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# BEHAVIOUR OF HIGH-ALLOY STEEL WELDED JOINTS OF STEAM PIPELINES UNDER THE INFLUENCE OF TEMPERATURE AND EXPLOITATION TIME

**Summary**

The aim of this paper was to determine, as comprehensively as possible, the influence of temperature on the behaviour of welded joints made of high-alloy steel and intended for operation at elevated temperatures in thermal power plants, i.e. steam pipelines, during their exploitation. The influence of exploitation conditions (temperature and exploitation time) on the mechanical exploitation and structural properties of the base metal and welded joint made of high-alloy steel X20 CrMoV 12-1 was analysed by testing samples of the new material and samples of the material that was in operation. Testing of the new and the used material, i.e., base metal and welded joint components (weld metal and heat affected zones), included determination of tensile properties at room temperature of 20 ºC and at elevated temperatures of 545 ºC and 570 ºC.

*Key words:* *welded joint, tensile properties, temperature, exploitation time, experiment*

## 1. Introduction

The development of steels intended for the production of steam pipelines in thermal power plants is subject to the ever-present demand for increased power of thermoblocks as well as general requirements for operational reliability and safety. The requirement for the steam pipeline wall to be as thin as possible for the required pressure can only be met when steel with adequate properties is used. Steel X20 CrMoV 12-1, belonging to the group of steels intended for operation at elevated temperatures and high pressures which are at the same time corrosion resistant, exhibits high strength and toughness at elevated temperatures and is primarily used for steam pipelines in thermal power plants [1][2].

For steam pipelines and thermoblocks to be reliable and safe, it is especially important to determine properties of the material, parameters of production, and to collect data on operating conditions. Significant data on steam pipelines is obtained from the analysis of exploitation damage [3-5].

Steels used for the construction of steam pipelines for thermal power plants belong to the group of steels used for operation at elevated temperatures and to the group of fire resistant steels, which retain the required properties up to the temperature of 600 °C. The first and most important property of high-alloy steels with a high Cr content is their corrosion resistance. A Cr content of about 12% also significantly increases oxidation resistance. In addition to good mechanical properties at elevated temperatures, good weldability is a very important property of this group of steels. Compared to other fire resistant steels, X20 CrMoV 12-1 steel enables the production of thinner wall components and more flexible systems. Hence the additional advantage of the observed steel, which is reflected in the high starting speed of the plant, and thus increased productivity [6-8].

In essence, weldability almost equally depends on the material, the conditions of the production of welded components and the construction solutions, i.e. it indirectly depends on the suitability of the welding material, the possibility of welding, and the reliability of the welded structure. During the construction of a welded structure, errors in welded joints often occur. The quality of welded joints largely determines the operational safety and cost-effectiveness of the structure. The presence of defects in welded joints, failure to meet the required properties, shape and homogeneity of the seam, or properties and homogeneity of the material in the heat affected zone (HAZ) can all change the strength and other performance properties of the structure [9][10].

In order to determine the behaviour of welded joints of high-alloy steels during exploitation, some researchers performed microstructural tests on welded joints of pipes of different diameters and wall thicknesses, which were in exploitation under operating and maximum pressures, operating and maximum temperatures, different operating times and different loads. Microscopic examinations have shown that the base metal still has a pronounced martensitic structure after exploitation, while in the weld metal the martensitic structure is found only in the middle and upper part, and in the HAZ, only in the area of the weld side [10-12].

Tensile properties of the base metal and the welded joint of high-alloy steel X20 CrMoV 12-1 at room and elevated temperatures, found in several literature sources [13-17], showed that the yield stress ($R_{p0,2}$) lies above the minimum values according to DIN 17175 in the entire observed interval, while tensile strength ($R_m$) remains in the allowable range of scattering. Relative elongation ($A$) also shows satisfactory values, and the scattering of individual results is slightly higher in relation to the strength properties.

The appearance of cracks in welded joints of shaped pieces is a typical type of damage, which is evidenced by a large number of reported data [10][12][15]. The data obtained by studying cracks and damage show that the cracks are a result of loads and stresses higher than the predicted ones, as well as adverse changes in the structure and material properties in the area of the welded joint at such loads. Cracks in steam pipelines most often occur at the transition from the pipe to the T-piece or from the T-piece to the pipe, but also at the pipe extension.

Fig. 1 shows the position of the most commonly observed cracks:

- cracks in the weld metal (WM), which may be transverse or longitudinal, developed only in the weld metal (type 1) or extended into the HAZ (type 2), and
- cracks in the HAZ, parallel to the seam, mostly in the fine-grained area, but in some cases also in the coarse-grained area (types 3 and 4)

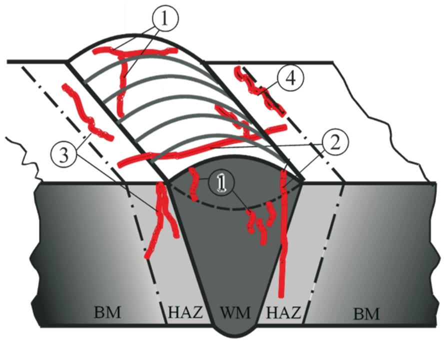


**Fig. 1** Typical cracks in a welded joint

As transverse cracks occur at sharp transitions from shaped pieces to pipe extensions, it can be concluded that this type of cracks is conditioned by the design solution, due to the stress concentration, rather than the material and its behaviour in operation. It should be noted that all these cracks are most often found on outer surfaces of the steam pipeline, which sometimes facilitates repair [10][12][15].

The analysis of the behaviour of steel steam pipelines during exploitation requires knowledge of both the properties of steel and of the welding method. These two groups of data make it possible to assess the properties of the welded joints, which, along with the operating conditions, is the basis for understanding the causes and development of damages and cracks, and thus for taking measures to eliminate them [18-20].

The investigation presented in this paper included tensile properties tests using base metal and welded joint test tubes obtained from a sample of a new and a used X20 CrMoV 12-1 steel pipe. The tests were performed at room temperature of 20 °C, operating temperature of 545 °C and maximum operating temperature of 570 °C. The investigation aimed to show the behaviour of the welded joint under the influence of temperature and exploitation time. In other words, the objective was to determine whether the obtained tensile test results can contribute to the assessment of the quality of the welded joint, and whether the results can serve as input data for revitalization and extension of the service life of vital components of thermal power plants.

## 2. Materials and methods

In the analysis of the influence of temperature and exploitation time on the mechanical, structural and operational properties of the base metal (BM) and the welded joint (WJ) of high-alloy steel X20 CrMoV 12-1, used for the manufacture of vital components of thermal power plants, two available samples were used :

- a sample of a new pipe (Sample - N) with dimensions of ∅450x50 mm and length of 400 mm, ($R_{p0,2}$ = 500 MPa and $R_m$ = 700-850 MPa),
- a sample of a welded pipe with a weld seam in the middle (Sample - S) with dimensions of ∅450x50 mm and length of 500 mm. The S sample was taken from the fresh steam pipeline of the thermal power plant and was in operation for over 116,000 hours.

The chemical composition of the pipe samples was tested on a JOEL quantometer on specially prepared plates with dimensions of 40x40x10 mm, the results of which are given in Table 1.

**Table 1** Chemical composition of tested pipe samples

| Batch | % mass | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *C* | *Si* | *Mn* | *P* | *S* | *Cr* | *Mo* | *Ni* | *V* |
| Sample - N | 0,21 | 0,27 | 0,563 | 0,017 | 0,006 | 11,70 | 1,019 | 0,601 | 0,310 |
| Sample - S | 0,22 | 0,31 | 0,539 | 0.019 | 0,005 | 11,36 | 1,033 | 0,551 | 0,314 |

Welding of the new pipe sample (Sample - N) was performed by manual arc welding (MAW) with coated electrodes, with the root passage and the next two to three subsequent passages performed by welding with an insoluble electrode shielded by argon (TIG).

Tensile tests of the base metal at room temperature as well as the geometry of the test tubes are defined by EN ISO 6892-1 [21] and ASTM E8/E8M-21 [22], which determine the yield stress, tensile strength, percentage elongation, contraction and stress-strain diagram. The test procedure for butt-welded joints at room temperature, including the shape and dimensions of the test tubes as well as the test procedure itself, are defined by standard EN 895 [23], which determines transverse tension, i.e., the introduction of load transverse to the welded joint. The form of the test tubes for the base metal and welded joint tension testing at room temperature of 20 ºC is given in Fig. 2.

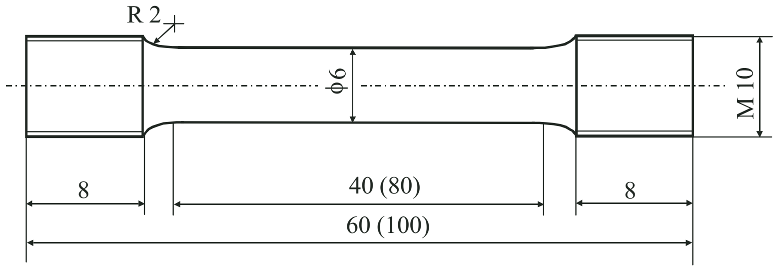


**Fig. 2** Test tube for determining tensile properties at room temperature [21]

Unlike the room temperature testing, the testing procedure at elevated temperatures of 545 °C and 570 °C, including the geometry of the test tubes and the heating of the test tubes to a specific temperature, are defined by EN ISO 6892-2 [24]. An outline and form of the test tubes at elevated temperatures are given in Fig. 3.

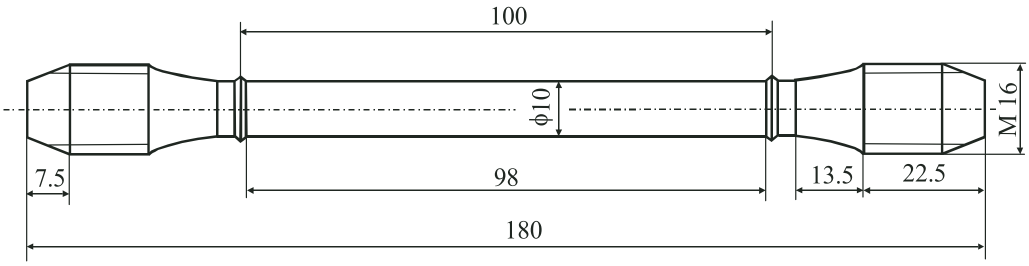


**Fig. 3** Test tube for determining tensile properties at elevated temperature [24]

The tensile tests of the tubes obtained from a sample of new pipes and used pipes at room temperature were performed on an electromechanical ripper SCHENCK-TREBEL RM 100 as part of deformation monitoring. The speed of loading was 5 mm/min. Elongation was registered using a double extensometer HOTTINGER DD1 and an inductive encoder GS1. The accuracy of the extensometer measurement was ±0.001 mm.

The testing of the base metal and the welded joint tubes obtained from the sample of new and used pipes at elevated temperature was performed on an electromechanical ripper SCHENCK-TREBEL RM 400 as part of deformation monitoring. The speed of loading was 5 mm/min. Elongation was registered using an inductive encoder GS1. The accuracy of the extensometer measurement was ±0.01 mm. Operating temperature of 545 °C and maximum operating temperature of 570 °C were achieved in the electric chamber furnace. The temperature was measured in three places along the test tube, due to its relatively large length (100 mm). The aim was to ensure, by precise control and timely correction, approximately the same temperature along the test tube, as defined by EN ISO 6892-2 with a tolerance of ±3 °C.

## 3. Results and analysis of tensile properties

### 3.1 Welded joint test results

The results of the transverse tensile tests performed on the butt-welded joint test tubes taken from a sample of new and used pipes made of the X20 CrMoV 12-1 steel and tested at room temperature of 20 °C, operating temperature of 545 °C, and maximum operating temperature 570 °C are shown in Table 2.

**Table 2** Results of tensile tests of welded joint test tubes

| Sample | Testing temperature $T$ / °C | Yield strength $R_{p0,2}$ / MPa | Tensile strength $R_m$ / MPa | Elongation* $A$ / % | Fracture point |
|---|---|---|---|---|---|
| New pipe | | | | | |
| WJ - 1 - 1N | | 516 | 722 | 11.1 | BM |
| WJ - 1 - 2N | 20 | 518 | 725 | 11.6 | BM |
| WJ - 1 - 3N | | 510 | 720 | 11.3 | BM |
| WJ - 2 - 1N | | 221 | 296 | 14.1 | BM |
| WJ - 2 - 2N | 545 | 217 | 294 | 14.6 | BM |
| WJ - 2 - 3N | | 224 | 302 | 13.9 | BM |
| WJ - 3 - 1N | | 190 | 246 | 15.0 | BM |
| WJ - 3 - 2N | 570 | 185 | 241 | 15.5 | BM |
| WJ - 3 - 3N | | 193 | 250 | 14.7 | BM |
| Used pipe | | | | | |
| WJ - 1 - 1S | | 477 | 696 | 12.7 | BM |
| WJ - 1 - 2S | 20 | 472 | 691 | 12.4 | BM |
| WJ - 1 - 3S | | 465 | 688 | 13.1 | BM |
| WJ - 2 - 1S | | 216 | 274 | 14.6 | BM |
| WJ - 2 - 2S | 545 | 210 | 268 | 14.2 | BM |
| WJ - 2 - 3S | | 212 | 269 | 14.5 | BM |
| WJ - 3 - 1S | | 167 | 208 | 14.8 | BM |
| WJ - 3 - 2S | 570 | 163 | 201 | 15.3 | BM |
| WJ - 3 - 3S | | 172 | 212 | 15.2 | BM |

* measured at $L_0$ = 80 mm as comparative quality (not as material property)

A typical stress-elongation curve for the test tube WJ-3-1N, sampled from the welded joint of the new pipe tested at 570 °C, is shown in the diagram in Fig. 4, while a curve for the test tube WJ-3-1S, sampled from the welded joint of the used pipe, is shown in the diagram in Fig. 5. Other diagrams are not shown because they illustrate an almost identical character of the material behaviour.

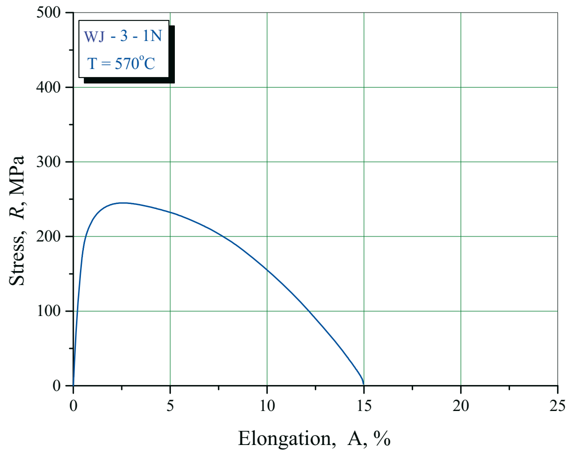


**Fig. 4** Diagram stress - elongation of test tube WJ-3-1N

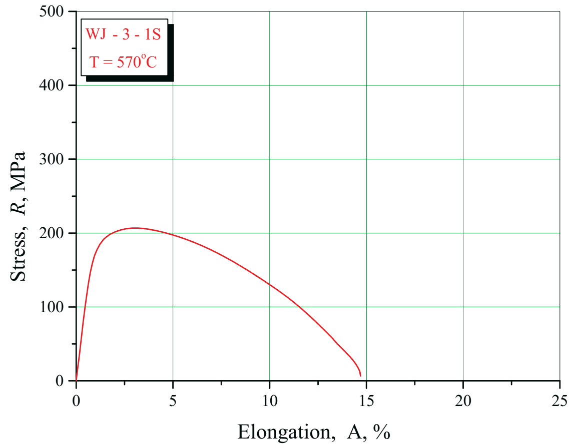


**Fig. 5** Diagram stress - elongation of test tube WJ-3-1S

The influence of the test temperature on the values of yield stress and tensile strength of the welded joint (WJ) of the X20 CrMoV 12-1 steel is shown graphically in Fig. 6 for the test tubes sampled from the new pipe and for the test tubes sampled from the used pipe are shown in Fig. 7.

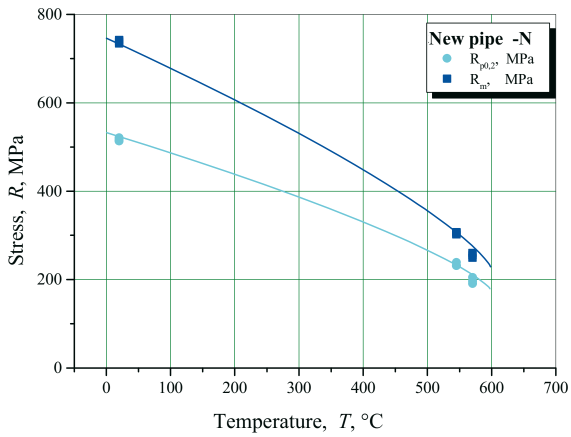


**Fig. 6** Change of $R_{p0,2}$ and $R_m$ depending on test temperature in WJ of new pipe

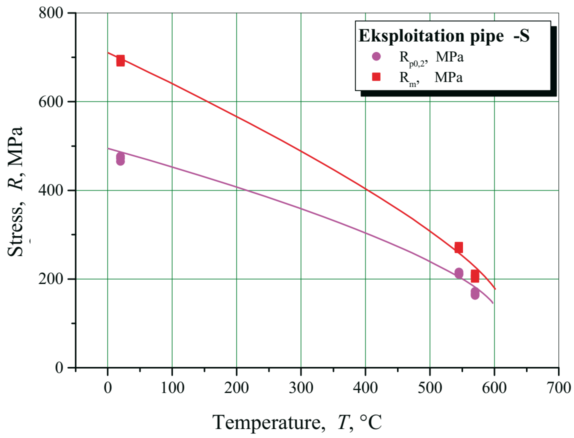


**Fig. 7** Change of $R_{p0,2}$ and $R_m$ depending on test temperature in WJ of used pipe

The change in elongation, depending on the test temperature in the test tubes removed from the WJ of the new pipe and the used pipe made of steel X20 CrMoV 12-1is shown in Fig. 8.

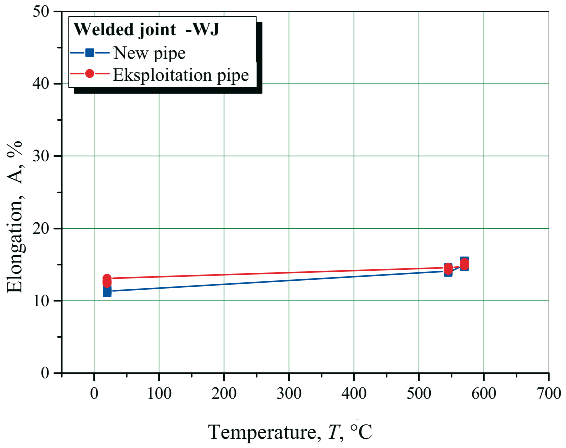


**Fig. 8** Elongation change depending on test temperature in WJ of new pipes and used pipes

The analysis of the results of the transverse tensile testing of the welded joint test tubes shown in Figs. 6, 7 and 8 indicate that with an increased test temperature there is a decrease in the value of yield stress and tensile strength, but an increase in elongation.

### 3.2 Base metal test results

The results of the tensile testing of the base metal (BM) test tubes obtained from a sample of a new pipe and a used pipe made of X20 CrMoV 12-1 steel and tested at room temperature of 20 °C, operating temperature of 545 °C and maximum operating temperature of 570 °C are given in Table 3.

**Table 3** Results of tensile tests of base metal test tubes

| Sample | Testing temperature $T$ / °C | Yield stress $R_{p0,2}$ / MPa | Tensile strength $R_m$ / Mpa | Elongation $A$ / % |
|---|---|---|---|---|
| New pipe | | | | |
| BM - 1 - 1N | | 521 | 742 | 17.3 |
| BM - 1 - 2N | 20 | 516 | 738 | 17.9 |
| BM - 1 - 3N | | 513 | 734 | 18.2 |
| BM - 2 - 1N | | 239 | 307 | 18.6 |
| BM - 2 - 2N | 545 | 231 | 302 | 19.2 |
| BM - 2 - 3N | | 232 | 306 | 18.1 |
| BM - 3 - 1N | | 191 | 249 | 22.3 |
| BM - 3 - 2N | 570 | 205 | 260 | 21.2 |
| BM - 3 - 3N | | 196 | 255 | 22.7 |
| Used pipe | | | | |
| BM - 1 - 1S | | 467 | 702 | 16.6 |
| BM - 1 - 2S | 20 | 471 | 709 | 16.4 |
| BM - 1 - 3S | | 468 | 707 | 17.1 |
| BM - 2 - 1S | | 224 | 281 | 18.4 |
| BM - 2 - 2S | 545 | 217 | 269 | 18.9 |
| BM - 2 - 3S | | 220 | 275 | 18.1 |
| BM - 3 - 1S | | 179 | 215 | 21.5 |
| BM - 3 - 2S | 570 | 188 | 231 | 21.7 |
| BM - 3 - 3S | | 185 | 228 | 20.9 |

A typical stress-elongation curve for the test tube BM-3-1N, sampled from the base metal of the new pipe and tested at 570 °C, is shown in the diagram in Fig. 9, while a curve for the test tube BM-3-1S, sampled from the base metal of the used pipe, is shown in the diagram in Fig. 10. Other diagrams are not shown because they illustrate an almost identical character of the material behaviour.

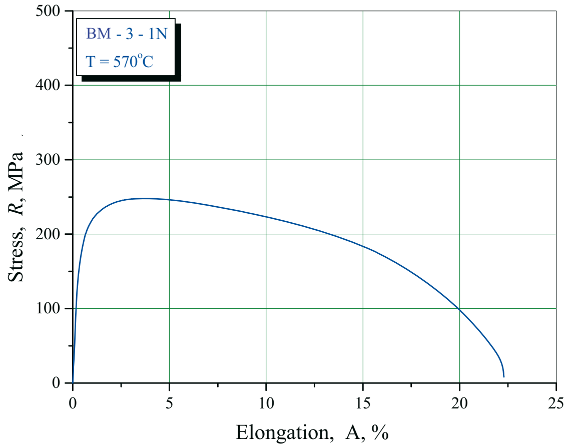


**Fig. 9** Stress-elongation diagram of test tube BM-3-1N

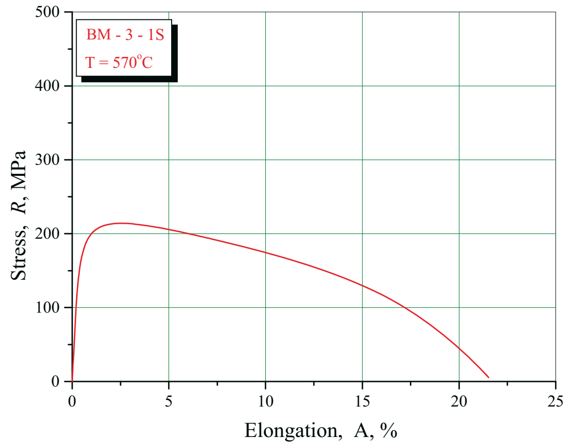


**Fig. 10** Stress-elongation diagram of test tube BM-3-1S

The influence of the test temperature on the values of yield stress and tensile strength is shown graphically for the BM test tubes of the new pipe in Fig. 11 and for the used pipes it is shown in Fig. 12.

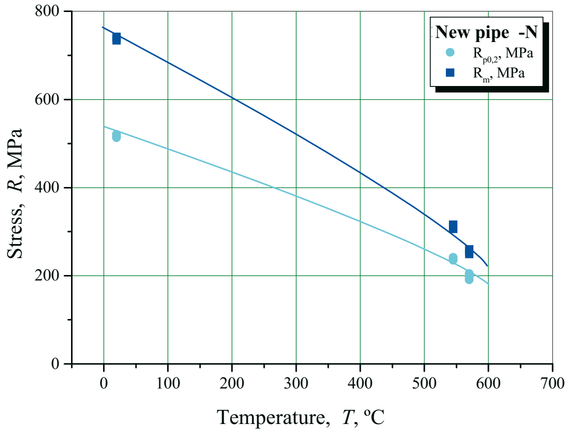


**Fig. 11** Change of $R_{p0,2}$ and $R_m$ depending on test temperature in BM of new pipe

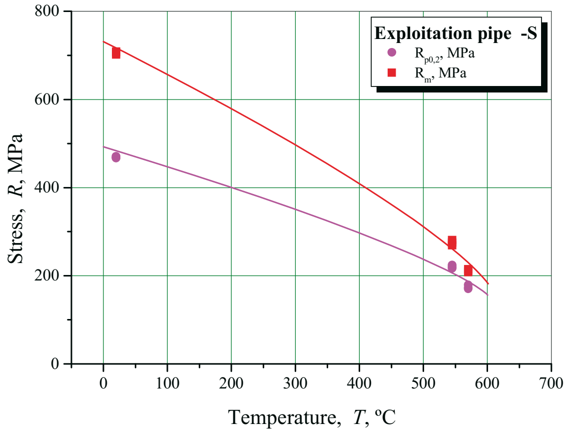


**Fig. 12** Change of $R_{p0,2}$ and $R_m$ depending on the test temperature in BM of used pipe

The change of elongation depending on the test temperature for the BM test tubes of the new pipe and the used pipe is shown in Fig. 13.

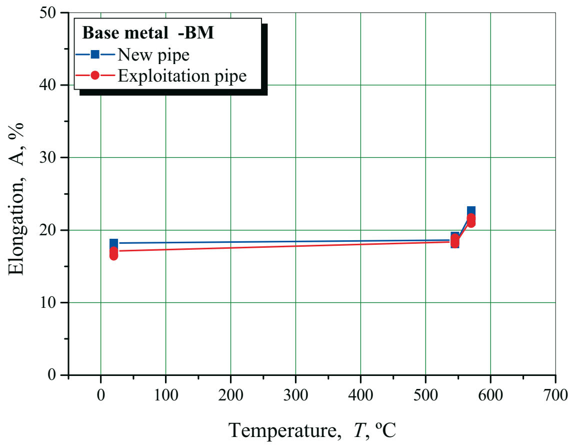


**Fig. 13** Change of elongation depending on test temperature of BM for new and used pipe

The analysis of the obtained results for the tensile strength of BM test tubes, shown in diagrams in Figs. 11, 12 and 13, indicates that with an increased test temperature there is a decrease in yield stress and tensile strength, and an increase in elongation.

## 4. Discussion

The influence of temperature and exploitation time on the tensile properties of high-alloy steel X20 CrMoV 12-1, used for the manufacture of vital components of thermal power plants, i.e. steam pipelines, was analysed by testing test tubes extracted from samples of the welded joint and base metal of a new and a usedpipe. The aim of the testing was primarily the following:

- determination of strength properties (yield stress and tensile strength) of the welded joint as a whole (maximum breaking force) by applying a load transverse to the welded joint,
- determination of tensile properties (yield stress, tensile strength, elongation) of the base metal.

By testing a WJ test tube from a sample of a new and a used pipe by applying a load transverse to the welded joint, the results were obtained, as shown in Table 2, which indicate that even with a sample of the welded joint of a new pipe and a used pipe, the chosen welding technology does not have a significant influence on the welded joint strength, nor its components. The welded joint, designed according to the principle of higher strength of the weld seam, should crack in the base metal during the tensile test, which occurred in fact in the subject tests. All tested tubes, regardless of whether it was a welded joint of a new pipe or of a used pipe, cracked in the base metal, listed in Table 2, which clearly indicates the character of the welded joint.

The results of transverse tension of the welded joint test tubes in both new and used pipes indicate that with an increased test temperature there is a decrease in yield stress and tensile strength, and an increase in elongation, as seen in Table 2 and diagrams in Figs. 6, 7 and 8. An interesting fact and characteristic of these tests are the relatively low elongation values, i.e. low plasticity of the base metal in the zone around the welded joint. The drop in elongation is most likely due to the deformation of three different materials.

The analysis of the obtained results of the base metal tensile testing at room temperature of the test tubes extracted from a sample of the new and the used X20 CrMoV 12-1 steel pipe shown in Table 3, indicates that the test results of the new material are within the standard values for this material, i.e. within the values given by the manufacturer in the attestation documentation ($R_{p0,2}$ = 500 MPa and $R_m$ = 700-850 MPa). This statement does not apply to the test tubes taken from the used material. Namely, the obtained values of yield stress for the used material do not meet the values prescribed by the standard, while the values of tensile strength are at the limit of satisfactory values.

The influence of test temperature on the values of yield stress and tensile strength of the new and the used material is shown in the diagrams in Fig. 11 for the new material and in Fig. 12 for the used material. A decrease in strength properties with an increased test temperature can be clearly observed. There is a greater influence of the increase in the test temperature on the decrease in the value of tensile strength compared to the yield stress, which is clearly seen in the slope of the decreasing curves. It is evident that the service life of over 116,000 hours affects the tensile strength values more than the yield stress values. Comparing the tensile strength values of the new and the used base metal, as well as the yield stress values, we can see an interesting phenomenon. The curves of the tensile strength and yield stress values are almost parallel up to 570 °C. Therefore, as the temperature increases, the difference in strength properties between the base metal of the new and the used pipe remains constant.

## 5. Conclusion

The test results obtained in this investigation represent a practical contribution to the assessment of the quality of welded joints of new and used material. The ultimate goal of the paper is to consider the possibility of revitalization and extension of life of vital components of thermal power plants made of high alloy steel X20 CrMoV 12-1, intended for work at elevated temperatures. Based on the performed experimental testing, the performed analyses and discussions, the following can be concluded:

- the results of transverse tensile testing of both the welded joint test tubes and the base metal test tubes extracted from new and used pipes indicate that the value of yield stress and tensile strength decrease as the test temperature increases, while the elongation increases,
- there is a greater influence of service life on tensile properties at room temperature of 20°C than at temperatures of 545 °C and 570 °C, i.e., the properties of the used material are slightly inferior to the properties of the new material, but the difference decreases as the test temperature increases, and
- increase in elongation with an increase in temperature is explained by increased plasticity of the material at higher temperatures, i.e., the new unused material has a higher increase in the elongation value and a higher plastic potential, compared to the tested used material, which indicates that the exploitation period of 116,000 hours did not significantly affect the decrease in deformation properties.

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