

Evaluation of Service-Induced Damage and Restoration of Cast Turbine Blades

C. Persson and P.-O. Persson

Conventionally cast turbine blades of Inconel 713C, 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 life is defined by statistical values. The statistical methods can prove to be uneconomical, because 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, to better optimize blade usage. Ways to use service-induced γ' rafting and void formation as quantified microstructural damage parameters in a service lifetime 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 discussed briefly.

Keywords
IN 713 alloy, γ' precipitates, superalloys, cast turbine blades

1. Introduction

GAS turbine blades operate in very hostile conditions. Due to high temperatures, high loads, and the surrounding atmosphere, service life is limited by mechanisms such as creep, thermal shock, fatigue, oxidation, sulfidation, and erosion. For cast turbine blades, service lifetimes currently are defined statistically. These methods can prove to be uneconomical, because 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, to better optimize blade usage. Procedures to evaluate residual lifetime by nondestructive metallographic methods and to rejuvenate wrought turbine blades have been used successfully at Celsius Materialteknik for more than 20 years, with substantial reduction in life cycle cost for engines.

The following article describes initial steps in an attempt to develop a similar procedure for service lifetime prediction of cast turbine blades. Blades made of conventionally cast Inconel 713C (In 713C), from a military gas turbine aircraft engine, were investigated with regard to service-induced microstructural damage in different areas of the airfoil.

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

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2. Microstructural Deterioration of Service-Exposed Blades

In service, the microstructure is affected by high temperatures 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 IN 713C blades:

- Excessive precipitation of grain boundary carbides
- Rafting of γ' particles
- Void formation in grain boundaries due to creep
- Precipitation of brittle 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 h, significant microstructural change was evident at the midheight of the airfoil near the trailing edge, whereas other areas of the blade were almost unaffected. With increased service exposure, the microstructural degradation increased, spreading toward the leading edge. The formation of voids early in service life implies that the primary life-limiting factor for the actual blade is creep.

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

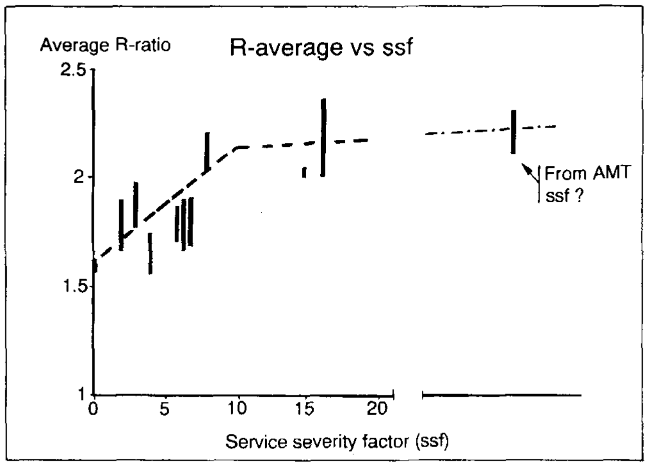


Fig. 1 Average R ratio measured at trailing edge versus service severity factor (ssf).

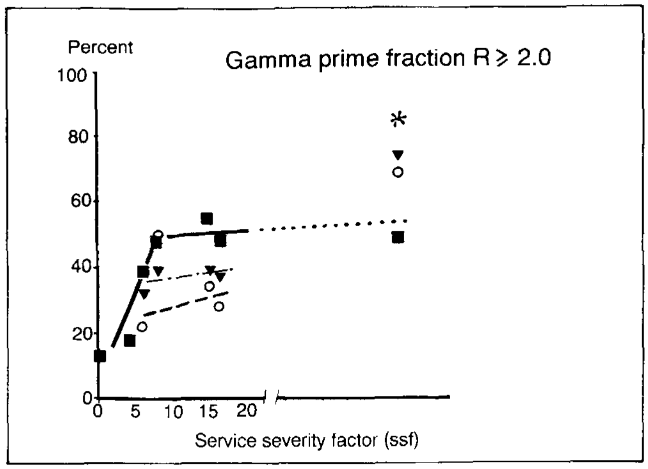


Fig. 2 Fraction of γ′ particles with R ratio ≥ 2 versus ssf. Measured at trailing edge (■); midposition (○); leading edge (▼); creep test at 160 MPa (✻).

3. Evaluation of Damage Parameters

3.1 *Change in γ′ Particle Shape*

Previous investigations on single-crystal superalloys[1-3] have shown that, if constant temperature and stress are applied, the γ′ particles will become elongated. With increased time, they change into platelets (rafts) oriented 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. Because the grains are randomly oriented, the rafting effect will not be uniform.

Because of the variation in crystal orientation, quantitative evaluation of γ′ elongation must be based on a very large number of γ′ particles, which cannot be done effectively by manual methods. For that reason, evaluation by means of image analysis is necessary.

For the IN 713C blade, the γ′ elongation was quantified by measuring the length/width ratio (R ratio) for approximately 10,000 γ′ particles. Each particle was measured in an elliptic projection of D_{max} (length) and D_{min} (width). The average was calculated using a computerized image analysis system.[4]

Microsections cut from the trailing edge position from a total of 35 serviced blades, and four virgin blades for reference, were evaluated with regard to average R ratio. The results are shown in Fig. 1, in which service exposure is given as the service severity factor (ssf). The service severity factor is based on individual engine history and is evaluated from total service time, turbine temperature, rpm loading, etc.

Examined blades within Fig. 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.

Evaluation by elliptic projection yields an average R ratio of approximately $R = 1.5$ for virgin blades. Up to a service severity factor of 8 to 10 (equals approximately 600 to 800 service hours for average engines), γ′ elongation increases to approximately $R = 2.2$. Higher ssf values provide 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 Fig. 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 Fig. 1 makes it clear that using the R ratio, measured at the trailing edge, as a tool for lifetime prediction has little relevance, because the equilibrium R ratio level is reached at a service exposure where approximately 50 to 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. To attain a better resolution of obtained data, the fraction of γ′ particles with R ratio ≥ 2.0 was calculated. In Fig. 2, this parameter is plotted versus increased service exposure (ssf) for trailing edge, middle, and leading edge positions of a few serviced blades.

Figure 2 illustrating the trailing edge measurements reveals the same trend as shown in Fig. 1, reaching an equilibrium γ′ raft level at relatively moderate service exposure.

However, the middle and leading edge positions exhibit a slower increase in γ′ elongation at low and intermediate ssf values. The AMT blades with considerably higher ssf values also exhibit a higher equilibrium level for γ′ elongation at the leading edge and middle position. The fraction of highly elon-

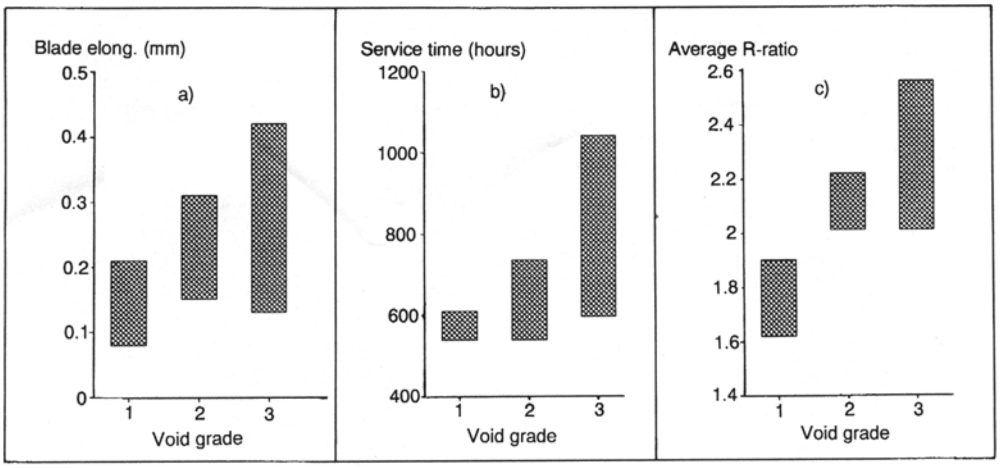


Fig. 3 Correlation of void grade to total blade elongation (left), service time (middle), and average R ratio at trailing edge (right).

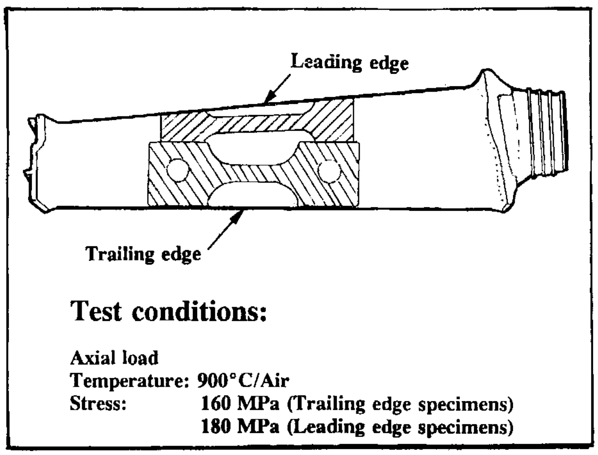


Fig. 4 Location of creep specimens and test conditions.

gated γ' particles also approaches values measured previously in creep tests after fracture (* in Fig. 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 points, 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 that is better matched to the total blade life than the R ratio measured at the trailing edge.

3.2 *Void Formation*

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

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

Void grade 1: no voids

Void grade 2: number of voids <6, size <8 μm

Void grade 3: number of voids 5 to 12, size 8 to 25 μm

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

Generally, all of the correlated parameters increase with increasing void grade, although extensive overlapping exists between the void grades. Accumulated creep damage according to void grade 3 (worst case) is represented by an interval in blade elongation of 0.13 to 0.42 mm and service times between 600 to 1040 h. These results indicate that severe creep damage is evident at the trailing edge even at moderate blade elongation 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 exhibits a lower average R ratio level. This is consistent with the results presented in Fig. 1 and 2 and suggests that the equilibrium γ' raft level is not reached until the accumulated creep damages have increased to void grade 2.

4. Remaining Creep Life

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

4.1 *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 Fig. 4. Twenty-one specimens from service exposed blades and (as reference) six

Table 1 Residual creep life at trailing edge and damage parameters

Average service severity factor, SSF	Average service time, h	Total blade elongation, mm	Average R ratio	Residual creep life at trailing edge, h
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

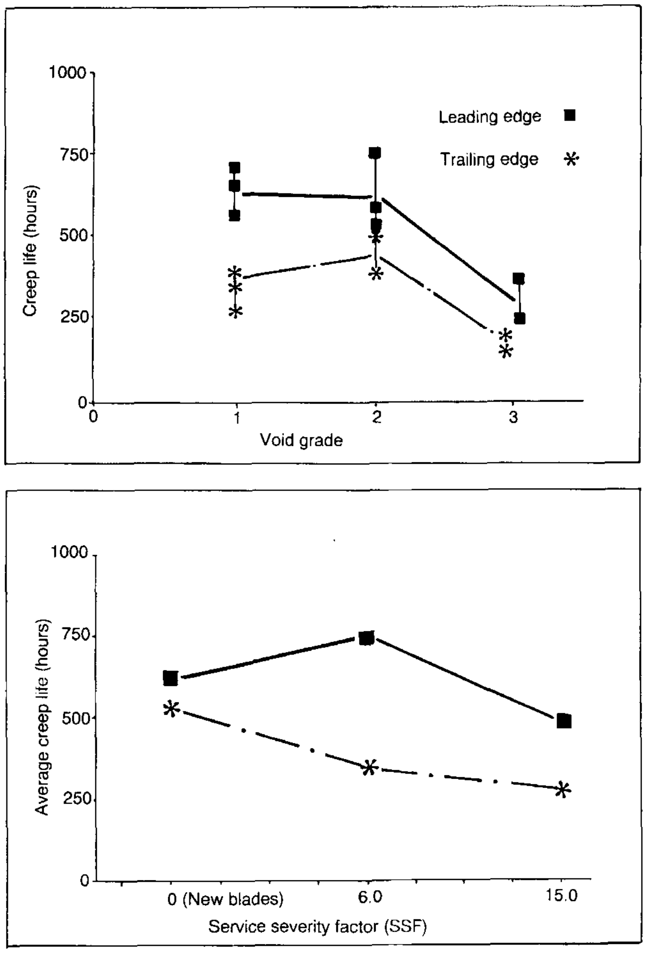


Fig. 5 Comparison of residual creep life at trailing and leading edge versus void grade (above) and ssf (below).

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. Residual creep life after service was compared to virgin creep life and was 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.

4.2 *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 1.

Residual creep life at the trailing and leading edge positions has been evaluated based on void grade at the trailing edge and service severity factor, according to Fig. 5. At void grade 3 and high ssf values, 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 values. This is because void grade 3 is represented among the tested specimens from intermediate ssf values.

5. Rejuvenation Treatments

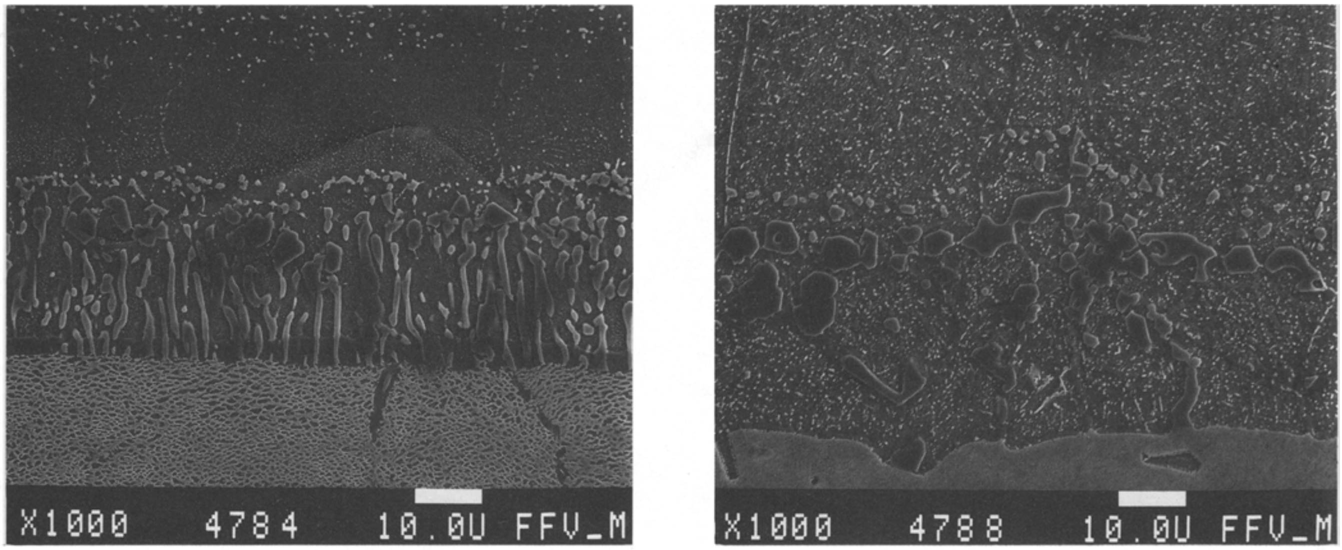
Different rejuvenation treatments have been tested previously on separately cast specimens of IN 713C.[4,5] Improvements in total creep life, for specimens pre crept to 50% of nominal virgin creep life before rejuvenation treatment, were 75 to 107%. The best process included hot isostatic pressing at 1180 °C, 105 MPa, 2 h followed by solution heat treatment and aging.

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 IN 713C blades investigated were 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 used in the process will degrade the microstructural stability of 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



(a) (b)

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

minor geometrical changes in the airfoil profile were found, the most significant was midheight in the airfoil in areas where the most severe microstructural deterioration was previously established.

The most significant effect on the coating during the rejuvenation process was the degradation of the diffusion zone. The normal and typical needle-like phase (Fig. 6) transforms to a blocky chromium-rich phase (presumably $M_{23}C_6$). The same type of degeneration has been observed[6,7] for similar types of aluminide coatings in high-temperature aging tests. The degeneration of the diffusion zone to blocky carbides is also reported to detrimentally affect sulfidation resistance.

A subsequent overcoat process did not fully restore the coating microstructure. The blocky carbides precipitated during the rejuvenation process still existed, although minor re-precipitation of the needle-like phase was observed in the diffusion zone.

6. Conclusions

By a scanning electron microscopy (SEM)/image analysis procedure, microstructural deterioration such as γ' elongation and void formation can be quantified and used in a lifetime prediction model. Reduction in residual creep life of serviced blades was evaluated by creep testing and correlating results to several degradation parameters such as service time, service severity factor (ssf), total blade elongation, γ' elongation, and void formation.

General degradation parameters such as service time, service severity factor, and total blade elongation must be used within very conservative limits, when correlated to blade life. If such 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 to blades, including HIP and reheat treatment, service blade elongation was restored up to 70%. Rejuvenation treatments tested on separately cast specimens indicate substantial increase in total creep life.

Acknowledgment

The authors would like to thank the Swedish Defence Materials Administration for the financial support and the permission to publish this work.

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