Remnant lifetime assessment of service-exposed tube material of a refinery process heater

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Summary
In the present lecture the authors report about remnant lifetime assessment by means of Iso-stress-tests. The investigation was conducted on long-term service exposed tube material, removed from the tube coil of a refinery heater. In detail the concept of sampling of suitable tube material, the performance of short-term nondestructive and destructive tests and the choice of relevant test parameters for the planned longer running Iso-stress-tests is described. Furthermore the extrapolation procedure is demonstrated to find a conservative statement for the remnant lifetime. There has been performed statistical analysis and assessment of the obtained test results. Thereby it could finally be determined, that the equipment is safe for a defined extended time period. The investigation moreover has supported the development and scheduling of planned maintenance and repair activities for the coils of the analyzed process heater.

Key Words
refinery, service-exposed material, Iso-stress-test, extrapolation, time-temperature-parameter, remnant lifetime

Introduction
In many technical applications creep-exposed components can be longer used as initially designed. There are various reasons for this behavior like better material properties (e. g. creep resistance), overly conservative design parameters or less severe operating conditions of the relevant components as anticipated during the design phase. An economical use of the asset and a reliable and safe operation are major targets for the equipment owner. Therefore material investigation and assessment of the remnant lifetime are needed to extent the run length above the originally chosen design values.

Subject of investigation/Background

Some units of the german refinery Mineraloelraffinerie Oberrhein GmbH & Co. KG in Karlsruhe (MiRO) started-up in the early 60ies of 20th century. In this time the design standards for Fired Heaters were using creep rupture strength values, given for 100.000 hours. Some of the Heaters, operating within the creep range, are still running with the originally designed coil systems since more than 300.000 hours. Clearly, no creep rupture strength values can be found in material standards for such long term operation. Today measured creep rupture strength data are given up to 200.000 hours or 250.000 hours (2 1/4Cr-1Mo-steel-type in EN 10216-2).
Additionally, it is at least a difficult task to define the loading parameters (stress, temperature) which has occurred in the past due to different reasons :

1) Lack of instrumentation (thermocouples) in the past
2) Lack of digital stored historical operating data (pressure, temperature)

Therefore the theoretical assessment of remnant lifetimes of such coil systems is affected by uncertainties.
The further operation is often possible, but for safety and reliability reasons a well-considered concept of testing followed by an evaluation of the remnant lifetime is strictly needed.

At first a workflow was created, which consists of three steps:

First step: ***Selection of sampling area and looking for the possibly most deteriorated component or tube***

- Study of existing material certificates or comparable documents
- Study of previous results of non-destructive testing (UT, RT, Replica, control of OD)
- Experiences from previous indications or damages (optional from similar equipment)
- Study of service history and information coming from process engineering
- Consideration of tube position related to the location within the coil (closed to the inlet or to the outlet) and influence of burners nearby

Second step: ***Material sampling on-site***

- Random non-destructive testing of several similar loaded single tubes (e.g. by replication, hardness testing, wall thickness and OD measurements)
- Selection of most deteriorated tubes on the basis of testing results (sampling of material from several tubes is helpful for statistical purposes)
- Adhesive (waterproof) marking of the exact sample position, flow direction and location related to the burners

Third step: ***Short and long-term investigations of sampled material, followed by final assessment of the achieved results***

The paper is mainly focused on details of the third step, which will be following reported.

Selection of tested tubes and material characterization

The refinery process heater considered for the assessment consists of three different parts. The material of the tube coils is the low-alloyed 2 1/4Cr-1Mo-steel-type. The material was delivered on the one hand as Grade T22 acc. ASTM A200 for part 1 and on the other hand as 10CrMo9-10 acc. EN 10216-2 for parts 2 and 3 with initial tube dimension o. D. 141,3 x 9,5 mm.

The service parameters are given as follows:

Internal pressure: max. 35 bar
Tube Metal temperature: max. 580 °C
Service time at sampling: 395.000 hours

Deriving from the results of ***steps 1 and 2*** it was decided, to remove material samples from in total 11 individual tubes for destructive testing in ***step 3***. Table 1 shows the sample location and the kind of performed short-term material tests.

After the long exposure to high temperatures the metallographic investigation of the tube samples showed a typical structure of ferrite with carbides, as seen in Figure 1. Only a small number of creep cavities could be identified correlating with damage assessment class 2 according german guideline VGB S517-00-2014-11 [1].

Hardness measurements in various depths of tube cross section indicated a wide range between 126 HV 10 and 177 HV 10, which shows the very different influence of heat input into the tube material related to the individual location of samples within the process heater.

The tensile tests resulted in UTS-values for the majority of tube specimens in the range of minimum values of the standard EN 10216-2. Most of the yield strength values are significantly lower than the minimum value, given in the standard. This is the result of the long lasting annealing effect at high temperature.

Furthermore the geometrical dimensions were measured, to look for the metal loss (wall thickness) as well as for dimensional increase of the Outside Diameter (OD).

The assessment of all obtained results from metallographic investigation, tensile tests and dimension control has led to the decision, to choose tubes C (sampled in part 1), D (sampled in part 2) and K (sampled in part 3) for the further planned and below described long-running tests.

Methodology, experimental procedure and results

Iso-stress-tests are especially suitable to determine remnant lifetimes of creep-exposed material. The tests were conducted at higher temperatures compared to the service conditions to reduce the test duration and to obtain results in a reasonable timeframe. The test stresses should be in a range of practically occurring values during the operation of the heater tubes. The procedure of time extrapolation is schematically seen in Figure 2.

Round specimens were machined from tubes C, D and K to perform the Iso-stress-tests. The range of test temperature (640 °C to 720 °C) is sufficiently below the lower critical temperature for 2 1/4Cr-1Mo-steel-type acc. API Standard 530 for petrochemical applications. The range of stresses (from 15 up to 30 MPa) were planned in such a way that test durations between 500 and 5.000 hours should result.

To ensure a good statistical approach, 12 tests per tube and therefore a total of 36 tests were started. Finally six tests were interrupted before fracture of the specimens could be observed. Thus, test results of 30 failed test specimens were available for the final assessment with maximum test durations of more than 6.000 hours.

The results are shown and summarized in Figure 3. The constant C for the used Larson-Miller-Parameter was fitted through regression by using all test results. Tubes D and K are showing similar creep rupture strength level. Compared to this the Tube C has a slightly lower creep rupture strength.

Modeling

To evaluate the test results the following mathematical model was applied.

First a time-temperature-parameter (Larson-Miller) was used, but for reasons of simplicity it was divided by the factor 10^4 :

$$\overline{P} = \frac{T\,[K]}{10.000} \cdot \left[C + \log(t_u\,[h])\right]$$

The stress-function can be written in form of:

$$\lg R_{u,t,T} = B_0 + B_1 \cdot \overline{P} + B_2 \cdot \overline{P}^2 .$$

This simple formula is sufficient for interpolation purposes and statistical analysis of test result and can furthermore easily be handled. In principle other time-temperature-parameters (e. g. Manson-Haferd) and other stress-functions can be used for such analysis.

The constants B_0, B_1, B_2 as well as C can be determined by multiple regression analysis, either for all results together or, if required, for the results of an individual tube.

Lifetime assessment and statistical analysis

The derived constants can be used to recalculate the best fitted theoretical specimen lifetimes and the scattering of the results. Figure 4 shows the recalculated test results versus the observed test results. All points are within the 2*s-scatterband (lines for double standard deviation).

To increase the conservatism respectively the safety of further operation of the remaining tube systems there was decided, to use the minus 3*s-curve for extrapolation purposes.

By using the stress-function (with fitted constants) and the standard deviation an extrapolation of remnant lifetime based on tube stresses and tube metal temperature can be conducted.

Figure 5 shows as an example the minimum lifetimes for the minus 3*s-criteria and a constant stress of 20 MPa (hoop stress of tubes) dependent on the relevant tube metal temperature. As expected for the used model, the curve is slightly curved. The differences to a linear model (e. g. by using Manson-Haferd-Parameter) are very low in the range of service temperature of 580 °C. For temperatures above 580 °C, which would be relevant for significantly life usage, the differences are disappearing.

Implications for component behavior

To monitor the lifetime consumption of heater tubes mainly two information must be provided:

1) The knowledge of real tube metal temperature (external skin) and the change of this temperature by measurements of good applied thermocouples with a longtime stability over the heater runlength. Often inner layer(s) of fouling deposits result in an increase of the tube metal temperature over the time.

2) The knowledge of the minimum wall thickness within the tubes. Dependent on the process medium quality inside the tubes as well as the flue gas quality on the outside the wall thickness will decrease and this fact has to be taken into account for the stress calculation.

The optimal approach for safe operation of Fired Heaters is a process that will result in an online-monitoring of the percentage of consumed lifetime. This process requires online information about the tube metal temperature, the internal pressure and additionally at least an estimated corrosion rate of the tubes.
Having such a process in place, will allow monitoring the degradation due to creep and finally results in safe longtime operation of the Process Heater.

The knowledge of a realistic minimum lifetime or life consumption of the coils is very helpful to ensure a safe and reliable service, to determine necessary inspection intervals or to organize maintenance steps in a planned manner.

Tables and Figures

Heater part	Tube ID	Sample location related to burners	Geometry	Metallography, Hardness, Oxide scale thickness	Tensile tests
1	A	III	x	x	-
		V	x	x	x
	B	V	x	x	x
	C	VIII	x	x	x
2	D	I	x	x	x
		II	x	x	-
	E	I	x	x	x
	F	I	x	x	-
		I	x	x	x
	G	I	x	x	-
		II	x	x	x
	H	I	x	x	x
		IV	x	x	-
3	I	III	x	x	x
	J	III	x	x	x
	K	III	x	x	-
		V	x	x	x
		VI	x	x	-

Table 1: Sampled tubes and performed short-term material tests

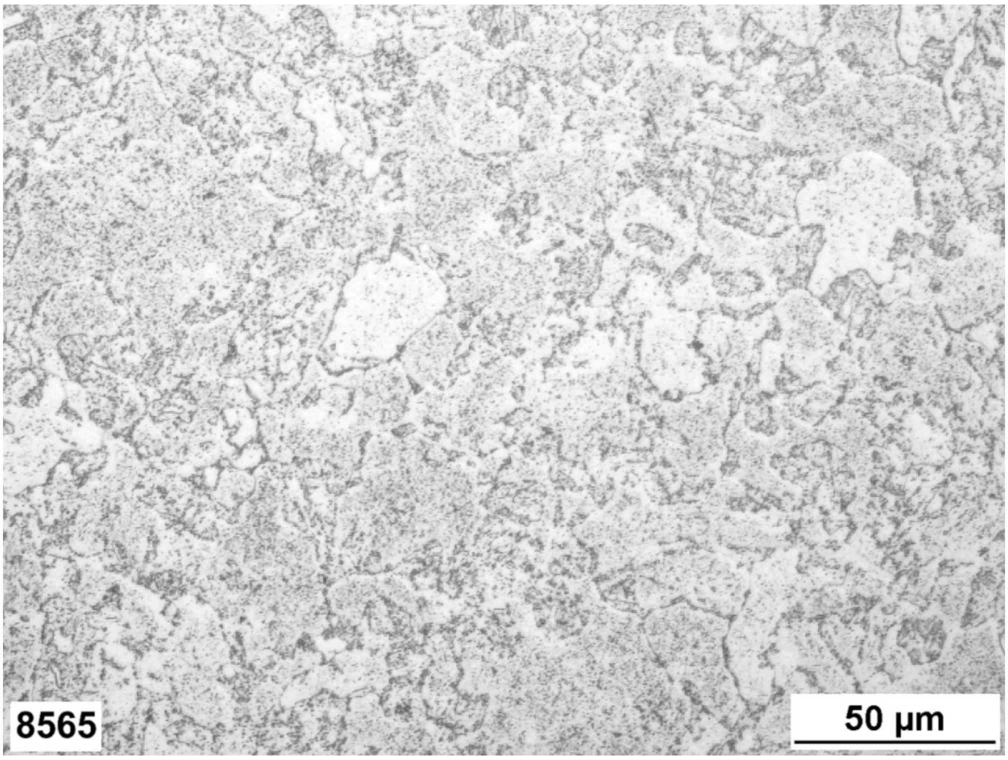

Figure 1: Microstructure of 2 1/4Cr-1Mo-steel after long-term-creep exposure

Conclusion

Iso-stress-tests are suitable to predict the remnant lifetime of creep-exposed material. This was conducted for tube material of a refinery heater tube system. The generated mathematical model is the basis for an online monitoring of life usage of considered heater system. The results were analyzed regarding their transferability to the remaining tubes.

Abbreviations

B_0, B_1, B_2	constants for stress-function
C	constant for Larson-Miller-Parameter
OD	outside diameter
P	Larson-Miller-Parameter
$R_{u,t,T}$	creep rupture strength
s	standard deviation
t_u	fracture time
T	temperature
σ	stress
UTS	Ultimate tensile strength

References

[1] VGB-S-517-00-2014-11-EN; Rating charts for rating the microstructural composition and creep rupture damage of creep-resistant steel for high pressure pipe-lines and boiler components and their weld connections