EVALUATION OF SERVICE INDUCED DAMAGE AND RESTORATION OF CAST TURBINE BLADES

C Persson and P-O Persson

FFV Materials Technology
P.O. Box 13200
S-580 13 LINKOPING
SWEDEN

Abstract

Conventionally cast turbine blades of Inconel 713 C, from a military gas turbine aircraft engine, have been investigated with regard to service induced microstructural damage and residual creep life time.

For cast turbine blades, service limits often are stated by general methods. General methods can prove to be uneconomical, as safe limits must be stated with regard to the statistical probability that some blades will have higher damage than normal. An alternative approach is to determine the service induced microstructural damage on each blade, or a representative number of blades, in order to better optimize blade usage.

Ways to use service induced γ' rafting and void formation as quantified microstructural damage parameters in a life time prediction model are suggested. The damage parameters were quantified, in blades with different service exposure levels, and correlated to remaining creep life evaluated from creep test specimens taken from different positions of serviced blades.

Results from tests with different rejuvenation treatments, including Hot Isostatic Pressing and/or heat treatment, are briefly discussed.

Superalloys 1992
Edited by S.D. Antolovich, R.W. Stusrud, R.A. MacKay,
D.L. Anton, T. Khan, R.D. Kissinger, D.L. Klarstrom
The Minerals, Metals & Materials Society, 1992

Introduction

Gas turbine blades are operated in very hostile conditions. Due to high temperatures, high loads and surrounding atmosphere, the service life is limited by mechanisms such as creep, thermal shock, fatigue, oxidation, sulphidation and erosion.

For cast turbine blades, service limits today often are stated by general methods. General methods can prove to be uneconomical, as safe limits must be stated with regard to the statistical probability that some blades will have higher damage than normal.

An alternative approach is to determine the service induced microstructural damage on each blade, or a representative number of blades, in order to better optimize blade usage. Procedures to evaluate residual life time by non destructive metallographic methods and to rejuvenate wrought turbine blades have been used successfully at FFV Materials Technology for more than 20 years, with substantial reductions in life cycle cost for engines.

The following presentation describes initial steps in an attempt to develop a similar procedure for life time prediction of cast turbine blades. Blades made of conventionally cast Inconel 713 C, from a military gas turbine aircraft engine, have been investigated with regard to service induced microstructural damage in different areas of the airfoil.

Based on some of the microstructural break down mechanisms identified, damage parameters have been quantified and correlated to remaining creep life. Results from tests with different rejuvenation treatments including HIP and/or heat treatment are briefly discussed.

Microstructural deterioration of service exposed blades

In service, the microstructure is affected by high temperature in combination with high load levels. However, the degree of deterioration in individual blades differs due to several factors, such as:

- total service time
- engine conditions (temperature, rpm etc)
- manufacturing differences (grain size, porosity, alloy composition etc)

By metallographical examination, different types of microstructural degradation were identified in the IN713C blades:

- Excessive precipitation of grain boundary carbides.
- Rafting of γ' particles.
- Void formation in grain boundaries due to creep.
- Precipitation of TCP-phases.
- Interaction of coating and base material.

Variations and severity of the degradation in different areas of the blade were mapped.

After a relatively moderate service exposure of approximately 600 hours, significant microstructural degradation was evident at the midheight of the airfoil near the trailing edge, while other areas of the blade were almost unaffected. With increased service exposure, the microstructural degradation is enhanced, spreading towards the leading edge. The formation of voids early in the service life implies that the main life limiting factor the the actual blade is creep.

Two breakdown mechanisms, i.e. void formation and the change in γ' shape, were focused on for further attempts to quantify damage parameters.

Evaluation of damage parameters

Change in γ' particle shape

Previous investigations on single-crystal superalloys (ref 1,2,3) have shown that if constant temperature and stress are applied, the γ' particles will become elongated. With increased time, they change into platelets (rafts) orientated perpendicular to the applied stress. After a certain time, the γ' elongation will reach an equilibrium state where no further elongation takes place. The time to reach the equilibrium state is stress and temperature dependent so that the time to maximum γ' raft length decreases with increased temperature and/or stress. The final equilibrium γ' raft length also differs depending on applied stress and temperature level.

For conventionally cast material with an equiaxed grain structure, the tendency for rafting differs between individual grains due to variations in crystal orientation to the main stress axis. Since the grains are randomly oriented the rafting effect will not be uniform.

Because of the variation in crystal orientation, quantitative evaluation of γ' elongation has to be based on a very large number of γ' particles, which is not effectively done by manual methods. For that reason an evaluation by means of Image Analysis is necessary.

For the In 713C blade the γ' elongation was quantified by measuring the length/width ratio (called R-ratio) for approximately 10,000 γ' particles. Each particle is measured in an elliptic projection of D max (length) and D min (width). The average is calculated by the computerized Image Analysis System (ref 4).

Micro sections cut from the trailing edge position from a total of 35 serviced blades, and 4 virgin blades for reference, were evaluated with regard to average R-ratio. The result is given in the graph in figure 1, where the service exposure is given as the service severity factor (ssf). The service severity factor is based on individual engine history and evaluated from total service time, turbine temperature, rpm loading etc.

Examined blades within figure 1 originate from nine engines operated in normal service and one engine from an Accelerated Mission Test (AMT). For the AMT engine the actual ssf value is not known, but it is considerably higher compared to engines from normal service.

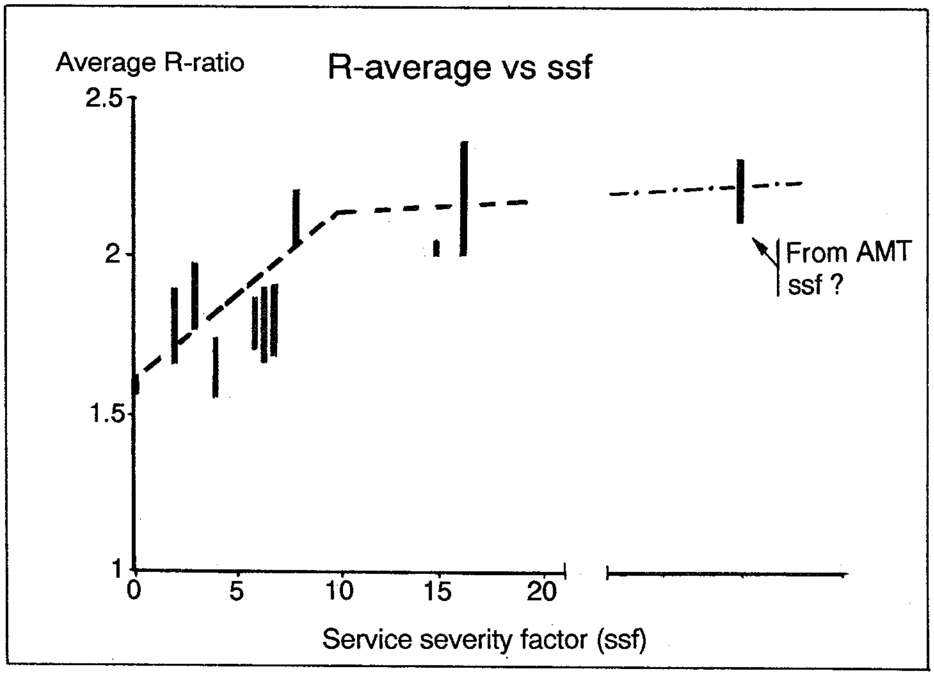


Figure 1: Average R-ratio measured at trailing edge vs service severity factor (SSF).

Evaluation by elliptic projection gives an average R-ratio of approximately R - 1.5 for virgin blades. Up to a service severity factor 8-10 (equals approx. 600-800 service hours for average engines), the γ' elongation increases to a R-ratio of approximately R=2.2. Higher ssf gives no further increase in average R-ratio. This indicates that the equilibrium γ' raft level is reached, within approximately 700 service hours under the conditions, regarding stress and temperature, prevailing at the trailing edge.

At equal service exposure levels a relatively broad scatter in R-ratio is evident in figure 1, indicating differences in stress and temperature exposure for individual engines and blades during service. Scatter in R-calculation as well as batch dependence probably also influences the R-ratio scatter at constant service exposure levels.

The trend found in figure 1 makes it clear, that using the R-ratio, measured at the trailing edge, as a tool for life time prediction has little relevance, as the equilibrium R-ratio level is reached at a service exposure where approximately 50-70% of the creep rupture life (see section below on Remaining creep life) of the blade still remains. For this reason, further investigations were initiated to evaluate the R-ratio in other areas of the blade, i.e. middle and leading edge position. In order to attain a better resolution of obtained data the fraction of γ' particles with R-ratio $\geq$ 2.0 was calculated. In figure 2 this parameter is plotted vs increased service exposure (ssf) for trailing edge, middle and leading edge positions of a few serviced blades.

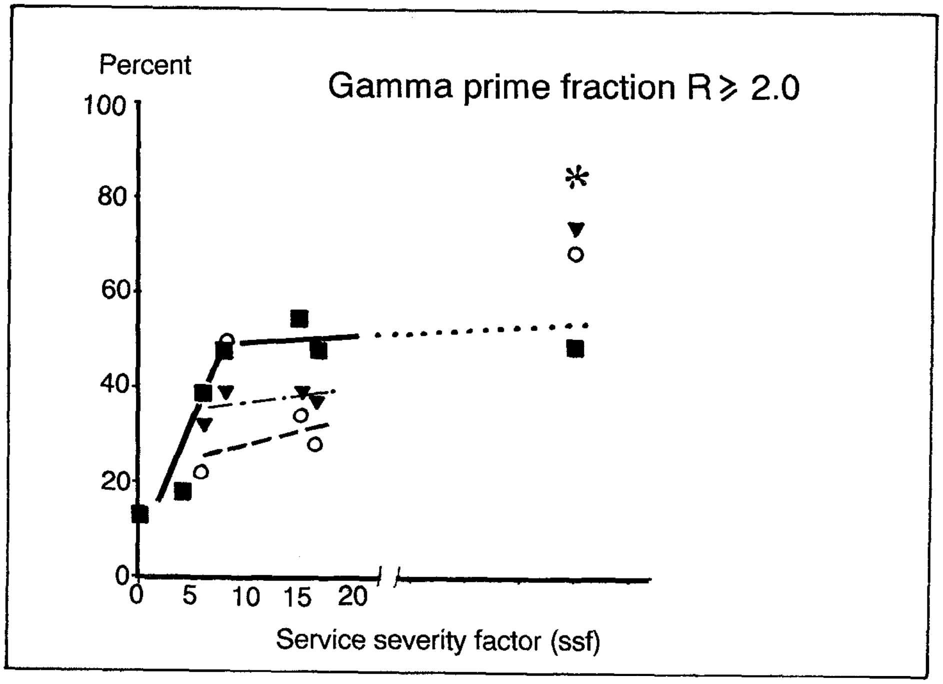


Figure 2: Fraction of γ' particles with R-ratio $\geq$ 2 vs SSF. Measure at
Trailing edge   Mid position
Leading edge   Creep test (160 MPa)

The graph representing the trailing edge measurements shows the same trend revealed in figure 1, reaching an equilibrium γ' raft level at relatively moderate service exposure.

However, the middle and leading edge positions show a slower increase in γ' elongation at low and intermediate ssf. The AMT blades with considerably higher ssf also indicate a higher equilibrium level for the γ' elongation at leading edge and middle position. The fraction of highly elongated γ' particles also approaches values earlier measured in creep tests after fracture (in figure 2).

The higher γ' raft values at the middle and leading edge positions imply a different combination of stress and temperature in those areas compared to the trailing edge. The results are based on very few data and more data should be evaluated to estimate the significance. However the data suggest the possibility of establishing a damage parameter based on γ' elongation which is better matched to the total blade life, than the R-ratio measured at the trailing edge.

Void formation

In blades, with approximately 600 hours of service, void formation due to creep appears at the trailing edge. The void formation occurred in grain boundaries perpendicular to the main stress axis.

In order to estimate the severity of the creep damage, a classification was carried out based on number of voids per area unit and average void size. The evaluation was done using a microscope on longitudinal trailing edge micro samples, according to the following void grades:

1. no voids
2. number of voids < 6, size < 8 μm
3. number of voids 5-12, size 8-25 μm

The results were correlated to total blade elongation, running time and average R-ratio, and are shown in figure 3.

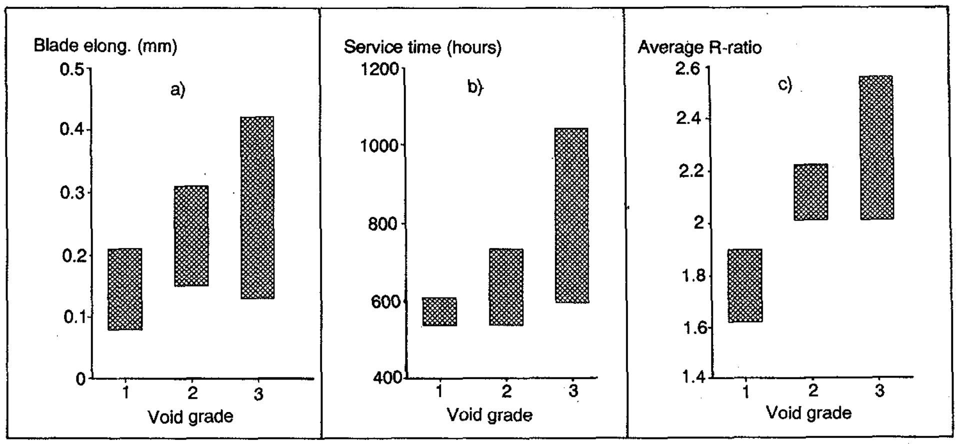


Figure 3: Correlation of void grade to Total blade elongation, service time and average R-ratio (trailing edge)

Generally, all of the correlated parameters increase with increasing void grade, although an extensive overlapping exists between the void grades.

Accumulated creep damage according to void grade 3 (worst) is represented by an interval in blade elongation of 0.13 to 0.42 mm and service times between 600 to 1040 hours. These results indicate that severe creep damage is evident at the trailing edge even at moderate blade elongations and service times.

Regarding γ' elongation, no void formation occurred at R-ratio levels below R=2.0. On the other hand, the R-ratio interval for void grade 2 is completely overlapped by grade 3, although grade 2 shows a lower average R-ratio level. This is consistent with the results presented in figure 1 and 2 and suggests that the equilibrium γ' raft level is not reached until the accumulated creep damage has increased to void grade 2.

Remaining creep life

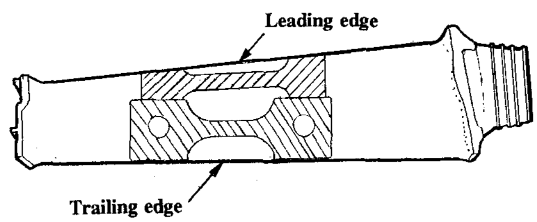
For the actual IN 713C blades, microstructural evaluation identified creep as the main life limiting mechanism. Creep testing of specimens from service exposed blades was carried out in order to correlate degree of damage and remaining creep life.

Creep testing

Specimens were taken from areas with a high degree of microstructural degradation near trailing edge, and from less affected areas near leading edge according to figure 4.

Twenty-one specimens from service exposed blades and (as reference) 6 specimens from virgin blades were tested. Due to variations in cross section over the blade profile, different specimen geometry had to be used for the two positions.

Figure 4: Location of creep specimens and test conditions.



Test conditions:

Axial load
Temperature: 900°C/Air
Stress: 160 MPa (Trailing edge specimens)
180 MPa (Leading edge specimens)

Residual creep life after service was compared to virgin creep life, and correlated to different degradation parameters quantified before creep testing, such as:

- blade elongation
- accumulated service time
- service severity factor
- γ' rafting
- void density

γ' rafting and void density were evaluated according to the procedures previously described. Total blade elongation was measured after service.

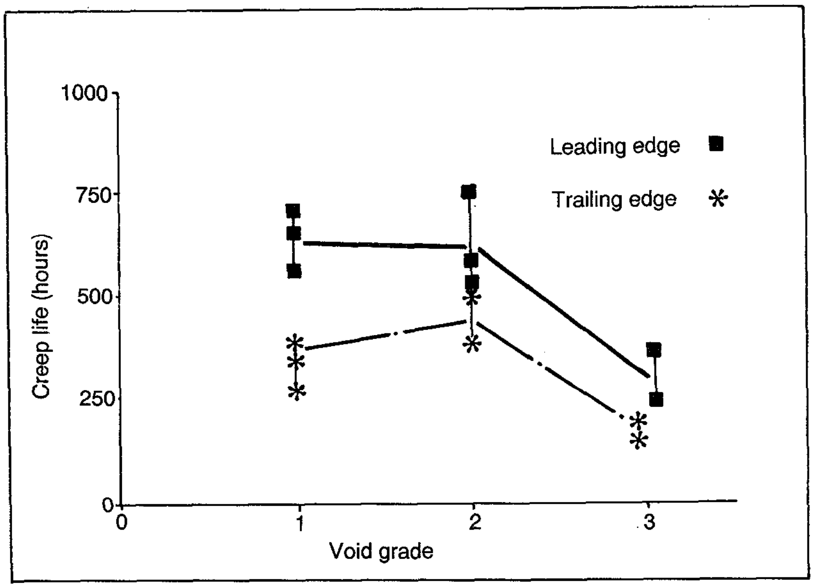
Results

At the trailing edge, where the microstructural deterioration develops early in service, the correlation to reduced residual creep life is more or less consistent for all the studied parameters, according to table I.

Average service severity factor(SSF)	Average service time (hours)	Total blade elongation (mm)	Average R-ratio	Residual creep life at trailing edge (hours)
0 (new blades)	-	-	1.6	505
6	565	0.15-0.31	1.62-2.0	405
8	736	0.25	2.20	351
15	616	0.40-0.42	2.01-2.05	223
16	1041	0.32-0.36	2.02-2.13	283

Table I: Residual creep life at trailing edge and damage parameters.

Residual creep life at trailing and leading edge positions has been evaluated based on void grade at the trailing edge and service severity factor, according to figure 5.



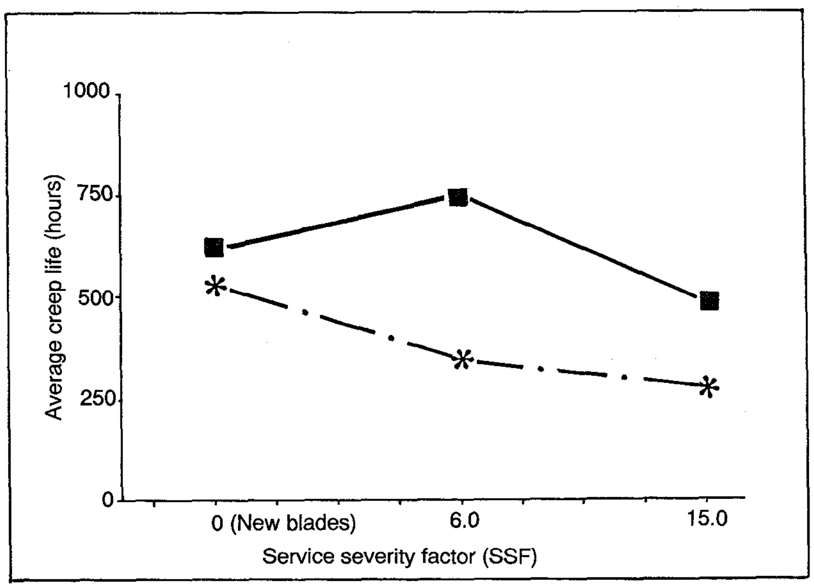


Figure 5: Comparison of residual creep life at trailing and leading edge vs void grade (above) and SSF (below)

At void grade 3 and high ssf, creep life is reduced to 55% at the trailing edge and to 74% at the leading edge, compared to virgin blades. At the trailing edge, a substantial reduction in residual creep life is evident even at intermediate ssf. This is because void grade 3 is represented among the tested specimens from intermediate ssf.

Rejuvenation treatments

Different rejuvenation treatments have previously been tested on cast specimens of IN 713 C (ref 4,5). Improvements in total creep life, for specimens pre-crept to 50% of nominal virgin creep life before rejuvenation treatment, were 75% to 107%.

The best process included Hot Isostatic Pressing (HIP) at 1180°C/105 MPa/2h followed by solution heat treatment and ageing.

Only fundamental conditions for a practical rejuvenation process have been evaluated:

*Renewed surface protection
*Blade geometry stability

Renewed surface protection is an important part of the rejuvenation process. The investigated IN 713 blades are protected against oxidation/corrosion by a conventional aluminized coating.

At overhaul, an overcoating process (without stripping) is often preferred for economical reasons and/or the fact that geometrical restrictions do not allow base material removal. When rejuvenation is applied on coated blades, the high temperature in the process will degrade the microstructural stability in the coating and at the coating base material interface.

Rejuvenation treatment with a subsequent overcoating was performed to evaluate geometrical changes and determine to what extent the coating can be restored.

The service induced blade elongation was restored up to 70% by the treatment. Only minor geometrical changes in the airfoil profile were found; most significant was the midheight of the airfoil in areas where the most severe microstructural deterioration was previously established.

The most significant effect on the coating during the rejuvenation process is the degradation of the diffusion zone. The typical needle-like phase (figure 6) transforms to a blocky Cr-rich phase (presumably $M_{23}C_6$). The same type of degeneration have been observed (ref 6,7) for similar types of aluminide coatings in high temperature ageing tests. The degeneration of the diffusion zone to blocky carbides is also reported to give negative effects on sulphidation resistance.

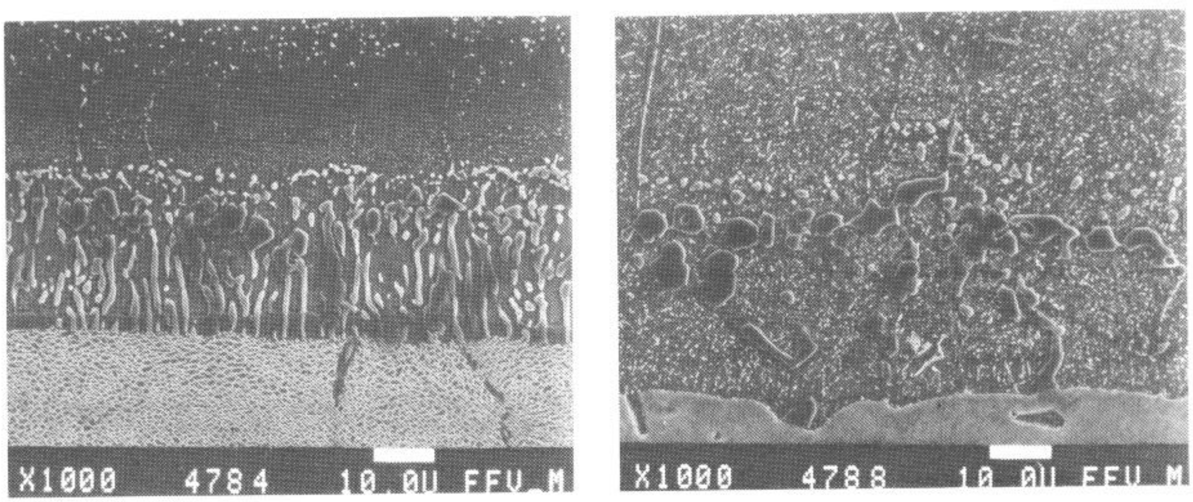


Figure 6: Normal coating diffusion zone (left) and degraded coating diffusion zone after rejuvenation treatment (right).

A subsequent over-coat process did not fully restore the coating microstructure. The blocky carbides, precipitated during the rejuvenation process still exist, although minor reprecipitation of the needle-like phase was observed in the diffusion zone.

Conclusions

The γ' elongation and void formation can be used as quantified microstructural damage parameters in a life time prediction model.

Remaining creep life of serviced blades, evaluated by creep testing can be correlated to several degradation parameters such as service time, a service severity factor (ssf), total blade elongation, γ' elongation and void formation.

General degradation parameters such as service time, the service severity factor and even total blade elongation must be used within very conservative limits, when correlated to blade life.

If general parameters are used together with quantified microstructural damage parameters, more cost effective and safe methods for practical life time prediction can be utilized.

By applying a rejuvenation treatment, including HIP and reheat treatment, the service induced blade elongation was restored up to 70%.

Acknowledgement

We thank the Swedish Defense Materials Administration for the financial support and the permission to publish this work.