

EXPERIMENTAL DETERMINATION OF HIGH-CYCLIC FATIGUE PARAMETERS OF WELDED JOINT OF HIGH-ALLOY STEEL X20

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Abstract: Experimental research in this paper included the influence of exploitation time and temperature on the behavior of the welded joint of high-alloy steel X20 CrMoV 12 1 (X20) under conditions of variable load. The influence of exploitation conditions was analyzed by determining the permanent dynamic strength, construction of the Weller diagrams (S-N diagrams) of the base material and components of the welded joint.

1 INTRODUCTION

Certain components of process equipment in thermal power plants operating in conditions of elevated temperatures are critical places due to operating conditions, since they are in use longer than the projected service life. Eventual failure of these components would pose a danger not only to people and the operation of the plant but also to the environment that surrounds them [1].

The usual service life of process equipment in thermal power plants operating in elevated temperatures is up to 20 to 30 years, or 100,000 to 150,000 operating hours. Economic interests have influenced the extension of the projected period, because the service life of a large number of power plant components is usually longer than projected, which indicates conservatism in design. Due to that, the importance of extending the working life and revitalization of the components of thermal power plants has increased, as a way to keep older power plants in operation for 40-50 years, and even longer. Preliminary studies [2-4] show that the cost of revitalization of typical thermal power plants can be 20 to 30% of the cost of building a new thermal power plant.

Monitoring and control of the properties of construction materials of high-temperature loaded parts, exposed to high pressure in corrosively active environments, is a basic indicator of the reliability of their work. The most important and extensive control whose purpose is to determine the state of the metal in the second half of the remaining service life is performed after 60% of the service life of components, because the probability of cracks that can grow to fracture increases rapidly after that limit. Therefore, it is important to estimate the residual life of the component and the remaining service life of the plant [1].

One of the most commonly used steels for operation at elevated temperatures and high pressures, and also resistant to corrosion is steel marked X20 CrMoV 12-1 (X20), primarily intended for steam and piping in thermal power plants due to good strength and toughness, at elevated temperatures.

The influence of operating conditions (operating time and temperature) on the characteristics of high-cyclic fatigue of the base material (BM) and the welded joint of high-alloy steel X20 was analyzed by testing a new pipe and a pipe that was in operation for 116000 hours. Tests of the new and exploited X20 steel pipe included the determination of the permanent dynamic strength and the construction of the Weller diagrams (S-N diagrams), at room (20°C), operating (545°C) and maximum (570°C) operating temperatures.

The obtained test results and their analysis should give a practical contribution to the assessment of the quality of BM and welded joints of steel X20, all with the aim of revitalizing and extending the service life of vital thermal power plants made of high alloy steels for elevated temperatures [5].

2 MATERIAL

For analysis of the effect of exploitation temperature and time on properties of high-cycle fatigue in a welded joint of high alloy steel X20, we had a sample of new welded pipe that had not been in exploitation (*Sample N*) dimensions of which were φ450 x 50 mm and approx. 400 mm long, and a sample of a welded pipe (*Sample E*) dimensions of which were φ450 x 50 mm and approx. 500 mm long sampled from the steam line for fresh steam at a thermal power plant that had been in exploitation approx. 116,000 hours.

Table 1. Chemical composition of tested pipe samples [5]

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 E	0,22	0,31	0,539	0,019	0,005	11,36	1,033	0,551	0,314

Chemical composition of the samples of new and exploited pipe has been presented in Tab. 1. Mechanical properties of the welded joints of new and exploited pipe at room and operating temperatures have been presented in Tab. 2.

Table 2. Results of tensile tests of welded-joint specimens [5]

Sample design.	Testing temperature / °C	Yield stress R _{p0,2} / MPa	Tensile strength R _{ms} / MPa	Elongation* A / %	Fracture location
New pipe					
WJ - 1N	20	518	725	11,6	BM
WJ - 2N	545	217	294	14,6	BM
WJ - 3N	570	185	241	15,5	BM
Exploited pipe					
WJ - 1E	20	472	691	12,4	BM
WJ - 2E	545	210	268	14,2	BM
WJ - 3E	570	163	201	15,3	BM

*WJ – Welded Joint

Manual electric arc welding (MEA) procedure using plated electrodes is a fundamental procedure of welding for assembling of steel X20, but in most cases, it is necessary to make the root pass and next two to three passes by applying the procedure of welding with non-consumable electrode, i.e. argon-shielded electric arc welding (ASEAW). According to DIN 8575 for steel X20, the wire designated as CM2-1G (old designation SG CrMoWV 1-2) of $\phi 3.2$ -mm dia. and electrode designated as FOX20MVW (old designation EKb CrMoWV 12-26 of $\phi 4$ -mm dia. are recommended. Flow of argon as a shielding gas for ASEAW was 10 l/min, and its purity 99.99%.

3 STEEL WELDING TECHNOLOGY X20

The shape of the groove for welding preparation was chosen in relation to the diameter and wall thickness of the pipe in accordance with the appropriate standards. In Fig. 1. the scheme of groove preparation is given, as well as the sequence of welding according to the MANNESMANN procedure [6].

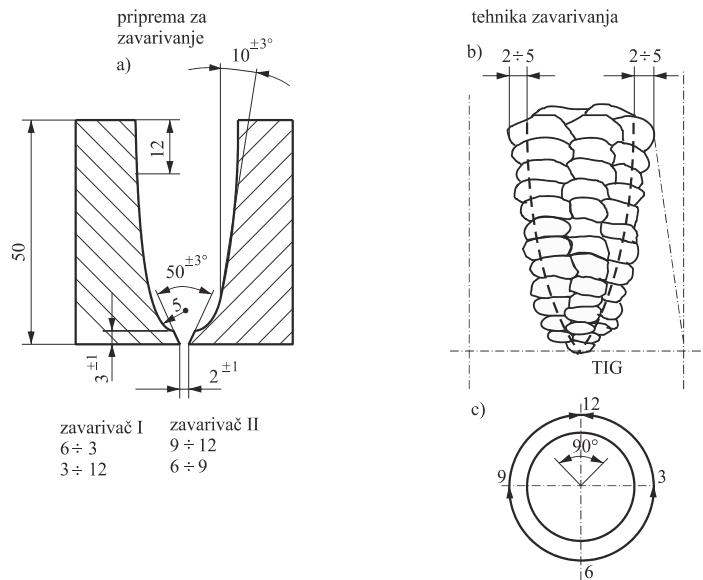


Figure 1. The groove preparation and welding sequence [6]

Prior to welding, the pipes were brought to the coaxial position, taking into account the gap in the root, which should be 1 to 2.5 mm, depending on the dimensions of the additional material, and which in this case was 2 mm. The number of connections must be such as to ensure the correct position of the pipe. As it is a pipe with an outer diameter above 150 mm and a wall thickness above 10 mm, the connection is done with 3 to 4 bridges, which are sanded after the root passage. It is extremely important that no additional stresses are introduced into the welded joint during the connection, which is why the support of the pipe ends is envisaged [1,6].

The preheating temperature of X20 steel for TIG welding (root pass and first few passes, usually up to four) is 225 to 250°C. The width of the preheated zone should be equal to three times the pipe wall thickness, but should not be less than 100mm. The preheating temperature must be maintained throughout the welding process. The heating rate until the preheating temperature is reached should be moderate, and in this case up to 10°C/min. For pipes with an outside diameter above 108mm and a wall thickness greater than 16mm, electro-resistant or electro-induction heating is required, while smaller pipes can also be heated by a gas flame.

The root passage is usually performed by TIG procedure. In order to avoid the formation of tungsten carbide in the weld, it is recommended to use a TIG device with a high-frequency device, which ensures the establishment of an electric

arc between the tungsten electrode and the base material without contact. The shielding gas flow must be calm to prevent the arc from blowing, and it should last a few seconds after the welding is completed in order for the molten weld metal to cool in the shielding atmosphere. For steels with a Cr content above 1.25% (which also includes X20 steel), protection of the root passage from the inside is mandatory (Fig. 2).

Immediately after the completion of the application of the root passage and the next four passes, the filling of the groove E was approached by the procedure, with the recommended basic coated electrode, which is connected to the "+" pole of the current source. The current is selected from the catalog of the electrode manufacturer according to the type and diameter of the electrode. Special attention should be paid to the establishment and termination of arches. The arc should be established by touching the electrode and the base material in the groove. The beginning of the next layer should be at least 20 to 30mm overlapped on the finished previous layer. For welding pipes with a diameter above 219mm, the work of two welders is recommended (Fig. 1). Each weld must be stamped by the welder [1, 6].

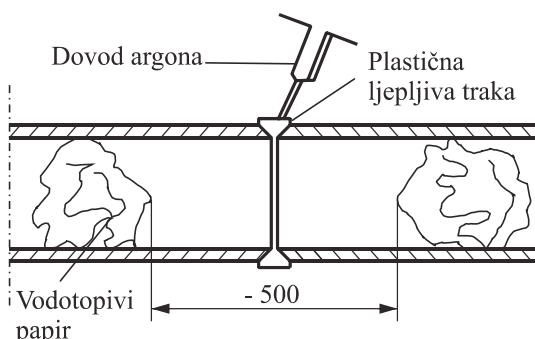


Figure 2. Protection during TIG welding of the root passage of X20 steel pipes [1]

Heat treatment to remove residual stresses was done under the expert supervision of welding technologists, immediately after welding. In principle, heat treatment for X20 steel is performed at 720-780°C, with a heating rate of up to 220°C/h and a cooling rate of up to 150°C/h. The retention time at the heat treatment temperature is 5 min/1 mm of wall thickness, and at least 2 hours. The width of the heat treatment zone is at least equal to three times the wall thickness of the pipe, but never below 100mm. Cooling is performed at the prescribed speed to a temperature of 300°C, and then the welded joint is cooled in still air. The welded joint of steel X20 must be kept for one hour at a temperature of 120-150°C after welding [1,6].

4 TEST RESULTS

4.1 Testing with variable load

Fatigue of metal is defined as a process of cumulative damaging affected by variable loading, resulting in fatigue-crack initiation and fracture. The fatigue strength of welded joints is determined by testing tubes or models at variable load until a crack or fracture occurs. In the case of steam pipelines, tests of high-cycle, low-cycle (low-cycle) fatigue and thermal fatigue are of particular importance.

The strength of the welded joint at variable loads, such as those occurring in non-stationary modes of operation of the steam line in the period of starting and stopping (Fig. 3) is an important characteristic of life. Due to the scope of the experiment, high-cycle fatigue is especially interesting, which has been the subject of experimental research.

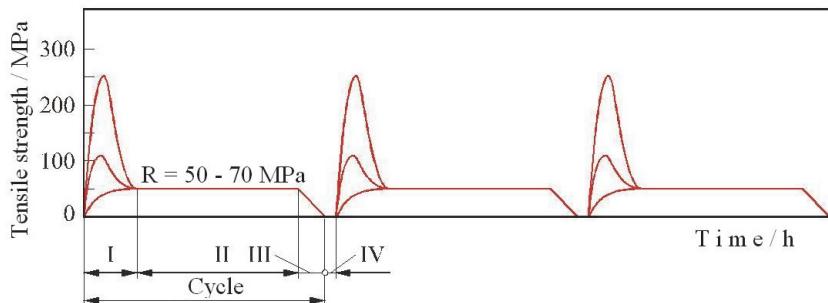


Figure 3. Typical diagrams of stresses of main steam lines at thermal power plants:
I – start-up; II – stationary regime; III stoppage; IV - pause

At the load level lower than the yield stress, characteristic of high-cyclic fatigue, the test is most often performed in the rigid regime, ie at a given voltage amplitude S_a , MPa. It is best for the load cycle to simulate the operating conditions of the structure, but simplified forms of the load cycle (usually alternating) are practically used.

It is clear that the strength at high cyclic fatigue depends on the properties of the constituents of the welded joint. Therefore, data are required for BM and WM, but also for HAZ, which makes testing of welded joints in high-cyclic fatigue complex and expensive. Given this, laboratory testing of realistic construction forms or models is also justified, but one of the important factors is the operating temperature. It should be borne in mind that the characteristics of high-cyclic fatigue change significantly only at temperatures above 450°C for steel for X20 steam lines and for their welded joints, and these tests are justified only for operating temperatures, which for X20 steel are 545°C to close to 600°C [7,8].

The influence of temperature and operating time on the behavior of the base metal and welded joint of steel X20 under conditions of variable load was done on test tubes taken from a sample of a new pipe and a pipe that was in operation for 116000 hours. These tests were performed in order to determine the points in the S-N diagram (construction of the Weller diagram) and to determine the permanent dynamic strength S_f . The test procedure as well as the specimen are defined according to the ASTM E466 standard [9]. The sketch and layout of the specimen with variable load is shown in Fig. 4.

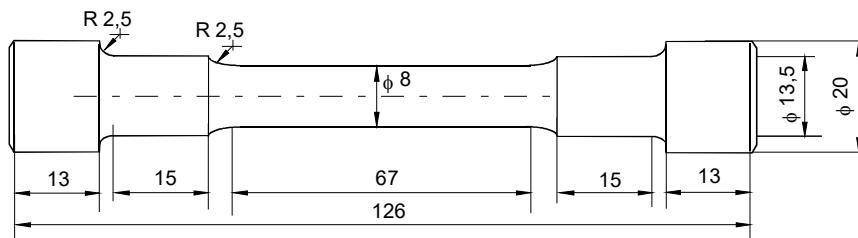


Figure 4. Specimen for dynamic tests [9]

In this test, as a rule, only the number of variations until fracture occurs should be determined under loading of constant range, and the standard requires only information on stress value at which fracture does not occur after certain number of cycles (usually between 10^6 and 10^8 cycles). For steel materials, standard ASTM E466 defines permanent dynamic strength, S_f , after 10^7 cycles. Therefore, this test is necessary when the data are required for design, mainly from the point of view of fatigue and fracture mechanics, i.e. when the parts exposed to long-lasting variable loading during whole projected life of the structure, should be designed.

4.2 Results and discussion

The results of determining the permanent dynamic strength, S_f , i.e. the maximum dynamic stress at which no crack initiation occurs in smooth structural shapes, are shown graphically in the form of Weller diagrams (S-N diagrams) in Fig. 5 for BM new pipes etc. 6 for BM pipes from operation. The behavior of the welded joint depending on the operating time and temperature is also shown graphically in the form of Weller diagrams for the welded joint of the new pipe in Fig. 7, and for the welded pipe joint from operation in Fig. 8.

Analyzing the Weller diagrams, obtained by testing the BM and the welded joint of the tubes of the new pipe and the pipe from operation, we see that the operating time and test temperature significantly affect the obtained values of permanent dynamic strength, Fig. 10. As the test temperature increases, the value of permanent dynamic strength, S_f . The operating period of 116,000 hours led to a decrease in the value of permanent dynamic strength in BM tubes by about 25%, which can be a very important figure if the operating conditions of the steam line are known.

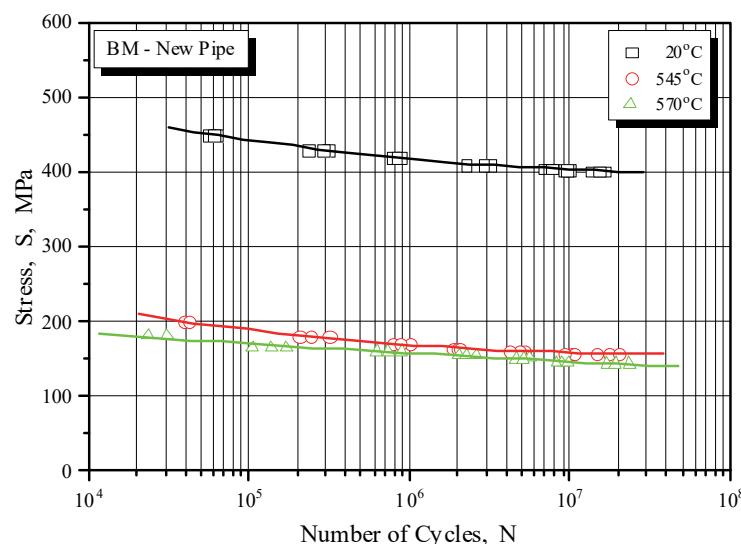


Figure 5. S-N diagrams of the BM-New Pipe [5]

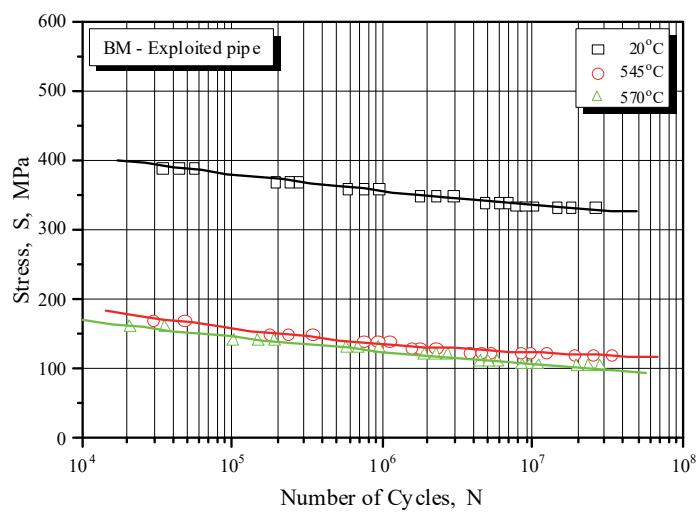


Figure 6. S-N diagrams of the BM-Exploited Pipe [5]

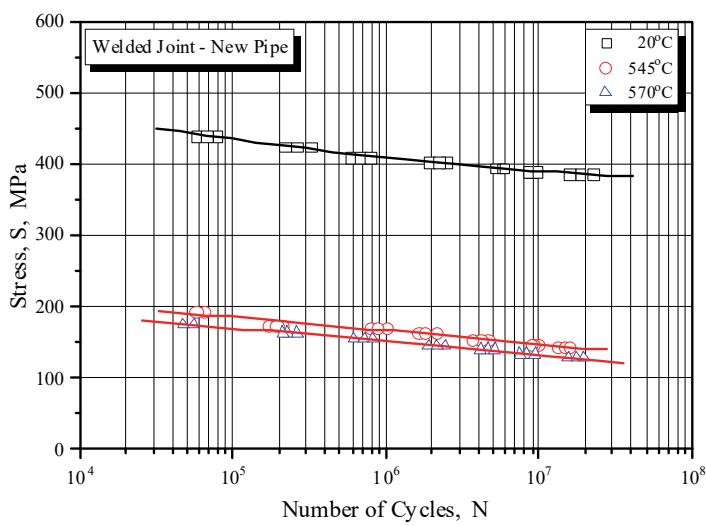


Figure 7. S-N diagram of the welded joint - New Pipe [5]

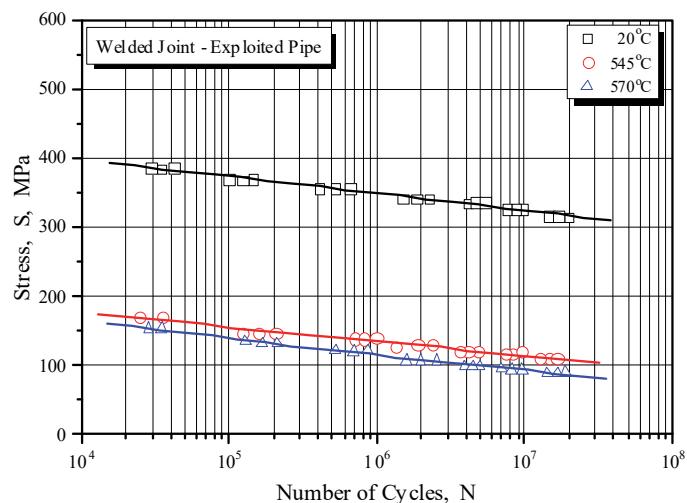


Figure 8. S-N diagram of the welded joint - Exploited Pipe [5]

When it comes to the test results of welded test specimens, the obtained values of permanent dynamic strength S_f , test tubes taken out of welded joint new pipe, range from 386MPa obtained by testing at 20°C, 144MPa obtained by testing at 545°C to 128MPa obtained by testing at 570°C. Regarding the testing of welded joint pipes from operation, the

obtained values of permanent dynamic strength S_f range from 316MPa obtained by testing at 20°C, 110MPa obtained by testing at 545°C to 89MPa obtained by testing at 570°C

Analysing the Weller diagrams obtained by testing the specimens of the welded joints of new and exploited pipe, one can see that exploitation time and temperature substantially affect the values obtained for permanent dynamic strength. The values of permanent dynamic strength, S_f , decrease with an increase of testing temperature. Exploitation period of 116,000 hours lead to decrease of the values of permanent dynamic strength, which can be important information if the conditions of steam-line operation are known.

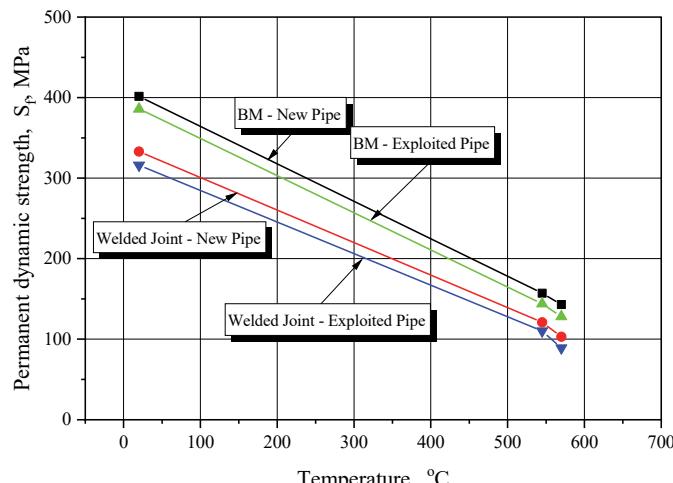


Figure 9. Change of values of permanent dynamic strength S_f depending on exploitation time and temperature

5 CONCLUSION

Based on what has been presented above, one can conclude the following:

- The period of exploitation (new and exploited material) affects the values of permanent dynamic strength, so that the new material has a higher resistance to crack initiation in smooth construction forms, ie it has a higher permanent dynamic strength.
- The value of permanent dynamic strength decreases with increasing test temperature.
- The base material generally shows better crack initiation resistance than the welded joint, because the welded joint is a stress concentrator, and as such is prone to easier crack initiation than the base material.

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