Advanced Blading for Last Stages of Heavy Duty Gas Turbines: A Joint German Action

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ABSTRACT

Large stationary gas turbine blades are highly stressed by static and dynamic loads. In 1986, ABB and Siemens/KWU initiated an R&D-program to develop large blades of Ni-base superalloys with higher operating capability. The aim of the program is to develop with main suppliers new manufacturing routes and non-destructive testing methods for measuring residual stresses as well as to generate with institutes the relevant material/component property data. So far - scheduled end of the program in mid 1993 - new manufacturing routes are established which allow a higher stressing of blades. The current status and future outlook will be highlighted.

The requirements could be fulfilled by developing new alloys, but in the short term they can only be achieved by the best exploitation of available materials.

For this purpose a German joint program "AG-Turbo", subprogram "Turbotherm" has been started in which blade suppliers, gas turbine manufacturers and institutes cooperate (fig.1).

The current status and future outlook of this program will be reported.

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Fig.1 Turbotherm, Subprogram: Manufacturing of Large Gas Turbine Blades, Partners of the Program

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Forged turbine blades can exhibit high residual stresses due to manufactural methods, especially straightening operations and fast cooling down from forging or heat treatment temperatures. Under certain circumstances service loads and superimposed residual stresses may exceed the material's strength and lead to premature failures.

Additionally the microstructure achieved with common treatments was not optimal with regard to long term stability. So during service a loss in toughness and ductility may occur which is generally detrimental to highly stressed areas and to foreign object damages as well.

Conventionally cast blades reveal an inhomogeneous coarse grain structure with to some extent enlarged areas of microporosity. Both features are detrimental especially to fatigue strength.

The chemical composition and the different creep rupture strength levels of the particular materials are shown in fig. 3 and fig. 4.

The structure of this program includes 5 main actions "A" to "E" (fig. 5). In action "A" new manufacturing technologies were evaluated and basic investigations of material/component properties were carried out.

Fig.3 Chemical Composition of Forged- and Cast Alloys for GT-Blades

On this basis (1st milestone) 2 or 3 modifications of each material were evaluated for several mechanical short-term tests up to 3,000 h (action "B"). After the 2nd milestone only one modification of each material continues in long-term testing up to 20,000 h (action "C").

During the duration of the program microstructural examinations have to be performed to get a corre-
lation between mechanical properties and microstructure (action "D").

A Development of new manufacturing technologies
Investigations of material/component properties

Choice of 2 or 3 versions for each type of blade

1. Milestone

B Evaluation of material properties up to 3000 h

Choice of the best version for each type of blade

2. Milestone

C Evaluation of service relevant material properties up to 20 000 h

D Accompanied metallurgical examinations and
E development of a non-destructive measurement for residual stresses

Fig.5 Structure of the Turbotherm Subprogram

Besides the optimization of service relevant materials properties, low residual stresses in the blades should be obtained. In order to check this, adequate methods for calculation and non-destructive testing have to be developed (action "E").

To realize the goals of the program an accurate analysis of the requirements on large gas turbine blades for the particular service range was necessary.

Fig.6 Behaviour of Fine and Coarse Grain Microstructures under Combined Static and Dynamic Loads at Low Temperatures

The grain structure plays an important role, i.e. grain size, grain size distribution. Fig. 6 to 8 show schematically the relation between grain size and creep rupture-/fatigue strength.

Fig.7 Behaviour of Fine and Coarse Grain Microstructures under Combined Static and Dynamic Loads at Intermediate Temperatures

The diagrams exhibit advantages of a fine grain structure for large blades of the last rows (T ≤700°C). Therefore the reproduction of the optimum grain structure is very important.

Fig.8 Behaviour of Fine and Coarse Grain Microstructures under Combined Static and Dynamic Loads at High Temperatures

STATUS OF THE PROGRAM

I) Destructive Measurement and Calculation of Residual Stresses

Residual stresses were examined for forged blades. During cooling after forging or heat treatment stresses occur due to temperature gradients and can exceed the
yield strength of the material. This can lead to local deformation and distortions. Residual stresses and deformations can decrease the life expectancy of a blade.

A method for destructive measuring of residual stresses using a calculation method with finite elements has been established. This allows stress calculation over the entire blade volume (fig. 9,10) and gives information about the history of stress origin.[1]

This enabled to quantify the difference in residual stresses between fast air and slow furnace cooling and to find a good compromise between cooling rate (residual stresses) and microstructure, which is strongly influenced by the cooling rate.

III) Development of a Non-Destructive Method for Measuring Residual Stresses

Methods for non-destructive measuring of residual stresses by means of X-ray examination are well known for ferritic steels but have not established for Ni-base superalloys. The basis for this type of material had to be established. Previous work performed in this field showed that a fine grain structure of forged material caused no testing problems. For a more coarse grain cast structure the application of this method is also possible, although the measurements are more difficult [2]. The database of laboratory tests must now be transferred to a portable component diffractometer which allows measurements on installed blades.

III) Forged Blades

A) Nimonic 101

Microstructural examinations on this material revealed that very slow cooling from the solution temperature was possible without degradation of microstructure (e.g. γ'-phase, grain boundaries). Due to slow cooling minimal residual stresses will occur avoiding component distortion.

Moreover the standard precipitation hardening treatment was modified by introducing a 2-step "low-high" temperature cycle. This allows the fatigue- and
toughness properties to be improved. The fatigue endurance limits were increased by almost 100 MPa and the impact toughness was be doubled. The essential advantage of the modifications was that these properties degrade only slightly during service. The tremendous reduction in residual stresses and the improvement in deformation and fatigue capability together with no or negligible changes in static strength make the overall service behaviour much more reliable.

B) Udimet 720

This alloy was tested in 2 grain size modifications. The coarse grain version has a grain diameter of about 300 µm (ASTM 1) and the fine grain version a size of about 20 µm (ASTM 8).

In short-term tests the coarse grain version shows that the temperature cycle of the 4-stage standard heat treatment gives the best compromise between strength and toughness properties.

The distinctly reduced cooling rate of about 30 K/min. from solution- and stabilizing temperature which does not influence the microstructure leads to components with very low residual stresses. The microstructures are shown in fig. 11 and 12. (Note: Bar stock material behaves different under the same cooling conditions because of better homogeneity in forgings)

Fig.11 Influence of Cooling Rate on the Grain Boundaries of Udimet 720

Under critical forging conditions the formation of "elephant" grains may occur (fig. 13a). The production route was then optimized with respect to the amount of deformation per forging step. This solves the problem (fig. 13b).
Room temperature rotating bending fatigue tests on mechanically refined material show an endurance limit $\pm \sigma_a$ of about 280 MPa which is indeed a higher fatigue strength compared to conventionally cast (CC) material, but nevertheless a lower level than expected.

Furthermore, the mechanically refined version exhibits a decrease in impact strength which is harmful in case of foreign object damages.

Initial production of blades by this method produced hot tearing at the fillet radius between the airfoil and shroud (fig.16). This problem was solved by changing the solidification procedure.

Fig.14 Creep Rupture Strength of Udimet 720 Coarse and Fine Grain Version

V) Cast Blades

A) IN 792 MKF (Mechanical Grain Refinement)

Cast blades typically have an inhomogeneous coarse grain structure in comparison to forged blades. The coarse grains offer benefits for smaller blades running in the hot section of the gas turbine with respect to static loads (creep rupture strength). A finer grain size is more suitable for blades of the last rows which carry high dynamic stresses in an intermediate temperature range.

To get a fine uniform grain size the solidification process must be influenced (fig.15). In this program the technique of mechanical movement of the mould was used to interrupt the dendrite growth.

Fig.15 Macrostructure of IN792 with and without Mechanical Grain Refinement

Fig.16 Hot Tearing on IN792 Castings

During the course of this program a further development on conventionally cast blades allows a finer grain size to be produced by using a low temperature pouring method (fig.17).

Fig.17 Macrostructure of a Modified Conventionally Cast IN792 Blade Airfoil

The grain size of the modified conventionally cast material was comparable to that of the mechanically grain refined version, but initial tests found an endurance limit $\pm \sigma_a$ of about 400 MPa, i.e. a
remarkable step of improvement.
A comparison of mechanical short-term properties of both fine grain materials showed no differences. It has been decided to test the modified conventionally cast version and the mechanically grain refined version in parallel to check the property potential on a long term scale.

B) UDM 56 MKF (Mechanical Grain Refinement)

This recently developed Ni-base superalloy was mainly chosen because of its 30% lower price for raw material as advertised when introduced. Its strength level is between IN 738 LC and IN 792.
Meanwhile the advantage of its lower price has decreased to 10-15%. Furthermore, heat treatment trials determined that the heat treatment window was too small for large blades, i.e. a uniform grain structure could not be guaranteed.
Further development work on this alloy has been suspended in favour of IN 792 modified conventionally cast.

CURRENT STATUS

The course of this program showed, an intensive cooperation in joint projects among all partners results in effective progress in a relative short time.

The current status of this program is as follows:

- an improvement in manufacturing technology for forged blades was obtained and can to a high extent be transferred to serial production.
- technology for cast blades with a more uniform fine grain structure in root and airfoil has been developed.
- the basis of a non-destructive method for measuring residual stresses in fine and coarse grain structures of Ni-base superalloys has been established.
- a portable component diffractometer for measuring residual stresses on installed blades was designed and will now be tested.
- the goals for the improvement in mechanical properties were mostly achieved.

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