Fachbeitrag in der MTZ 10/2013

Titel: Lifetime estimation of high temperature components made of ferritic sheet metal

Lightweight and economic hot-end exhaust components can be made from ferritic sheet metals. The design of such components is difficult, because materials are pushed to their limit. To support the design process, experimental investigations and consecutively models for deformation and damage were set up within the joint FVV research project „Life prediction of high temperature components of ferritic sheet metals“. The models are available to be used in conjunction with finite element analysis. The project was carried out by the Fraunhofer Institute for Mechanics of Materials IWM and the Institut für Werkstoffkunde IfW of the Technische Universität Darmstadt.

Autoren: Dipl.-Ing. Philipp von Hartrott
Dipl.-Ing. Alexander Cueva
Dr.-Ing. Friedrich Ohmenhäuser

(Die Anzahl der mit Foto aufgeführten Autoren ist auf vier begrenzt. Weitere Co-Autoren sind in einer Danksagung unterzubringen, siehe Seite 10)

Abgabetermin: 26.04.2013
Aufmacherbild: Eberspächer, Riekers

Umfang aktuell:
ca. 18000 von max. 18000 Zeichen (inkl. Leerzeichen)
10 von max. 10 Bilder/Tabellen (inkl. Aufmacherbild)
1 Motivation

High chromium ferritic sheet metals make it possible to design high temperature components that are economical and that meet lightweight construction requirements at the same time. However the design of such components with regard to durability is complicated. Several time-consuming and expensive test bench runs are usually needed until the design target is met (See Fig 0). From this situation arises the requirement for a methodology that allows for an early estimation of local loadings and resulting damages. The availability of well suited simulation concepts is limited: available models for metal plasticity only insufficiently incorporate the special requirements for thermomechanical fatigue at very high temperatures. The situation for damage and lifetime models is similar. Lastly the data needed for an adequate adjustment of the models is often not available. Within the pre-competition joint research project “Life prediction of high temperature components of ferritic sheet metals” [1] funded by the association of industrial research associations (AiF) and coordinated by the research association for combustion engines (FVV) the widespread ferritic sheet metal 1.4509 (X2CrTiNb18) was thoroughly tested with regard to the mechanical properties and damage mechanisms at high temperatures. Based on these findings models for plasticity and lifetime were extended, adjusted and made available for the finite element method.

The practicability of the methodology was demonstrated on a component like specimen and a demonstration component. The project was accompanied by an industrial committee. Many exhaust system manufacturers were members of the committee.
2 Experimental Investigations

Because of the widespread usage in thermally high loaded parts of the exhaust systems, the ferritic steel 1.4509 was selected by the projects working committee. Due to its chromium content of about 18 % the material has good corrosion properties, is well formable and weldable. The alloying of titanium and niobium causes precipitation of fine Ti- and Nb-carbides which precipitation-harden the material up to very high temperatures. The typical microstructure of the material is shown in fig. 1, the chemical composition according to EN 10088-3 is shown in table 1. Several batches provided by Outokumpu Nirosta were investigated within the project.

![Light-optical graph of the typical microstructure: ferritic matrix with primary carbide precipitations.](image)

<table>
<thead>
<tr>
<th>Element in mass-%</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Nb</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard specification EN 10088-3</td>
<td>min.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>17.5</td>
<td>3\times C + 0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>max.</td>
<td>0.03</td>
<td>1.00</td>
<td>1.00</td>
<td>0.04</td>
<td>0.015</td>
<td>18.5</td>
<td>1.0</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The parameters for the experimental investigations were deduced from typical exhaust applications. The upper investigation temperature is 900 °C. Application scenarios for high temperature components yield mechanical loading due to constrained thermal expansion and chemical reactions on the surface as well as inside the materials. The mechanical loading of components combined with high temperatures generally leads to time dependent permanent deformation as a result of creep with force controlled loadings or stress relaxation with displacement controlled loadings. The mechanical loading driven by thermal cycling typically exceeds the yield limit of the material and causes micro-crack initiation with consecutive micro-crack growth. The high temperatures inevitably lead to oxidation which reduces wall thickness and plays an important role in micro-crack growth. Diffusion is activated by the high temperatures and generally involves changes of the microstructure by the means of phase transformations. This is accompanied by changes of the deformation and damage behaviour. In order to adequately capture and describe these numerous influencing
factors and their interdependency an experimental program was derived that is necessary for the TMF-life modelling and allows for scientific insights about the deformation and damage mechanisms. All experiments were performed on original sheet metals with a thickness of 2 mm.

In the short time regime the experimental program comprises hot tensile tests with different strain rates and different orientations to the rolling direction and a metallographic characterization of the “as delivered” material. Temperature-dependent thermophysical properties were determined.

The oxidation behaviour was tested in continuous and interrupted oxidation tests in air. Long crack growth was tested on some samples at high temperature and under thermocyclic conditions. The creep behaviour was also tested in a time- and temperature-range relevant to the applications. The main focus of the experimental investigations were low cycle fatigue tests under isothermal (LCF) and non-isothermal (TMF) conditions. The experiments were performed on two specimen types. First, tubular specimens machined from the sheets were tested. During the project a test system for flat specimens was developed and set up (fig. 2). This system is capable of testing in tension and compression in the elastic and time-dependent plastic regime over a wide temperature range. The strain is measured using a high temperature extensometer, the heating is done by induction. With the tubular and the flat specimens tension-compression experiments were performed that are closely interlinked with the plasticity-modelling. Additionally strain-life curves at different temperatures (fig. 3) were generated and served as a basis for the lifetime modelling. It can be observed that fatigue life curves are arranged according to increasing temperature. The scatter with respect to the isothermal curve doesn’t exceed about 30%.

The damage mechanisms as a function of the loading conditions were documented in extensive metallographic and fractographic investigations. Fig. 4 exemplary shows that at temperatures below 650 °C the deformation and crack initiation is oriented on slip bands. At high temperatures intercrystalline and oxidation enhanced crack growth can be observed.

Bild 2:
Left: Tension-compression testing on 2 mm sheet material up to 800 °C, example of a specimen with a crack-starter notch. Right: Validation of the temperature distribution by thermography.

Bild 3:
Strain life curves at temperatures between 20 and 800 °C.
Bild 4: Macrograph of a flat LCF-specimen tested at 500 °C (a) and corresponding micrograph of transcrystalline microcracks (b).
### 3 Modelling

Based on the sound data base of experimental results, models for the computation of plasticity and damage were enhanced and adjusted to the experimental findings. A Chaboche-type plasticity model was chosen for the description of time-dependent deformation. The formulation is capable of describing the main phenomena of high temperature plasticity like creep and relaxation. The model equations have been reported for example in [2] and were successfully adjusted to a large number of materials in the past.

For the lifetime modelling different approaches were pursued in parallel. All approaches use a load cycle based concept. They consider damage due to fatigue, oxidation and creep and partially an interaction of the mechanisms. The model of Neu and Sehitoglu [3] uses an additive approach with terms for damage due to fatigue $D_{\text{fat}}$, oxidation $D_{\text{ox}}$ and creep $D_{\text{creep}}$. The contributions of the respective damage mechanisms to a cycle are considered independently and summed to the cycle-based total damage $D_{\text{tot}}$:

$$D_{\text{tot}} = D_{\text{fat}} + D_{\text{ox}} + D_{\text{creep}}.$$  \hspace{1cm} (1)

The identification of most model parameters was performed using data from isothermal base-experiments on fatigue behaviour as well as experiments on the time dependent deformation and oxidation behaviour. Some parameters, which require special experiments for their determination, were adopted from literature-values. The potential of the model is the lifetime estimation at different strain rates and under thermomechanical loading conditions with arbitrary time-temperature history. The model formulation after eq. 1 facilitates a separate analysis of the damage contributions due to the three mechanisms. Depending on the loading, different damage mechanisms dominate the lifetime (fig. 5). Overall the model gives an adequate description of the experimental lives (fig 6a).

Furthermore the $D_{\text{TMF}}$-concept, a model after Riedel [4] motivated from fracture mechanics, was used for lifetime estimation. The model assumes that periodic loading entails a damage increment in the form of a crack growth of a short crack. The crack length increment of such a crack is:

$$\frac{da}{dN} = \beta \cdot a \cdot D_{\text{TMF}}$$  \hspace{1cm} (2)
with the proportionality constant $\beta$, the crack length $a$ and the damage parameter $D_{TMF}$. The $D_{TMF}$-concept was extended by a term which considers environmental effects on the crack growth:

$$da_{env} \propto \sqrt{sZ_d a}$$

were $s$ is the size of a seam damaged by environmental influence, and $Z_d a$ a measure of the mechanical loading at the crack tip. With this extension the influence of fatigue, oxidation and creep on the overall damage can be explicitly accounted for. This model could also give an adequate description of the experimentally determined lifes (fig. 6b). As a third variant the $D_{TMF}$ model in the standard formulation was adjusted. This model is available as finite element post processing routine for the evaluation of components.

Bild 6:
Computed life $N^*$ compared to experimental lifes $N_i$ (determined by 5 % load drop criterion). Left: Model after Neu and Sehitoglu. Right: extended $D_{TMF}$ concept.
4 Model application

The practical applicability of the models was demonstrated on two examples. For a simple and clearly laid out example a V-Shape test after Santacreu [4] was chosen. The company Tenneco provided the model and the test results of a test series for model validation purposes. The experimental lives of the series were about 1200 cycles. The experimental and computed lives were in good agreement.

A second example closer to real applications was provided by the company Benteler: a model of a manifold that was tested on a bench test in the past. The component had been tested in an endurance test with a cycle period of about 7 minutes. The failure criterion was leakage. The finite element model considers thermal and mechanical boundary conditions. The mechanical loading due to constrained thermal strains quickly shows a stabilized behaviour with the employed plasticity model. Due to the high temperature during the hot part of the cycle plastic flow occurs, which entails very high stresses during the cool part of the cycle. The stress-temperature evolution of a stabilized cycle was evaluated using the damage parameter $D_{TMF}$. Fig. 7a exemplarily shows the computed damage distribution, fig. 7b the component after the bench test with a main crack leading to leakage and a secondary crack.

Bild 7: Computed damage locations, critical elements in red (a) and component after bench test (b)

The mechanical loading at the critical locations is characterized by a superposition of normal forces and bending moments in the sheet. Due to the bending moments the damage distribution along the thickness direction of the sheet varies. Fig 8a shows the damage distribution for the two critical locations. Based on the relation between the damage parameter and the crack advance given in eqn. 2, a virtual crack advance can be computed. Strictly speaking this crack advance is only valid for the uncracked section. The computed crack length over the number of cycles is shown in fig 8b. The result for the secondary crack is in good agreement with the component. The result for the main crack differs from the component test. The clarification of possible reasons was out of the scope of this project.

Bild 8: Distribution of the damage parameter $D_{TMF}$ over the sheet thickness and resulting crack depth over the number of cycles.
5 Conclusion

Within the research project a sound experimental database was set up for typical loadings occurring under TMF conditions of high temperature components made of ferritic sheet metal. The models for plasticity and lifetime adequately describe the experimental findings. It could be demonstrated with the help of practical examples that the models and methodologies are suitable for practical applications and that they can deliver convincing results. However there is a need to validate the crack depth computation methodology. Furthermore a need for research exists with regard to welds, which are often critical locations. With the thorough knowledge about the base material now at hand, it would be a good opportunity to approach this metallurgical and geometrical challenging case.

Acknowledgement

The authors thank the German Ministry for Economy and Technology for the funding through the association of industrial research associations AiF under Grant 16234, the research association for combustion engines (FVV) for the coordination of the project, the always very active and committed project committee for their support. Prof. Dr.-Ing. Matthias Oechsner, Dr.-Ing. Alfred Scholz and Dr.-Ing. Falk Müller from Zentrum für Konstruktionswerkstoffe of Technische Universität Darmstadt and Dipl.-Ing. Stefan Eckmann of Fraunhofer IWM are thanked for their valuable advice and the good cooperation.

References


