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Evaluation of microstructure and mechanical properties of a steam turbine casing after long-term service

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Properties

ABSTRACT

Purpose: of this paper is to reveal the microstructural changes in Cr-Mo and Cr-Mo-V cast steels steel exposed to long-term service at elevated temperatures. The paper presents results of research and failure analysis undertaken to determine failure causes of a steam turbine casing. After 130,000 hours of service the crack in a outer shell of the turbine casing was found.
Design/methodology/approach: Following research were performed in order to determine causes of the casing failure: chemical analysis; microstructure examinations with the use of light microscope, scanning electron microscope (SEM); transmission electron microscopy (TEM); mechanical properties examinations using the Charpy impact test, and Vickers hardness test; fracture mode evaluation with SEM; the energy dispersive X-ray spectrometry (EDS).
Findings: The cracking of the outer casing occurred due to various causes. The main cause was stress distribution and stress changes during service of the turbine. The microstructure of ferrite and bainite/perlite is more susceptible to cracking than tempered martensite. Carbides coagulation process occurs at ferrite grain boundaries which increased embrittlement. Big nonmetallic inclusions also contribute to brittleness of material.
Research limitations/implications: The whole history of start-ups and shutdowns of the turbine during long term service has not been recorded. There was no possibility to take samples with fracture area. Thus, service conditions of investigated samples and material of cracking area were different.
Practical implications: Useability of the method for assessing the current degradation based on analysis of carbides morphology was confirmed for Cr-Mo and Cr-Mo-V cast steels.
Originality/value: Microstructure composed of ferrite and perlite/bainite is more liable for degradation processes, during long-term exploitation at elevated temperature, than microstructure of tempered martensite.
Keywords: Cracking; Structure degradation; Cr-Mo-V steels; Steam turbine casing

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1. Introduction

The casing of a turbine is a pressure vessel where high temperature and high pressure steam from the boiler passes through nozzles to rotate turbine discs. The casing withstands the steam pressure and supports internal components, i.e. turbine shaft with blades. A turbine casing is a massive cast structure with a large wall thickness. A casing is subjected to thermal stress across a wall, and to cyclic and sustained pressure/stress in service. Frequent start-ups and shutdowns generate cyclic compressive and tensile stresses in the casing walls [1].

Increased efficiency requires higher steam pressures and temperatures. It requires materials with improved thermal fatigue resistance, greater toughness and higher strength. Materials used for casings are usually low alloy Cr-Mo, and Cr-Mo-V cast steels, with ferrite, ferrite-bainite, or tempered martensite microstructure. The strength of these steels at elevated temperature is obtained by solid solution strengthening and precipitation hardening.

High pressure turbine casings are liable to damages caused by distortion and cracking. Distortion occurs due to: thermal gradient, rapid start-ups and shutdowns cycles, or load shifts. Casing distortion can cause damage by allowing contact between stationary and rotating parts. Cracking can be caused by three reasons: thermal fatigue (65%), brittle fracture (30%), and creep (5%) [2]. Degradation of material toughness due to long term service exposure can result in rapid crack growth and catastrophic brittle failure. Temper embrittlement, creep embrittlement, and stress relief cracking have been found as causes of toughness loss, which could subsequently lead to cracking of turbine casings. Thus, the cracks have to be removed by machining (grinding) or the casing should be repaired by welding at early stage of crack propagation [3,4].

2. Materials

The casing has been a part of an action steam turbine type 13UP55 with nominal power 55 MW with steam working parameters 535°C/12.7 MPa. The turbine was made by Zamech Elbląg, Poland. The turboset has been exposed to service for 130,000 hrs at a Heat and Power Plant. During a periodic inspection the crack in the outer shell (upper part) of the turbine casing was found. The crack was transverse to the turbine axis, and had 700 mm in length and 19 mm in depth. Thickness of the casing in the crack vicinity was 90-100 mm. The outer shell of the casing was made of cast steel grade G20CrMo4-5 (older Polish grade L20HM), while the inner shell of grade G21CrMoV5-7 (L21HMF). The crack was removed by grinding and the casing was thought to be repaired by welding.

Table 1.
Samples designation, and areas of sampling

Sample	Casing shell	Side	Material
1	inner	inlet	G21CrMoV5-7
2	lower part	outlet	
3	inner	inlet	
4	upper part	outlet	
5	outer	outlet	G20CrMo4-5
6	lower part	inlet	
7	outer	outlet	
8	upper part	inlet	

Four samples, both from the outer and inner shell of the casing, were cut to perform metallographic investigations. Samples with dimensions 60×15×15 mm were taken from the flanges of the casing (Table 1). Unfortunatly, there was no possibility to take a sample with fracture area. Thus, service conditions of the samples and cracking area were different.

3. Experimental procedure

Following research were performed in order to determine a state of materials, changes of structure, development of precipitation processes, and the internal damages related to the exhaust degree of material:

- control chemical analysis,
- microstructure examinations with the use of a light microscope (LM), scanning electron microscope (SEM), and and transmission electron microscope (TEM),
- mechanical properties examinations using the Charpy impact test, and Vickers hardness test,
- fracture mode evaluation on Charpy samples with scanning electron microscope.

4. Results and discussion

4.1. Chemical composition

The chemical compositions of the tested samples are given in Table 2. Elements concentration in all tested samples meet requirements for ladle analysis of grade G21CrMoV5-7 and G20CrMo4-5 included in Polish standard PN-89/H-83157 [16].

4.2. Microstructure

Microstructures of the materials used for inner and outer shell of the turbine casing were examined with the use of the optical microscope and SEM on cross sections etched with nital. Additionally, carbon extraction replicas were examined with SEM and TEM.

Microstructure of the samples taken from inner shell of the casing (made of G21CrMoV5-7) composes of tempered martensite (Figs. 1-3). It indicates that the inner shell was quenched and tempered. The level of microstructure degradation (changes in microstructure resulting from long-term impact of temperature and stress in service) is low.

Microstructure of the samples taken from outer shell of the casing (made of G20CrMo4-5) composes of tempered ferrite and bainite/perlite (Figs. 4-6). It indicates that the inner shell was annealed - normalized and stress relived. The level of microstructure degradation is intermediate. Metallographic examinations revealed changes in microstructure, i.e. partial decomposition of bainite/perlite along with carbides precipitation on ferrite grain boundaries. No evidences of creep failure in the form of voids were observed. Many big nonmetallic inclusions were found in the outer shell of the casing (Fig. 7). The diameter of the nonmetallic inclusions was as high as 100-200 µm. Chemical composition of the inclusion presented in Fig. 7 was determined with the use of EDS spectrometer. The inclusion is composed of complex oxides of iron, aluminum, titanium, silicon, with cesium, lanthanum, and potassium (Figs. 8-9). The origin of it is from the casting process.

Table 2.
Chemical composition of tested samples

Analysis	Chemical composition, wt%								
Sample	C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu
G21CrMoV5-7 PN-89/H-83157	0.18 0.25	0.20 0.50	0.40 0.70	max 0.030	max 0.030	0.90 1.20	0.50 0.70	max 0.30	0.20 0.35	max 0.30
1	0.22	0.43	0.58	0.006	0.007	0.94	0.64	0.07	0.27	0.10
2	0.21	0.43	0.58	0.005	0.006	0.93	0.64	0.07	0.27	0.09
3	0.23	0.43	0.58	0.004	0.010	0.96	0.63	0.12	0.24	0.07
4	0.23	0.44	0.59	0.007	0.009	0.97	0.63	0.12	0.24	0.08
G20CrMo4-5 PN-89/H-83157	0.15 0.25	0.20 0.50	0.50 0.80	max 0.030	max 0.030	0.40 0.70	0.40 0.60	max 0.30	-	max 0.30
5	0.17	0.40	0.65	0.007	0.010	0.48	0.52	0.08	0.01	0.07
6	0.20	0.43	0.70	0.010	0.014	0.51	0.50	0.08	0.01	0.07
7	0.16	0.40	0.64	0.011	0.011	0.53	0.47	0.07	0.01	0.06
8	0.18	0.40	0.65	0.011	0.011	0.53	0.47	0.07	0.01	0.06

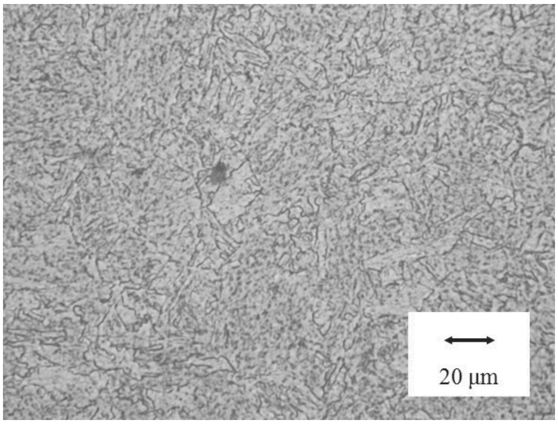


Fig. 1. Microstructure of inner shell of the casing made of G21CrMoV5-7, nital etched, LM

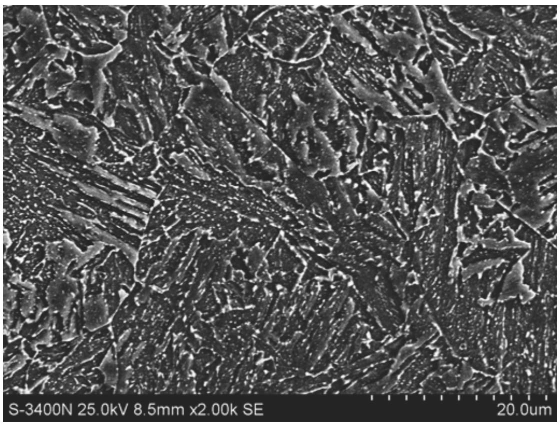


Fig. 2. Microstructure of inner shell of the casing made of G21CrMoV5-7. Cross section, nital etched, SEM

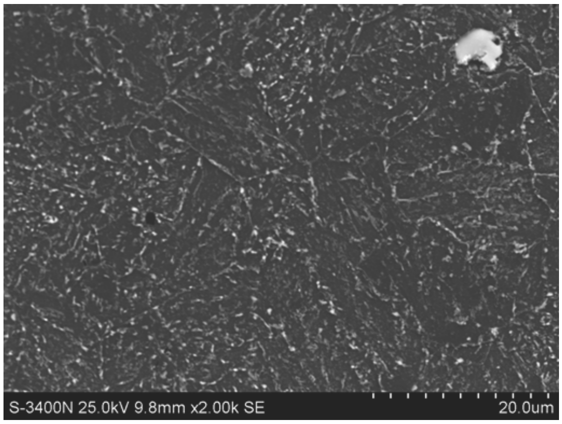


Fig. 3. Microstructure of inner shell of the casing made of G21CrMoV5-7. Carbon extraction replica, SEM

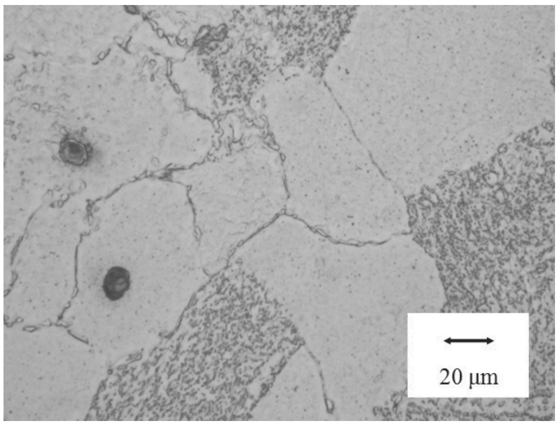


Fig. 4. Microstructure of outer shell of the casing made of G20CrMo4-5. Nital etched, LM

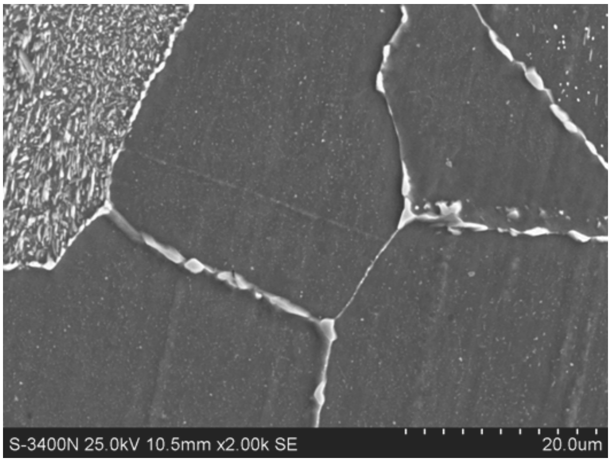


Fig. 5. Microstructure of outer shell of the casing made of G20CrMo4-5. Cross section, nital etched, SEM

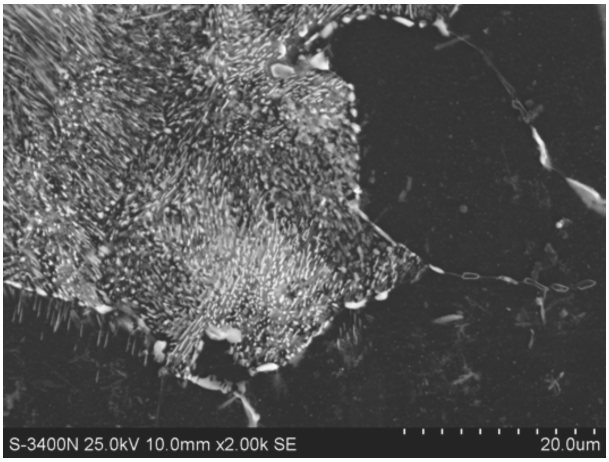


Fig. 6. Microstructure of outer shell of the casing made of G20CrMo4-5, carbon extraction replica, SEM

Structural studies, including analysis of phase composition was performed using the transmission electron microscopy operating at 100 kV accelerating voltage. Research was conducted on thin foils. Diffraction studies were performed using selective diffraction.

TEM examinations revealed the presence of the following components of microstructure. The inner casing microstructure composed of tempered lath martensite with fine precipitations of MC type carbides. At martensite lath borders M_3C type carbides were observed. At subgrain borders and inside subgrains $M_{23}C_6$ type carbides were found (Fig. 10). The outer casing microstructure consisted ferrite and perlite/bainite. At ferrite grain borders coarsed M_3C and $M_{23}C_6$ carbides were identified. Inside perlite/bainite grains coarsed plate-like M_3C carbides and spheroided $M_{23}C_6$ carbides were presented. Additionally, fine needle-like M_2C type carbides were observed (Fig. 11), which indicates that microstructure degradation process of the outer casing is more advanced.

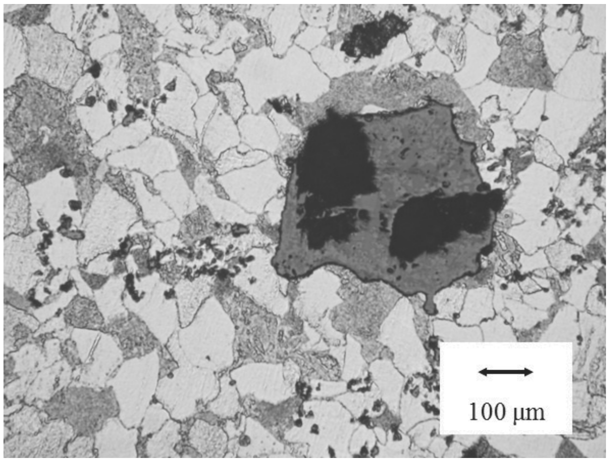


Fig. 7. Microstructure of outer shell of the casing made of G20CrMo4-5 with big nonmetallic inclusion, nital etched, LM

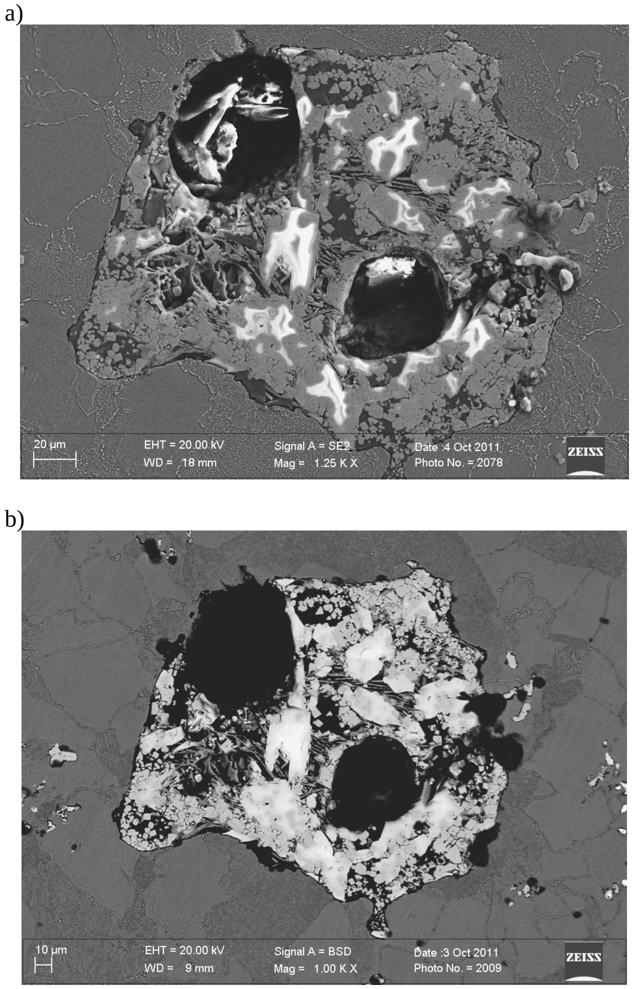
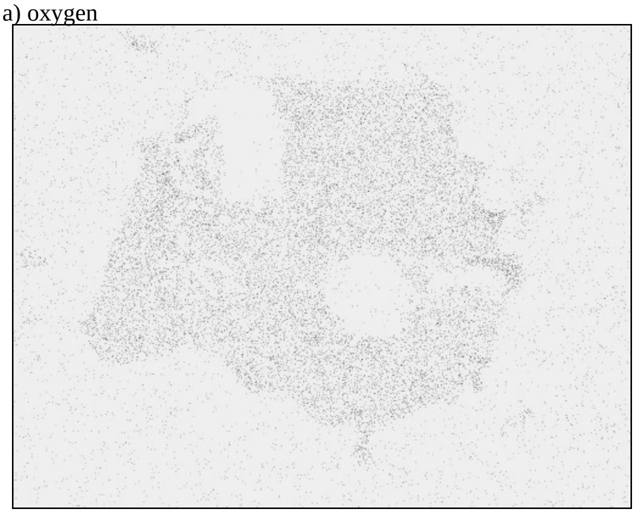
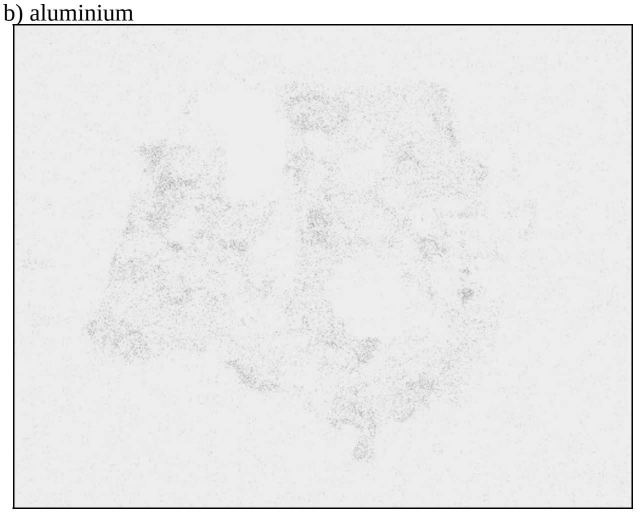


Fig. 8. Nonmetallic inclusion in outer shell of the casing made of G20CrMo4-5, SEM with detector: a) SE; b) BSE

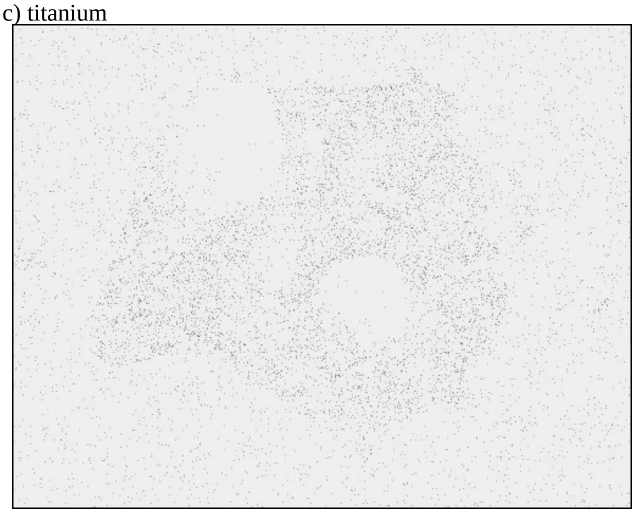
a) oxygen



b) aluminium



c) titanium



d) silicon

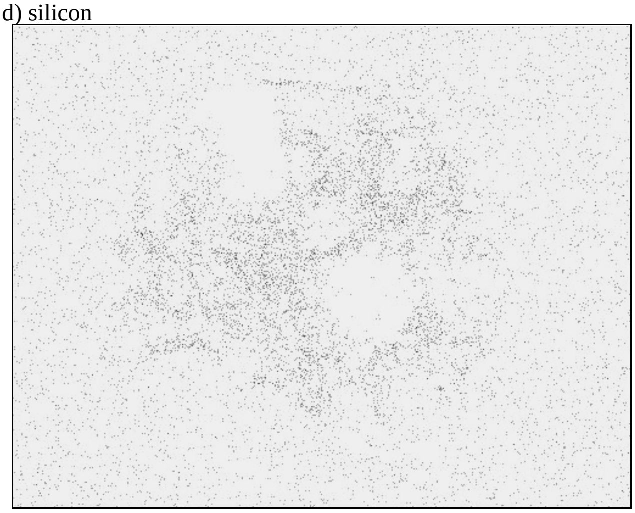


Fig. 9. Elements concentrations in nonmetallic inclusion presented in Fig. 8. SEM-EDS X-ray mapping

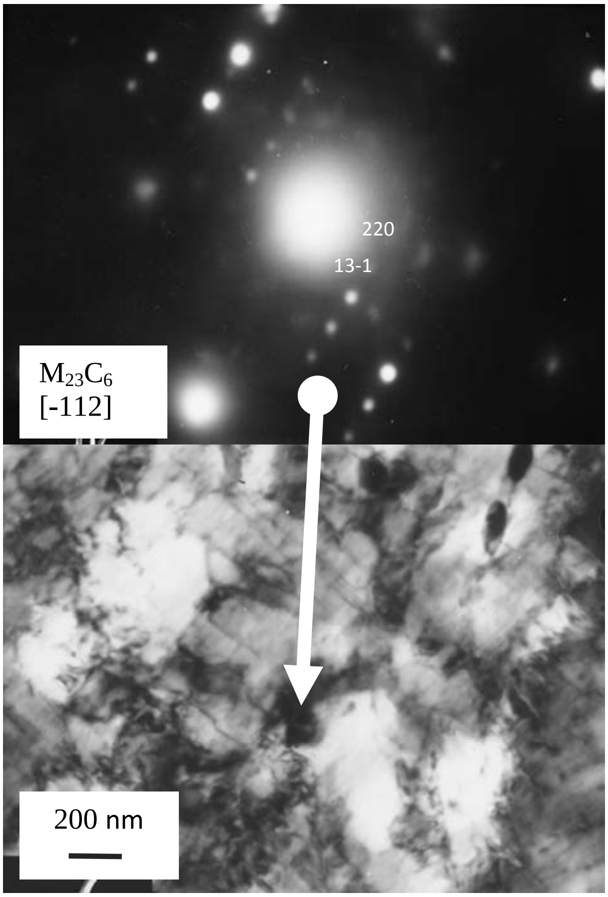
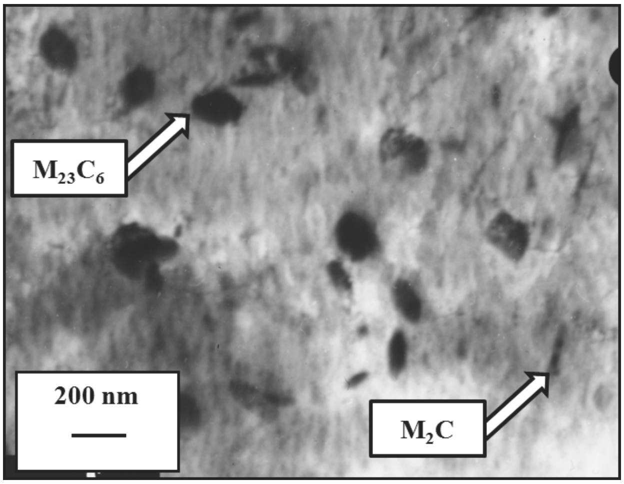


Fig. 10. Microstructure of inner shell of the casing made of G21CrMoV5-7, thin foil, TEM



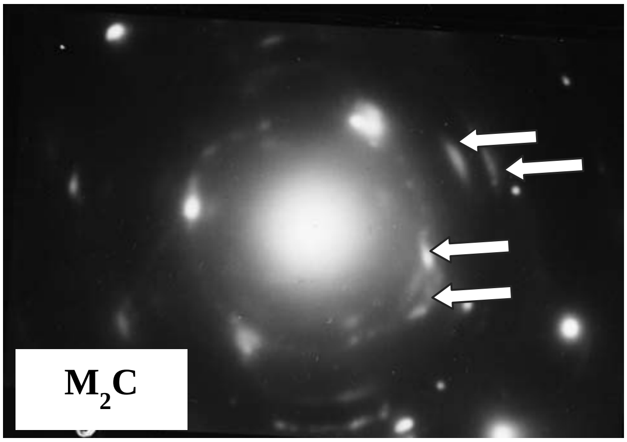


Fig. 11. Microstructure of outer shell of the casing made of G20CrMo4-5, thin foil, TEM

4.3. Hardness

Hardness of casing materials was measured on cross sections using 98.1 N load (10 kG) according to PN-EN 6507-1 [17]. Mean hardness of the inner shell of the casing was 244 HV10, and of the outer shell was 155 HV10. Obtained values of hardness confirm that the inner shell was quenched and tempered, while the outer shell was normalized. Results of hardness test are presented in Table 3.

4.4. Toughness

Charpy-V impact test was used to evaluate toughness of casing materials. Tests were performed at room temperature according to PN-EN ISO 148-1 [18]. Mean impact energy of the inner shell of the casing was 96 J, and of the outer shell was 8 J only. Results of hardness test are presented in Table 4. Received results point out that inner shell of the casing possesses good toughness, but outer shell, which failed, is brittle at low temperatures. Observation of fracture surfaces of Charpy samples confirm good toughness of inner shell of the casing with micro-void coalescence mode of fracture (Figs. 12-13). High brittleness of outer shell of the casing is confirmed by transgranular cleavage mode of fracture (Figs. 14-15).

Table 3.
Results of hardness test

Sample	Hardness HV10					HV10
	1	2	3	4	5	mean
Inner shell of the casing G21CrMoV5-7						
1	237	238	233	238	-	**236**
2	251	254	254	250	-	**252**
3	240	233	240	235	-	**237**
4	247	251	251	251	-	**250**
Outer shell of the casing G20CrMo4-5						
5	141	139	145	145	-	**143**
6	166	158	164	160	-	**162**
7	165	160	164	160	-	**162**
8	156	151	151	156	-	**153**

Table 4.
Results of Charpy-V impact test

Sample	Absorbed Energy, J	Impact strength, J/cm^2	Test temperature, °C	Cleavage fracture area,%
Inner shell of the casing G21CrMoV5-7				
1	94.0	117.5	20	30
2	118.0	147.5	20	10
3	51.0	63.7	20	60
4	121.0	151.2	20	10
Outer shell of the casing G20CrMo4-5				
5	9.3	11.6	20	100
6	7.0	8.7	20	100
7	8.3	10.3	20	100
8	8.0	10.0	20	100

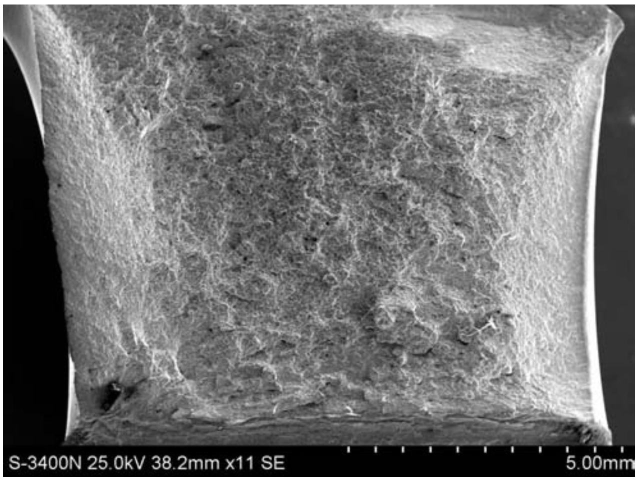
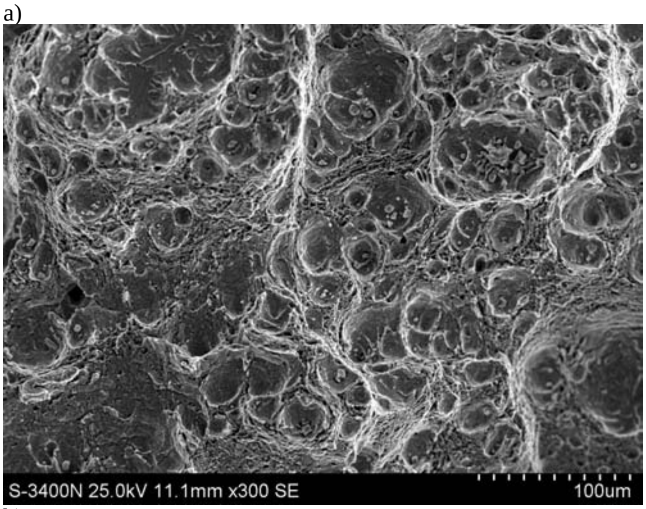


Fig. 12. Macroscopic view of fracture surface of the Charpy sample. Inner shell of the casing made of G21CrMoV5-7, SEM

a)



b)

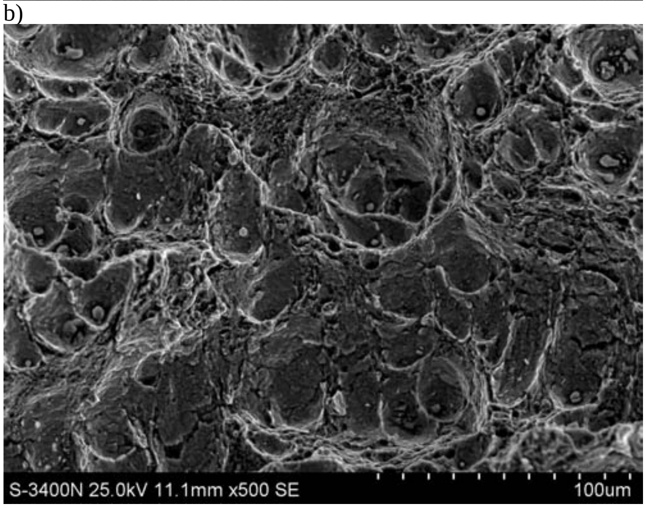


Fig. 13. Microscopic view of fracture surface of the Charpy sample. Inner shell of the casing made of G21CrMoV5-7, SEM

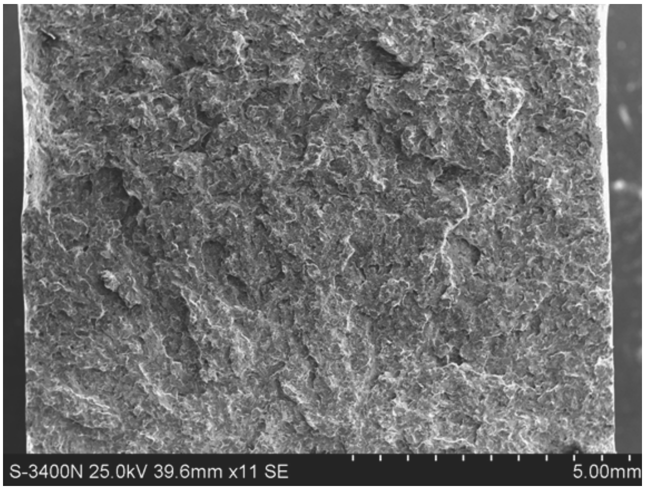
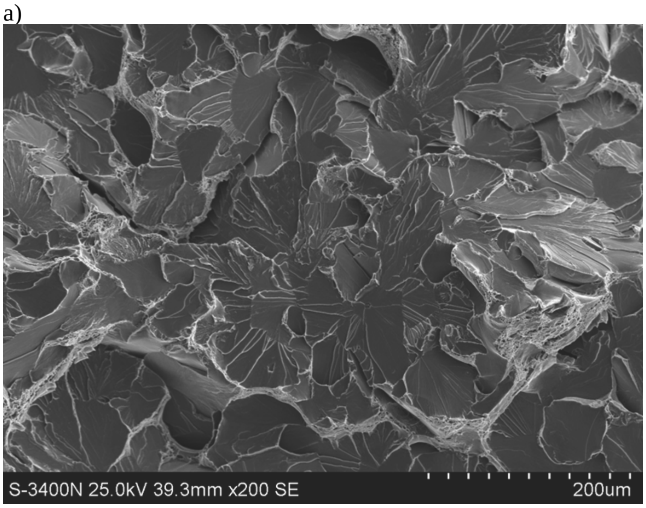


Fig. 14. Macroscopic view of fracture surface of the Charpy sample. Outer shell of the casing made of G20CrMo4-5, SEM

a)



b)

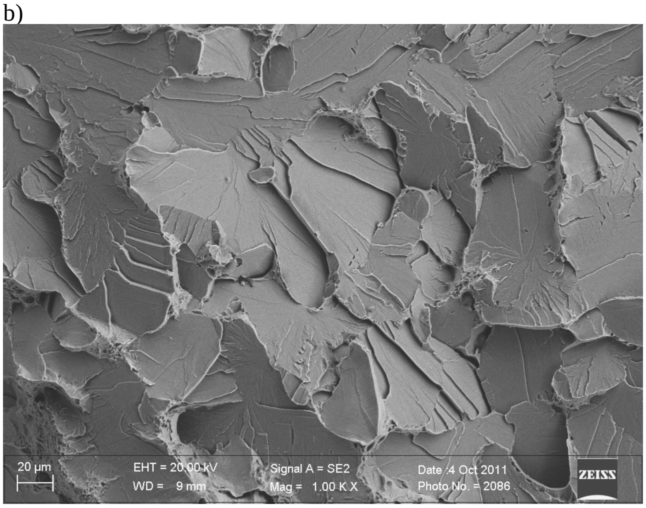


Fig. 15. Microscopic view of fracture surface of the Charpy sample. Outer shell of the casing made of G20CrMo4-5, SEM

5. Conclusions

- The cracking of the turbine outer casing occurred during cooling of the casing (near room temperature) due to various causes.
- The main cause was stress distribution and stress changes during service of the turbine.
- The microstructure of the casing outer shell composing of ferrite and bainite/perlite is more susceptible to cracking than tempered martensite microstructure of the inner shell.
- Carbides coagulation process occurs at ferrite grain boundaries which increased embrittlement of material.
- Casting imperfections (big nonmetallic inclusions) also contribute to brittleness of material and the causes of the outer shell cracking [5-15].

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