

PREDICTION OF THE KINETICS OF THE 3D STRESS-STRAIN STATE OF HIGH-TEMPERATURE GAS TURBINE BLADES WITH LIMITED EXPERIMENTAL DATA

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Annotation

This paper discusses the usage of several creep models in combination with ANSYS finite element analysis software to predict stress-strain state kinetics and to characterise the stress rupture of turbine components in the case of limited experimental creep data. The original numerical method is used to obtain creep information beyond the limits of the testing conditions. The predictions are compared with experimental results to demonstrate the effectiveness of the approach.

Introduction

The primary ways to increase engine efficiency include increases in working temperature as well as speed rotation and operating time. The turbine blades operate for extensive periods of time under heavy loads in conditions of non-uniform heating. The blade stress-strain state (SSS) changes over time due to the creep phenomenon. It is essential to use three-dimensional geometric models and the physically nonlinear properties of the material (including creep) for the reliable prediction of creep deformation and stress rupture in turbine components.

In reality, the thermo-stress state of turbine components extends far beyond creep test boundaries. Fig 1 shows the typical correlation between stress and temperature. A thermo-stress state was obtained using finite element analysis and is represented by black dots. The creep data for nickel-based alloy #1 have been established at 900°C (382, 480, 667 MPa) and 1000°C (176, 245, 372 MPa). The test condition boundaries

are shown as Zone C in fig. 1. Zones A and B refer to the most critical parts of the blade.

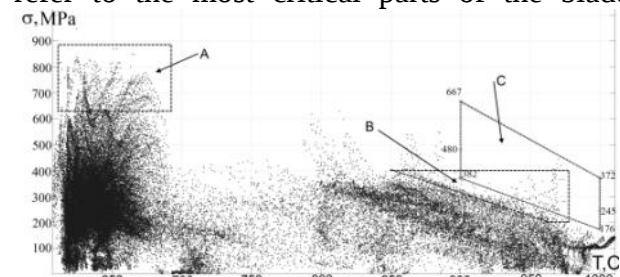


Fig.1. The typical thermo-stress state of a cooled blade

It is essential to establish creep properties over all ranges of temperatures stresses and durations of time. However, the availability of experimental data is very limited. Often, the results of only a few experiments are available.

When looking for material creep properties the designer or life management researcher is usually confronted with the dilemma of insufficient data. In the literature, there are many creep strain and creep rupture models for creep life and creep strain prediction [1]. However, in most cases, the data used for the models are not published and the resulting models require many (in some cases as many as 20 fitting parameters) to describe the creep response. In these cases, it is almost impossible to validate the models. This leads to potential errors in extrapolation. Though it is common sense to avoid using models where the range of data or the accuracy of the models is unknown, this approach may be the only one available.

This paper presents a method for obtaining creep information at all ranges of stress and temperatures using a limited amount of experimental data.

The validity of the calculation was determined by comparing experimental data to numerically defined results.

Several methods are used to determine SSS kinetics using original data, and creep data are used to predict creep deformation and the extent of damage to the turbine blade.

It is of considerable interest to be able to reliably predict and extrapolate creep behaviour from relatively small sets of supporting creep data.

Methods

Multiaxial stress states are encountered in the majority of structural components. To generalize from uniaxial to multiaxial creep data where multiaxial data do not exist, the author has used effective (Von Mises) stress, which is defined as follows:

$$\sigma = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

$$\varepsilon = \frac{1}{1 + \mu} \sqrt{\frac{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}{2}},$$

where, $\sigma_1, \sigma_2, \sigma_3, \varepsilon_1, \varepsilon_2, \varepsilon_3$ – principal stress and strain; μ – Poisson ratio.

Creep is the tendency of a solid material to move slowly or deform permanently under the influence of stresses.

According to Andrade, three stages can be considered in a typical creep curve: the first stage (primary or reduced creep), the second stage (secondary or stationary creep) and the third stage (tertiary or accelerated creep). During the primary creep stage, the creep rate decreases to a certain value (minimum creep rate $\dot{\varepsilon}_{cr}$). The secondary stage is characterized by the approximately constant creep rate. During the tertiary creep stage, the strain rate increases significantly. At the end of the tertiary stage, creep rupture of the specimen occurs at time moment τ_r .

The shape of the creep curve depends on material and test conditions and is determined by several competing reactions including:

1. Strain hardening;
2. Softening processes such as recovery, recrystallization, strain softening, and precipitate overaging;
3. Damaging processes, such as cavitation and cracking, and specimen necking.

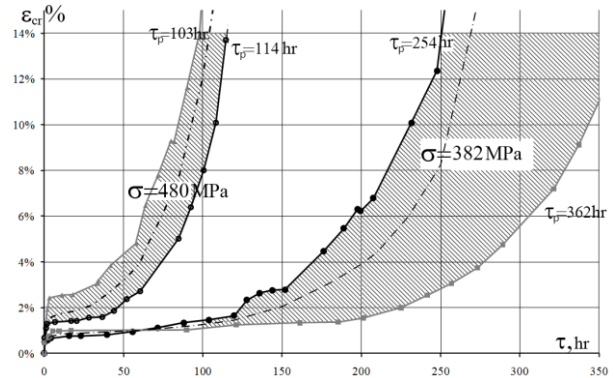


Fig. 2. Creep curves for alloy #1 at 900°C

The experimental creep data exhibit significant scatter. For example, fig. 2 shows that the difference in the time of strain accumulation (τ_r) for the same test conditions may differ by 1.5-2 fold.

In this regard, the use of the creep hypotheses and determination of the constants in the related equations based on a small number of specimens may not be accurate. It was difficult to detect a trend in the dispersion of the blade alloy data related to temperature or the duration of the operation. The scatter appears to be significantly reduced in the tertiary stage as compared to the primary and secondary stages of creep [2].

The creep data for experimental alloy #1 were averaged (dash-dot lines in Fig. 2).

Mathematical modelling of the experiments

The numerical determination of creep properties is based on the parametric model developed by Larson and Miller in 1952.

The Larson-Miller parameter (PLM) was selected for use in this study because it is traditionally the parameter used most widely to study creep [3]. PLM was used to combine test temperature and operation duration:

$$PLM = T \cdot (\log_{10}(\tau) + C)$$

where, T is absolute temperature (K), C is the Larson-Miller constant and τ is the loading time (hrs). Typically, the Larson-Miller constant value, (C) is 20 if the time is shown in hours.

Diagrams of the Larson-Miller parameter were made assuming that rupture and creep stress could be modelled similarly. One has to specify several selected experimentally determined values of creep deformation (e.g.,

0.1, 0.2, 0.5, 1, 2, 5%). The author suggests to use no less than 7-8 values.

Fig. 3 shows creep rupture and creep stress versus PLM values. The graph may take on a zigzag shape due to competing processes of failure.

The curves are extended to the high-temperature, equidistant creep rupture curve. It is believed [4, 5] that the processes of creep developed from the homologous temperature $\theta = T_{mat} / T_m$ above 0.3, where T_{mat} - the current temperature of the material and T_m - melting temperature of the alloy. Therefore, it is assumed that at temperatures below 450 °C and with brief time periods (<0.1 hours), all of the curves approach the creep rupture curve. The extrapolated curves are shown as dashed lines in Fig. 3.

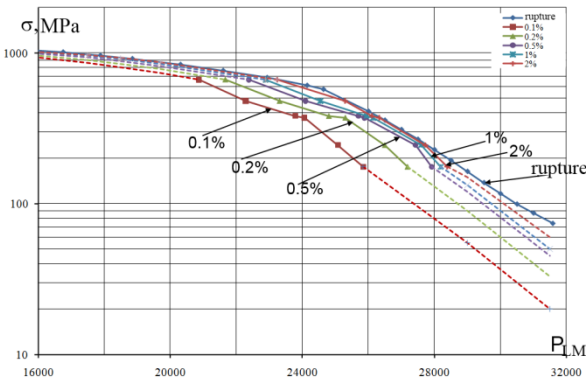


Fig. 3. Larson-Miller plot for alloy #1

One may obtain creep data at all ranges of turbine component stresses and temperatures using the proposed method.

The proposed method was used to obtain creep information for alloy #1 outside of test condition boundaries (650°C, 700°C и 800°C). Figures 4 and 5 show the creep curves obtained at 650° and 800°C. The solid lines represent data fit using the creep equations (see below).

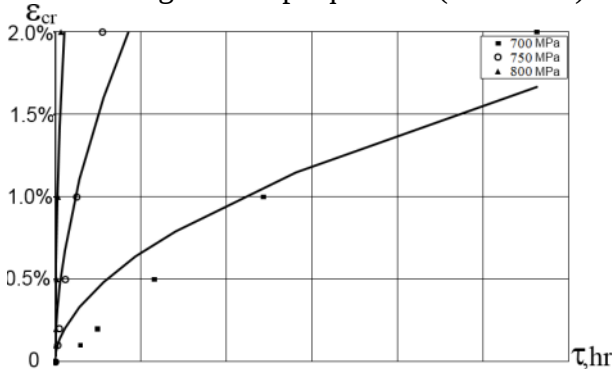


Fig. 4. Creep curves for alloy #1 at 650°C

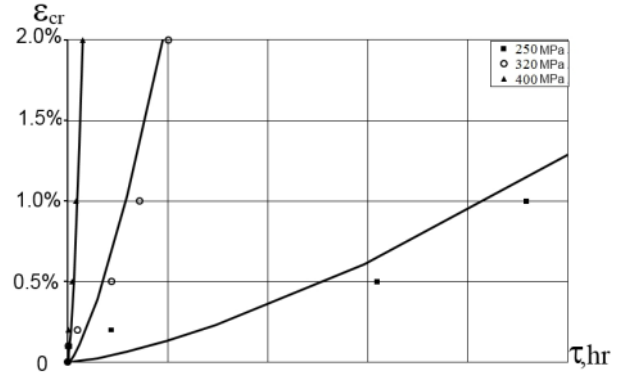


Fig. 5. Creep curve for alloy #1 at 800°C

Verification

Verification of the proposed method consists in obtaining creep properties for each experimental regimen.

For example: the creep resistance of specimens of alloy # 2 was tested at 750, 850, and 950°C.

Larson-Miller diagrams were created according to the requested method using experimental data obtained at 750 and 950°C (Fig. 6, 7). The 850°C creep data were excluded from consideration. (Dashed lines in fig. 8 show the stress values at 850 °C).

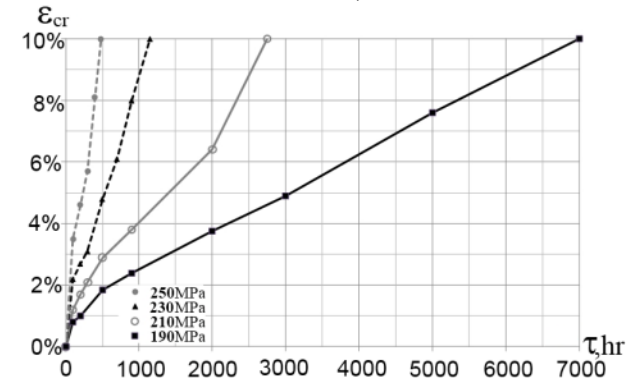


Fig. 6. Creep curves for alloy #2 at 900°C

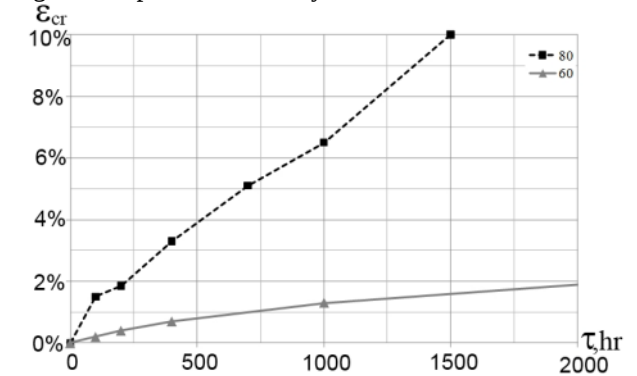


Fig. 7. Creep curves for alloy #2 at 1000°C

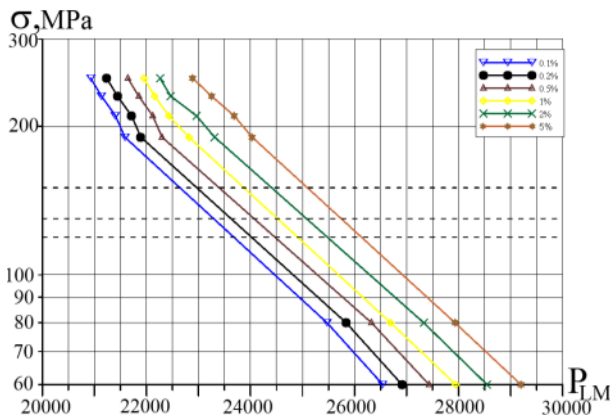


Fig. 8. Larson-Miller plot for alloy #2

Then creep data were obtained for a temperature of 850° C, using the proposed method. For the sake of comparison, original test data (markers) and experimental data (solid lines) are shown in fig. 9.

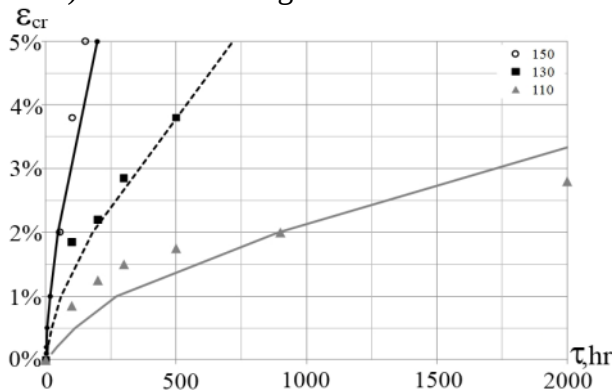


Fig. 9. Creep curve for alloy #2

The theoretical and actual values are similar. This method was tested on a long list of alloys for interpolation. In the future, similar experiments will be performed at low temperatures.

Note that caution and engineering expertise are necessary when using this approach.

Determination of the SSS kinetics of turbine parts

ANSYS provides several approaches with which to model the creep deformation of materials under constant loads and temperatures:

- isochronic curves
- creep equations that determine characteristics such as strain (ϵ_{cr}) or the creep rate $\dot{\epsilon}_{cr}$, depending on the stress, loading time and temperature
- a user-specific creep model

Isochronic curves

The method of determining the SSS kinetics using isochronic curves is based on the similarity of the tensile and isochronic creep curves at constant temperatures ($T = \text{const}$) and loading times [6, 7].

A series of isochronic curves (Fig. 10) reflects the stress σ dependence of the total strain ϵ_{tot} , for several values of time ($\tau = \text{const}$ for each curve at a given temperature).

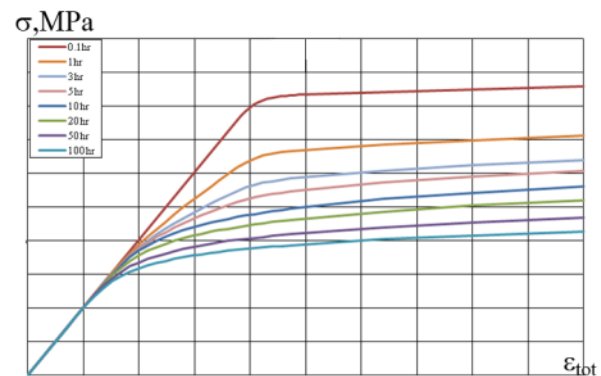


Fig. 10. Isochronic curves

The upper curve in fig. 10 is a tensile curve; others represent the relationship between stress and total deformation, including accumulated deformation, for different loading times.

In the calculations using isochronic curves, accumulated strain is plastic strain. Due to the fact that this method applies to the hypothesis of aging [6], it cannot accurately describe step loading.

Creep equations

Many classical creep laws developed by Norton, Garofalo, and Blackburn, among others, are implemented in commercially available finite element (FE) software such as ANSYS.

ANSYS provides 13 creep equations for use with implicit creep. These range from the simple Norton law to the hyperbolic sine form.

The classical analysis approach is to calculate creep and plastic deformations separately. Plasticity laws are based on Tresca or Von Mises stresses and use a flow rule to model incremental plastic strains. Similarly, incremental creep strains are calculated based on effective (Von Mises) stress.

ANSYS solves the creep problem by using two time integration schemes. Both methods are applicable to the calculation of static or transient processes. The implicit creep method is stable, fast, accurate and is recommended for general use. It can use the constants that depend on temperature and time combined with a model of plasticity with isotropic hardening.

The specific creep hypothesis used in order to calculate the SSS kinetics of turbine parts that work under constant loads has no significant effect on the result [6].

In this paper, creep equation # 6 (according to the ANSYS library) [8] is used:

$$\varepsilon_{cr} = \frac{C_1 \cdot \sigma^{C_2} \cdot \tau^{C_3+1} \cdot e^{\frac{-C_4}{T}}}{C_3 + 1} \quad (1)$$

where, ε_{cr} – creep strain, σ (MPa) – Mises stress, T (K) – temperature, τ (hour) – loading time, C_1 - C_4 - unknown coefficient, depending on the material.

As a first step, the value of the coefficient C_4 is taken to be zero for all temperatures in order to ease the problem of approximation. The set of coefficients C_1 - C_3 is defined for each temperature separately.

The least squares method is used to fit the experimental data to the equation selected. The author used a special module of ANSYS FEA software (curve fitting) to this end.

Notably, the creep process is accelerated and far more detrimental at elevated temperatures, because the additional thermal energy activates different mechanisms for creep. The Arrhenius law [5] is typically used to express the thermally activated creep rate

$$\dot{\varepsilon}_{cr} \sim \exp\left(-\frac{Q}{RT}\right), \quad (2)$$

where, Q is the activation energy, T is the absolute temperature and R is the gas constant.

According to (2), strain and creep rate at constant loads are proportional to $\exp(-T^{-1})$.

Because the values of the coefficients for the intermediate temperature range are determined by ANSYS using linear interpolation, it is necessary to check the level of significance (2) for all stresses and durations of time.

As a second step, successive iterations yield C_4 values. As the third step, a comparison of numerical and experimental creep curves is implemented. Figures 4 and 5 show solid lines that correspond to the results obtained using equation (1) and using the calculated coefficients. Very often, accurate and adequate approximations are impossible at all levels of stress, strain and operation duration. The ideal approximation is that most closely related to the curves with characteristics similar to those of the critical zones of the turbine components.

User-specific creep models

Despite the wealth of capabilities available on ANSYS to calculate SSS kinetics, one may wish to incorporate one's own creep law into ANSYS.

Equations are applicable under specific regimes of creep deformation (such as primary and/or secondary). This limits their applicability in situations where all three stages of creep (primary, secondary and tertiary) have to be modelled to accurately predict the response of a component. The adequate approximation of experimental data in all working ranges is extremely difficult and sometimes impossible. The isochronic curves method is not suitable for step loading.

A creep model that provides an analyst with the ability to predict creep deformation and stress relaxation using original creep data and allows for the selection of a creep hypothesis is ideally suited to predict the performance of turbine components. Ideally, the creep rupture data should be correlated at all temperatures.

The implementation of a user creep model involves the calculation of incremental creep strain $\Delta\varepsilon_{cr}$ and two additional parameters that are used in calculating the tangent stiffness matrix [8, 9, 10]. These parameters represent the sensitivity of calculated incremental creep strain to applied stress $d(\Delta\varepsilon_{cr})/d(\sigma)$ and the current value of creep strain $d(\Delta\varepsilon_{cr})/d(\varepsilon)$. The incremental creep strains as well as the other two parameters are calculated at element integration points and then entered back in to the main program.

Calculation method of incremental creep strain using Larson-Miller parameter (fig. 3, 8)

is proposed. It is possible to decide which creep hypothesis to use (strain or time hardening).

State variables were used to store creep damage and other calculated variables such as remaining life, which are not normally stored by ANSYS in the results database.

Creep analysis of turbine blades

Turbine blades showing stress rupture failure in the shroud during the 115-hour experiment were analysed to demonstrate the effectiveness of the 3D creep calculations. The experiment was carried out by Aviadvigatel OJSC specialists [11]. The experimental results were provided to the author for study.

The blade was modelled for analysis along with disk sectors using quadratic hexahedral and tetrahedral 18-x series elements. Contact elements were used for modelling blade and disk interaction and shroud tightness.

Appropriate linear and nonlinear (plastic) properties were used in the analysis. Plasticity was modelled using multi-linear isotropic hardening. A non-linear geometry option (NLGEOM) was turned on during analysis.

This blade was made from a single crystal alloy. Material properties were evaluated using test data in the <001> direction. Because the direction of centrifugal load in the airfoil coincides with the primary crystal axis, it was assumed that the <001> creep model and stress vs. strain curves were adequate for this analysis.

Fig. 11 shows temperature distribution along the blade.

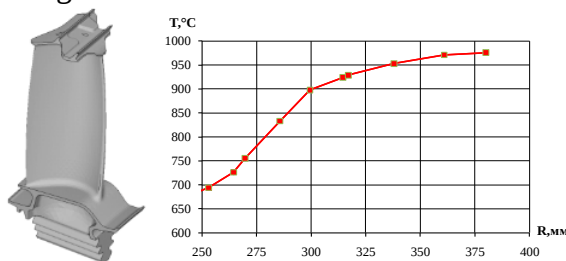


Fig. 11. Blade model and temperature distribution along the blade.

Several methods described above were used to determine SSS kinetics: isochronic curves (# 1), the creep equation (# 2), and a user-specific creep model (#3).

Linear damage summation based on Robinson's life fraction rule was used in these

analyses. Equivalent stress [7] is used for damage determination, which is defined as follows:

$$\sigma_m = \sqrt[m]{\frac{1}{\tau_\Sigma} \int_0^{\tau_\Sigma} [\sigma(\tau)]^m d\tau}$$

where, $m(T)$ – creep rupture exponent, τ – time, τ_Σ – duration of loading.

Creep damage is calculated using equivalent stress:

$$D_\tau = \tau_\Sigma / \tau_{rup},$$

where τ_{rup} – time to rupture with stress σ_m .

Damage is assumed to be zero when the material is new and is equal to one at the point of local stress rupture failure.

Results

The experiment was interrupted every 15-20 hours for the measurement and severity estimates and was stopped after 115 hours due to extensive deformation of the shroud.

The analyses were stopped at 100 hours because the solution time steps in calculations 2 and 3 became very small.

Every node was examined in order to locate the critical parts. Fig. 12 shows the stress distribution and zones of interest. Fig. 13, 14, 15 show typical curves of stress relaxation, strain and damage accumulation at critical location #3.

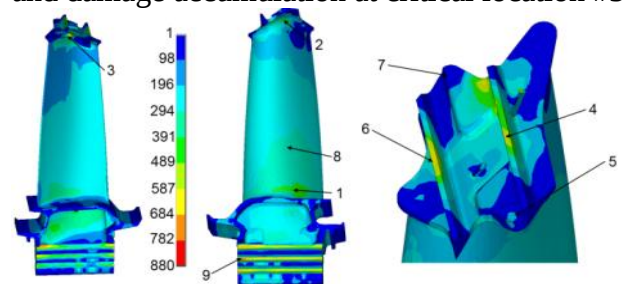


Fig. 12. Von Mises stress distribution

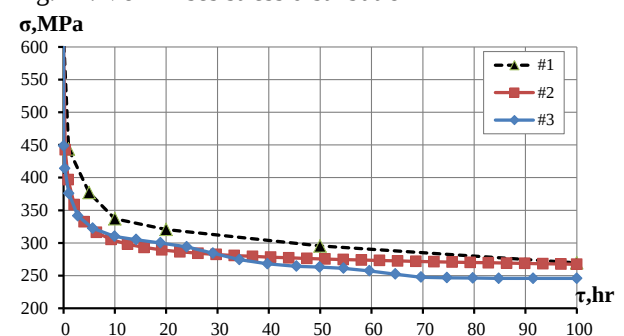


Fig.13. Stress relaxation curve. Point # 3

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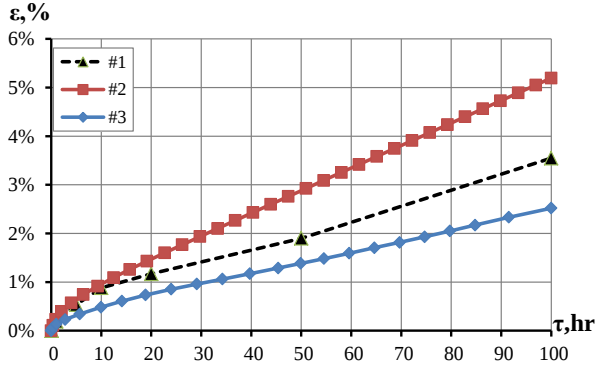


Fig. 14. Creep strain accumulation curve. Point #3

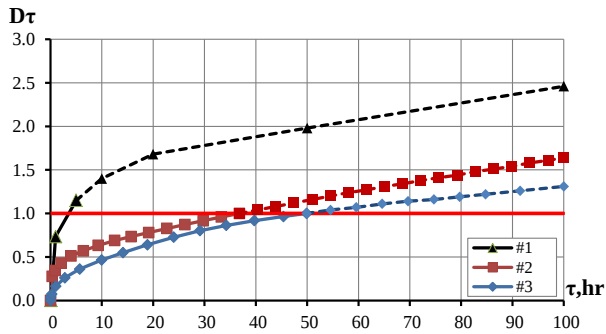


Fig. 15. Damage accumulation curve. Point #3

The analysis of calculation results # 1,2,3 indicated that SSS kinetics behaviour was similar in each case.

As expected, stress relaxes with time and ultimately reaches a somewhat steady-state condition. Creep damage increases rapidly at the beginning of the test but slows gradually towards the end (due to reduced stresses).

Table #1 shows the several important calculation results, such as: elastic-plastic stress (σ_0), accumulated strain (ε_{ac}) and damage (D_τ). With regard to comparison, the D_τ^{**}/D_τ ratio is provided for every calculation, where D_τ and D_τ^{**} represent accumulated damage with and without any consideration of creep phenomena.

Table 1. Calculation results.

Zone #	2	3	4	6	8	9
$T, ^\circ\text{C}$	975	975	976	975	931	726
σ_0, MPa	501	603	526	585	324	855
$D_\tau(1)$	>1	>1	0.52	0.78	0.27	0.34
$D_\tau(2)$	~1	>1	0.29	0.43	0.23	0.39
$D_\tau(3)$	>1	>1	0.27	0.30	0.23	0.33
$\varepsilon_{ac}, \% (1)$	1.98	3.55	2.35	3.74	0.38	0.29
$\varepsilon_{ac}, \% (2)$	2.95	5.19	3.38	5.44	0.42	0.24
$\varepsilon_{ac}, \% (3)$	2.52	4.50	3.02	4.70	0.48	0.31
$D_\tau^{**}/D_\tau(1)$	48	132	36	62	2	293
$D_\tau^{**}/D_\tau(1)$	63	239	69	119	2	750
$D_\tau^{**}/D_\tau(1)$	54	300	74	172	2	295

* A multiplying coefficient (1.3) was used for points 4 and 6 because of the prevailing compressive stress.

Table 1 shows that the most critical parts were: point #3 –at the fillet on the shroud, point #2 – at the fillet between the shroud and airfoil, and point #9 - at a fir tree.

Discussion

Numerically defined and experimental results were compared. The location of maximum creep damage is at the shroud fillet (zone 3), where the 12 blades had failed after 45 work hours; 20 failed after 59 hours. Predicted service life was 4, 37, and 50 hours for calculations #1, 2 and 3, accordingly.

The shroud deformation observed at the end of analyses matched with the actual deformed shape very well. The experimental values of deformation at points 5 and 7 after 100 hours of work were 0.43 and 0.53 mm, respectively. The numerically defined values were: 0.33 and 0.52 (calculation #1), 0.46 and 0.58 (calculation #2), 0.42 and 0.55 (calculation #3).

The accumulated damage at the fillet between the shroud and airfoil (Zone # 2) was graded as about 1. Significant residual deformation of the shroud was detected, which may have represented the beginning of a failure process.

The accumulated damage at most critical blade foil locations was graded as 0.27 or less. No defect was detected after the experiment.

A multiplying coefficient of 1.3 was used for damage determination at points 4 and 6 because of the prevailing compressive stress. Because no defects were found in these zones, the approach is considered to be reliable.

Very often, SSS kinetics at turbine component zones with relatively low temperatures ($<750^\circ\text{C}$) are not calculated due to a lack of creep data. That can lead to an underestimation of the estimated service life. Considering creep phenomena at location #9 with temperatures about 700°C allows the extent of the damage accumulated to be predicted more accurately. The D_τ^{**}/D_τ ratio for

every calculation method was more than 290. The effectiveness of the proposed method was therefore demonstrated convincingly.

The various calculations ultimately yielded similar results. Because the user-specific creep model provides results that are closer to experimental data and due to the ease of preparing creep data it is advisable to use proposed method. Further research on evaluation of model parameters in other crystal directions will be necessary to predict failure of the blade at the platform or shroud more accurately.

Conclusion

The results obtained in this study demonstrate that 3D creep and stress rupture analyses of turbine components are feasible, and that the proposed methods can be used for a wide range of stresses, temperatures and durations of time during the development phase, and validate final designs.

Acknowledgements

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