Reference-No.: ICF10059OR

FATIGUE BEHAVIOUR OF A SINGLE CRYSTALL NICKEL SUPERALLOY USED IN HEAVY-DUTY GAS TURBINE BLADES WITH FILM COOLING

Y. Pan, R. Zimmer, B. Bischoff-Beiermann and D. Goldschmidt

Siemens AG Power Generation Group (KWU)
Mulheim, Germany

ABSTRACT

The low cycle fatigue property of a single crystal (SC) superalloy applied in heave-duty gas turbine blades with film cooling holes has been investigated. Special material tests have been carried out for evaluation of the crack behavior. This paper presents results of the testing and appropriate finite element (FE-) calculations. Advantages of SC blades can be revealed and a reliable fatigue life assessment can be achieved with the local approach concept.

KEYWORDS

Single Crystal Superalloy, High Temperature Low Cycle Fatigue, Heavy-Duty Gas Turbine, Film Cooling Hole, Crack Behaviour, FE-Calculation, Life Assessment

INTRODUCTION

A new generation of heavy-duty gas turbines with substantially increased output and efficiency has been developed by Siemens [1]. One of the important new technologies applied in this gas turbine, that is well proven in aircraft engines, is the application of single crystal turbine blades with an extensive film cooling.

The high temperature mechanical properties of superalloys are strongly dependent on the volume fraction and morphology of γ'-precipitation. In the investigated single crystal superalloy PWA 1483 there is a lower content of grain boundary strengthening elements compared with conventional cast superalloys, [2-3]. This causes a higher alloy melting point and permits a higher solution heat treatment temperature. Therefore a higher volume fraction of the γ'-precipitation's with proper morphology can be achieved. This is one of the important reasons for the better mechanical properties of PWA1483 blades.

The Laser-Drilling will be widely used in manufacturing of these cooling holes, as a precise hole pattern with exact relative positions can be thereby efficiently produced. However, micro cracks could, especially in a remelt-layer around of the internal hole surface, come into existence. The depth of these cracks must be within the manufacture tolerance.

The first-stage blading is illustrated in Fig. 1. As shown, a large number of cooling holes has been manufactured into the surface of blades and vanes, where cooling air will be discharged.

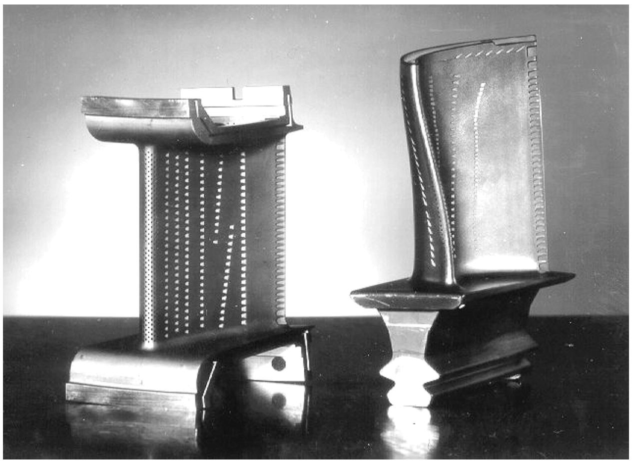


Figure 1: Blade and vane stage 1 with film cooling holes

The first stage turbine blades operate at high gas temperatures. There is a pronounced temperature gradient between outside and inside of blade walls due to an indispensable intensive cooling. This temperature difference will cause high thermal stresses. Additionally, the centrifugal force has also to be considered for the blade design.

The life prediction procedure for components with stress concentration can be carried out using the local approach concept, [4-5]. The applied material design curve is usually determined with standard cylindrical smooth samples under consideration of materials data scatter. However, for a reliable life prediction, not only the maximum local stress and strain is to be determined by elastic-plastic FE-calculations. Inhomogeneous stress states, manufacturing processes and surface quality should also be taken into account. In order to verify the local approach concept and to insure the long-term operational reliability of the SC blades in land based gas turbines for power generation, special LCF test specimen with holes on the gauge length has been used to determinate the life time and to investigate the crack behaviour under fatigue loading close to the operation conditions.

EXPERIMENTAL DETAILS

Fig. 2 shows the shape of the LCF-specimen. Holes were drilled by laser using the same tolerances and operating parameters as in blade manufacturing. The thickness of the specimens was similar to the wall of the blades.

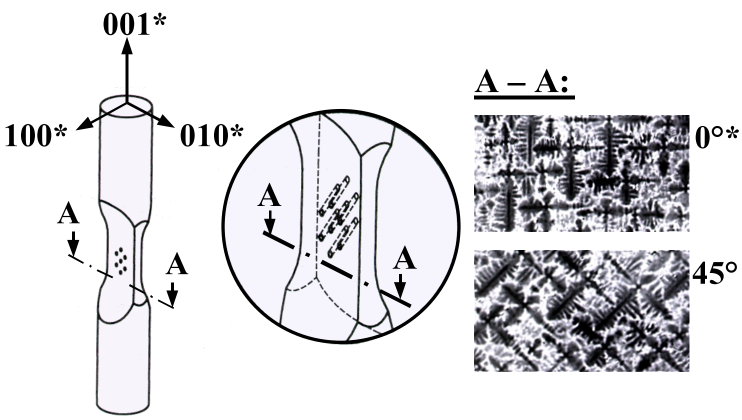


Figure 2: Special LCF test specimen with illustration of secondary orientation of 0° and 45°

The holes had a pattern with hole density, diameter and angel to surface as found in the leading edge, where a „shower head“ cooling is applied, giving the highest cooling hole density. Comparative specimens without holes had the same shape. To investigate the influence of different secondary orientations on the fatigue life some specimens were drilled with 45° secondary orientation in the planar gauge length (see Fig. 2).

The LCF tests were performed on a servohydraulic test machine with inductive heating under total strain control. The integral strain on the gauge length of the sample was taken as the control signal. The SC-Ni-basis superalloy PWA 1483 was investigated at temperatures of 900°C and 700°C, which are typical temperatures for material close to the outer and inner surfaces of the first stage blade.

The loading during gas turbine operation is predominately controlled by thermal strain. This results in compressive strains at the hot outer surface and tensile strains at the colder inner surface. Therefore the strain ratio $R=\varepsilon_{min}/\varepsilon_{max}$ was equal $-\infty$ for 900°C test temperature and equal 0 for 700°C test temperature.

A camera system was used to continuously observe the surface of the specimens during the fatigue tests. It was composed of two CCD-Cameras with specially developed control programs so that the crack initiation and propagation could be recorded automatically by computer.

After tests, an evaluation was made for crack behaviour relating to the hole pattern and to micro-cracks. The failure cycles N_f were defined as the cycle number after which a drop of the stress amplitude of more than 5% was found.

RESULTS AND DISCUSSIONS

Fatigue Test Results

Fig. 3 shows the LCF-life *in form of* the S-N-curves based on the integral strain range for specimens at 900°C and 700°C test temperature. Specimens with 45° secondary orientation are marked separately.

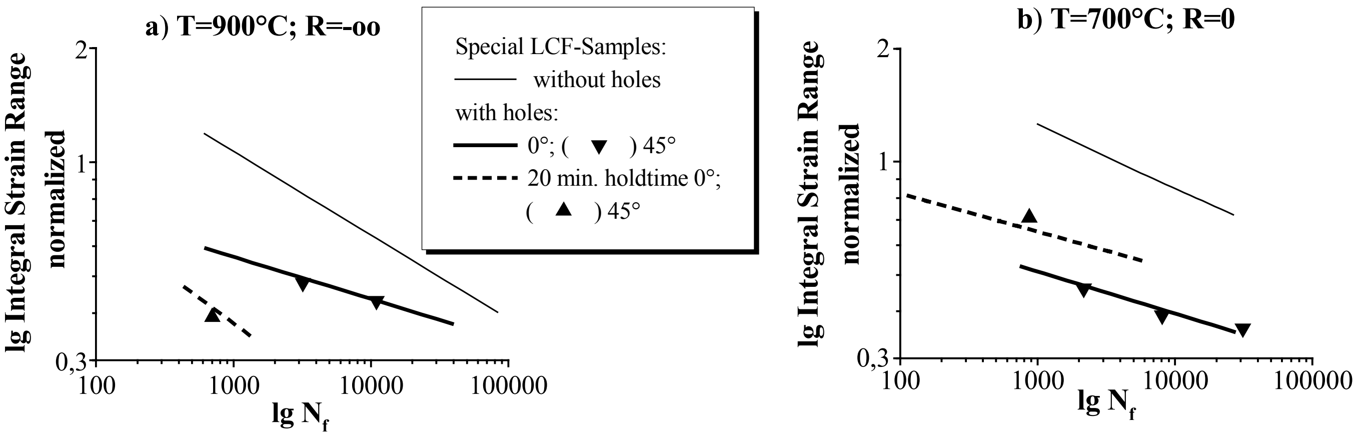


Figure 3: Influence of cooling holes and holdtime

For both temperatures it can be seen that the number of cycles to failure N_f for the samples with holes are lower at all strain levels. This is obviously due to the stress concentrations at the holes. The 45°-secondary orientation has hardly influence on the LCF-lifetime compared to the results of the mainly tested specimens with 0° secondary orientation.

In Fig. 3 a) a further reduction of the fatigue life was caused by a holdtime of 20 minutes at the maximum compressive strain. In contrast with that the tests with holdtime at maximum tensile strain for 700°C (Fig. 3 b)) reach a higher cycle number to failure than the tests without holdtime. This could be explained through mean stress relaxation.

In Fig. 4 the relaxation behaviour of 2 specimens cycled under the same strain range, but one of them with a holdtime, is compared. The holdtime at the maximum tensile stress caused a much stronger relaxation of the mean stress, which became negative after only 20% of the lifetime. The specimen without holdtime had a high positive mean stress and only about a third of lifetime compared to that one with holdtime.

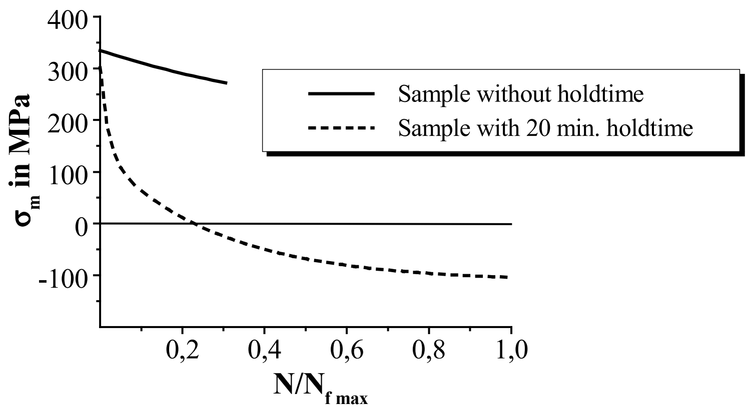


Figure 4: Example of mean stress development at 700 °C

The stress concentrations at the holes have been calculated with finite elements under the assumption of linear elastic material behaviour with cubic symmetry, see Fig. 5. Only the part of the test specimen between the extensometer has been modelled. Constant displacements have been applied to the corresponding cross sections between the extensometer to simulate the strain controlled LCF-test. The displacement is directly proportional to the nominal strain over the gauge length. The specimen is horizontally symmetrical with an additional axis of symmetry. Therefore, only one quarter of the specimen was modelled. Highest stresses are found along the curve where the holes intersect the outer surface of the specimen.

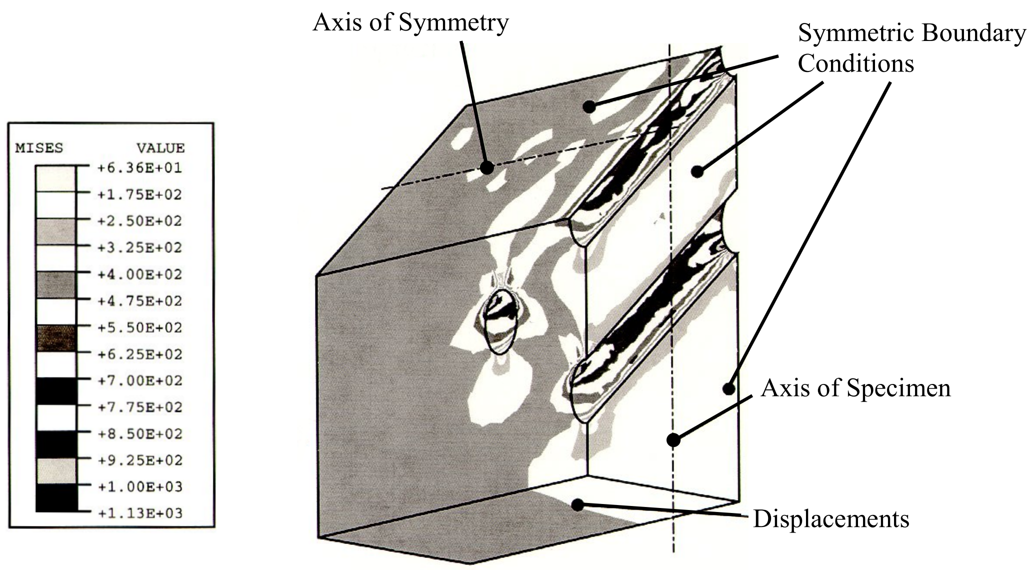


Figure 5: FEM-calculation of local stress

With the help of the FE-model the maximum local stresses were calculated as a function of nominal strain. Based on these results the maximum local total strain (with elastic and inelastic parts) is estimated with Neuber´s rule [6-8]. The cyclic stress-strain curve is used to take plastic deformations into account. From this the relation between the nominal strain over the gauge length and the local strain is derived.

S-N curves for specimens with holes at 900°C and 700°C test temperature, which are based on the local strain and compared with the normalised design curve, are presented in Fig. 6. In both cases the design curve under-estimates the cycles to failure so that a conservative, reliable life prediction using the local approach concept can be expected for the loading conditions considered here.

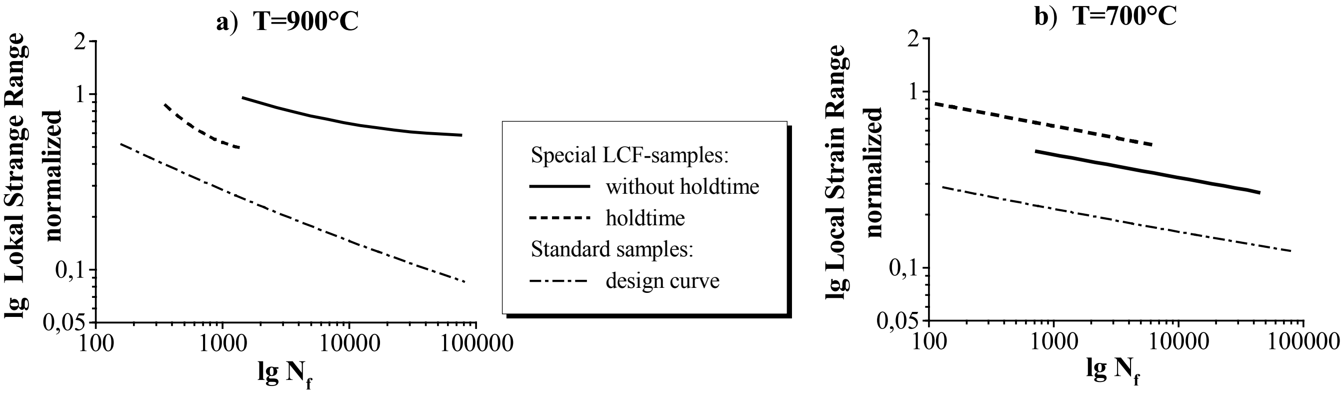


Figure 6: Comparison of results from cooling hole samples with design curve

In Fig. 7 results of an equiaxed conventional cast superalloy are compared with that of PWA 1483 SC. The PWA 1483 SC is generally better than the equiaxed material. Even with holes the integral strange range of SC-specimens is higher than that of the equiaxed samples for the same failure cycles. The application of SC-material brings therefore obviously a significant advantage for the gas turbine blades with film cooling holes. However the equiaxed material shows less relative decrease of the integral strange range due to cooling holes.

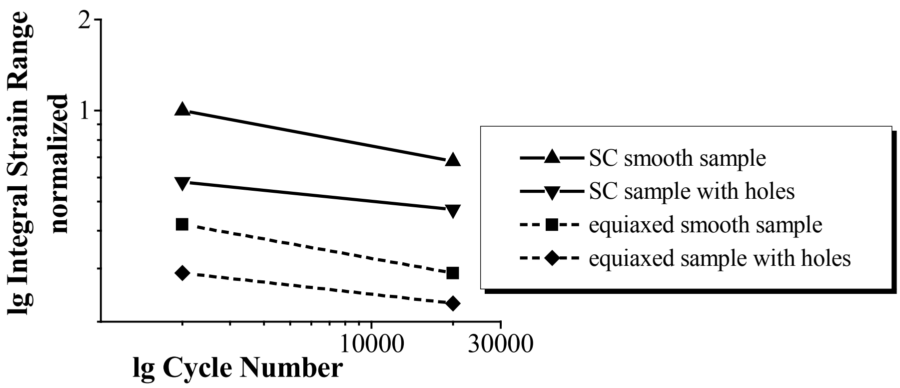


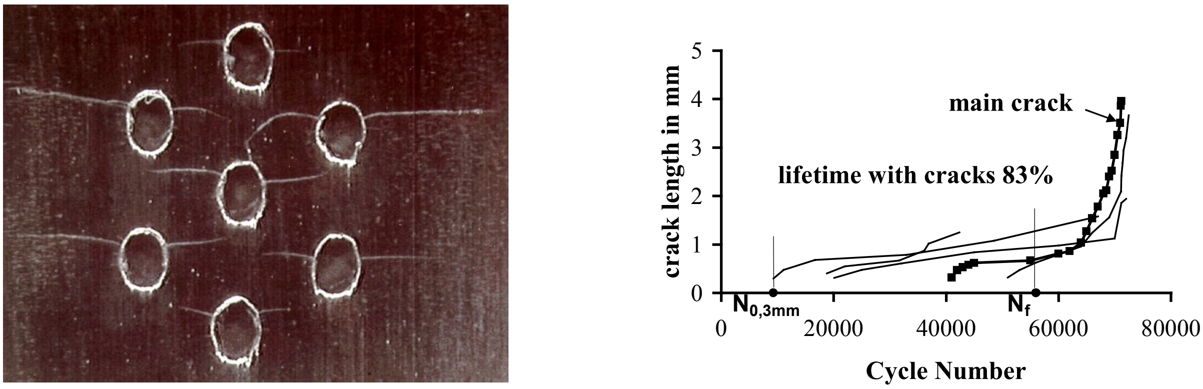
Figure 7: Comparison with a conventional cast superalloy

Crack Propagation

Metallographical investigations were carried out on samples after the tests. The most tests had more loading cycles than the defined N_f, (5% stress drop). The sample surface with cracks starting at the edges of the holes is shown in Fig. 8 a). The cracks grew perpendicular to the loading direction. After the final loading cycle there were still no direct links of cracks between the holes.

One typical example of crack history, happened during an LCF-test, is shown in Fig. 8 b).
A crack, initiated by cyclic loading, with a length of more than 0,3 mm on the sample surface could be recorded by the camera system in the fatigue test. After initiation the crack propagation of each crack slowed down while more and more cracks arose, some of them stopped before N_f. The samples were further loaded as usual until the test machine was automatically shut down by its control system.

When N_f had been reached at a 5% stress amplitude drop, all observed cracks were no longer than 1,5 mm and they were still in a stable propagation phase.



a) Cracks initiated from cooling holes b) Typical crack initiation and propagation

Figure 8: Typical crack development within the hole pattern after LCF-test,

As shown the main crack initiated after some other cracks. In this case about 83% lifetime of the specimens was with cracks of more than 0,3 mm. The random distributed micro-cracks due to laser-drilling have obviously no major influence on the total lifetime.

CONCLUSIONS

A significant improvement of LCF property has been achieved through the application of the single crystal superalloy PWA 1483 SC for gas turbine blades with film cooling holes. The special LCF-fatigue-tests using specimens with laser-drilled holes have shown, that:

- SC-material can withstand higher strain ranges, even with holes, than an equiaxed material.
- Micro-cracks due to laser drilling have no significant influence on the total lifetime.
- After initiation the crack propagation of each crack will slow down while cracks at other locations will appear.
- With the local strain, determined by FE-Analysis, a conservative and reliable life assessment can be obtained by using the local approach concept.
- There won't be unstable crack propagation before the in design procedure used N_f has been reached.

REFERENCES

1. Becker, B., Schulenberg, T. and Termuehlen. H. (1995), The 3A Series Gas Turbines with HBR Combustors, ASME 95-GT-456, Turbo Expo. Houston, Texas
2. Stoloff, N. (1987), Superalloys II, pp. 87-95, Wiley&Sons, New York
3. Wege, R. and Wortmann, J. (1989), Mat.-wiss. Und Werkstofftech. 20, pp. 207-216
4. Seeger, T. and Heuler, P. (1980), Generalized Application of Neuber´s rule, J. Test, Eval. 3, pp. 199-204
5. Savaidis, G., Dankert, M. and Seeger, T. (1995), An Analytical Procedure for Predicting Opening Loads of Cracks at Notches, Fatgue Fract. Engng. Mater. Struct. Vol. 18 No. 4, pp. 425-442
6. Neuber, H. (1961), Theory of Stress Concentration for Shear-Strained Prismatical Bodies with Arbitary Nonlinear Stress-Strain Law, Journal of Applied Mechanics, 12, pp. 544-550
7. Chaudonneret, M. and Chaboche, J. L. (1988), Fatigue Life Prediction of Notched Specimens, Int. Conf. Of Fatigue of Engineering Materials ans Structures, Sheffield
8. Lemaitre, J. (1992), A Course on damage Mechanics, Springer Verlag