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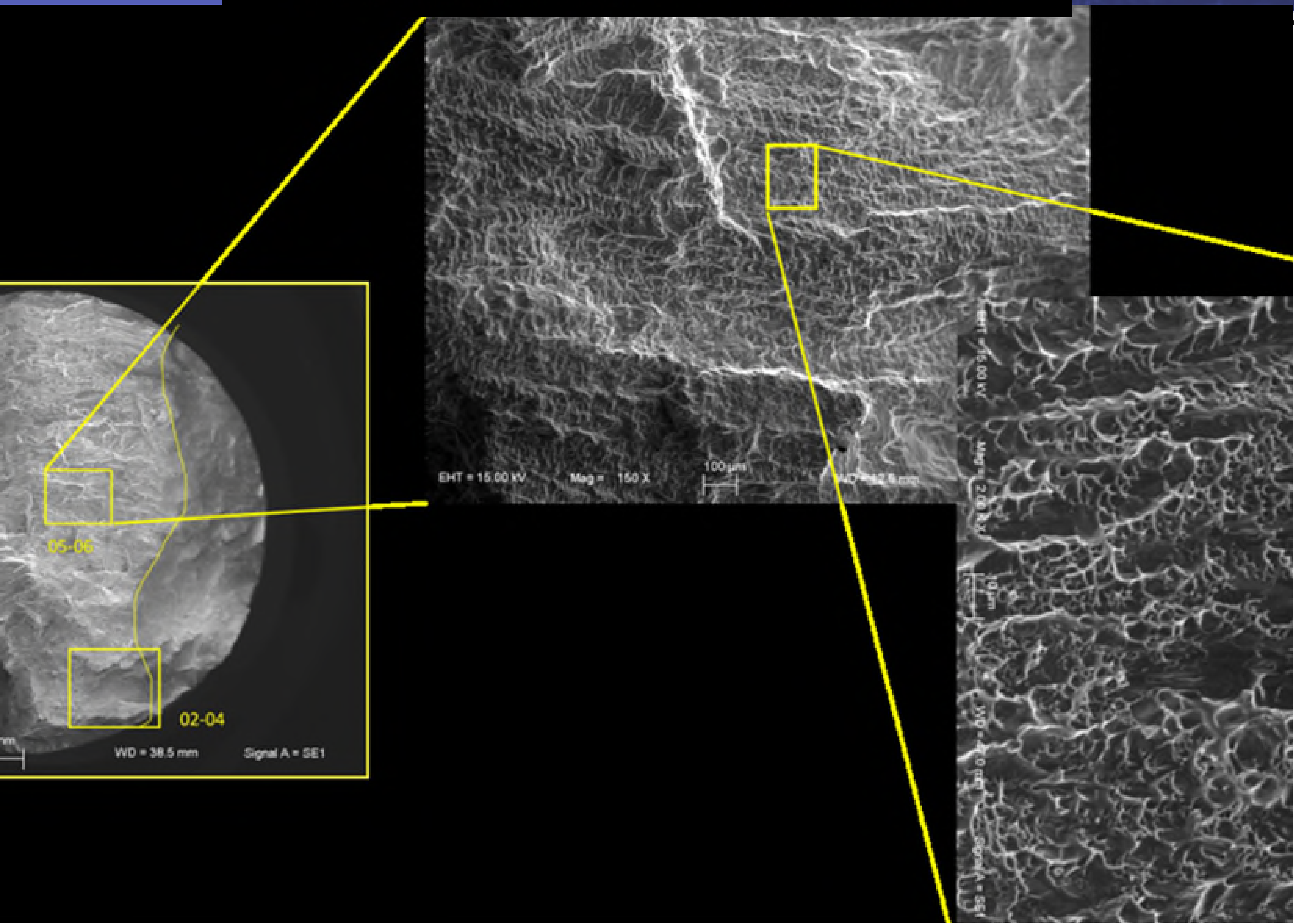

European Creep Collaborative Committee

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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 the proceedings. Copies of the proceedings are available for purchase from the ECCC website https://www.eccc-creep.com/

Plenary Paper 001: Global Overview of the Energy Scene

Dr Andrew Minchener OBE
General Manager International Centre for Sustainable Carbon

Introduction
Global energy is a very large subject so this presentation will focus on how the global power generation sector is developing, the different drivers that have advanced the technology options, with some thoughts on likely evolution and regional differences.

Brief description of the International Centre for Sustainable Carbon
The International Centre for Sustainable Carbon (ICSC) is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes (TCPs). These TCPs are organised under the auspices of the International Energy Agency (IEA) but are functionally and legally autonomous
The ICSC is funded by national governments (contracting parties) and by corporate industrial organisations (sponsors). We provide independent information and analysis on how biomass, coal and other carbon sources can become cleaner sources of energy, compatible with the UN Sustainable Development Goals.

Power generation technologies, impacts and issues
The world is far from a homogeneous place, with very significant differences between the OECD economies and those of developing nations. OECD economies were built on coal use for power generation, which provided a robust dispatchable system that created significant economic benefits although there were adverse environmental impacts. The need to address these were firstly local, such as smog in London in the 1950s. then regional such as acid gas emissions. Legislation was introduced to improve efficiency and reduce the environmental impact of coal power plants, followed by the introduction of gas-fired plants that were less polluting, and to a limited extent the building of large nuclear power plants.

More recently, climate change concerns, and the link to carbon emissions from fossil fuel power and large industrial systems, has led to global interactions to reduce emissions. There has been a push for significant efficiency improvements plus the development of CCS. However, CCS is still struggling to get established as a commercially viable option for CO2 control, even though it appears to be an

essential part of any coherent solution. The other approach, which has been promoted heavily by OECD governments is the introduction of nominally zero carbon variable renewable energy (VRE) sources, even though these have significant availability limitations. The VRE sources comprise solar and wind power and to a lesser extent, hydropower.

For developing countries, like the OECD countries before them, there has been economic development based on robust dispatchable power, using coal and to an extent gas. Their priorities include a focus on ensuring their populations have access to reliable power to end energy poverty and facilitate development. As such, establishing a robust infrastructure is critical to a successful outcome.

This raises some key questions for future fossil fuel power plants, especially for coal. Asia is home to almost 60% of the world's population while only having access to some 38% of the energy resources. Many Asian countries have a strong focus on fossil fuel use for the reasons set out above. However, over the coming decades it is likely that fossil fuel use, especially coal, will continue to decline in the OECD regions and beyond that its use will start to diminish in the developing regions. This change will partly be due to financial and political pressure from the OECD countries on the developing regions to cease coal use and replace it with VRE. That said, there is not much evidence at present that developing countries will give up on coal and gas in the near to medium term.

In summary, as the power sector becomes ever more complex to meet the growing and changing needs of stability and flexibility, both for power production and transmission, the importance of critical minerals becomes ever more important. These minerals comprise metals and non-metals that are considered vital for the economic well-being of major and emerging economies. Currently, the focus is on minerals that are needed to ensure the operation of the green energy technologies, which differ from those fuelled by traditional hydrocarbon resources.

The political drivers associated with climate change concerns will have a global impact on technology development and deployment. This is evident when one considers the current power sector technology mix for operational plant, which remains dominated by the traditional technologies, while those under construction and at the planning stage show a move away from fossil fuels towards 'green options'.

The final point is that technology choice cannot be solely dependent on environmental considerations. It is essential to consider all aspects of the energy trilemma, namely energy security, economy and environmental sustainability.

 

Plenary Paper 002: Experiences on the materials service in the Chinese Ultra Super Critical power plant

Dr Chang Che[1] & Prof Zhengdong LIU[2]
[1]China Special Equipment Inspection and Research Institute
[2]China Iron and Steel Research Institute (CISRI) Group Company

9Cr martensitic heat-resistant steels are widely used for high temperature pipes in ultra-supercritical (USC) power plant. These pipes are exposed at high temperature and high pressure during long-term service, resulting in microstructure aging and mechanical properties degradation.

China has the biggest amount of supercritical boilers in the world. The number of USC power plants in service in China exceeds 800 units, and the operating time is close to 200,000 hours. The statistical results show that, from 2004 to 2018, the cumulative consumption of T91 and P91 reached 330,000 tons and 190,000 tons respectively in China, which were mainly used for superheaters, reheaters, outlet headers, main steam pipes and reheating pipes of USC boilers. Considering the corrosion and oxidation thinning of boiler components during high temperature service, design margin was added to the actual design of boilers based on the wall thickness calculated in the design specifications. The design margins of the superheater and reheater tubes are the largest, generally increased by 5-10% and 10-15% respectively. The design margins of main steam pipes and reheating steam pipes have also reached 1-5% and 5-10%, respectively. For superheater and reheater tubes, the increase of design margin is mainly due to the loss of wall thickness caused by steam oxidation of the inner wall, followed by the thermal corrosion and mechanical wear of the outer wall, and creep is not the main factor. For the main steam pipes and reheat steam pipes, the increase of design margin mainly considers the internal steam oxidation and high temperature creep.

In order to ensure long-term service safety, China has strict control over the production and manufacturing quality of Gr.91 and Gr.92 steel pipes, and the reinspection of the material are usually carried out before installation. At present, the unqualified rate of reinspection of domestic materials maintains below 1%.

In this research, 482 inspection reports are studied, among these inspection reports, 372 defects and failures are found in Gr.91 and Gr.92 steels. It is worth noting that the defects include both base metal defects and weld joint defects. Typical defects have high hardness (185 cases), low hardness (169 cases),

microcracks and propagation cracks (152 cases), internal defects (124 cases), severe microstructural aging (28 cases), welding defects (3 cases) and other defects including manufacturing defects, slight corrosion, etc. (6 cases). The defects of the Gr.91 and Gr.92 steel materials have mainly four categories: low hardness, cracks, microstructure aging and high hardness. According to this statistic, the Gr.91 and Gr.92 steels have a total of 185 records of material-related defects. The defect detection rate accounts for 38.38%.

The defects in Gr.91 and Gr.92 steels show different characteristics under different service conditions. The defects of base material will be illustrated in four aspects of different unit capacity, superheater outlet temperature, operating time and defect location.

Plenary Paper 038: Can Long Term Time to Rupture data be Predicted Using Only Tensile Test Data?

EDF UK

The original ORNL (1984) data package for modified 9Cr1Mo has been revisited with the aim of answering the question: Can long term time to rupture data be predicted using only tensile test data? The predictions that have been made using only the results of tensile tests are compared with the 30,000 hour rupture data contained in the ORNL data package and the 100,000 hour rupture data published in NIMS data sheet 43A.

Plenary Paper 004: Update on United States Advanced Ultra-Supercritical Component Test Project for 760°C Steam Conditions

Robert Purgert
Energy Industries of Ohio

Following the successful completion of a 15-year effort to develop and test materials that would allow advanced ultra-supercritical (A-USC) coal-fired power plants to be operated at steam temperatures up to 760°C, a United States-based consortium has been working on a project (A-USC ComTest) to help achieve technical readiness to allow the construction of a commercial scale A-USC demonstration power plant. Among the goals of the ComTest project are to validate that components made from the advanced alloys can be designed and fabricated to perform under A-USC conditions, to accelerate the development of a U.S.-based supply chain for key A-USC components, and to decrease the uncertainty for cost estimates of future commercial-scale A-USC power plants. This project is intended to bring A-USC technology to the commercial scale demonstration level of readiness by completing the manufacturing R&D of A-USC components by fabricating commercial scale nickel-based alloy components and sub-assemblies that would be needed in a coal fired power plant of approximately 800 megawatts (MWe) generation capacity operating at a steam temperature of 760°C (1400°F) and steam pressure of at least 238 bar (3500 psia).

The A-USC ComTest project scope includes fabrication of full-scale superheater / reheater components and subassemblies (including tubes and headers), furnace membrane walls, steam turbine forged rotor, steam turbine nozzle carrier casting, and high temperature steam transfer piping. Materials of construction include Inconel 740H and Haynes 282 alloys for the high temperature sections. The project team will also conduct testing and seek to obtain ASME Code Stamp approval for nickel-based alloy pressure relief valve designs that would be used in A-USC power plants up to approximately 800 MWe size.

The U.S. consortium, principally funded by the U.S. Department of Energy and the Ohio Coal Development Office under a prime contract with the Energy Industries of Ohio, with co-funding from the power industry participants, General Electric, and the Electric Power Research Institute, has completed the detailed engineering phase of the A-USC ComTest project, and is currently engaged in the procurement and fabrication phase of the work.

This paper will outline the motivation for the effort, summarize work completed to date, and detail work scope for the remainder of the A-USC ComTest project.

Plenary Paper 142: High temperature material requirements for the design of next generation Nuclear Power Plants

Hyeong-Yeon Lee
Korea Atomic Energy Research Institute

Thermal efficiency of the currently deployed fleet of Generation III+ nuclear power plants with water-cooled reactors cannot be increased significantly without totally different innovative designs, which are Generation IV reactors with at a high level of fuel efficiency, safety, proliferation-resistance, sustainability and cost. The high performance and reliability of materials when subjected to the higher temperature and neutron dose environments are material requirements in Gen IV nuclear reactors. In this study, reviews on materials, requirements and challenges for structural Gen IV material are made associated with design of Gen IV nuclear reactors that operate at high temperature in creep range. The requirements of nuclear-grade heat-resistant materials codified in high-temperature design rules of ASME Section III Division 5 Subsection HB (hereafter 'ASME-HB') and RCC-MRx are reviewed along with comparison of the two design rules with more focus on damage of creep and creep-fatigue. High-temperature design evaluation platform of 'HITEP' was developed by KAERI which enables a designer to perform high-temperature design in reliable and efficient way according to the design rules of ASME-HB and RCC-MRx. Application of heat resistant materials to pressure boundary components and piping in a next generation nuclear reactor system was conducted by using the HITEP platform.

Paper 005: Creep Deformation and Rupture Behavior of Pre-Strained Type 304 Stainless Steel

H. Shigeyama & Y. Takahashi
Central Research Institute of Electric Power Industry

Austenitic stainless steels are known to harden significantly by the introduction of plastic strain, leading to reduced ductility. Creep rupture life of austenitic stainless steel after cold working is extended under high stress conditions but might be shorter than that of unprocessed materials under low stress conditions. Therefore, when cold-worked austenitic stainless steel is used as a high temperature component without any heat treatment, creep cracks may occur earlier than expected without major deformation. In this paper, the effect of cold working on the creep properties of type 304 stainless steel were studied. Creep tests were conducted at 600°C for type 304 steel, which was subjected to tensile and compressive plastic pre-strain up to 20% at room temperature. Based on limited experimental data, a creep constitutive model and a creep ductility model in consideration of plastic pre-strain have been developed. Then, creep damage evaluation for the cold bent portion of the boiler tube was carried out based on the ductility exhaustion approach using the developed models and the effect of plastic pre-strain on the creep life of the tube bend was investigated.

Paper 006: Development of creep-resistant steels by self healing: from model alloys to more robust steel compositions

Y. Fu[1], H. Yu[1], N. H. van Dijk[1], W. Xu[2] & S. van der Zwaag[1,3]
[1]Delft University of Technology, [2]Northeastern University, [3]Tsinghua University

During creep, quasi-spherical micron-sized cavities form preferentially at the grain boundaries oriented perpendicular to the load direction. These cavities subsequently grow and coalesce into micro and macro cracks, which ultimately lead to failure. The concept of self healing provides a new principle to extend the creep lifetime. Supersaturated solute atoms can selectively segregate at the free internal surface of the grain boundary cavities and fill them, thereby preventing the coalescence of cavities. This reduction in coalescence rate leads to an extended lifetime.

In this study, we investigate the creep behaviour of a series of ferritic steels, which are computationally designed to have a self-healing capability. In our previous research on a Fe-W model binary system, Fe_2W Laves phase has been proved effective in autonomously healing of creep damage [1]. In the present study, Fe_2W Laves phase is again selected as the healing agent. Three steels are designed in such a way that the chemical driving force for Laves phase nucleation and the equilibrium amount of Laves phase vary gradually from steel to steel, resulting in rather different predicted kinetics for Laves phase formation on free internal surfaces. Creep tests at a fixed temperature of 550 °C with different applied constant loads are applied to evaluate the creep properties of the designed alloys. The creep cavity filling behaviour and the Laves phase formation kinetics are evaluated and compared among the three alloy candidates. This first generation of self-healing creep steels provides new insight for the design of following generations, in which an even better balance between regular creep behaviour and healing of early-stage creep cavities is obtained.

[1] H. Fang *et al.*, "Self healing of creep damage in iron-based alloys by supersaturated tungsten," *Acta Materialia,* vol. 166, pp. 531-542, 2019.

Paper 007: Physical Background and Simulation of Creep in Steels

Stan T. Mandziej
Advanced Materials Analysis

Conventional "constant-load" creep tests of new steels and welds for thermal power generation and chemical processing are very long lasting, thus delaying application of newly developed steels for years. The conventional creep tests are usually carried out in air, seldom in vacuum, while in most of real installations the active atmosphere is water steam. New generation ferritic-martensitic steels can deform substantially during the "constant-load" tests, so the initial stress of the test is never true stress in the critical cross-section of the creep sample. Most promising new Co+B modified ferritic/martensitic steels in conventional creep tests after the initial high strength show sigmoidal drop of the creep curve, as mentioned by F.Abe (Bainitic and martensitic creep-resistant steels; in: "Current Opinion in Solid State and Materials Science", Volume 8, Issues 3–4, June–August 2004, pp. 305-311) thus making impossible to predict their long-term creep life by extrapolation. Finally, the recent frequent power plant shut-downs due to adding solar/wind power to the net, call for creep-fatigue data which standard creep tests cannot provide. While most of the component's design and estimation of power plants lifetime is based on long-¬term creep data, generally provided by manufacturers for the plate and pipe creep resisting steels, for welded joints on these components such data are seldom available, while the heat-affected zones (HAZs) of the welds are considered as weakest links of many joints, and welding procedures seriously influence their creep properties. In response to these needs a thermal-mechanical fatigue procedure was designed, called accelerated creep test (ACT), accounting for physical phenomena related to microstructure transformation during creep, in particular generation of dislocation substructures, their role in nucleation of voids and cracks, intensification of carbide precipitation and gradual decay of mechanical properties during long-time exposure under stress to elevated temperatures. The actual ACT procedure generates in less than 24 hours adequate data for calculating true lifetime of the tested creep resisting steel or weld. ACT records response of the tested steel or weld metal to the programmed thermal-mechanical deformations that generate dislocation substructures characteristic of creep. Changing intensity of loading in ACT allows studying various situations of creep and fatigue as well as strain-induced precipitation hardening.

As creep is plastic deformation at elevated temperature, with small strains and very small strain rates (R.W.K.Honeycombe: Creep in Pure Metals and Alloys, in The Plastic Deformation of Metals, E. Arnold Publishers, London 1984, p.356), next to its short duration the ACT offers:

1. Applied temperature like at true creep and strains preventing odd transformations e.g. secondary dissolution of carbides and formation of non-equilibrium phases.

2. Avoidance of extrapolation by running test up to fracture, with deformation at fracture, in particular crosswise strain, like at real creep - just a few pct in total.

3. Depletion of steel matrix in alloying elements achieved similar to that of crept steels and carbide phases or other precipitates at onset of cracks are not different.

4. The ACT samples having adequate “bulk” size, as in creep of the steel’s matrix thousands of grains or hundred thousands of subgrains participate.

The present article highlights the physical principles of the developed accelerated creep test, shows examples of its application and obtained results.

Paper 008: Fracture damage evolution and structural integrity assessment under creep-fatigue interaction

V. Shlyannikov & A. Tumanov
FRC Kazan Scientific Center of Russian Academy of Sciences

In this study, we analyzed the behavior of creep damage and fracture resistance parameters in a 3D finite thickness cracked body by employing damage-evolution equations. A damage model for the fracture process zone is represented using a ductility-based formulation. Following the ductility model, a new multi-axial failure creep strain condition is derived. Both damage-free and defective creeping solids are analyzed. The variations in the creep damage contour and crack tip governing parameters in terms of the creep I_n-integral with respect to time, as well as the crack size, are considered using full-field finite element model solutions. A crack growth rate approach is developed for the case of creep and fatigue interaction. Creep-fatigue crack growth rate tests are performed on a specially designed program test cycle using standard compact-tension specimen. The main finding based on the numerical and experimental results carried out is that the creep-fatigue interaction effect during the low-frequency fatigue crack growth may be represented in terms of the creep stress intensity factors (SIF), which are sensitive to the damage accumulation processes. The increase in creep-fatigue crack growth rate can be eliminated by inserting the ductile damage model into the governing parameters in the form of the I_n-integral and creep SIF K_{cr}.

An aviation GTE rotating turbine disc made from heat-resistant XH73M steel is the focus of this innovative application of basic analytical and numerical solutions. In operation the failures have occurred by semi-elliptical cracks developed on the inner surface of the coupling hole in a turbine disc hub. The effect of the elastic–plastic and undamaged/damaged creep crack tip fields on the behavior of low-cycle fatigue and creep fracture resistance parameter, are represented by numerical calculations. The crack growth rate models include the fracture process zone size and damage parameters. For the GTE turbine disc, the constraint parameters, local fracture process zone sizes, and nonlinear plastic (K_p) and creep (K_{cr}) stress intensity factors are calculated by finite element analysis to characterize the fracture resistance along the semi-elliptical crack front as a function of the flaw aspect ratio, operation temperature, and low-cycle fatigue and creep material properties. Predictions of the creep–fatigue crack growth rate and residual lifetime are given for different combinations of operation loading conditions and damage of the GTE turbine disc.

Paper 010: A proposal and methodology for the accelerated implementation of probabilistic approaches in the nuclear sector

J. D. Booker[1], R. Bradford[1], S. Z. Chavoshi[2], M. Martin[3], P. Reed[3], R. Marshall[3], H. Cathcart[4], J. Johns[5], M. Chevalier[5], N. J. Underwood[6], C. Pyke[6] & O. Tuck[6]

[1]University of Bristol, [2]Imperial College London, [3]Rolls-Royce, [4]Frazer-Nash Consultancy, [5]EDF Energy, [6]National Nuclear Laboratory.

Probabilistic approaches allow the uncertainties and variabilities present in reactor design, operation, material properties and degradation mechanisms to be understood and the reliability to be quantified. Improved knowledge in the structural integrity field continues to highlight that the unquantified margins associated with current deterministic methods do not provide a consistent measure of component risk, sometimes resulting in unexpected failures but more often resulting in over engineered structures. The benefit of probabilistic methods, in conjunction with setting target reliabilities, is a more consistent approach to ensuring safety by quantifying margins. This approach enables system-level analysis within which the individual contributions of material, manufacturing, inspection and operational load variability to the overall reliability to be evaluated and optimised to ensure safety. The nuclear community, in particular, would benefit from applying probabilistic methods to structural assessment more widely and implementing general probabilistic frameworks for design, analysis and assessment in engineering structural integrity. The transition from determinism to probabilism is a natural one, but requires considerations of user knowledge, method choice, computational intensity and accuracy of outcome, as well as selection and use of case studies for training and benchmarking. This paper proposes a methodology to implement probabilistic approaches specifically in the nuclear sector and explores these drivers for implementation acceleration. The research draws on a number of case studies to demonstrate the probabilistic methods utilised in recent years by the authors as well as proposal for benchmarking cases. Case studies are taken from a range of relevant applications and will be tailored towards features also expected to be critical in the design of new Advanced Modular Reactors (AMRs). The main output of this research will eventually be a UK guidance document on probabilistic approaches which will reflect best practice and will provide advice on what would be suitable for inclusion within international codes and standards, supported by engagement and dissemination activities with stakeholders and wider industry.

Paper 011: Probabilistic creep-fatigue: a plant component case study

N. Zentuti[1], R. Bradford[2] & J. D. Booker[2]
[1]Faculty AI, [2]University of Bristol,

This paper presents a probabilistic methodology for assessing the structural integrity of plant components susceptible to creep-fatigue failure and demonstrates the methodology on a plant case study. The methodology is based on the Monte-Carlo approach for estimating failure probabilities, which requires the definition of the underlying procedure for assessing the failure mechanisms of interest, as well as the statistical modelling of the key input parameters. The case-study assesses a plant component (a tubeplate made of 316H stainless steel) for creep-fatigue crack initiation using the R5 Volume 2/3 procedure. This is intended to provide context and demonstrate the utilities of implementing the probabilistic methodology. Building on previous work, four important issues are highlighted: the correlations between dominant input parameters, conducting post-assessment sensitivity analyses, the extrapolation of assessment point probabilities to component-level and, thereafter, population-level estimates. The aim of the research is to promote wider application and acceptance of probabilistics within the international structural integrity community, and identify requirements for further development of the methodology and constituent methods.

Paper 012: Express Evaluation of Resource Characteristics of Metal of Pipeline Details

V.I. Gladshtein & A.I.Troitsky
All-Russia Thermal Engineering Institute

Life time at 600°C and allowable metal stresses of two parts from 10Cr9MoNbV (DI82) were assessed: ∅ 630x25 mm pipes and ∅ 345x80 mm ESR billet. A special feature of the technique is the testing of samples with particularly deep and sharp notch. To determine of the time of the final stage of fracture, the notch opening was record-ed with an increased frequency of 0.003 hours. It was shown that the metal of electroslag billet has an advantage in durability in comparison with a hot-deformed pipe. A simplified version of the method with fixed values of the conditions final stage of fracture was proposed for the base metal and welded joint metal.

Paper 015: Verification of Long-term Creep Rupture Properties and Microstructure Stability of Ni based Alloy 45Ni-24Fe-23Cr-7W-Ti Parent Metal and Weldment

T. Tokairin[1], K. Yamada[1], K. Kishikawa[1], T. Tokiyoshi[1], K. Tominaga[3] & M. Kitamura[2]

[1] Mitsubishi Heavy Industries, [2] Mitsubishi Power.

Since Japanese national project launched in 2008, continuous and extensive works have been going to develop 700°C A-USC (Advanced Ultra Super Critical) power plants. Ni based alloy HR6W (45Ni-24Fe-23Cr-7W-Ti, ASME Code Case 2684) was selected as one of the promising candidate materials of A-USC boiler tube and pipe. In this paper, to clarify the long-term creep rupture strength and microstructure stability of both of parent metal and weldment, creep tests were conducted, and microstructure of crept specimens were experimentally investigated. On the basis of the creep rupture data up to about 70,000h for weldment and 117,000h for parent metal, the weldment showed comparable strength with the parent metal, which is satisfied from the practical viewpoint. Furthermore, the microstructure evolution during creep was characterized. According to the quantitative evaluation on the precipitation behaviour of strengthening phases, it is made clear that the precipitation strengthening of Laves phase, $M_{23}C_6$ carbide and αCr phase in the HAZ and parent metal contributing to the long-term creep rupture strength stability of weldment. The alloy was proven to have good microstructural stability without distinct microstructural degradation during long-term creep at 700°C up to around 117,000h. Furthermore, internal pressure creep test of circumferential weldment was carried out to verify damage and failure morphology of the actual components under multi-axial loading.

Paper 016: Creep properties of ASTM A335 P92 pipe parent material and erection welded joint simulation: effect of 1 or 3 PWHT

A. Gotti[1], A. Di Gianfrancesco[2], A. Ferrara[3], E. Gariboldi[4], G. Merckling[5], S. Navone[6], S. Parodi[7], E. Poggio[7], D. Ripamonti[8] & S. Verdino[7]
[1]Rina Consulting, [2]Compusystem, [3]Tenaris Dalmine, [4]Politecnico di Milano, [5]RTM Breda, [6]IIS SERVICE – IIS Group, [7]Ansaldo Energia, [8]Consiglio Nazionale delle Ricerche (CNR) - Istituto ICMATE.

Over the last years, the demand for improved efficiency of power plants led to a proportional increase of operating temperatures, which was made possible thanks to the development of new generation creep strength-enhanced ferritic steels, such as grade 92, which display a significant increase in rupture strength with respect to the older 9Cr compositions.
Due to the still quite small field experience with grade 92 steels, the Italian Creep Working Group (GdL) launched a joint testing effort, with the aim to characterize creep performance of a pipe weld joint, representative of true current manufacturing and on-site assembly processes and conditions.
A length of P92 pipe (20” outer diameter, 20 mm wall thickness) from standard production was supplied by Tenaris and welded by Ansaldo Energia with an experimental set-up reproducing in a controlled way all details of on-site erection welding procedures (ASME process GTAW+SMAW, ISO 4063 141+111, PH/5G position).
The welding procedure was qualified by Istituto Italiano della Saldatura (IIS, Italian Welding Institute) according to EN 15614-1, performing both non-destructive and destructive testing, and assessing the mechanical properties of the parent material and the weldment; finally, all working group members jointly investigated both parent material and cross-weld creep behaviour, according to the ECCC testing requirements.
In ECCC2017 conference the GdL presented the characterization results of the parent material and the welded joint after one PWHT, discussing mechanical and long-term properties after fabrication with in field procedures, addressing the related metallurgical relevant issues and their potential influence on the component in service performance.
According to PED (directive 2014/68/UE) requirements, material worst conditions for service need to be assessed. These conditions may occur when, for example, a weld after a first PWHT in oven during prefabrication undergoes a second one after welding during site erection, or if a weld needed a second (or

third) PWHT due to repair. To simulate the worst conditions, a section of the test joint

underwent two further post-welding heat treatments in addition to the mandatory first PWHT cycle. In fact, previous experiences indicate that the behaviour of the repaired and or re-heat-treated welds can be critical for components long term behaviour. The present work focuses on the long-term creep behaviour of parent material and welded joints after triple PWHT in comparison with original parent material and classical single PWH treated welds.

Paper 018: Thor™115 pipes in Refinery Furnaces

R. Locatelli[1], T. Coppola[2], L. Di Vito[2], E. Escorza[1] , A. Ferrara[1], P. Lombardo[3] & N. Monteleone[3]

[1]Tenaris, [2]Rina Consulting, [3]ISAB.

Nowadays crude fired heater furnaces for topping, vacuum or reactor feeding in Refineries are adopting P5 and P9 steel grades, depending on temperature and feed characteristics. Process conditions, however, are characterized by elevated temperatures (up to 600°C), well above the conventional creep threshold temperature which eventually cause a considerable over-tempering of the material. At the same time, crudes being processed have become more and more “critical” in terms of sulphur content and TAN (Total Acid Number). THOR®115 steel grade designed by Tenaris already showed very good corrosion resistance against oxidation and sulphidation. In the present work, THOR®115 and P9 have been analysed and compared, considering their static and creep resistance, together with oxidation rate and corrosion rate occurring on the external and internal surface respectively. The output of the benchmark, resulting in a better performance of THOR®115 rather than P9, has been used to develop an economical comparison between the two materials and quantify the advantage to adopt THOR®115 in Furnaces application.

Paper 019: Evolution of Precipitation Particles with Respect to Grain Boundary Energy in Grade 91 Steel during Creep Exposure

Y. Yamamoto[1] & A. Ferrara[2]
[1]Tenaris NKKTubes, [2]Tenaris Dalmine.

The superior creep strength of Grade 91 steel is attributed to the stability of the elongated ferritic micrograins microstructure inherited from the lath martensite substructure. During creep exposure, the microstructure is maintained by the dispersed MX carbonitrides and the substitutional Mo atoms as well as the boundary M23C6 carbides. Under long-term creep conditions, some MX carbonitride particles are consumed by the coarse Z-phase and the substitutional Mo atoms are partially consumed by the Laves phase: These evolutions lead to the drop of the long-term creep strength. The dependence of grain boundary energy on misorientation angle was recognized and the high-energy boundary model has been proposed: Low energy up to 15°, high-energy from 15°~45°, and medium energy from 45°~63°. The high-energy boundary is often associated with a disordered structure and high diffusion rate, which facilitate precipitation process. This study provides the precipitation particles evolution with respect to the high-energy boundary model in Grade 91 steel after over 233,823 h of creep exposure at 600 °C.

Paper 020: The Creep Strength of Aberrant Grade 91 Steel

S J Brett[1], A Bridges[2] & D Purdy[2]
[1]Consultant, [2]Electric Power Research Institute.

The high temperature steel grade 91 is intended to operate in service with a fully martensitic microstructure, achieved by a specific and well-defined heat treatment. Unfortunately lack of control, either during the initial material manufacture or later during post weld heat treatment, can lead to components entering service in a substandard condition. In the worst cases this can be a fully ferritic microstructure with a complete absence of martensite. In this aberrant condition the steel can have a creep strength significantly lower than that of normal martensitic grade 91 with an associated risk of early failure in plant life.
This paper reports on investigations into the creep strength of aberrant grade 91. Measurements have been obtained from (a) conventional uniaxial rupture testing, where large enough quantities of material have been available, and (b) small scale impression creep testing, where only limited amounts of material have been available, usually obtained by on-site scoop sampling. In the case of the small scale tests, creep strain rate has been converted into equivalent rupture life using a modified Monkman Grant type relationship which has been developed for impression creep testing. Based on tests on 14 different aberrant materials at 600°C, creep strength has been found to fall into the range Mean-35% to Mean-50% in terms of stress relative to the most recent (2019) ECCC rupture life assessment of grade 91. The implications for operation in service are considered.

Paper 024: Study on microstructural evolution of the cast MarBN steel during high temperature aging

C.X. An[1], SH. Shi[1], L.G. Sun[1] & Q.F. Guan[2]

[1]Shanghai Electric Power Generation Equipment Co.,[2] Jiang Su University.

Increasing steam parameters is the most effectual way to improve the power generation efficiency of coal-fired units. With the increase of steam parameters, more stringent requirements are raised for unit materials. Shanghai Turbine Plant (STP) has carried out a lot of research works on developing and testing new materials.

MarBN steel has attracted much attentions as a candidate material for advanced ultra-supercritical steam turbines at 650℃, and STP has conducted a series of studies on this particular material. The main research of this paper is microstructural evolution of the cast MarBN steel during high temperature aging. MarBN steel after heat treatment was exposed at 650℃ for long time, and then the mechanical property and microstructure are researched. The results showed that no obvious decrease of strength and plasticity of the MarBN cast steel was found. However, the impact energy of MarBN steel decreases from about 50 J to just 20 J at the aging time of 300 h and then nearly keeps stable with further increasing aging time to 10000 h. The corresponding microstructure was also experimentally obtained by field emission scanning electron microscope (FESEM), field emission transmission electron microscope (FETEM) characterization. The structural changes of our experimental results were compared with other 9%-12%Cr heat resistant steel, and good microstructural stability was demonstrated. Our research clarified the microstructural evolution of the cast MarBN steel during high temperature aging, including martensite laths, dislocation density, $M_{23}C_6$ carbides and Laves phases.

Paper 025: Effects of chemical composition and heat treatment on creep properties of P91 steel welded joint

M. Yaguchi[1], T. Inukai[2] & K. Nomura[3]
[1]CRIEPI, [2]Toshiba Energy Systems & Solutions, [3]IHI.

Welded joints of P91 steel as well as the base metals of the steel exhibit large heat-to-heat variation of creep properties, the reason for which is not yet clear. Thus, the effects of the chemical composition and heat treatment on the creep properties of P91 steel welded joints were experimentally examined and compared with those of the P91 base metals, where the Al, Cr, and Ni contents were systematically varied or the normalizing and tempering temperatures were varied. The creep tests were performed for approximately 20,000 h at 650^{o}C. The effects on the creep properties of the welded joints were approximately the same as those of the base metals, that is, the creep strength of the P91 steel welded joints decreased with increasing Al content or decreasing Cr content, whereas the Ni content had little effect on the creep strength of the welded joints. Regarding the heat treatment, the creep strength of the P91 steel welded joints increased with increasing normalizing temperature and decreasing tempering temperature. The comparison of the test results obtained for the welded joints with those obtained for the base metals revealed a positive correlation between the creep strength of the base metals and that of the welded joints, which means that the creep strength of welded joints increases with that of the base metals.

Paper 026: Effects of chemical composition and heat treatment on creep properties of P91 steel base metal

M. Yaguchi1, T. Hamaguchi[2], K. Miki[3], Y. Yamamoto[4], K. Nomura[5], E. Murakami[6] & N. Komai[7]

[1]CRIEPIndustry, [2]Nippon Steel, [3]The Japan Steel Works M&E, [4]Tenaris NKKTubes, [5]IHI, [6]Mitsubishi Power, [7]Mitsubishi Heavy Industry.

Creep strength enhanced ferritic steels, such as P91 steel, exhibit large heat-to-heat variation of creep properties, the reason for which is not yet clear. Thus, the effects of the chemical composition and heat treatment on the creep properties of P91 steel base metal were experimentally investigated by conducting creep tests on materials whose Al, Cr, and Ni contents were systematically varied or the normalizing and tempering temperatures were varied. The creep tests were performed for approximately 20,000 h at 650°C. The creep strength of P91 steel decreased with increasing Al content or decreasing Cr content, whereas the Ni content had little effect on the creep strength.

Regarding the heat treatment, the creep strength increased with increasing normalizing temperature and decreasing tempering temperature. There was a possibility that the 20,000 h creep test conducted in the present work was insufficient to determine the effect of the elements under actual operation conditions. Thus, long-term creep tests on the materials are still being conducted to clarify this issue.

Paper 030: Short-term creep behaviour of Additive Manufactured Hastelloy X material

E. De Bruycker[1], A. Gotti[2], E. Poggio[3], K. Boschmans[1], O. Tassa[2], A. Costa[3] & A. Sanguineti[3]
[1]ENGIE Laborelec, [2]Rina Consulting, [3]Ansaldo Energia.

Additive manufactured components are increasingly being applied in operational equipment. If these components are going to be used at higher temperatures, their creep behaviour needs to be verified. In the ECCC workgroup 3C an exploratory study of the short-term creep behaviour of the HASTELLOY® X alloy produced by Selective Laser Melting was carried out, with the aim of characterising the material behaviour and collecting input for the heat treatment optimisation, if necessary. Hastelloy X is a nickel-chromium-iron-molybdenum alloy for applications where a combination of oxidation resistance and high-temperature strength is required together with good fabricability.
Creep test results up to about 3000h were compared with creep results of conventionally produced Hastelloy X. Two orientations were tested: parallel and perpendicular to the building direction. In addition, the microstructure of the ruptured creep specimens was investigated to determine the fracture location/mechanism and the main microstructural features.
The obtained results can be considered promising and give useful indications in the perspective of SLM material application at high temperatures.

Paper 032: CreeSo – Software for creep simulation of complex alloys

Gerold Zuderstorfer[1], Florian Riedlsperger[1] & Bernhard Sonderegger[2]
[1]Graz University of Technology, [2]Johannes Kepler University.

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The prediction of creep rates is essential for the estimation of the lifetime of materials under high mechanical loads at high temperatures. A major problem is the fact, that a proper test of a material is expensive and takes nearly as long as the lifespan of the material in question. Only if creep mechanics are understood thoroughly, a prediction of creep rates for new materials can be made before the experiments to select the best candidate. Understanding of the underlying parameters and their sensitivity with respect to the creep rate can thus help in designing new materials.

The CreeSo-MDC-model (Microstructural Dislocation Creep – model) is an advanced approach incorporating numerous creep mechanisms in complex alloys. However, this model leads to differential equation systems that cannot be solved in a closed algebraic form. Some parameters of these equations cannot be measured directly and thus have to be adapted using actual creep data.

The application CreeSo can solve the differential equation systems of the model numerically and can also help determining the missing parameters by comparing simulated with experimental creep curves. In addition, CreeSo is not limited to the MDC-model but open to any model formulated in its script language.

It must be emphasized that CreeSo at this point is not a universal tool for engineers to get creep data, but it is a tool for scientists to build and adapt creep models. Also, CreeSo is still a prototype and is continuously improved and enhanced.

Initially, CreeSo was designed as desktop version. However, the ongoing corona situation and difficulties in meeting people personally motivated us to develop an online version of CreeSo as well. The software CreeSo is written in the programming language C++ (for best performance) and JavaScript. The operating system is Windows for the desktop version and Linux for the server-side of the online version.

Paper 035: Creep behaviour and microstructure changes of heat resistant steel P92 processed by severe plastic deformation

P. Kral[1], J. Dvorak[1], L. Kral[1], V. Sklenicka[1], Z. Horita[2,3,4], Y. Takizawa[5], Y. Tang[6], L. Kuncicka[1], M. Kvapilova[1] & M. Svobodova[7]

[1] Institute of Physics of Materials, [2] Kyushu Institute of Technology,
[3] Magnesium Research Center, [4] Saga University, [5] Nagano Forging Co.,
[6] WPI, International Institute for Carbon-Neutral Energy Research (WPI-I2CNER),
[7] UJP PRAHA a.s..

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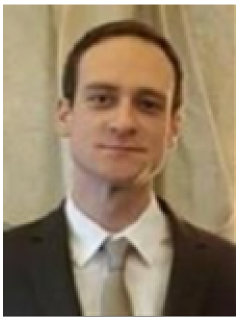
The influence of reduction of grain size to the ultrafine-grained level on the creep behaviour of P92 martensitic steel is investigated in this work. The specimens of as-received coarse-grained states were processed by two methods of severe plastic deformation at room temperature, namely rotary swaging and high-pressure torsion. Constant load tensile creep tests were conducted at 650°C under different applied stresses. Microstructures were examined using a scanning electron microscope Tescan Lyra 3 equipped with NordlysNano EBSD detector operating at an accelerating voltage of 20 kV with the specimen tilted at 70°.

It was observed that reducing in the grain size down to (sub)microscopic level resulted in a significant reduction of creep life when compared to the as-received coarse-grained states. In comparison to their coarse-grained counterparts, the creep behaviour of ultrafine-grained states exhibited a two-orders-of-magnitude faster minimum creep rate and a larger creep ductility. The microstructural results indicate that that the frequency of high-angle grain boundaries and dynamic particle/grain coarsening during creep influence the creep behaviour of P92 steel processed by severe plastic deformation.



Paper 036: Application of a physically-based dislocation creep model to P92 for constructing TTR diagrams

F. Riedlsperger[1], G. Zuderstorfer[1], B. Krenmayr[2] & B. Sonderegger[2]
[1]Graz University of Technology, [2]Institut für Metallische Konstruktionswerkstoffe.
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To raise the efficiency of thermal power plants, operation temperature and pressure must be increased. This can be achieved by higher creep resistance and longer creep life of materials such as martensitic Cr-steels. To understand the underlying mechanisms of degradation, physical creep modelling provides a detailed and profound insight into microstructural processes. For such a physically-based dislocation creep model it is demonstrated that on basis of a parameter set found for one experimental creep curve, numerous creep curves on different stress levels can be simulated without any additional experimental data. These simulation results are then used for constructing a complete TTR diagram for a 9% Cr-steel. Our approach is not only able to extrapolate rupture times for different applied stresses, but also for different temperatures. In all cases, microstructural evolution of the simulated material is considered including dislocation density, subgrain size and precipitates. The obtained rupture times in the simulated TTR diagram are compared to reference data, achieving good agreement.

Paper 038: Can Long Term Time to Rupture Data be Predicted Using Only Tensile Test Data?

M. W. Spindler
EDF UK.

The original ORNL (1984) data package for modified 9Cr1Mo has been revisited with the aim of answering the question: Can long term time to rupture data be predicted using only tensile test data? The predictions that have been made using only the results of tensile tests are compared with the 30,000 hour rupture data contained in the ORNL data package and the 100,000 hour rupture data published in NIMS data sheet 43A.

Paper 041: Correlation of hardness with maximum allowable stresses and service/remaining lives of Grade 91 steel

Zhifang Peng[1], Sheng Liu[1], Chao Yang[2] & Huachun Yang[3]
[1]*Wuhan University,* [2] *Jiangsu Frontier Electric Technology Co. Ltd.,*
[3]*Dongfang Boiler Group Co. Ltd.*

Two groups of creep-rupture data are used as the data source of this investigation. One of them is from the NIMS datasheet for the specimens sectioned from heat treated Grade 91 plates/tubes with hardness values ranging from 192 to 216HBW (coded FG as the first group). The other is from the creep-rupture tests on specimens sectioned from the Grade 91 components with hardness values ranging from 205 to 145HBW after service exposures at 530~610℃ at several coal-fired power plants in China (coded SG as the second group). Separately using the FG data at the individual hardness levels of 192-197, 206-211 and 216HBW, we have analysed the correlation of 550, 575, 600 and 650℃ creep-rupture properties of the specimens with the given hardness levels, showing that the creep-rupture lives/strengths are evidently shorter/lower for the specimens of ≤ 197 HBW than those of ≥ 206 HBW. The ranges of hardness values satisfying the requirement of maximum allowable stresses at the elevated temperatures specified by the ASME BPVC 2017 and the ASME BPVC 2019 are respectively presented by using an approach proposed, indicating that the necessity for the reduction of maximum allowable stress may directly depend on the lower limits of the hardness values at the temperatures given. Typically, a hardness value of 205HBW satisfying the maximum allowable stress requirement is demonstrated to be suitable not only for the application of the present Type 1 and Type 2 Grade 91 materials at a temperature of ≤ 600℃ but also for the previous Grade 91 components with a wall-thickness of ＞ 75mm at a temperature of ≤ 575℃. On the other hand, two function sets are respectively established to predict service / remaining lives of Grade 91 components based on the FG data at 550 and 600℃ and on the SG data at 570℃. The correlation of hardness with service / remaining lives of the components with various wall-thicknesses is investigated through a comprehensive consideration on hardness, creep-rupture strength and life, as well as maximum hoop stress under the operating conditions given. It is evidently demonstrated that no change in either wall-thickness or operating parameter is possible to keep a relatively long service life provided that the components with the previous/present wall-thicknesses possess a sufficiently high hardness level.

Besides, it is found that the hardness values are gradually decreased with the wall thickness reduction of a T91 eccentric tube fractured after a service exposure. The equivalent stress (von Misses stress) distribution and microstructure of this tube are analysed, showing an increase in the cross-sectional equivalent stress and a degradation in substructure and hardness due to the decrease in wall-thickness till to the thinnest position where the tube is broken.

Paper 045: Use of THOR®115 in design of new generation Combined Cycle Power Plant

A. Ferrara[1], G. Fortunato[2], M. Ortolani[1] & G. Silva[2]
[1]Tenaris, [2]ItalyEnergia.

Today's deregulated and thus continuously changing energy market sees a steady increase of the renewables' share. This poses several concomitant challenges to the operation of combined cycle power plants, among which the demand of high efficiency through a large load range. In this context, conventional power plants increasingly act as dispatchable sources of electricity and are required to quickly ramp up or down their output based on the demand of electricity. This trend imposes new demands to the material industries. Under fast and frequent cycling operation ferritic steels are favoured thanks to their limited thermal expansion compared to austenitic stainless steel. Very popular and highly employed steel grades such as the 9% Cr CSEF steels are however limited in terms of service temperature, mainly due to capping their steam oxidation resistance capabilities at temperature levels required by the drive for efficiency increase. For heat-exchangers manufactured from conventional materials, the formation, growth and spallation of oxide scale on the steam side may eventually impair plant operations and damage other downstream components. A new generation of CSEF has been developed with increased oxidation resistance and long-term stability: one of these new grades, THOR®115, has started to be used for industrial applications. This paper presents the assessment in terms of time-independent and time-dependent properties of THOR®115, welded to itself and to other CSEF steels. Weldments have been fabricated both using the same procedures developed for the standard grade 91 and also further optimizing the welding practice and the filler metal selection according to the service conditions of the power plant.

This analysis supported the design of a more efficient PP using the new generation ferritic steel instead of stainless, reducing the impact of material selection avoidance of dissimilar metal weld along with their drawback in plant operated under cycling condition.

Paper 046: Recent progress on the modelling of creep cavitation, deformation, and creep fracture

Qiang Xu & Zhongyu Lu
The University of Huddersfield.

Recent progresses in creep damage mechanics are reported in this paper including: 1) the development of and the applications of a modified hyperbolic sine in order to depict the minimum creep strain rate over a wider range of stress level; 2) the calibration of creep cavitation using the cavity histogram and the development of the creep fracture model based on the cavity area fraction along grain boundary, where the most representative and comprehensive 3 dimensional cavitation data, such as obtained from X-ray synchrotron investigation and SAND (small angle neutron diffraction), were utilized; and 3) the development of mesoscopic modelling of creep deformation and creep damage.

The progress in the above first point facilitates to overcome the difficulty in creep deformation modelling caused by stress breakdown phenomenon. The progress in the second point is a breakthrough to truly based on the creep cavitation to develop creep cavitation model, unlikely the conventional only associate, phenomenogically, its effect on the creep deformation, and this approach is a truly mechanism-based and fundamental new approach, first in the world. The progress in the third point provides the concept and tool, at the appropriate size scale, for a better modelling of the creep deformation and creep fracture. They all contribute to the specific knowledge and new methodology to the topic area.

Furthermore, it is expected that cavitation fracture modelling methodology reported here will find use in the analysis and modelling of other type of failure such as ductile and fatigue failure.

This paper disseminates the important research progress and presents an example of interdisciplinary research.

Paper 048: Recent progress on the modelling of creep cavitation, deformation, and creep fracture

J. Storesund[1], D. Andersson[1], J. Rantala[2], H Andersson Östling[3] & F. Sorsh[1]
[1]*Kiwa InspectaTechnology,* [2] *VTT,* [3]*Swerim AB, SE-164 07.*

The present work is performed on the main steam pipe system in Heleneholmsverket, a CHP in Sweden and consists of the following parts *i)* numerical analysis of the in-service creep behaviour of the pipe system *ii)* creep testing of new and service exposed materials from welded components, *iii)* characterisation of the creep damage distribution in creep tested welds of the actual piping. The entire system has been modelled for creep evaluation to make it possible to compare the simulated creep stress and strain distributions in selected welds with observed amounts of creep cavitation, which can be correlated to the accumulated creep strain. Creep data for the analyses were produced by creep testing of service exposed base and weld metals from a pipe weld and a T-piece branch weld from the system. In addition, the creep tested welds were studied metallographically to map the creep damage and make it possible to compare the damage development with the resulting creep stress and strain distributions in the weld. In the previous project also a T-piece branch weld was investigated in a similar way and those results were used for verification of the re-analyses in present project with the updated system model. The following results were achieved:

- The model of the entire steam pipe system was created in Abaqus and the strain distributions were verified in comparison to a corresponding elastic Caepipe model.
- The Norton creep law was used for the simulations. In addition, also primary creep was analysed. The effects of primary creep on the long-term creep behaviour was significant and the results shows the importance of including primary creep into the model.
- There is no effect of starts and stops on the stress and strain distributions in the system during creep.
- The system analysis results showed enhanced strains up to 2,1 % at one bend and 0,5 % - 1,0 % in some parts of the system. Although replica testing had not been conducted directly at the bend the high strains indirectly agreed with the observations of small creep cracks had been observed in replica testing of in a weld at one of the ends of the actual bend. Furthermore, several components in the system have been exchanged due to creep crack formation.

- Moderate levels creep damage was observed in the pipe weld. The analysis of this pipe weld gave somewhat lower creep strains than expected. The stress and strain distributions matched with the maximum principal stress criterion but not with the von Mises stress that Abaqus uses for creep analyses by default.
- The analysis of the branch weld matched well with observed creep damage distributions whereas the maximum strain level of 0,4 % appears to be rather low in comparison to the quite extensive creep damage. However, local constraint and multiaxiality in welds lead to significantly lower creep ductility compared to uniaxial creep and contribute to a reasonable agreement between the strain and the damage levels.
- The creep tests of service exposed material resulted in relatively high Norton creep law exponents and no shift to lower values at the lowest tested stresses. It is hardly possible to perform tests at even lower stresses and therefore the simulations at service conditions resulted in unreasonably low creep strains.

Paper 051: Is it time to rehabilitate the power law?

John M Brear
Plant Integrity.

Based in part on observation and in part on mechanistic considerations, a power-law relationship between creep rate and stress was once all-but-ubiquitous in creep modelling. Most commonly taken to summarise the dependence of minimum creep rate on applied stress, it could also serve as an evolving equation of state describing the entire creep curve. Integration with an appropriate final condition can generate the usual matching expression for rupture life.

Criticisms are often based on its simplicity, on its unreliability in extrapolation and its failure to generate the expected values for stress dependence, n, and activation energy, Q.

Taking data obtained on low alloy and austenitic steels, it is shown that simple modifications to the power-law expression can resolve many of these issues. Addition of a primary creep term usually brings n and Q into line with expectation, better integration conditions greatly improve extrapolation at high stresses and threshold stress and damage terms enlarge the mechanistic coverage.

Both advocates and critics of the power law formulation need to consider carefully the nature of the various terms discussed. For example, rupture life, minimum creep rate and ultimate tensile strength are not, strictly, materials properties but the results of processes controlled by materials properties. Separation of such concepts leads to deeper insights.

Paper 053: Excessive Creep Strain Design Check with Simulations based on Material Properties from Material Standards

Franz Rauscher & Alexander Seifert
Technsiche Universität Wien.

The possibility of doing the Excessive Creep Strain Design Check (ECS-DC) according to EN 13445-3 Annex B [1] based on simulations was investigated. As a constitutive law for creep, Norton's law and, as an alternative, a hyperbolic sine law was considered. Creep strain limits given in material standards are the basis for the parameters of these creep laws. A check for reversal creep ensures that repeated primary creep does not occur.

The application of this method on a nozzle in a spherical shell shows the calculation of the parameters of the constitutive law and possibilities of damage determination. At first, the geometry is analysed at constant temperature and with uniform material. Afterwards the example was generalised by introducing different materials for the shell, the weld, the reinforcement, and the nozzle. In Addition, temperature variations were introduced.

The focus of the paper is the conservative creep damage determination for design calculations. Therefore, the use of safety factors is included, and appropriate values are discussed.

Paper 055: The Influence of an Evolving Multiaxial Stress on Small Punch Creep of a Nickel Superalloy

W. Harrison, T. Williams & M. Evans
Swansea University.

The small punch creep test is used to measure creep properties when only a small volume of material is available. During a small punch creep, material is subjected to an evolving multiaxial stress state. At the beginning of the test, the stress is compressive beneath the punch: however, as the test continues, the disc is subjected to shear stresses and equibiaxial tension. Typically, results from the small punch test are compared to uniaxial test data using a simple correlation, however this does not consider the effect of the non-constant stress. This paper aims to improve the understanding of creep during this miniaturised test, using finite element modelling to investigate the influence of the evolving multiaxial stress state on small punch creep deformation and damage. A constitutive creep model based on the Theta Projection method is used to predict creep behaviour in the nickel-based superalloy, Waspaloy.

Paper 056: Mechanical Properties of CB2 Cross-Welds

S. Baumgartner
Voestalpine, Böhler Welding.

Within the frame of the European COST Programes 501, 522 and 536 (1993-2009) advanced martensitic steels have been developed and tested. The B alloyed 9Cr-1.5Mo-1Co steel designated as "CB2" evolved as the most promising candidate for cast components used at operating temperatures up to 620-630°C.

As welding is an important part in the production process of heavy cast components where welding processes are required, which offer high productivity and good out-of position weldability, flux cored arc welding (FCAW) is the preferred process. Therefore, a matching flux cored wire for welding CB2 cast components has been developed and qualified.

This contribution gives an overview on the mechanical properties of the cross weld at initial state as well as on the results of the performed creep tests at 625°C and the microstructural investigation of the fractured specimens with rupture times up to nearly 50,000 h. The fracture location is in the fine grained heat-affected zone (FGHAZ).

Paper 057: Assessment of creep damage in Fe-Ni-Cr alloys

F. Sorsh
Kiwa Inspecta Technology.

It is only a matter of time before components working in high temperature environments fail due to creep. Design for creep is therefore of vital importance to maximize the lifetime of components and reduce costs that may arise from maintenance and replacement of components. This thesis used metallographical methods and finite element modelling to assess creep damage in a hydrogen reformer. The decommissioned reformer, made of Fe-Ni-Cr alloys, was investigated thoroughly via replica testing, hardness measurements as well as finite element modelling of the welds. A literature review was performed to gain a better understanding of creep in Fe-Ni-Cr alloys, welds, and the modelling of creep generally. The microstructures of samples from the reformer were analysed and mapped out in terms of creep damage which were then compared to a creep analysis of the welds with a simulation time of 100 000 h. The FE results yielded high stresses and creep strains with a maximum of 0.95% in the boundaries of the welds which gave realistic representations of strain distributions when compared to the metallographical results. Hardness measurement indicated that a relatively narrow zone with altered mechanical properties is present along the weld boundaries. This area, called the heat affected zone, was found to be most affected by creep with microcracks reaching maximum lengths of 2 mm. The creep strains obtained from simulation did not fall in line with the observed creep damage, it was thus concluded that a material model that considers tertiary creep would yield a more realistic representation in FEM for Fe-Ni-Cr alloys.

Paper 061: Constitutive Description of Creep Behaviour of Nuclear Grade 316LN SS with Varying Nitrogen Content

S. C. Praveen, J. Christopher, V. Ganesan, G.V. Prasad Reddy, Shaju K. Albert & A.K. Bhaduri

Indira Gandhi Centre for Atomic Research (IGCAR).

Constitutive modelling of creep deformation behaviour of high temperature structural materials enhances understanding of the kinetics of deformation mechanisms and enables reliable prediction of life and performance of engineering components during service. In view of the above, creep deformation and damage behaviour of nuclear grade 316LN SS with varying nitrogen content (0.07-0.22 wt.%) have been discussed in the framework of two constitutive models at 923 K. For the description of primary and secondary creep, internal stress based sine hyperbolic creep rate law is employed that not only provides accurate description of creep strain-time behaviour, but also can be used to evaluate the basic quantities such as the evolution of activation distance, swept area and obstacle spacing with strain for different nitrogen levels. A decrease in activation distance with an increase in nitrogen is observed for the 316LN SS. The steady state creep rate vs. effective stress obeys the power law with a stress exponent value in the range of 3.5 to 4.7, indicating dislocation creep as the creep deformation mechanism irrespective of nitrogen content. To describe the secondary and tertiary creep behaviour, continuum damage based Kachanov-Robotnov (KR) model has been employed. From the analysis of iso-damage contour lines on creep curves, the evolution kinetics of coupled strain and damage is observed to be unique for a given applied stress level. The predicted higher strain-rate to damage-rate ratio using KR model for low nitrogen steel substantiated the observed higher creep rupture ductility and larger fraction of dimple features as compared to high nitrogen steel. In addition, the KR model is implemented into finite element formulation using user-subroutine code to understand the influence of notch creep behaviour of 316LN SS with 0.07% N. Simulation results indicated development of higher von-Mises stress and triaxiality near notch root, signifying damage accumulation near notch.

Paper 063: Effect of prior austenitisation temperature on creep rupture in Grade 22 steel

S. von Willingh & R.D.K. Knutsen
University of Cape Town.

Prior heat treatment during component manufacture as well as welding procedures in situ will influence the conditioning of austenite during the thermal cycles. Not only will precipitates dissolve and form, but the austenite grain size will grow in proportion to the thermal exposure. Consequently, the microstructure that evolves during cooling, and correspondingly the mechanical properties, will be determined by the combination of phase transformations and diffusion events that occur during the total thermal cycle. The uniaxial tensile creep resistance at 600°C for Grade 22 bainitic steel was measured as function of prior normalisation heat treatment which was carried out in the range 900-1100°C. A decrease in creep rate is favoured by larger prior austenite grain size, but creep ductility is substantially reduced. Of particular interest is the significant difference in creep performance for the 900°C and 1000°C heat treatment conditions. Although the prior austenite grain size is only marginally different for the two conditions, the creep rupture time is substantially longer for the 1000°C condition. Dilatometry tests, which simulate the normalisation thermal cycles, indicate differences in phase dissolution during normalisation and hence it is proposed that variations in solute distribution account for the differences in creep behaviour.

Paper 065: Creep rupture ductility of ferritic creep resistant steels

K. Kimura & K. Sawada
National Institute for Materials Science.

Creep rupture ductility of not only creep strength enhanced ferritic steels, but also conventional one of 2.25Cr-1Mo steels was investigated with particular reference to remarkable drop in the long-term. Remarkable drop in creep rupture ductility was well described as a function of yield ratio of applied stress and it appeared at about 50% of 0.2% offset yield stress at the creep test temperature with decrease in a yield ratio. Trade-off relation between creep rupture strength and creep rupture ductility was recognized on Grade T/P23 steels. The similar trade-off relation between creep strength and ductility was observed also on conventional 2.25Cr-1Mo steels. Remarkable drop in creep rupture ductility of the quenched and tempered 2.25Cr-1Mo steels was recognized in conjunction with large drop in creep rupture strength. Remarkable drop in creep rupture ductility of the steels was considered to be caused by microstructural change due to inhomogeneous progress in recovery of tempered martensitic microstructure. Beneficial effect on creep rupture ductility of a modified heat treatment process with an intermediate tempering on partially quenched dual phase microstructure was observed on Grade P92 steel. It was considered to be obtained by reducing residual stress introduced by martensitic phase transformation accompanied with shape change and volume expansion.

Paper 067: Status of writing a comprehensive engineering composition about the martensitic steel grad family a collaboration of VGB FDBR FVWHT and research institutes in Denmark and Germany

E. K. M. Bader[1], J. Bareiß[2] & P. Kozlowski[3]
[1]Uniper Kraftwerke GmbH, [2]EnBW Energie Baden-Württemberg AG, [3]LEAG Lausitz Energie Kraftwerke AG.

Since the actual discussion about the down grading of P91 and the discussion about P92, a multilateral working group was installed with agreement of VGB, FDBR and FVWHT.

The aim of the working group is to summarize the important knowledge around the martensitic steel grade family leading the final part of the pressure parts in the best-in-class power stations with temperatures of 560 - 580 °C and 600 – 620 °C. The document will reflect the historical development, the major features of the alloying concepts, the welding technologies, long term behaviour under load, the dimensioning, concepts for inspection and methods for fracture mechanics analysis.

The documents should help to give a knowledge base for the important discussion now and in future, knowing that the numbers of experts will degrease and the long-term running power stations will increase.

The document will include actual results of research programs e.g. interpretation of material status after long term running with the change in a more cycle mode, discussion about hardness levels and the interpretation. The document will also reflect examples of quality deviations.

This all should give the needed background knowledge of martensitic steels for the next years.

Paper 069: Reliability of API 530 for creep life prediction of long service exposed 9Cr-1Mo steel tubes

Reza Khadem Hosseini
Research Institute of Petroleum Industry.

API 530, "Calculation of Heater Tube Thickness in Petroleum Refineries", is an API standard used for the design of fired heater tubes as well as the remaining life assessment of service exposed tubes in the refining and petrochemical industry, which its seventh edition was released in 2015 as the latest one. Stress- rupture master curves in the standard are the main tools to achieve its goals that were changed in the latest version in comparison to previous editions (5th and 6th Ed.). As a part of a study, it was investigated how tube service exposure time could affect creep life prediction and which version of the standard could be more closely matched to the results. The creep behavior of three 9¬¬Cr-1Mo steel tubes, received from the three major refineries of the country, had been exposed in service for 75,000, 150,000, and 250,000 hours, respectively, were examined over a temperature range of 600 to 650 °C and a stress range of 37.5 to 117.5 MPa using stress- rupture test for a short-term, less than 50 hours, to a long-term, more than 10,000 hours, to determine their reliability for future service according to API 530. According to this study, the ability to accurately predict the remaining life of tubes depends on their service life. Also, the seventh edition was more consistent with results in general.

Paper 073: Effect of segregation on creep strength in Grade 91 steels

E. K. Sawada & K. Kimura
National Institute for Materials Science.

For T91 steels, the effect of segregation of alloying elements on creep strength was reported in previous study [1]. In addition to the previous study, several heats of T91 steel and P91 steel were evaluated, focusing on distribution of segregation and its effect on creep strength.

Hardness distribution was evaluated along the wall thickness direction. It seemed that the hardness distribution correlated with that of Cr segregation. However, in some heats of tube, the hardness near outer surface was different from other areas. The difference between the maximum and minimum Cr content, ΔCr, at a constant distance (x) was estimated in the range of 1 mm along the wall thickness direction for T91 steels. Standard deviation of ΔCr was employed as an indicator of the degree of segregation. The standard deviation correlated with time to rupture at 650oC when the Cr content is relatively high. However, no clear correlation between them was observed when the Cr content is very low in the range of specification. In addition to Cr segregation, the Cr content itself should be considered as a cause of reduced creep strength when the Cr content is low. In the case of P91 steel, the distribution of segregation was inhomogeneous as compared with T91 steel. For example, strongly segregated area was confirmed at the position of 3/4t from outer surface of pipe. On the other hand, no segregation band was observed in other area of the same pipe. In the case of P91 steel, the standard deviation of ΔCr is not suitable for evaluating the degree of segregation because the distribution of Cr segregation is inhomogeneous as compared with T91 steel.

[1] K. Sawada et al., Effect of Initial Microstructure on Creep Strength of ASME Grade T91 Steel, ISIJ International, 60 (2020), p.382-391.

Paper 076: Thermal ageing and creep damage in 316L(N) alloys: a 3D analysis

O. Ozdemir[1], S. Valiyev[1], S.M. Montes[2], E. Ferrie[1], M. Blat-Yrieix[3], F. Delabrouille[3] & L. Salvo[1]

[1]Univ. Grenoble Alpes, [2]Universidad Politecnica de Madrid, [3]EDF R&D.

Creep behavior of two alloys classical 316 L(N), labelled as LN, and N modified 316 L(N), labelled as an HN in this present work, have been studied at 575 °C at a stress level of 310 MPa. 3D analyses have been done by using two different X-ray sources. Additions of nitrogen in 316 L(N) have demonstrated to be beneficial for extending the life of austenitic stainless steels, decreasing the creep damage. Creep cavities have been classified based on their shape and the growth orientation of cavities are analyzed. Even though the total life time of LN sample is shorter (649 h) compared to HN (9203 h), it exhibits more cavities. The orientation of the cavities and the complex shape of cavities have been proving that stress direction has a huge effect on the LN sample damage development with concentration on 10° and 90°.

Paper 079: Issues and solutions for integrity of pressure vessels and piping subjected to long-term creep exposure in supercritical thermal plants

Hyeong-Yeon Lee & Jewhan Lee
Korea Atomic Energy Research Institute.

Boiler components can be designed as per ASME BPVC Section VIII Division 2 ('ASME VIII(2)') and piping as per ASME B31.1, not only for low-temperature design but also for high-temperature design in the creep range in supercritical thermal power plants. However, creep effects in ASME VIII(2) and B31.1 are taken into account implicitly, and there could be significant technical issues in their designs in terms of conservatism in the case of long-term operation in the creep range because the evaluation results according to their design rules do not change across plant operation time. The conservatisms of ASME VIII(2) and B31.1 in the case of long-term creep exposure have been quantified based on comparisons in design evaluations with nuclear-grade design rules of ASME BPVC Section III Division 5 Subsection HB and RCC-MRx which take creep hold time into account explicitly. It was shown from the present comparison study that ASME VIII(2) and B31.1 results could be non-conservative if operation time exceeds a certain time limit, which raises concerns around non-conservatism in the designs according to ASME VIII(2) and B31.1 in the case of long-term operation within the creep range.

Paper 082: Microstructural Characterisation of Creep Tested Advanced Austenitic Stainless Steel Super 304H

C. Puslford[1], M.A.E. Jepson[1], R. C. Thomson[1], T. Lolla[2], J. Siefert[2], N. Komai[3], K. Hashimoto[3] & K. Tominaga[4]

[1]Loughborough University, [2]Electric Power Research Institute,
[3]Mitsubishi Heavy Industries, [4]Mitsubishi Power.

Super 304H is an advanced austenitic stainless steel that is used as superheater and reheater tubes in power plants. The presence of second phases such as MX particles, M23C6, Cu particles and sigma phase that evolve during creep testing and during service expose can have an impact on the creep rupture properties and lifetime of these components manufactured from Super 304H. In this research, the phases present in the gauge section of two creep rupture samples of Super 304H that had been exposed to a uniaxial creep test at temperatures of 650°C (Sample B) and 700°C (Sample A) and stresses of 120MPa and 75MPa respectively, have been identified and quantified. These two creep samples had exhibited low creep ductility. Within the two creep samples, six phases have been identified: MX (Nb rich), sigma, Cu rich, M23C6 (Cr rich), modified Z phase and Fe (BCC). Quantification of Nb rich and Cu rich particles revealed approximately 10% more Nb rich and 16% more Cu rich particles in Sample A compared to Sample B. Furthermore, the average particle size measured in Samples A and B are similar for both the Nb and Cu rich particles. This shows that differing temperatures and stresses of the two creep tests did not have a significant impact on the presence, number or size of Nb and Cu rich particles in these samples. The amount of sigma phase measured in Sample A and Sample B was similar and lower than that predicted by thermodynamic calculations. However, there appears to be an association between the sigma phase and creep cavities as shown in 2D microstructural characterisation. The association of sigma and creep cavities could have contributed to the low creep ductility exhibited by these two creep samples.

Paper 084: The 2019 ECCC Datasheet for Grade 91 – Using ECCC Recommendations to Resolve the Rupture Properties of an Industry Workhorse

A. Riva[1], C. Bullough[2], A. Norman[3], M. Subanovic[4], M. Schwienheer[5] & J. Hald[6]
[1]Ansaldo Energia S.p.A., [2] GE Power, [3]UK Atomic Energy Authority,
[4]Vallourec, [5]TU Darmstadt, [6]Technical University of Denmark.

The martensitic steel Grade 91 (X10CrMoVNb9-1, W. Nr. 1.4903) has become a "workhorse" for high temperature power plant since it was introduced in the 1980's first as boiler tube and later in other wrought product forms, and as a cast variant. In 2019, however, a new ECCC (European Creep Collaborative Committee) datasheet of the creep rupture strength values of Grade 91 was approved replacing the previous datasheet published in 2009, at the same time downgrading strength values at key design conditions by ~7%. This has potentially serious consequence for existing plant designed for higher strength values, and could reduce the future use of Grade 91.

In common with other ECCC data assessments, the process started with the collation of data from worldwide sources, including the manufacturers of many product forms of Grade 91 as well as from plant manufacturers, research institutes (many of whom are members of ECCC) and collaborative programmes. The data set is likely to be the largest assembled on Grade 91, with more than 220 heats at more than 15 temperatures, and data extending to 150kh. The ECCC data assessments that followed were in accordance with the Recommendations in ECCC Volume 5, with pre-assessment, main-assessment and post-assessment phases, to establish, respectively: the quality and extent of the data; to perform the rupture data fitting (often considering several models); and followed by objective tests of the results on such matters as physical realism, goodness of fit, resistance to instability on partial culling. To improve objectivity the post assessment tests were performed with the automatized ePAT software recently developed by ECCC.

Four experienced ECCC assessors separately performed assessments. Early on however, it became clear that the consolidated dataset showed an unusually large scatter, which increases with test time and thus reveals many challenges. Whilst all four assessments determined lower strength values than the ECCC datasheet of 2009, the different assessments also delivered mean curves for the isothermals of the creep rupture strength which differed considerably at some temperatures. The process that led from the data collation to selection of the most accurate assessment, and then to the publication of a new ECCC datasheet, is a complex and challenging path.

Difficulties can potentially arise from the inhomogeneous distribution of strong and weak batches, their potential chemical and process differences, data scatter and presence of outliers, the metallurgical stability of the specimen after high temperature exposure, accumulation of plasticity during specimen loading, the impossibility to physical observe the failed specimens, and the identification of a robust mathematical data fitting method able to manage large datasets.
This paper illustrates how such difficulties can be faced and solved with the methodological support of a consolidated process, such as the ECCC Recommendations. The paper also introduces the possibility to improve some aspect of the process to better support the assessors in the difficult task of identifying the creep rupture model capable of maximizing the reliability of its prediction both in interpolation and extrapolation regime.

Paper 088: A Continuum Damage Mechanics approach to model stress relaxation and its relationship with primary creep and anelastic recovery

R. Donnini[1], M. Maldini[1], E. Poggio[2], D. Ripamonti[1] & A. Riva[2]
[1]CNR ICMATE, [2]ANSALDO ENERGIA.

The experimental results of creep, stress relaxation and anelastic strain recovery tests performed at 350°C in the stress range 450-600MPa on the martensitic steels X20Cr13, utilized in many high temperature applications including heavy duty gas turbines, are presented.

The results show that during the primary creep at least three different mechanisms act: the first one is the fastest and it quickly exhausts during the first primary creep, producing a recoverable strain after complete unloading the specimen. Its contribution on the primary creep stage can be important for the creep tests performed at stresses below the yield stress. Other two mechanisms, attributed respectively to stress redistribution between regions of the specimen with different creep resistance and to the decrement of mobile dislocations during creep, last longer until the steady state is reached.

Performing a series of stress relaxation tests on the same specimen, at the same initial stress, but at different initial strain, it is shown that only after the exhaustion of the slow mechanisms, the stress relaxation tests can be utilized as a relatively quick way to generating long term minimum creep rate data. A set of equations, based on the formalism of the Continuum Damage Mechanics, are proposed to describe many aspects of the experimental results.

Paper 089: The new ECCC Datasheet for Alloy 617: multi-regime models to cover a wide range of temperature

Riva[1], M. Spindler[2], R. Krein[3], O. Tassa[4] & E. Poggio[1]
[1]Ansaldo Energia S.p.A., [2] British Energy, [3] Voestalpine Böhler Welding,
[4]RINA Consulting - CSM S.p.A.

Alloy 617 is solid-solution hardened nickel-chromium-cobalt-molybdenum alloy used for components that in the range between 600 and 1000°C. Its oxidation resistance and high-temperature strength are the key elements that make this alloy widely used in combustion components in both aircraft and land-based gas turbines.

The European Creep Collaborative Committee Working Group 3C on Nickel Alloys performed a creep rupture dataset collation, merging data from different organizations and institutions worldwide, updating the previous dataset with new experimental results. This enabled the possibility to generate a new and improved creep rupture model.

The process of generating a model on the basis of a large data set is characterized by abundant difficulties that have to be carefully addressed to ensure the creep rupture model reliability and accuracy: the wide temperature and stress range and the possible changes in the deformation and damage mechanisms that happen across this interval, the data set inhomogeneities (i.e. the abundance of strong and weak heats at some temperatures), the information contained in the discontinued test results, and several others. When facing these kind of obstacles, crucial support comes from the consolidated ECCC methodologies and practice and the knowledge of the microstructural behaviour of the material.

In this framework, ECCC Nickel Alloys Working Group, consistently with its usual practice, carried out several independent assessments and compared the model performances, verifying that they satisfy the desired accuracy in interpolation and extrapolation. The whole process was repeated when such requirements were not satisfied, and eventually the assessment to be used in for the generation and issuing of the updated ECCC datasheet was selected. For the 617 data set, a multi-regime modelling approach proved to be helpful in achieving the desired accuracy over the wide range of temperature.

This paper illustrates the process that led from the collation of the data set, to the pre-assessment, then the assessment (i.e. the model fitting), the post-assessment according to ECCC recommendations, and eventually to the generation of the creep rupture strength table.

Paper 091: Extrapolation Methods: Development, Application and Validation of Novel Methods, Part 1: Advanced Testing Concepts

C. Heinemann[1], C. Kontermann[1], M. Schwienheer[1], F. Müller[1], M. Speicher[2] & M. Oechsner[1]
[1]Technical University of Darmstadt, [2]University of Stuttgart.

The significance of accelerated determination of creep properties is reflected by the amount of available research work, which comprises a variety of material types and application fields. As an outcome, several analytically based as well as experimentally based extrapolation methods have been developed or evolved. In contrast to experimental methods, analytical methods are already introduced and genuinely used for practical application.

Especially in the context of creep of metallic high temperature materials fundamental research work providing guidelines and concepts for the application of experimentally based extrapolation methods are strongly demanded, yet missing. Within that given framework, this publication focuses on the examination of experimentally based extrapolation methods particularly with regard to accelerated determination of creep properties required for high temperature applications.

Results and conclusions of recently finished research work will be presented, which subjected a variety of accelerated testing methods to in-depth analyses on the basis of comprehensive experimental testing programs followed by extensive analytical analyses. Individual influencing factors and sensitivities as well as the individual application possibilities and application restrictions regarding different types of heat resistant steels were determined. On this experimental and analytical basis recommendations for future testing concepts were developed, validated and summarized in this paper.

Paper 092: Creep behavior and microstructural Evolution for TP347H Austenite Steel used in China plants

C. Che, K. Yan, S. H. Ma & G. Qian
China Special Equipment Inspection and Research Institute.

TP347H (18Cr-10Ni-Nb) austenite steel has high creep strength and has been used as the material of tubes in 600℃ USC power plants in China. The TP347H materials used in actual power plants are useful in estimating the changes of material properties caused by long-term aging and damage at low stress conditions. An understanding of the long-term microstructural evolution under actually used conditions is a key for the improvement of these heat resistant steels. In this article, microstructural evolution of TP347H steel under different service conditions in Chinese power plants was studied using optical microscope (OM), transmission electron microscopy (TEM) and small-angle X-ray scattering (SAXS) techniques. The results show, M23C6, MX, and σ phases were found to precipitate. A quantitative characterisation of microstructure evolution was evaluated during long-term exposure, focusing on the content and the size of precipitates for the TP347H steel after long-term service.

Paper 094: Extrapolation Methods: Development, Application and Validation of Novel Methods, Part 2: Microstructure

M. Speicher[1], C. Heinemann[2] & C. Kontermann[2]
[1]University of Stuttgart, [2]Technical University of Darmstadt.

The microstructure of martensitic steels changes during long-term high-temperature exposition. This could be a critical factor influencing the materials behaviour during service. For this reason, the materials for the application at high temperatures in power plants have to exhibit high microstructural stability for a long time. Only under these conditions, reliable lifetime or extrapolation approaches of creep rupture behaviour can be achieved. Therefore, the changes in the microstructure must be determined and correlated with the creep behaviour. In this work, the microstructure from long-term and interrupted creep tests at 600 °C of a heat resisting 10Cr forged steel (X12CrMoWVNbN10-1-1) was analysed by using optical microscopy (OM) and transmission electron microscopy (TEM). The results, such as subgrain size and dislocation density as well as precipitation structure and hardness, were discussed and correlated to the creep behaviour and time to rupture. In addition, it was studied whether it is possible to reproduce the time-dependent and temperature-dependent changes in the microstructure in accelerated creep tests (multi-step creep rupture tests) on virgin and aged material. Furthermore, simulation methods for the microstructure using Thermocalc and TC Prisma are used as comparison.

Paper 097: Heavy wall forged pipes of grade 92: effect of heat treatment conditions on microstructure and creep resistance

E. Anelli [1] & S. Holmström [2, 3]
[1]Franchini Acciai SpA, [2]SCKCEN, [3]JRC Petten (affiliation at the time of this work).

The design of grade 92 steel seamless pipes has progressed significantly due to the need to increase the thermal efficiency of steam power plants and meet the operational perspectives for potential nuclear applications. However, very little has been published on forgings and specifically on heavy wall forged pipes. In this work the creep properties of 180 mm thick F92 pipes both normalized and tempered (N&T) and quenched and tempered (Q&T) are studied. Pipe sections instrumented with thermocouples, optical microscopy, and mechanical tests, were used to understand microstructural evolution and creep resistance. Volume fraction of ferrite was measured according to ASTM E562 and creep behaviour was assessed using both uniaxial tests according to ISO 204 and small punch creep test data analysis. Quenching treatment was able to develop cooling rates greater than 0.6 °C/s, limiting the presence of ferrite to less than 1%, while in case of normalizing the ferrite percentage was 3-4.5% (average cooling rate < 0.12 °C/s). Consequently, the Q&T steel exhibited creep strength 20-25% higher than that of the N&T forged pipe of same thickness. These results were exploited for the set-up of a new proprietary heat treatment able to develop on heavy wall forged pipes creep strength levels similar to those of N&T thin seamless pipes.

Paper 099: Type IV creep crack initiation and propagation in mod.9Cr-1Mo steel welds

T. Honda[1], T. Fukahori[1], T. Tokiyoshi[1], T. Igari[1], K. Tominaga[2] & ACF. Cocks[3]
[1]Mitsubishi Heavy Industries, Ltd., [2]Mitsubishi Hitachi Power Systems, Ltd., [3]University of Oxford.

The ratio of crack initiation and crack propagation life is important from the viewpoint of residual life prediction of mod. 9Cr-1Mo steel welds under Type IV creep damage. Both the creep void density distribution and the failure process with crack initiation/propagation/final failure are predicted for three types of welds in pipes and nozzles, which are compared with experimental results at 650°C. The ratio of crack initiation and final failure life depends on weld type and loading conditions; the ratio is about 0.95 in the cases where redistribution of stress occurs only in the thickness; the ratio is 0.59~0.65 in the cases where redistribution of stress occurs in both the thickness and circumferential directions of the pipe. Influence of stress ratio (axial vs. circumferential stress) is also predicted for circumferential welds subject to internal pressure / axial load and is compared with experimental results at 650°C.

Paper 108: New approaches to determine negligible creep

G. Baylac [1], C. Bullough [2], S. Holmström [3], W. Smith [4], A. Tonti [5] & C. Forot [6]
[1]CEN TC54 WG59, [2]GE Power, [3]SCK CEN Belgian Nuclear Research Centre, [4]University of Leicester, [5]INAIL, [6]Framatome.

The working group WG59 of the CEN/TC54, has drafted a report regarding the study of new approaches to determine negligible creep. The purpose is an in-depth explanation of the test and assessment methods used for determining the no- and negligible creep temperatures of steels. The work was prepared in the frame of the standard EN 13445-3 for unfired pressure vessels. Presently the standard assumes "rule-of-thumb" values for no-creep temperatures of ferritic and austenitic steels, 375°C and 425°C correspondingly. However, it is well known that the lower ferritic grades could be creeping below the limit temperature and creep strength enhanced ferritic steels may show significant creep at temperatures well beyond it. A similar situation exists for the austenitic steels; nickel and other alloys that are likely to have an even wider range of negligible and no-creep temperatures.

This paper also aims to describe data assessment, and test methods to determine the no- and negligible creep temperatures for specific materials grades in EN material standards. The industrial need for negligible and no creep temperatures has also been reviewed, as well as the negligible creep definitions in current nuclear design codes and related public domain documents and the corresponding reference stresses. The background to this work is also addressed. Then the new approaches to determine the no- and negligible creep temperatures of steels are introduced, promoting test programmes of iso-stress tests in the low temperature range and applying the Wilshire Equations on historical data. The final aim of this work is to minimize the inherent risk and over-conservatism in the current EN13445-3 design procedures for creep-weak grades and creep-resistant grades, respectively.

Paper 116: Estimation of uniaxial and creep properties by small punch testing in support of ECCC test programmes

S. Holmström[1], K.F Nilsson[2], E. De Bruycker[3], E. Anelli[4], A. Guery[5], J. Rantala[6], A. Tonti[7] , I. Simonovski[2] & D. Baraldi[2]

[1] SCK CEN Belgian Nuclear Research Centre, [2]JRC Petten,
[3] ENGIE Lab Laborelec, [4] Franchini Acciai SpA, [5] EDF R&D, [6] VTT, [7] INAIL.

The small punch test techniques, SP for tensile properties and SPC for creep properties, will in the near future become a more frequently used tool for material property determination as the new standard EN-10371 is published in June 2021. The testing techniques are especially useful for applications where only a small amount of material is available, e.g., for in service materials or for nuclear (irradiated) materials. In the ECCC Work Groups 1, 3A and 3B, the technique has been studied and used for estimating the creep and tensile strength of a range of materials relevant to the corresponding working groups. In this paper tests conducted on ferritic/martensitic steels P91 (virgin, aged and creep damaged), P92 (virgin and weld), F92 (two different heat treatments) for the Work group; WG3A (ferritic / martensitic steels) and 316L, 316L(N), 316L(N) weld metal and a range of SLM (3D printed) 316L steels for the Work Group 3B (austenitic steels), are analysed according to the new standard. The applicability of the SP/SPC for the case studies and some methodology development needs are addressed. The excellent results of these test programs are expected to promote the acceptance of SP/SPC assessments in industry and for research.

Paper 119: Development of a new Small Punch Creep Testing machine

A. Alvino[1], A. Antonini[1], S. Budano[2*], A. Di Gianfrancesco[2], A. Tonti[1] and F. Troiani[2]

[1]INAIL, [2]Compusystem Srl.

This paper describes work done for the development of a new Small Punch Creep Test machine installed in the INAIL Laboratories. The new SPCT machine operate with dead weight, in Argon atmosphere to avoid the specimen oxidation, but several improvements have been made in the hardware and software equipment's. Electronic devices used for industrial application have been installed to guaranty low-cost, long-term stability and high resolution of the SPCT machine. The software has been developed by a wizard procedure to lead step by step the test parameters input and the testing start, making the machine fully automatic.

The applied load, the deflection, the temperatures and the Argon flux parameters are continuously monitored respectively by a high-resolution extensometer system, 3 thermocouples and gas flowmeter. All the testing data (time, specimen and furnace temperatures, deflection and argon flux) are acquired and stored also in a dedicated computer, with tailored Software able to elaborate the acquired dataset.

The operation of the new SPCT machine has been validate by tests up to more than 1000 hours at 600°C on forged grade 91 specimens and compared with literature data on similar grade 91 materials. Microstructural analyses by LM and SEM have been carried out to characterize the material.

Paper 122: Metallic replica technique for residual life assessment for components serviced in creep regime

G. Merckling, D. Benini, L. Casiraghi, A. Corsi & A. Staffolani
RTM Breda S.r.l.

For 9-12%Cr creep resistant steels, a new kind of replica, contemporaneously morphological and extractive, is nowadays in use. This method is non-destructive and "in situ" applicable via a customized portable equipment and allows the study of the steel microstructure evolution during in-service inspections. The technique produces a neat imprint of the steel microstructure, like a morphological replica, but contemporaneously extracts particles down to 15-20nm diameters. The use of a good electrical conductor extraneous to the steel composition as a replication basis allows the investigation of the martensitic (sub-) microstructure together with the particle distribution, nanometric dimensional and chemical analyses using a tungsten electrode Scanning Electron Microscope (SEM) at magnifications up to 500000x.

For component residual life assessment, besides a measuring technique and a damage witnessing criterion, a reference is needed against which spent life time or actual damage can be estimated. These references are now established to a quite extended amount, although not yet fully statistically underpinned, by analysing with "metallic replica" creep specimens specifically interrupted during the test and reloaded.

The applicable assessment route, based on metallic replicas, in practical plant residual life determination as undertaken in the last period, gives credible results also in comparison with particle analyses by TEM and micrographic cavitation evaluation. Metallic replicas give similar information but with significant more statistics and allow with the aid of the reference curves a credible residual life time estimate. Nevertheless, missing information about the original microstructure of the investigated component, for instance PWHT duration or repetition, can cause relevant, although generally conservative, estimation errors for the actual local damage.

Paper 126: Effects of abnormal structure on creep strength of long-term used 9Cr steel welded joint

S. Zhang, H. Tokunaga, M. Kanai, S. Lin, M. Yaguchi, K. Tamura & Y. Minami
Central Research Institute of Electric Power Industry.

Microstructural characteristics of abnormal structure in long-term used Gr.91 steel weldments and its effect on creep strength of welded joint are presented in this paper. The abnormal structure is defined as a structure in which the hardness is clearly lower than that in the normal region (base and weld metals), and the grain is coarsened. Creep strength of the abnormal structure is significantly lower than that of normal weld metal, and the difference in creep strength between abnormal and normal structures was discussed in relation to the observation of precipitates. There is little effect of abnormal structure formed in the HAZ on creep life of standard welded joint specimens with 6-10mm in diameter. In case of abnormal structure formed in the weld metal, on the other hand, times to creep rupture of standard specimens are shorter than those of specimens without abnormal structure, but the difference seems to decrease with decreasing the applied stress. Full thickness welded joint specimen consisting more than half abnormal structure in the weld metal ruptured at the weld metal before the HAZ. Time to creep rupture decreased with increasing the abnormal structure ratio in thickness direction according to an exponential function.

Paper 127: Creep Rupture Properties of ATI 718Plus – An Approach to Assessing Sparse Data

C. Bullough[1], E. De Bruycker[2], E. Poggio[3], M. Schwienheer[4] & M. Spindler[5]
[1]GE Power, [2]Engie Laborelec, [3]Ansaldo Energia, [4]TU Darmstadt, [5]EdF UK.

The nickel base alloy ATI 718Plus © (UNS N07818) was introduced in 2003 with the intention of providing similar properties to Waspaloy but having the fabricability of Alloy 718. Such characteristics make it of strong interest for use in aeroengines for disk forgings, blades and bolting bar. Within power generation, the advent of higher temperatures in industrial gas turbines, and advanced supercritical steam turbines, the combination of properties and processability make it an increasingly attractive proposition for a range of applications.

In this paper we report an exploratory creep test programme of beyond 30kh duration leading to an Interim ECCC Datasheet on ATI 718Plus. We demonstrate how even small volumes of test data can be assessed to produce a datasheet that can be used for preliminary design. In particular, we consider how best to determine the rupture behaviour, by including the data from unfailed tests, using both polynomial and Wilshire Equation models, with coefficients estimated by conventional regression estimation, and also with maximum likelihood methods. Additionally, creep-strain time data are modelled and extrapolated, using simplified equations developed and/or applied in ECCC in recent work.

The results confirm the temperature advantage in creep of 718Plus over Alloy 718. Recommendations of how to assess sparse datasets have also resulted from this work, leading to an expectation that new materials can be developed more quickly and with higher reliability. Nevertheless, there is no substitute for long-term multi-heat testing to prove the predicted behaviour and to examine the stability of materials in the long term.

Paper 131: The Assessment of Creep Rupture Properties for the ECCC 2019 Datasheet for Grade 92

C. Bullough[1], M. Norman[1], J. Hald[2], S. Holmström[3], M. Ortolani[4], M. Subanovic[5], M. Schwienheer[6]

[1]GE Power, [2]Technical University of Denmark, [3]Joint Research Centre, [4] Tenaris, [5]Vallourec Research Center, [6]TU Darmstadt.

The steel Grade 92 steel – X10CrWMoVNb9-2, W. Nr. 1.4901 – is the second most widely used creep strength enhanced ferritic grade in thermal power plant. At the same strength level, it has a temperature advantage of 20-25°C over its close relative, Grade 91 described elsewhere in this conference. It is most widely used for steam tubes, pipework, headers and valve internals; finding application in ultra-supercritical up to 620°C. Its greater creep strength also makes it particularly attractive as an alternative to Grade 91 at lower temperatures, where its correspondingly lower thickness affords greater resistance to the thermal cycling - more common in thermal power plant due to the intermittency of renewable energy sources.

Grade 92 was introduced via ASME Code Case 2179 into the Boiler and Pressure Vessel Code in 1994, based on a Larson-Miller assessment to 40kh test data. Grade 122 was assessed similarly, but after some industry problems in Grade 122, the allowable strength values for both grades were reduced in 2004. A re-assessment of Grade 92 is expected to be published by ASME soon. In Europe, the strength values of Grade 92 were assessed by the ECCC with the first datasheet issued in 1999, and revised downwards in 2005. The values were then reviewed periodically, but it is only now after significantly longer-term test data has become available, that a reassessment has been undertaken.

Like other ECCC data assessments, data were collated from worldwide sources, including the manufacturers of many product forms of Grade 92 as well as from plant manufacturers, research institutes (many of whom are members of ECCC) and collaborative programmes. The resulting data set had 48 heats at temperatures of 550-700°C, with test-data extending to 150kh (failed)/ 198kh (unfailed). Four separate assessments were prepared including: parametric / linear regression approaches; "region-splitting" models; and the application of maximum likelihood/error model approaches. The results of the assessments were all subjected to ECCC post-assessment tests using the newly developed ECCC ePAT software.

Unlike the comparable ECCC Grade 91 assessment performed at the same time, the four Grade 92 assessments gave similar strength values, both amongst themselves and against the ECCC 2005 Datasheet for Grade 92. This paper explains how the data were evaluated, and the selection of the assessment / fitting approach. It is also described how the risk of any downturn in properties, and the potential reduction in creep ductility was considered. The ECCC 2019 datasheet for Grade 92 has now been published on the ECCC website, www.eccc-creep.com and released to both ECCC members, and at CEN discretion, for use within EN standards.

Paper 140: Operating parameters monitoring in pressure equipment working under creep range

C. Delle Site & F. Giacobbe
National Institute for Insurance against Accidents at Work.

The values of operating parameters (pressure, temperature, number of cycles, etc.) have a direct impact on damage mechanisms acting on pressure equipment components. As a consequence a precise monitoring of these parameters allows the designer to carry out a detailed and reliable life assessment especially in case of creep, fatigue and corrosion. The monitoring process can be carried out continuously or discontinuously with the aid of special digital sensors installed on the equipment. The processing of the recorded data allows the engineer to examine the speed of potential degradation phenomena and therefore to predict specific inspection intervals in the short, medium and long term. This paper underlines the elements to be considered to have a reliable monitoring system in pressure assemblies with reference to operating parameters and indicates a possible guideline for the user which originates from the normative works at the Italian Standardization Body (UNI - CTI). An example concerning creep operated components shows that a reliable monitoring systems in same cases allows the user to extend by 20% the inspection interval, thus encouraging small users to adopt it. This is due to the fact that creep is strongly temperature dependent and is considered potentially dangerous for a given material, if the service temperature of a component is greater than a given threshold - therefore a small difference in terms of temperature and pressure values can result in a large difference in terms of stress and of life consumption.

Plenary Paper 142: High temperature material requirements for the design of next generation Nuclear Power Plants

Hyeong-Yeon Lee
Korea Atomic Energy Research Institute

Thermal efficiency of the currently deployed fleet of Generation III+ nuclear power plants with water-cooled reactors cannot be increased significantly without totally different innovative designs, which are Generation IV reactors with at a high level of fuel efficiency, safety, proliferation-resistance, sustainability and cost. The high performance and reliability of materials when subjected to the higher temperature and neutron dose environments are material requirements in Gen IV nuclear reactors. In this study, reviews on materials, requirements and challenges for structural Gen IV material are made associated with design of Gen IV nuclear reactors that operate at high temperature in creep range. The requirements of nuclear-grade heat-resistant materials codified in high-temperature design rules of ASME Section III Division 5 Subsection HB (hereafter 'ASME-HB') and RCC-MRx are reviewed along with comparison of the two design rules with more focus on damage of creep and creep-fatigue. High-temperature design evaluation platform of 'HITEP' was developed by KAERI which enables a designer to perform high-temperature design in reliable and efficient way according to the design rules of ASME-HB and RCC-MRx. Application of heat resistant materials to pressure boundary components and piping in a next generation nuclear reactor system was conducted by using the HITEP platform.

Paper 143: The creep and fracture behavior of additively manufactured Inconel 625 and 718

M.E. Kassner[1*], K.T. Son[1], K.A. Lee[2], Tae-Hoon Kang[2] & R. Ermagan[1]
[1]University of Southern California, [2]Inha University.

Additive manufacturing by selective laser powder bed fusion of alloys followed by hot isostatic pressing (HIP) has gained attention by industry as it provides economical production of complicated-configuration engine parts with fewer joining steps and greater geometric freedom. The creep behavior of additively manufactured (AM) Inconel 625 and 718 at 650 and 800°C was compared with that of the wrought alloy after 24 hour and long-term tests up to about one year. Inconel 718 is precipitation strengthened while 625 is solid-solution strengthened. It was discovered that the creep strength of the 625 and 718 produced by additively manufacturing is essentially identical than that of the wrought alloy. Complications occur, however, with a marked loss of ductility in the AM alloys. Fatigue and impact toughness were adversely affected as well. The basis for these degradations was particularly investigated.

Paper 145: Effect of solution heat treatment temperature on creep rupture strength of 18Cr-9Ni-3Cu-Nb-N steel

K. Hashimoto[1*], K. Arisue[1], Y. Ayukawa[1], N. Saito[1], N. Komai[1], K. Tominaga[2] & M. Fujita[2]

[1]Mitsubishi Heavy Industries Ltd, [2]Mitsubishi Power Ltd.

18Cr-9Ni-3Cu-Nb-N steel is widely used for heat exchanger tubes such as those in superheaters and reheaters of ultra-supercritical power generation boilers. In this study, long-term creep rupture tests were carried out on 18Cr-9Ni-3Cu-Nb-N seamless steel tubes of 7 heat materials and same heat material with different final ST temperatures. As the results of creep rupture tests, since creep rupture strength tended to be higher with higher final ST temperature, analysis of extraction residue and SEM observation were conducted immediately after final ST in order to consider the effect of metallurgical factors on creep rupture strength. When the ST temperature changed, the amount of Nb dissolved in the matrix also changed. Normally, as Nb content increases, creep rupture strength increases, however, as results of the creep rupture tests indicated, creep rupture strength was not always higher when the amount of Nb dissolved in the matrix was larger. On the other hand, material with larger grain size had higher creep rupture strength and this was consistent with the tendency assumed from the constitutive equation of high temperature deformation. Therefore, it was considered that grain size relatively affected creep rupture strength.

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