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BRITE/EURAM PROJECT 4285

VALID

VERIFIED APPROACHES TO LIFE ASSESSMENT AND IMPROVED DESIGN OF ELEVATED TEMPERATURE TURBINE EQUIPMENT

PUBLISHABLE SYNTHESIS REPORT

INITEC

INSTITUTE OF MECHANICS OF MATERIALS AND GEOSTRUCTURES S.A.

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ABSTRACT: ---
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SYNTHESIS REPORT

Verified Approaches to Life Assessment and Improved Design of Elevated Temperature Turbine Equipment - BRITE/EURAM Project "VALID"

1. Introduction

The integration of steam and gas turbines {combined cycle plant) has recently become a favoured power generation option in view of its proven technology, low commissioning costs, fuel flexibility and high efficiencies with associated environmental advantages. Additionally, the re-powering of old fossil plant by retaining the steam turbine and integrating gas turbine plant is an option being implemented to achieve the advantages of higher efficiency and the lower capital costs associated with life extension/planned refurbishment strategies.

Turbine plant is not generally bound by national codes but is designed to the engineering practices of the manufacturers. Whilst the allowable loading parameters are specified, manufacturer's operational guidelines cannot, in general, be translated to predict accurately operational lifetime and associated acceptance criteria, which in turn forms the basis of improved design.

Lifetime evaluation of elevated temperature steam turbine plant is in most cases carried out using operational data in association with stress analysis codes and material data. For steam turbine rotors, codes have been developed by EPRI in the USA (SAFER Code}, with improvements by CRIEPI in Japan. For bolting, operational codes of practice have been developed in Europe (e.g. German TRD codes, CEGB GOM rules).

Predictive maintenance schemes for gas turbines are normally based on formalised rules laid down by the turbine maker and an equivalent operating hours concept for evaluation of cyclic life consumption is often used to establish inspection intervals.

However, in many of these eases the complex multiaxial stress states, which invariably arise in practice, are not taken into account. This is an important omission in critical turbine equipment (e.g. rotors, bolting, blades) where, for example, local geometrical changes lead to triaxial stress states. It is known that different materials respond differently to multiaxial stress situations and, depending on stress state, predicted lives can be in error by up to an order of magnitude or more. This uncertainty can lead to major inaccuracies in design and plant life assessment. A knowledge of the multiaxial stress response can thus provide considerable scope for improved design, higher efficiency and availability and life extension of power generation plant, particularly as the demand grows for higher performance and optimised maintenance.

2. Objectives and Industrial Applications

In order to address the above, BRITE-EURAM project BE4285 "VALID" was initiated by a consortium comprising turbine manufacturers, power generation companies, service and engineering design organisations.

The overall goal of the project was the development and specification of validated life prediction techniques with improved transferability to elevated temperature design and predictive maintenance of critical mechanical equipment operating under complex loads. The aim of the work was to provide the basis for a new Code of Practice for design and operational reliability assurance for rotors, bolting and blading relevant to steam and gas turbine plant.

One of the key objectives was to develop and validate practical means of modelling multiaxial creep and fatigue behaviour by means of representative stresses and strains in order to predict the response of simulated component tests.

In order to arrive at the project goals, the project was split into a number of tasks as follows:

- Task 1: Procurement of materials
- Task 2: Uniaxial and Multiaxial creep and fatigue testing techniques and development of constitutive laws
- Task 3: Validation of notch bar testing route
- Task 4: Algorithms for creep-fatigue crack initiation
- Task 5: Validation of algorithms on feature tests and field experience
- Task 6: Condition assessment technique by means of an X-ray lifetime monitor
- Task 7: Code of Practice
- Task 8: Project Management

3. **Roles** of the Partners

The project consortium comprised the following organisations, and indicates their contribution to each task :

Organisation	Country	Organisation Type	Status	Tasks
INITEC	E	Engineering Construction and Services	Prime Partner	7,8
ERA	UK	Semites	Partner	2,3,4,5,6,7,8
MPA	D	Services	Partner	1,2,5
IMMG	GR	Services	Partner	2,3
ABE	D	Manufacturer	Associate	1 ,2,4,5,?
KWU	D	Manufacturer	Associate	1,2,4,7
MAN	D	Manufacturer	Associate	1,5,7
RR-IRD	UK	Manufacturer & Services	Associate	2,7
PowerGen	UK	End User	Associate	2,4,5,7
ESB	IRE	End User	Associate	5
National Power	UK	End User	sponsor	

4. Description of the Research Work

The workscope comprised seven technical tasks, Below is a summary of the work performed within each of the task activities indicating the key elements.

Task 1- Materials Procurement

The materials selected for the test programme were based on the requirements of designers, manufacturers and users to ensure generic application to existing and future steam and combined cycle power plant.

Each material was procured from a single heat. The materials and chemical compositions are given in Table 1. The 1 CrMoV steel represents a conventional material used for the manufacture of steam turbine rotors. The 2CrMoNiVW steel is a candidate material for advanced steam turbines, and combines the good creep resistance of conventional rotor steels with higher toughness. Nimonic 80A is a commonly used bolting material and IN738~C is a conventional] y cast nickel base superalloy widely used for first stage cooled blading applications in gas turbines.

Task 2 - Development of Representative Stress and Strain Approaches for Modelling Creep and Fatigue Crack Initiation

A common feature of each application area is its criticality in terms of plant integrity and the multiaxial nature of stresses prevalent under service loading. Multiaxial states of stress arise either through direct mechanical or thermal loading conditions e.g. at rotor bore regions or under more simple loading conditions in combination with geometrical features e.g. rotor grooves or thread roots. In many of these cases the multiaxial state of stress is triaxial tension, which is of most concern because of the potential for non-conservatism in predicted crack initiation times if assessments are made on the basis of uniaxial data alone.

The proposed, practical, test route for determining materials behaviour under triaxial tension was to subject circumferentially notched bars, having a variety of notch acuity ratios, to axial static and cyclic loads. The notch bar geometries used for both creep and fatigue testing are shown in Figs. 1 to 3. Varying the notch acuity allows the significant stress parameters - maximum principal stress σ_1, the von Mises effective stress σ_e and the hydrostatic stress σ_h to be systematical y varied over a range Of values typical of those present in critical turbine components. Numerical inelastic stress analysis of the notch bar geometries subjected to static and cyclic loading were conducted to determine the magnitude and spatial variations of the significant stress components and to derive the appropriate reference stress for creep and fatigue. These results together with experimental uniaxial and notched bar test data generated on each material were used to determine the multiaxial stress rupture criterion (MSRC) for creep and fatigue loading for each material.

For creep, the multiaxial creep rupture life can be described using the following formulation:

$$t_{rm} = B / (\sigma_1^{\gamma} \cdot \sigma_e^{n-\gamma}) = t_{ru} / (\sigma_1 / \sigma_e)^{\gamma} \qquad [1]$$

where t_{rm} and t_{ru} are the multiaxial and uniaxial life respectively and γ is the multiaxial stress rupture exponent. A typical MSRC plot for the 1CrMoV rotor steel is shown in Fig. 4. The multiaxial creep rupture response for this material can be described using an effective stress controlled parameter at low levels of multiaxiality and for short times to failure. At lower stress levels and higher stress states, the influence of the maximum principal stress increases: this can be accounted for by introducing a time to rupture dependency on the exponent γ viz

$$\gamma = A + B \cdot \ln (t_{ru}) \qquad [2]$$

In this way multiaxial creep life can be rationalised over a wide range of stress states and stress levels as shown in Fig. 5.

For fatigue an appropriate reference stress can be formulated by means of the elastic energy density **release** rate viz

$$\sigma_{ref} = \sigma_e \, [\, 2/3\,(1+\mu) \;+\; 3\;(1-2\mu) \cdot (\sigma_h/\sigma_e)^2 \,]^{1/2} \qquad [3]$$

where μ is Poisson's ratio and σ_h is the hydrostatic stress. In Eq [3] σ_h/σ_e represents the multiaxiality of stress state which can be expressed as $h = \sigma_h/\sigma_e$. This reference stress is a characteristic stress, by means of which a **cm-responding** relationship between multiaxial fatigue test data and uniaxial fatigue data can be made. The stress components in Eq [3] are the maximum values in a cyclic fatigue test and these need to be calculated by means of finite element analysis. Once the references stress is determined the total reference elastic strain range can be evaluated from

$$\Delta\varepsilon_t = \Delta\sigma_{ref} \,/\, E \qquad [4]$$

which can be compared with uniaxial data, An example data set using this approach is shown in Fig. 6 for the 2CrMoNiVW steel at 550°C

The above has provided validated test techniques and analysis procedures for establishing multiaxial creep and fatigue constitutive laws, which can be used as input into appropriate algorithms for evaluating creep-fatigue damage in components.

Task 3 - Laboratory Validation of Representative Multiaxial Stress and Strain Approach

An axially loaded notch bar subjected to time dependent deformation results in a spatially non-uniform, time **varying state of'** stress. **A** methodology for creep and fatigue crack initiation using notched bars ideally requires validation by subjecting materials to an homogeneous time-invariant state of stress. This can potentially be realised by testing materials using specially designed triaxial cell test machines and testpieces. Task 3 was aimed at just such a validation exercise. The experimental requirements for loading, heating and strain measurement were very demanding, and a number of' novel and innovative techniques were implemented to achieve this end. **A** patent has been accepted for the novel test machine,

Task 4- Establish Algorithms for Determination of Time or Cycles to Failure Initiation in Operating Components

There are numerous algorithms available for calculation of uniaxial creep-fatigue damage. Some of these tentatively address loading situations where a state of multiaxial stress exists but often assume effective stress control for both fatigue and creep. Whereas this maybe reasonable for fatigue, it could potentially be non-conservative for creep, especially under triaxial tension.

The most popular algorithms from a users standpoint attempt to use simplifying procedures, and on the whole these determine creep and fatigue damage components separately using baseline uniaxial creep, cyclic stress-strain and fatigue data and then the damage components are combined using an appropriate damage summation rule. This provides the most attractive and practical way forward for an analogous multiaxial route whereby baseline multiaxial creep and fatigue data are instead used. In this way conventional algorithms can be used but the uniaxial rupture lives, ductilities and cycles to crack initiation constitutive laws replaced by their multiaxial counterparts.

A number of candidate algorithms, based on design and life assessment, have been put forward and evaluated in the VALID project. The critical features addressed included steam turbine bore and periphery discontinuities, turbine easing bolt thread regions and turbine blade cooled wails.

Task 5- Validation of Failure Initiation Algorithms by Representative Component Tests and Evaluation of Field Data

In this task the algorithms developed in Task 4 were evaluated and validated where possible for the critical components through the use of simulated component laboratory testing or on the basis of field experience of actual in-service components.

For the steam turbine rotor steels model laboratory sized rotors subjected to rotational loading were conducted. The spin testpiece is shown in Fig. 7. Finite element analysis established the stress state and stress distribution behaviour using laws developed in Task 2. Fig 8 illustrates how the multiaxiality of stress state changes with time across the radius of the testpiece. Creep damage detected at the expected crack initiation site could be adequately predicted using material laws and a simple algorithm for multiaxial creep.

A condition assessment technique was evaluated in this task based upon a temperature accelerated extrapolation methodology in which a notched bar is customised to simulate the state of multiaxial stress generated in the component or feature. These are then tested at a common effective stress and lives extrapolated to the service temperature. This technique, which involves the testing of removed samples, potentially offers enhanced accuracy in long-term remaining life predictions in situations where triaxial stresses predominate

For the Nimonic 80A bolting case, full size nut-bolt assembly tests were carried out under creep and creep-fatigue loading to simulate base load and transient operation. The testpiece geometry is shown in

Fig. 9. Finite element analysis provided information on the important stress components in the thread locations and a design-based algorithm for multiaxial creep-fatigue damage provided validation.

For gas turbine blading, model simulation testing was not a feasible option within the project because of the complexity of the operating conditions. Validation for this case was carried out against service experience data. This involved detailed physical and metallographic examination of retired IN738LC blades, which had suffered in-service cracking. Well documented service behaviour, together with appropriate materials data provided input into a thermal transient and finite element stress analysis of the blade geometry (Fig. 10) for determination of the critical stresses and strains. These were used, together with the damage algorithms from Task 4 and material laws in Task 2 to establish the time/cycles to crack initiation which were compared to the actual service condition. The predicted level of creep-fatigue damage indicated that no cracking should have occurred during the 43,000h and 1100 cycles the blades had experienced, although the location of cracking at the cooling holes was correctly predicted. The difference between the prediction and in-service experience was ascribed to the effect of oxidation, which was not modelled.

For the assessment of microstructural degradation in gas turbine blade superalloys such as IN738LC it is realised that the processes are complex involving such factors as coarsening and rafting of primary γ' particles, dissolution of *secondary γ' particles,* degeneration of MC carbides and formation of grain boundary networks of y' and $M_{23}C_6$. Furthermore, cavitation and microcracking are also very important contributors to failure.

The whole spectrum of degradation processes will need to be taken into account in order to arrive at an accurate prediction of life and quantitative information on these processes is often lacking. There is, however, considerable evidence in the literature that accurate mean service exposure temperature in various parts of blades may be estimated from quantitative metallographic characterisation of γ' particle sizes volume fractions and shapes. Reasonable estimates of remaining creep life can be made using these temperatures and calculated operating stresses, by reference to laboratory creep rupture data.

It was clear that a number of factors, ranging from metallographic sample preparation, imaging, measurement, to data treatment techniques could all lead to considerable errors or differences in results and hence in life estimates. As a consequence, it was decided that it would be worthwhile for participants to carry out a round-robin exercise on a standard sample of IN738LC with a view to making recommendations for standardisation of techniques to be used for quantitative metallography on the alloy. As a result of this round-robin exercise a number of recommendations were made, in particular the use of "positive etching" to enable realistic measurement of γ ' area fractions.

Task 6- Development of an Off-Line Lifetime Monitor Based on a Non-Destructive X-Ray Analysis System

A non-destructive means of assessing life expenditure of critical component features to improve predictive accuracy either directly or by refining the analytical approaches was evaluated in this task. The principle of the proposed technique relies on X-ray diffraction line profile analysis which can be related to inelastic strain. Within the project, the technique was explored for the case of steam turbine rotors under creep loading, yet is likely to have broader applications.

The success of the technique was verified by applying it to a number of relevant test features being analysed elsewhere in the project. In particular localised strain measurements were made on notch rupture specimens in an attempt to support the theoretical predictions. Additionally, localised strain measurements were made for the same purpose on "spin-rig" specimens from Task .5. Task 6 therefore occupied a key position in helping to validate the multiaxial creep methodologies produced within the project.

Development work was initially focused on the 1 CrMoV rotor steel being tested elsewhere in the programme, but the scope was eventually broadened to include 2CrMoNiVW steel. A range of specimens crept to different strain levels were produced at 550°C and 6 10°C. These were tested using high accuracy laboratory based X-ray diffractometer equipment in order to quantify the relationships between X-ray line breadth and strain. Line profile analysis was carried out using software developed by Siemens for use on their diffractometer system. It was found that most data could be well described by means of Pearson functions which enabled ready determination of "FWHM" line breadths.

It was found that creep strain accumulated under load leads to a significant reduction in FWHM line breadth, particularly for the higher order X-ray reflections. In some cases, thermal exposure alone also contributes to line broadening and therefore due account must be taken of thermal ageing effects when seeking to isolate the effects of creep strain.

It was found that creep gave rise to a 15% (or so) drop in FWHM throughout specimen life. This is not a large change and clearly data scatter is important. However, the results indicate that the most rapid changes occur during the first 1 % (or so) of creep strain which is the strain regime of particular interest for service components such as rotors (see Fig. I I).

It was found that the variation in FWHM difference (aged blank-crept values) with creep stain was independent of temperature. Thus it appears that the parameter is uniquely related to strain.

A survey was conducted to indicate the potential and requirements for introducing a portable system for application to service components.

Task 7 - Code of Practice for Improved Design and Life Assessment of Turbine Equipment Operating under Multiaxial Creep-Fatigue Loading

The development of algorithms and techniques, as described in the previous tasks above, were incorporated into a code of practice for life assessment of critical components in combined cycle power generation plant. A number of example applications of the code were documented covering the life assessment and design of steam turbine rotor equipment. It is concluded that the code requires further validation work before it can be used comprehensively with confidence.

5. Benefits

The economic benefits arising from a capability for accurate life prediction of turbine equipment are substantial. Major beneficiaries include:

- Plant Manufacturers

Increased competitiveness in world markets for new and refurbished plant contracts through improved design and improved fitness for purposes guarantees.

- Plant Users

An improved life assessment capability leading to optimised future maintenance and plant rehabilitation strategies, reduced investment for new plant, increased plant operational flexibility and the safety, conservation of fuel and environmental benefits resulting from optimised availability and reliability of old high-merit plant.

6. Conclusions

The following conclusions can be drawn from the work carried out in the BRITE-EURAM VALID project.

A Code of Practice has been formulated offering a route for improved life assessment techniques of critical turbine components subjected to complex multiaxial loads.

The Code requires further validation before it could be used comprehensively with confidence. On the other hand it is expected to have improved accuracy over other codes which do not explicitly address multiaxial loading.

Uniaxial and multiaxial materials data have been generated on four important steam and gas turbine materials which has led to an improved understanding of material performance under complex loading conditions relevant to operating experience.

Test techniques and analysis procedures have been developed to enable multiaxial constitutive laws to be established with confidence.

A patent has been submitted on a new triaxial stress testing machine.

- A range of candidate algorithms have been developed addressing multiaxial creep and fatigue damage in a range of industrial turbine components that have led to improvements in the capabilities for life assessment for end-users and design considerations for manufacturers.

Laboratory based and in-service field experience validation exercises have been conducted that have established the strengths and weaknesses of the candidate algorithms and highlighted the areas where further validation is required.

Two condition assessment techniques have been developed and partly validated. These can both be incorporated into life assessment routes in order to refine or periodically re-calibrate the calculational based approaches.

7. Acknowledgements

The BRITE-EURAM VALID Participants wish to acknowledge the support of the CEC under Contract Number BREU-CT-9 1-0.524.

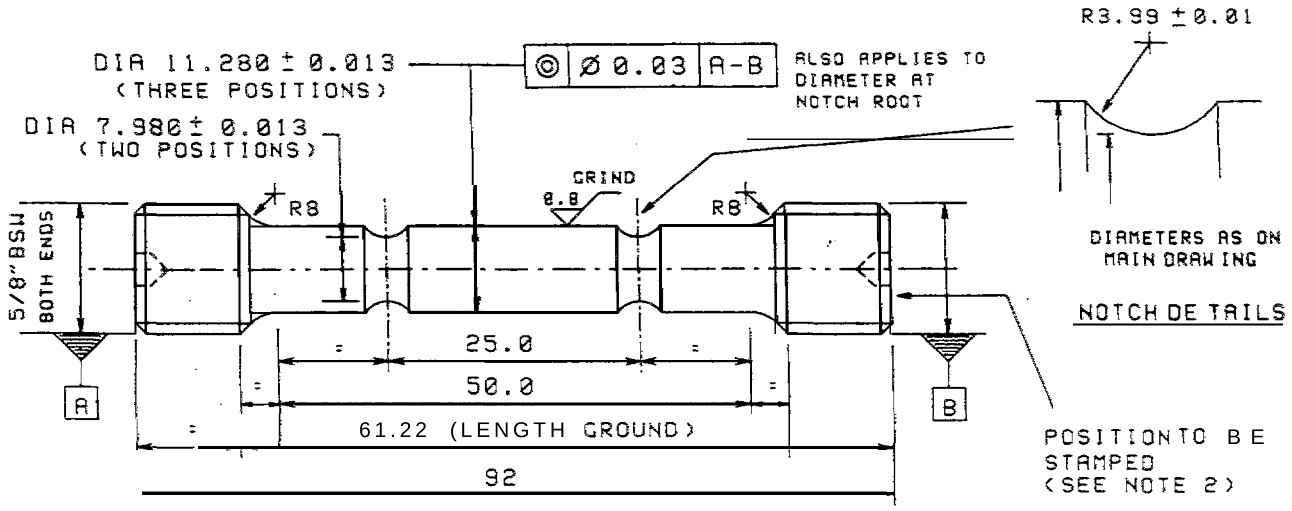

Fig.1: BluntNotchB arGeometry

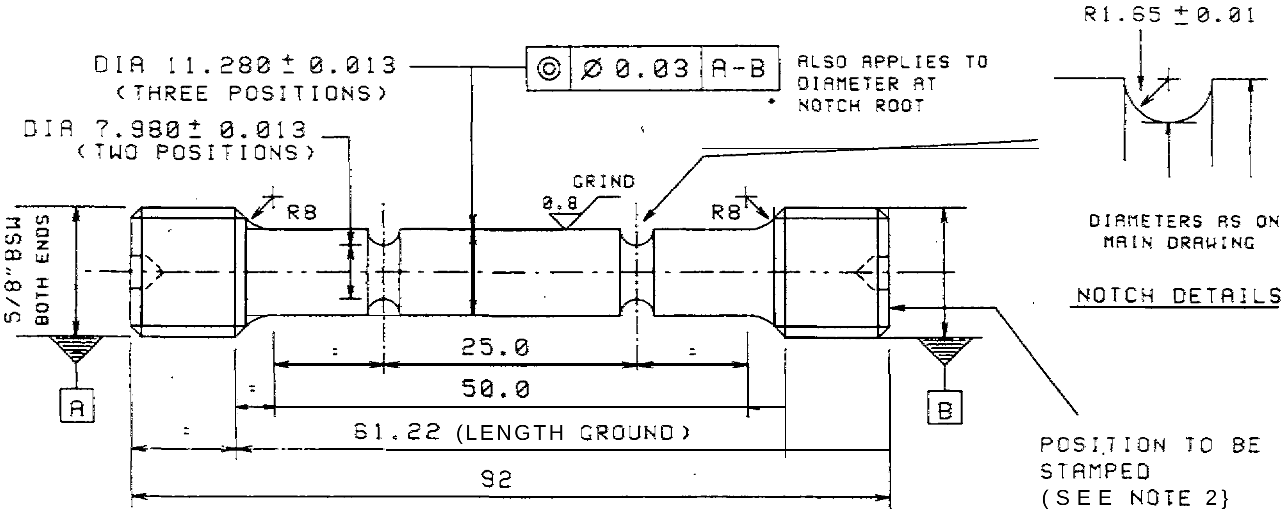

Fig. 2: Semi-Circular Notch Bar Geometry

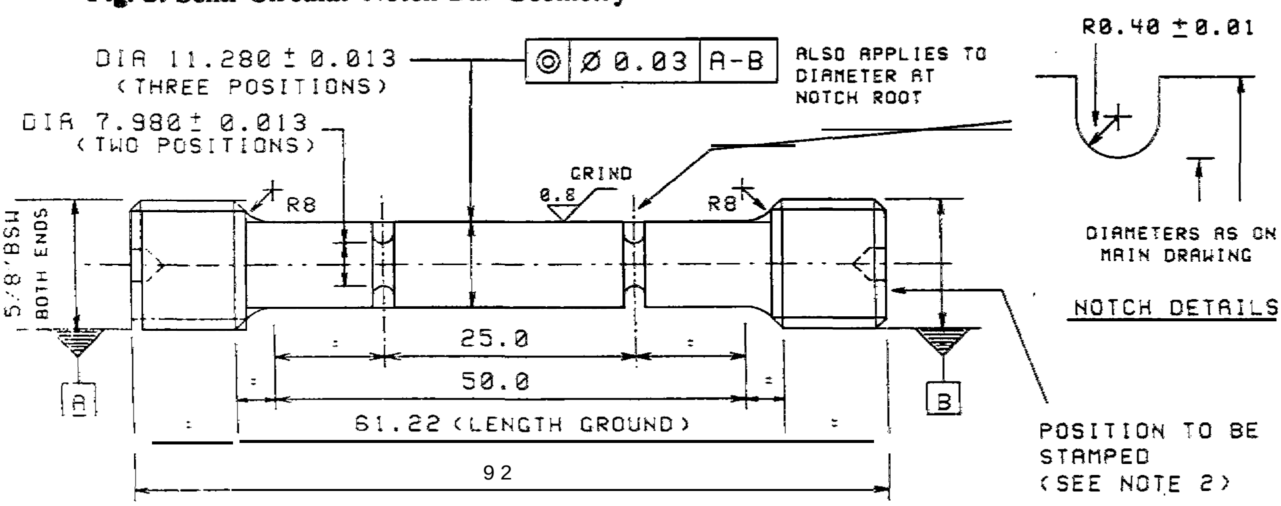

Fig. % SharpNot chBar Geometry

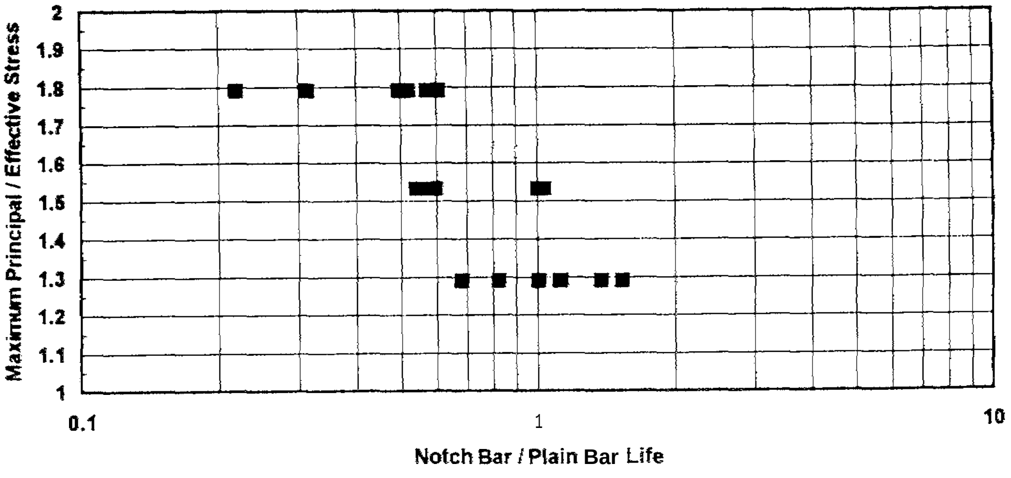

Fig. 4: Multiaxial Stress Rupture Criterion Plot for 1 CrMoV Rotor Steel at 550°C

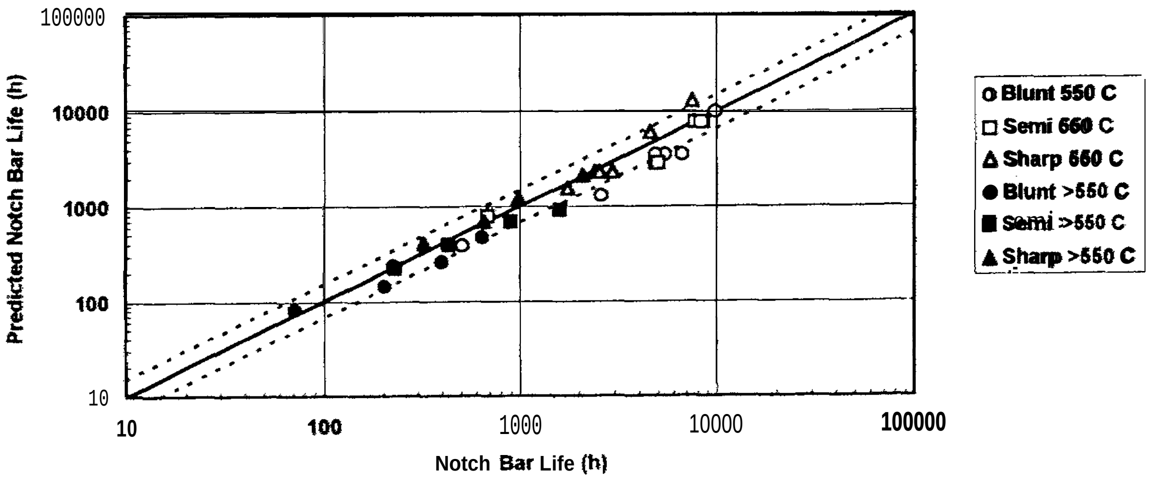

Fig. 5: Predicted Notch Bar Rupture Life for 1 CrMoV Rotor Steel

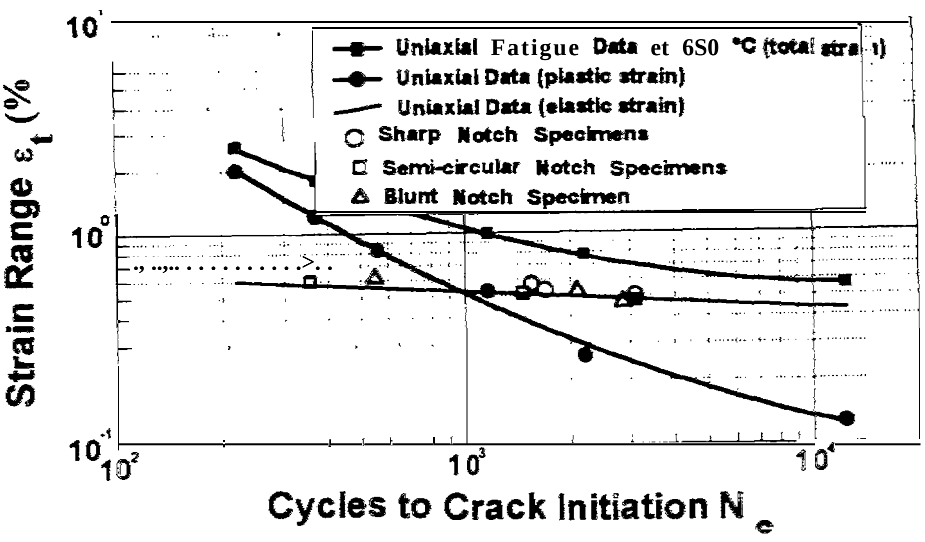

Fig. 6: Uniaxial and Multiaxial Fatigue Data for 2CrMoNiVW Rotor Steel at 550°C

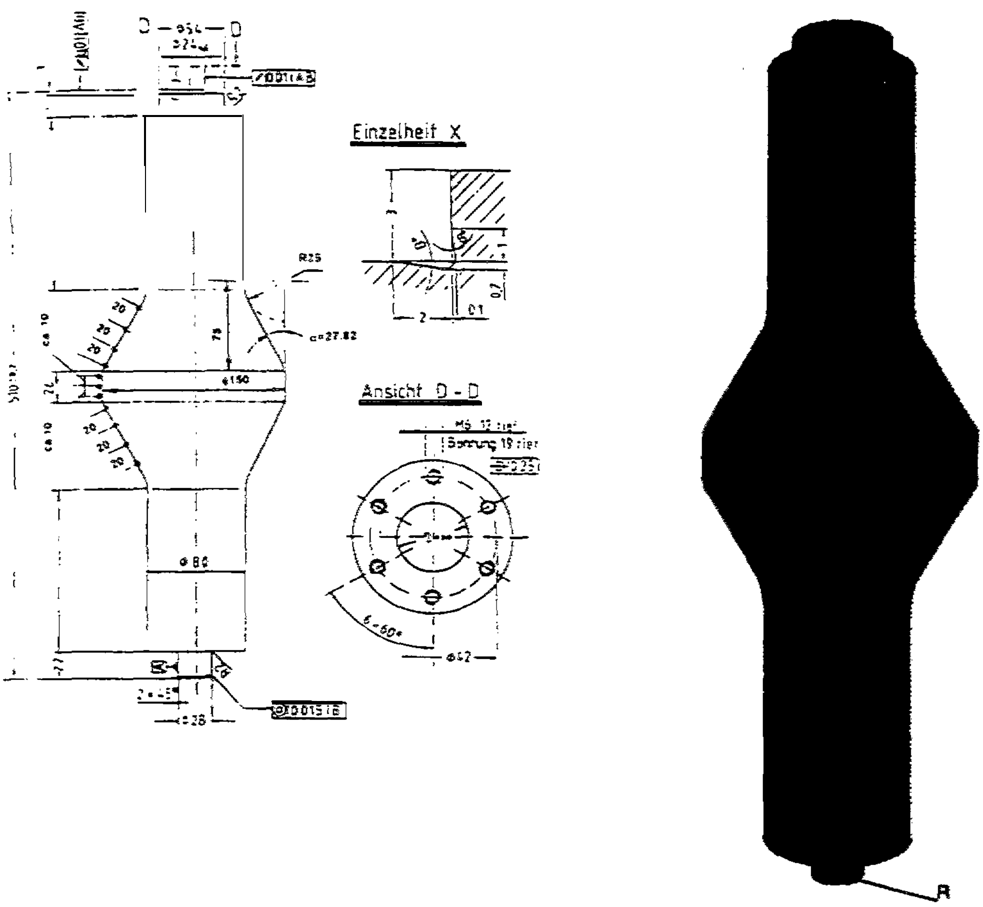

Fig. 7: Spin Testpiece Geometry for Simulating Multiaxial Conditions on a Rotor

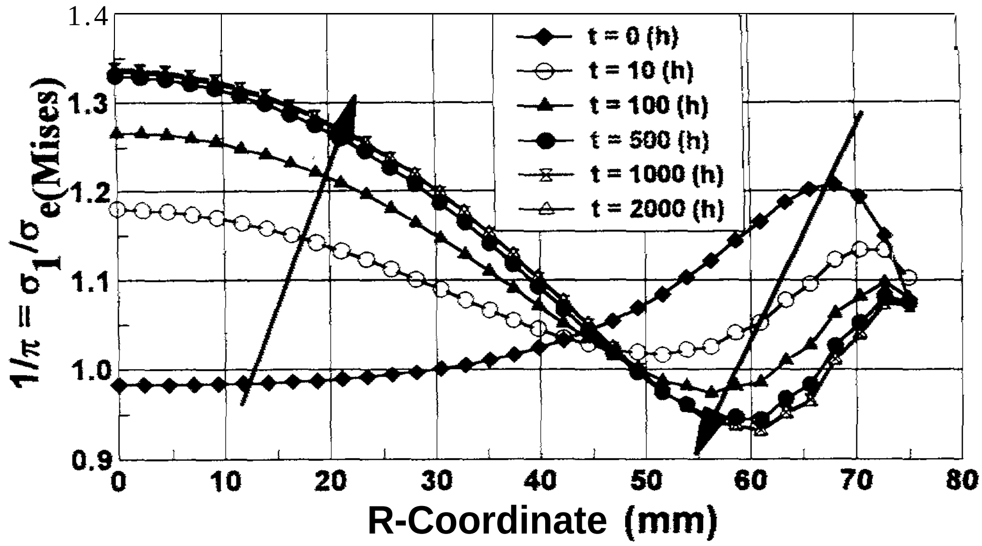

Fig. 8: **Multiaxiality of** Stress State in the **Spin** 'Test during **Creep**

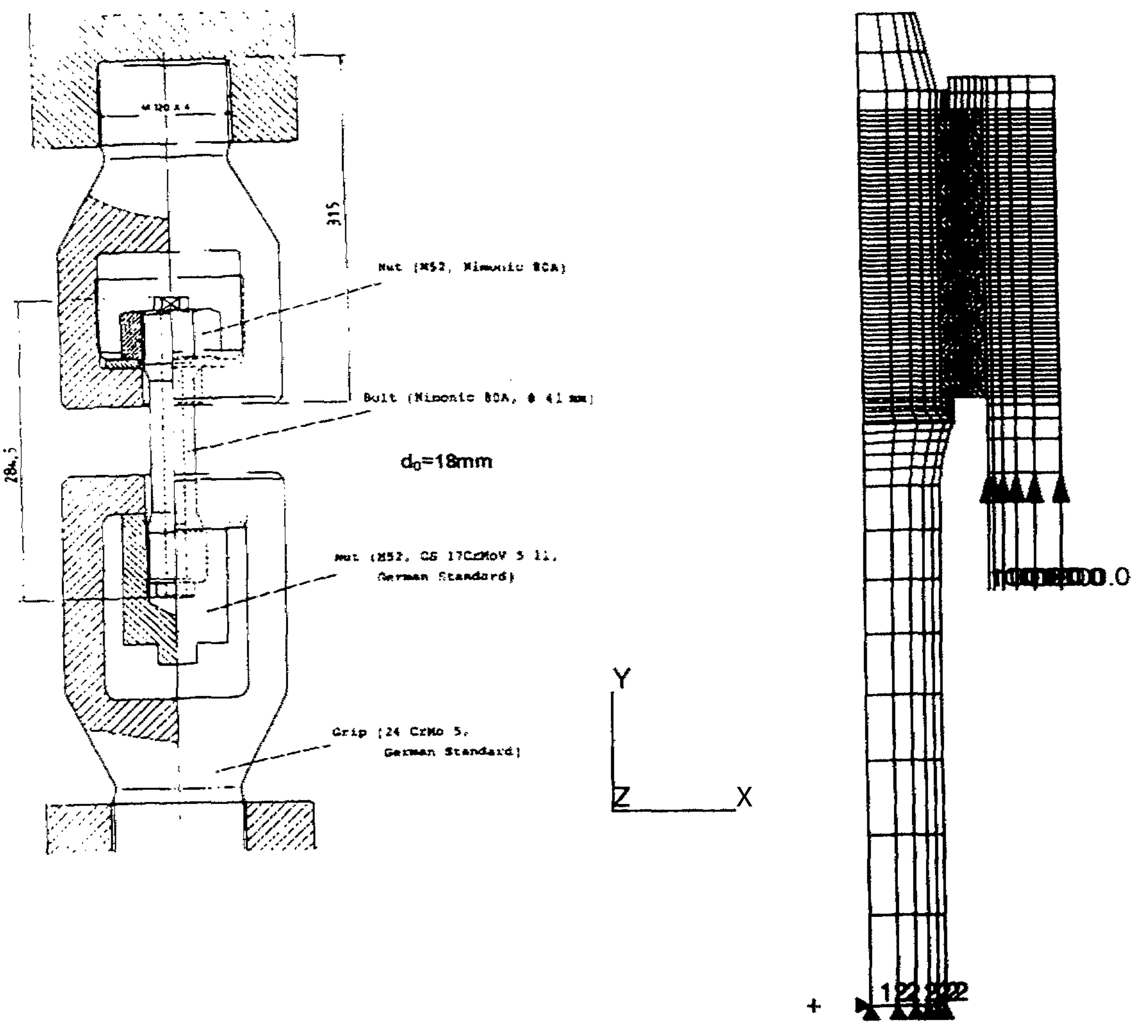

Fig. 9: **Nut-Bolt** Assembly Geometry Details **and Finite Element Model**

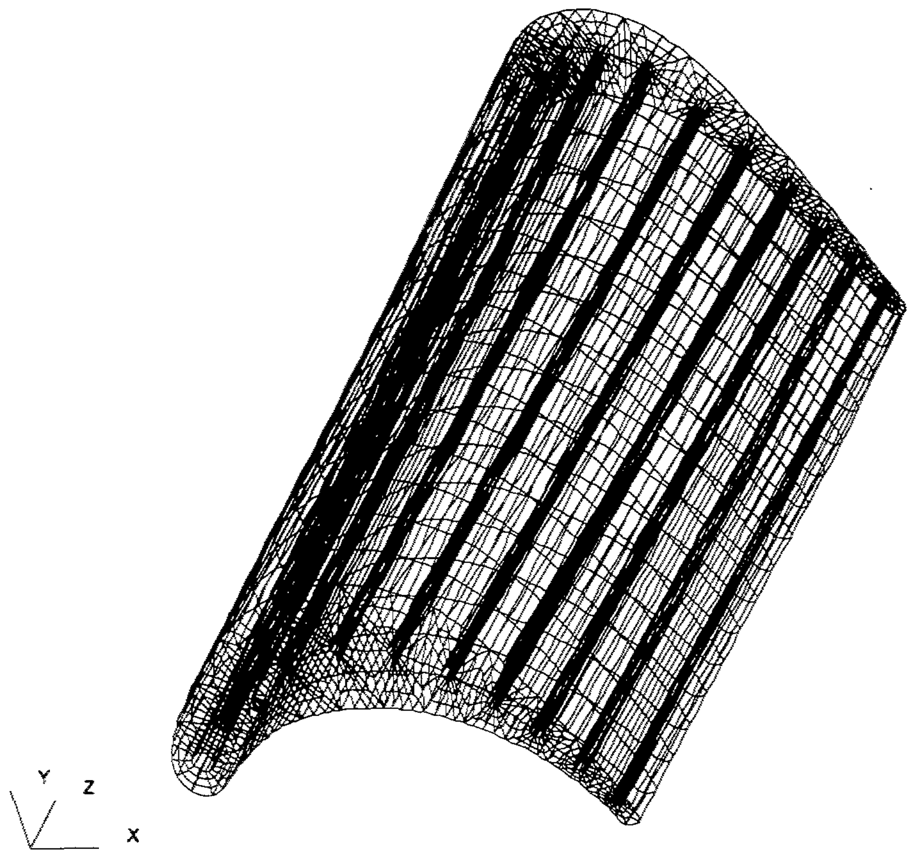

Fig. 10: **Finite** Element **Model** for **First** Stage **Cooled** Gas Turbine Blade

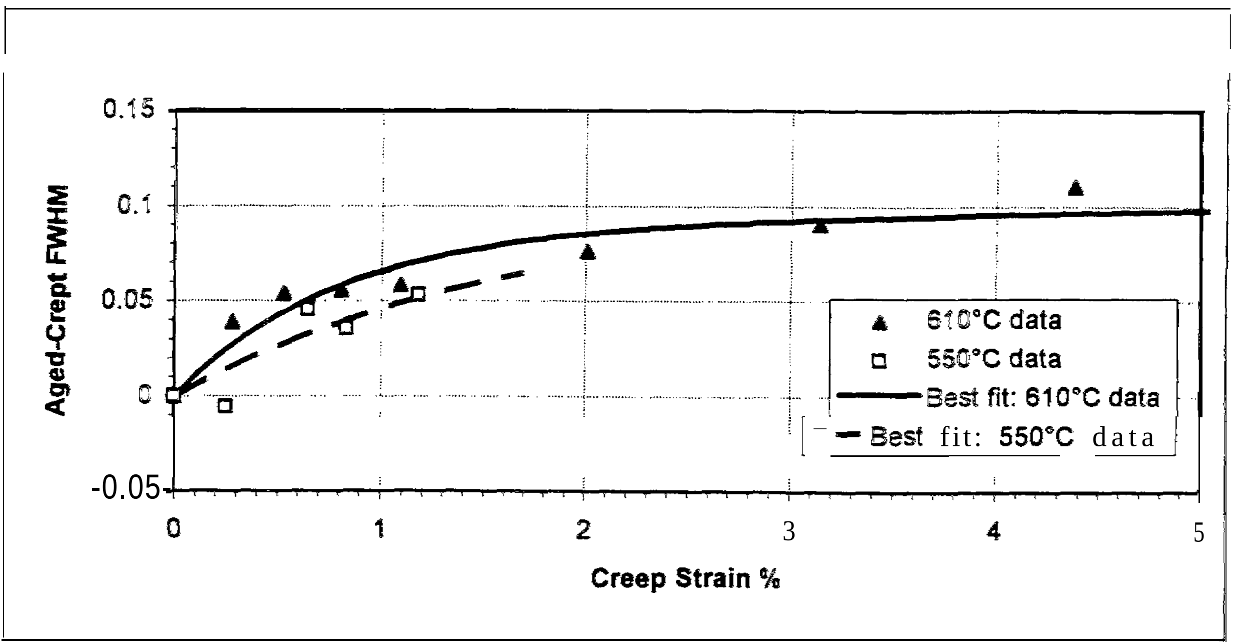

Fig. 11: **Effect of Creep** Strain **on** [211) **X-Ray** Line Profile **FWHM values** for **1CrMoV**