Advanced Tools for Design and Analyses of High Temperature Cyclic Loaded Turbine Components

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ABSTRACT

Creep-fatigue interaction is the dominating material degradation mechanism in high temperature plants and their components. The paper addresses the design of components subjected to creep-fatigue interaction in general and, because of increasing importance of combined cycle plants in the power generation pool, the design of cooled gas turbine blades in particular.

Research is undertaken worldwide to close the gaps in prediction of material degradation under these - mostly complex - loading conditions.

The paper presents a new concept to predict viscoplastic deformations in components under thermal mechanical loading. This approach is based both on material data from uniaxial creep tests and additional laboratory component tests to consider the influence of multiaxiality. This concept was used for analysis of feature tests of flat tensile specimens with central hole. The maximum test temperature was 600 °C and the surface of the hole was attacked by cyclic thermal shocks.

Finally the authors report about their ongoing works on thermal mechanical fatigue (TMF) of cooled components. These investigations address cooled gas turbine blades. The interaction of TMF of the blade and blade cooling is investigated experimentally in a high temperature gas test rig with maximum temperature 1000 °C. Nickel-base super alloys for turbine blades and in particular the single-crystal alloy CMSX-4 and advanced cooling technologies like effusion cooling are investigated.

1 INTRODUCTION

Today, the power generation industry is operating in an area of tension which is surrounded by contrary boundary conditions. High plant efficiency, low costs in design and operation and alternating demand in electricity, which is caused by liberalisation, are now the challenges for power plant industry. Because of the changes in demand and competition even components designed for base load conditions are now subjected also to two shift operation. In addition higher process parameters result in new high temperature materials and - with regard to gas turbine components in combined cycle plants – in advanced cooling technologies to reach service life. Thus, creep-fatigue interaction is the dominating material degradation mechanism in high temperature plants and their components. Despite world wide research on material degradation of power plant components life prediction for interacting creep and cyclic thermal fatigue includes uncertainties and needs improvement especially in the material laws, which describe the material behaviour vs. time and loading. But, that is essential both for life assessment of plants in service – especially with regard to life extension – and for “fatigue design” of high temperature components.

Today design process is highly interdisciplinary to obtain optimum solutions in shorter time with lower costs and in a more flexible manner. Efficiency and output, component weight, service life and costs are the relevant target functions for power engine optimisation (Figure 1). But, quality of modelling and simulation depends on the physical correlations for material behaviour, heat transfer and cooling conditions etc..

The authors are involved in research projects of turbine manufacturers in this field addressing creep-fatigue ratchetting, e.g. in turbine discs, and thermal-mechanical fatigue of cooled gas turbine blades [1, 2].

These investigations are based on laboratory component tests, which play an important role in development of life assessment procedures.

2 STUDYING CREEP RATCHETTING IN COMPONENTS

2.1 Experiments

Material and Laboratory Components

Because of its relevance for steam turbines the 12% Cr cast steel G-X12CrMoWVNbN10-1-1 was procured to manufacture flat tensile specimens with central hole. This specimen type simulates both the multiaxiality of a turbine component like a wheel disc and the thermal mechanical loading of the actual component by primary tensile load and cyclic thermal shock at the surface of the hole. The maximum temperature was 600 °C. Figure 2 shows the specimen.

The test material was sampled from a valve which was cast for the research project COST 501 [3]. Creep data of the test material were available from COST 501. Only some additional tests of standard lab specimens were conducted for verification. This test material was sampled at the same locations like the material for the feature test specimens. The creep rupture data are indicated in Figure 3.

Test Conditions

The feature test parameters were specified to reflect the real damage mechanisms of turbine components during reasonable test durations. The first test series of 3 specimens were performed at two stress levels as indicated in Table 1 at 600 °C and creep only. On the basis of these test results the decision on primary loads for the creep fatigue tests was made (tests number 4, 5, 6, 7). The inner surface of the hole of these specimens was attacked by cold air for cyclic thermal loading. A twist chamber was used for inlet of cooling air (Figure 2), which resulted in mean heat transfer coefficients of about 1000 W/m^{2}K. The final test (number 7) with longer test duration of about 16 000 h at lower primary load was performed to verify the results of the previous tests with shorter test duration. As already expressed, the test duration is a crucial issue: The conversion of findings from experiments to real components needs test conditions which simulate the real damage mechanisms.

	Test/ specimen number					
	1	2, 3	4	5	6	7
Primary load	Tension					
Tensile force in kN	120	96	96	108	96	68
Nominal stress in the narrowest cross section of the bridge in MPa	150	120	120	135	120	85
Maximum temperature in °C	600					
Secondary load			**Cold thermal shocks by air (25 °C)**			
Time per cycle in min			158,6	79,3		158,6
Total test duration in h	928	5 000 3 000	1 991	1 030	2 961	16 067
Number of thermal cycles			743	775	2 221	6 075
Stress ratio s_{mech}/s_{th} of the hot spot at the surface of the hole			0.98	1.1	0.98	0.74
Hardness HV1						
Pre test	250 - 270					
Post test	241 - 207	226 - 216	236 - 265		236 - 265	
Remarks	Failure after 928 h		Holding time before first thermal cycle in h			
			14			

Table 1. Loading conditions

Specimen Instrumentation/ Measurements

The specimens were instrumented with thermocouples for on-line temperature measurements. The tests were cyclic interrupted for deformation measurement and visual testing of the surface for crack initiation. Measuring marks were located at the specimen surface around the hole for deformation measurement in longitudinal and transverse direction.

Test Results

Figure 4 shows the results of the transverse creep deformation (y-direction) in the narrowest cross section of the specimen bridge beside the central hole. Although the low strain range of the pure secondary load wouldn't result in fatigue damage the test results showed accelerated creep deformation for creep-fatigue interaction compared with pure creep. This acceleration increases with stress ratio s_{mech}/s_{th}. The acceleration was a ˜ 5 for the tests with s_{mech}/s_{th} = (0.98…1.1) and a ˜ 2 for s_{mech}/s_{th} = 0.74.

2.2 Test Data Analysis

The test data were analysed by FEM starting with the pure creep tests. The 3-Parameter-Law from LEMAITRE [4] was used to describe creep of the material. This material law considers primary and secondary creep. The calculated creep deformations and strains of the feature test specimen were in good accordance with the experimental results.

The FE-calculations of the test series with creep-fatigue interaction started with the temperature fields. For that purpose the thermal boundary conditions at the surface of the hole were iterative adjusted until the calculated temperatures met the measured data.

The stress analysis started with the LEMAITRE-Law again. But, the calculation showed for these testing conditions for test durations > 100 h significant underestimation of the real measured viscoplastic deformations and strains.

Thus, a different method based on the creep data base of the testing material was used. The basic idea of this “THEMAN-Concept” is illustrated in Figure 5. The material data base is described by data sets $\ln \dot{e}_{cr} (\ln e_{cr} ; s ; t)$ from uniaxial creep tests which cover all creep phases from primary to tertiary. Transition of stress and temperature from one level to another of the structural elements needs to define a particular transition criterion which reflects the progress in damage. After checking established criterions like strain hardening criterion and others, which didn`t result in satisfactory creep strains compared with the test results, the parameter

$$dam = \sum \left(\frac{\left| \Delta e_{cr} \right|}{e_{MCR}} \right) \tag{1}$$

was defined. ? e_{cr} represents the increment of creep strain in time unit and e_{MCR} the creep strain at minimum creep rate for stress and temperature. A fictive stress s_{eqv}^{*} is introduced, which is only used to draw the appropriate creep data from the material data base for multiaxial stress fields in components:

$$h_m = \frac{s_x + s_y + s_z}{3 s_{eqv}} \tag{2}$$

$$s_{eqv}^{*} = s_{eqv} (1 + f(h_m ; \dot{h}_m ; \Delta h_m ; P_1 ; P_2 ; P_3)) \tag{3}$$

The temperature independent parameters P_1, P_2 and P_3 are derived from multiaxial tests.

This procedure is programmed in an user subroutine for ANSYS. The analysis of the test data using this approach showed that the calculated and measured creep deformations were in good accordance (Figure 6). Of course, the proposed concept needs further validation for other materials and test conditions. This is one of the objectives of the research project “Thermal Mechanical Fatigue of Cooled Components”, which has just been started (see section 3).

2.3 The COUSSERAN-Diagram: An Engineering Method to Assess Interacting Primary and Secondary Loads with Regard to Creep

The COUSSERAN-Diagram [5] is an engineering method to estimate the effects of additional secondary stresses with regard to creep. This method is straightforward in its use. Thus, the test data were also placed in the COUSSERAN-Diagram to check its conservatism (Figure 7).

The COUSSERAN-Diagram is based on the concept of effective stresses. The effective stress is defined as that stress which results in the same creep strain like the combination of primary stress and cyclic secondary stress. Elastic stresses are considered only. The effective stress is used as reference stress for life assessment on the basis of creep rupture curves.

Figure 7 shows that the test data from the feature tests are located above the "design curve" of the COUSSERAN-Diagram which means that the "design curve" covers the experiments conservatively. This was also found by the European project C-FAT as shown in the graph.

3 THERMAL MECHANICAL FATIGUE OF COOLED COMPONENTS

A new research project has just been started on the basis of the previous works [2]. This project addresses thermal mechanical fatigue of cooled gas turbine blades. The objectives are to

- Investigate deformations and damage propagation in cooled laboratory components of Ni-base super alloy MARM-247 and single-crystal alloy CMSX-4, which allows also to study non isotropic material
- Study the effect of component cooling on crack initiation for non isotropic material
- Validate the "THEMAN-Concept" for analysis of creep-fatigue interaction (see section 2.2).

The tests are performed in a high temperature gas test rig with maximum temperature 1000 °C [6] (Figure 8). This test rig is designed for thermal cyclic loading of laboratory components from outside, cooling by air from inside and additional mechanical loading by tensile force.

The loading conditions of cooled gas turbine blades are simulated by a hollow feature test specimen with simplified drop shape and outlet holes at the profile nose (Figure 9).

The specimen is attacked by the hot gas flow and subjected to tension with nominal stress of 150 MPa to simulate also the mechanical loads acting on the rotating blade of a gas turbine.

So far test results are not available. The experimental works are scheduled to start in Summer 2001.

Parallel to these investigations with simplified modelling of blade cooling, advanced cooling technologies are being analysed. The contrary requirements of increasing turbine inlet temperatures on the one hand and keeping allowable material temperatures with minimum compressor air mass flow for cooling on the other hand are the driving forces for progress in cooling technologies parallel to other actions in design of gas turbines which are taken with regard to service life. Figure 10 shows a comparison of various cooling technologies with regard to their cooling effectiveness. Because cooling air consumption is essential, new technologies have to address both maximum cooling effectiveness and minimum air consumption. The ideal blade is located in the upper left corner of the diagram in Figure 10.

Today effusion cooling is the most advanced technology, which has already been used for combustors and leading edges of gas turbine blades. While film cooling blocks the hollow, inside cooled blade from the gas flow by a homogeneous air film along the blade surface, effusion cooling effects in addition an intensive cooling of the wall also from inside by high density of cooling holes. In the result the temperature distribution gets more homogeneous with resulting lower local secondary stresses.

Beside the cooling effectiveness, effusion cooling needs optimising with regard to its effect on aerodynamic efficiency [8]. Influence factors are both geometrical parameters (blow out angle, row distance, diameter of holes) and thermal parameters (pressure and temperature of cooling air). Previous investigations addressed cooling effectiveness using plane models [9]. In addition the quantity of rows was restricted. How the blade profile effects on formation of the cooling film and temperature distribution in the wall haven't been investigated so far. The present investigations on advanced cooling technologies just address these questions. The models simulate gas turbine blades with multirow holes (Figure 11). The experiments are performed in the high temperature gas test rig at 650 °C outside gas temperature. In connection with the available air pressure and mass flow these test conditions gives representative results.

4 CONCLUSIONS

Feature tests of flat tensile specimens with central hole, which was attacked by cyclic thermal shocks, showed significant acceleration of creep deformations compared with the pure creep test. The acceleration increases with stress ratio s_{mech}/s_{th}.

These tests were analysed by FEM using the 3-Parameter-Law from LEMAITRE. The calculation showed for thermal mechanical loading of the specimens significant underestimation of the real measured viscoplastic deformations and strains for test durations > 100 h. Thus, a different method based on the creep data base of the testing material and a modified transition criterion for stress and temperature from one level to the other was used. This approach resulted in creep deformations which were in good accordance with the measurements. Of course, this concept needs further validation.

In addition the data from feature testing were placed in the COUSSERAN-Diagram for engineering assessment of thermal mechanical loadings at high temperature. It was found that the "design curve" of the COUSSERAN-Diagram covers the test data conservatively.

The new project "Thermal Mechanical Fatigue of Cooled Components", which has just been started, continues the research on thermal mechanical fatigue of high temperature components. This project addresses the complex loading of cooled gas turbine blades and considers non isotropic material behaviour in addition.

Within the various actions with regard to service life at high turbine inlet temperatures (Ni- and Co-base super alloys, thermal barrier coatings, reduced reaction of the first turbine stage) cooling of high temperature components has a key position. Because component cooling uses reasonable shares of the compressor air mass flow and effects on the flow characteristic of the blade its influence on turbine efficiency is high. Today effusion cooling is the most advanced technology, which combines high effectiveness of cooling and homogeneous temperature distributions with lower secondary stresses. The interaction of cooling film and gas flow, the arrangement of the holes and the resulting temperature distribution and stresses are investigated.

Both the investigations on thermal mechanical fatigue under complex loading conditions (interaction of mechanical stresses, non stationary thermal stresses from temperature transients and stationary thermal stresses from cooling) and the investigations on effusion cooling deliver valuable contributions for design of gas turbine components, which today represents an interdisciplinary optimisation [e.g. 10-14]. Design has to meet various – also contrary - boundary conditions. It needs to be very flexible and cannot be focused on optimisation of particular parameters like efficiency or output only. Today interdisciplinary optimisation combines both efficiency and output, weight, costs and service life.

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REFERENCES

[1] Soergel, G., Raddatz, M., Thermische Ermuedung moderner Hochtemperaturbauteile II, Vorhaben Nr. 608, Forschungsvereinigung Verbrennungskraftmaschinen FVV, Reports 571-2 (1997), 571-3 (2000)

[2] TMF gekuehlter Bauteile, AIF-Project 12613

[3] COST 501, Werkstoffe fuer hochbeanspruchte Komponenten von fossilbefeuerten Kraftwerken mit hohem thermischen Wirkungsgrad und geringer Umweltbelastung, European Research Project , 1993-1995

[4] Lemaitre, J., Chaboche, J.-L., Mechanics of solid materials, Cambridge University Press, Cambridge 1990

[5] Clement, G., Lebe, J., Roche, R. L., A Design rule for thermal ratchetting, Transactions of the ASME, Vol. 108 (1996), p. 188-196

[6] Homepage www.tu-dresden.de/mw/iem/theman

[7] Scheurlen, M., Kuehlkonzepte der 3A-Gasturbinenfamilie von Siemens, XXX. Kraftwerkstechnisches Kolloquium, Dresden, 1998, Paper

[8] Ganzert, W., Untersuchung zur Optimierung der Kuehlluft-Ausblasekonfigurationen fortschrittlicher Turbinenbeschaufelung, BMWi/ AIF-Projects 10686, 11938, 1996-99

[9] Hahn, W., Urner, G., Untersuchung zur Kuehlung von Brennkammerelementen, BMFT-Project 20T9104 Verbundvorhaben „Schadstoffe in der Luft“, Report, 1994

[10] Kroo, I., Altus, S., Braun, R., Gage, P., Sobieski, I., Multidisciplinary Optimization Methods for Aircraft Preliminary Design. AIAA94-4325 Paper, Stanford University, Stanford (USA) 1994

[11] Subel, C., Barner, J., Steinhardt, E., Feature-Based CAX Geometry Model of Compressor Disks for Multidiciplinary Optimization. AIAA 2000-4869 Paper, MTU Motoren- und Turbinen-Union Muenchen 2000

[12] Dulikravich, G. S., Martin,T. J., Dennis, B. H., Lee, B, Han, Z.-H., Aero-Thermal-Structural Design Optimization of Internally Cooled Turbine Blades. The Pennsylvania State University, RTO-MP-8, 1998

[13] Soergel, G., Buchheim, G., Schoene, S., Henrich, E., Complex Optimization Of Cooled Gas Turbine Blades. Proc. of the Conference on Modelling and Design in Fluid-Flow Machinery, Gdansk, Nov. 18-21, 1997, p.531ff.

[14] Henrich, E.; Schoene. S.; Buchheim, G.: Optimierung gekuehlter Turbinenschaufel-profile, Brennstoff Waerme Kraft 52(2000) Nr.7/8, S.42f.

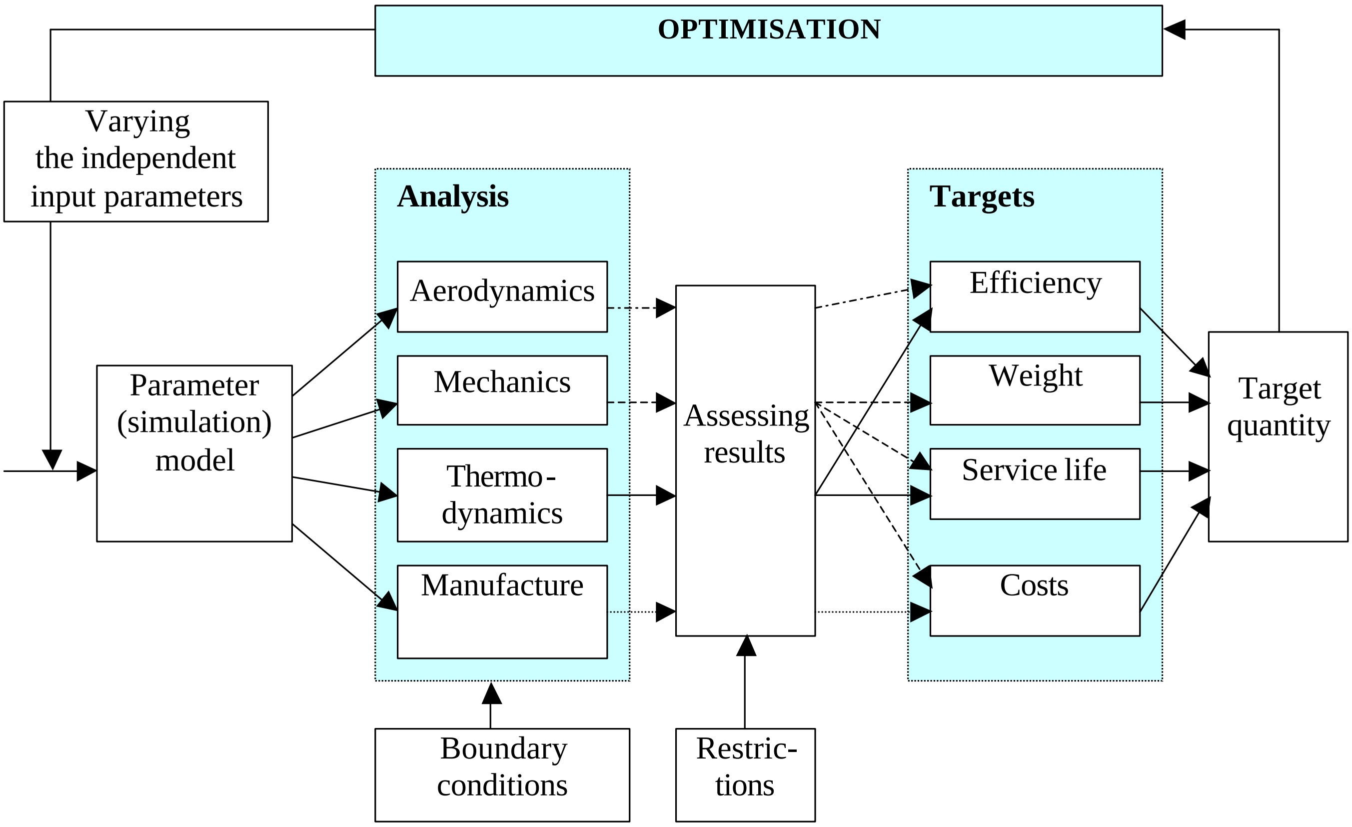


Figure 1. Principle (simplified) optimisation procedure

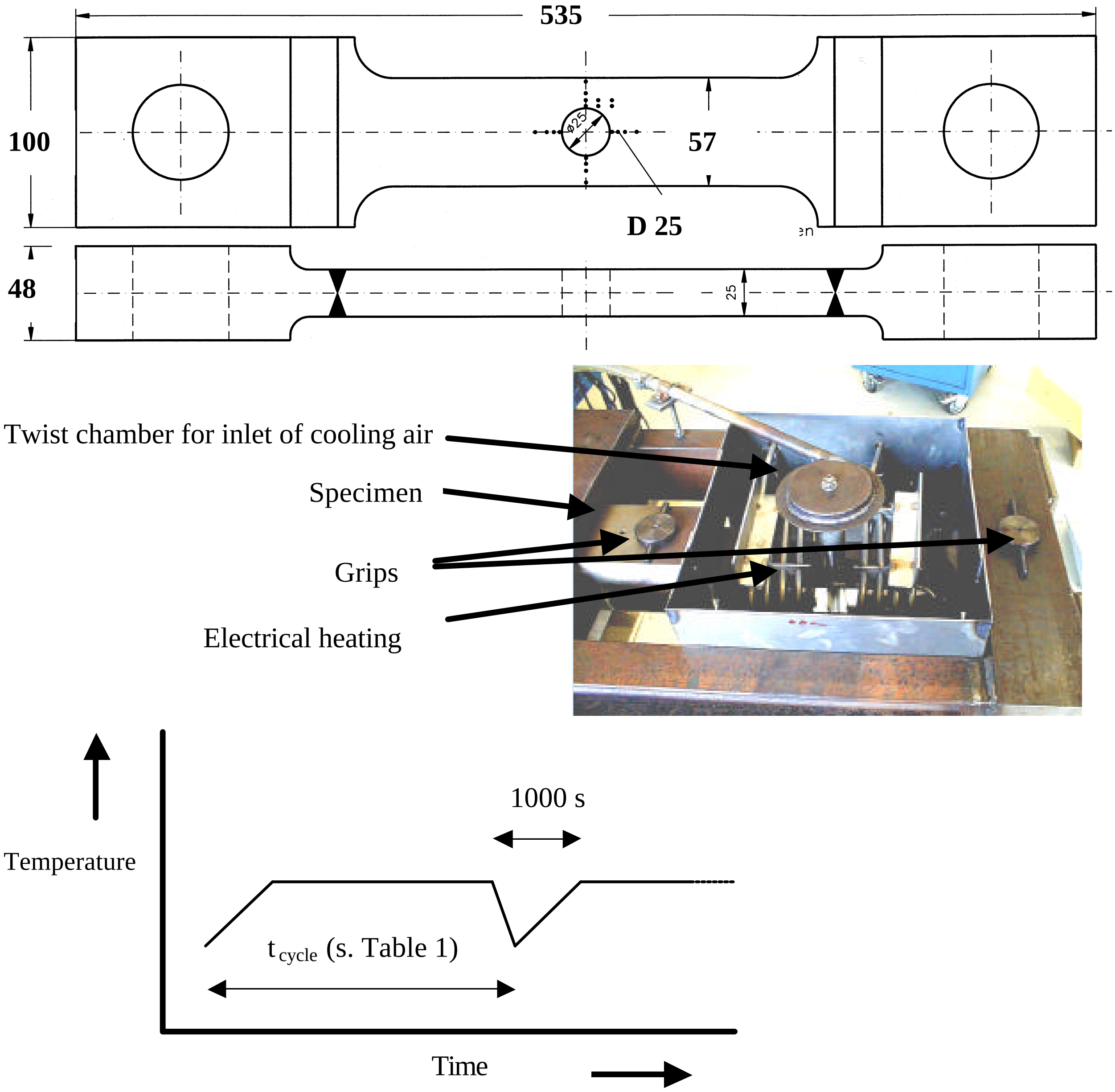


Figure 2. Design and loading of flat tensile specimen with central hole

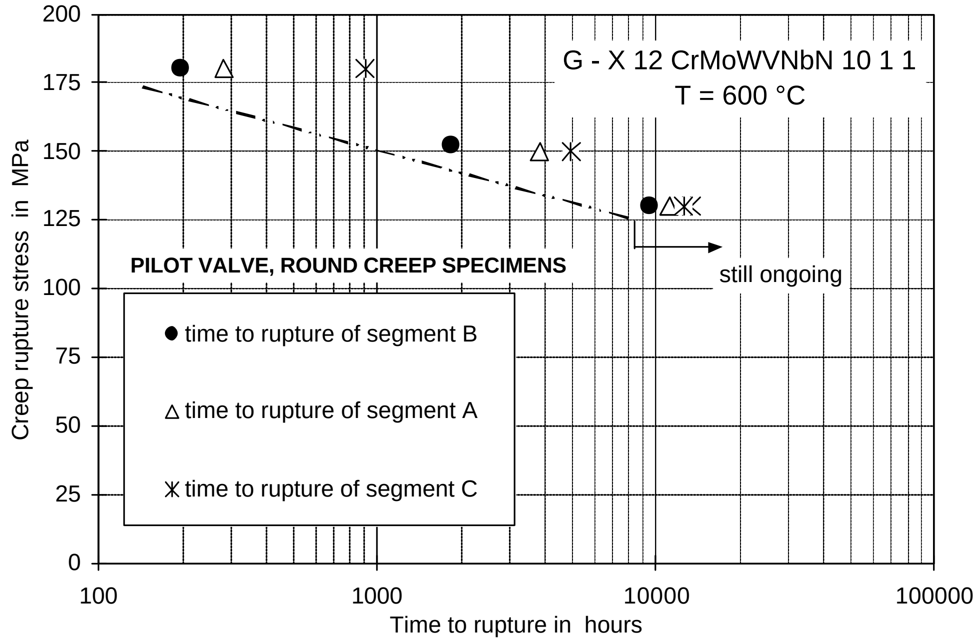


Figure 3. Creep properties of the test material

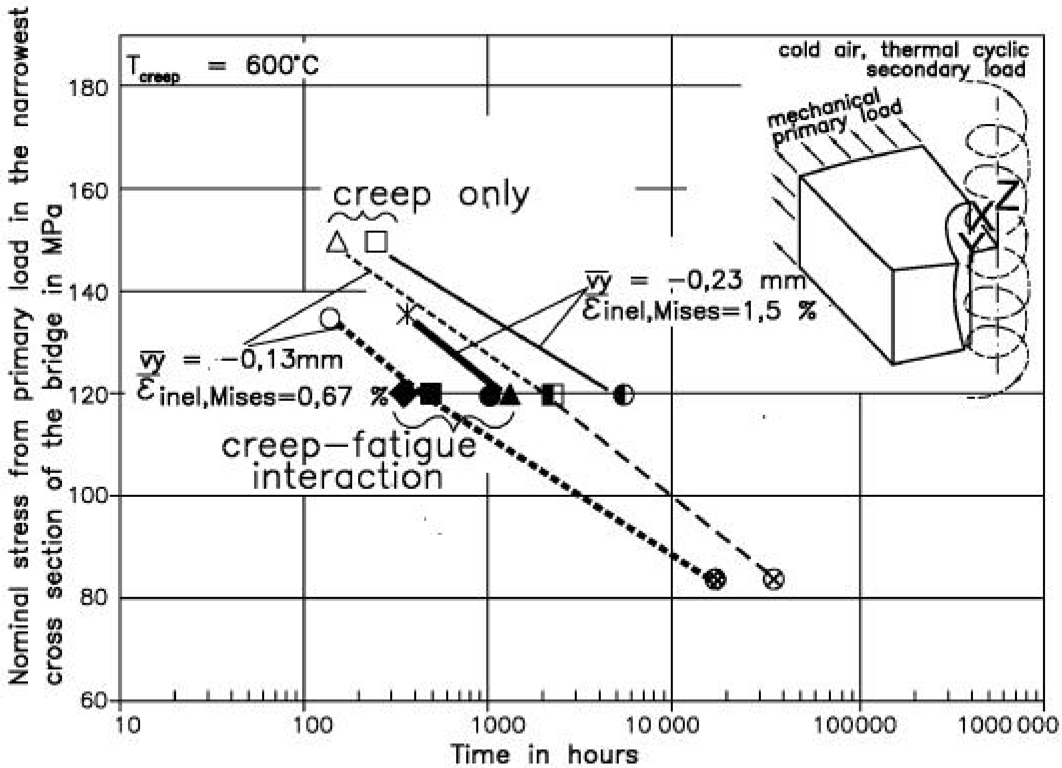


Figure 4. Results from creep deformation measurements

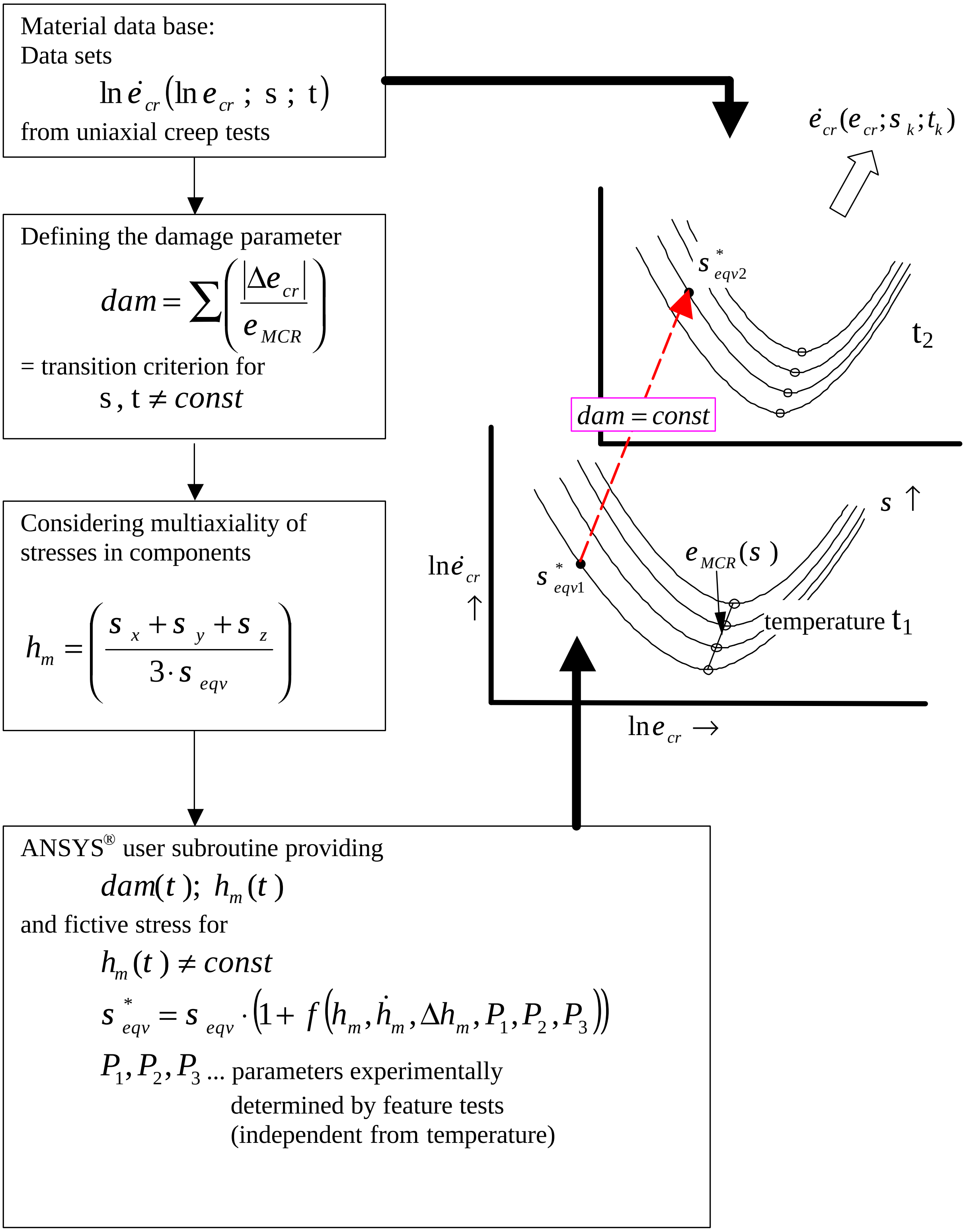


Figure 5. The “THEMAN-Concept” for analysis of components subjected to creep-fatigue interaction

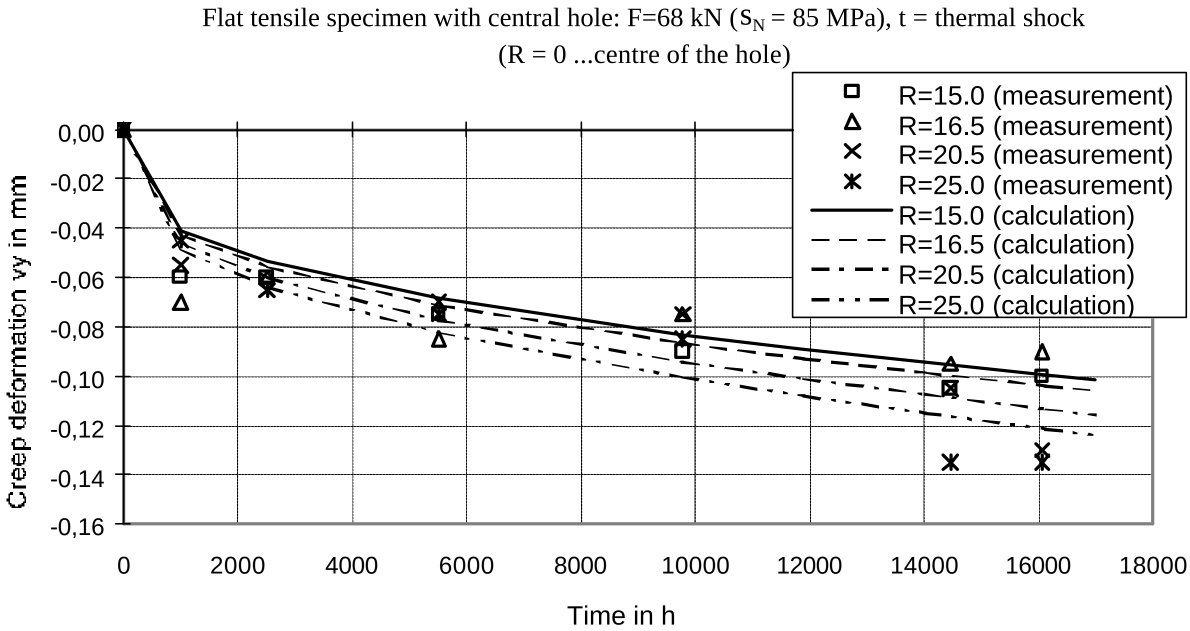


Figure 6. Example for comparison of calculated and measured creep deformations: Transverse deformations of various locations in the bridge beside the central hole

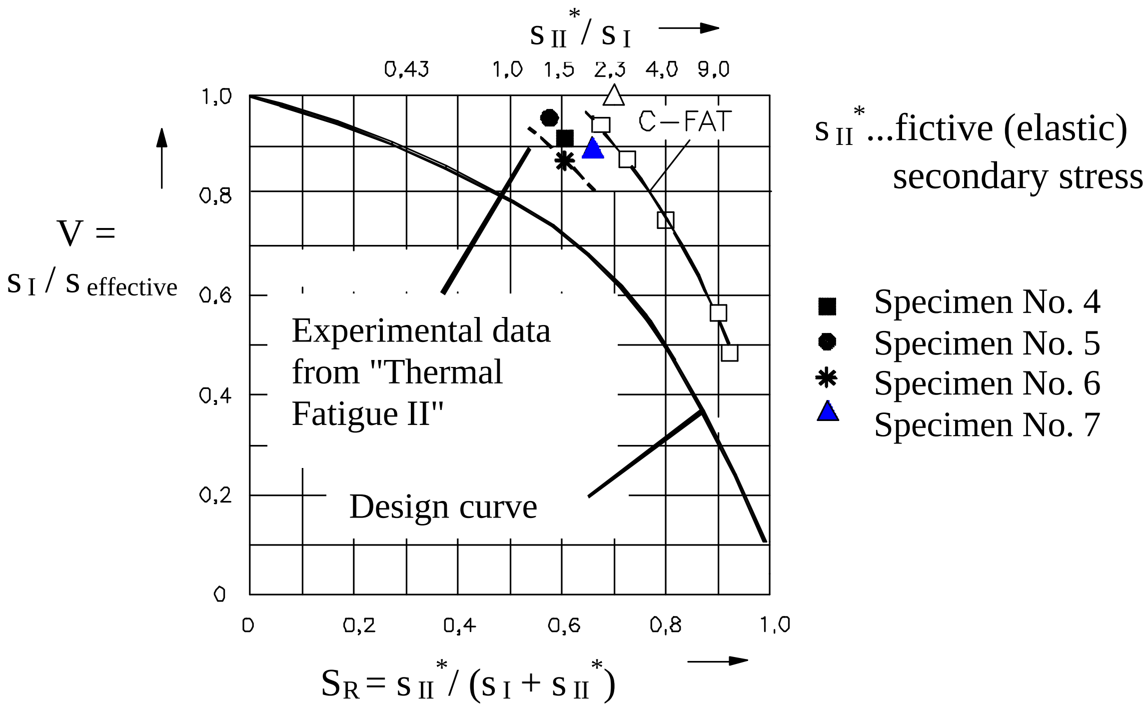


Figure 7. Placing the measuring data in the COUSSERAN-Diagram

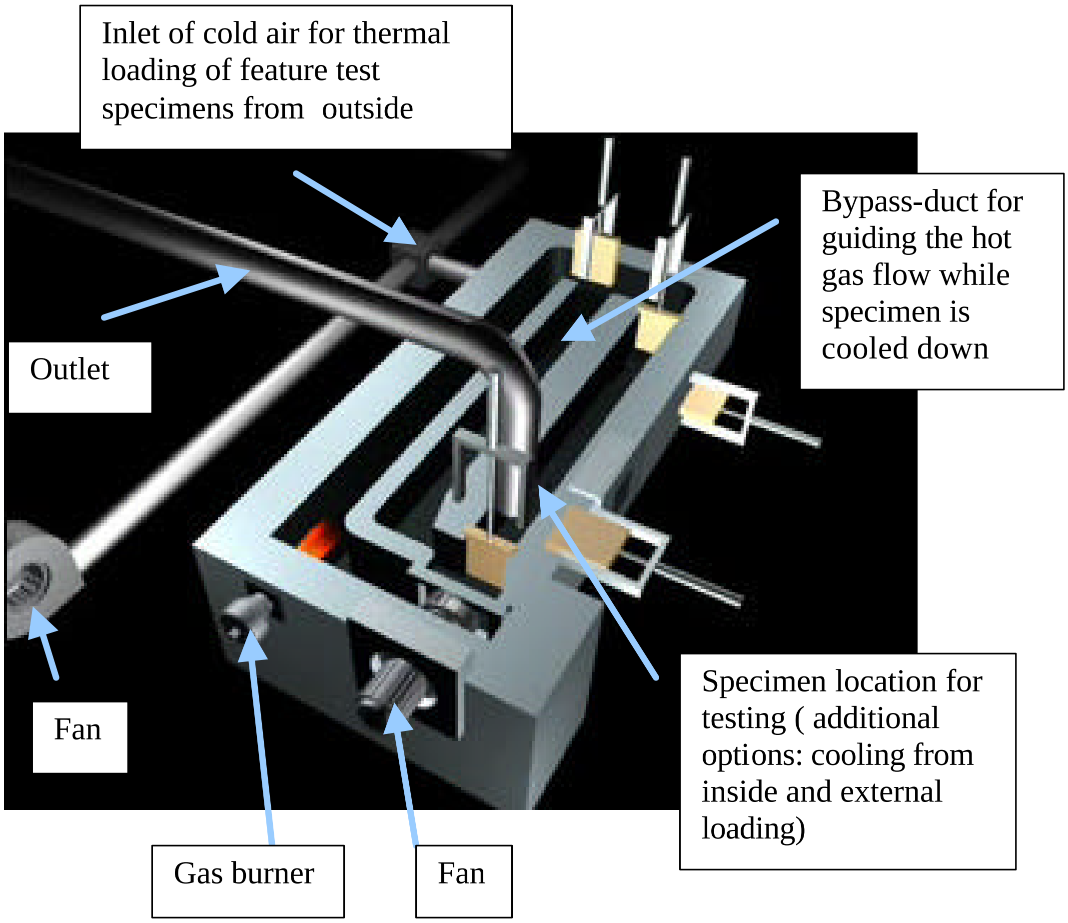


Figure 8. High temperature gas test rig for thermal mechanical loading of laboratory components

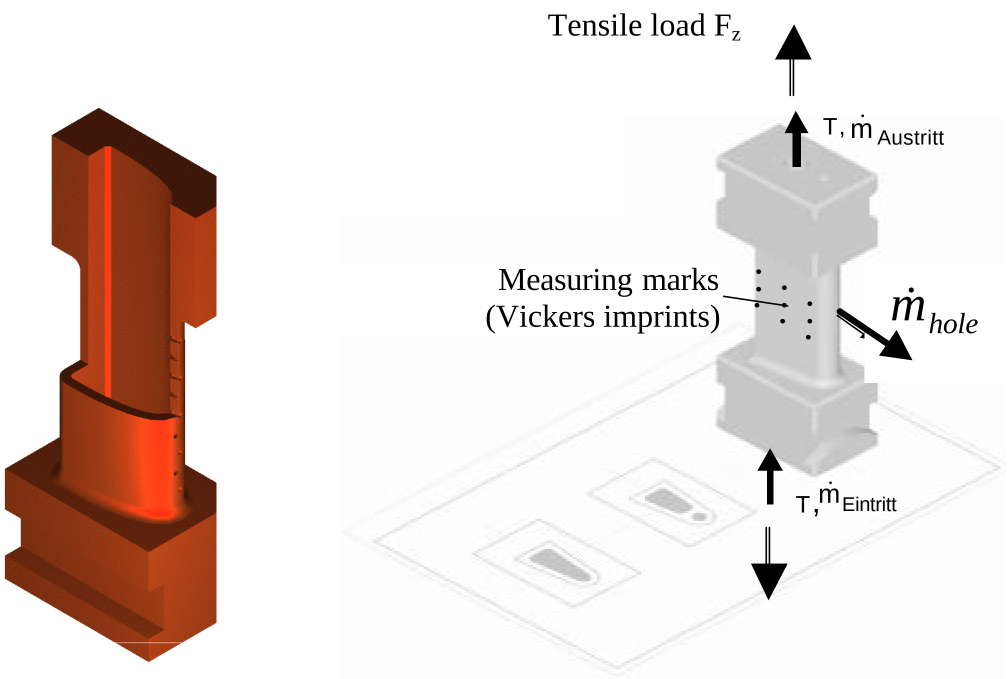
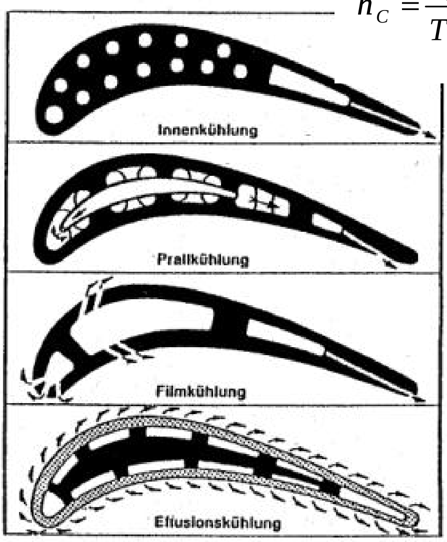
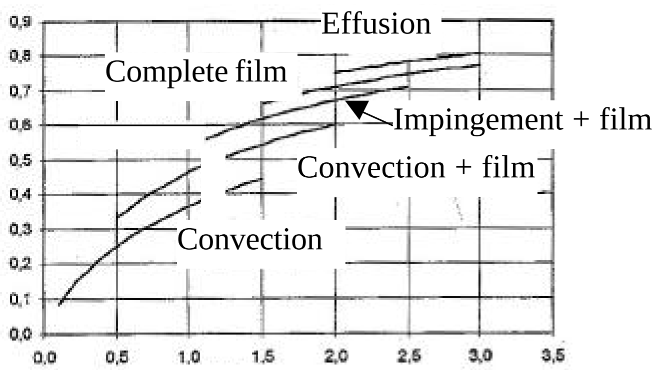


Figure 9. Feature test specimen: Cooled gas turbine blade



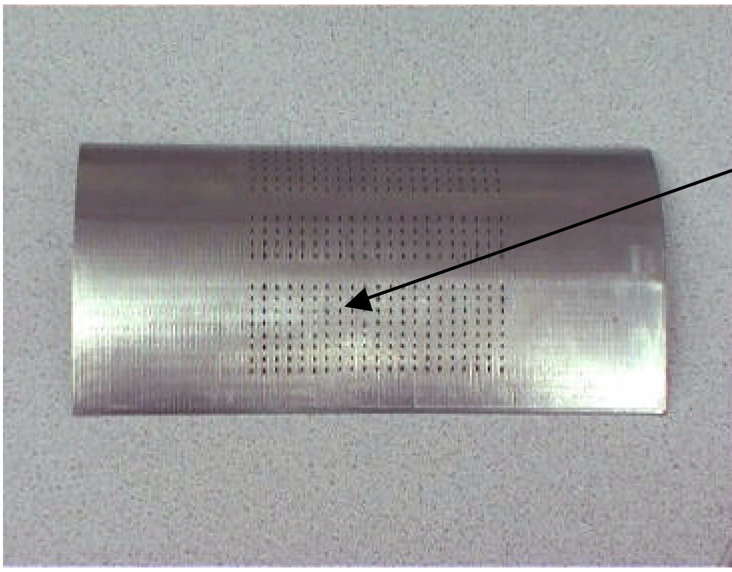
$$h_C = \frac{T_G - T_W}{T_G - T_C}$$



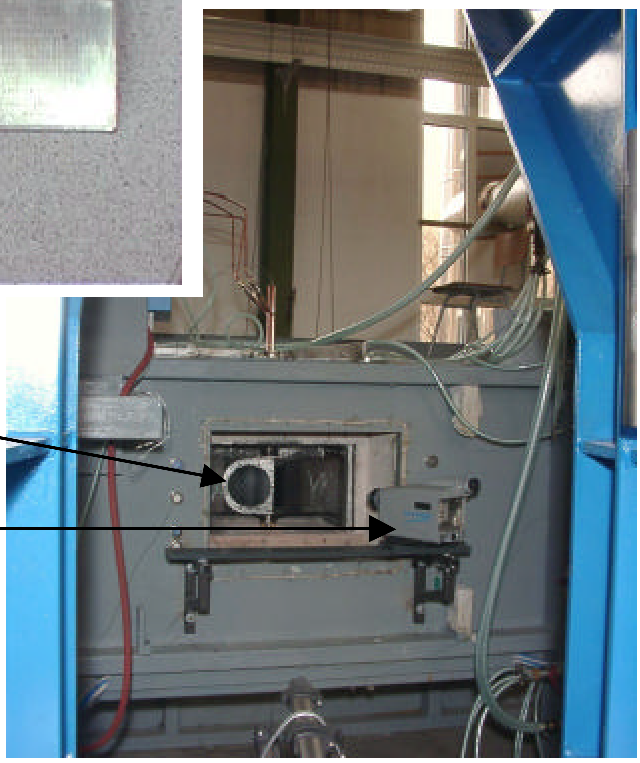
$$HLP = \dot{m}_c c_{pc} / A_G a_G$$

1 Convection cooling
2 Impingement cooling
3 Film cooling
4 Effusion cooling

Figure 10. Methods of blade cooling and cooling effectiveness ?$_C$ [7]



Field of holes for effusion cooling (suction side)



Blade position inside the high temperature gas test rig

Camera for IR-thermography

Figure 11.
Model of cooled blade for experiments on effusion cooling