MICROSTRUCTURAL DAMAGE EVALUATION IN NI-BASED SUPERALLOY GAS TURBINE BLADES BY FRACTAL ANALYSIS

Mita Tarafder[1*], M. Sujata[2], V. R. Ranganath[2], S Tarafder[1], SKBhumik[2]
[1]National Metallurgical Laboratory, Jamshedpur-831007
[2]National Aerospace Laboratory, Bangalore 560 0117

ABSTRACT

Ni-based superalloys are used as turbine disc and blade material in which creep, fatigue and creep-fatigue are the important damage mechanisms. Mechanical properties of these alloys depend upon the amounts of γ - γ' present in the microstructure as well as precipitation of carbides along the grain boundaries. The distribution of γ' depends on the chemical composition, operating temperature and the length of service exposure. During service exposure, as damage accumulates progressively, the morphological characteristics of microstructure change which needs to be assessed using metallographic technique. Conventionally, the extent of damage resulting in deterioration of mechanical properties is quantified by hardness measurement. The variation in hardness is correlated with the morphological features in the metalographic images by identifying precipitation of carbides, presence of cuboidal γ' and the structural changes that occur in the matrix. In this paper, we report fractal dimensions of the insitu metallographic images which can correlate the progressive damage accumulation at various locations of the blades.

*Corresponding Author: mt@nmlindia.org

1. INTRODUCTION

For the remaining life assessment (RLA) of turbine blades, structural damage evaluation is carried out by microstructural analysis [1] and by hardness measurement. The deterioration of high temperature properties is correlated with the formation of directional coarsening of γ' precipitates known as rafting, in the microstructures of the high pressure turbine rotor (HPTR) blades manufactured using Ni-base superalloys. The formation of the raft structure is a measure of creep damage which is unacceptable during the service life of the turbine blade. In order to measure the extent of creep damage, in addition to the hardness measurement, it is imperative that a quantitative methodology for the microstructural damage be adopted. This quantitative metallographic technique can be used as a diagnostic tool for component health assessment. This paper reports a fractal [2,3] image analysis based quantitative methodology for evaluation of microstructural damage in cast Ni based superalloy used in gas turbine applications. The microstructural damage is quantified by fractal dimension (FD) which is correlated with the progressive damage accumulation at various locations of the blades. Fractals based quantification method evolves from the concept of self-similarity and self affinity in natural objects. A microstructural image also contains statistical self affine fractal patterns [4, 5] characterized by the fractal dimension *FD* which remains invariant within certain length scales.

2 EXPERIMENTAL DETAILS

2.1 Component, Material & Service Exposure

The HPTR blades utilized in this study were withdrawn from a particular type of aero engines. The blades were made of directionally solidified Ni-base superalloy with MCrAlY coating. The composition of the blade material is given in Table 1. Nine blades with various service exposures ranging from 7 hours to 500 hours were characterized to generate microstructural database for comparative study and for establishing engine operating conditions as an aid to failure analysis [6].

Table I: Nominal composition of blade material (wt.%)

C	Cr	Mo	W	Co	Fe	Nb	Ti	Al	Ni
0.17	4.0	1.1	10.8	9.5	0.2	1.6	1.0	5.2	Balance

Figure 1 shows the blade indicating the line of sectioning adopted for microstructural investigation. The root of the blade is marked as 0.0 and the microstructure was studied along the longitudinal section of the blade axis, as a function of distance from the blade root upto the tip. The blade is divided into two zones: cold zone and hot zone. While the cold zone is about one third from the root of the blade, the remaining portion is the hot zone which is exposed to high temperature. The blade received for this study was of 65 mm length and the cold zone is about 10 mm from the root.

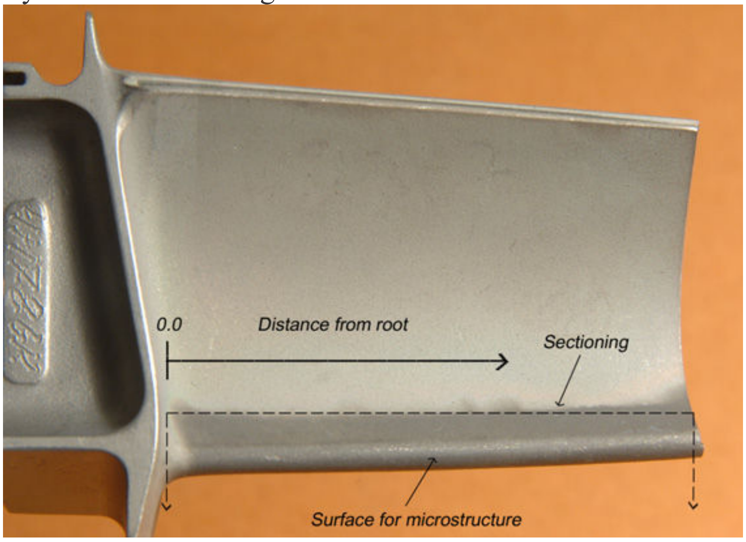

Figure 1: The HPTR blade indicating the line of sectioning for microstructural investigation.

2.2 Microstructural Examination

During service exposures, the temperature variation along the length of the blade creates graded microstructure which is examined for damage evaluation. Since the root of the blade is least affected, the microstructure at this location is considered as undamaged and represents that of the virgin materials. The comparative assessment at different distances from the blade root gives an indication of the damage gradient. For metallographic examination, the samples were polished and etched in Nimonic reagent and the images of 5000x captured using Scanning Electron Microscope (SEM).

In the microstructures of Ni based super alloy, the two prominent features [7,8,9] or phases that describe the damage during the service exposures are (1) TCP phases and (2) the γ' precipitates. The effect of these phases and the their morphological changes given in Table II.

Table II : Phases contributing to the damage in the cast Ni based super alloy

Phase	**Morphology**	**Detrimental effect**
Topologically close packed (TCP) phases: brittle and hard σ phase	Plate like	Impact strength, elevated temperature rupture strength, casting defects, stress rupture
γ' precipitates	Cuboidal, completely dissolve	Directional coarsening or rafting at high temperature and stress , creep damage due to rafting

From each blade, metallographic samples were taken from five locations: 0, 5 mm, 8mm, 12mm and 17mm and from the root region. Figure 2 shows microstructures corresponding to four locations of a typical blade exposed to maximum service life .

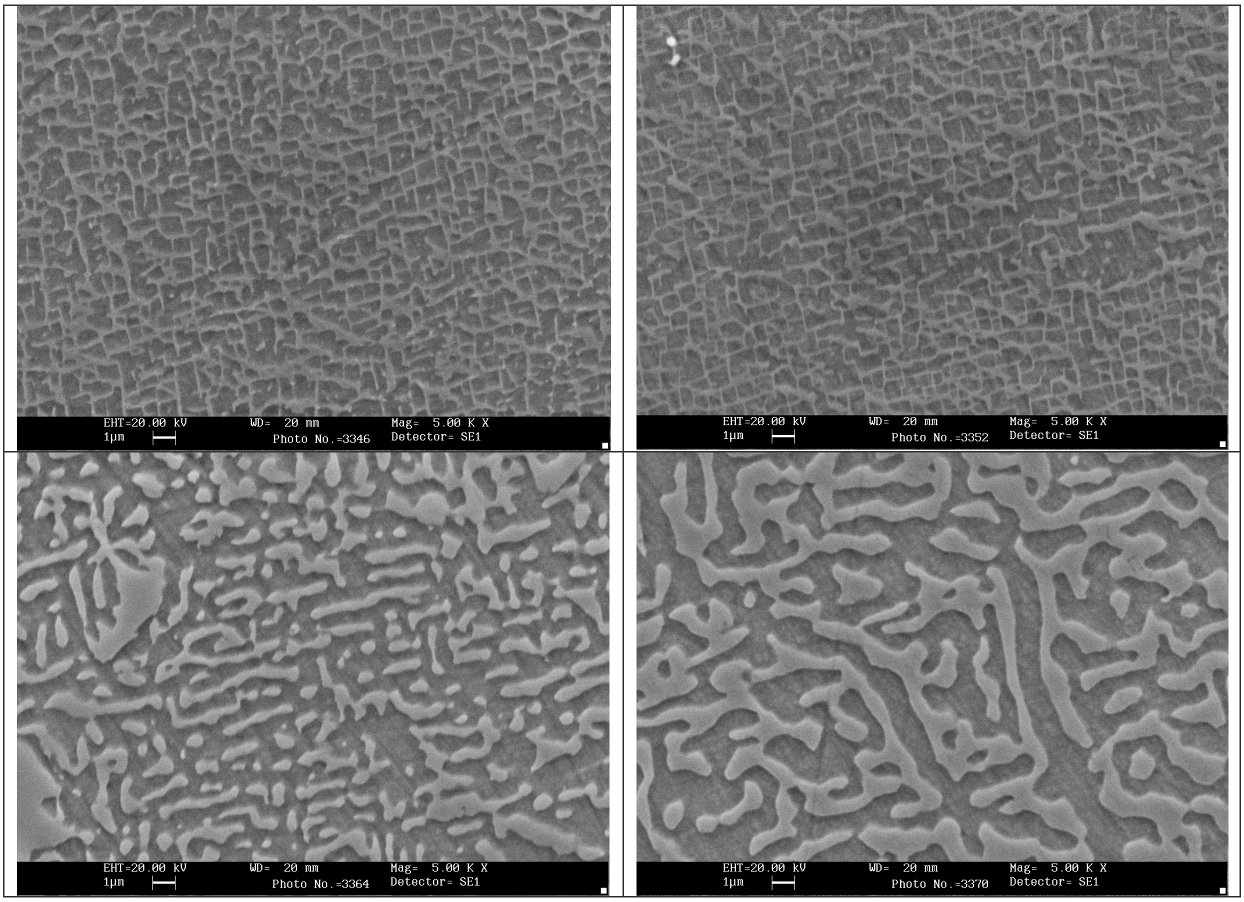

Figure 2: Microstructures of the maximum service exposed blade at locations: (a) root, (b) 5mm, (c) 12 mm and (d) 17 mm from the root.

It can be seen that the microstructures at the root region comprises cuboidal γ' precipitates in a γ-matrix . At 5mm distance, the coarsening or merging of γ' precipitates is minimal. At 12 mm and 17 mm distance, there is well developed raft structure which is effect of directional coarsening of γ' precipitates due to long service exposures. Similar structure can also be found if the blade is operational beyond the recommended temperatures for longer time.

3 FRACTAL ANALYSES

For fractal based analysis of microstructural images obtained by SEM, rescaled range(R/S) [5,10] method has been used. The R/S fractal analysis method computes Hurst exponent [10] of any irregular surface features or images. The Hurst exponent, H is essentially the difference between the Topographic dimension, D_T and the fractal dimension, FD i.e. $H= D_T - FD+1$ since the range of H varies between 0 and 1. A completely random phenomenon is represented by H equal to 0.5. When $H>0.5$ the phenomenon is said to be persistent in nature. For $H<0.5$, the phenomenon is anti–persistent. In the context of microstructural images, the complex features produce anti-persistent behaviour and the fractal dimension is more than 2.5. For Ni based superalloy, the virgin microstructure would give higher fractal dimension compared to microstructure taken from service exposed samples.

To compute the fractal dimension FD from a microstructural image, it is necessary to define image based measurable quantities with respect to the scale of quantification so that the logarithmic correlation between the measured quantity and the scale, known as the Richardson plot [11], can be obtained. Some of the measurable quantities relevant to image are the power, energy or statistical parameters like range, standard deviation, average, variance or a composite statistical parameter like rescaled range, *etc.* The scales are frequency or wave number, level, box dimension, *etc.*

For one dimensional signal, $X(t)$, average deviation is computed for a segment of length, k, of the data series as $Y(t,k) = X(t,k) - \overline{X}$, t=1,2,3,4,…,$k$ where $\overline{X} = \frac{1}{k}\sum_{t=1}^{k} X(t)$. Range, $R(k)$, and standard deviation, $S(k)$, for the data segment, $Y(t,k)$ are given as

$$\left.\begin{aligned} R(k) &= Max\big(Y(t,k)\big) - Min\big(Y(t,k)\big) \\ S(k) &= \sqrt{\frac{1}{k}\left(\sum_{t=1}^{k}\big(X(t)-\overline{X}\big)^2\right)} \end{aligned}\right\} \tag{1}$$

The rescaled range of an irregular time series $X(k)$ can be defined as

$$\left.\begin{aligned} R/S(k) &= \frac{R(k)}{S(k)} \\ \langle R/S(k)\rangle &= C.k^{H} \end{aligned}\right\} \tag{2}$$

where $FD=D_T+1-H$. For one dimensional spatial or time series $D_T=1$ and for two dimensional image $D_T=2$. Equations (1) and (2) can be used for computing H from an image of (N x N) by dividing it into 4^L square segments where L is the level of segmentation and the segment length k is $N/2^L$.

4 RESULTS AND DISCUSSION

Fractal analyses of microstructures of samples from six blades at different time exposures and from five locations have been carried out. Figure 3 shows the variation of fractal dimensions with service exposures for samples taken from different locations of the blade. The higher fractal dimension (*FD*) corresponds to virgin microstructures at the blade root and the value of *FD* gradually decreases with the service exposure.

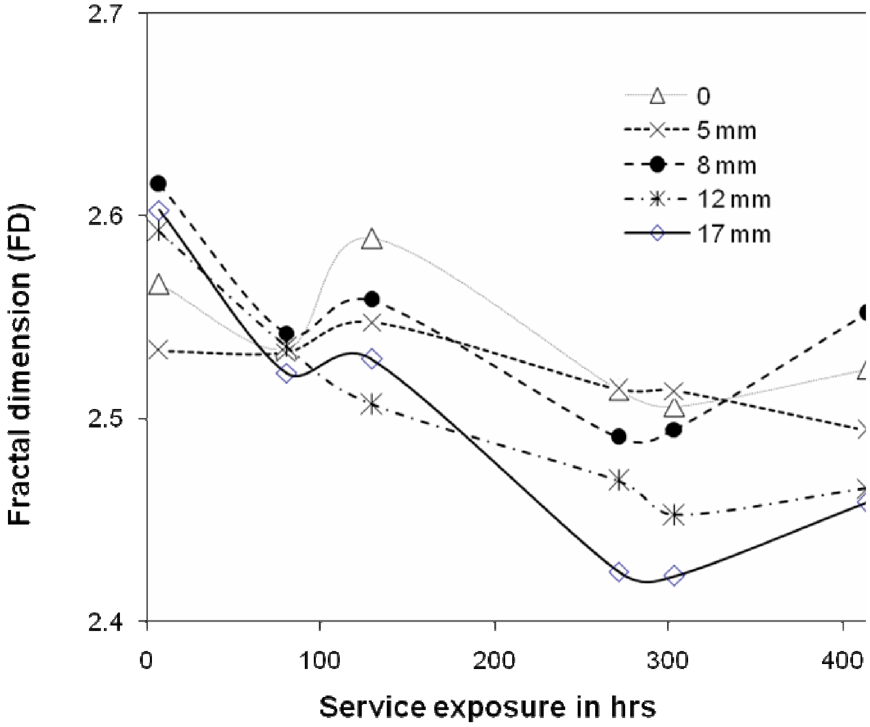

Figure 3: Variation of fractal dimension with service exposure

The variations of fractal dimension with service exposure show non linear trend, especially for the microstructure taken from the root and from 8 mm samples. This may be due to the highly stochastic nature of the microstructural images. Nevertheless, the linear fitting of the variation of fractal dimension is done to obtain the gradient (dFD/dT i.e change of fractal dimension with service exposure) for microstructures taken from different locations. Figure 4 shows the variation of fractal gradient with the spatial locations.

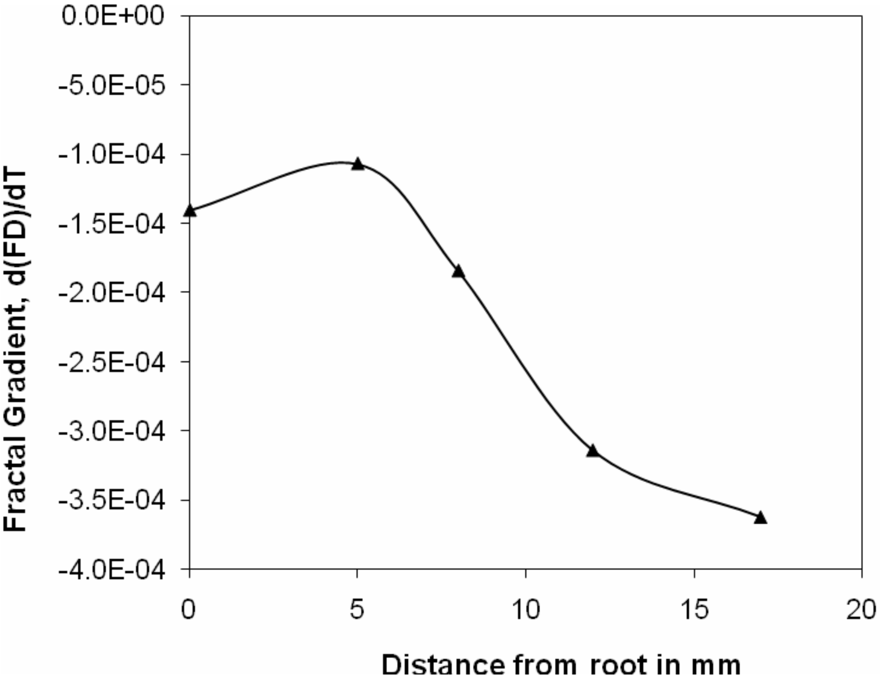

Figure 4: Variation of fractal gradient with the spatial location.

The fractal gradient is significantly high for microstructures corresponding to the regions beyond 8 mm from the blade root. Considering the fractal gradient as damage parameter due to service exposure, it can be noticed that till 5 mm, the damage is lower than the remaining section. It would be possible to correlate hardness variation with the distance and can be correlated with the fractal gradient to devise a health assessment protocol. The advantage of using fractal dimension is that the microstructural assessment is quantitative and the fractal gradient gives agreeable correlation with the qualitative results.

5 CONCLUSIONS

In this paper, a new methodology based on fractal mathematics has been reported for quantifying microstructure to determine the extent of damage in cast Ni based superalloy used in aero engine turbine blades. The extent of damage is found to be inversely proportional to the fractal dimension. The advantage of using fractal dimension is that the microstructural assessment is quantitative and it can be used as diagnostic tool for component health assessment.

6. REFERENCES

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