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Effect of Mechanical Properties of Material on Strength and Resistance to Fracture of the Turbine Runner Cover at Hpp 'Djerdap 1'

RESUME

Vertical Kaplan turbines with nominal output power of 200 MW, fabricated in Russia, are installed in six hydroelectric generating units of the hydroelectric power plant 'Djerdap I'. The calculation of all basic and dynamic loads turbine parts are subjected to (runner blades, all parts of the blade rotating mechanism, runner casing, runner cover, shaft, stator cylinder of the turbine, apparatus guide etc.) has been performed during the design process, while mechanical properties of the material are just a starting point for the evaluation of the resistance to fracture. In order to perform the evaluation of integrity and estimation of service life of turbine components, it is necessary to carry out the analytical and numerical calculation of strength based on the stress state, and in some cases experimental tests in order to obtain fracture mechanics parameters.

Turbine runner cover of the hydroelectric generating set A6 at HPP 'Djerdap 1' has been made of cast steel 20GSL. The results of chemical composition analysis, hardness testing and metallographic tests performed on 2 samples in the longitudinal and transverse cross-section are presented in this paper, as well as mechanical tests that refer to yield strength (R_{02}), tensile strength (R_m) and impact strength KCU that were carried out on four samples cut out from the turbine cover.

Results of tests performed on two samples confirmed that chemical composition meets the requirements of standard GOST 977/88, and also that results of hardness tests according to Vickers (HV10) and Brinell HB (2,5/187,5/20"), as well as that results of microhardness tests according to Vickers (HV1) meet the predefined technical requirements. It has also been established that both samples in the longitudinal cross-section have coarse grained ferrite-pearlite microstructure with large local porosity, while in the transverse cross-section both samples have dendritic ferrite-pearlite microstructure, which could cause the fracture to occur. Results of tests carried out on 4 samples showed that values of yield strength (R_{02}), tensile strength (R_m) and impact strength KCU for all samples meet the requirements of the standard, while values of parameters which define the plasticity of base material, elongation A_5 and contraction Z, have a large dispersion. Two samples meet the requirements of the standard (A_5 = 23% i A_5 = 27%), while two have significantly lower values of elongation (A_5 = 8% and A_5 = 9%).

Taking into account the fact that values of A_5 and Z are not universal and that it is impossible to evaluate whether the fracture mechanism could be implemented for the runner cover material, analytical and numerical calculations of stress state and experimental tests in order to determine the fracture mechanics parameters were carried out. Test results that referred to fatigue crack growth rate da/dN showed that internal deformations shaped as circles or ellipses (detected through ultrasonic testing), with an initial size up to 6 mm, will not disturb the reliable operation of the cover for the next 29 years.

Keywords: *hydro turbine, runner cover, cast steel 20GSL,* resistance to fracture, service life

Uticaj Mehaničkih osobina materijala na čvrstoću i otpornost na lom poklopca radnog kola turbine NA hidroelektrani „Đerdap 1"

REZIME

Na šest hidro – generatorskih jedinica „Đerdap 1" ugrađene su vertikalne cevne turbine Kaplan, nominalne izlazne snage 200 MW, izrađene u Rusiji. U okviru projekta turbine izvršen je proračun tehničkih resursa svih osnovnih i dinamičkih opterećenja delova turbine (lopatica radnog kola i svih delova obrtnog mehanizma lopatica, kućišta radnog kola, poklopca radnog kola, vratila, cilindra statora turbine, vođica aparata itd.), pri čemu mehaničke osobine materijala predstavljaju samo polaznu osnovu za ocenu otpornosti na lom. *Za ocenu integriteta i procenu veka delova turbine neophodno je izvršiti i proračun čvrstoće (analitički, numerički) na osnovu naponskog stanja i u nekim slučajevima eksperimentalna ispitivanja parametara mehanike loma.*

Poklopac radnog kola turbine agregata A6 na hidroelektrani „Đerdap 1" izrađen je od čeličnog liva 20GSL. U radu su dati rezultati analize hemijskog sastava, merenja tvrdoće i metalografskih ispitivanja u uzdužnom i poprečnom preseku dva uzorka, isečenih iz epruveta ispitanih zatezanjem u Centralnoj laboratoriji fabrike LMZ (Sankt Peterburg, Rusija), kao i rezultati ispitivanja granice tečenja (R_{02}), zatezne čvrstoće (R_m) i energije udara KCU za **četiri** *uzorka isečena iz poklopca radnog kola.*

Ispitivanjem dva uzorka je utvrđeno da hemijski sastav odgovara zahtevima standarda GOST 977/88, da tvrdoće po Vikersu (HV10) i Brinelu HB (2,5/187,5/20"), kao i mikrotvrdoće po Vikersu (HV1) odgovaraju definisanim tehničkim uslovima, ali da oba uzorka u uzdužnom preseku imaju ukrupnjenu zrnasto feritno - perlitnu mikrostrukturu sa mestimičnom krupnom poroznošću, a u poprečnom preseku dendritnu, feritno - perlitnu mikrostrukturu, koja može da dovede do loma. Rezultati ispitivanja sprovedeni na četiri uzorka su pokazali da vrednosti granice tečenja (R_{02}), zatezne čvrstoće(R_m) i energije udara KCU za sve uzorke zadovoljavaju zahteve standarda, a da vrednosti koje definišu plastičnost osnovnog materijala, izduženje A_5 i suženje Z, imaju veliko rasipanje. Dva uzorka zadovoljavaju zahteve standarda (A_5 = 23% i A_5 = 27%), dok dva imaju značajno manja izduženja (A_5 = 8% i A_5 = 9%).

S obzirom da vrednosti A_5 i Z nisu univerzalne i da je nemoguće proceniti da li će se u ovom materijalu poklopca radnog kola implementirati mehanizam loma, izvršeni su analitički i numerički proračuni naponskog stanja i eksperimentalna ispitivanja parametara mehanike loma. Rezultati ispitivanja brzine rasta zamorne prsline da/dN su pokazali da unutrašnje deformacije oblika kruga ili elipse (greške utvrđene ultrazvučnim ispitivanjem), početne veličine do 6 mm, omogućuju pouzdan rad poklopca 29 godina.

Keywords: *hydro turbine, runner cover, cast steel 20 GSL,* resistance to fracture, service life

1. INTRODUCTION

Vertical Kaplan turbines, made in Russia and with nominal power of 200 MW each, are installed in 6 hydroelectric generating sets at hydro power plant „Đerdap 1" [1]. They have been designed for the service life of 40 years due to their structural solution or, to put it differently, due to the incapability to perform periodic inspections and state analyses. Basic components of the hydroelectric generating set A6 are presented in figure 1, while basic components of the turbine runner cover are presented in figure 2.

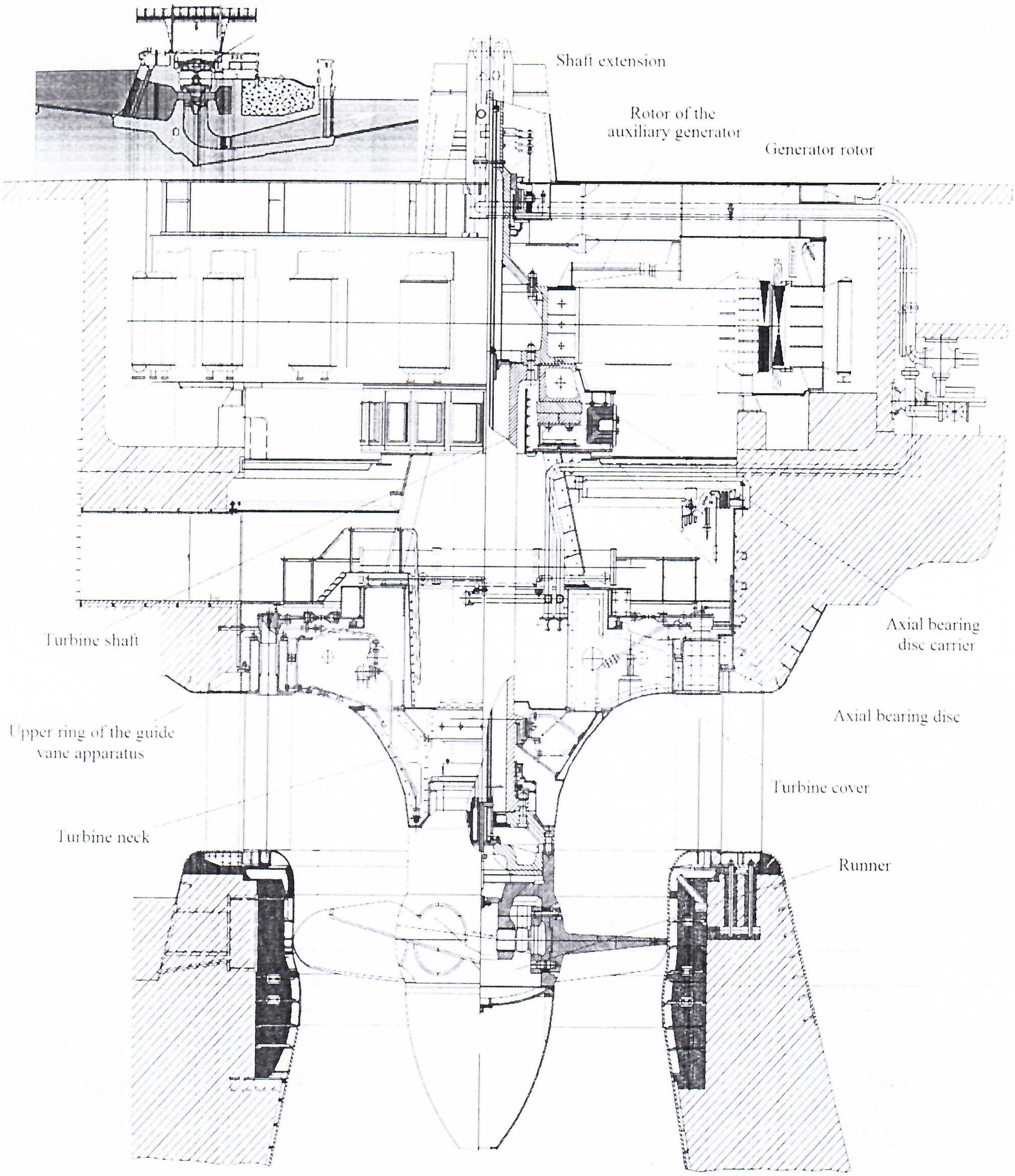


Figure 1. *Appearance of the vertical Kaplan turbine, nominal power 200 MW*

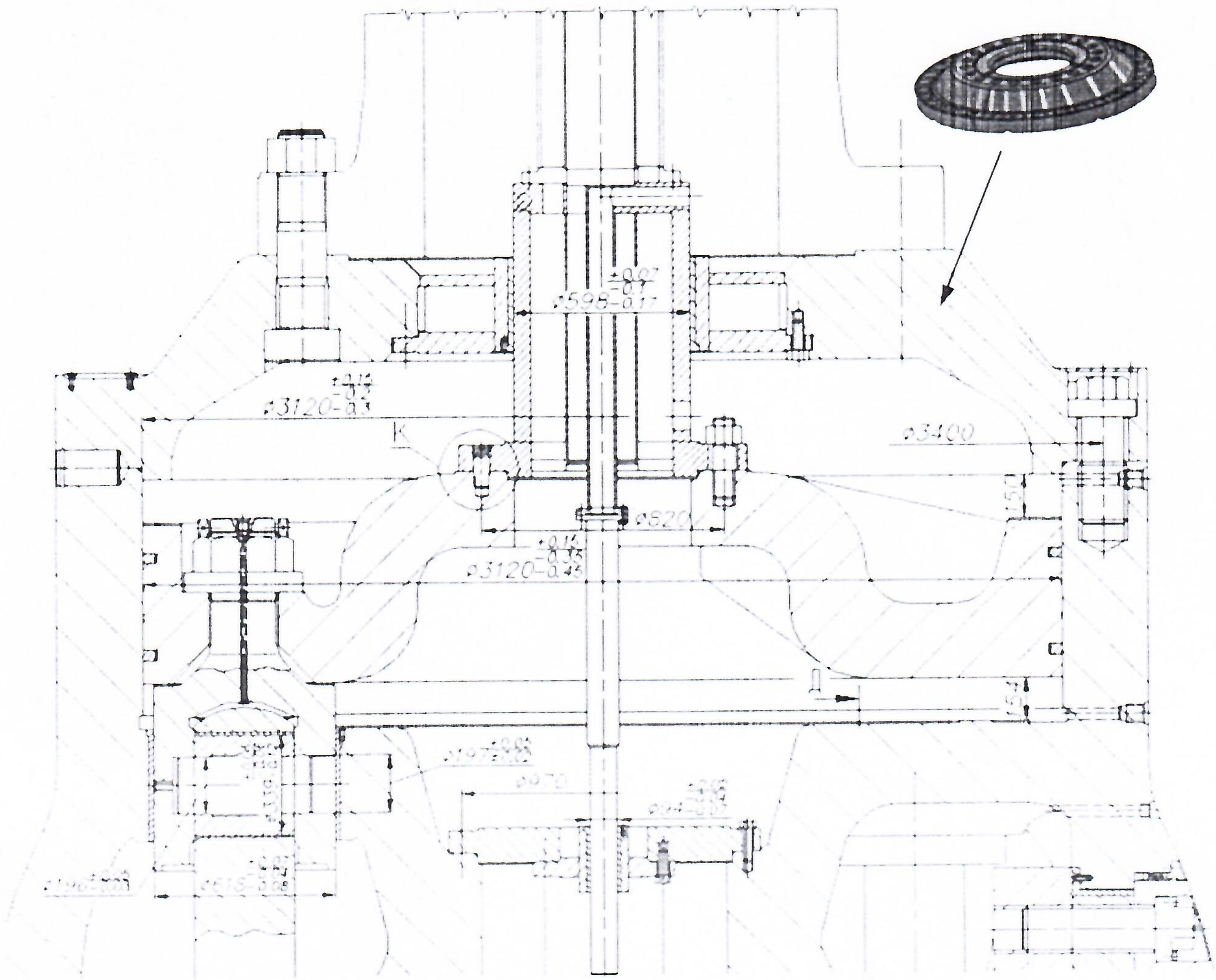


Figure 2. *Segment of the vertical Kaplan turbine, runner cover model*

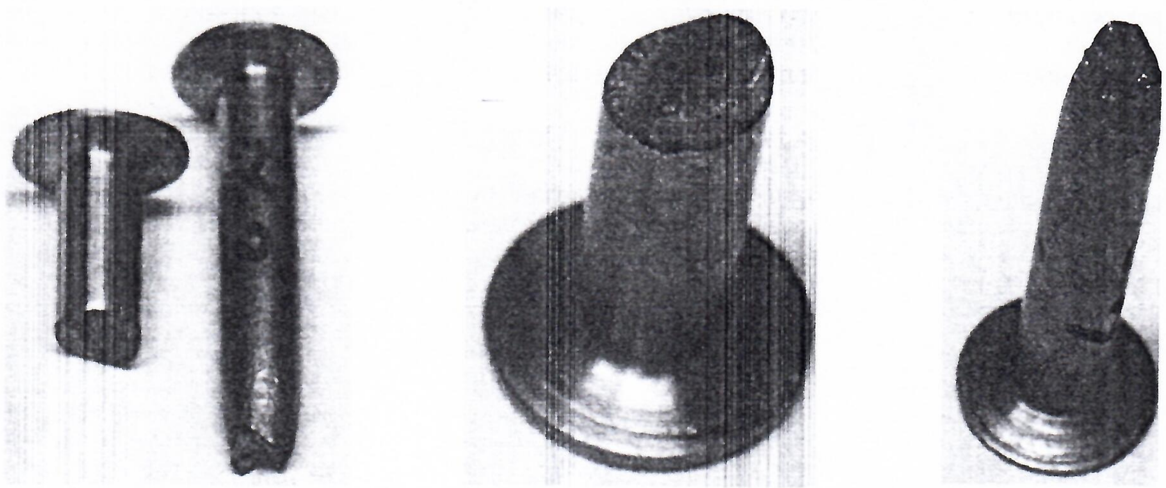
Design and putting into exploitation of the hydro power plant comprises a series of complex tasks. Researches carried out all around the world, which consider the reliability of turbine and hydromechanical equipment, mostly refer to fatigue corrosion, cavitation and vibrations of the turbine as a whole. State analyses of turbine and turbomechanical equipment in Serbia are recent and very modest in scope. That is one of the reasons why comprehensive researches that are supposed to improve determination of equipment condition have been carried out lately. A certain number of researches, which were used for the assessment of the resistance to fracture of the turbine runner cover, are listed under literature [2 – 8].

2. EXPERIMENTAL TESTS

During the fabrication of the turbine runner cover which was made of cast steel 20GSL [9], for the hydroelectric generating set A6, the analysis of chemical composition, hardness testing and metallographic testing were carried out on two samples in the longitudinal and transverse cross-section, cut out from samples subjected to tensile testing in the central laboratory of LMZ Power Machines company (Saint Petersburg, Russia) [8].

2.1 Sampling for Specimen Fabrication

Specimens subjected to tensile testing and their fracture surfaces are presented in figure 3. Specimen labels are 4 – 1 and 4 – 2. Surfaces have been prepared for metallographic tests by grinding, polishing and abrasion through the use of 3% nital. Tests have been performed through the use of METAVAL microscope, designed by 'Carl Zeiss', by using the brightfield technique.



a) Specimens b) Specimen 4 – 1 c) Specimen 4 – 2

Figure 3. *Appearance of specimens and fracture surfaces*

2.2 Chemical Composition

Results of chemical analysis, for which the samples of turbine runner cover were used, are presented in Table 1. Based on results of this analysis it was concluded that the chemical composition of analyzed samples meets the requirements of GOST 977-88, aside from certain deviations in Mn percentage. It should be noted that alloying elements Ni and Cr had an effect on the enhancement of mechanical properties.

Table 1. Results of chemical analysis

% mass	C	Si	Mn	S	P	Ni	Cr	Mo	V	Al
Sample 4 – 1	0,213	0,747	1,349	0,014	0,028	0,221	0,296	0,041	0,009	0,058
Sample 4 – 2	0,217	0,758	1,380	0,017	0,030	0,214	0,291	0,046	0,009	0,063
GOST 977- 88	0,16 - 0,22	0,60 - 0,80	1,00 - 1,30	≤ 0,030	≤ 0,030	–	–	–	–	–

2.3 Hardness Testing

Hardness values according to Vickers and Brinnel, in the longitudinal and transverse cross-section of samples, are acceptable, although slightly higher than those required by Technical conditions nr. 108.11.158-86, where minimum prescribed values range from 124 to 151 HB, tables 2 and 3.

Table 2 Hardness testing results (HV10), in accordance with SRPS C. A4.030:1986

Sample	Longitudinal cross-section	Transverse cross-section
4 – 1	156, 158, 156	143, 147, 148
4 – 2	147, 165, 176	168, 167, 160

Table 3 Hardness testing results (HB 2,5/7500/20«), in accordance with SRPS C. A4.003:1985

Sample	Longitudinal cross-section	Transverse cross-section
4 – 1	148, 150, 153	147, 150, 152
4 – 2	156, 158, 160	156, 158, 158

2.4 Microhardness Testing

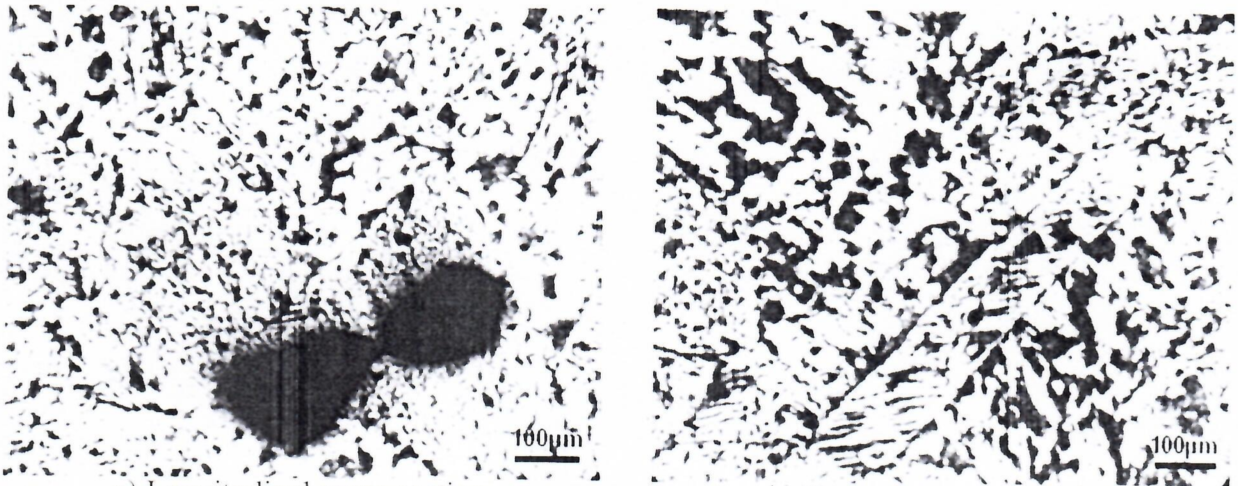
Microhardness testing results according to Vickers (HV1), performed on metallographic samples in the longitudinal and transverse cross-section, are presented in table 4.

Table 4 Microhardness testing results (HV1), in accordance with SRPS 4516:1993

Sample	Longitudinal cross-section	Transverse cross-section
4 – 1	159, 156, 165	182, 178, 175
4 – 2	185, 178, 175	178, 175, 182

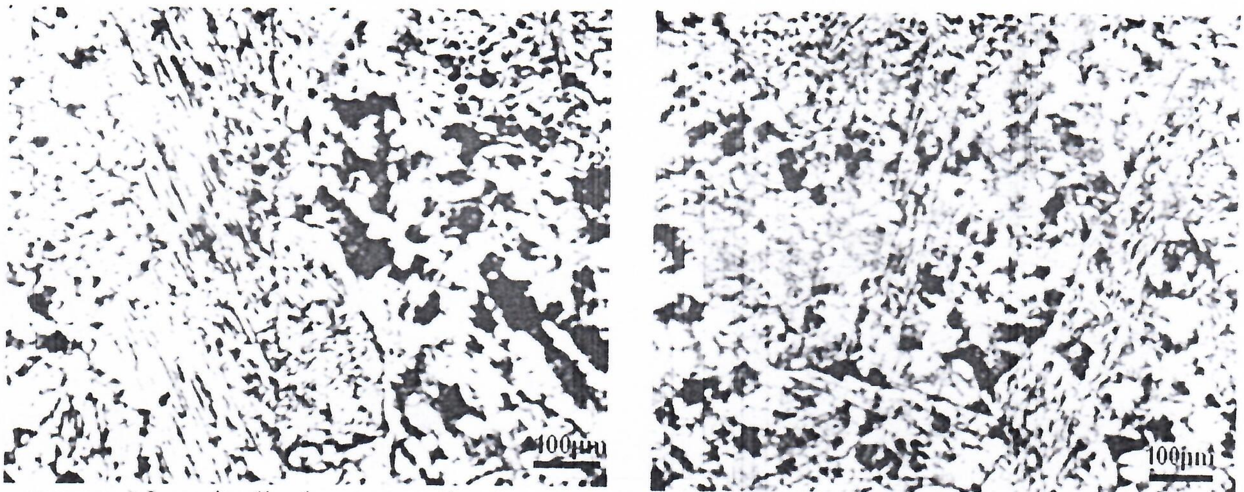
2.5 Metallographic Tests

Metallographic tests, performed on samples 4 - 1 and 4 - 2, are presented in figures 4 and 5.



a) Longitudinal cross-section b) Transverse cross-section

Figure 4. *Microstructure of sample 4 - 1*



a) Longitudinal cross-section b) Transverse cross-section

Figure 5. *Microstructure of sample 4 - 2*

Through the inspection of the longitudinal cross-section it was determined that the microstructure is coarse grained ferrite-pearlite with local porosity. At cross-sections of sample 4 – 1 it was determined that the microstructure is dendritic ferrite-pearlite, while the microstructure of sample 4 – 2 is nonuniform ferrite-pearlite, with the remains of dendrite microstructure. Results of microstructural testing showed that nonhomogeneity is more noticeable at longitudinal cross-sections of samples. Brittle fracture of specimen 4 – 1 (figure 3b) could be explained by the presence of large pores, as shown in figure 4a.

2.4 Additional Experimental Tests

Taking into account that on the basis of results of tests performed on samples 4 – 1 and 4 – 2 it was impossible to estimate the effect of mechanical properties of material on strength and implementation of the fracture mechanism for the turbine runner cover, additional experimental tests were carried out on four samples, cut out from the runner cover.

2.4.1 Mechanical Tests

Results of mechanical tests, which were carried out on four samples, showed that values of yield strength (R_{02}), tensile strength (R_m) and impact strength KCU for all samples meet the requirements of the standard, while values of parameters which define the plasticity of base material, elongation A_5 and contraction Z, have a large dispersion. Two samples meet the requirements of the standard (A_5 = 23% and A_5 = 27%), while two have significantly lower values of elongation (A_5 = 8% and A_5 = 9%).

2.4 Fracture Mechanics Tests

Results of fracture mechanics tests, performed in order to obtain values of the following parameters (critical stress intensity factor - KIc, critical length of the fatigue crack - a_c, fatigue threshold - ΔKth, Paris Law constant - C, Paris Law exponent - m_p, fatigue crack growth rate - da/dN) are presented in table 5.

Table 5. Fracture mechanics parameters at 23°C, for the stress intensity factor range ΔK=10 [$MPa \cdot m^{1/2}$]

Specimen	KIc [$MPa \cdot m^{1/2}$]	ac [mm]	ΔKth [$MPa \cdot m^{1/2}$]	C [(m/cycle)/ ($MPa \cdot m^{1/2}$) ^{mp}]	m_p	da/dN [m/cycle]
With reduced plasticity	46,3	9,3	7,4	$5,7 \times 10^{-11}$	3,15	$6,36 \times 10^{-08}$
With adequate plasticity	50,4	10,2	8,7	$3,0 \times 10^{-11}$	3,02	$5,11 \times 10^{-08}$
Minimum allowed value of KIc for 20GSL at temperatures below 0° C is KIc = 41 - 44 [$MPa \cdot m^{1/2}$]						

3. EFFECT OF PLASTICITY REDUCTION DURING RUNNER COVER CASTING ON FATIGUE STRENGTH

Effect of plasticity reduction and internal defects on fatigue of cast steel 20GSL is important concerning the establishment of technical conditions for casting, norms for allowable defects and quality inspection. For that purpose and with participation of representatives of LMZ factory and Mechanical Engineering Institute AN from Saint Petersburg, the mechanisms of microcrack initiation and conditions of propagation from microcracks to macrocracks have been established. Tests have been carried out on specimens of dimensions from 100 to 300 mm. Analysis of test results enabled the establishment of the empirical dependency which enables the evaluation of resistance to fatigue of cast steel with internal defects, or in other words with reduced plasticity:

$$\sigma_{-1}^{*} = \frac{\sigma_{-1}}{(1+\beta \cdot d_{max})^{1/2}} \qquad (1)$$

where: σ_{-1} – lower limit of fatigue strength dispersion;
β – coefficient which depends on properties of the metal;
d_{max} – maximum defect size in cast material.

As a result of testing of cast steels with reduced plasticity the dependency between stress amplitude σ_{-1} and maximum number of loading cycles N (Wöhler's fatigue strength curve), which with the calculated scale factor has the following form:

$$\lg(\sigma_{-1}) = 2,69 - 0,155 \times \lg(N) \qquad (2)$$

It was determined that defect sizes from 0,2 to 0,5 mm in 20GSL do not influence fatigue strength, as well as that maximum allowable defect size of d = 1.5 mm causes the reduction of fatigue strength from σ_{-1} = 118,5 MPa to σ_{-1} = 91,15 MPa, in which case the corrosion-fatigue strength reserve (safety level) is still satisfactory, S_σ = 1,63.

5. ASSESSMENT OF RUNNER COVER SERVICE LIFE THROUGH THE USE OF FRACTURE MECHANICS

Assessment of runner cover service life through the use of fracture mechanics has been carried out according to methodology presented in the paper [7]. In the area of stable crack growth, Paris' Law describes the behaviour of the material with sufficient accuracy:

$$\frac{da}{dN} = C \cdot (\Delta K)^{m_p} \qquad (3)$$

where: ΔK – stress intensity factor range, which is, when the internal defect exists, being calculated by the following equation:

$$\Delta K = \Delta\sigma\sqrt{\frac{1.21\pi a}{Q}} \tag{4}$$

For the internal defect measuring 6 mm in diameter in the steel cast 20GSL, detected by ultrasonic inspection, characteristic magnitude is circle radius or half-length of the short axis of the ellipse, which magnitude a_0 is being calculated by the following equation:

$$a_0 = \frac{\sqrt{3}}{2}d = \frac{\sqrt{3}}{2}6 = 5{,}2m \tag{5}$$

Stress intensity factor K_I is being calculated by the following equation, when the internal defect exists:

$$K_I = \sigma_{max}\sqrt{Ma_0} = 98{,}5\sqrt{2.38\times 0.0052} = 11 \quad \text{MPa}\sqrt{\text{m}} \tag{6}$$

where: σ_{max} – maximum operational stress ;
M – coefficient which depends on shape and dimensions of defects and structure, M = 1,25 π/Q,
a_0 – characteristic size of the defect;
Q – defect shape parameter,
$\Delta\sigma$ – stress range, which is being calculated by the following equation:

$$\Delta\sigma = \frac{\sigma_{max} - \sigma_{min}}{2} = \frac{98{,}5 - 93{,}6}{2} = 2{,}45mm \tag{7}$$

For the ratio of half-lengths of the short and long axis of the defect ellipse $a/2c = 0.3$, as well as for the ratio of the maximum projected stress on the turbine cover and yield strength for the specimen with the lowest plasticity $\sigma_{max}/R_{02} = 98{,}5/309 = 0{,}32$, value of defect shape parameter is Q = 1.65 [10].
Critical length of the internal crack in cast steel in which deformation weakening occurs, which can cause the fracture in the structure, can be calculated by the following equation (6):

$$a_{cr} = \frac{1}{M}\left(\frac{K_{Ic}}{\sigma_{max}}\right)^2 = \frac{1}{2{,}38}\left(\frac{46{,}3}{98{,}5}\right)^2 = 92{,}8mm \tag{8}$$

Number of cycles until reaching the critical size of the internal defect within the turbine runner cover, made of cast steel 20GSL with reduced plasticity, gets calculated through the integration of Paris' equation, as well as values from table 5 and other calculated values:

$$N = \frac{2}{(m_P - 2)\cdot C_P \cdot M^{\frac{m_P}{2}} \cdot \Delta\sigma^{m_P}}\left(\frac{1}{a_0^{\frac{m_P-2}{2}}} - \frac{1}{a_{cr}^{\frac{m_P-2}{2}}}\right) = 2{,}61\cdot 10^{10} \tag{9}$$

Number of load cycles during a one year period is:

$$Nu = n_h \cdot 60 \cdot 7000 \cdot 30 = 71{,}43 \cdot 60 \cdot 7000 \cdot 30 = 9 \cdot 10^8 \text{cycles} \tag{10}$$

where: n_h – number of revolutions of the hydroelectric generating set, n_h = 71.43 o/min;
60 – number of minutes per hour,
7000 – overall number of hours of operation of the hydroelectric generating set during a one year period,
30 – number of years of operation number of the hydroelectric generating set.

Estimated service life of the turbine runner cover with reduced plasticity is:

$$n = \frac{N}{N_u} = \frac{2{,}61\cdot 10^{10}}{9\cdot 10^8} = 29 \text{ years} \tag{11}$$

CONCLUSION

Results of fatigue strength tests carried out on large specimens, as well as obtained values of fracture mechanics parameters enabled the estimation of service life of the turbine runner cover with reduced plasticity (particularly fatigue corrosion).

Based on the analysis of mechanical properties, as well as metallographic tests and fracture mechanics tests performed on samples of the new turbine runner cover meant for installation in hydroelectric generating set A6 at HPP 'Djerdap 1', and taking into account the long-term experience, it can be generally concluded that resistance to fracture of the cover is basically influenced by the non-homogeneity of the casting and characteristics of the environment during exploitation (or, to put it differently, fatigue corrosion).

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