress amplitude, $M$ is the Taylor Factor of the matrix, $k$ is the lattice friction stress, $μ$ is the shear modulus of the matrix, $μ'$ is the shear modulus of the NMP, $a$ is the radius of the NMP, and $W_i$ is the specific fracture energy per unit area of NMP. Above formulations assume irreversibility of slip, which may be applicable in the case of slip accumulation at NMP-matrix interfaces by an Orowan looping mechanism [3], and at elevated temperatures. A factor that accounts for slip reversibility can be included as proposed in Mura and Nakasone [15] for the case of crack initiation in slip bands when slip may be more reversible.

The life-limiting event can be defined to occur when the combination of parameters in the right hand side of equation (1) results in the crack initiation lifetime, $N_i$ of less than or equal to 1. Equivalently, the inverse of the expression on the right hand side of equation (1) has to be greater than 1 for initiation of a life-limiting failure. After rearranging, this criterion can be represented by:

$$1 \left[ \frac{μM^2(μ + μ')W_i}{πμ'a} \right] > 1$$

The left hand side of equation (2) can be considered as a metric that correlates with fatigue damage. The metric depends on both the NMP and its neighborhood parameters, some of which will vary with temperature. Due to the assumption of homogenous slip, grain size (or a slip length parameter) is absent in equations (1) and (2) as an explicit parameter [3] but the effect of grain size is indirectly included through the friction stress, $k$, which can be different for a fine grain and a coarse grain microstructure [16, 17] and via the Taylor Factor, $M$, as illustrated in Figure 2. In a fine grain microstructure, a NMP can be thought to interrogate a larger number of grains, resulting in a near-average value of $M$ for the surrounding matrix (Figure 2(a)). On the other hand, a coarse grain microstructure will present a smaller number of grains around a NMP of the same size, leading to a wider variation in average $M$ of the neighboring grains (Figure 2(b)).
fatigue volumes. The sizes of NMPs and the neighboring grains were randomly assigned from respective size distributions given for the bulk material. The NMP + neighborhood locations in the simulated volumes were equivalent to 2500 times the desired surface layer volume. The surface layer was defined to have the thickness of the average γ grain size. The surface layer volume can be approximated for other geometries such as double-edge-notched tension (DEN(T)) specimens [19] or the stressed region at features in a component after conducting a stress analysis. A Monte Carlo analysis was performed with random instances of fatigue volumes, which were interrogated for the occurrence of NMP-grain neighborhood configurations in the surface layer that satisfied the criterion given by equation (2). For the purpose of the simulation, surface crack initiation was defined as the case where any part of the NMP is within one average grain size of the surface, which implied that the NMP had to, at least, touch the surface layer.

![Figure 2](image.png)

Figure 2. Schematic illustration of the effect of grain size on the configuration of NMP and neighboring grains; (a) Fine grain microstructure and (b) Coarse grain microstructure.

Model Inputs

Since the main objective of the modeling exercise was to conduct a parametric study to assess the sensitivity of predictions to the material and loading parameters, microstructural information from literature were adapted for the model inputs. The grain and the NMP parameters used in the first set of calculations are given in Table I. The model was exercised with ten different combinations of grain and NMP parameters, as listed in Table I. The parameters for the first six microstructures were roughly adapted from a study on Udimet 720 by Kantzos et al. [7]. The authors conducted a study with seeded NMPs in order to assess the effect of NMP size and content on the debit in lifetime [7]. The grain size distribution for Microstructure 1 (Table I) was adapted from reference [20] to represent that of Udimet 720 used in the study by Kantzos et al. [7]. The mean grain size was 8 µm and the standard deviation was taken as 2 µm [20]. The lognormal distribution was used to describe the grain size distribution. In addition, a coarser grain microstructure was also implemented with a mean size of 16 µm and a standard deviation of 4 µm (Table I) in order to assess the effect of grain size for the same NMP parameters. The friction stress, \( \gamma \), which is a contributing factor in the yield strength [21, 22], was held constant for the two grain sizes in order to isolate the effect of grain size on the probability of life-limiting failures. The friction stresses in \( \gamma \) solid solution and \( \gamma + \gamma' \) ensemble are found to be more sensitive to the solute parameters [21, 22] and \( \gamma' \) precipitate size [16, 17], respectively. Grain size will have an indirect effect on the \( \gamma \) solid solution and the \( \gamma' \) precipitate size and, therefore, the friction stresses [16], which is not captured in the coarser grain microstructure used here. The NMP parameters for the first six microstructures were also adapted from the study on Udimet 720, reference [7]. As listed in Table I, three different distributions for NMPs were used for the first six microstructures. The first distribution was meant to represent the unseeded NMP size distribution and occurrence rate [7]. The occurrence rate based on the Heavy Liquid Separation (HLS) method, given in reference [7], was used for the unseeded case. The actual occurrence rate in the unseeded material was not known. The other two sets of NMP parameters approximately represented the size distribution and occurrence rate in the seeded materials, given in [7]. The ratio of standard deviation to the mean size was assumed the same for the three sets of NMP parameters.

<table>
<thead>
<tr>
<th>Microstructure No.</th>
<th>Grain Size Parameters</th>
<th>NMP Parameters</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \mu = 8 \mu m ) ( \sigma = 2 \mu m )</td>
<td>( \mu = 47.87 \mu m ) ( \sigma = 14.95 \mu m ) ( \lambda = 0.0005/mm^3 )</td>
<td>[7]</td>
</tr>
<tr>
<td>2</td>
<td>( \mu = 8 \mu m ) ( \sigma = 2 \mu m )</td>
<td>( \mu = 54.0 \mu m ) ( \sigma = 16.74 \mu m ) ( \lambda = 0.3/mm^3 )</td>
<td>[7]</td>
</tr>
<tr>
<td>3</td>
<td>( \mu = 8 \mu m ) ( \sigma = 2 \mu m )</td>
<td>( \mu = 122.0 \mu m ) ( \sigma = 37.82 \mu m ) ( \lambda = 0.07/mm^3 )</td>
<td>[7]</td>
</tr>
<tr>
<td>4</td>
<td>( \mu = 16 \mu m ) ( \sigma = 4 \mu m )</td>
<td>( \mu = 47.87 \mu m ) ( \sigma = 14.95 \mu m ) ( \lambda = 0.0005/mm^3 )</td>
<td>[7]</td>
</tr>
<tr>
<td>5</td>
<td>( \mu = 16 \mu m ) ( \sigma = 4 \mu m )</td>
<td>( \mu = 54.0 \mu m ) ( \sigma = 16.74 \mu m ) ( \lambda = 0.3/mm^3 )</td>
<td>[7]</td>
</tr>
<tr>
<td>6</td>
<td>( \mu = 16 \mu m ) ( \sigma = 4 \mu m )</td>
<td>( \mu = 122.0 \mu m ) ( \sigma = 37.82 \mu m ) ( \lambda = 0.07/mm^3 )</td>
<td>[7]</td>
</tr>
<tr>
<td>7</td>
<td>( \mu = 24 \mu m ) ( \sigma = 6 \mu m )</td>
<td>( \mu = 24.15 \mu m ) ( \sigma = 122.0 \mu m ) ( \lambda = 0.005/mm^3 )</td>
<td>[8]</td>
</tr>
<tr>
<td>8</td>
<td>( \mu = 24 \mu m ) ( \sigma = 6 \mu m )</td>
<td>( \mu = 24.15 \mu m ) ( \sigma = 122.0 \mu m ) ( \lambda = 0.027/mm^3 )</td>
<td>[8]</td>
</tr>
<tr>
<td>9</td>
<td>( \mu = 24 \mu m ) ( \sigma = 6 \mu m )</td>
<td>( \mu = 225.7 \mu m ) ( \sigma = 69.96 \mu m ) ( \lambda = 0.005/mm^3 )</td>
<td>[8]</td>
</tr>
<tr>
<td>10</td>
<td>( \mu = 24 \mu m ) ( \sigma = 6 \mu m )</td>
<td>( \mu = 225.7 \mu m ) ( \sigma = 69.96 \mu m ) ( \lambda = 0.027/mm^3 )</td>
<td>[8]</td>
</tr>
</tbody>
</table>

\( \mu = \text{mean}, \sigma = \text{standard deviation}, \lambda = \text{volumetric number density} \)

Huron and Roth [8] conducted a study of the effect of size and occurrence rate of NMPs on fatigue lifetime as well as the surface versus subsurface failure rates in René88DT by using seeded specimens. The last four microstructures given in Table I were chosen to roughly represent the seeded René88DT specimens reported by Huron and Roth [8]. The mean grain size parameter was approximately based on the grain size information provided in [8]. The standard deviation to mean ratio was assumed the same as in Microstructures 1 to 6 (Table I). Two sets of NMP size and number density parameters were used for Microstructures 7 to 10, which were roughly based on the data given by Huron and Roth [8].
for the two seeded cases in their study. Once again, the ratio of standard deviation to mean NMP size was assumed the same for all cases.

Besides the grain size distribution and the NMP size and number density parameters, the model requires several other material parameters, which are briefly described here. These material parameters were assumed to not depend on the grain size and the NMP parameters but varied with temperature. The lattice friction stress, \( \mu' \), in the model was interpreted to be the minimum resolved shear stress required to move dislocations in the \( \gamma \) matrix. The friction stress of the \( \gamma' \) phase was based on the work of Maciejewski et al. [23] in which the authors provided the dependence of friction stress in the \( \gamma' \) solid solution in IN100 as a function of temperature. Although the relationship given in [23] was for IN100, it was implemented in this study since a similar temperature dependence of friction stress in the \( \gamma' \) matrix was not readily available for Udimet 720 and René88DT. As a future study, more rigorous treatment of the friction stress will be explored, for example, Kozar et al. [21] developed a relationship of friction stress to concentration of alloying elements, which was adopted by Parthasarathy et al. [22] in modeling the yield strength of various Ni-base superalloys. The shear modulus of the matrix, \( \mu \), was assumed to be similar to that of IN100. Temperature dependence of \( \mu \) was approximated after the results of Sieborger et al., [24] on CMSX-4. The temperature relationship given by Sieborger et al. was scaled for IN100 based on the shear modulus value at 600 °C reported by Chan [14]. The Taylor Factors were assigned randomly to the grains from a uniform distribution, where the values ranged between 2 and 3.7. Previous studies have shown that, while different types of NMPs, in terms of their morphology and appearance are possible in powder metallurgy superalloys, they tend to be ceramic particles with Al and O as major components [7, 8]. The shear modulus of the NMP, \( \mu' \), was therefore, approximated to that of Al2O3. The value of \( \mu' \) also depended on temperature and the temperature dependence was approximated by the empirical relationship given in reference [25]. The parameter \( W_f \), which represents the fracture energy per unit area of NMP was taken as \( W_f = \frac{\Delta k_\gamma}{E} \) [26] where \( \Delta k_\gamma \) is the fracture toughness and \( E \) is the elastic modulus. The relationship of \( E \) to temperature given for Al2O3 in reference [25] was adopted. Based on the results in [27], \( k_\gamma \) was assumed to be constant in the temperature range of 400 to 700°C, which was the regime of interest for the parametric study.

### Results and Discussion

**Effect of NMP and Grain Parameters on the Sensitivity to Stress Level**

The model was exercised to calculate the probability of occurrence of the life-limiting failure with respect to the grain size and the NMP parameters listed in Table I. The results are given in Figures 3 (a) and (b) for the 10 sets of grain and NMP parameters based on references [7] and [8]. The temperature in Figure 3 was kept constant at 650 °C, which was the temperature used in the study by Kantzos et al. [7] and very close to one of the temperatures in the study by Huron and Roth [8]. Fatigue tests by Kantzos et al. [7] and Huron and Roth [8] were run in strain control. The stress levels in the parametric calculations were varied from 800 to 1200 MPa for the first six microstructures, which covers the typical range of stress levels in low cycle fatigue studies at intermediate temperatures on Udimet 720 [28]. The stress levels for Microstructures 7 to 10 were varied from 800 to 1400 MPa in order to include the range of effective stress levels for René88DT given by Huron and Roth [8], which was about 1000 to 1400 MPa at 649 °C. The probability values were based on 1000 Monte Carlo samples with the exception of Microstructures 1, 4, 7, and 9 for which 10000 samples were used due to the relatively low number density of NMP in those cases.

Figure 3(a) shows the results for Microstructures 1 to 6, which were based on the Udimet 720 study [7]. As shown in Figure 3(a), the sensitivity of the probability of occurrence of life-limiting failures by surface NMP crack initiation to the stress level depends on the number density of NMP. For the number density levels corresponding to the seeded materials (Microstructures 2, 3, 5, and 6) the results are very sensitive to stress level where the probability at lower stress levels decreases significantly. This is similar to the trend observed experimentally in a fine grain microstructure of IN100, reported in [1], and in the René88DT study by Huron and Roth [8].

![Figure 3](image_url)

**Figure 3.** Prediction of the probability of occurrence of the life-limiting mechanism with respect to stress level (a) using the grain and NMP parameters adapted from the seeded study on Udimet 720 in [7] and (b) grain and NMP parameters adapted from the seeded study on René88DT in [8]. The temperature for all simulations was kept at 650 °C. The surface layer volume, \( \delta V \), was determined from the specimen dimensions given in [7] and [8] where the surface layer thickness was taken as the average grain size.
The Udimet 720 study [7] reported the mean trends in lifetime and crack initiation modes but a statistically significant amount of data was not reported to make any conclusions about the probability of occurrence of a given failure type. Relatively higher number of tests were reported in the René88DT study [8] but the amount of data may not be considered statistically significant at conditions where the percent surface failure was very low. Furthermore, in the present model, some assumptions were made in the material inputs, as discussed before. Given these factors, it is not useful to directly compare the predictions to data but the predicted trends can be qualitatively compared to the experimental trends. The unseeded Udimet 720 microstructure (Microstructure 1) showed a relatively negligible probability of occurrence of the life-limiting mechanism, based on 10000 Monte Carlo samples. The data in reference [7] for the unseeded material indicates surface initiation at the higher strain ranges but subsurface initiation at the lower strains based on a limited number of specimens at each strain level. It is not possible to assess the failure probabilities due to the limited data. In the unseeded case, the model predicts negligible surface NMP-initiated failures at stress ranges of 800 to 1200 MPa. It is not clear if the surface initiation specimens seen at the higher strain ranges in the unseeded material failed from NMPs [7]. Using the number density of 0.0005/mm³ (based on the H1LS method [7]), a rough estimate of approximately 1.3 NMPs are expected in the gage volume (assuming the specimen dimensions of 10.2 mm diameter and 31.8 mm gage length [7]). The expected number of NMPs in the surface layer volume (which is estimated to be about 8.15 mm² assuming the surface layer thickness to equal the average grain size) will be about 0.004. The actual probability of occurrence of life-limiting mechanism will be less than that number since not all NMP and grain combinations will satisfy the life-limiting crack-initiation criterion. Therefore, it may be unlikely in a few tests to encounter a specimen with a surface NMP that satisfies the life-limiting criterion, for the given specimen size. The predicted trends for Microstructures 1 and 4 seem consistent with the given inputs.

Microstructures 2, 3, 5 and 6 represented the seeded NMP parameters in Udimet 720 [7]. In particular, Microstructures 2 and 3 had roughly similar grain size as that of the Udimet 720 used in that study [7]. The predicted results at the highest stress level for Microstructures 2 and 3 indicate probabilities of about 88% and 41%, respectively of occurrence of the life-limiting mechanism. The probabilities for both microstructures decrease at lower stress levels. The data reported by Kantzos et al. [7] for the seeded materials show a similar trend, although the tests were run in strain control and the effective stress levels were not given. Results for Microstructures 2 and 3 (and 5 and 6) also demonstrate the effect of an interplay between the number density versus the size of NMPs, which produces a crossover between the predicted trends below certain stress level. This suggests that below the crossover stress level, the probability of life limiting failure will be dominated by the size of NMP resulting in higher probability values in Microstructure 3 but at higher stress levels the occurrence rate of NMP becomes a limiting factor leading to higher probabilities of life-limiting failure in Microstructure 2 (Figure 3(a)).

The results on the grain size effect are also informative (Figure 3(a)). As mentioned before, under a homogeneous slip assumption, grain size has indirect effects on the friction stress, k, and the average Taylor Factor of grains intersecting the NMP. For this parametric exercise, the friction stress in the γ phase was held constant between the two grain sizes in order to isolate the effect of the average Taylor Factor. The results indicate that firstly, grain size has a significant effect on the predicted probabilities for the same NMP parameters and friction stress, for e.g., Microstructures 2 and 5 had the same NMP parameters but different grain size distributions and similarly, Microstructures 3 and 6 differed in terms of the grain size distribution while the NMP parameters were kept the same. Secondly, larger grain size microstructures showed a higher probability of occurrence of the life-limiting mechanism for both sets of NMP parameters. This can be rationalized in terms of the earlier discussion on random combinations of NMP and neighborhood grains (Figure 2). As mentioned before, in a fine grain size material, a larger number of grains can be expected to intersect the NMP and in that case the average Taylor Factor of the neighborhood grains is expected to have relatively less variation between combinations. In the coarser grain size microstructure, due to smaller number of grains at the boundary of a NMP, variation in the average Taylor Factor of the neighborhood will be greater, thereby increasing the chance of lower average Taylor Factors. According to the criterion in equation (2), this is expected to lead to increased probability that the life-limiting criterion will be satisfied.

Results for the NMP parameters corresponding to the seeded René88DT study [8] (Microstructures 7 to 10) are shown in Figure 3(b). Huron and Roth [8] studied two types of seeded NMPs both of which were based on Al₃O₅. The percentage of surface initiated failures did not seem to be strongly dependent on the NMP type [8], therefore, for the purpose of comparing the trends, data from both types of NMP are considered as a single population. The effective stress range was between about 1000 and 1400 MPa [8]. Microstructures 8 and 9 in Figure 3(b) can be considered to correspond to the “Small” and “Large” seeded specimens under no peening with volumetric number densities of 0.027 and 0.005 per mm³, respectively. [8]. The “High” and “Low” stresses in their paper [8] are considered to correspond to 1400 and 1000 MPa. For Microstructure 8, the predicted probabilities at 1400 and 1000 MPa are about 34% and about 28%, respectively. The prediction at the higher stress level roughly compares with the data in reference [8] in which the observed probability based on 10 tests (including Type I and Type II seeded specimens) was 40%. The probability based on 10 tests (including Type I and Type II seeds) at the lower stress level was 0% for surface initiation and 20% for near-surface initiation, reference [8]. It is not clear how the near-surface initiation was defined. In the model, the definition of surface initiation includes the case where a NMP is at least touching the surface layer. Therefore, if the edge of a NMP that satisfies the life-limiting criterion is 24 μm (which is the average grain size) from the surface, the resulting failure is counted as a life-limiting failure. Assuming that the experimental probability at the lower stress level is between 0 and 20% when the surface initiation definition used in the model is invoked, the predicted trend declines at a slower rate between 1400 and 1000 MPa than the data in [8]. The results for Microstructure 9 did not compare well with data in reference [8]. The data in [8] showed 57% and 25% surface initiations at high and low stress level, respectively but the predictions were about 7% with not much variation with respect to stress level. The average size of seeds in Microstructure 9 was about 225.7 μm [8], which can be considered significantly larger than the critical size based on previous studies on other superalloys [1]. Minimal variation in predicted probabilities with stress level in case of Microstructure 9 suggests that the result is limited by the occurrence rate of NMP. A rough calculation assuming the number density of 0.005 per mm³ for “large” seeds [8] shows that the expected number of NMPs in the surface layer volume is about 0.07 per specimen (assuming the
specimen dimensions given in [8] and a surface layer thickness equivalent to the average grain size of 24 μm). Therefore, the predicted values for Microstructure 9 seem reasonable for the given inputs. Another possibility can be that the assumptions for the other model inputs in this case were not accurate, although the NMP parameters are expected to have a more dominant effect on the results when the occurrence rate is very low. In any case, sensitivity of the results to the assumptions needs to be examined to make a better comparison of the model with these studies.

Effect of Temperature

The probability of occurrence of the life-limiting mechanism was calculated with respect to temperature and the results are shown in Figure 4. For the model runs in Figure 4, the stress level was kept constant at 1000 MPa and the surface layer volume was taken as that of the specimen in reference [7], which was about 8.15 mm³. The NMP parameters were taken to correspond to that of Microstructures 2 and 3. As shown, the probability of occurrence of life-limiting failures increases with temperature, in the range of 400 to 700 °C but the sensitivity to temperature was strongly dependent on the size and number density of NMP. Microstructure 3, which had a larger size but lower number density of NMPs, showed a relatively weaker variation in results with respect to temperature.

Volumetric Effect

Results on the volumetric effect on the probability of occurrence of life-limiting mechanism are presented in Figure 5. For these simulations, the material parameters were chosen to correspond to that of Microstructures 2 and 3 (Table I). These microstructures had the same grain size distribution but varied in terms of the NMP size and number density. The stress level was kept constant at 1000 MPa and the temperature was taken as 650 °C. Figure 5 suggests a strong volumetric effect on the probability of occurrence, as expected. The sensitivity to volume depends on the NMP parameters, which is also demonstrated by Figure 5. In these two microstructures, a lower number density of NMP in Microstructure 3 appears to have more than cancelled the effect of larger NMP sizes leading to lower probabilities at the same surface layer volume. The results might be different for other combinations of size and number density parameters. Figure 5 also suggests that, at 1000 MPa, the probability of occurrence of the life-limiting mechanism for Microstructures 2 and 3, which represent seeded materials, approaches 1.0 beyond surface layer volumes of about 20 and 50 mm³, respectively. In case of unseeded materials, the volume at which the probability reaches almost 1.0 will be much larger. The volumetric prediction can be used to assess the likelihood of the life-limiting mechanism in other specimen geometries by accounting for the total stressed volume after performing a stress analysis, e.g., see [19] for a rough estimation of the stressed volume in a DEN(T) geometry.

This modeling exercise, along with a previously proposed model of life-limiting distribution [1], point to an alternate approach for fatigue life prediction and life management of fracture-critical parts. This method does not rely only on fatigue-life data, but seems to be applicable when sufficient data are not available. As stated before, a key difference is that while a data based approach can be largely driven by the mean trends with respect to material and loading variables, the methods discussed here and previous studies [1,2] focus on the probability of occurrence and distribution due to the life-limiting mechanism. In addition, this approach allows for fast assessment of new materials, loading conditions, and surface treatments based on the likelihood of life-limiting mechanism and the resulting life-limiting distribution without the need for generating full databases at each condition.

Conclusions

A model has been developed for predicting the probability of occurrence of the life-limiting fatigue mechanism in P/M Ni-base superalloys that is sensitive to microstructure and loading variables. The model is based on the Tanaka and Mura crack-initiation model [5]. The life-limiting mechanism was assumed to occur due to crack-initiation in one cycle from a surface NMP, leading to a largely crack growth dominated failure. The model was exercised to study the effects of microstructure, stress level, temperature, and volume on the probability of occurrence of the life-limiting mechanism. Predictions were compared to experimental trends reported in literature. The following concluding points can be made based on this study:

(i) The probability of occurrence of the life-limiting mechanism is sensitive to stress level and temperature in the regimes of
interest for the two variables; however, the sensitivity depends on the NMP parameters.

(ii) For the same NMP parameters and friction stress, grain size had a strong influence on the probability through the effect on the average Taylor Factor of the grains interrogated by a NMP.

(iii) The predicted probabilities exhibited a strong volumetric effect, suggesting that the occurrence of life-limiting failures will depend strongly on the specimen geometry and the stressed volume at stress-concentrating features in a component.

(iv) The model assumes knowledge of the life-limiting mechanism but does not require any other inputs from fatigue tests. Although further development is needed, this model, along with the model-based prediction of the life-limiting distribution, may be useful for a rapid and cost-effective assessment of the effect of microstructural and loading variables for the purpose of fatigue life prediction and life management of fracture-critical components.

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References


