Thermo-Mechanical Lifetime Assessment of Components for 700°C Steam Turbine Applications

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Thermo-Mechanical Lifetime Assessment of Components for 700°C Steam Turbine Applications

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Summary

In order to increase the thermal efficiency and to reduce resource exploitation, recent development of advanced steam turbine technology has been targeted to steam inlet temperatures above 700°C and corresponding steam pressures exceeding 350 bar. These temperature levels are not sustainable for heat resistant steels and alternatively the much more expensive nickel- and cobalt based alloys have to be exploited. Previous European collaborative research and development activities between turbine manufacturers, forgemasters and research centres have identified candidate Ni-base alloys as suitable forgable high pressure steam turbine rotor materials and have also comprised welding procedure development for joints between Ni-base alloys and low as well as high alloyed ferritic steels. Due to economical reasons it is desired to replace the expensive Ni-base alloys with conventional heat resistant steels in these regions of the steam turbine rotor that are operating below ~500-550°C. Since a welded rotor design is favoured, dissimilar metal weldments are required.

The presented research work is aimed at the development of thermo-mechanical lifetime assessment methodologies for the evaluation of 700°C steam turbine components involving the formulation of advanced constitutive deformation and damage model equations. The first main objective was the development and verification of the effectiveness of advanced creep-fatigue lifetime assessment methodologies and determination of the required material input parameters for the accurate and reliable evaluation of Alloy 617 steam turbine rotor features at maximum application temperatures. To achieve the appointed objectives an extensive material testing campaign was required. For the characterisation of the material behaviour under static loading conditions creep rupture experiments for medium and target application temperatures have been conducted in order to investigate the influence of ageing treatment of Alloy 617. Taking into account material property data from previous research activity a constitutive creep deformation equation was developed on the basis of a modified Graham-Walles law, which well represents the mean creep behaviour of the investigated and reviewed Alloy 617 heats. In order to determine the time-independent plastic flow as well as the fatigue endurance characteristics, continuous cycling LCF experiments have been performed for the entire temperature range. On this basis a constitutive plasticity model of Chaboche type have been developed, which accurately describes the observed material response under cyclic loading. Furthermore cyclic/hold experiments have
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been conducted on Alloy 617 in order to investigate the occurring creep-fatigue damage mechanism and to determine the CF endurance characteristics. Thereby a modification on the creep law was introduced for description of the materials decreased creep resistance under combined creep-fatigue loading. For the assessment of creep and fatigue damage fractions a very promising approach considering plastic and creep dissipated energy as failure criterion was developed. The effectiveness of this energy exhaustion method was verified with the calculation of endurance curves for continuous cycling LCF and cyclic/hold conditions over a broad range of temperatures, strain ranges and hold periods. The effectiveness of the developed constitutive deformation model was further verified on a service-type TMF experiment, which cycle definition was determined from a life-limiting location in a 700°C high-pressure steam turbine rotor under realistic loading conditions while featuring significantly different strain ranges within an anisothermal cycle. The developed creep-fatigue lifetime assessment methodology for Alloy 617 was verified with the help of post test microstructural investigations, where the accordant damage appearances could reliably be represented.

For further characterization of Alloy 617 and accordant verification of applicability of the material in future steam turbine technology, with particular respect to the planned long-term operation in steam turbine rotors, additional creep-rupture experiments are necessary for a reliable creep rupture strength prediction. Additionally creep-fatigue experiments, preferably also thermomechanical experiments, with representative strain ranges and sufficiently long hold durations are to be performed to further investigate the apparent creep-fatigue damage mechanism. The post-test metallographic investigation on the TMF test conducted within the present work have revealed, despite the comparable large strain range of the experiment, extensive creep damage development under the imposed thermomechanical cycle.

The second main objective of the present research work was the identification of the maximum application temperatures of dissimilar metal welded joints between the Ni-base Alloy 617 and a 1% CrMoV low alloy bainitic rotor steel as well as a higher alloyed 10% Cr martensitic rotor steel, with respect to their creep rupture and fatigue properties. A testing procedure for the static creep and cyclic testing of the DMW joints was developed and a extensive testing campaign was conducted comprising creep rupture, continuous cycling LCF as well as CF cyclic/hold experiments for target temperatures defined on experience with accordant similar metal weldments. Based on the experimental results the fatigue and creep-fatigue endurance characteristics have been determined and corresponding models have been developed for their description. Accordingly the creep rupture strength curves have been determined, whereas CR strength extrapolation were only possible to maximum rupture times of 30kh, due to the limited test duration of available DMW joint creep data. On this basis information could be obtained on the maximum achievable application temperatures of the investigated DMW joints. Post-test
metallographic investigations revealed Type IV creep damage in the FGHAZ of
the steels, which constitutes the main creep failure observed during creep loading
of similar metal weldments. Additionally fusion line cracking associated with a
Type I precipitate condition at the interface between Alloy 617 weld metal and the
steel HAZ was observed in the investigated Alloy 617 - 1% CrMoV and Alloy 617 -
10% Cr DMW joints. Whereas the Type I carbide layer was apparent in Alloy 617
- 1% CrMoV DMW joint specimens even after short duration high temperature ex-
posure, the situation was not clearly visible within the Alloy 617 - 10% Cr DMW
joint. One major reason for the development of these Type I precipitates are the
cross fusion line chemical composition gradients, mainly for the constituents C and
Cr, which are obviously larger for the low alloyed 1% CrMoV steel compared to the
10% Cr steel with respect to the chemical composition of Alloy 617. For long-term
creep loading conditions, representative of service condition existing in steam tur-
nbine rotors, the predominant failure mechanism for both DMW joints appeared to
be FL cracking associated with the Type I precipitate condition. Since additional
element diffusion is to be expected during long-term high temperature exposure,
the experimental verification of long-term creep rupture strength is absolutely es-
sential in order to guarantee the safe operation of the dissimilar metal weldments
under service conditions. Additionally it should be noted that the presented exper-
imental results have been obtained by uniaxial loaded cross-weld specimens with
relatively small cross-sections that have been extracted from the weldments. On
the one hand possible welding residual stresses have been reduced by the cutting
out of the specimens and on the other hand no experience has been obtained on
the effect of multiaxial stress states on the creep behaviour of the investigated
DMW joints.
Zusammenfassung


Für eine erweiterte Beschreibung des Werkstoffverhaltens und Verifizierung der Anwendbarkeit von Alloy 617 in zukünftigen Dampfturbineentechnologien sind zusätzliche Kriechexperimente für eine zuverlässige Voraussage der Kriechfestigkeit notwendig, was besonders für die geplanten Einsatzzeiten für Dampfturbinenrotoren gilt. Weitere Kriechermüdungsexperimente, bevorzugt auch anisotherme TMF-Experimente, mit repräsentativen Dehnungsschwingbreiten und ausreichend langen Haltezeiten sollten durchgeführt werden, um den auftretenden Schadensmechanismus unter Kriechermüdung noch eingehender zu untersuchen. Die mikrostrukturellen Untersuchungen der TMF-Probe der vorliegenden Arbeit zeigten eine erhebliche Kriechschädigung für den beanspruchten thermomechanischen Zyklus mit vergleichbar grosser Dehnungswirkung.

Die zweite Zielstellung der vorliegenden Forschungsarbeiten war die Bestimmung der maximalen Einsatztemperaturen von artgleichen Schweißverbindungen zwischen der Nickelbasislegierung Alloy 617 und einem niedriglegierten bainitischen 1% CrMoV-Stahl sowie einem hochlegierten martensitischen 10% Cr-Stahl, in Bezug auf deren Kriech- und Ermüdungsfestigkeiten. Im Rahmen dieser Arbeit wurde ein Testverfahren für Kriech- sowie LCF-Experimente von artgleichen Schweißverbindungen (DMW) entwickelt und ein umfangreiches Testprogramm durchgeführt, welches LCF-Experimente mit und ohne Haltezeit sowie Kriechexperimente