

SUPERGEN

Conventional Power Plant Lifetime Extension Consortium

Case Study: Cracked Header

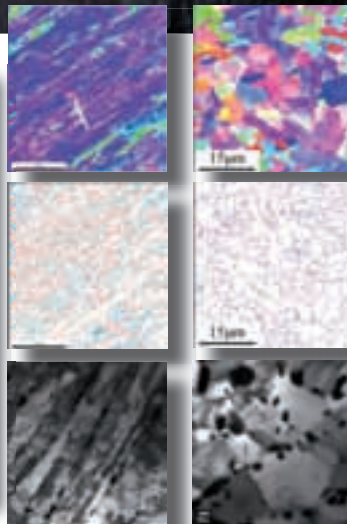
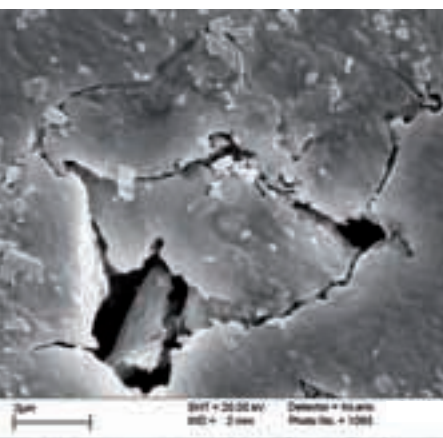


The Engineering Problem

This case study focuses on a header, which is a major component in a coal fired power station. The role of the header is to combine the flow of steam from the many elements in the boiler into one flow to drive the turbines of the power station.

The header is a complex construction comprising a number of cylindrical steel barrels butt welded together, each with an outside diameter of 450 mm and a wall thickness of 50 mm. Several hundred connections are welded onto the header, which itself is over 25 m long and weighs ~18 tonnes. It was designed to BS1113:89 for a steam pressure of 17.5 MPa, an operating temperature of 580°C and a service life of 150,000 hours. The header was manufactured from Grade 91 steel, which contains a high concentration of alloying elements, particularly chromium, and which was first introduced into the power industry in the UK in the late 1980s as a replacement for components made from lower alloy steels which were experiencing problems with cracking at the time.

This particular header was a retrofit component installed in a power station in 1992. Routine maintenance in 2004 found cracks after only 58,000 hours of service. These cracks were quite small so that it was possible to repair them safely. However, cracks had reappeared by 2006, leading to the replacement of the complete header assembly in 2008. Inspection of the header showed that the Type IV cracking had occurred, which is a mode of cracking where cracks initiate and grow within the heat affected zone adjacent to the welds.



Finding the Solution

Possible reasons for the observed cracking include both environmental conditions, such as the service temperature and system stresses, and the properties of the steel itself. Detailed investigation of the service conditions indicated that the temperatures or stresses are unlikely to be the sole contributing factors to the observed cracking.

Work carried out at Loughborough University has established that the concentration of minor elements, nitrogen and aluminium, in Grade 91 steel are extremely important in determining its mechanical properties. Indeed, examination of the test certificates, showed that the cracks had occurred in parts of the component with the lowest nitrogen to aluminium ratio. This therefore provides a simple tool to identify components which might be susceptible to premature cracking, and which then should be the subject of more detailed inspections.

Further research has used advanced characterisation techniques to examine the underlying reasons why the concentration of these minor elements has such an influence on creep life, and has led to an in-depth understanding of the evolution of the fine scale structure of the steel. Furthermore, the structures observed in laboratory experiments under accelerated conditions have been benchmarked against those obtained under 'real' service conditions and the results from miniaturised mechanical testing, giving confidence in ranking the behaviour of different components.



Advancing the Technology

Key technologies to improve understanding of the important problem of Type IV cracking have been developed encompassing three main areas. The first is a comprehensive understanding of the factors controlling the mechanical properties of different Grade 91 steel casts (Loughborough). The second is by finite element simulation of the temperature, stress and microstructures developed during welding (Nottingham). The third is the development of direct experimental techniques to measure the stress state in situ and the ability to remove small samples from deep within a welded component (Bristol) which are invaluable for assessment of the mechanical properties. These methodologies are now being applied to assist in the development and lifing of new steels which will be used in future high efficiency, low CO2 emission, power plant.

We are particularly grateful to Dr S J Brett of RWE npower for his contribution to this Case Study.



We would like to acknowledge the support of EPSRC through the Supergen 2 programme (GR/S86334/01 and EP/F029748) and the following companies: Alstom Power Ltd., Corus, E.ON Engineering Ltd., Doosan Babcock Energy Ltd., National Physical Laboratory, QinetiQ, Rolls-Royce plc, RWE npower, Sermatech Ltd. and Siemens Industrial Turbomachinery Ltd. for their valuable contributions to the project.

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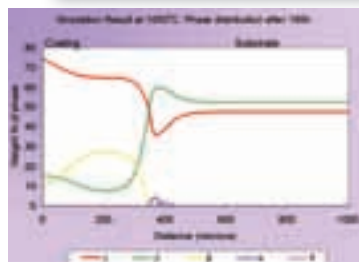
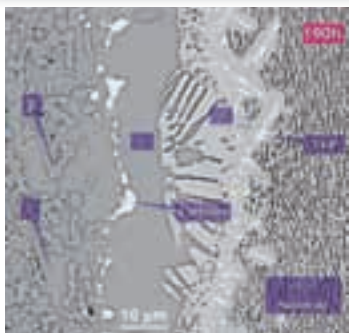
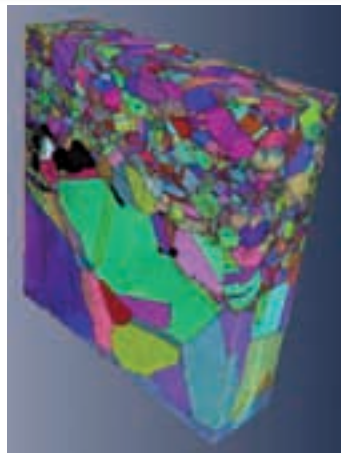
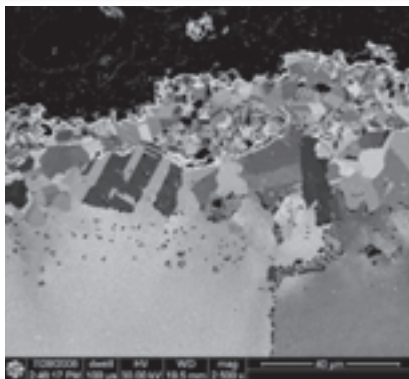
Case Study: Coatings for Industrial Gas Turbine Blades



The Engineering Problem

Gas turbine engines are widely used in industrial power generation and will continue to be a significant part of the UK energy portfolio for the foreseeable future. However, the demands placed on these engines are changing, including the requirement to cycle more frequently, to utilise increasingly 'dirty' fuels, and most importantly to operate with increased efficiencies to reduce emissions. These engines typically operate at gas temperatures of approximately 1150-1450°C, resulting in a need for materials which can withstand not only these high temperatures, but also the aggressive operating environments. Nickel-based superalloys are usually employed for the turbine blades because they have excellent high temperature resistance, whilst retaining high strength at operating temperatures. However, in order to provide additional protection against oxidation and corrosion, and therefore to minimise the risk of service failures, these alloys are often coated. The coating systems typically comprise a metallic coating rich in elements such as chromium and aluminium, used either on its own for corrosion resistance, or as a bond coat between the substrate and a ceramic thermal barrier coating to protect against the high temperatures.

During service in an engine, a variety of changes can occur in the coated blade system due to the mixing of elements between the coating and the superalloy, which can in turn affect the mechanical properties and remaining useable service lifetime of the component. It is therefore necessary to optimise the choice of coating and blade material to best suit the operating conditions. In addition, inspection of power plant components is extremely costly and it is crucial for plant operators to know when a particular component needs replacing.

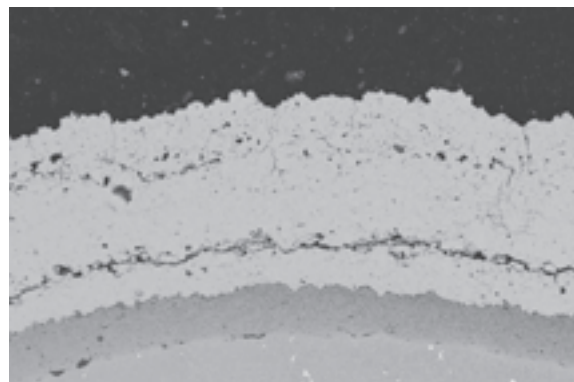
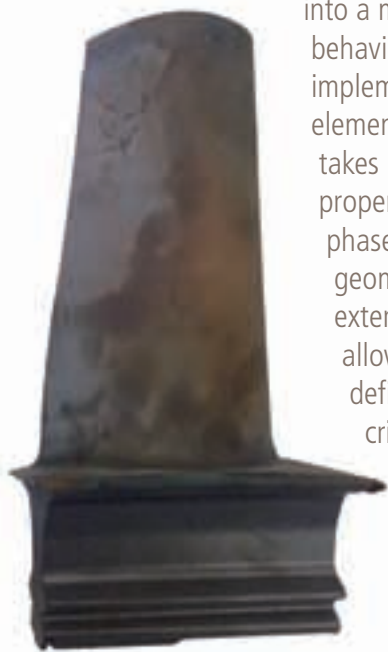


Finding the Solution

The aim of this research has been to model simultaneously and characterise experimentally the environmental degradation of selected coated turbine blade systems in order to improve life prediction and failure assessment methods for these critical high temperature components in gas turbines. Service conditions have been simulated by thermally treating samples in combustion gas environments (Cranfield), and then the resulting oxide at the outer surface of the metallic coating has been accurately quantified (Bristol).

A novel model has been developed (Loughborough) which is capable of predicting the microstructure of a coated blade system as a function of time. The model is based on principles of diffusion, oxidation and thermodynamics, and can accurately predict the phases present throughout the coated system as a function of increasing exposure. The model has been successfully applied to a number of practical systems to simulate their behaviour under service conditions, and validated by careful experimental quantification using a range of advanced analytical techniques for a variety of laboratory aged and ex-service materials. The microstructural model has been used as an input

into a model for mechanical behaviour (Nottingham), implemented using a finite element scheme which also takes into account the properties of the various phases, complex blade geometries and applied external loads. This then allows, through the definition of a failure criterion, prediction of the likely remaining life of the coated system.



Advancing the Technology

An advanced and holistic approach has been developed for the modelling of complex coatings systems, unifying various previously separate strands of chemical, metallurgical, microstructural and mechanical predictions. It is now possible to forecast, using parameters such as the chemical compositions of the coating and superalloy system, coating thickness and the exposure history as inputs, the evolution of the microstructure across the coating/substrate system, to estimate the losses due to oxidation and most importantly the likely remaining life of the component based on a specified failure criteria.

The models developed are additionally now being used in reverse to develop both new, improved coatings and also to better tailor the coating chosen to the particular superalloy substrate in order to optimise the useful service life of the component in the increasingly harsh environments in which they will need to operate. This also has the potential to reduce development costs as only the most promising solutions require experimental testing, and to significantly reduce the time to market of new materials systems for industrial power generation.

We would like to acknowledge the support of EPSRC through the Supergen 2 programme (GR/S86334/01 and EP/F029748) and the following companies: Alstom Power Ltd., Corus, E.ON Engineering Ltd., Doosan Babcock Energy Ltd., National Physical Laboratory, QinetiQ, Rolls-Royce plc, RWE npower, Sermatech Ltd. and Siemens Industrial Turbomachinery Ltd. for their valuable contributions to the project.

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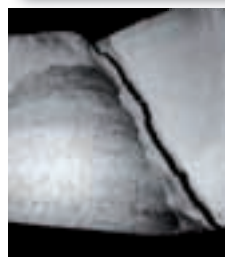
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Case Study: Residual Stress Modelling in Welded P91 Pipes



The Engineering Problem

Welds are an integral part of pipeline steel components in power generation plants. The process of welding involves multiple thermal cycles which induce thermal and residual stresses in the weld regions and heat affected zones (HAZ). Residual stresses can sometimes lead to premature failure, for example by causing intergranular stress corrosion cracking. Multi-pass circumferential welds are typically applied to produce joints in steel pipes which conduct steam under high temperature and pressure. Such joints are considered to be the weakest part of the structure. Therefore, in comprehensive structural integrity and safety assessments in power plants, it is essential to examine pipelines stress states, including residual stresses.

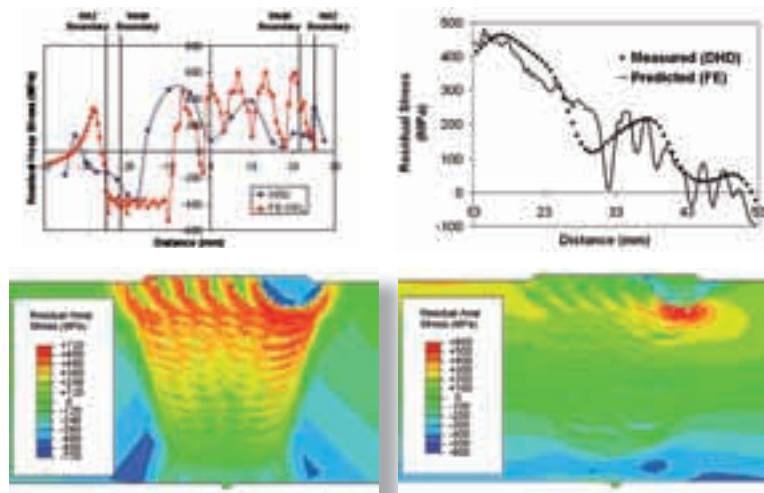
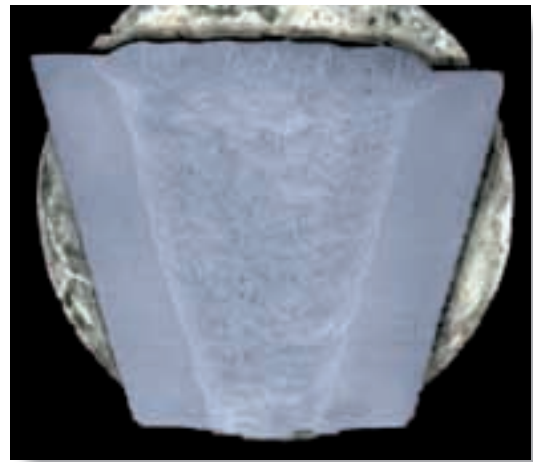


A versatile and efficient means of determining residual stresses in power plant pipes is the finite element (FE) method. Once the relevant material properties are fed into an FE numerical simulation, the residual stress field in the modelled component is obtained. In this case study, residual stresses in a multi-pass circumferentially butt-welded P91 steel pipe have been determined using the FE method. The results have been corroborated by comparing them with residual stresses obtained from two experimental techniques, X-ray diffraction (XRD) and deep-hole drilling (DHD), which have provided measurements of the stress field at the outer surface of the weld and HAZ and through the wall thickness at the weld centre, respectively.

Finding the Solution

The FE simulation of welding, including the determination of residual stresses, consists of a thermal analysis, which represents the thermal process during welding, followed by a sequentially coupled structural analysis, based on the temperature history obtained during the thermal analysis. An axisymmetric FE simulation has been performed using temperature-dependent material properties. The heat source is modelled by applying a triangular distributed heat flux for the application of each weld bead. A technique called 'element birth' is employed to connect the weld elements to the pipe parent material, preventing any displacement or strain mismatch. The modelled ferritic steel pipe has a 290mm outer diameter and a 55mm wall thickness. P91 grade steel contains 9% chromium, 1% molybdenum, and approximately 1/4% vanadium (wt%). The overall microstructure of the parent P91 steel pipe is tempered martensite with a prior austenite grain size of $\sim 20\mu\text{m}$ (mean linear intercept).

Measurements for the XRD technique have been made using Cr $K\alpha$ X-radiation to produce a diffraction peak at $2\theta \approx 156^\circ$ from {112} planes. An incident beam collimator of 1mm diameter has been selected. The DHD technique consists of gun drilling a small reference hole in a radial direction through the wall thickness. The diameter of the hole is then measured using an air probe system at 0.2mm intervals along the axis of the hole. A column of material with the reference hole as its axis is trepanned from the specimen using electro-discharge machining allowing the residual stresses in the column to relax. The diameter of the hole is then re-measured using the air probe system. The relaxed strains are determined from the diameter measurements before and after trepanning. The relaxed strains are converted to residual stresses assuming linear elastic material behaviour.



Advancing the Technology

During welding, thermal cycles cause microstructural changes in the P91 steel. The austenite (face centred cubic) to martensite (body centred tetragonal) phase transformation introduces changes in the volume, yield strength and strain hardening behaviour of the steel. It also involves shear, inducing transformation plasticity. This has all been accounted for in the FE simulation. The FE residual stress fields have been compared with the XRD and DHD stress results, demonstrating good correlation and proving that the FE method can be sufficiently accurate in determining residual stresses due to welding. The determined residual stress field can form part of a wider scheme for the integrity assessment of welded components under investigation.

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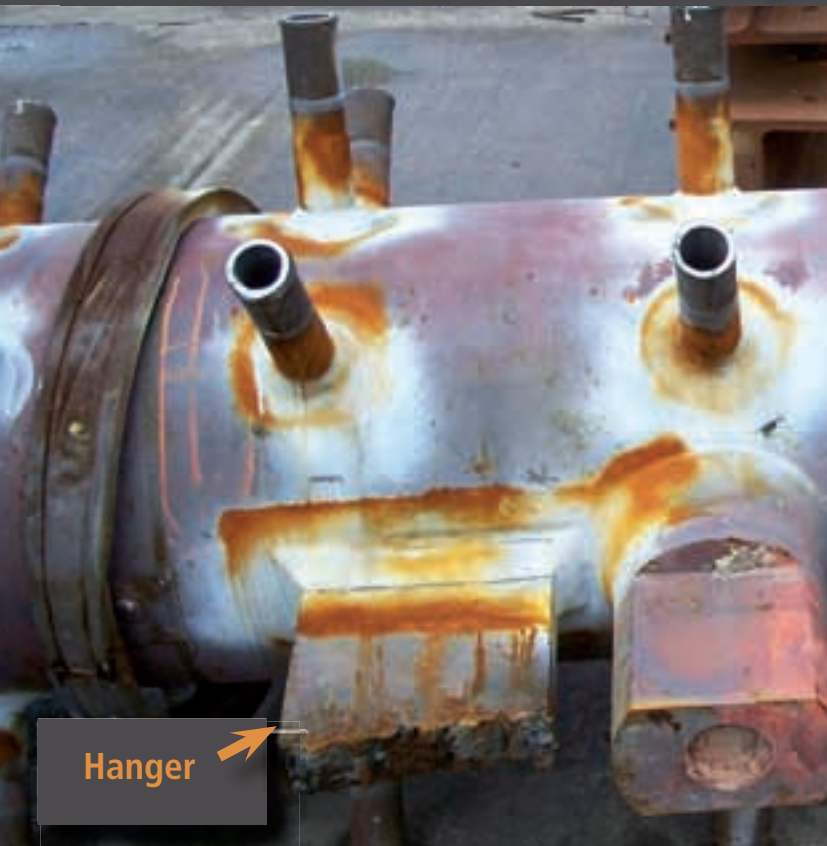
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Case Study: Creep Damage Modelling in a P91 Header Hanger



The Engineering Problem

P91 steel has been widely used in the UK power industry for the last two decades. This grade of steel is usually martensitic in structure and when correctly tempered is highly resistant to creep. For that reason, it has been specifically used in power plants for retrofit header applications. A typical example of this application is the P91 steel header shown here, which, until recently, had been used in the fossil-fuel power-generation industry in the UK. Although significant creep damage had not been expected during the header's early life, Type IV cracking initiated after approximately 50,000 hours of service and extensive cracking was detected at branch and attachment welds on the header after 58,000 hours of service. For that reason the header was taken out of service at 79,000 hours.

Although more cracks appeared at header stub welds compared to other attachments, it was generally deemed representative of header cracks due to creep to consider the structural integrity of a hanger plate welded to the steel header. The header operated at an average steam temperature of 570°C and pressure of 16.6MPa. It was constructed from six P91 cylindrical barrel sections having an outer diameter of 450mm and a wall thickness of 50mm. There are many attachments to the header including 408 stubs. The steel hanger plates, which are welded to the top surface of the header along its axis, are 50mm thick, 220mm long and around 0.5m in height.

