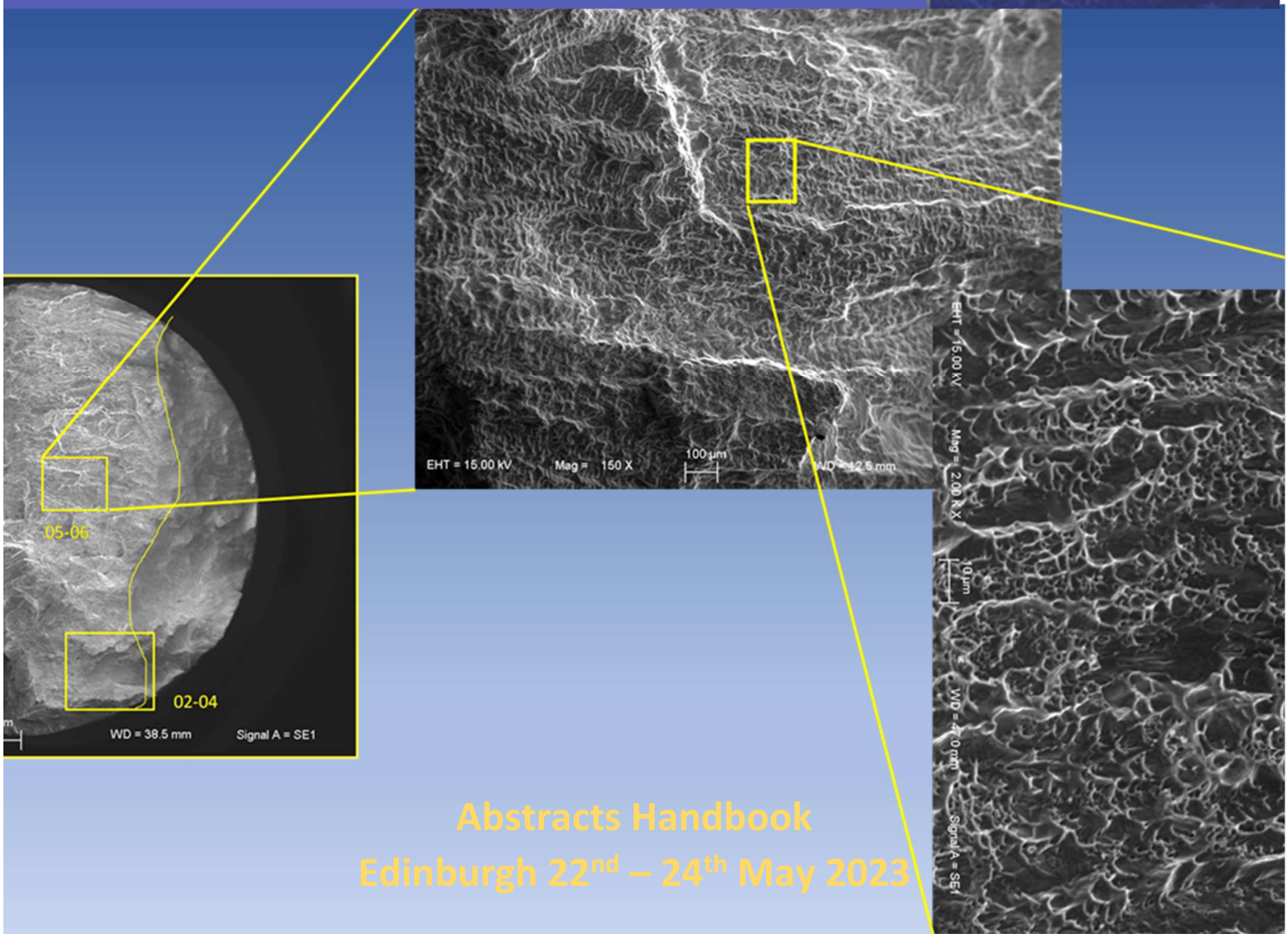
ECCC 2023

6th International Creep & Fracture Conference



Abstracts Handbook

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European Creep Collaborative Committee

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The UK High Temperature Power Plant Forum, a working group of the High Temperature Mechanical Testing Committee and represents the UK partners to the ECCC, were responsible for the organisation of the conference and the publication of these proceedings. Copies of the proceedings are available for purchase from the ECCC website https://www.eccc-creep.com/

Plenary Paper 001: The ECCC History and Current Activities: The Value of the Work That We Do for the Introduction and Use of Newer Materials.

Dr A Di GIANFRANCESCO
Chair of ECCC

Summary
ECCC is a voluntary grouping formed in 1991 to co-ordinate Europe-wide development of creep data to be used to design components for high temperature plants, bases on a Memorandum of Understanding, signed by all partners.

The ECCC is deeply involved in EU coordination for the development of knowledge on the damage caused by the creep phenomenon and the consequent reliability assessment activities. The link with the European Standard organizations correlated to the technical committees give an efficient network, an indispensable means of mutually exchanging technical information relating to current/future activities for the improvement or development of new materials.

For several years ECCC (1991-2005) concentrated efforts by EU support. Nevertheless, revitalization of ECCC has been generated by definition of Joint Industrial Project (JIP) started in 2011 and still running (JIP4).

ECCC has a very strong link to industrial applications and it is presently organized in four Work Packages: WG1 on common procedures, data generation/assessment and three material specific Working groups: ferritic steels, austenitic steels, nickel-based alloys. Two main outputs are ECCC data sheets and ECCC Recommendation Volumes. The ECCC activities are almost completely carried out by members' contribution-in-kind.

The ECCC plays a part of its role, in term of generation of design properties for new materials introduction into power plant and related applications. It therefore engages a crucial role in assessing and realising the potential of new developments.

Key Words
ECCC; European Creep Collaborative Committee, Datasheet, Ferritic steels, austenitic steels, superalloys, creep data assessment, Post assessment tests

Plenary Paper 002: Energy Sustainability and the Need for a Balanced Approach to Ensure Adequate Energy Security

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Abstract

Energy sustainability is not just about meeting environmental standards, including low carbon emissions, important though that is. It is also about ensuring that energy resilience can be maintained to ensure security of supply at an affordable price. An energy transition is underway, which is moving forward at different speeds in different regions depending in part on each country's commitment and political drivers, linked to each country's access to national and external energy sources. However, unless proper consideration is given to establishing a balanced energy mix there is the potential for security of supply to be badly compromised, which can readily spread to become a larger problem. These interlinked factors are presented and discussed, drawing on the situation that has arisen in the European Union as a cautionary example.

Plenary Paper 003: Results of United States Advanced Ultra-Supercritical Component Test Project for 760°C Steam Conditions

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Abstract

Following The U.S. Advanced Ultra-Supercritical (A-USC) Consortium was formed in 2001 as a government/industry program, sponsored by the U.S. Department of Energy (DOE) and the Ohio Coal Development Office (OCDO) and cost shared by industrial and not-for-profit partners. The purpose of the consortium was to advance the state of the art for power generation by evaluating and developing materials that allow the use of advanced steam cycles in coal-based power plants.

These advanced cycles, with steam temperatures up to 1400°F (760°C), can increase the efficiency of coal-fired boilers from an average of 35% to more than 45% higher heating value (HHV) (>49% lower heating value [LHV]). The increase in a plant's efficiency is limited unless new materials able to withstand these higher operating temperatures and pressures are identified and approved for use.

The A-USC Consortium identified these needed materials during earlier phases of the program. It developed the welding and joining techniques along with manufacturing processes for casting and wrought products made from these new high-nickel alloys. It subjected these materials to extensive laboratory and steam loop testing. It then obtained ASME code approval for their use in U.S. boiler systems. The program's successes leave this last remaining activity (ComTest Phase 2) that the U.S. utility industry has recommended to be accomplished prior to commercialization.

The focus of the activity is the evaluation and demonstration of commercial readiness for "full scale" components to be made from these nickel-based alloy materials and provided by a U.S. domestic supply chain that is new to working with these alloys.To reduce the final identified risk barrier to full-scale commercialization of these advanced materials and systems, the A-USC Consortium (guided by a utility industry advisory committee) has identified the key areas of the technology they desire to see as being capable of full-scale

manufacturing and/or fabrication from an identified, capable U.S. domestic supplier base.

A significant amount of work was accomplished during Phase 1 to identity the components, as well as the component size, that would be manufactured from advanced alloys such as Inconel 740H or Haynes 282 alloys. The Phase 2 effort used Phase 1 findings for designing these key full-scale components for A-USC boilers and turbines to include large castings; extrusions, forgings, fabrication of water walls and steam loops with headers from advanced materials, raw material (such as pipe extrusion billets) are at the commercial readiness level to permit advancement to a demonstration project. The Phase 2 work scope was addressed by a diverse team, including government, industry, and not-for-profit partners.

The work scope under Phase 2 addressed fabrication of components identified as being outside of the proven capabilities of the existing supply chain, including the following:

- Steam turbine rotor forging and Haynes 282 nozzle carrier casting
- Superheater and reheater header and tube assemblies
- Large-diameter pipe extrusions and forgings
- Test valve articles to support ASME Code approval

In addition, key fabrication steps were completed, including boiler weld overlays and simulated field repairs. Throughout, extensive inspection and quality assurance testing of the components were performed. The team worked to advance ASME Code approval for key components and processes.

Plenary Paper 004: High Temperature Properties of Reduced Activation Ferritic Martensitic Steels for Fusion Applications in ITER: Status of Activities and Design Needs for EUROFER97 Steel.

P. LAMAGNÈRE

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4. SCK CEN, Nuclear Materials Science Institute, Mol, Belgium
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Summary

The ITER facility, under construction at Saint Paul-Lez-Durance, southern France, is a major step towards the validation of the technologies required in a future Fusion Power Plant (FPP), connected to the grid and able to produce electricity. In particular, one of the missions of ITER is to demonstrate through Test Blanket Modules (TBM) the feasibility of tritium breeding and extraction of high heat fluxes, both of which are requirements for the Breeding Blanket components to be operated in the next DEMOnstration reactor currently under development in the EU. For the Initial Configuration of ITER, four TBM will be provided by the European Union (EU), Japan (J), China (CN) and Korea (K), each of them using a Reduced Activation Ferritic Martensitic steel (RAFM) as structural material.

Among the different RAFM grades proposed for future FPPs, the reduced activation 9%CrWVTa steel EUROFER97 has been developed by EU on the basis of conventional 8-12%CrMoVNb steels where Mo and Nb are replaced by W and Ta and a strict control of minor elements is specified in order to improve nuclear waste management. Four batches and various semi-finished products have been produced by Boehler, Austria and Saarschmiede, Germany. Plates and bars from batches 1 to 3 have been tested in several European labs, including high temperature creep and creep-fatigue experiments and material properties are

already included in the “probationary rules” tome of the French nuclear code RCC-MRx used for the design and manufacturing of the TBM. Full qualification to the code’s standards is ongoing with the characterization of batches 3 and 4 in order to complete the validation of design rules appropriate to RAFM and related supporting data.

This paper presents an overview of the creep properties of different RAFM steels, in particular, those of EUROFER97 as obtained during the ongoing qualification program for the design of the European TBM, supported by EUROfusion under agreement with F4E.

Key Words
Fusion, Reduced Activation Ferritic Martensitic steels, EUROFER97, Creep, Creep-Fatigue, RCC-MRx.

Plenary Paper 005: The Need for a Paradigm Shift in High-Temperature Design of Nuclear Reactors.

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Abstract

This paper gives and overview of the contribution of nuclear energy for the energy transition with a goal of net-zero green gas emission by 2050. The specific features of nuclear are crucial for the stability of the electrical grid and security of supply. Moreover, nuclear produces both hear and electricity through co-generation. A major challenge for the deployment of new nuclear, in particular Generation IV reactors that operate at higher temperatures and with more corrosive coolant such as liquid lead, is the need to qualify material for new operational conditions. This is discussed in the paper with examples. The conclusion is that the time for material qualification needs to be drastically reduced and that digitalization and artificial intelligence is expected be a key to achieve this.

Key Words

Material Qualification, Generation IV reactors, creep, corrosion, lead cooled reactors, advanced manufacturing, Digitalization, artificial intelligence, machine learning, prescriptive and performance-based regulation

Plenary Paper 006: Primary Energy Demand in South America: Current Status and Future Projects for Hydro, Nuclear, Renewable and Fossil Fuels.

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Abstract

The objective of this work is to present a quantitative description of energy demand in South America. Available information from different countries is analysed. Conventional demand of fossil fuel, hydroelectric and nuclear energy is considered. Additionally, focus is placed on current development of non-conventional energy sources (i.e. wind and solar), in different countries.

Given the world objectives of reducing CO2 production, available information about actions, objectives, and positions is presented. Updated targets set by individual countries are addressed.

Key Words

Primary energy consumption, electricity production, hydroelectric, nuclear energy, fossil fuels, renewable energy sources, CO2 emissions.

Paper 001: The status and forecast of lifetime assessment using small samples in Japan for fossil fuel power plants.

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Shinichi KOMAZAKI, Kagoshima University

Abstract

Although high accuracy is expected in the remaining life assessment by a destructive test method, there is a problem that a thickness of the assessment portion becomes to be thinner, or repair welding is required when the sample is taken from components to conduct the destructive test. Therefore, in Japanese fossil fuel power plants, the remaining life assessment by the destructive test method has hardly been performed for high temperature components except for boiler tubes. However, in response to the demand for high accuracy for the remaining life assessment, attempts toward the application of the destructive test method to actual components have recently become eminently active in Japan, as following. A creep remaining life assessment of high chromium steel welded portions using small samples was proposed by a research institute and has been applied to the assessment of hot reheat piping and main steam piping in several USC plants. A uniaxial creep test technique using a sample of almost the same size as the small punch test piece has also been developed by a testing-related company. It was confirmed by experiments that the test technique gives the same creep rupture life and deformation curve as the standard creep test specimens. Furthermore, discussion and examination on the application of small sample technologies to the life assessment of actual components started in 2022 as WG activity in the Society of Materials Science, Japan, which consists of utility companies, fabricators, inspection companies and academic organizations.

Key Words

Creep, small sample, destructive assessment, fossil power plant, small punch.

Paper 003: Review of the New Developments in Understanding Creep.

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Summary

This paper summarizes the recent creep research by the author including classic five power-law creep, power-law breakdown, Harper-Dorn creep, and a mention of long-range internal stresses in creep-deformed metals and alloys. Many of the models and theories for these phenomena persisted for a relatively long period of time. More recent developments in these phenomena are discussed that may lead to new interpretations of creep in crystalline materials. The review is relevant to pure metals and class M alloys (behaving as pure metals).

Key Words

Creep, five power-law creep, power-law breakdown, Harper-Dorn creep, long-range internal stresses, metals, alloys.

Paper 004: Metallographic Analysis of the Type IV Damaged HAZ with Reference to the Electromagnetic (EM) Inspection Technology.

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Abstract

To assess the creep life of the heat-affected zone (HAZ) of a welded joint, the development of a microstructure was investigated using a transmission electron microscope (TEM) with regard to electromagnetic hysteresis loop analysis, coercivity, and x-intercept in the B-H diagram. The magnetic domain wall mobility was assumed to be related to the microstructure development. It increased with creep damage accumulation up to the local minimum with regard to small creep life fraction and decreased to the local minimum at ~0.3 of creep life fraction. Coercivity again increased for the latter half of the life fraction and reached the maximum level up to the fracture. The change in the coercivity was caused by the domain wall motion interference; coarse M23C6 precipitation and ripening in the HAZ based on creep deformation, i.e., the size and interparticle space of M23C6 at the HAZ. Such Precipitation morphology change decides also a creep deformation resistance. The latter half of the creep life in the HAZ was determined based on the creep cavity related to the crack growth process considering the scanning electron microscope analyses.

Therefore, coercivity represents the coarse precipitation number density in the HAZ for small creep life fractions, and it was decided based on the creep crack growth and unit domain partition considering the number of crack increase of the latter creep life fraction. The interaction between the domain wall and M23C6-type carbide was confirmed using focal point shifting based on the TEM analysis method. Integrating the results and discussion, coercivity change was considered to representing the creep-damaged microstructures with life fraction as relevant for a new creep life estimation method.

Key Words

Magnetic domain, Domain wall mobility, Creep resistance, Precipitates, Grain boundary, Crack growth, Coercivity.

Paper 006: An Update on the Development of the UK MarBN steel, IBN1

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Summary
Extensive research and development has been undertaken in the UK on MarBN steels. These were first proposed by Professor Fujio Abe at NIMS in Japan and the work in the UK has done much to commercialise them through a series of Government funded industrial collaborative projects (IMPACT, IMPEL, INMAP and IMPULSE). These projects have resulted in a number of significant achievements including: large scale melts with controlled composition; installation of trial tubes in an operational power plant; production of full-scale extruded pipes; development of a matching welding consumable; and most importantly, a new steel, IBN-1, with creep strength 25-30% higher than Grade 92. In 2020 UK Government industrial collaborative R&D funding has been awarded to a follow-on project IMPLANT which sought to codify the UK MarBN steel, IBN-1, to allow its use in new build and retrofit applications. In addition, the project investigated opportunities to further increase its creep strength. This paper highlights the work undertaken in some of these earlier projects and will provide an update on the progress of the IMPLANT project. The report will also discuss the potential implications of the findings from UK MarBN steel projects.

Key Words
MarBN steel, Grade 91, Grade 92, creep, castings, tubes, extruded pipe, new build, retrofit.

Paper 007: Anisotropy and Secondary Creep Behavior of Functionally Graded Cylinders under Plane Stress

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Summary

The present study analyses the influence of anisotropy on the secondary stage creep behavior of thick-walled functionally graded cylinders by considering plane stress condition. The cylinders under investigation were composed of 6061Al reinforced with silicon carbide whiskers (SiCw). The reinforcing whiskers decrease nonlinearly from the inner surface to the outer surface of the cylinder. The cylinder was subjected to internal pressure only. The extent of anisotropy was described by a parameter, δ which ranges from 0.6 to 1.4. During the study, it was found that cylinder having relatively higher strength in tangential direction as compared to radial and axial direction leads to considerable lower values of strain rates. Further, the presence of anisotropy does not have prominent effect on radial and tangential stresses. However the effective stress varies considerably in the presence of anisotropy.

Key Words

Anisotropy, Creep, Composite, Functionally Graded Cylinder, Pressure.

Paper 009: Some Important Considerations in Creep Modeling of Ferritic Steels and Nickel-Based Superalloys

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Abstract

Trends in creep life with respect to stress can vary significantly based on the form of the rate equation and this in turn is influenced by the nature of the rate controlling obstacle. Recognizing this aspect is important since shortcomings in creep models are in many cases attributed to myriad microstructural changes while in fact it is the basic creep mechanism which needs to be properly accounted for. It is proposed that nano-scale vanadium carbonitrides and dislocation nodes are the rate controlling obstacles in ferritic steels and superalloys respectively. We also posit that the main role of gamma prime particles in superalloys is composite reinforcement of the matrix. With these definitions, simple constitutive equations, similar in spirit to the Larson-Miller parameter are presented. The ability of these equations to predict long term behavior and remaining life are demonstrated using data on CrMoV steel, IN738 superalloy and T91 steel.

Key Words

Creep, ferritic steels, superalloys, Larson-Miller parameter, microstructure.

Paper 010: Prediction of 'Effective' Corrosion Rates By In–Situ Internal Pressure Creep Testing in LBE for Ti-Stabilized DIN 1.4970 (15-15Ti) Austenitic Stainless Steel Cladding Tubes

Stefan HOLMSTRÖM, Erich STERGAR, Serguei GAVRILOV, Valentyn TSISAR, Jasper JORIS, Eloa Lopes MAIA
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Abstract

In this paper a new high temperature methodology of determining 'effective' corrosion rates is presented. The methodology has been developed to estimate the interaction of corrosion and creep to establish temperature limits for the use of 1515Ti claddings in high temperature Lead-Bismuth-Eutectic (LBE) both for service conditions foreseen for the MYRRHA reactor concept and for assessing effects of temperature excursions in accident scenario simulations. The results presented are compared to static corrosion rates determined from earlier test campaigns in stagnant LBE. The initial internal pressure tests have been performed in the temperature range 650°C to 800°C conducted as 'blind test', i.e. the measured corrosion depth (and measured nominal corrosion rates) from the specific samples had not yet been measured beforehand. The test programme has since evolved to pin-point test conditions of interest to find optimal test settings for longer term testing closer to in-service temperatures. All tests are conducted on the specific heat of the 24% cold worked 1515Ti cladding tube batch fabricated by SANDVIK (now Alleima) that is currently used at SCK CEN as reference cladding material for the MYRRHA design efforts. The virgin material tensile strength and the high temperature creep properties that are the basis for the here presented corrosion rate estimation methodology is based on the creep failure model for the virgin material and is extended with the lifefraction rule to accommodate for the life reduction caused by the sought 'constant' effective corrosion rate at the specific test temperature and developing stress state. The creep models that is the basis of the iterative process for determining the corrosion rates in the significant creep range have been determined and optimized during the EERA JPNM pilot project TASTE, and more recently updated by the data collation put together at SCK CEN from historical data (specific cold work range of 16%-24%.) and the ongoing PATRICIA project.

Key Words

Creep, corrosion, 1515Ti austenitic stainless steel, Lead-Bismuth coolant, cladding tube

Paper 011: Thermal Creep Properties of Virgin and Irradiated Cladding Tubes Made of Ti-Stabilized DIN 1.4970 (15-15Ti) Austenitic Stainless Steel

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Summary
This paper presents assessments performed on a large database of virgin material and irradiated material thermal creep data from uniaxial and pressurized DIN 1.4970 Ti-stabilized austenitic stainless steel (i.e. EN 1515CrNiMoTiB or "15-15Ti" cladding tubes. The data base incorporates multi-heat data from uniaxial and bi-axial (internal pressure) creep tests conducted during the fast reactor R&D program of the DeBeNe (Deutschland-Belgium-Netherlands) consortium between the 1960's to the late 1980's together with more recent data, e.g. from the European projects MATTER and PATRICIA and the EERA JPNM pilot project TASTE.

The data comprises of a virgin material data base and a data base with irradiated creep data. The virgin material data comprises of time-to-rupture and time-to-0.2% creep elongation in a temperature range of 600-800°C and covers a large range of stresses. The irradiated data base has less data and does not cover all material heats tested for the virgin material properties. The irradiation conditions are also different depending on the test reactor specifics and the irradiation campaign targets. The attained 'irradiation damage' in displacements per atom (DPA) for the irradiated materials range from 0.1 up to 38.1.

Un-irradiated 'reference material' models for tensile strength and creep strength are constructed from the current-state of the art literature data and more recent results from the Sandvik 24% cold worked 1515Ti cladding tube currently used as the main material batch studied at SCK CEN. The tensile strength model is used throughout the paper for normalizing creep strengths by the tensile properties, needed when applying the Wilshire (WE) creep model. Time factors (TF), stress factors (SF) and temperature ratio factors (TRF) are calculated for different material states for describing the impact of heat treatments, (virgin and irradiated) and irradiation conditions. This initial study targets to give estimates of for the thermal creep properties of cladding tubes with a cold work range of 16-24% in a non-annealed state, as it is the preferred option for future designs according to the state-of-the art knowledge base.

However the main bulk of the available data on irradiated material is on claddings with a cold work range of 0-16% with and without annealing and at various levels of irradiation damage, thus leading to the need for estimation by interpolation and extrapolation assuming that irradiation damage levels and trends, e.g. time reduction factors found on a lower cold worked material can also be applied on materials with higher cold work levels. The results of the assessments clearly show relative strength differences between chosen material heats and heat treatments and has enabled constructing simple multilinear models for estimating the life of irradiated material. The models show that low creep test temperatures (and irradiation temperatures), low stress levels, low levels of cold work and high irradiation doses are increasing the detrimental difference between the specific material condition and the reference material.
Also, it was found that the general level of life reduction of irradiation damaged material roughly coincides with the virgin material time to 0.2% creep strain. The estimated 'failure creep temperature limits' for 30 000 hours of service are studied and compared for both virgin and irradiated materials at a reference stress level of 1/3 of the tensile strength (at temperature).

Key Words
Thermal creep, 1515Ti austenitic stainless steel, cladding tube, irradiated material creep properties.

Paper 012: Preparation of an ECCC Creep Datasheet on Sanicro 25 Tubes for Power Generation and Petrochemical Use

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Summary

The advanced austenitic stainless-steel Sanicro 25 © has been developed by Sandvik to provide a higher creep-strength, seamless steam tube and pipe steel for power generation use above 600 °C up to about 725 °C; with potential for related use in petrochemical industry. As part of its activities the ECCC produces property data for design and life assessment of pipes and tubes for pressure purposes, both for its internal membership and for consideration by European Standards. According to ECCC procedures, two independent assessments were performed by the authors from EdF and GE within Working Group 3B "Austenitic Alloys", and considered for an ECCC datasheet on Sanicro 25. A novel combined tensile and rupture data assessment was performed, according to the integrated approach - previously described in ECCC 2021 Creep Conference. The second assessment resulted in a split region Wilshire Equations approach, and extended that assessment to include traditional parametric forms, and a Manson-Haferd "Hybrid" model (with a single region sigmoid stress function), with a better fit at low stresses than polynomial models. This paper describes how such models were prepared and then selected for the ECCC Sanicro 25 datasheet on rupture and 1% creep properties. The resulting properties are considered in the light of previous assessments of those properties, e.g. for ASME and VdTüV, and the next steps for full commercial exploitation of Sanicro 25, and a brief comparison with alternative alloys.

Paper 013: Mechanical properties assessment of additively manufactured Ti64 alloy using Small Punch Tests

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Summary
A study of the mechanical properties of Ti64 alloy through Small Punch Test is presented in this paper. The method and the validity of the correlation coefficients developed for nuclear steels are first verified on wrought alloy and then applied to additive manufactured material. The yield strength values obtained agree with the literature and domains of negative strain rate sensitivity could be highlighted for the microstructure resulting from additive manufacturing. The creep tests carried out showed good agreement between the present results and those reported in the literature on usual creep representations. This allows to validate the models used and to extend the small punch methods to the case of Titanium alloys. The results are used for comparing the mechanical behaviour of additive manufactured Ti64 alloy to that of wrought alloys.

Key Words
Ti64, Small Punch Test (SPT), Additive Manufacturing, Creep, Strain Rate Sensitivity (SRS), Tensile testing.

Paper 014: Evolution and Criteria for Early Creep Damage

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Abstract

The life-limiting fitness for service of high-temperature pressure equipment is of interest at the times of design, fabrication, initial acceptance and later assessments of condition and remaining creep life. Of the associated indicators, strain reflects creep by definition in design and in service, while the emerging and growing discontinuities like creep cavities and cracks are targeted in the in-service inspections. In addition, microstructure and hardness can provide supporting information on the initial condition and its subsequent thermal and other change. In this paper we compare such indicators and criteria for the creep-associated damage, particularly at the early stages, and discuss the potential to reliably assess low life fractions. The uncertainties in the operating conditions, materials properties and in-plant measurements tend to constrain the predicted safe remaining life (or time to next inspection). Improvements appear possible, for example in microscopy to support metallographic inspections, and in utilizing the widening inspection experience on newer materials. The present work successfully integrated the Wilshire/LCSP creep strain and rupture models with FE analysis for predicting creep strain evolution for the example component saddle point regions with observed creep damage. Since the predictive model applies for the whole creep curve, it can be used in principle for early stages of creep down to the limit of negligible creep, and to the lower limit of the window where creep cavitation damage can be observed.

Keywords

Creep, early damage, steel, life assessment.

Paper 015: Crack Driving Forces Under Creep Conditions in Presence of Material Inhomogeneity

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Summary

Under time dependent creep deformation in metallic materials in presence of a crack, the driving force is influenced at a distance in presence of a zone (such as an interlayer, interface, hole etc.) which deforms differently in reference configuration. This influence may increase or decrease the crack driving force based on the type of inhomogeneity (Elastic, plastic, creep). The nature and extent of influence of material inhomogeneity is studied in this work with a configurational force based rate of crack driving force definition for a crack in presence of dissimilar metal weld zone, HAZ and second base metal.

Key Words

Creep crack, material inhomogeneity, configurational forces, Dissimilar Metal Weld.

Paper 016: On the Dominant Effect of Crack Shielding in Superalloys Failure at High Temperature

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2. Carl Zeiss Microscopy

Summary

The durability of turbine jet engines are strongly dependent on the environment humidity and contaminants along with the operating stresses and temperatures. Turbine blades often experience crack initiation at multiple locations, which has the potential for arresting damage (crack shielding) or accelerating catastrophic failures (crack coalescence). Indeed, blade failure is sometimes unexplained despite the extensive research in the area.

This presentation will explore an integrated computational and experimental approach that evaluates crack interaction in CMSX-4 superalloy using C-Ring tests with a layer of contaminant salts exposed to 550C. A phase-field model calculates the diffusion of species and reduces the material critical energy release rate accordingly. The model, which is parameterised to enable cracking above a threshold stress, predicts the critical crack spacing that results in shielding or coalescence. In addition, the integration of X-Ray microscopy (XRM) characterisation with FEM modelling demonstrates univocally the role of crack interaction in stress corrosion cracking. We conclude discussing the value of integrating models and experiments to understand complex failure mechanisms.

Paper 017: Cyclic Softening Behaviour of CSEF Steels Under Load-controlled Low Cycle Fatigue at Elevated Temperatures: Ratcheting & Constraint Effect

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Abstract

Creep Strength Enhanced Ferritic (CSEF) steels with 9–12% Cr are innovative high-temperature materials which have found increasing applications in various industrial fields, e.g., in power generation and petrochemical plants, owing to their superior high-temperature mechanical properties such as excellent creep strength, lower susceptibility to thermal fatigue and oxidation resistance [1, 2]. Due to the changing landscape of the power generation industry, power plants are now expected to operate under extreme temperature and pressure conditions to enhance thermal efficiency while reducing carbon emissions, thereby resulting in accelerated creep, fatigue and creep-fatigue damage, which may potentially limit the service life of energy components. This raises the need for an improved understanding of the high-temperature cyclic response and the associated damage mechanisms of CSEF steels under low cycle fatigue (LCF).

When subjected to cyclic loadings, CSEF Steels can undergo cyclic softening, which is typically characterised by the decrease in the peak stress amplitude (under strain-controlled cycling) [3-5]. However, cyclic softening can also occur under stress-controlled cycling as manifested by the increase in the visco-plastic strain with cycles (known as ratcheting or cyclic creep) [6-8]. The latter form of softening is relatively less investigated in the literature, and therefore, the present study is concerned with probing the cyclic deformation and damage behaviour of CSEF steels under stress-controlled cycling experimentally and numerically. Since engineering components typically operate under multi-axial stress states, an in-depth understanding of the effect of constraints on the LCF performance at elevated temperatures is crucial for more reliable structural integrity assessments. Thus, in this study, we also explore the cyclic visco-plasticity behaviour under constrained conditions.

In order to simulate cyclic softening at elevated temperatures, numerous damage models have been introduced and often coupled with the unified visco-plasticity model. Most of these models are empirical in nature and do not provide physical insights into the viso-plasticity damage behaviour. To overcome this challenge, physically based models for predicting cyclic deformation and damage can be more advantageous. A recently proposed physically based damage model [9] will be utilized in this study to simulate the cyclic softening under stress-controlled LCF and to predict the associated microstructural evolution.

The main aim of this work is therefore to provide an improved understanding of the notch (constraint) and ratcheting effects on the cyclic visco-plasticity behaviour of CSEF steels at elevated temperatures via experimental characterisation and physically based damage modelling. Within the experimental study, fully reversed uniaxial and multi-axial saw-tooth (SWT) low-cycle fatigue tests were carried out on CSEF steels under load-controlled mode at 600oC to characterise the cyclic softening behaviour. Further, to interpret the experimental findings, the cyclic deformation and damage behaviour was modelled utilizing a physically-based visco-plastic constitutive material model, which accounts for the microstructural degradation during LCF deformation. The experimental and numerical studies offered an improved understanding of the key factors contributing to the cyclic viscoplasticity damage in tempered martensitic steels at high temperatures.

Keywords: Visco-plasticity; Cyclic softening; Damage; Ratcheting; Constraint; Notch strengthening.

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Paper 018: Creep of IN738LC manufactured with Laser Powder Bed Fusion: Effect of Build Orientation and Twinning

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Summary

The microstructural anisotropy caused by the highly oriented solidification of metal Laser Powder Bed Fusion (PBF-LB/M) process affects mechanical short- and long-term properties. Component build direction influences grain morphology and orientation, and thus, mechanical properties. While the creep behaviour of samples manufactured parallel and perpendicular to the build direction are studied intensively, the 45° build orientation remains uncharacterized.

In this study, IN738LC creep samples are manufactured via PBF-LB/M in three build directions (0°, 45° and 90°). While the results of 90° and 0° are as expected, where 90° achieves the longest time to rupture and largest rupture strain, the 45° specimen shows the least fracture time. Differences in microstructure and twinning behaviour are identified as one of the root causes for this unexpected behaviour. This study discusses the correlation between microstructure, twinning and build direction and their effect on creep behaviour, with special focus on the 45° build orientation.

Key Words

Laser Powder Bed Fusion, IN738LC, Build Orientation, Creep, Microstructure, Twinning.

Paper 019: Quantitative Physical Modeling of the Effect of Precipitates in the Subgrain Interior on the Creep Curve and Service Life of P91

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Abstract

This work deals with a physically-based creep model of the martensitic 9% Cr-steel P91. In particular, we quantitatively study the effect of precipitates located in the subgrain interior on the creep curve and the lifetime of the material. Our creep model is capable of simulating the microstructural evolution parallel to creep curves, and has been further developed towards predicting time-to-rupture (TTR) diagrams. We demonstrate how the number density, size and shape of the precipitates in the subgrain interior affect the creep curve and thus the lifetime of the material. Three according parameter studies on the material P91 compare microstructures with/without precipitates and/or assuming specific shapes by introducing aspect ratios. These simulations can be used as a basis for further development of materials with regard to the precipitation phases.

Key Words

Creep, martensitic 9-12% Cr-steel, P91, modeling, dislocation creep, dislocation climb, precipitates, microstructure.

Paper 020: Long-term Isothermal Ageing of Type N and Type K Mineral Insulated Metal Sheathed (MIMS) Thermocouples


Loveday

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Summary

The use of Nisil-Nicrosil (Type N) thermocouples has grown in recent years mainly because they are cheaper than noble metal Pt based thermocouples and they are perceived to be more stable than the Type K nickel-Chromium/-(chromel-alumel) thermocouples. In addition, in the form of mineral insulated metal sheathed (MIMS) thermocouples they are less prone to contamination and damage in an industrial environment. However, there is very little reliable long-term data available demonstrating the response characteristics of Type N thermocouples which would be essential for reliable use in long term monitoring of power plant or for controlling creep tests in the mid temperature range of 600 °C to 800 °C. To help address this issue, approximately nine years ago, the High Temperature Mechanical Testing Committee (HTMTC, www.htmtc.net) instigated some long-term ageing experiments to investigate the behavior of some Type N & Type K MIMS thermocouples. This paper presents the findings of long-term soaking experiments of approximately 65,000 hours (7.4 years) at 650 °C and 37,200 hours (4.25 years) at 750 °C. At 650 °C it was found that electromotive force (emf) output of the Type N thermocouples increased by about 3 °C, whilst at 750 °C the drift was -1 °C during the respective soaking times. In addition, a series of cyclic tests were carried out, in which Type N thermocouples were cycled between 50 °C and 650 °C. The implication of these findings will be considered for achieving the temperature tolerances specified in the creep testing standard ISO 204 and for monitoring power generating plant.

Key Words

Thermal Drift, Ageing, Type K, N & R Thermocouples, MIMS, Creep.


Loveday

Paper 021: TEMPERATURE MEASUREMENT FOR HIGH TEMPERATURE MECHANICAL TESTING – A CODE OF PRACTICE

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Abstract

A variety of high temperature mechanical tests are regularly undertaken including tensile, torsion, compression, creep, high and low cycle fatigue, thermo-mechanical fatigue (TMF) and plane strain compression testing. Some of these tests present more of a challenge than others for ensuring that test temperature remains within the temperature tolerance specified within Standards. In Creep testing long term 'drift' of thermocouples present special problems, whilst in the TMF test verifying the dynamic response of the temperature sensors is difficult. It is generally recognized that the largest contribution to the inaccuracy of the measurement of material properties determined from high temperature mechanical tests is attributable to the uncertainty and inaccuracy of temperature measurement.

Although a lot of information has been published about temperature measurement there has not been a comprehensive guide bringing together information about the practicalities of ensuring reproducible and accurate temperature in mechanical testing. This paper presents the latest version of a Code of Practice (CoP) which has been compiled over a number of years by experts from several testing laboratories under the auspices of the High Temperature Working Group (WG) of the High Temperature Mechanical Testing Committee (HTMTC), which acts as Technical Committee 11 of the European Structural Integrity Society (ESIS). It is based on more than 200 years of the collective experience of practitioners in the HT Mechanical Testing field. Open publication of the CoP was delayed since the WG recognised the need for additional information about the drift of N type thermocouples & dynamic temperature measurement which is now included. In addition, an extensive bibliography is included covering a variety of publications relating to mechanical testing. Since 2005 approximately 40 people have attended or contributed to the various meetings of the Working Group and helped to draft the latest version; thanks are expressed to all for their views and contributions.

Paper 022: Investigations into Low Cycle Fatigue and Creep-Fatigue Interaction Behaviour of Cast 625 Alloy

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Abstract

Nickel-based alloy 625 is a strong contender for the turbine rotor casing components in advanced ultra-supercritical (AUSC) power plant which is to be operated with a steam temperature of 993 K and a pressure of 310 kg/cm2. The choice of this alloy is based on its excellent elevated temperature mechanical properties coupled with good oxidation resistance. Temperature gradients caused by heating and cooling during start-ups and shut-downs subject the turbine rotor casing to repetitive thermal stresses, inducing damage by low cycle fatigue (LCF). Additionally, steady state operation in the elevated temperature domain causes creep damage, leading to an interaction between creep and fatigue. The resultant creep-fatigue interaction (CFI) accelerates the damage in the materials which is an important aspect to be studied for the safe design of the AUSC components. In the present work, an attempt has been made to understand the LCF and CFI behaviour of an India-specific version of alloy 625 casting. Strain-controlled LCF and CFI tests with different hold periods, viz. 60, 120, and 300 s at peak tension were performed at the temperatures of 973 K and 1023 K under total axial strain control mode. Strain amplitudes of ±0.25%, ±0.4% and ±0.6% were employed at a constant strain rate of 3x10–3 s–1 for all the tests. The cyclic stress response of the material is significantly influenced by the temperature and strain amplitude. The alloy displayed a continuous hardening followed by saturation for a brief period before the rapid load drop due to crack propagation leading to failure at both the temperatures for the strain amplitude of ±0.25%. In contrast, saturation behaviour is not very predominant in the material tested at the higher strain amplitudes of ±0.4% and ±0.6%. The introduction of tensile hold and increase in temperature reduces the fatigue life of the alloy. The paper presents a comprehensive study on the stress relaxation behaviour, hysteresis loop evolution and the cyclic life variations, supported by detailed microstructural analysis.

Key Words

Cast 625 alloy; Low cycle fatigue; Creep-fatigue interaction; Advanced Ultra Super Critical (AUSC).

Paper 023: Effect of Overload on Deformation, Crack Growth Behavior and Crack Initiation/Growth Lives of a C(T) Specimen for 12Cr Steel Under Creep-Fatigue Condition.

Go OZEKI

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Abstract

In this study, using a C(T) specimen for 12Cr steel used for steam turbine rotor, crack growth tests under creep-fatigue conditions with and without overloading were conducted and fundamental behaviors of deformation and crack growth were investigated. As a result, load line displacement was found to be suppressed under overload condition regardless of temperature and stress holding time. Crack initiation life under high temperature and low stress condition with overloading was delayed as compared with no overload condition. However, under low temperature and high stress condition with short stress holding time, crack initiation time was accelerated remarkably. Furthermore, although crack growth life under creep-fatigue conditions with overloading was found to be shortened as compared with no overloading, the effect of overloading on crack growth life was decreased with increase in a stress holding time.

Key Words

Overload creep-fatigue, 12Cr steel, crack growth life, crack initiation life.

Paper 024: Assessment of Long-term Creep Life of Modified 9Cr-1Mo Steel by Monkman–Grant Relationship Considering Dependence of Creep Ductility on Loading Conditions.

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Abstract
When it is difficult to obtain creep rupture data due to its test duration, it is an effective method to estimate the rupture time from deformation data during the creep test based on the Monkman-Grant relationship, which has been applied to various high-temperature materials with sound accuracy. However, regarding the application of the Monkman-Grant relationship to creep strength enhanced ferritic steels such as modified 9Cr-1Mo and 12Cr steels, there have been many reports showing that results tend to be an overestimation of the creep life in the long-term region. To address this issue, an author conducted a study to improve the estimation accuracy in the long-term region by the Monkman Grant relationship. Analyzing the published creep test data for modified 9Cr-1Mo steel, the author found that the product of the minimum creep strain rate and rupture time (ε̇MG) is not constant but depends on the loading conditions, which are test temperature and stress. Then, the author proposed an extended Monkman-Grant relationship considering the dependence of ε̇MG on the loading conditions. When this model was applied to the data for modified 9Cr-1Mo and 12Cr steels, the creep life was predicted with reasonable accuracy from the short-term to long-term regions.

Key Words
Creep, Monkman-Grant relationship, modified 9Cr-1Mo steel, creep ductility, minimum creep strain rate.

Paper 025: Microstructures of Mod. 9Cr-1Mo Steels under Long-Term Creep Conditions.

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Abstract

When it is difficult to obtain creep rupture data due to its test duration, it is an effective method to estimate the rupture time from deformation data during the creep test based on the Monkman-Grant relationship, which has been applied to various high-temperature materials with sound accuracy. However, regarding the application of the Monkman-Grant relationship to creep strength enhanced ferritic steels such as modified 9Cr-1Mo and 12Cr steels, there have been many reports showing that results tend to be an overestimation of the creep life in the long-term region. To address this issue, an author conducted a study to improve the estimation accuracy in the long-term region by the Monkman Grant relationship. Analyzing the published creep test data for modified 9Cr-1Mo steel, the author found that the product of the minimum creep strain rate and rupture time (ε̇MG) is not constant but depends on the loading conditions, which are test temperature and stress. Then, the author proposed an extended Monkman-Grant relationship considering the dependence of ε̇MG on the loading conditions. When this model was applied to the data for modified 9Cr-1Mo and 12Cr steels, the creep life was predicted with reasonable accuracy from the short-term to long-term regions.

Key Words

Creep, Monkman-Grant relationship, modified 9Cr-1Mo steel, creep ductility, minimum creep strain rate.

Paper 026: Effect of Precipitation Microstructure on the Creep Deformation Behavior of 25Cr-20Ni-Nb-N Steel.

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Summary

Microstructural factors for the two-step minima of the creep rate of a 25Cr-20Ni-Nb-N steel at 873 K under 280 MPa were investigated through the microstructural characterization of creep interrupted specimens. It was identified that the first local minimum is caused by the precipitation strengthening by NbX and softening by dynamic recovery driven by the significant initial plastic strain introduced by the stress loading. The cause of the second local minimum was identified as the competition between grain boundary precipitation strengthening (GBPS) by M23C6 phase and weakening by the void/crack formation on grain boundary facilitated by the preferential deformation near grain boundary. This investigation clarified that GBPS by M23C6 phase is a strong strengthening microstructural factor that can switch the accelerating creep rate to the deceleration. The effectiveness of the GBPS by M23C6 phase was demonstrated by the extended creep rupture life with increase in the area fraction of M23C6 phase in the initial microstructure which controlled by pre-aging.

Key Words

Creep, austenitic stainless steel, grain boundary precipitation strengthening

Paper 027: Very-High Temperature Creep of Incoloy 800H Addressing Effects of Creep Mechanism Transition and Nitridation.

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Abstract

The microstructure of 800H samples affected by natural corrosion within industrial-like environmental conditions and their effect on the creep response have been studied. Smooth cylindrical specimens of the alloy extracted from rolled sheet material have been placed into an industrial furnace, where they were exposed to high temperature thermal cycles within an air atmosphere. Samples spending 0 to 4 years inside the furnace underwent a microstructural characterization campaign. Optical microscopy images show noticeable precipitate segregation. Macroscopic Vickers hardness shows a relatively wide surface hardness range ($105 \lesssim HV0.5 \lesssim 145$). Micro-hardness profiles from samples with 0-2 years of in-furnace time exhibit a consistent surface hardening trend, whereas samples with 3-4 years of in-furnace time exhibit an opposite softening trend. With the aid of scanning electron microscopy images and electron dispersive X-ray detectors, this phenomenon is correlated to the competition of both corrosion mechanisms: nitridation and oxidation.

Key Words

Austenitic Ni alloy, Precipitate Segregation, Creep mechanism transition, Nitridation, Oxidation, High temperature creep

Paper 028: Recent Progress in the Microstructurally-based Creep Modelling of Ni-based Alloy 617.

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Abstract

Solid solution strengthened (SSS) Ni-based superalloys, such as A617, show superior creep resistance at 700°C. They are promising candidates to raise the efficiency of future thermal power plants or turbines in aircrafts. Apart from SSS, the creep strength in A617 stems from γ' and carbide precipitates. In this work, a microstructurally-based creep model for A617 is presented. Mobile dislocations in the model interact with fine grain-interior precipitates, and grain boundaries act as dislocation sources/ sinks. The model is capable of simulating creep curves and time-to-rupture (TTR) diagrams based on the evolution of mobile dislocations. At lower stresses, the accuracy of modelled TTR can be improved by adding a share of diffusion creep to dislocation creep. The simulated evolution of dislocation densities is realistic compared to the literature data. The reduction of area of ruptured samples was included within a damage factor, enabling the consideration of sample toughness.

Key Words

creep, Ni-based alloy, A617, alloy 617, Inconel 617, modelling, precipitates, dislocation density.

Paper 029: Creep Crack Growth Characterization of SS316LN.

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Summary

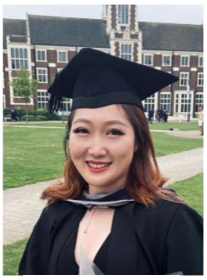
The metallic materials exhibit time-dependent deformation in high-temperature applications of Fast Breeder Reactor (FBR) structural materials, such as primary and secondary piping, heat exchangers, and the main vessel. To ensure the structural integrity of these components, it is important to understand the crack behaviour and the resistance offered by the materials used in these components. In creep conditions, conventionally, C* and C(t) line integrals are used for characterizing the crack tip. However, the true crack driving force or its rate cannot be described by any of the conventional parameters.

The theoretical validity of conventional crack tip-characterizing parameters like J or Ct is also restricted, making it hard to anticipate the driving forces underlying cracks. One of the important materials in nuclear as well as conventional power plant components is stainless steel SS316LN. To investigate the creep crack growth behaviour of this material an experimental analysis of SS316LN at 650 °C is performed. The crack extension is modeled through the node-release technique, and a configurational force-based rate of change of J integral is calculated by post-processing of the finite element results.

Key Words

Creep Crack Growth (CCG), configurational forces, node release technique, crack driving forces.

Paper 030: Evaluation of Metallurgical Risk Factors in Post-test, Advanced 9%Cr Creep Strength Enhanced Ferritic (CSEF) Steel.



X. ZHANG

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Abstract

9wt.% Cr steels are widely used in the design and fabrication of thick section components in combined cycle or coal-fired applications for working temperatures of 600~650°C. This family of materials possesses a martensitic microstructure stabilized by precipitates. The presence of nitrides, inclusions or evolution of second-phase particles may increase the metallurgical risk to creep. The chemical composition and microstructural evolution of 9wt.% Cr steels contribute to thermal stability and long-term performance. In some specialist alloys, Ta is added to the composition which causes the formation of fine MX precipitates which are only present at the nanometre scale in tempered martensite, which hinder the recovery of dislocations and the migration of laths to extend creep life. However, the presence of large Ta-containing particles or inclusions in the 9wt.% Cr steels may have a detrimental effect on its creep performance, as they may act as preferred sites for cavity nucleation. To fully appreciate the development of damage in these steels, it is necessary to link the pre- and post-test conditions, evaluate damage in the parent metal, develop procedures that provide consistency of results, and obtain statistically relevant data. The evolution of the Ta-containing phase has been tracked and quantified using a variety of correlative characterization approaches. Utilizing focused ion beam microscopy and two-dimensional electron-based microscopic characterisation, three-dimensional tomography has identified a strong relationship between creep cavities and Ta-containing phases from the early stages of creep.

Key Words

9wt.% Cr tempered martensitic steel, high temperature creep, creep cavitation, Ta enriched precipitation.

Paper 031: Rupture Strength Prediction of Martensitic Power Plant Steels.

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Summary

The creep resistance of martensitic power plant steels depends strongly on the dispersion of various types of precipitates formed during tempering. Reliable prediction of rupture strength of such alloys thus demands accurate description of the microstructure evolution during service. A material model that calculates the simultaneous precipitation kinetics and hardening in these steels has been reported previously. The creep rupture model reported here is a natural extension of the previous research, and the calculated results are provided in the form of "stress vs rupture life" plot at a given temperature. This model has been validated against experimental rupture data of wide-used 9-12% Cr steels including, but not limited to, Grades 91, 92 and MarBN, and demonstrates good agreement over a wide range of temperature and stress levels. The model predictions have been checked against the experimental data of a newly-designed 11 mass% Cr steel and good agreement is achieved. Moreover, this model allows, probably for the first time, the effect of variation in alloy conditions on rupture strength to be quantitatively evaluated for a given alloy grade. Results show that variation in alloy composition within its specification range or variation in strength before a component goes into service can lead to significant differences in the calculated "stress vs rupture life" plot. Such variations are believed to be largely responsible for the wide scatter observed in the experimental rupture data of such alloys.

Key Words

Rupture strength, rupture life, precipitation, power plant steels, materials modelling.

Paper 032: Stochastic and Systematic Deviations of Creep Experiments in Martensitic Steels.

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Summary

Since creep tests can last up to 10+ years, the main challenge is to estimate the long-term behaviour of the materials in question out of short-term experiments with the help of materials modelling in order to save time and experimental costs. However, one of the most important input parameters for the success of this strategy are thoroughly obtained experimental creep data.

Literature sources indicate a huge scatter between results stemming from apparently identical creep experiments. Potential reasons for deviating results include slightly different material starting conditions including composition and heat treatment, general inhomogeneity within a block of produced material, deviations from the nominal testing temperature, oxidation at the specimen surface, interruptions of the creep tests etc.

The presented research is examining residual impact factors whilst satisfying the standard for creep testing. A set of identical creep experiments (same temperature, stress, source of material etc.) with the material P91 is set up. The varying parameters in the study are the specimen diameter, measuring type (interrupted and uninterrupted) and specimen preparation order (heat treatment/machining). It is shown to what extent the variation of these parameters can lead to systematically varying results in the creep experiment. The results of the experiments are discussed, as well as potential strategies for reasonable accuracy of creep modelling.

Key Words

Creep, uniaxial creep test in tension, heat treatment, martensitic 9% Cr-steel, P91, time-to-rupture diagram, precipitates, microstructure.

Paper 033: Creep Strength Degradation in 18Cr-9Ni-3Cu-Nb-N Steel.

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Abstract

Creep strength degradation mechanism in the long-term was investigated for 18Cr-9Ni-3Cu-Nb-N steel (KA-SUS304J1HTB, ASME Code Case 2328), focusing on change of fracture mode and microstructural stability. At 650oC to 800oC, the creep strength degraded in the long-term. The creep ductility increased with increasing Larson-Miller parameter, and then decreased at high value of Larson-Miller parameter. The fracture mode changed from creep void formation on grain boundaries to cracking at □-phase and matrix interface in the long-term. Precipitation free zone (PFZ) was formed around □-phase on grain boundaries after long-term creep exposure. It was assumed that creep resistance was lower in the PFZ than in the grain interior because nanohardness in the PFZ was lower than that in the grain interior. The fracture mode change and decrease in creep resistance by the formation of PFZ can contribute to the creep strength degradation in the long-term.

Key Words

Creep strength degradation, austenitic stainless steel, precipitation free zone, fracture mode change.

Paper 034: On the Description of Stress Relaxation by Means of Creep Models Based on Standard and Non-standard Validation Experiments.

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Abstract

The requirements for a reliable and sustainable energy supply pose significant challenges to the power generation industry. Therefore, a flexible plant operation is required to maintain the stability and delivery of power demands. Due to such flexible plant operations, a better understanding of the fundamental behaviour of the materials in use is necessary to develop an improved description of the component behaviour under increasingly cyclic thermal and mechanical stresses. For example, flange and bolted joints in steam turbines seem to be structurally simple functional elements, but at elevated temperatures, they are increasingly subject to cyclic loads, which result in complex combinations of temperature-induced stresses, creep, and stress relaxation.

Many creep models exist, such as Norton-Bailey or Garofalo, which can describe the stress relaxation behaviour of a component utilised in the flange and bolted joints. However, they are limited in terms of describing the material behaviour under anisothermal and transient loading scenarios. Applying higher-order creep models can lead to a better description of the creep and stress relaxation behaviour under cyclic loading. In this work, a constitutive material model based on Chaboche and a kinematic hardening approach is utilised and simplified to describe the stationary and transient anisothermal and cyclic relaxation behavior. The plastic strain rate equation has been modified to enhance the model in describing the creep behaviour.

Several creep and stress relaxation experiments are performed for 10% and 12% chromium steels and a nickel-based alloy. Furthermore, four validation experiment types with varying temperatures and loading conditions are also performed to verify the model's applicability and performance. Finally, the model parameters are determined using automated optimization procedures such as Nelder-Mead, where the fitting is achieved by combined fitting of the creep and relaxation experiments.

Based on a prepared subroutine, a one-element cube model and a 2D symmetrical model of a bolted connection are utilised for Finite Element simulations. A comparison of the stress relaxation course for phenomenological creep models (such as Norton-Bailey and modified Garofalo) versus the Chaboche-like creep model for the validation experiments is performed and discussed in detail. Finally, the calculation times of the implemented creep models are compared.

Key Words
Stress relaxation, creep, modelling, constitutive material model, transient loading, bolted flange, bolted joint, NiCr20TiAl, X22CrMoV12-1, X12CrMoWVNbN10-1-1..

Paper 035: A Study on Creep and High Temperature Fatigue Properties of Additively Manufactured Ti6Al4V Alloy.

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Abstract

The Additive Manufacturing (AM) facilitates design freedom with near-net complex shape structures. Titanium alloys such as Ti6Al4V alloy that can be additively manufactured find a wide application in various areas including Aerospace, Automotive, Biomedical and chemical industries. Creep and high temperature fatigue performance is one of the main criteria of aeroengines in terms of its safety and reliability and thus needs to be investigated. The aim of this research is to investigate the creep and high temperature fatigue properties of selectively laser melted (SLM) Ti6Al4V alloy.

Specimens for tensile, fatigue, creep test and microstructural analysis of Ti6Al4V alloy were fabricated using Selective laser melting (SLM) process. A layer thickness of 60 µm and optimized process parameters were selected for manufacturing to understand the subsequent effect on creep properties. These as-fabricated samples were heat-treated (HT) at an annealing temperature of 800°C with a dwell period of 2 hours in a controlled environment. Microstructural and texture characterization was carried out using FE-Scanning Electron Microscope (SEM), High Resolution Transmission Electron Microscope (HR-TEM) and optical microscope. Tensile tests were performed on the specimen with an application of load perpendicular to the build direction. The creep test was done at room temperature and elevated temperature (400˚C) at two different load levels. The tension-compression fatigue test at elevated temperature (400˚C) with stress ratio of -1 and at a cycle frequency of 10 Hz shall be done using MTS servo-hydraulic fatigue testing machine. Furthermore, Fracture surfaces of broken specimens shall be examined using FE-SEM and HR-TEM to investigate creep and fatigue damage mechanism.

The as-fabricated Ti6Al4V alloy consists of acicular α’ martensitic phase with needle-like microstructure because of high cooling rate during the SLM process. Coarsening of the α laths within the prior β grain boundary took place with annealing heat treatment as shown in figure 2. The surface roughness of SLM Ti6Al4V alloy was found to be = 3.6 ± 1.2 with surface morphology as shown in figure 1. The tensile properties were superior as compared to its conventional wrought counterparts. The SLM Ti6Al4V alloy doesn’t show significant creep

phenomenon at room temperature as shown in figure 3. The elevated temperature creep and fatigue tests are currently ongoing in our laboratory and characterization of operating creep and fatigue deformation mechanisms would be done. The observed results with possible underlying mechanisms shall be discussed and presented.

Table 1 - Mechanical Properties of HT SLM Ti6Al4V alloy

YS (MPa)	UTS (MPa)	Elongation (%)	Hardness (HV)
908±14	948±11	14.6±1.2	373±6.96

YS- Yield Strength UTS – Ultimate Tensile Strength

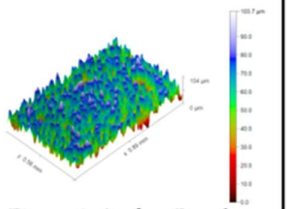

Figure 1– Surface Roughness (R_a = 3.6 ± 1.2 µm)

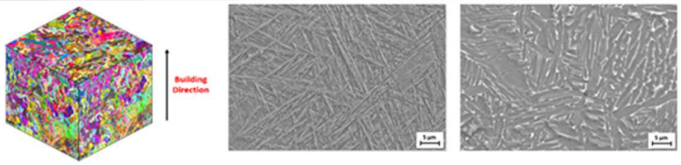

Figure 2 – *(a) EBSD IPF Map (b) As- built SEM microstructure (c) Heat treated SEM microstructure of SLM Ti6Al4V alloy*

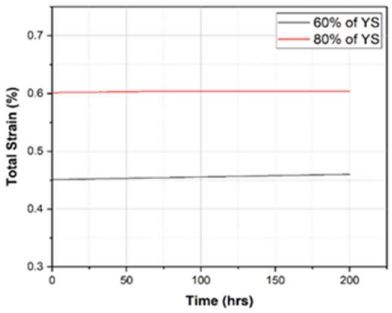

Figure 3– Room temperature creep behavior SLM Ti6Al4V alloy

Paper 037: Influence of MANUFACTURING PROCESS PARAMETERS on 9-12% CR CREEP ENHANCED FERRITIC STEEL in LONG TERM PERFORMANCE.

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Summary
The modified 9Cr-1Mo creep strength-enhanced ferritic (CSEF) steel, grade 91, is ubiquitously used in the boiler industry to manufacture a variety of pressure-critical components, such as tubing, headers, and piping.

Time-dependent properties of CSEF steels essentially depend on achieving the desired microstructure, and are therefore significantly affected by the manufacturing process, including steelmaking, hot and/or cold deformation, heat treatment and welding. Consequently, adequate fabrication process control is mandatory to ensure the de-sired service performance.

This work, following a prior publication by the same authors, describes the effect of process conditions and heat treatment parameters, within the permitted range prescribed by applicable standards (ASTM A213/ASME SA-213 T91, EN 10216-2 and VdTÜV WB-511 X10CrMoV9-10), on the creep properties of grade 91 tubes. Updat-ed results, including long-term creep tests and post-testing specimen characterization, are presented.

Key Words
Creep Strength-Enhanced Ferritic steel, CSEF, forming, boiler tube, 9Cr-1Mo, Grade 91, T91.

Paper 038: Development of a Model Bolt Testing Method to Determine Negligible Creep.

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Summary

Two methods of testing to experimentally determine negligible creep temperatures have been developed as part of recent work on negligible creep within European Standardization committee CEN/TC54 working group WG59 "Creep", and during the course of a PhD project co-funded by the ECCC. Both methods employed the principle of performing tests on specimens at the same test loading, but with different temperatures. The first of these, isostress testing using conventional creep tests, with lines drawn upon times to specific creep strain vs temperature, has become the preferred method of CEN TC/54 WG59 to determine negligible creep temperatures and has already been extensively reported. The second method, used model bolts in which a test specimen is held within a sleeve, loaded to a known displacement, and then exposed at temperature to induced relaxation. Each bolt is periodically removed from the furnace, and its remaining load and its remaining elastic strain measured in a universal test machine. Several such bolts were each exposed at different temperatures, resulting in an isostrain series of relaxation curves. The paper reports on the development of the test technique and associated assessment methods to determine retained load after exposure, and preliminary results on the determination of negligible creep on selected steels.

Paper 039: Assessment of Historical Datasets to Determine Negligible Creep.

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Summary

A series of investigations has been performed to evaluate the negligible creep temperature from historical datasets of creep test data generated from testing programmes undertaken from the early 1960's onwards to the present day. They often form the bedrock of strength values in national or international standards, and therefore are potentially a prime source of data in order to determine negligible creep temperatures. Initial investigations showed that often the analysis of existing strength properties derived from those datasets was inaccurate for determining negligible creep, and a more sophisticated approaches are required. The old material standards usually provide only creep rupture strengths for a set of temperatures and 100.000 hours, in few cases for 200.000 hours. Moreover, the test data are often sparse at low temperatures. Generally, this has led to relatively few materials having assessed strengths to 1% creep elongation, and then often at limited times; whereas the negligible creep criterion developed in European Standardization committee CEN/TC54 working group WG59 "Creep" requires data at long times to 0.2% creep.

Starting with a consideration of the available tensile data and moving on to an assessment of models to fit the lower temperature times to specific strain that might be present, the paper then compares different approaches to provide meaningful and realistic negligible creep temperatures from the available test data. The use of such approaches for standardization purposes is then considered, leading to recommendations for their use, and indeed how they might be augmented and improved with further limited testing.

G. CHAI

Paper 040: Long-term creep behaviours and structural stabilities of austenitic heat resistant stainless steels.

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Summary

For heat resistant alloys, long-term structural stability at high temperatures is a critical issue for alloy design and applications. In this paper, the long-term creep behaviours and structural stabilities of six heat resistant high Ni alloys and austenitic stainless steels have been studied by long-term creep testing and microstructure investigations. The longest creep rupture life is up to 359 283 hours. High Ni and Cr alloys such as Sanicro® 31H (Alloy 800H) and Sanicro® 28 show a good combination of high creep and oxidation resistances. Sanicro® 31H has a good structural stability. Precipitation of nano MX particles with a very low growth rate can improve long-term creep resistance at high temperatures. Sanicro® 25 shows the highest creep strength due to its long-term stable multiple nanoprecipitates of MX, Cu-rich, Laves and $M_{23}C_6$ phases. Low Ni austenitic stainless steels such as Alleima 3R12 (TP 304), 8R30 (TP 321) and 8R40 (TP 347) show comparatively low oxidation and creep resistances. It was first found that at 800°C, Cr_2N could form in the long-term crept 8R30 material by the absorption of nitrogen from the air into the matrix. This consequently changed the composition of the matrix and caused a structural instability and finally a phase transformation or creep induced phase transformation. This study increases the understanding on the long-term creep behaviours of the heat resistant materials.

Key Words

Creep, austenitic stainless steel, Ni based alloy, structural stability, microstructure.

Paper 041: Influence of Grain Size on Creep Behaviour of high Cr Martensitic Heat Resistant Steels for Steam Power Plant Application.

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2. voestalpine BÖHLER Edelstahl GmbH & Co KG.

Summary

To extend the application temperature and to increase the efficiency of steam power stations, advanced 9-10% Cr martensitic stainless steels were developed in Europe and Japan in the 1990's. The European steels known as COST-E (X12CrMoWVNbN10-1-1) and FB2 (9CrMoCoVNbNB9-2-1) are widely in application today. Different components have been manufactured such as turbine shafts, small forgings, and rings used in power stations. The long-term behaviour of these steels has been reliably tried and proven up to 600 - 620°C.

Long-term creep tests of material from different components are performed at several temperatures and times longer than 100kh by the German Creep Group. Data discussed here show no influence of the ASTM grain size for COST-E at 600°C and FB2 at 625°C. The strengthening mechanisms in the microstructure of these martensitic steels are much more relevant than austenite grain size effects known from conventional 12CrMoV steels. The gained results are very valuable for quality assurance reasons during the running production of turbine components and in turbine design approaches.

Key Words

Creep, creep rupture strength, martensitic steels, COST-E, FB2

Paper 042: Creep Property Assessment of Service-Exposed 2.25Cr-1Mo Steel Boiler Piping by Small Punch Test.

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Abstract

The small punch (SP) creep testing technique was applied to the long-term service-exposed 2.25Cr-1Mo steel, which had been actually used as a boiler piping in the fossil power plant for long periods of time, to investigate the applicability of this technique to the remaining-life assessment. The SP creep tests were carried out at the temperatures of 580 and 650°C and under the load range from 150 to 400 N using small disk-type specimens removed from the piping. In order to compare the results obtained from the SP creep test with those from the uniaxial creep test, the SP load (F) was converted to the stress (σ) with the load/stress conversion coefficient (F/σ) determined by the high temperature SP test, that is, the central deflection to the maximum load. The experimental results revealed that the SP creep rupture life was slightly shorter at around the outer surface than the inner surface. It was also found that the F/σ were determined to be around 2.9 irrespective of temperature, and the SP creep rapture data were well correlated with the uniaxial ones using this F/σ.

Paper 043: Welding P91 Steel with Nickel-Based Weld Metal.

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Abstract

Nickel-based weld metals of classes ENiCrFe-3 (e.g. Inconel 182) and ENiCrFe-2 (e.g. Incoweld A) have been successfully used for many decades for welding the low alloy high temperature steels ½CrMoV and 2¼Cr1Mo in a variety of welding and repair situations. The more recent use of these types of welding consumables on the creep strength enhanced ferritic steel P91, often to incorporate stainless steel components into steam lines, has however led to several failures and cracking incidents. The items affected have included large section welds in steam pipework as well as numerous types of small branch connections such as thermocouples. This history, over the last twenty years, is summarised and possible reasons for the poorer operational experience discussed. A key factor is the difference in coefficient of thermal expansion between P91 and the nickel-based weld metal, which is significantly higher than it is in the cases of the low alloy steels. It is concluded that direct interfaces between P91 and nickel-based weld metal should be avoided and the welding of stainless steel components to P91, where necessary, should be carried out using intermediate materials and interfaces. One such approach, using a 2¼Cr1Mo insert between the stainless steel and P91, is discussed.

Key Words

Nickel-based Weld Metal, Inconel, P91.

Paper 044: What's New for the Creep Analyses in the Next 2022 RCC-MRx Edition.

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2. CEA Cadarache, DES/IRESNE/DTN /STCP/LCIT 13108 St Paul Lez Durance, France.

Abstract

The 2022 edition of the RCC-MRx code [1] has been the occasion to improve or complete the rules dedicated to creep analyses. Even if the rules have their background on the last century, and if there is much less projects in the nuclear field reaching high temperatures compared to PWR perspectives, improvement of existing creep analyses rules and data are always in mind of the standard development organizations. It appears notably in creep-fatigue rules modifications implemented in the 2022 edition.

This article will present the last initiatives that were taken for creep in the frame of the RCC-MRx code.

Key Words

Creep, austenitic stainless steel, standardisation, RCC-MRx..

Paper 045: Steel Grades 91 and 92 Microstructure and Precipitate Evolution Atlas and Life Assessment Tool.

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2. RINA Consulting - CSM S.p.A. Rome- Italy.

Abstract

P91 and P92 steels are widely used in power plants and petrochemical industry for long-term service components. Due to high resistance to creep, fatigue and corrosion, the use of grade 91 and grade 92 steels allows ultra-supercritical conditions (600 °C, 300 bar), as well as the highest performances. To achieve this goal the alloy design was based on the following metallurgical concepts: stable tempered martensitic microstructure, precipitation strengthening through $M_{23}C_6$ (Cr, Fe, Mo or W carbides) and fine MX (V, Nb carbides), solution hardening through elements as Mo or Mo/W and high Cr content. This study is focused on the microstructure evolution of grade 91 and grade 92 steels under aging and creep conditions. Three sets of laboratory-aged specimens heated in oven at 550°C, 600°C and 650°C were examined. Furthermore, the influence of stress on the microstructure was evaluated. The microstructures were characterized by several means of investigations, such as scanning electron and transmission electron microscopy and the results were compared to literature.

Key Words

MX, $M_{23}C_6$, Laves Phase, Z phase, Creep cavity, inclusions

Liu JIE

Paper 046: Finite Element Analysis on Stress Field of Dissimilar Welded Joints under Deep Load Changing.

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Abstract

In order to cope with the impact of the development of new energy power generation technology and study the safety state of thermal power units under low load or deep load changing conditions. In this paper, a two- dimensional finite element model is established by using large-scale simulation software COMSOL Multiphysics to study the stress field distribution of T91/TP347H dissimilar welded joints commonly used in power station boilers under load changing conditions. The results show that, the stress gradually tends to be stable with the increase of cycle times in the simulation of deep load changing with cyclic fluctuation at a set temperature of 500-625°C and internal pressure of 15-25MPa. At the 200th cycle, the maximum stress appears at the innermost of the TP347 H side fusion line at the load trough, reaching 275.45MPa. The maximum stress value appears at the interface between the base metal and the weld, and the stress is distributed along the interface. Near the inner side of the welded joint, the stress on the TP347H side fusion line is slightly larger than that on the T91 side fusion line. Near the outside of the welded joint, the tensile stress from the heat affected zone on the T91 side to the T91 base metal side is greater than that on the TP347H side. After 200 cycles of deep load changing simulation, the tensile stress at each position of the welded joint varies to varying degrees. Each position of the welded joint undergoes a process of stress from small to large at the peak of the load; during the load trough, it experienced a process from large to small; as the number of cycles increases, the stress at the peak of the load gradually increases, and the stress at the trough of the load gradually decreases, reaching a relatively stable state after 50 cycles.

Key Words

Dissimilar welded joints, deep load changing, stress analysis.

Paper 047: Type IV Cracking Behavior of P92 Welded Joint Used in China Power Plants.

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Abstract

P92 (9Cr-1.8W-0.5Mo-NbV) martensite steel is widely used in high temperature pipes of ultra-supercritical boilers in China. During high temperature operation, microstructural evolution of the heat affected zone across welded joint lead to type IV cracking failure. An understanding of the long-term microstructural evolution under actual service conditions is necessary to improve the welded joint and prevent failure.

In this article, microstructural evolution and type IV cracking of P92 welded joint under an actual 605℃ supercritical boiler were analyzed. A full investigation into type IV failure was carried involving in Optical Microscope(OM), Vickers hardness test, Scanning Electron Microscope (SEM), Energy Dispersive Spectrum (EDS), Electron Back-scattering Diffraction (EBSD) and Transmission Electron Microscope (TEM). The results shows, the crack appeared in the fine-grained heat affected zone. Microcracks and creep cavities distributed along grain boundaries, Laves phase and $M_{23}C_6$ phase clustered around the cavity. Their precipitation and coarsening promote the nucleation and growth of cavities. The Z phase was also observed in the heat affected zone, Z phase reduce the dispersion strengthening of MX carbides. Compared with other regions, the fine-grained region has lower dislocation density, higher plastic deformation and degeneration of tempered martensite lath. The coarsening of Laves phase and $M_{23}C_6$ phase is more serious. These factors led to the creep property deterioration and Type IV cracking.

Key Words

Type IV cracking; P92 welded joints; Creep; Heat-affected zone.

Paper 048: Creep, Fatigue and Creep-Fatigue Behaviour of Martensitic/Bainitic Steels and Nickel-Based Alloys and Their Welded Joints at the Temperature Range 500°C-750°C.

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2. RINA Consulting – Centro Sviluppo Materiali S.p.A., Roma, Italy

Abstract

Future power plants face currently high design requirements due to aggravating climate change and environmental restrictions, which makes necessary high operational flexibility, superior thermal performance, minimal emissions and higher cyclic capability.

The aim of the paper is therefore to investigate experimentally the fatigue and creep-fatigue material behaviour of improved materials and welded joints for the application in highly efficient and flexible future power plants. These materials promise a reduction in manufacturing costs as well as an increase in flexibility by providing enhanced creep strength and therefore the possibility for wall thickness reduction.

At the temperature range between 500°C -550°C, the investigation focusses on the creep and low-cycle fatigue behaviour of dissimilar welded joints from conventional materials (bainitic and martensitic material T24 and T92) to nickel-based alloys (A617B and HR6W) fabricated as tubes.

At the temperature range between 700°C-750°C, it focusses on the creep, low-cycle fatigue and creep-fatigue behaviour of similar and dissimilar welded joints from high temperature resistant nickel-based alloys (A740H, A617B and A263) fabricated as tubes and as pipes.

Metallographic investigations after testing provide support for understanding the influence of temperature, strain amplitude and dwell time on the microstructure change and the fatigue strength.

Key Words

Creep, fatigue, creep-fatigue, martensitic/bainitic steels, nickel-based-alloy, weld joints, tube, pipe.

Paper 049: Creep Behaviour and Microstructure evolution of P91 Steel After 200,000 hours at 600°C.

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2. Department of Mechanical Engineering, Technical University of Denmark, Denmark

Abstract

Not available at time of publication.

Paper 050: Crystal Plasticity Model for Simulating Creep and Relaxation Deformation/Damage of OFP Copper.

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Abstract

We demonstrate a crystal plasticity model approach for simulating the mesoscale deformation and damage. The key aim is to introduce a sufficient number of plastic deformation mechanisms and to develop a failure model capable of depicting creep cavity formation and more severe damage in the material. A dislocation density-based model is used for the investigated doped copper material with modifications. The damage model is incorporated into the modelling framework to cause degradation of the material intra-grain and in the region of grain boundaries. The effect of local variations in material properties and state are evaluated and the model response is compared with experiments and characterization.

In detail, the basis of this work is a CP material modelling including grain orientation and size distribution, obtained using electron backscatter diffraction (EBSD) and experimental test data of real cyclic relaxation test specimens. EBSD imaging is performed both on undeformed material and deformed material. The deformed section is analysed and compared against the undeformed section to distinguish the deformation mechanisms and initial creep cavitation. This will yield a realistic description of texture and grain shape including case hardening characteristics, and ultimately accurate stress and strain response at the microstructural level for further evaluation of performance with respect to material creep(-fatigue) damage.

The existing crystal plasticity framework is extended to be compatible with the oxygen-free phosphorous (OFP) copper microstructure that is the focus of this study.

Key Words

Creep, creep cavity, crystal plasticity modelling.

Paper 052: Development of a P91 uniaxial creep model for a wide stress range with artificial neural network.

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2. European Commission, JRC, Petten, The Netherlands

Abstract

A uniaxial creep model which is capable of describing creep across the primary, secondary and tertiary regimes over a wide stress range was developed for P91 steel by means of artificial neural network (ANN). The model can be easily implemented in FEA codes, since it provides an analytical expression of the true creep rate as function of temperature, true stress and true creep strain. The initial dataset for the training data of the ANN model was based on measurements from creep uniaxial tests and information that were derived by a combination of the LCSP model and the Wilshire model for the time to rupture. The ANN model reproduces the training dataset with a high level of accuracy (R2=0.975 and RMSE=0.19) in term of true creep rate. In the FEA simulations under the same conditions of the training dataset, the model provides times to rupture and minimum creep rate very close to those in the training dataset. The model can be adapted for heat/batches with different properties from the average behaviour of the training dataset by means of a stress scaling factor.

Key Words

Creep, Creep model, P91, 316L(N), LCSP model, Wilshire, artificial neural network, artificial intelligence.

Paper 053: On the simulation of the Small Punch Creep Test - Applied to 316L(N) Austentic Steels.

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2. SCK CEN, Belgium

Abstract

Summary

This paper describes a numerical analysis to predict the deformation and time to rupture of the small punch creep test for 316L(N) austenitic steel. The constitutive model incorporates elasto-plastic nonlinear kinematic hardening and creep with primary, secondary and tertiary creep calibrated to the RCC-MRx code data. The computations are assesses by comparing with experimental data for a 500μm thick sample clamped with a diameter of 5mm loaded with a force 300,400 and 500N at 700°C. The model predicts the experimental quite well with respect to minimum deflection rate and time to rupture and its location using a local critical strain criterion. A very important feature is that the deformation and total effective strain distribution are almost identical for all loads as function of the time divided by the time to rupture.

Key Words

Small Punch Creep, relaxation, primary creep, secondary creep, tertiary creep, creep ductility, multi-axiality, plastic deformation, creep rupture criterion, 316L(N), austenitic steels.

Paper 054: Effect of material inhomogeneity and crack driving force for the case of UM-OM interface.

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Abstract
With the increase in demand for obtaining the required material properties at suitable places, it is necessary to use two differently deforming materials in a component, joined by different types of welding processes, especially for the applications like nuclear power plant, automotive and ship industries. This dissimilar joint results in spatial variation in the mechanical properties, which has been found to be influencing the crack tip behaviour [1,2]. It has been found recently with the use of configurational forces that the crack driving force may increase or decrease depending on the distance from the transitioning interface and the amount of differences in the mechanical responses (over or under-matching). This paper will be focusing on the idea of implementing J-integral for different proportions of Undermatched (UM) and Overmatched (OM) materials. Using configurational forces, we will discover the impact on the crack tip when the crack transitions from UM to OM material.

Key Words
Crack driving force, dissimilar metal joints, finite element method, configurational force.

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Paper 055: Creep Rupture Data Assessment - New Uncertain Challenges Require New Uncertain Answers.

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Abstract
Components of industrial plants with high temperature loading conditions are subject to progressive damage in the material over time. Even with complex loading conditions, knowledge of the creep behavior of the materials used remain essential for the service life calculation of high-temperature components. As early as the 1950s, attempts were made to determine the prediction of long-term creep life from creep tests with limited test durations. Over decades, many methods have been developed for extrapolating creep rupture strengths based on the fact that deformation and damage evolution in materials proceeds faster at high temperatures than at low temperatures. These methods usually use stress- and temperature-dependent numerical material models and are based on statistical evaluations of results from creep tests on single or on many casts of a material grade. The challenge with these Creep Rupture Data Assessments (CRDAs), however, always remains evaluating the predictive accuracy of creep life.

A milestone for the evaluation of CRDAs was reached with the development of standardized tests by the ECCC that define criteria to assess the validity of an evaluation, independent of the calculation model and assessor. These Post Assessment Tests (PATs) and guidelines for evaluating creep data sets help assessor generate reliable design parameters. Furthermore, new computer-aided calculation methods allow the use of extensive data on the casts and other experimental data, as well as the application of probabilistic methods. Sophisticated probabilistic methods allow quantifying the material scatter and take data of ongoing experiments (right-censored data), prior knowledge of the assessor as well as the uncertainty of the model parameters into account. Confidence regions and prediction intervals are important results of uncertainty quantification, among others. At the end, the available computing power and probabilistic methods enables the assessor, to obtain by far a more precise knowledge about the uncertain predictions of the material behaviour.

Within the ECCC, software tools are being developed that both leverage the capabilities of new powerful computer-aided computational methods and allow for simultaneous assessment with post-assessment testing in accordance with ECCC recommendations. The authors would like to point out that despite all available tools and guidelines, the expertise and experience of the assessor is an indispensable guarantor for a reliable evaluation.

Key Words
Creep, Creep Rupture Data, Assessment, Post Assessment Tests, Maximum Likelihood, Probabilistic Lifetime Model.

Paper 056: Prediction of Conventional Creep Test Parameter Using Small Punch Creep Test.

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Summary

The use of miniature disk bend testing has grown in popularity for estimating the life expectancy of power plants and nuclear reactors, as it requires small surveillance samples. Given that many components in nuclear power plants and advanced ultra-super critical plants experience creep deformation due to high operational temperatures, it is vital to understand the correlations between creep properties obtained from miniature/small punch testing for assessing component life. Small punch creep (SPC) testing of thin disc specimens can be a useful technique for determining creep properties at elevated temperatures. In this study, finite element method is employed to analyse small punch creep tests of two different materials. The proposed study seeks to evaluate power law creep parameters (A and n) using data obtained from small punch creep test (SPCT), and will compare the accuracy of various approaches for estimating these parameters. To improve the accuracy of these existing models, the study proposes substituting the displacement at the centre location used in these models with the displacement at the location of maximum thinning to evaluate the equivalent stress and strain from the output data of small punch creep test. By refining the existing models with this approach, this study aims to provide more precise and reliable estimations of the creep parameters A and n.

Key Words

ABAQUS, Creep, Finite element method, Small punch creep test.

Paper 057: Experimental Investigations on a Model of a Power Plant Flange Under Steady State and Transient Load.

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Abstract
The design and operation of conventional power plant components is affected by load changes with an increase in warm and hot starts to balance the fluctuations in renewable energy production. Essential parts of these power plant components are flanges e.g. connecting pipes and turbine housings. While being structural rather simple, many influences affect the functionality of these flanges, like the high temperature behaviour of the bolt material or the temperature distribution in the components.
In this paper, parts of a recently finished research project on different influences on the relaxation behaviour of flanges are presented. To investigate the influence of the bolt material, tests were carried out on a 1:2.5 scale model of an IP turbine flange using martensitic X12 and nickel-based Ni80A bolts. Each tests included 2000 h of steady state and 3000 h of transient load with a retightening of the bolts after 1500 h.
The results reveal a contrarily deformation behaviour with a view on the creep strain distribution within the components. In addition, a significant influence of the preceded creep deformation could be observed. Exemplary relaxation tests on the X12 material provide additional information towards the observed behaviour in the flange tests.

Key Words
Stress relaxation, creep, turbine flange, transient loads, retightening of bolts, component test, high temperature testing.

Paper 058: Implications of Creep Damage Susceptibility in Creep Strength Enhanced Ferritic Steels.

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Abstract

Creep strength enhanced ferritic (CSEF) steels such as Grades 91 and 92 are commonly used in power plant components that operate at elevated temperature. These steels are highly optimized to provide excellent creep strength but exhibit different susceptibilities to the evolution of creep damage (cavitation). Underlying metallurgical risk factors that contribute to this variability are reviewed, and the heat-to-heat or material dependency for these steels will be discussed. While these differences can be observed in uniaxial creep tests, they are most evident in tests that create multiaxial stress states such as circumferentially notched bars. Notched bar tests under creep conditions will be reviewed to illustrate trends in behavior for Grade 91 and 92 steel. The implications of variable creep damage susceptibility to component integrity and life assessment will be illustrated including a recent case study.

Key Words

Grade 91, Grade 92, creep, damage, multiaxiality.

Paper 059: Creep-Fatigue Life Estimation of Circumferential Welds in Thermal High Energy Piping System.

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Abstract

subjected to a load-controlled hoop stress due to internal steam pressure and a displace-controlled axial thermal expansion stress during plant operation. Therefore, it is necessary to rationally estimate the creep-fatigue life of circumferential piping welds in order to prevent accidents in thermal high energy piping systems.

Several damage cases have been reported for the 0.5Cr-0.5Mo-0.25V steel circumferential piping welds in Europe and for the 1.25Cr-0.5Mo steel ones in Japan. The mode of most damage cases was creep-dominated damage along the fine-grained HAZ (FGHAZ) i.e., Type IV damage which was mainly caused by an axial stress. As a result of internal pressure creep tests with the tensile load of the circumferential welded piping, it was found that the damage mode changed from longitudinal failure at the base metal to circumferential Type IV failure when the ratio of axial stress to hoop stress exceeded a certain value.

The initial stress value, the stress relaxation amount and the creep rupture strength of the welded joint seem to be three factors that determine the creep damage in circumferential piping welds. These factors depend not only on the type of material, but also on the structure of the piping system. In piping design, flexibility of the piping system is required to suppress the thermal expansion stress by using elbow structures, routing of piping, etc. However, the creep damage is likely to occur in the piping system where the relaxation of the thermal expansion stress is gradual due to the deformation restraint, such as near boiler outlets, turbine inlets, T- and Y-pieces.

In this report, the fundamental creep-fatigue life estimation method for welded joints was investigated. Strain controlled creep-fatigue tests have been performed using cross-weld specimens and their lives were estimated by a linear damage summation rule. Considering that the fracture mode was creep-dominant Type IV failure, the creep damage might be underestimated. One possible reason for this was that the elastic follow-up phenomenon of the welded joint was not taken into consideration in the estimation.

Key Words
Thermal high energy piping system, circumferential piping weld, creep-fatigue damage, Type IV failure, thermal expansion stress, 0.5Cr-0.5Mo-0.25V steel, 2.25Cr-1Mo steel, Mod.9Cr-1Mo steel, FGHAZ, elastic follow-up..

Paper 060: Microstructure and Creep Behaviour of Long-Term Service Aged and Lab Creep Tested Super 304H (UNS S30432/ DIN 1.4907/EN X10CrNiCuNb18-9-3).

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Summary

Super 304H is a new generation of advanced austenitic stainless steels that is increasingly being used in superheater/ reheater sections due to its superior oxidation resistance and microstructural stability at higher operating conditions of ultra-supercritical plants. Recent studies have however shown significant microstructural changes and associated degradation in creep performance during long-term service exposure in this alloy. Changes to the microstructure during service and its effect on the long-term creep performance this alloy has not been comprehensively assessed. In this work, variations in the microstructure of long-term service exposed Super 304H RH tubes (~99,600 hours at 596°C steam temperature) are documented. The results for the ex-service material are compared to well-documented laboratory studies to provide perspective on improved life management practices for this mainstay advanced stainless steel.

Key Words

Creep, microstructure, advanced austenitic stainless steel, boiler tube, Super 304H, sigma phase.

Paper 061: Variability in the Performance of Grade 91 Longitudinally Seam-Welded Components.

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Summary

The power generation industry continues to be challenged with unique complexities regarding the life management of creep strength-enhanced ferritic (CSEF) steels. Utility end users have recently identified and removed longitudinal seam-welded components fabricated from Grade 91 steel for post-mortem assessments. Several of these components were originally believed to be seamless but the accompanying specification at the time of new construction may not have explicitly prohibited seam-welds in fittings. This is leading to an increased number of findings for seam-welded elbows, reducers, tees and other fittings. This research involved extensive evaluation on four components ranging from clamshell fittings, straight section reheat piping and an outlet header that were all fabricated with longitudinal seam-welds. Microstructural evaluation included hardness and micro x-ray fluorescence mapping, optical imaging, and the use of scanning electron microscopy tools. High temperature creep testing was also carried out on each of the eight seam-welds using the full through thickness weld geometry. Post-test metallography was also conducted on each sample to determine the failure location and to evaluate the overall extent of damage in each specimen. Results showed there is extreme variability in performance of these components and overall creep behaviour can vary by >75X. The discussion section also expounds on the importance of understanding various factors, such as heat treatment, that can result in differences in microstructure, how this affects overall performance, and the lessons learned from the 5-year testing program.

Key Words

Grade 91, creep, seam-weld, piping, microstructure.

Paper 063: Service Experience of Wrought Tees Fabricated From Grade 91 and Grade 92 Steel.

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Abstract
>5 leaks have occurred over the last year in seamless tee intersections installed in high energy piping systems (main steam or hot reheat) operating for ~35,000 to 100,000 hours, and in grade 91 or 92 steels. Initial investigations confirm the primary concern is the evolution of creep-dominated damage in the branch weld HAZ (tee or branch-side), the main run HAZ (tee or pipe-side), the tee crotch, and potentially the tee flank (or saddle) position. The widespread nature of damage suggests these components are not fit for purpose. The objective of this paper is to summarize recent findings and contributing factors and secondly to describe the path forward in the implementation of a comprehensive life management methodology to identify at-risk tees across a fleet, prioritize future inspection(s), clarify relevant inspection or analysis technique(s), database failures, and issue improved guidelines for replacement components.

Key Words
Grade 22, Grade 91, Grade 92, creep, tee, piping.

Paper 064: Creep Deformation and Rupture Behaviour of Mod.9Cr-1Mo Steel Under Variable Loading.

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Abstract

This paper presents effect of variable loading on creep deformation and rupture behaviours of as-received and long-term used Mod.9Cr-1Mo steels. Creep tests were performed using solid bar specimens at 600°C under reversed loading condition, and the effect of reversed loading on the creep deformation and rupture behaviours was discussed. A representative creep-fatigue damage rule, time fraction rule, was applied to the experimental data. It was found that accumulative creep and fatigue damage were correlated within the current ASME damage criterion of 9Cr-1Mo-V steel, indicating that the criterion gave unconservative estimation. In addition, a new method based on time consumption law by quantifying the effect of reversed loading on creep life was proposed.

Key Words

Thermal power plant, Mod. 9Cr-1Mo, creep, variable loading, life evaluation.

Paper 065: High temperature properties of Reduced Activation Ferritic Martensitic steels for fusion applications in ITER: Status of activities and design needs for EUROFER97 steel.

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Abstract

The ITER facility, under construction at Saint Paul-Lez-Durance, southern France, is a major step towards the validation of the technologies required in a future Fusion Power Plant (FPP), connected to the grid and able to produce electricity. In particular, one of the missions of ITER is to demonstrate through Test Blanket Modules (TBM) the feasibility of tritium breeding and extraction of high heat fluxes, both of which are requirements for the Breeding Blanket components to be operated in the next DEMOnstration reactor currently under development in the EU. For the Initial Configuration of ITER, four TBM will be provided by the European Union (EU), Japan (J), China (CN) and Korea (K), each of them using a Reduced Activation Ferritic Martensitic steel (RAFM) as structural material.

Among the different RAFM grades proposed for future FPPs, the reduced activation 9%CrWVTa steel EUROFER97 has been developed by EU on the basis of conventional 8-12%CrMoVNb steels where Mo and Nb are replaced by W and Ta and a strict control of minor elements is specified in order to improve nuclear waste management. Four batches and various semi-finished products have been produced by Boehler, Austria and Saarschmiede, Germany. Plates and bars from batches 1 to 3 have been tested in several European labs, including high temperature creep and creep-fatigue experiments and material properties are already included in the “probationary rules” tome of the French nuclear code RCC-MRx used for the design and manufacturing of the TBM. Full qualification

to the code's standards is ongoing with the characterization of batches 3 and 4 in order to complete the validation of design rules appropriate to RAFM and related supporting data.

This paper presents an overview of the creep properties of different RAFM steels, in particular, those of EUROFER97 as obtained during the ongoing qualification program for the design of the European TBM, supported by EUROfusion under agreement with F4E.

Key Words
Fusion, Reduced Activation Ferritic Martensitic steels, EUROFER97, Creep, Creep-Fatigue, RCC-MRx.

Paper 066: Primary Energy Demand in South America: Current Status and Future Projects for Hydro, Nuclear, Renewable and Fossil Fuels.

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Summary

The objective of this work is to present a quantitative description of energy demand in South America. Available information from different countries is analysed. Conventional demand of fossil fuel, hydroelectric and nuclear energy is considered. Additionally, focus is placed on current development of non-conventional energy sources (i.e. wind and solar), in different countries.

Given the world objectives of reducing CO_2 production, available information about actions, objectives, and positions is presented. Updated targets set by individual countries are addressed.

Key Words

Primary energy consumption, electricity production, hydroelectric, nuclear energy, fossil fuels, renewable energy sources, CO2 emissions.

Paper 067: Results of United States Advanced Ultra-Supercritical Component Test Project for 760°C Steam Conditions.

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Summary

The U.S. Advanced Ultra-Supercritical (A-USC) Consortium was formed in 2001 as a government/industry program, sponsored by the U.S. Department of Energy (DOE) and the Ohio Coal Development Office (OCDO) and cost shared by industrial and not-for-profit partners. The purpose of the consortium was to advance the state of the art for power generation by evaluating and developing materials that allow the use of advanced steam cycles in coal-based power plants.

These advanced cycles, with steam temperatures up to 1400°F (760°C), can increase the efficiency of coal-fired boilers from an average of 35% to more than 45% higher heating value (HHV) (>49% lower heating value [LHV]). The increase in a plant's efficiency is limited unless new materials able to withstand these higher operating temperatures and pressures are identified and approved for use.

The A-USC Consortium identified these needed materials during earlier phases of the program. It developed the welding and joining techniques along with manufacturing processes for casting and wrought products made from these new high-nickel alloys. It subjected these materials to extensive laboratory and steam loop testing. It then obtained ASME code approval for their use in U.S. boiler systems. The program's successes leave this last remaining activity (ComTest Phase 2) that the U.S. utility industry has recommended to be accomplished prior to commercialization.

The focus of the activity is the evaluation and demonstration of commercial readiness for "full scale" components to be made from these nickel-based alloy materials and provided by a U.S. domestic supply chain that is new to working with these alloys.To reduce the final identified risk barrier to full-scale commercialization of these advanced materials and systems, the A-USC Consortium (guided by a utility industry advisory committee) has identified the key areas of the technology they desire to see as being capable of full-scale manufacturing and/or fabrication from an identified, capable U.S. domestic supplier base.

A significant amount of work was accomplished during Phase 1 to identity the components, as well as the component size, that would be manufactured from advanced alloys such as Inconel 740H or Haynes 282 alloys. The Phase 2 effort used Phase 1 findings for designing these key full-scale components for A-USC boilers and turbines to include large castings; extrusions, forgings, fabrication of water walls and steam loops with headers from advanced materials, raw material (such as pipe extrusion billets) are at the commercial readiness level to permit advancement to a demonstration project. The Phase 2 work scope was addressed by a diverse team, including government, industry, and not-for-profit partners.

The work scope under Phase 2 addressed fabrication of components identified as being outside of the proven capabilities of the existing supply chain, including the following:

- Steam turbine rotor forging and Haynes 282 nozzle carrier casting
- Superheater and reheater header and tube assemblies
- Large-diameter pipe extrusions and forgings
- Test valve articles to support ASME Code approval

In addition, key fabrication steps were completed, including boiler weld overlays and simulated field repairs. Throughout, extensive inspection and quality assurance testing of the components were performed. The team worked to advance ASME Code approval for key components and processes.

Paper 068: Matching Filler Development and Welding Procedure Optimization for the Thor® 115 CSEF Steel Grade.

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Summary
Today's deregulated and ever evolving energy market, with a steady increase of the renewables' share, poses several concurrent challenges to conventional thermal power plants. Additionally, conventional power plants act increasingly as dispatchable sources of electricity and are required to quickly ramp up or down their output based on the demand for electricity. This trend sets new challenges to the materials, which require improved mechanical properties such as higher creep strength in long term, and low corrosion rate at elevated temperature. Under fast and frequent cycling operation, ferritic steels are favoured to austenitic thanks to their lower thermal expansion. The existing Creep Strength Enhanced Ferritic (CSEF) steels are known to have some deficits, and new CSEF steels and welding procedures have been designed to mitigate these.
The new CSEF steel Thor®115 was developed to combine enhanced high-temperature oxidation resistance, creep strength and microstructural stability. A matching filler metal was developed to homogenize the same desirable properties across weldments. Trial productions were performed, and included stick electrodes (SMAW), rods (GTAW), and solid wire plus flux (SAW). Butt welded pipe and tube joints were fabricated and characterized in terms of metallurgical structure and mechanical properties, including creep testing across the weld. This paper presents and discusses test results, offering a comparison to earlier experiences made with non-matching CSEF grade 91 filler.

Paper 069: Influence of Incomplete Cooling Below MS on Microstructure and Properties of X20 Steel.

S. Allies

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Abstract

Process excursions during the production, or welding, of creep strength enhanced ferritic steels can lead to the evolution of aberrant microstructures which impact service performance. One such excursion involves incomplete cooling below the MS-MF temperature range followed by direct reheating to the tempering temperature. A series of heat treatments were performed on X20CrMoV11-1 steel (designated X20) to simulate incomplete cooling. Mixed microstructures developed which produced combinations of tempered martensite and new martensite after conclusion of the standard tempering step. Ductility reduced in proportion to the fraction of new martensite. Prolonged ageing at 650°C exacerbates the microstructural inhomogeneity that arises from the different populations of initial martensite and new martensite, as evidenced by the size and distribution of precipitates. Stress relaxation tests for periods up to 12 hours at 550°C are also shown to be useful in highlighting differences in creep strength between the standard and aberrant microstructures.

Key Words

Heat treatment, CSEF steels, process excursions, microstructure, creep, steam pipe.

Paper 070: CEN Workshop Agreement on Impression Creep – Round Robin Testing.

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Abstract

Impression creep testing is now an established small-scale testing technique in which the indentation rate of a rectangular indenter at high temperature can be converted into equivalent creep strain rate. Its increasing use and practical application to power plant has led to a need for standardisation, leading to the production of a CEN Workshop Agreement covering this testing methodology. This activity has led to a consensus on the details of the test itself, both in the form of the original single step test, and in the form of the more complex stepped stress test, which can provide data at multiple test conditions in the same specimen. It has also included standardisation of specimen and indenter sizes, a standard methodology for measuring indentation rate and creep strain rate, with an appropriate validity check, and agreement on a pre-test rig hysteresis check. This paper reports on a Round Robin exercise carried out by four laboratories using the agreed test procedure. The tests, at 600°C in the range 100-130MPa, on a grade 91 material with lower bound creep strength relative to the ECCC2019 grade 91 assessment, showed good agreement.

Key Words

CEN Workshop Agreement, Impression Creep, Round Robin Testing.

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Paper 073: Creep Rupture and Tensile Strength of Start of Life and Ex-Service 2¼Cr1Mo Steel.

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Abstract
An empirical model has been developed from a large dataset on 2¼Cr1Mo steels that predicts both the elevated temperature tensile strength and creep rupture strength in the start of life condition. Furthermore, this model includes the effects of chemical composition on tensile strength and rupture strength. The model is then modified to predict the effects of service exposure on both tensile strength and creep rupture strength.

Key Words
Grade 22, Creep Rupture, Tensile Strength, Service Exposure.

Paper 074: Uniform Elongation Measurements on Creep Specimens by a Novel 3D-Scanning System.

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Abstract

The ductility of a material represents a very important value for both the classification and the application of high-temperature alloys in real components. A low ductility results in a low resistance against initial flaws and crack-like defects because there is a limited ability to redistribute stresses in the vicinity of a crack by plastic deformation. In addition, a limited ductility results in a comparably low strain tolerance such that failure may occur spontaneously and after comparably low plastic deformations. In case of high temperature alloys and long-term applications, the ductility of the material is of even more importance because a sufficient ductility needs to be provided over the whole application duration. However, e.g. phase transformations, precipitation processes or other long-term activated effects might affect the ductility within the long-term range which needs to be considered, investigated and characterized by long-term creep testing.

Commonly, different values have been defined and can be used to characterize the ductility of the material, like measuring the “Reduction of Area” (Z) or “Rupture Elongation” (A) on lab specimens. However, those values strongly depend on characteristic specimen dimensions like the diameter over specimen length ratio. The reason here is, that e.g. the final value of the “Rupture Elongation” reflect two deformation processes: uniform elongation and necking. While the latter is strongly specimen geometry dependent, the uniform elongation value represents a pure material property. Even more important is that necking is more or less purely test specimen related and should not be expected considering real component features and dimensions.

Due to this, research has been spent in order to measure the material property “uniform elongation” accurately on fractured creep specimens. Because the necking portion needs to be subtracted in a robust and objective way, this measuring is quite challenging. In order to tackle this challenge, a novel a 3D-scanning technique has been developed targeting on an automatized detection of the uniform elongation.
Within this work, at first the 3D-scanning system as well as the developed software algorithms, which allow a highly precise digital reconstruction of fractured creep specimens, are briefly introduced. Following this, the digital reconstruction has been used to compare and re-fine conventions for determining the uniform elongation in order to get consistent and robust values. Finally, a large amount of long-term creep specimens was re-evaluated including P92 samples with challenging, since macroscopically low ductility values. The results will be discussed in form of uniform elongation trends and by use of the DECS (Ductility Evaluation of Creep Specimens) diagram.

Key Words
Uniform Elongation, 3D-Scanner, Creep Ductility.

Paper 075: Substructure & fracture toughness of 9Cr-1.5Mo-Co-V-Nb-N-B creep resisting cast steel (COST-CB2).

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Abstract

This article relates to testing of the COST-CB2 steel, one of a series of 9%CrMoCoVNbNB alloys for thick castings and forgings, intended to work at supercritical conditions of the steam main lines, designed and investigated in the frame of COST-522 and COST-536 actions of EU. This cast steel exhibits loss of fracture toughness when exposed to elevated temperature for long time. Substantial loss of ductility as well as creep life of CB2 appears in HAZ of welded joints, which was reported in two earlier articles by the authors, could not be correlated with appearance of precipitates on fracture surfaces neither ascribed to other embrittling effects. To address the questions received after these publications, here presented are results of fracture behaviour and creep properties of the CB2 steel and its heat-affected zone of weld joint after the long term annealing and creep testing, as related to substructure of the steel's matrix. An attention has been given to the appearance of sigmoidal shape creep curve, characteristic of some similar steels. Considering creep as a kind of plastic deformation, the initial dislocation substructures have been studied and their development during impact and creep deformations preceding the fracture, to establish correlation between the dislocation substructures and fracture modes. The results of this study indicated dissociation of initially stable dislocation configurations as responsible for rapid and unpredictable decrease of creep strength and life..

Paper 076: Practical Experience with Electron Beam Welding of Steel Assigned for Power Industry.

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Abstract

One of the main problems with the use of steels for elevated temperatures is their limited weldability. This is mainly due to the fact that these materials may contain in their chemical composition such elements as chromium, molybdenum, tungsten, boron or nitrogen. The materials used in power industry can be prone to overheating and grain growth mainly in the HAZ. Therefore, in some cases it is necessary to apply preheating and maintain the interpass temperature usually up to about 250°C. Due to the susceptibility to cold cracking, post-weld heat treatment is necessary, especially in high-stiffness welded structures. In addition, depending on the condition after heat treatment or in the absence of heat treatment, precipitates may appear in the microstructure of the steel, affecting its mechanical properties. The whole process of welding is nowadays elongated and expensive. It is important in this case to ensure the high quality of welded joints, which means that the power plant manufacturer has to demonstrate a very high technical culture, as these steels require full inspection and supervision before, during and after welding. Currently, thin-walled pipe butt joints are welded manually using a tungsten electrode with solid wire material (TIG method). One of the solutions that can significantly speed up the welding process of components for work at elevated temperatures is the use of an electron beam welding. In addition, the ability to make welded joints without the use of filler material and to achieve narrow heat-affected zones may find application in the welding of modern materials used in the power industry.

This paper presents the welding experience of T/P91 grade assigned for the power industry by use of electron beam. In this article authors present the results of non-destructive and destructive tests gained during first steps of welding homogenous welded joints. The article also includes preliminary results on the service life of the fabricated joints (creep resistance).

Paper 077: Microstructure Development After Long-Term Creep Testing of 600/620°C Turbine Materials with Boron.

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Abstract
The knowledge about advanced 9-10Cr creep resistant steels with Boron has been continuously increased. In Germany, research projects are running to generate very long-term creep data >100,000h at low operationally relevant stresses for forged and cast material of 9Cr with about 100ppm boron addition developed within COST522 (FB2, CB2).

The gained data and corresponding microstructural features (sub-grain structure and precipitation behavior) for more than 90,000 hours prove the long-term stability: The creep strength extrapolations based on the COST522 test melts and demonstration parts were confirmed or exceeded by the ongoing tests. This paper will introduce and discuss microstructure findings at different stages of creep loading, which provide a deeper understanding of the mechanism responsible for the excellent creep resistance.

It is confirmed that the development of advanced 9-10Cr steels has offered the possibility to produce reliable materials that form a stable alloy concept for 600-620 °C power plant and storage application.

Key Words
Creep, 10Cr steel, microstructure, long-term behaviour, extrapolation.

Paper 078: Creep and Creep-Fatigue Interaction for Rotor Material Made of MarBN (Howeflex).

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Abstract
The MarBN material family (Martensitic steels alloyed with Boron and Nitrogen) is known for years as new development of high strength creep resistant martensitic steels for application in pipes. But there are activities running to cover further component classes for power plants like castings and forgings with their special requirements in manufacturing and quality assurance.

The German funded project HOWEFLEX performed by a consortium of two turbine manufacturers, a forge master, and two research organizations, has made an upscaling of trial melt results of MarBN family alloys to a large rotor forging with diameter of up to 1,200mm and typical weight representative for e.g. intermediate pressure steam turbine rotor forgings. The manufacturability is confirmed, and different, service relevant material properties required for design purposes have been determined.

Long-term creep and creep-fatigue interaction are important features to allow meeting the requirements of future energy systems working on the base of rotating equipment, media like water, and thermodynamic processes.
The paper will discuss creep and creep rupture results comparing it with other MarBN alloys, and findings for creep-fatigue interaction by testing via LCF w/o and with dwell time, thermo-mechanical fatigue, and service relevant cyclic loading. Furthermore, results of modelling tools will be presented which are able to support long-term extrapolation, installation of creep curves for lower stresses, and describing the findings of creep-fatigue testing.

Key Words
Creep, creep-fatigue interaction, MarBN, large forging, creep modelling, fatigue modelling.

Paper 079: Microstructure Evolution of Grade P91 During Creep Test by Metallic Replica Non-Destructive Assessment.

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Abstract
9–12% Cr martensitic steels, e.g., P91 and P92 steels, have been widely used for high temperature applications in modern power plant components, such as boilers and piping systems, since their excellent high-temperature mechanical properties, and creep resistance. The creep damage associated to the extreme working conditions of these materials is not evaluable with the classic Neubauer methods based on the nucleation and growth of creep cavities (i.e., creep cavitation), since cavitation in these steels starts only immediately before the final rupture. The accurate estimate of the residual life of P91 components (as an alternative to the Transmission Electron Microscope (TEM) assessment of a standard extractive replica on cellulose acetate) can be made with a new type of replica using indium (In) thin strips, i.e., the so-called metallic replica, for which credible results can be produced just by Scanning Electron Microscopy (SEM). Metallic replica thus seems to be a candidate for life assessment of P91 components working in extreme conditions in power plants, e.g., pipes. This technique, to provide statistically robust results, now requires the definition of a unified and standardized procedure that considers every critical aspect of this innovative method, e.g., sampling, instrumental resolution and magnification and number of processed images – and various statistical and procedural problems.

Key Words
9-12% Cr steels, in situ metallography, extractive replica, carbide evolution, scanning electron microscopy, residual life estimation.

Paper 080: ECCC Working Group 3C – Superalloys Overview on the Activities and Future Perspectives.

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ECCC Working Group 3C.

Abstract

The Working Group 3C on superalloys is the most recent in ECCC. As the other WGs, its activity has been driven by the interest of the industrial members. During the last 20 years, many materials have been considered, in terms of experimental data production, data collation and assessment, and microstructural characterization.

Besides those produced through conventional routes, in the last years also materials obtained by non-conventional technologies, such as additive manufacturing (AM), started to attract the interest of the working group and were included in the group activities.

The methodologies for data assessment and model validation have followed ECCC WG1 Recommendations, but occasionally the assessors also experimented with innovative approaches, acting as input for discussion in WG1 and consequent upgrade of the procedures.

This paper provides an overview on the activities performed by WG3C, focusing on the most relevant or recent, and on its future perspectives.

Key Words

ECCC, Working Group 3C, Creep, Characterisation, Data Assessment, Ni-base superalloys.

Paper 081: M625 - A New Creep Resistant Martensitic 10%Cr Steel for Forgings.

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Abstract

Creep testing and deep microstructure characterization indicate that interstitial-substitutional (I-S) solid solution strengthening by V-N or V-N-V atomic pairs or triplets segregating to dislocations during creep is a key creep strengthening mechanism in boron nitrogen added martensitic 10% Cr steels.

To maintain high I-S strengthening during creep it is essential to control the "free" nitrogen content in the steels to a level of a few 10 ppm to limit or delay the precipitation of VN particles.

In the newly designed 10%CrMoWCoCuVNbNTiB steel M625 "free" nitrogen is controlled to a low level by titanium additions to obtain a defined Ti/N ratio.

Manufactured test steels and trial components show well balanced short-term mechanical strength and impact toughness. Creep testing at 600^{o}C up to more than 30kh indicate high strength and sufficient rupture ductility.

The M625 steel is currently under qualification for gas turbine applications.

Paper 084: Analysis of ECCC Cross-Weld Creep Test Data on Grade 92 Steel.

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Abstract

The UK High Temperature Power Plant Forum, in parallel with the Italian Creep Group, have completed a long term cross-weld creep test programme within ECCC Working Group 3A on a Grade 92 steel pipe. Whereas the Italian programme concentrated on evaluating the effects of multiple post-weld heat treatment, the UK programme has characterised long term performance over a wide range of stresses and temperatures.

This paper describes an analysis of the creep test data with particular emphasis on the comparative evaluation of weld HAZ and base material cross-weld creep rupture strength. The weld strength factor (WSF), i.e. the ratio of cross-weld strength to base material strength for a specified rupture time and temperature, is shown to be a unique function of a dimensionless parameter S, defined as the creep test stress divided by the ultimate tensile strength at the creep test temperature. The applicable function, as derived by empirical data plotting, is found to be essentially independent of the test temperature over the wide range employed in the UK test programme, 600-675^{o}C.

At a high threshold value of S close to 0.5, WSF reaches 100%, and cross-weld test failure takes place in the base material. At reducing S values, WSF gradually falls, and then reaches a minimum long term “plateau” level, of the order of 56%, when S has fallen to about $\lesssim 0.13$. This can broadly be explained in terms of the constrained failure of the thin weak HAZ sandwiched between the stronger base material and weld metal. As S is reduced, the extent of constraint gradually decreases. Constraint becomes negligible when the plateau is reached. Hence, WSF then simply becomes the intrinsic rupture strength ratio between the (unconstrained) HAZ and base material, which is relatively independent of the test conditions.

The key practical finding is that, since a single universal cross-weld creep life parametric is applicable to all temperatures, long term behaviour at service temperatures should reliably be predictable from short-term tests at

accelerated temperatures. The evidence for these conclusions, and their implications, are discussed.

Key Words
Creep, martensitic steel, Grade 92, steam pipe, boiler header, cross-weld test, weld heat-affected zone, “Type IV” failure.

Paper 086: Creep Fatigue Component Testing in the High Temperature Test Loop HWT.

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Abstract

Due to more and more flexible operation of conventional plants creep fatigue loading situations are more and more dominant for lifetime consumption. For this reason the test loop HWT III in the Mannheim Power Plant was designed to address specifically this issue by operating the cyclic part of the loop in the temperature range between 380 and 625 °C with hold times in the range of 4-6 hours. Experience form the previous test loop enabled the successful realisation of such cycles in the loop consisting of thick walled components made from P92, P93 and HR6W including typical stress raisers (tube-pipe-connections in a header-like component, T-Piece, component with reduced wall thickness etc). The test loop is operating since November 2021 and first results are available from an intermediate revision which was actually finished. The paper describes some details on the design and implementation, results from accompanying material tests mainly on P92, P93 and HR6W, numerical simulations of components using new constitutive models for deformation and damage for predictions and pre-assessments to ensure safe operation and experiences with the operation of other components in the test loop such as valves and armatures.

Paper 087: Quantification and Assessment of the Error Associated with Engineering Stress-Strain Analysis in Stress Accelerated Creep Tests in 316H Stainless Steel.

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Abstract

Historically, the reduction in sample cross-section has been neglected during uniaxial creep tests, and engineering stress-strain and strain rate have been considered rather than true stress-strain rate. In accelerated testing with high applied loads above yield, it becomes apparent that there is an increasing error associated with the engineering stress and strain, hence, this assumption is no longer valid. In this work, uniaxial creep tests on Type 316H austenitic stainless steel at temperatures ranging between 480 – 550 °C have been analysed in terms of both engineering and true stress-strain and strain rate. Significantly higher stresses and lower minimum strain rates have been determined from true stress-strain rate relationships compared to engineering stress-strain rate analyses for 316H in an as-received condition. These differences diminish as the material is strain hardened, limiting plastic loading strains and the creep ductility is reduced. Though the true stress-strain rate analysis method is known to be more accurate, the engineering stress-strain analysis generally predicts higher creep strain rates for a given stress and may therefore be considered a conservative measure for component lifetime assessments.

Keywords

Accelerated creep test, creep strain, austenitic stainless steel, pre-compression, true stress and true strain.

Paper 088: Creep Crack-Growth Behaviour in P91 Miniature and Standard Size Compact Tension Geometries.

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Abstract

There is interest in testing miniature compact tension fracture mechanics geometries for nuclear fission and fusion applications where miniature specimens may be preferably used to obtain properties of irradiated steels (Eurofer97, HT-9, Optifer). However, sample size is known to influence the crack-tip constraint, and hence crack growth behavior. In this work creep crack growth (CCG) tests have been performed on standard and miniature compact tension (C(T)) geometries of P91 steel. All tests were performed at 600°C. The CCG rates were correlated with the C* parameter calculated using a novel finite element analysis (FEA) approach. Post-test metallography and fractography were performed to examine the crack-path in both geometries.

Key Words

Creep Crack Growth, P91, Compact Tension, Miniature Specimen, Size Effect

Paper 089: Correlations Between Primary Creep and Stress Relaxation in a Single Crystal Nickel-Based Superalloy.

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Abstract

The creep strain rates during primary creep, measured from creep or evaluated from stress relaxation tests, are compared in the temperature/stress field between 650-1000°C/900-100MPa for a Ni-based single crystal superalloy used for gas turbine blades.

The stress relaxation tests were carried out at the creep test temperatures and with an imposed strain to cover the stresses of the performed creep tests. After a stress relaxation time, lasting up to 600 hours, the samples were reloaded at the initial stress (the stress was brought back at the initial value) and a new stress relaxation test restarted on the same initial specimen. This process of "repeated relaxation test" has been reiterated several times. Moreover specific "repeated relaxation tests" were carried out after creeping the specimens at constant load, in order to study the effect of a relatively large plastic creep strain.

The aim is to show that the "repeated relaxation tests" can represent an interesting method able to describe and estimate the primary creep stages of the alloy at the studied temperatures in a relatively short time. In particular the classical ever decreasing creep strain rate during the primary stage at the highest test temperatures and the experimentally observed sigmoidal primary creep for the corresponding test at 650°C were well-matched. The methods described in the following were developed and satisfactorily applied to turbine steels.

Key Words

Stress relaxation, creep, Ni-base single crystal.

Paper 090: INTERLABORATORY STUDY (ILS) on Load-Controlled Creep Test Using The Creep Reference Material – CRM-425.

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The Italian Creep Group

(Compusystem, RTMBreda, CSM-RINA, Ansaldo Energia, RSE, Concert, Hammer, CNR, Tenaris)

Abstract

The Italian Creep Group commonly delivers the National Annual Contribution to the ECCC (European Collaborative Creep Committee) by a joint creep test program, within which each participating member provides some creep test results. In order to guarantee the comparability of the joint creep tests, an Interlaboratory Study (ILS) / Round Robin tests (RRT) has been launched among the laboratories of the Italian Creep Group (ICG) to assess repeatability and reproducibility of load-controlled creep tests.

This paper presents the creep tests results carried out in eleven mechanical testing laboratories; cylindrical specimens, machined from the certified CRM425 Creep Reference material (Nimonic 75), available from the IRMM (part of JRC, former part of BCR®) have been loaded according to the testing procedure of each laboratory, based on UNI EN ISO 204 and respecting the additional requests of the IRMM guidelines related to the CRM.

Using CRM425 material the 'nominal' repeatability of the tests should be guaranteed both by the certified creep properties for this alloy and by the IRMM additional test prescriptions. The reproducibility will depend on the laboratory test procedures and in a big part also on the procedures for the processing of the raw test results, which is an essential part of each laboratory's test procedure.

Each laboratory machined the specimens from the CRM bars, according to their internal procedures, with a gauge length L0 ranging between 30 and 45 mm and diameter D ranging between 6 and 9 mm. The considered test variables, are: testing machine type (dead weight and servomechanical frames), extensometry details, thermocouple type and calibration details, data recording principle and system.

The ILS tests have been carried out at T=600°C and an initial stress □=160MPa according to the IRMM/BCR® prescription. The results have been assessed in terms of Creep Rate and Times to specific total creep strain of 2% and 4%, and were then compared to the expected scatter from the IRMM/BCR guideline, among the participating laboratories and with commonly expected result distributions in other creep testing ILS. The influence of particular testing details (thermocouples, extensometry, etc.) was analyzed.

As a general outcome, the data produced by the ILS are characterized by a quite reduced interlaboratory scatter for all the certified creep test results. The analyzed influence of the most relevant testing parameters was very limited compared to other international ILS, due to surprisingly similar testing procedures in all participating laboratories and due to the respect of the UNI EN ISO 204 prescriptions.

Key Words
Creep, creep strain, minimum creep rate, Nimonic 75, CRM 425, interlaboratory study, round robin.

G CHAI

Paper 092: Extra-Long Creep Rupture Life of Alleima 3R60™ (316/316L) Stainless Steel.

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Abstract

Alleima 3R60™ is an AISI 316/316L type of stainless steel. This alloy shows excellent corrosion resistance and high mechanical properties and has been well developed for different applications at elevated temperatures. In this study, it has been found that this alloy can have an extra-long creep life. At 700 °C with an applied load of 45 MPa, the predicted rupture time for the creep specimen is estimated to be 100 000 hours. However, the specimen broke first after 240,131 hours, a 140 % longer creep life. The reasons have been studied using electron microscopy techniques such as SEM/EDS, EBSD, ECCI and TEM. Two unexpected phenomena have been observed. One is the presence of homogeneously dispersed small $Mo_2Fe_4CrSi(Ni_{0.5})$ type of precipitates in the matrix. According to the thermodynamics calculation, this phase should not form in this alloy at 700°C. The other is the small or fine grains formed in the matrix during the creep-testing at 700 °C for such an extra-long time. It is believed that both small precipitates and fine grain size contribute to this extra-long creep life of the steel. With the microstructural study and thermodynamics simulation, the mechanisms to form precipitates and fine grains have been discussed. This work provides the knowledge and understanding to exploit high creep strength of 316/316L type of steels.

Key Words

Creep, 316/316L austenitic stainless steel, fine grain size, microstructures, precipitates.

Paper 094: Interaction and Superposition of Creep Damage and High-Cycle Fatigue Behaviour of Coarse-Grained Nickel-Base Alloy 247.

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Summary

Cast polycrystalline nickel-base superalloys are commonly used for high temperature components in power, aerospace, and automotive engineering. In this study, the coarse-grained polycrystalline Alloy 247 is investigated, which is typically used for blades in the rear turbine stages of land-based gas turbines. High turbine rotational speeds of up to 10,000 rpm led to considerable centrifugal forces, which, in combination with the high temperatures, induce creep deformation and damage. Additionally, gas turbine blades are subjected to high-frequency cyclic stresses, e.g., caused by resonances during start-stop processes or by vibrational excitations in the inhomogeneous flow field behind the guide vanes. This highly complex loading state requires the investigation of the interaction of creep damage and high-cycle fatigue (HCF) behaviour. Therefore, HCF tests with a stress ratio of $R\sigma = -1$ were carried out on specimens in the as-received condition, and on specimens that were pre-strained by creep loading applied on a pneumatic creep test rig. In comparison, an HCF test series with high mean stresses, i.e., a stress ratio of $R\sigma = 0.5$ was conducted to investigate the deformation and damage behaviour through a simultaneous superposition of creep and fatigue loading. To take the influence of creep-induced pores on fatigue crack formation and growth into consideration, the fracture surfaces of the specimens were analysed with scanning electron microscopy (SEM). Since nickel-base alloys exhibit a pronounced elastic anisotropy, the grain orientations in the crack initiation area were considered in the damage analysis. Hence, the grain orientations were determined using electron backscatter diffraction (EBSD). The obtained results show that the degree of creep-induced grain boundary damage is a dominant structural parameter for the HCF behaviour of Alloy 247 in case of both, sequential creep-HCF loading and HCF tests with high mean stresses.

Key Words

Creep, pores, cavitation, HCF, fatigue, fracture surface analysis, EBSD, superposition, Ni-base, superalloy.

Paper 095: Characterization of the Creep Cavitation Process on Grain Boundaries in a Polycrystalline Nickel-base Alloy 247.

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Summary

Hot gas path components such as gas turbine blades are loaded with constant centrifugal stress at high temperatures and thus the formation of creep cavitation on grain boundaries is considerably expedited. Especially conventionally cast polycrystalline nickel-base superalloys used as blade materials are prone to creep cavitation as many unfavourably orientated grain boundaries exist.

This research presents a diffusion based probabilistic creep model which describes the creep cavitation process on grain boundaries. It includes the three mechanisms pore nucleation, pore growth, and pore coalescence. The calibration of the model has been carried out by analysing as received Alloy 247 specimens with creep induced strain. For the evaluation of the pore numbers and sizes, a deep learning model for pore detection was trained on light microscopic and scanning electron microscopy (SEM) images. Electron backscatter diffraction (EBSD) images are analysed for further investigations regarding grain orientations and grain boundary angles to the loading direction. The calibrated model allows predictions of pore size distributions over time for the necessary parameters like temperature, stress, and strain rate for polycrystalline Alloy 247. The model can potentially be used for the creep cavitation prediction of other materials.

Key Words

Creep cavitation, grain boundary diffusion, machine learning, pore model, nickel-base superalloys.

Paper 096: Effect of a New Post Heat Treatment on Creep Resistant 15% Chromium Steels.

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Abstract

The shift to more sustainable energy production is placing new demands on thermal power plants. On the one hand, thermal efficiency and greenhouse gas emission requirements dictate that they operate at ever higher operating temperatures and pressures. On the other hand, the increasing reliance on fluctuating renewable energy sources relegates thermal power plants to operate as peaking plants which experience frequent start cycles and load changes. Furthermore, new technologies such as biomass power plants and molten salt reactors pose new difficulties regarding corrosion resistance. 15%Cr creep resistant steels are being developed to deal with these aspects. However, their dual phase microstructure presents new challenges to material scientists. In this work, we investigate several 15%Cr alloys, and we present a novel two step post heat treatment procedure which improves the pertinent mechanical properties of such steels and allows them to be tailored to specific applications. The phase fraction of martensite, and the nucleation of laves phase platelets have a strong influence on hardness, creep resistance and toughness. Extensive mechanical (Charpy, tensile, fatigue, creep) tests and microstructural (LOM, SEM, EDX, EBSD, TEM) investigations reveal insights into these future new developments.

Paper 097: Prediction of Mechanical Response due to Creep-Fatigue Loading Using Unified Mechanics Theory in Nickel-Based Superalloy.

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Summary

Components of aero-engine turbines are made with nickel-based superalloy, are subjected to complex thermos-mechanical loads. Creep-fatigue sequence of loading is one of the primary sequences of loading encountered in these engines, which will lead to failure in their components. The dominant mechanism due to creep-fatigue interaction (CFI) in nickel-based superalloys is multiple crack initiation and their propagation at high temperatures. Contemporary efforts to predict the mechanical response due to a combination of creep and fatigue loading, such as linear damage summation, use a procedure of combining damage estimations by creep and fatigue, in an arbitrary manner. The major drawbacks of these approaches are in terms of the extensive experiments required to estimate the model parameters and the limited predictive capability of these models. The combination of effects of creep and fatigue, as postulated in these models, are empirical and they do not seem to have any basis on the physics of deformation and failure in the materials. Such arbitrariness in combining the effects of creep and fatigue damages can be eliminated if the developed models are based on the mechanisms responsible for deformation and failure in these materials and the effects of these mechanisms are combined in some logical way. To address these issues, a thermodynamic-based unified mechanics theory (UMT) is proposed to capture the change in entropy due to creep and fatigue individually. An UMT-based model is used to monitor the degradation in the material due to a combination of these two types of loading, i.e., creep and fatigue, in nickel-based superalloys. The energy dissipated due to the hysteresis loop of CFI loading has been used to quantify entropy generation due to fatigue. The stress relaxation during hold time has been modelled using Norton's law of creep. The entropy generated and calibrated by these two loadings is combined using the framework of UMT, to predict the total damage in the material due to a combination of these two types

of loadings. The predictions of the model are later combined with typical experiments conducted on these materials.

Paper 098: Mechanical Behaviour of AISI 314, 316Ti and 321 Steels at Elevated Temperatures.

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Summary

This study brings comparison of high-temperature behaviour of three different austenitic stainless steels, AISI 314, 316Ti and 321. Steels are compared based on experimentally and numerically determined properties and characteristics. Experimentally, uniaxial tensile tests and short-term creep tests were performed at room and on a range of elevated temperatures (200°C to 600°C) to determine the change of ultimate tensile strength, yield strength and material creep response at different temperatures. Experimental results show that AISI 314 has the highest values of yield and ultimate tensile strength along the tested temperature range. Approximation curves are fitted through experimental values to describe dependency of the mechanical properties and temperature. This way, change of mechanical properties can be estimated for specific temperature in the tested temperature range. Creep behaviour at temperatures of 500°C and 600°C show higher strain percentage of AISI 314 at the same relative stress level, comparing to other two steels. As for the numerical research, finite element simulation of single specimen test method was performed whose stress analysis results were used to calculate J-integral and quantify crack driving force. This way, prediction of fracture behaviour for selected steels is possible. AISI 314 has higher J-integral values, making it more adequate to structures that need less susceptibility to fracture. Results of the presented study can be useful during industrial design when selecting adequate material for a construction that is intended to operate at elevated temperatures.

Key Words

Austenitic stainless steel, creep, fracture, tensile strength.

Paper 099: Creep Behaviour and Microstructure Evolution in Super 304H–P92 Heterogeneous Welds.

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Summary

The paper deals with results of long-term stress rupture tests on „cross-weld" specimens made of Super 304H–P92 heterogeneous welds. Stress rupture tests were carried out at temperatures of 625 and 650 °C up to 20 000 hours to rupture. Creep rupture strength values of Super 304H–P92 welds for 104 hours at both 625 and 650 °C were calculated. The preferential location of failure was the intercritical part of the heat affected zone in P92 steel. Local changes of hardness during creep exposure were evaluated by hardness profiles across the welds. Metallographic studies were performed in individual parts of heterogeneous welds. A special attention was paid to precipitation reactions in both base materials and heat affected zones. A residual content of vanadium in Super 304H steel affected precipitation processes. Vanadium partly substituted niobium in the modified Z-phase ((V,Nb)CrN).

Key Words

heterogeneous welds, stress rupture tests, creep rupture strength, heat affected zones, microstructure evolution, minor phases.

Paper 100: Creep Behaviour of Notched Specimens of MarBN-Cast-Steel.

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Summary

The concept of MARtensitic 9% Cr steel strengthened by Boron and Nitrides (MarBN) was developed to increase the working temperature for key components like thick section boiler parts, piping and turbine castings in steam power plants. For this purpose, the creep behaviour of such steels has to be investigated in detail. Within a KMM-VIN activity [1] and in a cooperation project between Technical University Darmstadt and Graz University of Technology [2] creep tests on round and notched specimens at 625 and 650 °C with applied stresses in the range of 90 to 200 MPa were performed.

The determined creep rupture strength of the examined MarBN-Cast steel is within the expected range. Beside the knowledge of strength values of structural materials for the application in power generation equipment, attention should be paid to the capacity of ductility and notch behaviour. These specifications are necessary for the determination of the allowed critical defect/flaw size in order to ensure a safe operation of critical components.

At 625 °C the lowest specific values of creep ductility parameters like rupture elongation and reduction of area were identified. At 650 °C an increase of these values was noted. The creep rupture strength of notched specimens is more or less similar to those of the smooth specimens in the tested parameter range, that means a notch sensitivity is observed.

On the basis of microstructure investigations typical characteristics of the material were determined. However, no clear microstructural evidence was found to explain the observed material behaviour.

The investigations were supplemented by creep crack tests, which were used to estimate a critical flaw size.

Key Words
MarBN-Cast, creep, creep deformation, creep ductility, creep crack growth, critical flaw size.

Paper 101: Advanced Analytical Methodology for Rapid Assessment of Cleanliness.

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Summary

The mechanical properties of alloys, and, in particular creep performance, are heavily dependent upon the cleanliness of the alloy where deleterious inclusions can lead to premature failure. In alloys for fusion reactors cleanliness is even more critical where potential in-service activation of the steels may lead to the rejection of the steel prior to installation. The Materials Processing Institute in collaboration with the University of Sheffield, European Technology Development Ltd. and the University of Warwick, are evaluating potential alloys that have higher performance at the temperatures above the limits of the current fusion alloys. The alloys were made at the Materials Processing Institute using vacuum induction melting (VIM). In addition to the chemical composition, the cleanliness was initially evaluated using an in-house method for scanning electron microscopy (SEM). Furthermore, a new analytical method was also created for optical emission spectroscopy (OES) offering a rapid assessment of inclusion distribution. This method was verified against the SEM evaluation. The scope was determined for the future assessment. This study offers a method development approach to streamline the chemical analysis and inclusion assessment of all alloys including those for fusion. In addition to a rapid and cost-effective evaluation, and minimal sample preparation, the method provides an analysis on a larger surface area that can be potentially used for rapid quality assessment.

Paper 102: Technical Scientific Report vgbe-TW 531:

Martensitic 9 to 12% Cr Steels –

Design, Production, Operation, and Safety Concepts.

Summary

A working group with members of steel maker and pipe manufacturer, weld metal producer, turbine manufacturer, utilities, universities, institutes, and vgbe (international technical association for the generation and storage of electricity and heat) has worked together to document experience and findings from energy and process industry.

The aim of the report vgbe-TW 531 is to summarize the current state of knowledge on the quality-compliant production, processing, design, and applications of the now established martensitic creep resistant 9 to 12% Cr steel grades used in the energy and process industry in Germany.

Furthermore, information and suggestions are given on the periodic testing and monitoring of components made from these steel grades under operating conditions. In addition, information is provided on new international research priorities and directions.

The authors agree that this document cannot be all-encompassing, as there is now a huge wealth of scientific publications on this family of materials and on individual grades in particular. It is rather a compilation of the relevant information as an introduction for the user in conventional power plant technology as well as in future energy conversion plants. The authors have included both in-depth details and comparative considerations.

The report, 155 pages, can be sourced at vgbe - www.vgbe.energy & www.vgbe.services

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Paper 103: Uniaxial Tensile and Creep Testing of Hot Isostatic Pressed P91 and 316H Steels.

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Summary
Hot isostatic pressed (HIPed) P91 and 316H steels are candidate materials for The Advanced Modular reactors (AMRs). During operation these steels must withstand temperatures of ~600°C and high pressures, which are conditions that promote creep failure. Hot isostatic pressing involves applying high temperature and isostatic gas pressure by means of an inert gas to metal powders. The HIPing processes produces components with near-net shapes, a more uniform material microstructure and superior material properties by removing internal porosity and voids. This eliminates, the need for machining and welding, reducing the introduction of defects to materials. Theoretically this results in materials withhigher yield and ultimate tensile strength and reduced creep and fatigue crack initiation.Steels P91 and 316H have been focused on as these are commonly used materials in nuclear power plant components due to their good performance at elevated temperatures and pressures. This study involved characterising the creep behaviour, mechanical properties and resulting microstructure of HIPed P91 and 316H. The results are compared to existing data from forged material. The forged samples used in this study were ex-service P91 pipes and 316H steam headers.To understand the creep behaviour of the two steels a series of high temperature uniaxial creep tests were conducted. The testing conditions were 600°C at around 145 – 155 MPa for P91, and 550°C at over 300 MPa for 316H. These were chosen based on existing literature with the intention of failure times > 1000 hours. In order to capture the different stages of creep, a novel methodology for creep strain measurement has been implemented which takes advantage of digital image capture. Images are taken of the sample at regular intervals for the entire test duration which can be used to give the variation in sample diameter, from which creep strains and true stresses can be determined. Creep curves for the HIPed samples can be compared to their equivalent forged samples. Stress-strain curves derived from high temperature tensile tests will be used to determine the area reduction at the relevant test load. This was done to reduce any errors due to sample motion upon loading. Preliminary findings have shown the P91 samples remaining in secondary creep beyond the predicted 1000 hours predicted, suggesting their

creep performance to be superior. Both of the 316H samples have failed without reaching secondary creep. Surface imaging has shown high levels of porosity within the sample, which is uncharacteristic of the HIPing process, suggesting a potential fault with the manufacturing process. Further material characterisation was done through a series of in-situ tensile tests. Having electro-etched samples of both 316H and P91. This allowed for microstructure evolution with tensile strain to be evaluated. Scans showed how the lattice orientation of the HIPed samples showed no preference unlike forged and hot-rolled samples, indicating more isotropic properties. Additionally grain boundaries were on average smaller, which would result in higher yield strength. Any difference in behaviour will be related to the samples microstructures.

Paper 104: Role of Crack Interactions on Rate of Failure in Nickel Superalloys Exposed to Intermediate Temperatures.

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Summary

The reliability of turbine engines strongly depends on the environment through which aircrafts fly. Humidity, contaminants, operating stresses, and temperatures determine the likelihood of cracking. Simultaneous crack initiation at multiple locations lead to crack interaction, either in the form of shielding or coalescence, which has the potential for arresting damage or accelerating catastrophic failures.

This poster will start by highlighting how Phase Field modelling was used to determine critical separation length scales needed to see different interactions and predict how it may have an effect. It will also show how these results were used to redesign the experimental setup, and how these novel experiments saw an increase in crack lengths by as much as ten-fold. This poster emphasises the importance of integrating models, experiments, and microscopy and how together they provide far more detail as to the degradation mechanisms occurring.

Paper 105: Uniaxial Creep and Creep Crack Growth Properties of 316L Stainless Steel Manufactured By Laser Powder Bed Fusion.

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Summary

Additive manufacturing, specifically laser powder bed fusion (LPBF), could become key to manufacturing parts with complex geometries and net-shaped metal components. By manufacturing components in successive layers, restrictions on geometric complexity as well as better material economy, reduced manufacturing variability and a reduced manufacturing footprint could be achieved. The current issues with this technique are that very high residual stresses can be developed, as well as significant variations in microstructure and large pores. The combination of defects and tensile stresses at the surface of the component mean that when in operation at high temperatures, defects can growth by creep processes even without applied loads. 316 L stainless steel has long been used in high temperature applications. As a well-established laser powder bed fusion (LPBF) alloy, there are opportunities to utilise additive manufacturing in such applications. However, to date there is limited creep data on LPBF material.

Uniaxial round bar creep tests have been performed at 700 °C and characterised using powerlaw relations to evaluate the creep strain and rupture properties of LPBF 316 L. Samples were manufactured in 2 orientations denoted (i) vertical i.e. build direction parallel to the build direction and (ii) horizontal, i.e. build direction perpendicular to the build direction. The creep response was found to be anisotropic with specimen build orientation, with samples loaded perpendicular to the build direction (Horizontal) exhibiting faster minimum creep rates than samples built parallel to the build direction (Vertical) and significantly shorter rupture lives. This was mainly attributed to the columnar grain structure, which was aligned with the build direction of the LPBF samples. Scanning electron microscopy has been performed to examine qualitatively the number and location of defects in the uniaxial samples and electron back scatter diffraction employed to examine the grain structure and texture relative to the build direction. The results were compared to existing test data performed at 650 °C.

In addition, creep crack growth (CCG) tests have been performed on compact tension samples manufactured by LPBF. The compact tension samples have been manufactured in orthogonal orientations to understand the anisotropic nature of LPBF. Finite element analysis (FEA) has been used to analyse the data. Vertically built samples have been found to be more creep resistant than the horizontally built samples due to the resulting large grain columnar structure and in the build direction, which reduce the effect of dislocation creep. The CCG data is analysed in terms of the C* parameter and compared to data from wrought materials. Metallographic analysis has also been performed to examine the crack path and the interaction of the main crack with existing defects. Optical metallography has been performed on the CCG test samples to examine the CCG path and its interaction with existing defects.

Paper 106: A Machine Learning Approach to Creep Life Prediction of Austenitic Steels.

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Summary
There are many factors which affect service life of high temperature components, such as operating conditions, component geometry, the chemistry of the material and any processing history. The work presented in this paper applies modern data science algorithms and machine learning techniques with more traditional approaches to life assessment to allow new understanding of the high temperature properties of austenitic steel. Through the work, different predictive models such as multi-variate linear regression, support vector machines, random forest regression and gradient boosting regression, are evaluated. Models are fit to a training subset of experimental data including test conditions, chemical composition, and grain size as independent variables. An evaluation of the most effective method in predicting rupture lives is given. The multi-variate machine learning approaches allow the effect of different independent variables for different heats to be quantified and through evaluation of impurity-based feature importance's. This provides an improved understanding of the many factors that affect operating lives in these steels and may help to provide more accurate predictions of remnant life and inform the development of new similar steels.

Key Words
Creep, austenitic stainless steel, machine learning, rupture lives.