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Aging investigation of metals of the pipes in Lithuanian Power Station

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1. Introduction

In order to supply hot steam in the thermal power stations from heat-exchanger to turbine, long pipes are used. Therefore, the efficiency of such pipeline depends on the load, temperature and aggressive influence of hydrogen from the supplied hot steam. The technological parameters of the supplied hot steam are very high: temperature reaches up to 570°C, the working pressure of Ø219 pipe when thickness of the wall is 28.5 mm – 13.2 MPa and the working pressure of Ø245 pipe when thickness of the wall is 45 mm – 25.4 MPa. These pipelines can be damaged by temperature, tension strengths, own weight (including isolation) and vibrations caused by the changes in vapour pressure and dynamic loads from unbalanced rotors of pumps [1-6]. Walls of the pipes are mechanically treated during manufacture and the pressure results in thickness decreasing of the wall. Thus the state of residual tension strengths initiates the cracks. This is the reason, why special attention is paid to the residual tension strengths, which appear during manufacture of thick-walled pipes.

The attention in this work was concentrated on the investigation of mechanical characteristics of the material of straight part of the pipe depending on exploitation life and operating temperature. Mechanical properties of the material in pipeline depends on temperature, because when the temperature is increasing, strength of the steel is decreasing and plasticity increases, while the increasing exploitation life causes degradation of metal's structure and increased saturation of the metal with hydrogen, which increases metal fragility and reduces its plasticity [7-9]. The hydrogen's diffusion into metal is happening within limits of its structure's grains. Such saturation of the metal with hydrogen weakens the interaction forces between metal's grains and stimulates disintegration of the boundaries of mosaic blocks. Even small changes of tension strengths in such local areas induce cracks.

2. Methodology of investigation of mechanical characteristics

While performing this work, mechanical characteristics of the material, steel 12Ch1MF, of hot steam supply pipeline for AB "Lietuvos elektrine" (Lithuanian Power Station Ltd.) (outer diameter 219 mm, wall's thickness 28.5 mm) were analyzed: the limit of proportionality – σ_{pl}, yield strength – $R_{p0,2}$, tension strength – R_m, fracture stress – σ_f, reduction of cross-section area – Z.

The listed mechanical characteristics were determined in the straight part of the pipeline in a new pipe and the pipes after the exploitation of 45000 and 16000 h at 20°C temperature and at operating temperature of 550°C. The specimens were cut in the longitudinal direction, as it is shown in Fig. 1. The tension tests were performed using the 25 kN testing stand [10].

The force was measured with strain gauge attached to circular cross-section dynamometer fixed in the top catch of the testing machine, and the displacement of specimens was measured using the transverse deformometer [11, 12]. The testing stand was calibrated in the State Metrological Centers in Vilnius and Kaunas, while the tests were performed using the Ignalina NPP certificate. Mechanical characteristics of the specimens were determined using usual standard methodology.

The tension tests were performed at the velocity of machine's catch of 0.8 mm/min. The allowable velocity of growth of tension strength during the test, according to the standard EN10002-1 [11-14] is 2-20 MPa/s. The velocity of the testing machine's catch that we were used – 0.8 mm/min – corresponds to the required velocity of tension stresses: $\sigma_1 \approx 20$ MPa/s.

When the tests were performed at the elevated temperature, inductive heating of the specimen was used [10]. The scheme of inductive heating is shown in Fig. 2.

The specimen *1* heats up from the inductor *2*, through which electric current of high frequency is

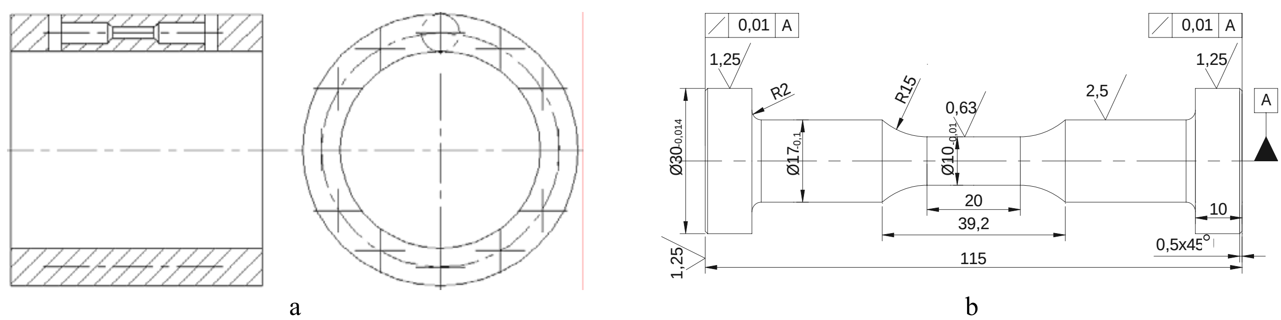


Fig. 1 Principal scheme of specimens, which are cut from steel 12Ch1MF pipes Ø219x28,5: a –layout; b – dimensions

passed from generator VCH4-10 *6*. The thermocouples *3* are welded to the specimen, which signals get into the potentiometer KSP-9 that registers temperature *5*. The difference in temperature in length of the testing part of the specimen at optimal form of the inductor does not exceed 2%, while there is no temperature's gradient in the thickness of specimen. The chromel and copel wires of 0.2 mm thickness is used to measure temperature. The thermocouples are attached to the specimen using the impulse electric welding. The accuracy of temperature's measurement is ± 0.5%, while the regulation accuracy is ± 1.5%.

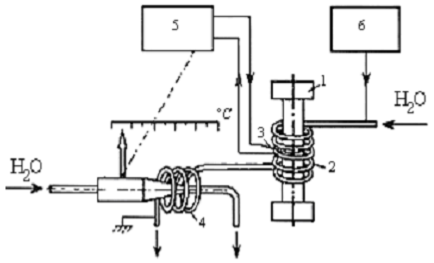


Fig. 2 Scheme of inductive heating: *1* – specimen, *2* – inductor, *3* – thermocouple, *4* – inductor's core, *5* – recorder of temperature's measurement, *6* – high frequency electric generator

3. Investigation of mechanical characteristics

While performing the tests, 13 specimens were tested at 20°C temperature, where 4 were from new, unused pipes, 4 – from the pipe after 45000 h of exploitation, and 5 – from the pipe after 160000 h of exploitation. 9 specimens were tested at the operating temperature of power station (550°C), where 3 specimens were from a new pipe, 3 – from the pipe after 45000 h of exploitation and 3 specimens from the pipe after 160000 h of exploitation.

The results from tension tests are shown in Tables 1, 2; the results of tension tests are shown graphically in Fig. 3, using the coordinates "tension strength-strain".

Table 1
Mechanical characteristics of not used pipes, pipes after 45000 and 160000 h of exploitation, $T = 20$°C

Hours	Mechanical characteristics, MPa, %				
	σ_{pl}	$R_{p0,2}$	R_m	σ_f	Z
0	398	425	601	1235	70.63
45000	284	292	494	786	72.91
160000	232	241	453	728	76.20

The average tension curves in the Fig. 3 were compared depending on the exploitation life and testing temperature. The tension strength curves are expressed taking into account real tension stresses, when the force is divided from the momentary cross-section area of the specimen (dotted lines), and taking into account so called engineering tension stresses, when the force is divided from in the initial cross-section area of the specimen (continuous lines). Besides, the tension curves up to strength's limit R_m is shown.

According to the Tables 1, 2 and Fig. 3 the main mechanical characteristics, such as yield limit $R_{p0,2}$ and strength limit R_m strongly depend on the exploitation life and testing temperature, because when the exploitation life and testing temperature increase from 20 to 550°C, these characteristics become significantly smaller.

Table 2
Mechanical characteristics of not used pipes, pipes after 45000 and 160000 h of exploitation, $T = 550$°C

Hours	Mechanical characteristics, MPa, %				
	σ_{pl}	$R_{p0,2}$	R_m	σ_f	Z
0	183	217	276	541	84.90
45000	128	175	237	292	86.44
160000	116	159	230	279	75.11

For example, at 20°C temperature $R_{p0,2} = 425$ MPa in case of a new pipe, while in case of the pipe after 160000 h of exploitation $R_{p0,2} = 241$ MPa, respectively $R_m = 601$ and 453 MPa. At 550°C testing temperature, $R_{p0,2} = 217$ MPa in case of a new pipe, while in case of the pipe after 160000 h of exploitation $R_{p0,2} = 159$ MPa, respectively $R_m = 276$ and 230 MPa.

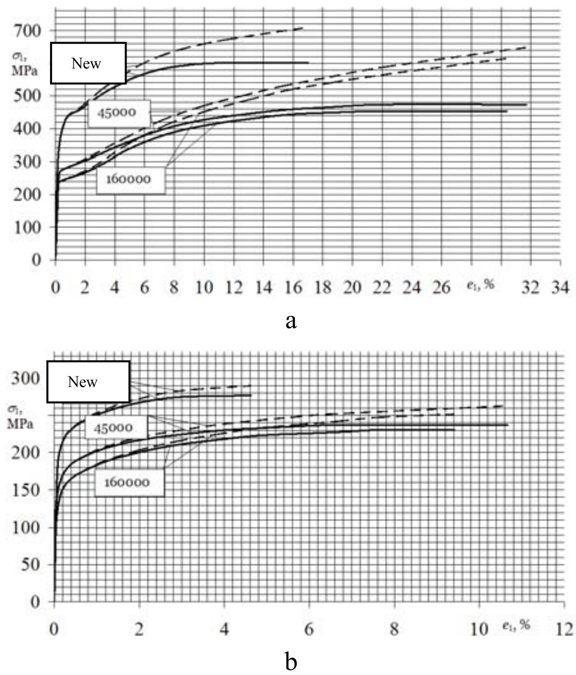


Fig. 3 Comparison of averaged tension curves with regard to new specimens and specimens after 45000 h and 160000 h of exploitation: a - at 20°C temperature; b - 550°C at temperature

The plasticity or reduction of cross-section area Z practically do not depend on the exploitation life, however if the testing temperature increases from 20 to 550°C, it also increases a little, about 8%.

These changes of $R_{p0,2}$, R_m and Z depending on temperature are characteristic to all grades of steel, because when the temperature is increasing, the steel becomes weaker and more plastic. But in our case growth of plasticity is stopped by structural changes in the pipe's material, because in case of the new pipe when the temperature increases from 20 to 550°C, Z increases from 70.63 to 84.90%, and in case of the pipe after 160000 h of exploitation Z practically is not changing, because at 20°C Z = = 76.20%, and at 550°C $Z = 75.11$%.

As it has been already mentioned, the strength characteristics $R_{p0,2}$ and R_m are decreasing with regard to the exploitation life and temperature. Such reduction depending on testing temperature can be partly explained by the influence of temperature, because in case of the new pipe, at 20°C temperature $R_{p0,2} = 425$, and $R_m = 601$ MPa, while at 550°C $R_{p0,2} = 217$ and $R_m = 276$ MPa, thus the changes of these characteristics with regard to exploitation life at 20 and 550°C depend only on structural changes of the metal during exploitation, and these changes are considerable. At 20°C temperature, yield limit decreases from 425 down to 241 MPa during 160000 h of exploitation, while strength limit decreases from 601 to 453 MPa. At 550°C temperature, yield limit decreases from 217 to 159 MPa, while strength limit decreases from 276 to 230 MPa. This shows that during exploitation, significant structural changes in the metal take place, and they change significantly strength characteristics, and a little – metal's plasticity.

The attention should also be paid to the change of fracture stress $-\sigma_f$ if a new pipe is used. This stress essentially does not depend on the exploitation life at 20°C temperature (Tables 1, 2); while at 550°C it decreases from 1057 to 541 MPa. When the exploitation life increases up to 160000 h, the fracture stress $-\sigma_f$ decreases from 541 to 279 MPa.

Dispersion of mechanical characteristics depend on the type of characteristics. The most precise measurement is the reduction of cross-section's area Z, which coefficient of variation was changing from 0.01 to 0.04. Besides, quite steady are the strength limit R_m and yield limit $R_{p0,2}$, because at 20°C, the R_m variation coefficient is up to 0.05, and that of $R_{p0,2}$ - up to 0.09. The dispersion at 550°C temperature is bigger, because instabilities of the testing temperature and its gradients in the testing part of the specimen create additional errors, and in this case, the R_m variation coefficients are up to 0.15, and $R_{p0,2}$ up to 0.20.

Bigger variation coefficients are of the limit of proportionality σ_{pl} and of the fracture stress $-\sigma_f$. Higher accuracy is needed to accomplish the experiment to determine the limit of proportionality σ_{pl}, while the variation in dispersion for fracture stress $-\sigma_f$ is big because of instability of disintegration process.

4. Calculation stresses for thick-walled pipes

In order to check strength of the straight part of the pipe, the analytical calculations and calculations based on the method of finite elements are performed. The analytical calculations were based on Lame theory, whereas the model of finite elements was formed from multilayered elements so that the distribution of tension stresses in the inner layer wall of the pipe could be determined more precisely.

The LS-DYNA preprocessor was used to form the model of finite elements. It is meant for calculations of nonlinear dynamics. In our case the static load of pressure was imitated with the occurring dynamic fluctuation of several tenths of percent using 164 Solid element as "fully integrated S/R solid[#2]" material model. The "piecewise linear plasticity" is indicated and both ends of the pipe are fixed tight. It should be noted that the calculations were performed for two types – Ø219 mm pipe with the wall of 28.5 mm thickness and working pressure was 13.2 MPa, and the Ø245 mm pipe with wall of 45 mm thickness and working pressure was 25.4 MPa.

According to Lame theory, the following stresses appear in the wall of thick-walled pipe: σ_R – radial stress, σ_H – circumferential stress, σ_L – longitudinal stress. When the pressure acts only on the inner surface of the pipe, the tension stresses in the wall of thick-walled pipe are calculated in the following way

$$\sigma_R = \frac{p\,R_2^2}{R_1^2 - R_2^2}\left(1 - \frac{R_1^2}{R_x^2}\right) \tag{1}$$

$$\sigma_H = \frac{p\,R_2^2}{R_1^2 - R_2^2}\left(1 + \frac{R_1^2}{R_x^2}\right) \tag{2}$$

$$\sigma_L = \frac{p\,R_2^2}{R_1^2 - R_2^2} \tag{3}$$

where R_1, R_2, R_x are external, central and internal radiuses of the pipe, p is working pressure of the pipe (Fig. 4). Results of the calculation are shown in Tables 3 and 4.

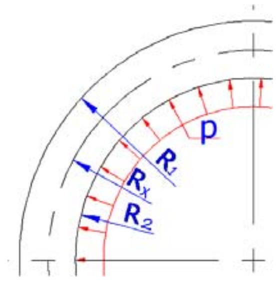


Fig. 4 Main parameters of the pipe R_1, R_2, R_x, p

The equation of circumferential and longitudinal stress in thin-walled pipes is as follows

$$\sigma_H^{Thin.} = \frac{p\,R_2}{h} \tag{4}$$

$$\sigma_L^{Thin.} = \frac{p\,R_2}{2\,h} \tag{5}$$

where h is thickness of the wall, p is pressure.

Table 3

Results of Lame and thin-walled pipes method for the pipe Ø219×28.5 when $p = 13.2$ MPa

	Stresses in the layers, MPa		
	Outer	Middle	Inner
σ_R	0.00	-5.21	-13.20
σ_H	31.90	37.59	45.10
σ_L	15.95	15.95	15.95
$\sigma_H^{Thin.}$	37.51		
$\sigma_L^{Thin.}$	18.76		

While working with LS-DYNA, the distribution field of stresses is received. In order to determine precise stresses at the outside, in the center and inside, we indicate three type of elements, which numbers are accordingly H35621 at interior, H35624 at center and H35625 at exterior – they are shown in Fig. 5.

Table 4

Results of Lame and thin-walled pipes method for the pipe Ø245×45 when p = 25.4 MPa

	Stresses in the layers, MPa		
	Outer	Middle	Inner
σ_R	0.00	-8.19	-25.40
σ_H	33.90	40.89	59.30
σ_L	16.95	16.95	16.95
$\sigma_H^{Thin.}$	42.19		
$\sigma_L^{Thin.}$	21.10		

The calculation result as presented in Figs. 6-11 were obtained after processing the calculation data by Excel program (curves in the pictures), and the obtained characteristics are presented in Tables 5 and 6.

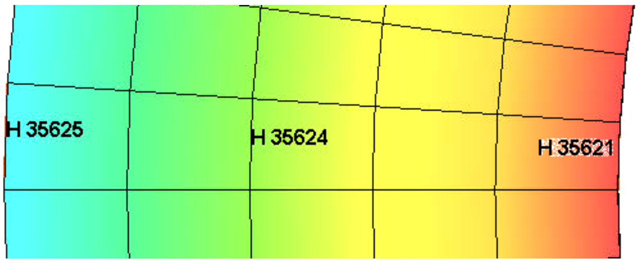


Fig. 5 Distribution of elements in the program Ls-Dyna

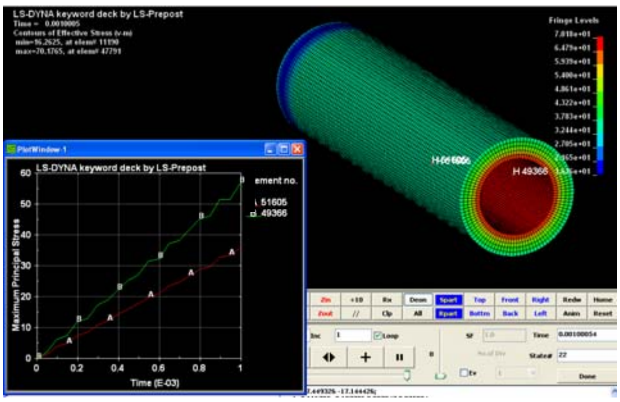


Fig. 6 Distribution of circumferential stress σ_H in steel 12Ch1MF pipe Ø219×28.5 when p = 13.2 MPa

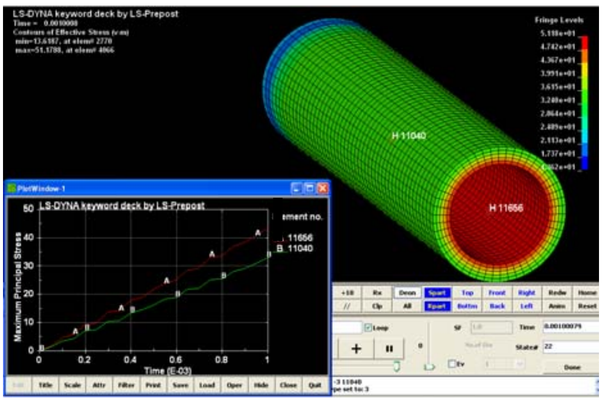


Fig. 7 Distribution of circumferential stress σ_H in steel 12Ch1MF pipe Ø245×45 when p = 25.4 MPa

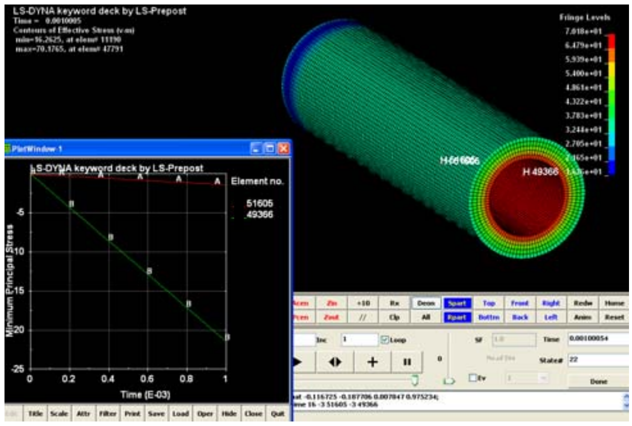


Fig. 8 Distribution of radial stress σ_R in steel 12Ch1MF pipe Ø219×28.5 when p = 13.2 MPa

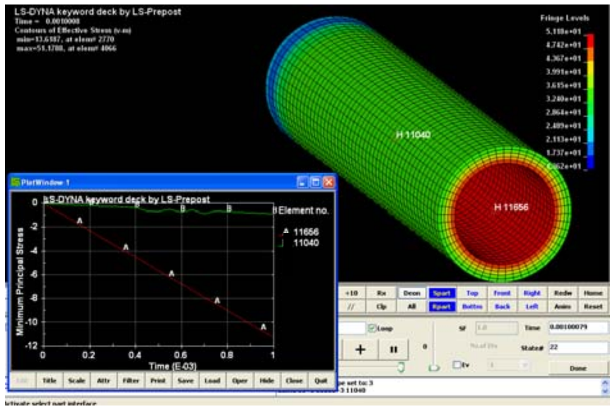


Fig. 9 Distribution of radial stress σ_R in steel 12Ch1MF pipe Ø245×45 when p = 25.4 MPa

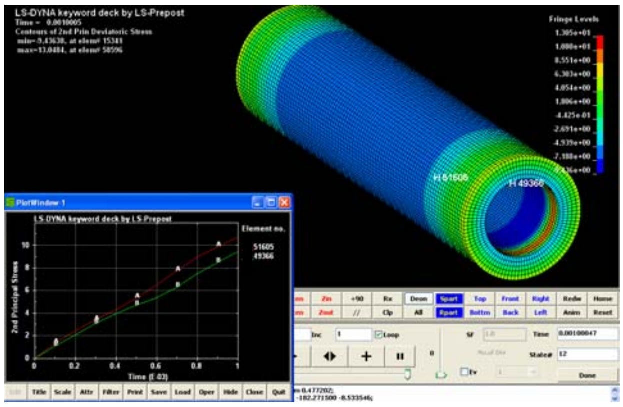


Fig. 10 Distribution of longitudinal stress σ_L in steel 12Ch1MF pipe Ø219×28.5 when p = 13.2 MPa

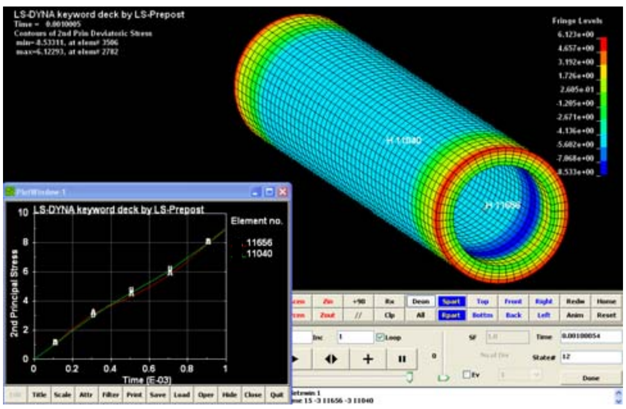


Fig. 11 Distribution of longitudinal stress σ_L in steel 12Ch1MF pipe Ø245×45 when p = 25.4 MPa

Table 5

Results of finite elements method for the pipe Ø219×28.5 when p = 13.2 MPa

	Stresses in the layers, MPa		
	Outer	Middle	Inner
σ_R	-0.82	-5.07	-11.15
σ_H	32.80	37.08	43.23
σ_L	9.01	9.01	9.01

Table 6

Results of finite elements method for the pipe Ø245×45 when P=25.4 MPa

	Stresses in the layers, MPa		
	Outer	Middle	Inner
σ_R	-1.29	-8.53	-21.08
σ_H	36.52	44.06	57.09
σ_L	10.77	10.77	10.77

The survey of received values of stresses using the method of finite elements resulted in high conformity between σ_R, σ_H values and lower conformity σ_L values, calculated on the basis of Lame theory method. Thus it is possible to state that the performed calculations are correct and can be used to determine durability of the pipes.

5. Analysis of mechanical characteristics

The mechanical characteristics from static tension test accomplished with the specimens of different work resources are shown in Figs. 12 and 13. They are described by equations

$$\sigma_{pl} = -14.055\, ln(t) + 398 \tag{6}$$

$$R_{p0,2} = -15.758\, ln(t) + 425 \tag{7}$$

$$R_m = -13.161\, ln(t) + 601 \tag{8}$$

$$\sigma_f = -42.2\ \ ln(t) + 1235 \tag{9}$$

where 398 is the limit of proportionality of not used steel, 425 is the yield strength of not used steel, 601 is the tension strength of not used steel and 1235 is the fracture stress of not used steel.

The determination coefficient of the equations (8) and (9) R^2 is 0.97 and 0.99 respectively.

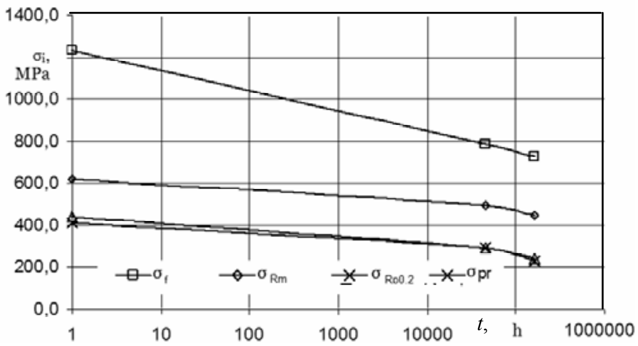


Fig. 12 Dependence of mechanical characteristics on work time: R_m - tension strength, $R_{p0,2}$ - yield strength, σ_{pl} - the limit of proportionality, σ_f - fracture stress

The equation of linear dependence of reduction of cross-section area on work time (determination coefficient R^2 = 0.99)

$$Z = 4 \cdot 10^{-5} t + 70.63 \tag{10}$$

where 70.63 is reduction of cross-section area of not used steel.

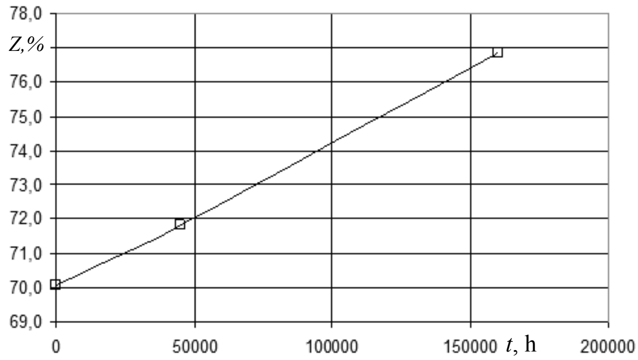


Fig. 13 Dependence of cross-section area on work time

6. Investigation of microstructures

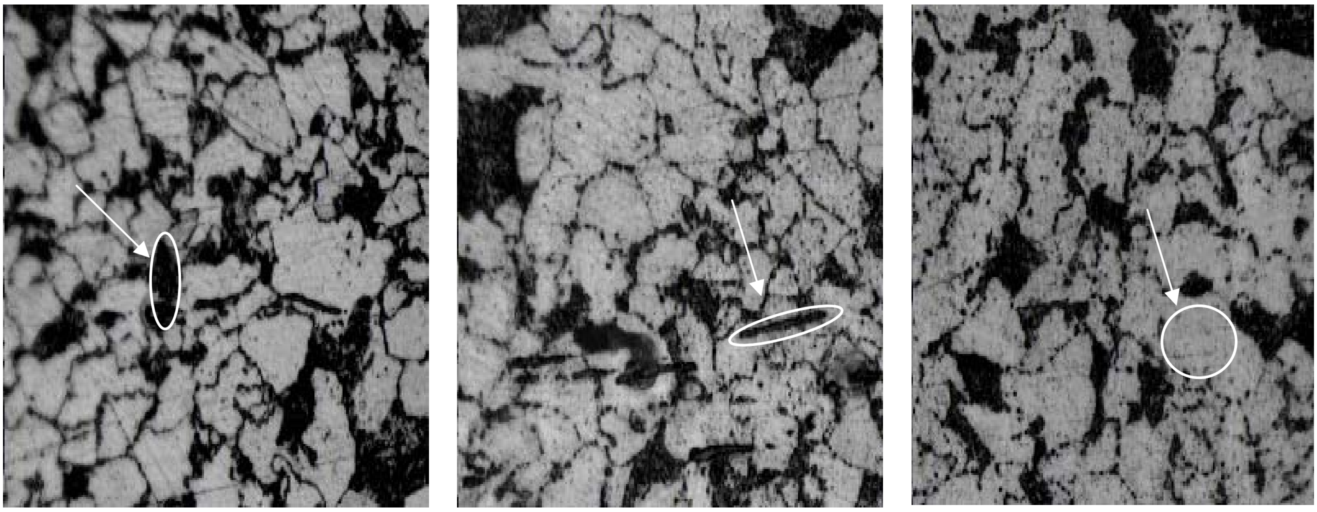
The specimens were made from the steel 12Ch1MF pipes, that had been working different time. The microstructure seen in the photos are, ferrite, perlite. During the carbon diffusion in perlite the carbides are formed, perlite grains disappear, the tension strength decreases and the plasticity increases. In order to see the changes of microstructure better, we present the samples corroded by HNO_3 10% alcoholic solution.

In Fig. 14, a-c microstructures of not used, steel 12Ch1MF are shown. Perlite (black area), ferrite (light area) and nonmetal inserts are seen. The microstructures correspond to grade 3, according to the standard TS 14-3-560 scale, while the ferrite grains correspond to grade 6, the grains of perlite phase correspond to grade 3 according to the standard GOST 5639-82 scale.

In Fig. 15, a-c microstructures of steel 12Ch1MF used for 45000 h are shown. The presented microstructures correspond grade 6, according to standard scale TS 14-2-460. The first changes are visible in the photos. The carbide particles start to separate within the limits of ferrite grain. The ferrite grains correspond to grade 8, the grains of perlite phase correspond to grade 2, according to the standard GOST 6539-82 scale.

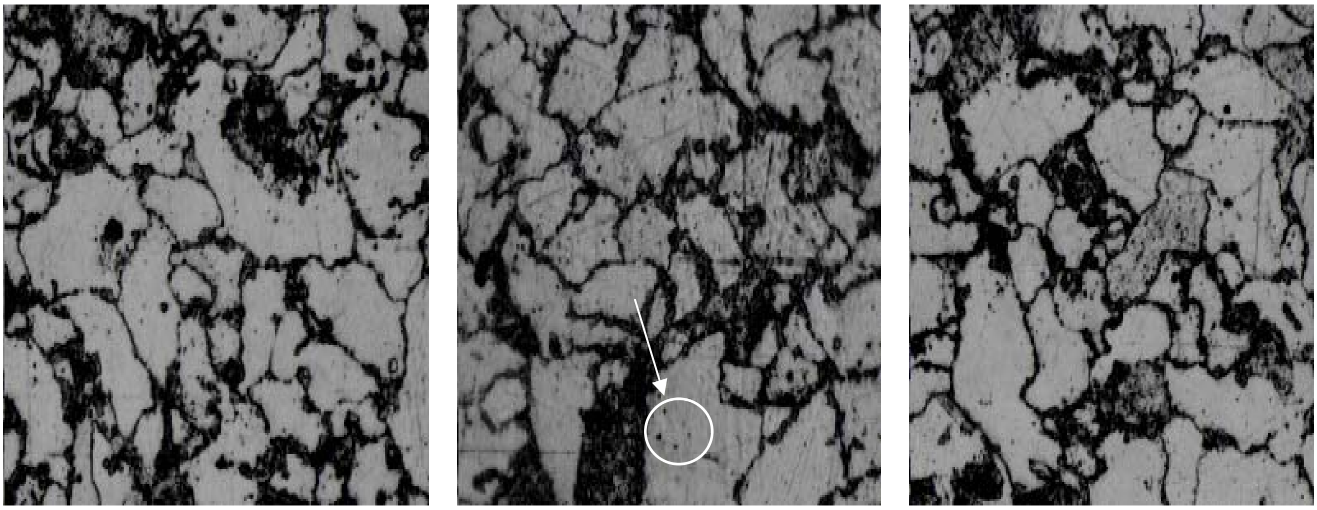
In Fig. 16, a-c microstructures of steel, 12Ch1MF, used for 160000 h are shown. The nonmetal inserts of ~20 μm are seen, as well as small carbide particles within the limits ferrite grains. The changes of microstructure affect mechanical characteristics, the strength characteristics are decreasing and plasticity is increasing.

After the investigation of specimens the conclusion was done that difference between of microstructures in the specimens are seen. We see that when steel 12Ch1MF is used at 550°C temperature long time, intensive carbon diffusion takes place. Thus carbon contained in perlite diffuses and forms carbides, which results in worsening of steel's properties, increase of plasticity and decrease of strength characteristics.



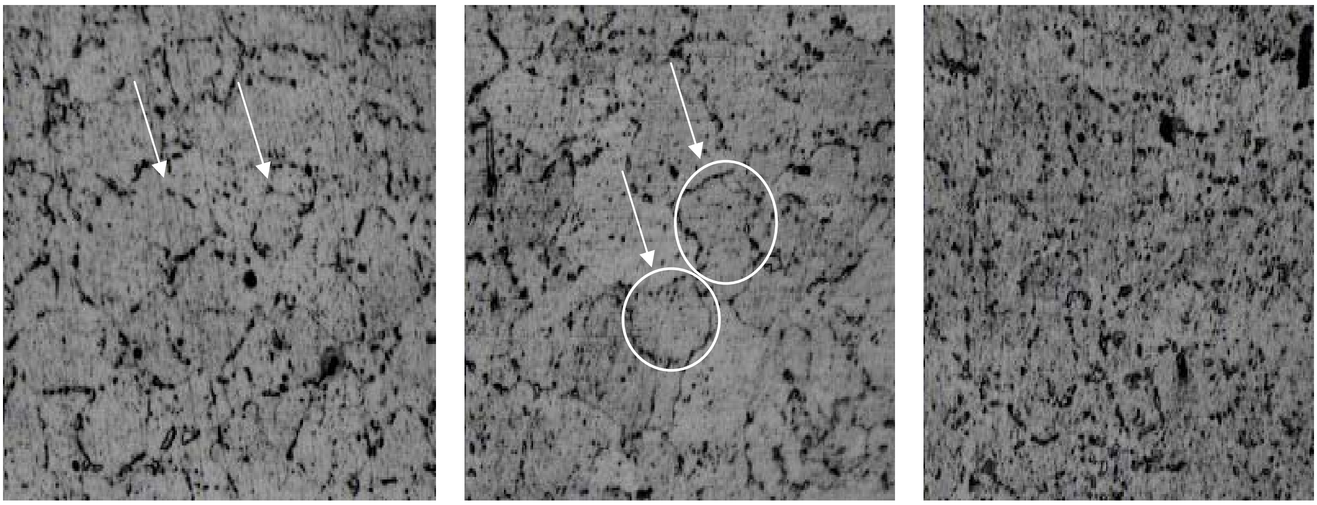
a b c

Fig. 14 Microstructure of not used steel 12Ch1MF in inner (a), middle (b) and outer (c) layers of the pipe wall, magnified ×350



a b c

Fig. 15 Microstructure of steel 12Ch1MF after 45000 h of work in inner(a), middle (b) and outer (c) layers of the pipe wall, magnified ×350



a b c

Fig. 16 Microstructure of steel 12Ch1MF after 160000 h of work in inner(a), middle (b) and outer (c) layers of the pipe wall, magnified ×350

7. Conclusions

The investigation of mechanical characteristics of the material of hot steam supply pipeline for AB “Lietuvos elektrine” (Lithuanian Power Station Ltd.) with regard to the straight part of the new pipe, the pipe after 45000 and after 160000 h of exploitation at 20 and 550°C temperature allows making the following conclusions:

1. The mechanical characteristics of the pipe material: σ_{pl}, $R_{p0,2}$, R_m, σ_f, Z depend on the exploitation life and testing temperature, because when the exploitation life grows from 0 to 160000 h and testing temperature increases from 20 to 550°C, the strength mechanical characteristics σ_{pl}, $R_{p0,2}$, R_m and σ_f decrease. For example, in case of the new pipe at 20°C temperature $R_{p0,2}$ = 425 MPa, while after the 160000 h exploitation $R_{p0,2}$ = 241 MPa, respectively R_m = 601 and 453 MPa. In case of the new pipe at 550°C temperature, $R_{p0,2}$ = 217 MPa, while after the 160000 h of exploitation- $R_{p0,2}$ = 159 MPa, respectively R_m = 276 and 230 MPa. The plasticity and reduction of cross-section area Z practically do not depend on the exploitation life, however if the testing temperature increases from 20 to 550°C, it also increases a little, about 8%.

2. The dependency of mechanical characteristics on structural changes of the metal during exploitation is high, because the yield strength after 160000 h of exploitation decreases from 425 MPa (for new pipe) to 241 MPa, while the tension strength decreases from 601 to 453 MPa at 20°C testing temperature, while at 550°C temperature the decrease is accordingly from 217 to 159 MPa and from 276 to 230 MPa. There have not been noticed any significant changes in the material’s plasticity with regard to exploitation life.

3. Fracture stress σ_f after 160000 h of exploitation decreases from 541 MPa (for new pipe) to 279 MPa at 20°C testing temperature, while at 550°C σ_f of the new pipe decreases from 1235 to 728 MPa.

4. It was determined that the reliability of mechanical characteristics mostly depends on the type of characteristics, testing temperature and number of specimens. In our tests the smallest variation coefficient at 20 and 550°C temperature was in the reduction of cross-section area Z (changes from 0.01 to 0.10). Besides, the tension strength and yield strength were also sufficiently stable, because at 20°C, their variation coefficients were changing up to 0.05, and up to 0.09 respectively. The dispersion of results at 550°C temperature is bigger, because instabilities of testing temperature and its gradients in the testing part of the specimen create additional errors, and in this case, the R_m variation coefficient was changing up to 0.015, and $R_{p0,2}$ up to 0.20.

5. When steel 12Ch1MF is used at 550°C temperature and long working time, intensive carbon diffusion takes place. Thus carbon contained in perlite diffuses and forms carbides, which results in worsening of steel’s properties, increase of plasticity and decrease of strength characteristic.

6. Calculations results made according to thick walled pipes theory (Lame) and thin walled pipes theory were compared with the results from finite element method and can be drawn a conclusion, that Lame theoretical equation describes stresses in the pipes more precisely, than equations of thin walled pipe.

Acknowledgement

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LIETUVOS ELEKTRINĖS VAMZDYNŲ METALŲ SENĖJIMO PROGNOZAVIMAS

R e z i u m ė

Straipsnyje aprašyti tiesios vamzdžio dalies mechaninių charakteristikų tyrimai, atlikti esant skirtingai eksploatacijos temperatūrai ir trukmei. Nustatyta, kad visos mechaninės charakteristikos priklauso nuo eksploatacijos trukmės ir bandymo temperatūros. Stiprumo charakteristikos $\sigma_{pl}, R_{p0,2}, R_m, \sigma_f$ ilgėjant eksploatacijos trukmei ir didėjant temperatūrai, mažėja, plastiškumas Z nuo eksploatacijos trukmės priklauso mažai, o didėjant temperatūrai – didėja, išskyrus vamzdį, eksploatuotą 160 000 h.

Stebint bandinių, dirbusių 550°C temperatūroje ilgą eksploatacijos trukmę, mikrostruktūrą, perlite buvusi anglis difunduoja sudarydama karbidus, todėl mechaninės charakteristikos prastėja: plastiškumas didėja, stiprumo charakteristikos mažėja.

Atlikus plieno 12Ch1MF vamzdžio tiesiosios dalies, dirbusios 45 000 h, įtempių skaičiavimus pagal storasienių (Lame) ir plonasienių vamzdžių analitines išraiškas bei patikrinus baigtinių elementų metodu gautus rezultatus, galima teigti, kad, tyrime naudotiems vamzdžiams Lame teorijos analitinės išraiškos tiksliau apibūdina vamzdyje darbo metu atsirandančius įtempius.

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AGING IVESTIGATION OF METALS OF THE PIPES IN LITHUANIAN POWER STATION

S u m m a r y

This article presents the investigation of mechanical characteristics of the pipe's straight part dependence on operating temperature and exploitation times. The strength characteristics $\sigma_{pl}, R_{p0,2}, R_m, \sigma_f$ decrease with increasing exploitation life and temperature, whereas the plasticity characteristic Z a little depend on the exploitation life. It increases with the increasing temperature, except for the pipe after 160 000 h of exploitation.

When steel 12Ch1MF is used at 550°C temperature long time, intensive carbon diffusion takes place. Thus carbon contained in perlite diffuses and forms carbides, which results in worsening of steel's properties: increasing plasticity and decrease strength characteristics.

Comparison thick walled pipes (Lame) and thin walled pipes equations results with results the finite element method showed that Lame theoretical equation describes stresses in the pipes more precisely.

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ИССЛЕДОВАНИЕ СТАРЕНИЯ МЕТАЛЛА ТРУБ В ЛИТОВСКОЙ ТЕПЛОВОЙ ЭЛЕКТРОСТАНЦИИ

Р е з ю м е

Прочностные характеристики $\sigma_{pl}, R_{p0,2}, R_m, \sigma_f$ при увеличении времени эксплуатации и температуры увеличиваются, пластичность Z от времени эксплуатации мало зависит, а при повышении температуры повышается за, исключением трубы после 160000 h эксплуатации.

Эксплуатация стали 12Ch1MF при температуре 550°C интенсифицирует диффузию углерода и образование карбидов, что приводит к ухудшению свойств стали, то есть повышению пластичности и уменьшению прочности.

Сопоставление расчетов напряжений, проведенных в прямой части трубы из стали 12Ch1MF после эксплуатации 45000 h по зависимости для толстостенных труб (Ламе) и тонкостенных труб с результатом расчета методом конечных элементов показало, что для использованных труб предпочтительнее расчет по зависимостям Ламе.

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