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# LIFETIME EVALUATION OF A STEAM PIPELINE USING NDE METHODS

## OCENA PREOSTALE TRAJNOSTNE DOBE PAROVODA Z UPORABO NEPORUŠITVENIH PREISKAV (NDE)

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Before its shutdown, the steam pipeline made from X20CrMoV121 steel in the Power Plant Toplarna – Ljubljana operated at 530 °C and 95 bar for 150 000 h. A non-destructive evaluation (NDE) of the microstructure using the replica method and hardness measurements on pipeline bends and welded joints with the aim to evaluate for possible damage due to creep deformation was applied. The hardness of the different zones of the welded joints, base material, heat-affected zone and the weld material itself was appropriate and corresponded to the tensile strength in the range required by the standards. A martensitic appearance in all the observed locations was noticeable.Micro-voids that arise due to creep deformation along the former austenite grain boundaries and along the martensite lamellas on the inspected sites were not observed. According to the VGB[1]classification, the steel corresponds to the 2b class.

Keywords: steel X20CrMoV121, steam pipelines, life time, micro-voids, NDE methods

Ob zaustavitvi je bil parovod v Termoelektrarni-Toplarni Ljubljana v obratovanju že 150 000 h pri tlaku 95 bar in temperaturi pare 530 °C. Parovod je izdelan iz jekla X20CrMoV121. Na cevnih kolenih in zvarjenih spojih parovoda smo naredili neporušitvene preiskave (NDE) mikrostrukture po metodi replik in meritve trdote za oceno stanja parovoda ter ocenili morebitne poškodbe zaradi deformacije z lezenjem. Trdota različnih delov zvara, osnovnega materiala, toplotno vplivanega področja in vara je ustrezna in ustreza natezni trdnosti, ki je v mejah, določenih po standardu. Martenzitni habitus je na vseh mestih izrazit. Mikropore, ki nastanejo zaradi deformacije z lezenjem po mejah prvotnih avstenitnih zrn in po martenzitnih lamelah, na pregledanih mestih nismo opazili. Po klasifikaciji VGB[1] ustreza jeklo razredu 2b.

Ključne besede: jeklo X20CrMoV121, parovodi, preostala trajnostna doba, mikropore, neporušitvene preiskave (NDE)

## 1 INTRODUCTION

High-temperature and high-pressure components in large-scale steam generating power plants are manufactured from creep-resistant steels. Steam pipelines, as important parts of these components, are required to operate for many years under severe conditions of temperature and stress; therefore, they are usually designed for a certain lifetime, for example, $10^5$ or $2 \times 10^5$ h. However, because of uneven distribution of stresses, the lifetime of different elements is not the same.[2] The microstructure of materials operating under such conditions changes with time and accelerates the different mechanisms of degradation of these materials, such as creep, fatigue, thermal fatigue, creep-fatigue, progressive embrittlement, corrosion/oxidation, etc., of which the most important is the creep deformation. The damage caused by creep deformation is permanent.[3] The final evidence for the development of creep damage during service is the initiation and growth of discrete cracks, either by creep processes alone or by creep fatigue interactions. These may form either as a single crack at stress-concentrating features or as the final phase of more generalized damage, and both of them ultimately result in creep failure.[4] It is important to mention that the creep deformation is far from homogenous, also on the microstructural scale. One manifestation of this is the formation of cavities at the grain boundaries between differently oriented crystals.[5] In some steels the grain-boundary cavitations develop early in life, progressing steadily through the stages of growth and linkage into microcracks before reaching the failure point. This behavior is generally characteristic of low-ductility steels, the cavities forming preferentially at grain boundaries orientated normal to the maximum principal stress on particles, such as sulfides or carbides.[6,7] Conversely, higher ductility materials may not exhibit detectable cavitations until a late stage in life and the cavities or voids may form intragranularly or at grain boundaries, supporting the maximum shear stress. For example, in the low-alloy steels and X20CrMoV121, the cavities become visible ($N \approx 50–100$ mm$^{-2}$) when a life fraction of between 0.3 and 0.55 have been consumed. But this usually differs in the case of welded joints. The lower residual creep ductility of the heat-affected zone (HAZ) and the creep rate of the surrounding base materials dictates the development rate of cavities and microcracks in the HAZ.[8] In these cases also premature damage in the form of cracks, which are parallel to the weld, may arise. There are two reasons for this: one is the increase of the stress due to the welding, the other one is the initial microstructure that influences the creep resistance of the steel.[2] In either case the detection of cavities as early as possible is essential and this has become one of the major tools in any life-management program.[4]

The severity of creep cavitation and its effect on remaining life has been studied extensively and both qualitative and quantitative procedures have been variously developed or proposed. The semi-quantitative procedure proposed by Neubauer[9,10] is the best known and remains the basis for most procedures in use today. The degree of cavitation is described by five "damage parameters" ranging from "undamaged" through to "macro-cracked". The damage parameters are then related to the stage that the material has reached on a classic primary-secondary-tertiary creep curve and on the basis of these recommendations, future plant actions are made (**Figure 1**).[2,4,11] Similar procedures are incorporated in European guidelines for in-service damage assessment.[12,13] However, because of the high conservatism included into each of these theories, they are actually used as monitoring techniques, rather than life-prediction methods.[14]

The metallographic replication technique together with other conventional, non-destructive evaluation (NDE) methods form an important part of the base-line and progressive inspection philosophy of HTP components.[8] The replication technique is carried out at certain intervals on components that operate in such conditions that damage due to the creep deformation is present.[2,14] The initial damage due to the creep deformation always arises on the outer surface of steam pipelines and it is impossible to detect it with other non-destructive investigations because they are at the microscopic scale. Despite the relatively small area, the replicas are representative if they are taken from regions of components where stresses, deformations and temperatures are the highest. Therefore, good experience is very important in these investigations. [15]

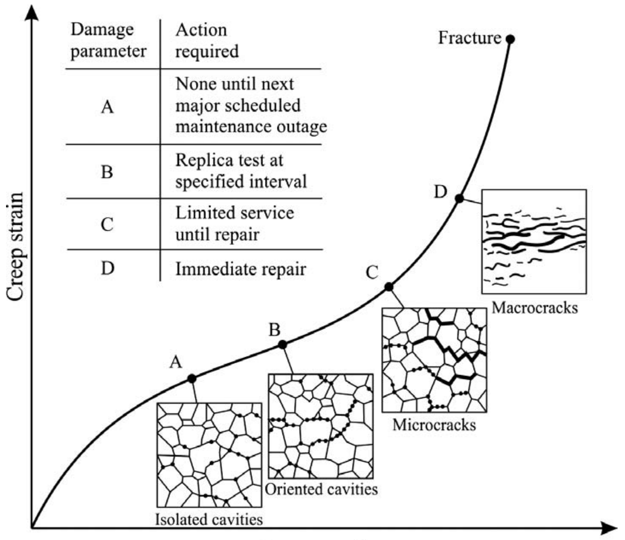

**Figure 1:** Degradation of steel depending on the duration of the creep deformation 1

**Slika 1:** Degradacija jekla v odvisnosti od trajanja deformacije z lezenjem 1

Along with the replication technique, in-situ hardness measurements can provide information of great importance regarding the actual condition of materials in HTP components. The hardness of all creep-resistant steels operating in the creep range is a function of time, temperature, and stress. The relative simplicity of hardness measurements on service components has promoted interest in using these for remnant-life assessment purposes, either as a means of determining or confirming the operating temperature, as a qualitative indicator of a material's condition, or in the extreme, as a means of a direct estimation of the remaining creep life.[4]

In the present work, both the metallographic replication technique and in-situ hardness measurements of pipeline bends and T-fittings as well as welded joints between them and the straight parts of steam pipelines were carried out. The aim was to evaluate their condition for possible damage due to creep deformation. Due to the microstructural features and different hardnesses on different regions of the welded joints, they are less resistant to creep deformation. For this reason, the inspection of welded joints is of particular importance. The pipeline is made of X20CrMoV121 steel. Before the shutdown, the pipeline was subjected to operating conditions of 530 °C and 95 bar for 150 000 h. The dimensions of the pipeline are 323.9 mm × 20 mm.

The investigation consisted of:

- preview and study of the pipeline's plan
- visual inspection of the pipeline
- replication on the bends
- replication on the welded joints
- hardness measurements on both the bends and the welded joints
- microstructural investigation using light microscopy

Based on the investigation carried out, the evaluation of the pipeline's condition according to the VGB[1] criteria (microstructural features, damages due to the creep deformation) was carried out.

## 2 EXPERIMENTAL

Microstructural investigations and hardness measurements were performed on the outer part of five bends, on welded joints between the bends and the straight parts of pipelines, and also on the base material and the welded joints of T-fittings. On three regions of welded joints, i.e.,base material, heat-affected zone (HAZ) and the weld itself, the replication was performed.

Prior to the replication, the surface of chosen regions was properly prepared for this purpose. First, the surface was properly cleaned and dried with hot air. After that, the surface was ground using fine abrasive paper, in a depth of less than 0.2 mm. Low hand-pressure was applied during this step, in order to prevent any overheating or cold hardening of the material on the surface. This procedure consisted of consecutive short grinding steps, applied in directions perpendicular to each other. After each of these steps, we had to remove the remains of the grinding process. After the grinding, the surface was carefully polished using a "Muvipol-3"electrolytic polisher, followed by the process of cleaning with alcohol and drying. The next step was the etching of the surface, also followed by cleaning and drying. In order to make sure that the surface is properly prepared, we used a portable optical microscope to observe the condition of this surface. Finally, a special solvent was overspread on the transparent replication foil of thickness 0.06 mm, and the foil was placed on the surface and pressed for approximately 60 s. The replicas were observed using a "Nikon Microphot FXA" optical microscope with a "Hitachi HV-C20A 3CCD" video camera at magnifications of 100-times and 200-times.

Using a "InstronDynaTestor" portable hardness-measuring instrument, we performed hardness measurements on the same locations where the replicas were taken. Measurements were performed at 5 different locations for each prepared surface by applying a load of approximately 20 N. The average of 5 measurements was taken as the actual value of the hardness. The instrument we used in this case gave us the possibility that through hardness measurements we could directly determine the corresponding values of the tensile strength.

## 3 RESULTS AND DISCUSSION

The microstructure on the outer side of the bends is a highly tempered martensite. A martensitic appearance in all the investigated locations is noticeable. We observed a few regions with numerous cavities or micro-voids without preferred orientation, which arose due to the creep deformation. The microstructural features are the same in all the observed locations (**Figures 2 and 3**).

The microstructure of the tempered martensite in the base material is the same as in the pipeline bends. The microstructure of the welds is also a tempered martensite; however, it was observed that the size of the former austenite grains was larger compared to those of the base material. Because of welding effects, the tempered martensite microstructure in the transition region between the weld and the heat-affected zone is strongly blurred. In the heat-affected zone and in the weld material, which are loaded with internal steam pressure, stresses due to the welding and with additional static and dynamic loads during the operation (temperature fluctuations, bending moments, vibrations, etc.), we also observed a few micro-voids. The microstructural features of the welded joints are shown in **Figures 4, 5 and 6**.

The microstructural characteristics in the base material and in the welded joints of the T-fitting are the same as in the pipelines (**Figures 7, 8 and 9**). The base material has an appropriate microstructure of tempered martensite. In the microstructure of tempered martensite of the weld and the heat-affected zone there are a few regions with micro-voids, which as in the case of bends, have no preferred orientation.

The average hardness values measured using a portable instrument on the base material and on welded

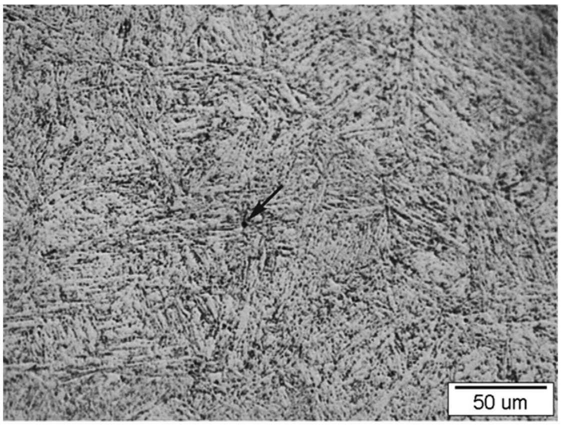

**Figure 3:** Microstructure of steel in the bend 5
**Slika 3:** Mikrostruktura jekla na kolenu 5

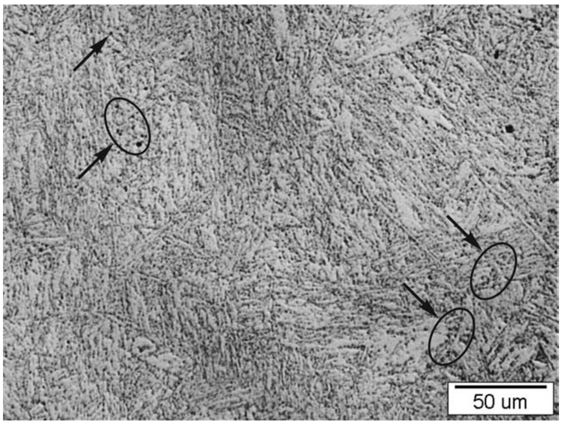

**Figure 2:** Microstructure of steel in the bend 1
**Slika 2:** Mikrostruktura jekla na kolenu 1

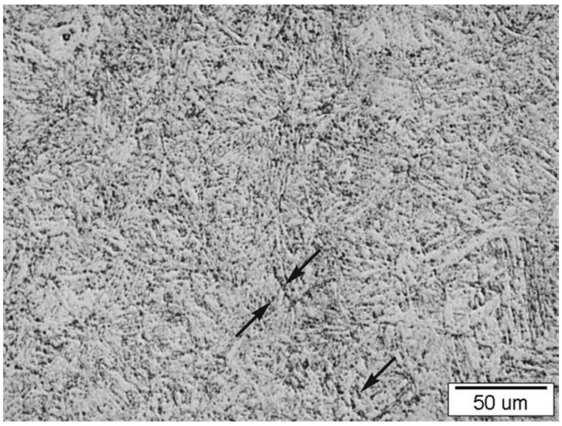

**Figure 4:** Microstructure of the base material in the welded joint of the bend 1
**Slika 4:** Mikrostruktura osnovnega materiala ob zvaru na kolenu 1

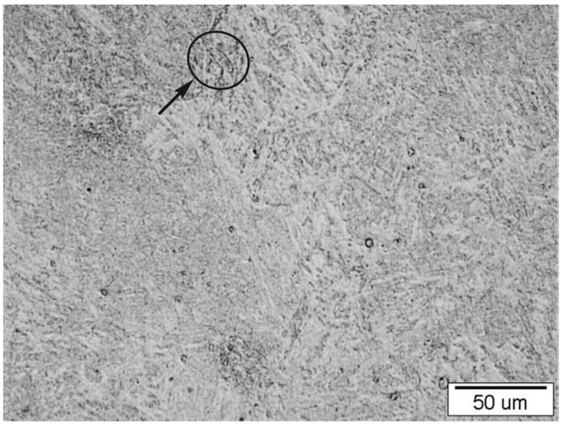

**Figure 5:** Microstructure of the weld in the welded joint of bend 1
**Slika 5:** Mikrostruktura vara ob zvaru na kolenu 1

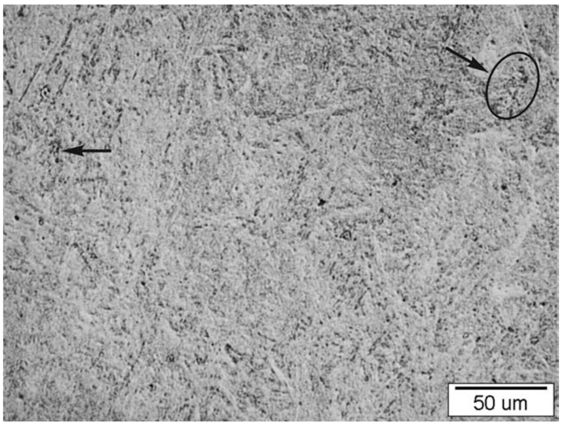

**Figure 6:** Microstructureof the HAZ in the welded joint of bend 1
**Slika 6:** Mikrostruktura TVP ob zvaru na kolenu 1

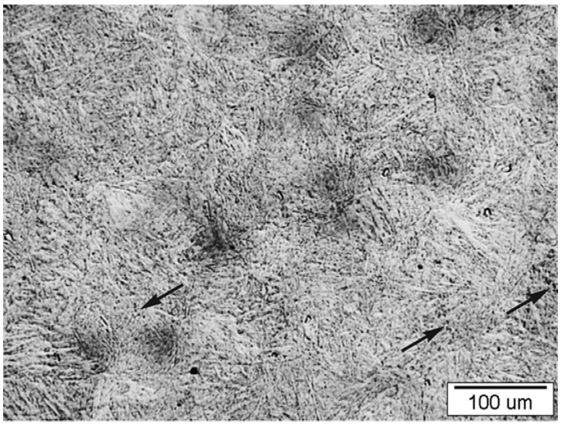

**Figure 7:** Microstructureofthe base material in the welded joint of the T-fitting
**Slika 7:** Mikrostruktura osnovnega materiala ob zvaru na T-kosu

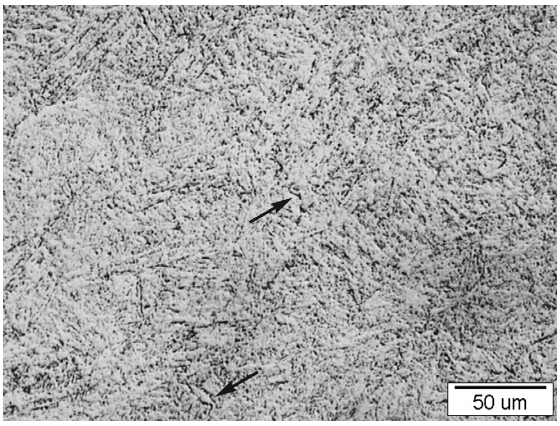

**Figure 8:** Microstructure of the weld in the welded joint of the T-fitting
**Slika 8:** Mikrostruktura vara ob zvaru na T-kosu

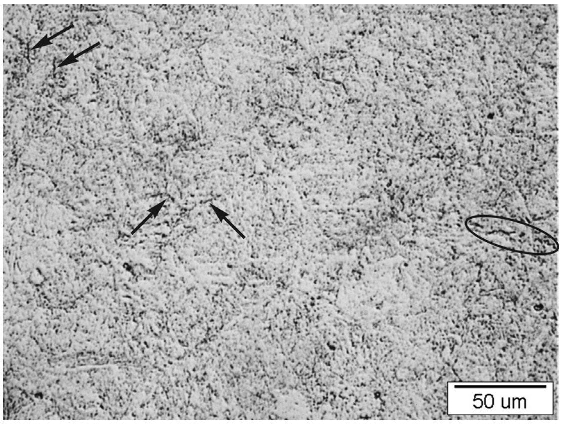

**Figure 9:** Microstructureofthe HAZ in theweldedjointofthe T-fitting
**Slika 9:** Mikrostruktura TVP ob zvaru na T-kosu

**Table 1:** Average values of HV hardness for base material and welds, as well as the lowest and the highest values measured on the heat-affected zone
**Tabela 1:** Povprečne vrednosti trdote HV osnovnega materiala in varov ter najnižje in najvišje vrednosti, izmerjene v toplotno vplivanem področju

| Elbow | Base material | Weld | Heat-affected zone |
|---|---|---|---|
| 1 | 236 ± 7.9 | 264 ± 4.6 | 248–280 |
| 2 | 236 ± 3.9 | 275 ± 6.0 | 269–279 |
| 3 | 231 ± 5.7 | 281 ± 4.9 | 253–289 |
| 4 | 241 ± 8.5 | 287 ± 6.8 | 264–284 |
| 5 | 240 ± 7.3 | 269 – 279 | 257–286 |
| T-fitting (A) | 245 ± 9.4 | 248 ± 8.9 | 241–264 |
| T-fitting (B) | 239 ± 4.6 | 267 ± 6.2 | 263–278 |

joints are given in **Table 1**. The hardnesses of the base material, the heat-affected zone and the welds are appropriate. The lowest hardness of the material, namely 231 HV, corresponds to atensile strength of 741 N/mm$^2$, whereas the highest value, 245 HV, corresponds to atensile strength of 785 N/mm$^2$. These values, compared to the values of the tensile strength of the steel X20CrMoV121 determined by the standard DIN 17 175 (690–840 N/mm$^2$), are within the given limits.

For both bends and T-fittings, having minor non-localized micro-void damages, according to the VGB[1] classification, the steel corresponds to the 2b class. In addition, considering the residual life of these elements under given service conditions and their current state (microstructure and hardness/tensile strength) they can continue to operate for an additional 45 000 h. It is recommended that a lifetime assessment should be taken after 25 000 h service exposure for safety reasons.

## 4 CONCLUSIONS

Microstructural investigations using non-destructive evaluation (NDE) methods, i.e., the replication technique and hardness measurements with a portable instrument, were carried out. These investigations were performed on the outer part of five bends, on welded joints between the bends and the straight parts of pipelines, and also on the base material and the welded joints of T-fittings.

The microstructure of the base material, the welds and the heat affected-zone is tempered martensite. The martensitic appearance is noticeable. Numerous micro-voids or cavities with no preferred orientation, which arise due to the creep deformation along the former austenite grain boundaries and along the martensite lamellas on the inspected sites were observed. For both bends and T-fittings, having minor, non-localized, micro-void damage, according to the VGB[1] classification, the steel corresponds to the 2b class.

The hardness of the bulk material, welds and the heat-affected zone is appropriate. The lowest hardness of the material, i.e., 231 HV, corresponds to the tensile strength of 741 N/mm$^2$, whereas the highest value, 245 HV, corresponds to the tensile strength of 785 N/mm$^2$. These values, compared to the values of the tensile strength of the steel X20CrMoV121, determined by the standard DIN 17 175 (690–840 N/mm$^2$), are within acceptable limits. The mechanical properties of the initial state of the steel are unknown, and thus we cannot define the reduction of the mechanical properties based on 150 000 h of operation of the pipeline.

Considering the residual life of these elements under given service conditions and their current state (microstructure and hardness/tensile strength) it was concluded that these elements are in a good condition and can continue to operate for an additional 45 000 h. It is recommended that a lifetime assessment, including more detailed investigations, should be performed after 25 000 h of service exposure for safety reasons.

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