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Remaining Life Assessment of a Power Plant Steam Pipeline Containing Cavities Using the Replica Method

Srđan BULATOVIĆ*, Zorica KOVAČEVIĆ, Vujadin ALEKSIĆ, Ivan SAMARDŽIĆ

Abstract: Assessing the condition of welded steam pipes is a key activity for the safe operation of the power plant and preventing future failures. This paper presents a method of estimating the remaining service life of a steam pipeline made of high-alloy steel, which has been in operation for a long time. The tested steam pipeline, operating for a long period of time under high pressure and high temperature conditions, experiences a series of microstructural transformations in both the base material and the weld, including cavitation due to creep. This study shows how, based on the examined microstructure, to estimate the remaining service life of a steam pipe under creep conditions, using the method of non-destructive replication metallography. Based on the classification of damage due to creep according to Wedel and Neubauer, an assessment of the remaining service life of the steam pipeline was made. The test results indicate that after long-term operation, noticeable microstructural damage occurs due to creep, and the estimated remaining service life indicates that the tested steam pipeline meets the conditions for further use. The purpose of this paper is to show the microstructural changes of a steam pipe made of high-alloy steel X10CrMoVNb9-1 after long-term operation in creep conditions. The presented data provide technical support for the safe operation of the high-temperature steam pipeline in the power plant, helping to formulate a maintenance strategy and eventual replacement of the steam pipeline, in order to ensure the safe and efficient operation of the power plant.

Keywords: creep; damage classification; remaining life; replica method; steam pipeline

1 INTRODUCTION

Thermoenergetic (TE) components, which are exposed to high temperatures during operation, can fail after long-term exploitation due to excessive stress, deformation or cracking in creep conditions. The stages during components failure due to fracture consist of initial crack formation, crack propagation, and final component failure when the crack reaches a critical size.

Estimating the remaining working life of TE components in the power plant is one of the modern methods of preventive maintenance. Remaining life assessment (RLA) techniques therefore aim to quantify the general or localized initial damage prior to crack initiation, as well as the rate of crack growth to its critical value that causes component failure. RLA techniques involve multiple non-destructive tests to find anomalies that include, among others, various microstructural damages. The expected working life of most power plants is between 30 and 40 years. Due to the increasing awareness of the technological feasibility of extending the life of components, the goal of many plants is to continue operating for another 20 to 40 years. The purpose of life extension activities is not to continue operation of the plant beyond its useful life, but only to ensure full utilization until its useful life. A key activity for plant life extensions is the RLA technique [1].

In the case of TE high-temperature components operating under creep conditions, both deformation and fracture are time-dependent. For this reason, the design service life is usually based on a certain amount of allowable stress or fracture ranging between 50,000 and 200,000 operating hours depending on the quality of the steel material. Many operational and metallurgical factors can affect extending the actual life of a component beyond design. Alternatively, adverse impact factors may reduce actual life expectancy [2].

A number of factors can lead to premature component failure. In addition to internal influencing factors, such as hidden residual stresses, system stresses and locally concentrated stresses, there are also external influencing factors from the environment, which lead to corrosion, pitting and stress corrosion cracking. Likewise, operating temperatures in TE components always exceed design temperatures at least for a short time, reducing the lifetime of the components. In case of component damage, i.e. the lack of ability of the component to safely, economically and reliably perform its planned function, there is a need to carry out the process of assessing the remaining useful life. One of the aims of extending the life of the plant is to determine the feasibility of this preventive technique, while the more common aim is to determine periodic intervals for inspection, repair, and maintenance. In this sense, extending the service life of components should be seen as a constant and not a one-time activity. Calculation procedures are often used to determine the extended life of components subject to creep.

Metallography in RLA methodology

Non-destructive metallography has been used for a long time to assess the degree of damage in high-temperature TE components. The use of the replica method enables a non-destructive evaluation of the microstructure on the basis of which the current state of the material can be determined.

In the early 1980s, Neubauer and Wedel began the application of the replica method for the evaluation of microstructural creep-damage.

The basis of their work was a methodology for a qualitative and only partially quantitative assessment of the remaining safe life of high temperature resistant components, with a recommendation for future periodic inspections. The principle is based on the fact that the evolution of creep in heat-resistant steels is associated with the appearance of voids that can be detected at a relatively early stage during creep.

Creep pores, or creep cavities, are a form of damage that occurs in steel structures subjected to prolonged stress at high temperatures. These cavities are formed in the microstructure of the steel material, i.e. at the grain boundaries, and their growth, coalescence and interconnection can eventually cause component fracture. The size of these cavities is at the micron level, so they are usually called micro-pores or micro-cavities.

Wedel and Neubauer classified the development of creep voids in steels into four different classes, noting that there is also an initial state of material without voids, called undamaged. Fig. 1 provides a graphical representation of these four classes of creep damage, on a creep strain/time exposure curve (Neubauer and Wadel, 1983).

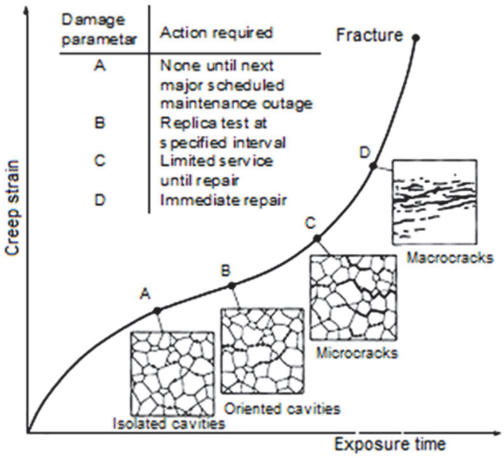


Figure 1 Creep-life assessment based on cavity classification [3]

2 RLA METODOLOGY

The first indication of the relationship between the presence of voids and the progress of creep can be found in the work of Neubauer et al., where it is stated that "noticeable void formation takes place at the grain boundary at the end of secondary creep". According to the damage classification in Fig. 1, Neubauer and Waddell summarized a critical review of these data and other data in power plant research and from the overall analysis derived the following classification of creep damage into five classes, namely: undamaged (no voids), class A (isolated voids), class B (oriented voids), class C (microcracks), and class D (macrocracks). This classification provides a simplified correlation between the degree of creep damage and the proportion of spent life. These five damage classes correspond approximately to values of fraction of spent creep life of 0,12, 0,46, 0,5, 0,84, and 1, respectively, using a conservative lower bound curve [4].

The consumed fraction of the total life, $t_{\mathrm{exp}}/t_{\mathrm{r}}$, can be expressed in relation to the remaining life through the equation [4]:

$$t_{\mathrm{rem}} = t_{\mathrm{exp}} \left(t_{\mathrm{r}} / t_{\mathrm{exp}} - 1 \right) \quad (1)$$

where, t_{rem} - remaining life; t_{exp} - expended life; t_{r} - rupture life.

This RLA method uses the correlation between the Neubauer and Wedel classification and the $t_{\mathrm{exp}}/t_{\mathrm{r}}$ shown in Fig. 1. The $t_{\mathrm{exp}}/t_{\mathrm{r}}$ value corresponding to the class of identified cavitation can be entered into Eq. (1) to directly determine the remaining lifetime of the component.

Below is an overview of general interpretations:

Remaining life usually refers to the time a component or plant is expected to function before necessary repair or replacement occurs [5].

Expended life refers to the total number of operating hours of a component or plant.

Expended creep-life fraction, denoted as $t_{\mathrm{exp}}/t_{\mathrm{r}}$, used, is a value that indicates how much of the component's total creep life has been used [6]. For the 9Cr steels group, to which the X10CrMoVNb9-1 steel also belongs, this parameter represents the relationship between the creep exposure time and the total design life of a component under creep conditions.

Expended creep-life fraction is a dimensionless parameter, ranging from 0 to 1, that represents the fraction of the total creep life that has been used. For example, a spent creep life fraction of 0,5 indicates that 50% of the material's creep life is spent [7].

For the Neubauer and Waddell classification of creep damage, the following activities are suggested during periodic inspection:

1. Undamaged material: Re-inspection after the next system shutdown.
2. Class A - Re-examination after three to five years.
3. Class B - Re-examination after one and a half to three years.
4. Class C - Replacement or repair is required within six months.
5. Class D - Immediate replacement or repair required.

3 REPLICATION MICROSCOPY TECHNIQUE

Replication is a non-destructive sampling procedure that records and stores the topography of a metallographic sample as a negative relief on plastic film.

3.1 Equipment

The regular equipment for a replica inspection includes: grinder; power drill with grinding equipment; transportable grinding and polishing equipment; etching and cleaning fluid; replicas; transportable metal microscope.

3.2 Preparation of the Test Surface

Exploited components usually have corrosion products or an oxidized layer on the surface that must be removed before replication. The oxidized surface layer is removed by rough grinding, and according to the recommendation of the ISO standard [8], the thickness of the layer that may be removed is up to 0,2 mm. Rough grinding equipment can be used as long as precautions are taken to prevent the introduction of foreign particles into the structure due to possible overheating or plastic deformation. Sandblasting and abrasive discs can be used for this purpose.

Subsequent sanding should be done in at least three steps, with successively finer types of paper, ending with sandpaper of fineness No. 400.

With each finer type of sandpaper, traces of previous sanding must be removed. The grinding direction should be changed by 90° after each granulation. The recommended grits of sandpaper for these purposes are No. 120, 220 and 400.

While sanding is in progress, a low pressure must be used, in order to prevent heating and deformation of the surface.

After the initial preparation steps are completed, standard mechanical polishing methods can be used.

Depending on the quality of the material, in the preparation step before etching, abrasive silicon carbide discs of different grits can be used, together with polishing discs with cloth, diamond polishing paste or alumina of different grits [9].

The final grain size of the polishing agent is 1 μm for steel materials.

After the final polishing, the surface is washed first with water, then with acetone and dried in a stream of warm air.

The final stage of surface preparation is etching with any suitable reagent. The choice of etching reagent is made depending on the quality of the tested material and the required information.

In this case, picric acid (925 ml of ethyl alcohol + 25 g of picric acid + 50 ml of hydrochloric acid) was used as an etching agent.

In order to identify micro damages using the replica method, etching must be more intense than conventional etching to reveal the microstructure. After etching, the surface is washed with water and acetone and dried in a stream of warm air.

3.3 Replica Method

After proper surface preparation and etching, the surface is ready for testing. Examination can be done in the laboratory or in special cases *on-site* using a portable metal microscope

In order to obtain a replica of adequate quality, the prepared surface must be clean, dry and dust-free.

A thin plastic film replica is moistened with solvent and placed on the tested surface. In order for the replica to adhere to the surface of the metal, it is pressed with the fingers, starting from the middle, in the direction of the two opposite edges. The replica is removed from the metal surface by properly lifting one edge.

There must be no fingerprints on the replica.

After lifting from the tested surface, the replica is glued to the glass support.

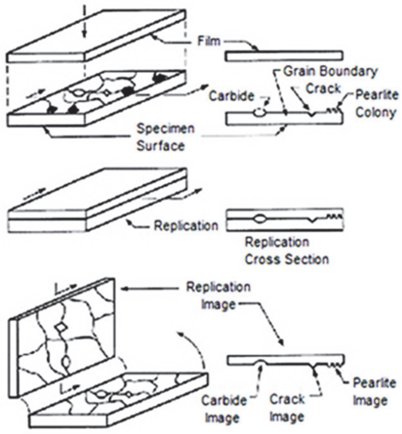


Figure 2 Schematic representation of the plastic replica technique [10]

A schematic representation of the technique of taking a plastic replica is shown in Fig. 2.

The quality of the produced replica is preliminarily assessed inside the facility where the examination is carried out, first visually, and then under a portable metal microscope.

After replication and preliminary assessment of the taken replicas inside the facility, the replicas are delivered to the metal testing laboratory where microstructural analysis is performed [11].

3.4 Microstructural Analysis of Replicas

Replicas are observed in the laboratory under a light optical microscope at different magnifications, from 50 - 500×. The choice of magnification is most often defined by the microstructural characteristic that is recorded (for example, identified macrocracks will be recorded at a lower magnification, in order to give a clearer visual picture of the size of the crack, while the end of the crack itself (as well as small microcracks) will be recorded at a higher magnification.

Microstructure/microstructural damage analysis using a light microscope is one of the most commonly applied metallographic testing procedures. The purpose of microstructure analysis is to accurately and clearly show the structure of the examined material and determine the type, size and amount of individual microconstituents (phases), as well as their distribution.

Microstructural analysis can also give us insight into the presence of: macro- and microcracks, isolated micropores, carbide precipitates, non-metallic inclusions, pitting corrosion, microstructural inhomogeneities, etc.

4 EXPERIMENTAL WORK

4.1 The Basic Material of the Steam Pipe

The basic material of the steam pipe used in this study is martensitic steel X10CrMoVNb9-1. The main alloying elements of this steel are chromium and molybdenum. The chemical composition of this steel according to the EN 10216-2 standard [12] is shown in Tab. 1.

Table 1 Chemical composition (wt.%) of steel X10CrMoVNb9-1

Element	% by mass
Carbon (C)	0.08-0.12
Silicon (Si)	0.20-0.50
Manganese (Mn)	0.30-0.60
Phosphorus (P)	≤ 0.020
Sulfur (S)	≤ 0.010
Chromium (Cr)	8.00-9.50
Molybdenum (Mo)	0.85-1.05
Niobium (Nb)	0.06-0.10
Vanadium (V)	0.18-0.25%

Due to the fact that this steel has superior creep and fracture strength as well as good corrosion resistance, it is suitable for the construction of steam pipelines and work at temperatures up to 595 °C [13].

4.2 Design and Service Data

The designed and operational data of the tested steam pipeline are shown in the Tab. 2.

Table 2 Design and service data for the steam pipe

Design pressure	201 bar
Operating pressure	183 bar
Design temperature	550 °C
Operating temperature	545 °C
Material	X10CrMoVNb9-1 / EN 10216-2
Pipe size	Ø323,9 × 3,2 mm

The tested steam pipeline has been in use for about 150000 working hours. For this reason, as it approaches the intended number of operating hours, it is necessary to assess whether it is still safe to use.

Analysis of the microstructures of the examined steam pipeline showed that long-term exposure to high temperature and pressure led to changes in the microstructure and that there is a definite connection with creep due to cavitation. This was confirmed by the identification of creep damage due to the appearance of micropores at the grain boundaries, their growth and in places connection.

4.3 Microstructure Analysis

A light optical microscope model CARL Zeiss - Jena, Germany was used to examine the microstructure of steam pipes.

The tested zones included both the base material zone and the weld metal zone.

4.4 Selection of Representative Components/Welds

Part of the isometry of the tested steam pipeline is shown in Fig. 3. There are three original welds in the section, marked MS26-RA102, MS27-RA102 and MS28-RA102.

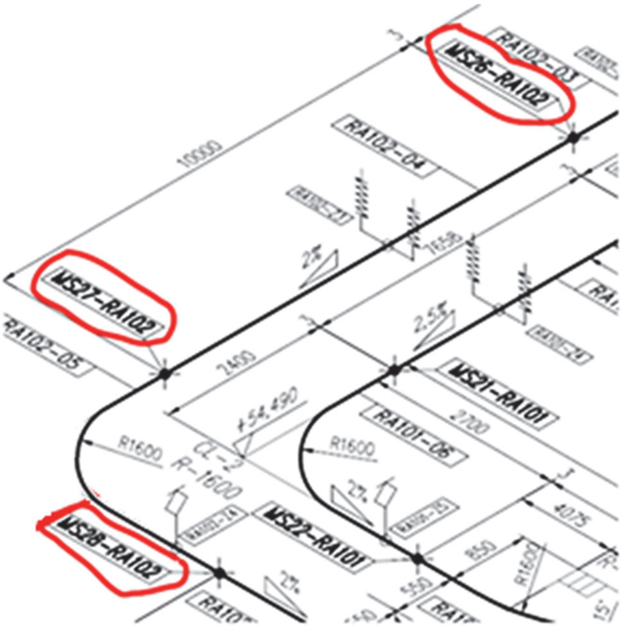


Figure 3 Isometric part of the steam pipeline. The three welds that are scheduled for creep testing are marked in red.

As part of this study, replicas taken from the base material zones, as well as from the weld metal zones of all three welds, were sent to the laboratory for metallographic characterization of creep damage.

5 RESULTS AND DISCUSSIONS

5.1 Microscopic Examination

The as-received X10CrMoVNb9-1 steel has a microstructure of tempered martensite with finely dispersed MX precipitates, mainly of vanadium, and M23C6 carbides, rich in vanadium and niobium. A common picture of the microstructure of the tested steam pipeline in the as-received state is shown in Fig. 4.

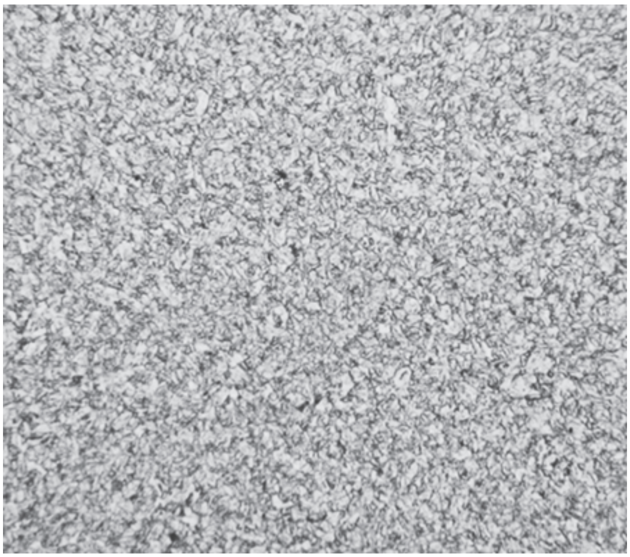


Figure 4 The as-received microstructure of the base steam pipe material tempered martensite. Magnification 100×

The degree of degradation of the microstructure of the steam pipe was determined according to the recommendations of the ECCC (European creep collaborative committee) and the damage classification according to Wedel and Neubauer, which provides an overview of the correlation between the estimation of the remaining service life and the microstructural aspect, for the material operating under creep conditions [14-17].

The replication location, the state of the microstructures, and the degradation class of the base material microstructure and the weld metal microstructure are shown in Tab. 2.

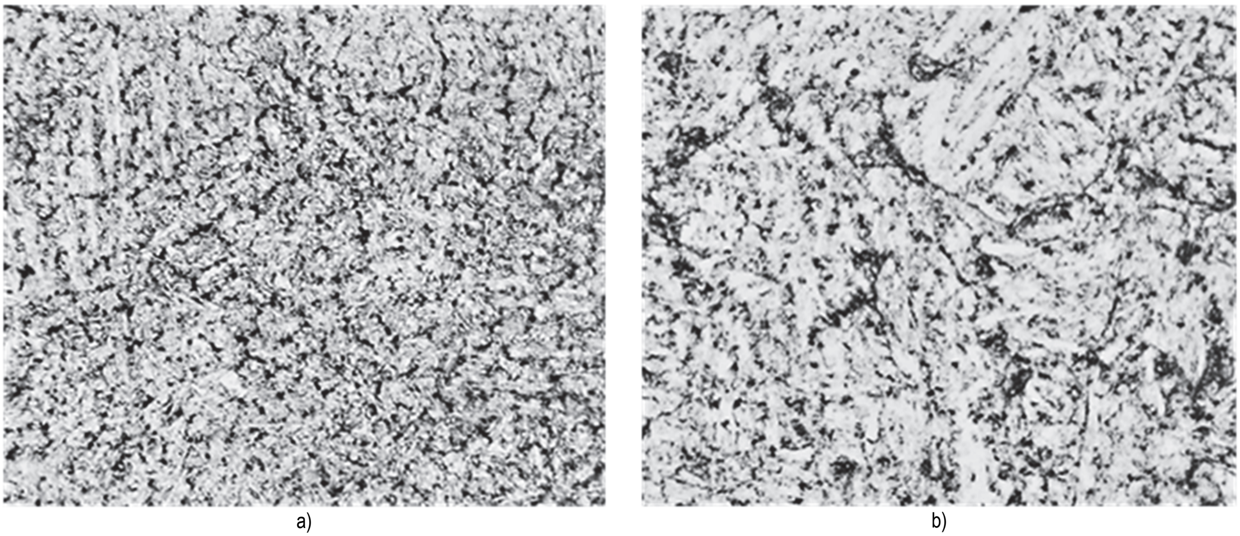
Photomicrographs of the examined microstructures are shown in images from 5 to 10.

Table 2 Steam pipe section/weld, microstructure condition and level of degradation

Steam pipe section/weld	Replica	Microstructure condition	Class of degradation	expended creep-life fraction
MS26 - RA102				
MS26 base material 1	MS26 BM1	Presence of directional oriented microcavities	B	0,5
MS26 weld material	MS26 W	Presence of microcracks	C	0,84
MS27 - RA102				
MS27 base material 1	MS27 BM1	Presence of directional oriented microcavities	B	0,5
MS27 weld material	MS27 W	Presence of microcracks	C	0,84
MS28 - RA102				
MS28 base material 1	MS28 BM1	Presence of isolated microcavities	B	0,5
MS28 weld material	MS28 W	Presence of microcracks	C	0,84

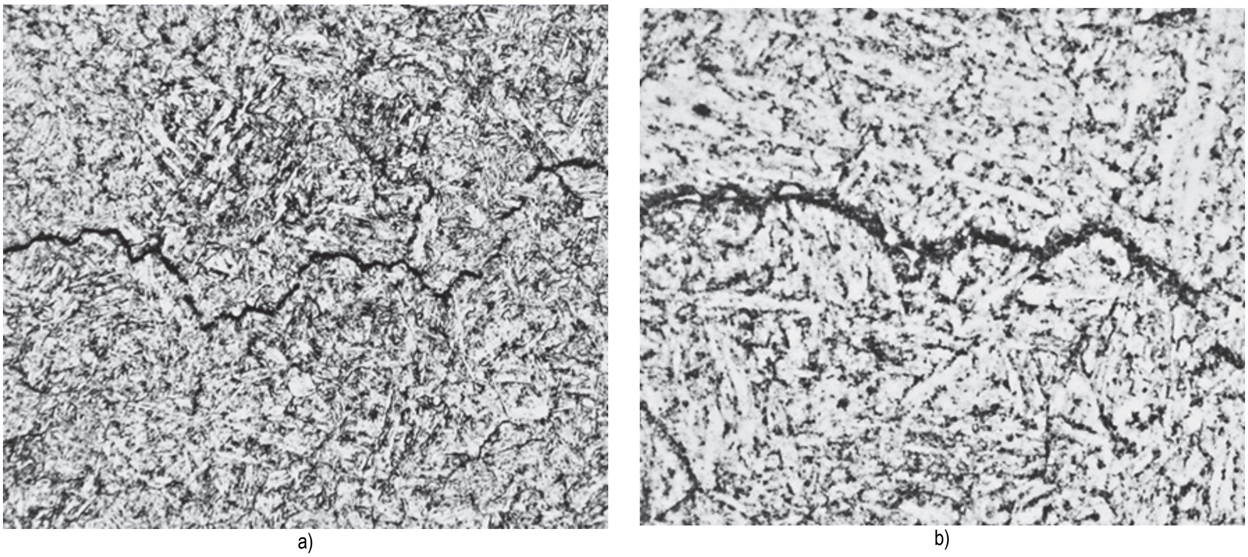
5.2 Calculation of the Remaining Service Life

The Photomicrographs of the examined microstructures show different class of damage due to creep, namely: damage class B (oriented voids) is present in the microstructures of the base material, see images: 5, 7 and 9, while damage class C (microcracks) is present in the microstructures of the weld metal, see images: 6, 8 and 10.



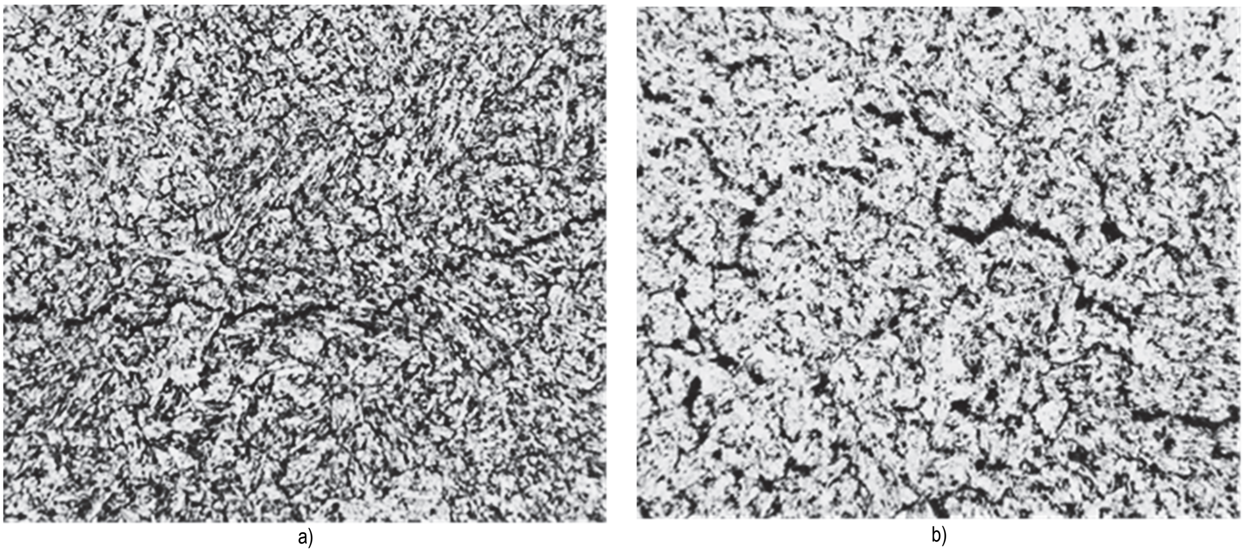
a) b)

Figure 5 Pipe section/weld: MS26 - RA102. Replica MS26 BM1. Original magnification: a) 100×; b) 500×



a) b)

Figure 6 Pipe section/weld: MS26 - RA102. Replica MS26 W. Original magnification: a) 100×; b) 500×



a) b)

Figure 7 Pipe section/weld: MS27 - RA102. Replica MS27 BM1. Original magnification: a) 100×; b) 500×

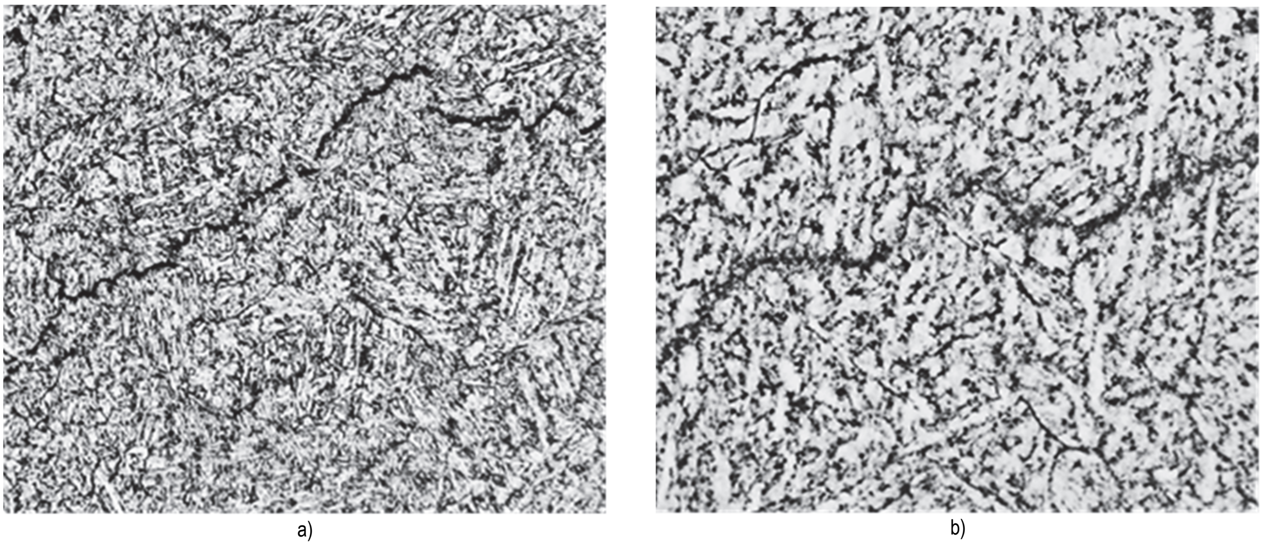

a) b)

Figure 8 Pipe section/weld: MS27 - RA102. Replica MS27 W. Original magnification: a) 100×; b) 500×

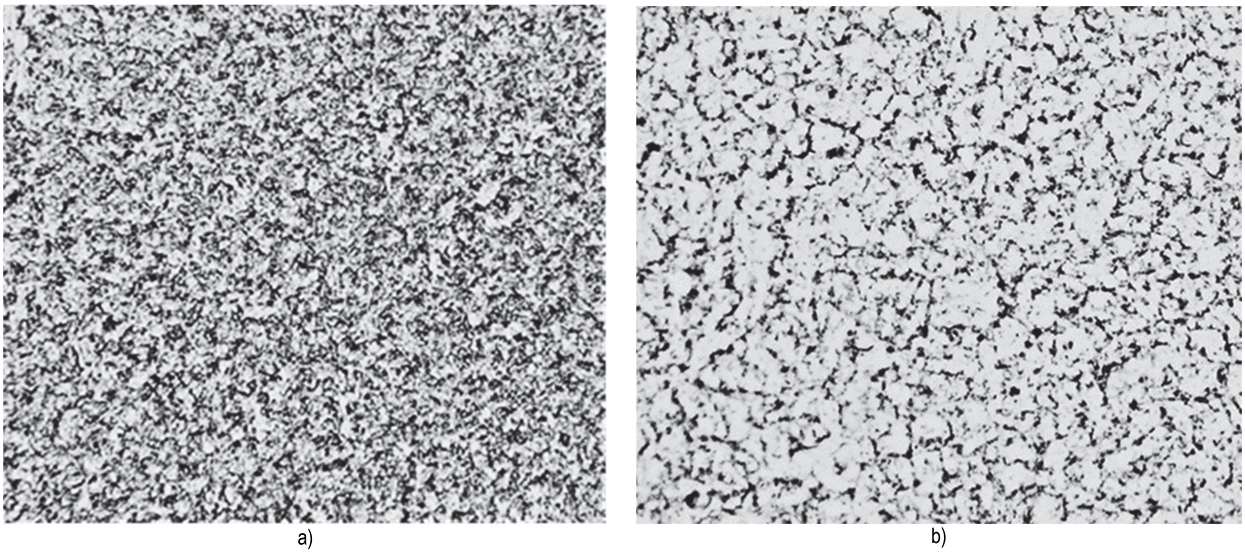

a) b)

Figure 9 Pipe section/weld: MS28 - RA102. Replica MS28 BM1. Original magnification: a) 100×; b) 500×

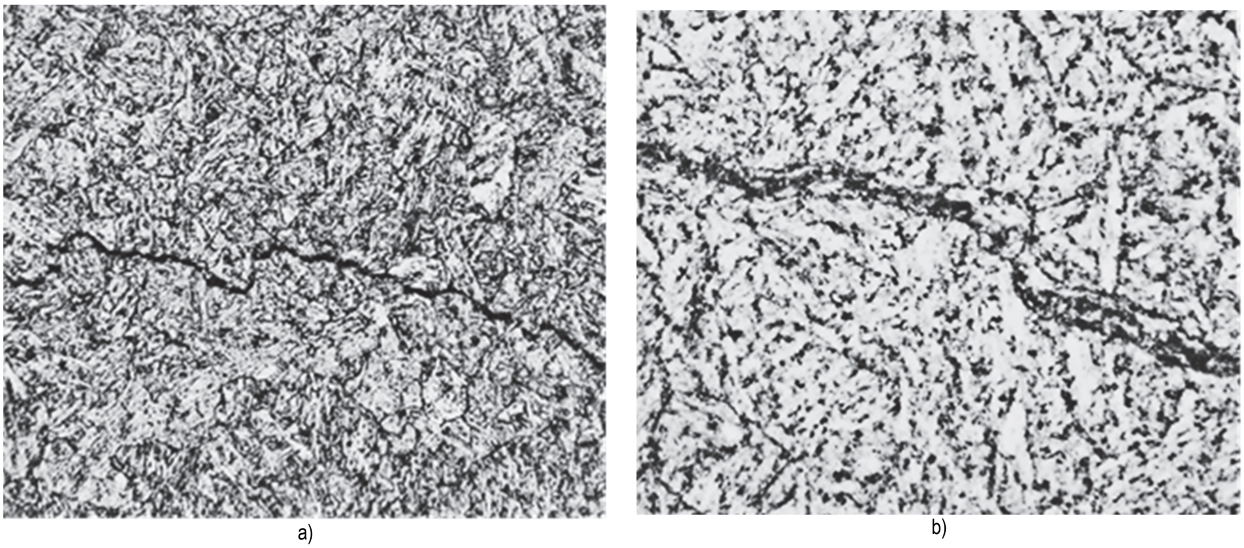

a) b)

Figure 10 Pipe section/weld: MS28 - RA102. Replica MS28 W. Original magnification: a) 100×; b) 500×

The identified damage class of the microstructure of the base material corresponds to the expended creep-life fraction $t_{\mathrm{exp}}/t_{\mathrm{r}}$ = 0,5, while the identified damage class of the weld metal microstructure corresponds to the expended creep-life fraction $t_{\mathrm{exp}}/t_{\mathrm{r}}$ = 0,84 (see Tab. 2).

The remaining life of the base metal/weld metal of the steam line was calculated using the expended creep-life fractions, and the results are shown in Tab. 3.

Table 3 Calculation of the remaining service life of steam pipelines based on the microstructural classification of damage due to creep

Damage class	B - class	C - class
Expended creep-life fraction	0,5	0,84
Total running hours of plant	~ 150000	~ 150000
Remaining life, t_{rem}	$t_{\mathrm{rem}} = t_{exp}\left(t_r / t_{exp} - 1\right)$ = 150000(1/0,5 – 1) = 150,000 hours	$t_{\mathrm{rem}} = t_{exp}\left(t_r / t_{exp} - 1\right)$ = 150000(1/0,84 – 1) = 28,571 hours

6 CONCLUSION

This study evaluates the remaining service life of high-alloy steel steam pipelines using a method based on creep damage classification.

For the purposes of the estimation of the remaining service life of the steam pipeline, the replication technique was used, which included taking replicas (imprints) from the surface prepared on the element and their subsequent analysis in the metallographic laboratory.

Oriented voids are present in the microstructures of the base material, which corresponds to damage of class B, while microcracks are present in the microstructures of the weld metal, which corresponds to damage of class C according to the Wedel and Neubauer classification.

Based on the test results and calculation of the remaining service life of the steam pipe base material/weld metal, the following recommendations are given for re-examination by replication metallography:

- for class B - re-examination after 3 years of work,
- for class C - re-examination after 6 months of operation, in order to monitor the level of degradation and take further preventive measures.

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Contact information:

Srđan BULATOVIĆ, PhD, Senior Research Associate
(Corresponding author)
Institute for Materials Testing (IMS),
11000 Belgrade, Bulevar vojvode Mišića 43, Serbia
E-mail: srdjan.bulatovic@institutims.rs

Zorica KOVAČEVIĆ, Principal Technical Associate
Institute for Materials Testing (IMS),
11000 Belgrade, Bulevar vojvode Mišića 43, Serbia
E-mail: zorica.kovacevic@institutims.rs

Vujadin ALEKSIĆ, PhD, Senior Research Associate
Institute for Materials Testing (IMS),
11000 Belgrade, Bulevar vojvode Mišića 43, Serbia
E-mail: vujadin.aleksic@institutims.rs

Ivan SAMARDŽIĆ, PhD, Full Professor
Mechanical Engineering Faculty,
University of Slavonski Brod,
35000 Slavonski Brod, Trg I. B. Mažuranić 2, Croatia
E-mail: isamardzic@unisb.hr