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Metallographic Replicas and Creep-Strain-Measurement for Lifetime-Assessment at High-Temperature Components

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Abstract

Plant life of fossil fuel power plants is usually sought by power generation companies near the end of their project life and it is based on a combination of economic, environmental and technical factors, which dictate the final decision upon whether it should be carried out. The final objective is usually to increase the plant service life beyond its project life, through the introduction of a certain number of technological modifications, which result in a reduction of the cost involved, normally of two thirds, when compared with the cost of erection of a completely new plant.

The safe operating of creep loaded components of thermal power plants or chemical plants is mostly depending on the local material properties and discontinuities due to design, welding or cracks. Local crack initiation starts at those areas with stress concentration, which crack growth should be assessed either by calculation or by experiment. It is the aim to gain a better usage of the material not reducing the safe operation and even extending life and service-cycles. The material damage is depending on the geometry and size of the component and also of the crack-, notch- or defect-geometry and in addition of amount, type and time of mechanical and thermal loading, and also of local material properties and its possible change because of long-term-loading [/1/ to /4/].

So far, the experience obtained in the remaining life assessment of the main components of aged fossil fuel power plants has shown that in general, relevant information needed to perform the required lifetime consumption calculations is not readily available or, in some cases, is even missing. In addition, the project documentation provided by the manufacturer at the time of power plant erection does not specifically address plant life extension requirements or the maintenance procedures available tend to be mainly focused on a routine basis.

In order to overcome these difficulties, the Initial State Characterization of main power plant components can be considered as an integrated maintenance methodology, which provides a set of reference information that can be used during the entire service life of the power plants. This paper aims to describe the two experimental methods to assess finally the lifetime of high temperature components of low alloy steel (bainitic microstructure) or 9-12% Cr alloyed steel (martensitic or austenitic microstructure). The metallographic method is long time used for bainitic-steels, for the new martensitic steels the strain-measuring method must be used.

1. Introduction

The Initial State Characterization, sometimes also called States of Reference, consists of the sorted storage of the initial features (process conditions) of main components of thermal power plants, following a logical maintenance-based procedure. Such component features include materials, dimensions, microstructure and hardness. The collection of design data, medium characteristics and the processing of operational data obtained during the subsequent power plant operation (pressure, temperature), enable the calculation of life consumption by creep, fatigue, corrosion and erosion, with an increased degree of accuracy.

Together with the degradation mechanisms (detected by metallographic or creep-strain-measurement) and a plant-related criticality-policy a criticality assessment can be performed /5/.
All the information useful to perform the criticality assessment is illustrated schematically in Fig. 1.

Lifetime Assessment and condition of thermal power plant components is considered as being an important and decisive activity to support maintenance and operation decisions. In this period of increasing competition amongst electricity producers, the need for maximization of the customer value at the lowest cost, without causing adverse impacts on safety, availability and reliability of power plants, is at the top of the corporate objectives.

To respond effectively to a world of increasing competitiveness, the operational performance of power plants relies on more accurate and consequently, more reliable component lifetime expenditure calculations. Part of the uncertainty related with these calculations can be reduced, in some extent, if relevant technical information regarding main components is adequately collected and organized, from the erection of the thermal power plant. This initial characterization, or state of reference, provides precise information about certain features of the components, like exact dimensions (relevant to the lifetime expenditure calculations) and initial material microstructure and hardness (obtained mainly from components subjected to temperatures in the creep range).

In adopting this initial state characterization methodology, future maintenance cost can be avoided or substantially reduced due to a certain number of reasons:

- knowing sooner the damage pattern of the component enables the maintenance personnel to undertake specific preventive and planned maintenance actions /6/;
- reducing in the uncertainty on the assessment of the component damage rate enables an increase in the period between any two successive planned outages or to reduced time to perform the inspection work at planned outages;
- detailed information about the equipment is obtained and organized in accordance with specific maintenance requirements, which is relevant for condition monitoring and lifetime assessment purposes. The lack of relevant information when it is absolutely necessary can mean production losses;
- finally, and to some extent, the decrease of the uncertainty about the equipment condition knowledge reduces the failure risk associated with it, and provides a solid basis that can eventually lead to savings in insurance costs.

In order to follow a logical way for the collection of the relevant technical data of the thermal power plant under analysis, the State of Reference methodology can be divided into several phases, namely:

1. Analysis of Plant Operating Conditions;
2. Identification of Damage / Degradation Mechanisms;
3. Identification and Selection of Critical Components;
4. Identification of Materials Properties of Selected Components;
5. Identification of Type of Testing;
6. Definition of Test Locations in Critical Components;
7. Elaboration of the State of Reference Report and Database;
8. Application of Testing to the Critical Components Location (Field Work); and
9. Recording of the NDT Measurements in the Database;

In this paper the two most important tools for the Identification of damage (see 2.) due to the degradation mechanism creep the metallographic method and the creep-strain-measurement are discussed.
Mechanical components of thermal power plants are generally submitted to 4 basic damage/degradation mechanisms:

- Creep
- Fatigue
- Corrosion
- Erosion

Regarding creep, it's well known that the degradation mechanism for the type of steels usually employed in thermal power plants is only considered to be relevant at the following temperature ranges:

C-steel and C-Mn-steel	T > 400°C
Low alloy ferritic steels (e.g.: 1Cr ½ Mo; 2 ¼ Cr1Mo	T > 450°C
Austenitic steels (e.g.: AISI type 300 series)	T > 550°C

Thus, it is generally considered the value of 400°C is the lowest limit in steels for considering creep as an influencing degradation mechanism.

2. Creep-Degradation

2.1 Classical Creep Behavior

Microstructural Changes during Creep

During creep, significant microstructural changes occur on all levels (Fig. 2). On the atomic scale, dislocations are created and forced to move through the material. This leads to work hardening as the dislocation density increases and the dislocations encounter barriers to their motion. /7/
Primary creep, also known as transient creep, represents a stage of adjustment within the metal during which rapid thermally activated plastic strain occurs (Fig. 3).

Primary creep occurs in the first few moments after initial strain and decreases in rate as crystallographic imperfections within the metal undergo realignment. This realignment leads to secondary creep.

Secondary creep is an equilibrium condition between the mechanisms of work hardening and recovery; it is also known as steady-state creep. Secondary creep is essentially a transition between primary and tertiary creep, where the creep rate reaches a minimum value. This often occupies the major portion of the duration of the creep test, and the strain rate in this region for many creep-resistant materials is sufficiently constant to be considered as a steady-state creep rate. For these materials, the minimum creep rate is a steady-state creep-rate-value that can be empirically related to rupture life and is widely used in research and engineering studies.

Tertiary Creep. Primary creep has no distinct endpoint and tertiary creep has no distinct beginning. Tertiary creep refers to the region of increasing rate of extension that is followed by fracture. Principally, it may result from metallurgical changes, such as recrystallization under load, that promote rapid increases in deformation, accompanied by work hardening that is insufficient to retard the increased flow of metal. It also may correspond to the onset of necking in some alloys. In service or in creep testing, tertiary creep may be accelerated by a reduction in cross-sectional area resulting from cracking or necking. Environmental effects, such as oxidation, that reduce cross section may also initiate tertiary creep, is apparently caused by inherent deformation processes and occurs at creep strains of 0,5% or less. In designing components for service at elevated temperatures, data pertaining to the elapsed time and extension that precede tertiary creep are of the utmost importance; design for creep resistance is based on such data. However, the duration of tertiary creep is also important, because it constitutes a safety factor that may allow detection of a failing component before catastrophic fracture /8/.

2.2 No classical Creep Behavior

Although the classical pattern of creep deformation can be made to fit many materials and test conditions, the relative duration of the three periods differs widely with materials and conditions. For example, in many super alloys and other materials in which a strengthening precipitate continues to age at creep temperatures, brief primary creep often shows transition to a long, upward sweep of creep rate, with only a point of inflection for the secondary period. /9/.

Cavitations Damage. The most common for of micro structural change is the accumulation of nucleation and growth of voids. Void growth is well understood, because voids grow by the same mechanisms that cause creep deformation. In contrast, void nucleation is not fully understood, although it appears to be the result of strain “misaccommodation” similar to crack nucleation in

some low-temperature fractures. For the high-temperature case, two adjacent grains may move at different creep rates. If the rates cannot be made to match, a gap forms between the grains. In general, higher creep rates cause voids to form earlier during the creep process. Thus, any material alternation that leads to a lower creep rate also improves creep strength.
Creep damage begins as small holes or cavities that typically form at grain boundaries or second phases. With time and stress, these holes or cavities can link up and form cracks, by both void growth (diffusion controlled) and by shear strain on the grain boundary that eventually lead to failure of the component. The damage is progressive and may occur in bulk or, more predominately, in localized regions. The formation of creep cracks is usually very localized in thick-section components; they form in welds, bends or other highly stressed regions. Determining the extent of this progressive damage is thus an important imperative for regular inspections of components exposed to elevated temperatures. Various damage rules are also used to approximate remaining time to rupture for components that have undergone prolonged high-temperature exposure.

3. Experimental methods to quantify the degradation due to creep

3.1 Replication methods for assessment of creep damage of low alloy steels with bainitic microstructure

Surface replication is a well known sample preparation technique that can be used to assess the condition of high-temperature power plant and petrochemical components form creep damage. The usual method of metallographic investigation involves cutting large pieces from components, which thus renders the component unfit for service. In contrast, surface replication allows examination of micro structural damage without cutting sections form the component. Plastic replicas lend themselves to in-plant nondestructive examination because of their relative simplicity and short preparation time. Plastic replicas can be examined with the light optical microscope, the scanning electron microscope, and the transmission electron microscope, and the transmission electron microscope, depending on the resolution required (Fig. 4, 5, 6, 7).

Replication techniques are sufficiently sophisticated to allow classifications of micro structural damage (Fig. 8, 9) that can be directly correlated to life fractions. Bulk damage from creep deformation typically occurs by the nucleation and growth of voids, either within grains or, as is more common, along grain boundaries. Internal voids first nucleate during creep deformation and then grow. The qualitative-quantitative relation is advantageous, because data from surface replication can be predictive in terms of generating a conservative minimum- and maximum-life estimate. The maximum life is useful in a predictive maintenance environment, because it would dictate the planning of future or replacement.

The information provided by metallographic replication and hardness can also be used in support of results of creep calculation. For example, it will be possible to detect micro structural changes prior to entry into operation, associated with wrong selection of welding or post-welt- heat treatment parameters during component fabrication or during on site assembly.

3.2 Creep-strain-measuring method

This method can be used for the creep-assessment of all types of steels.

3.2.1 Procedure

- The procedure of the method is as follows /10/:
- Defining of the measuring point at the most interesting spots or areas at a component
- Grinding and cleaning the metal surface

- Spot welding two austenitic metal-sheets (gauges), where the distance of the spot welding is the measuring length (5 mm or more) on the surface of the component at room-temperature the two halves of the gauge form a gap /6/.

- Producing of replicas of the gauge surface and its gap in shut-down condition of the plant. For the replicas either the material for metallographic replicas is used or a plastic material is pressed on top of the gap (Fig. 10).

- Evaluation of the replicas in the scanning electron microscope (SEM) or light optical microscope to estimate the gap distance at the beginning of the measuring sequence (zero-measuring).

- After zero measuring, the component is put into operation. For example after one year of operation there is a shut-down for inspection. Now a new replica is produced and measured as described before. If the gap has enlarged after this period of operation, related to the measuring length, a certain amount of creep strain has occurred.

- The gauges can form either single measuring points or a measuring-chain of multiple gauges (Fig. 11).

- Assessment of creep-damage for the operating time using the possible measured creep-strain with the two spotwelded gauges (Fig. 12/Fig. 13).

- Using the data of additional metallographic and non-destructive examinations an additional proof of the creep-damage-stage can be derived for the measured TCR-creep-strain /11/ and /12/.

Long term-measuring starting in 1989 has shown that the described method has a max. scatter of ± 0,2 % creep-strain. To answer engineering questions this is acceptable.

In the moment work is finished to perform the replicas also during operation of the component, this means under temperature condition (non-intrusive). In addition it is possible to measure the gap by laser (Fig. 14).

For every maintenance decision it should be clear, that because of the uncertainties in calculation due to the scatter of boundary conditions like:

- missing or insufficient operating data (start-up/shut-down, number of cycles…)

- incomplete material property-data (Young’s Modulus E, Poisson’s ratio coefficient of thermal expansion, real creep strength data in the heat affected zone of a weldment, multiaxial stress-state…)

- difference between design and operating data (pressure, temperature, gradient..)

- deviation in fabrication (wall-thickness, oval shape of a pipe-cross-section…)

- unknown additional operating loads (bending-moments, friction…)

the theoretical (mathematical) life consumption can only be a basic result which should be confirmed by additional NDT-tests.

To reduce these mentioned uncertainties in the calculation of residual life-time the following inspections and their data are performed: Visual checks, real wall-thickness, diameter-widening, deviation of circle-shape, metallurgical-inspections, strain-measuring and NDT. Form the economic point of view an optimal additional proof is now possible for all types of steels.

3.2.2 Advantages for utilities

Because the real creep-strain can be measured at any component, questions to reliability, life consumption, schedules for maintenance outages, times for repair-replace can be answered or updating for the applied calculation methods for residual life is possible.

The main advantages can be listed as follows:

- Most economic and cost-reducing measuring of creep-strain if it is required by codes or standards (e.g. in Germany TRD 508,2% creep-strain is allowed (Fig. 15).
- Preventing unplanned shut-downs
- Increasing the reliability of components like boiler drums, vessels, pipe-lines
- Questions to realistic schedules for condition oriented maintenance outages, economic times for repair-replace and possible life-extension can be answered, because the local stress-state is considered.
- Mailing of the replicas, their pictures or world-wide transmission (fax, e-mail) of the SEM-pictures from a plant or a laboratory to any place of an inspector or Expert Engineer for assessment is possible.
- Reliable reducing of damage-probability
- Improving the applied methods for calculating the residual life-time of creep-loaded components (because of uncertain boundary conditions, by measuring the real creep-strain during operation.
- Reliable chance of assessing the life-time of a component of new developed high-temperature-steels when the historic proof and experience of the metallurgical creep-damage processes are not yet available.
- Because the amount of creep cavities in modern martensitic steels is considerably lower, the long term experience of the microstructure change of low alloyed creep resistant steels-gained by metallographic replicas – can not be used any more for the conclusion on the damage stage of those steels (Fig. 16 and 17). For these martensitic 9-12% Cr-steels the creep-strain measured by the TCR-method must be used for an assessment,
- because the third creep stage can not be determinated any more metallographically in a safe time before fracture /13/ (Fig. 18).

4. Tools to estimate the life-time of a component under creep condition

4.1. The Fitness-For-Service-Method in the API 579 Code

- **Basic Information**
  - The ASME and API design codes do not address the fact that equipment degrades while in-service and that deficiencies due to degradation or from original fabrication may to be found during subsequent inspections.

- Fitness-For-Services (FFS) assessments are quantitative engineering evaluations which are performed to demonstrate the structural integrity of an in-service component containing a flaw or damage.

- API 579 provides guidance for conducting FFS assessments using methodologies specifically prepared for equipment in the refining and petrochemical industry.

- The guideless provided in API 579 can be used to make run-repair-replace decisions to help ensure that pressurized equipment containing flaws which have been identified by inspection con continue to operate safely.

- Methods in API 579 can be used for assessments based on "generally recognized good engineering practices" until references form inspection codes are provided /14/.

– **API 579 Development Background**

- An FFS assessment is a multi-disciplinary engineering analysis of equipment to determine whether it is fit for continued service, typically until next shutdown.

- The product of a FFS assessment is a decision to run as is, alter, repair, monitor, or replace; guidance on an inspection interval is also provided.

- Maintaining safe, reliable operations with an increase in run-lengths and decrease in shut-down periods.

– **Overview of API RP 579**

- Applicable to pressurized components in pressure vessels, piping, and tankage (principles can also be applied to rotating equipment).

- Multi-level assessment – higher levels are less conservative but require more detailed analysis/data
  - Level 1 – Inspector/Plant Engineer
  - Level 2 – Plant Engineer
  - Level 3 – Expert Engineer

- Provides recommendations for in-service monitoring and/or remediation for difficult situations.

- Section – Remaining life

- Section – In-service monitoring

- Section 10 – Assessment of Equipment Operating in the Creep Regime

– **Future Directions of the API In-Service Inspection Codes**

- Use RBI (API 580) to set interval, scope, method for inspection, supplemented by appropriate monitoring.

- If flaws or damage are found, use FFS (API 579) to assess acceptability for typically one operating period, can be reendorsed for future operating periods.

4.2. Codes for creep-assessment

To realize a safe and economic operation of older components in power plants or chemical plants it is necessary to have a strategy for maintenance which gives the chance to operate a component reasonably longer than 200.000 hours if – for example – the operating conditions have changed in relation to the original design /15/ and /16/. The experimental results (creep-strain = life consumption) can be compared with national codes like TRD 301 and TRD 508 or KTA 3201-2, BS 5500, AFCEN and ASME N-47-28, but also with metallurgical and further non-destructive investigations.

5. Conclusion

In most cases, bodies that write standard specifications have directed their attention primarily to the rules to design manufacture and testing to the hand-over-stage. The rules for the operation and inspection/maintenance has largely been left to government and survey bodies regulation in the field of offshore plants, the refining and the petrochemical industry but not for steam boilers, pressure vessels and pipe works. Increasing profitability also in this sections is the reason that work on engineering life assessment, in-service-inspection, fit-for service-inspection justified mainly on safety and reliability reasons – is becoming increasingly justified by economic factors. For example possible points to be considered are materials degradation due to creep and fatigue damage and its monitoring.

The two methods to determine the life-time of low alloy steel (bainitic microstructure) are the metallographic and the creep-strain-measuring method. For the modern steels (9-12% Cr) with martensitic and austenitic microstructure the strain-measuring method must be used, because the change of the microstructure (creep cavities) is different (considerably lower), so the third creep stage can not any more be determined metallgraphically in a safe time before fracture.

With the TCR (TÜV-Creep-Replica)-Method form the engineering and the economic point of view an optimal new inspection method for creep loaded components (/17/ and /18/) and their Fitness-for-Service assessment (API 579) is available now. It is possible to measure the real creep-strain due to service conditions, which allows a check and up-date of the boundary conditions in applied calculation methods or a comparing with other methods for predicting the life-time of components which are operated at higher stresses and temperatures. It is a tool to increase their reliability, availability and economic operation. It gives a chance for a risk informed assessment to define a monitoring schedule and maintenance strategy in view of optimized plant availability /19/.

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