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REPAIR OF CRACKS DETECTED IN CAST COMPONENTS OF VERTICAL KAPLAN TURBINE ROTOR HUB

REPARACIJA PRSLINA OTKRIVENIH NA LIVENIM KOMPONENTAMA VERTIKALNE KAPLAN TURBINE ROTORA

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Keywords
- hydroelectric generating station
- generator rotor hub
- crack
- repair technology

Ključne reči
- hidroelektrični generator
- sistem rotora generatora
- prslina
- tehnologija reparacije

Abstract

During the revitalization of the hydroelectric generating station A4 at the hydro power plant 'Djerdap 1', all of its parts are subjected to non-destructive testing. Cracks are detected in cast part of generator rotor hub, in the flange area toward the turbine shaft. Cracks were 10-500 mm long (determined by magnetic particle tests) and 60-100 mm deep (ultrasonic tests). The generator rotor hub is made of cast steel 25L, in accordance with the standard 977-75.

The welding/surface welding repair technology in the detected crack zones of the cast part of generator rotor hub includes a large number of details, due to the structural solution and generator rotor function in service. It was also necessary to provide the carefully undertaken activities in order to enable safe operation and continuous use of the rotor hub. Failing to notice, underestimation or incorrect perception of important details could cause significant problems in hydroelectric generating station operation. The paper, due to specifics of reparation technology, contains arranged preparatory activities for the procedure apart from the welding/surface welding technology.

It is of importance to mention a huge amount of money savings, The manufacture of a new generator rotor would cost over 4 million EUR (generator mass is over 300 tonnes), not taking into account the time needed for its making (6-12 months), which is directly related to the amount of energy a hydroelectric generating station can produce during that period. This technology of repair welding is also applicable for other components and structures of the turbine and the hydromechanical equipment subjected to various causes of damage during exploitation.

Izvod

Tokom revitalizacije hidroelektričnog generatora A4 u hidroelektrani 'Đerdap 1', izvršeno je ispitivanje bez razaranja svih delova. Prsline su otkrivene u livenim delovima rotora, u okolini prirubnice prema vratilu turbine. Njihove dužine su iznosile od 10 do 500 mm (utvrđene ispitivanjem magnetnim česticama), a dubine su bile od 60 do 100 mm (određene ultrazvučnom metodom). Rotor generatora je od livenog čelika 25L, u skladu sa standardom 977-75.

Tehnologija reparacije zavarivanjem/navarivanjem oblasti u kojima su otkrivene prsline u livenom delu rotora generatora treba da uzme u obzir veliki broj detalja, usled konstrukcijskog rešenja i funkcije rotora pri eksploataciji. Takođe je bilo neophodno obezbediti veoma pažljivo izvođenje svih aktivnosti kako bi se osigurao bezbedan i kontinuiran rad sistema rotora. Previdi, potcenjivanje ili pogrešna predstava o veoma bitnim detaljima je moglo da rezultira u ozbiljnim problemima tokom rada sistema rotora generatora. Usled specifičnosti metode reparacije, u radu su prikazane pripremne aktivnosti za ovu proceduru, pored uobičajenih aktivnosti za tehnologije zavarivanja/navarivanja.

Naročito je bitno spomenuti jako veliku novčanu uštedu, s obzirom da bi proizvodnja novog rotora koštala 4 miliona EUR (masa generatora je preko 300 tona), ne računajući vreme potrebno za proizvodnju (6-12 meseci), koje je direktno vezano za količinu energije koju bi hidroelektrični generator proizveo u tom periodu. Ova metodologija reparaturnog zavarivanja je takođe primenljiva na reparaciju drugih komponenata i konstrukcija u turbinama i hidromehaničkoj opremi, koje trpe različite mehanizme oštećenja u eksploataciji.

INTRODUCTION

Vertical Kaplan turbines are installed in 6 hydroelectric generating stations at 'Djerdap 1', of 200 MW nominal power, produced in Russia, /1/. They have been designed for service life of 40 years due to the structural solution, or in other words because of the impossibility to perform periodic inspections and state analyses. Basic components of the hydroelectric generating station A4 turbine are presented in Fig. 1. The generator rotor is presented in Fig. 2, while the cast part of the rotor hub with the marked area where cracks were detected is presented in Fig. 3.

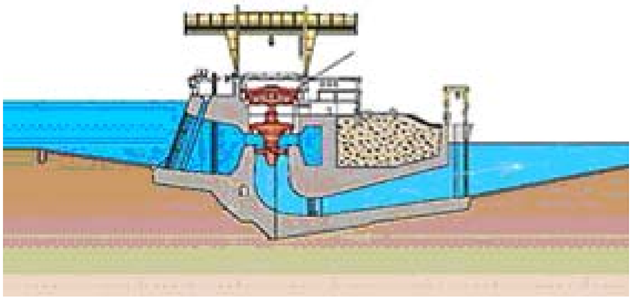
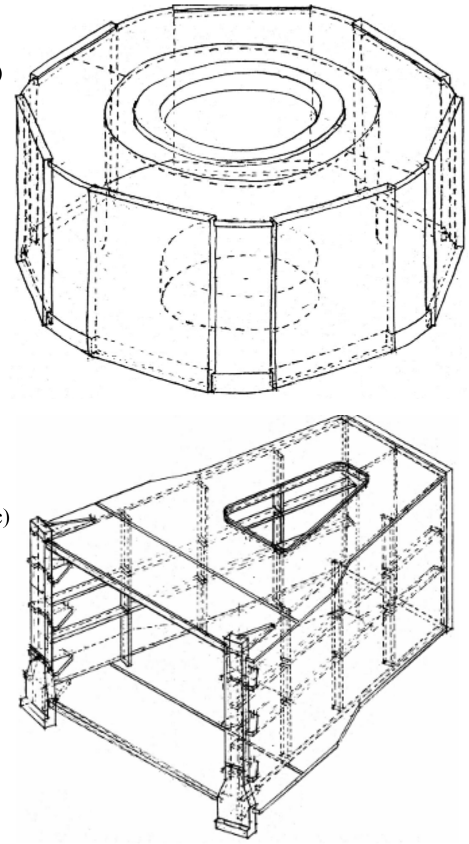


Figure 1. Appearance of the vertical Kaplan turbine.



(a)

(b)

(c)

Figure 2. Parts of generator rotor hub station: a) rotor; b) hub; c) arms.

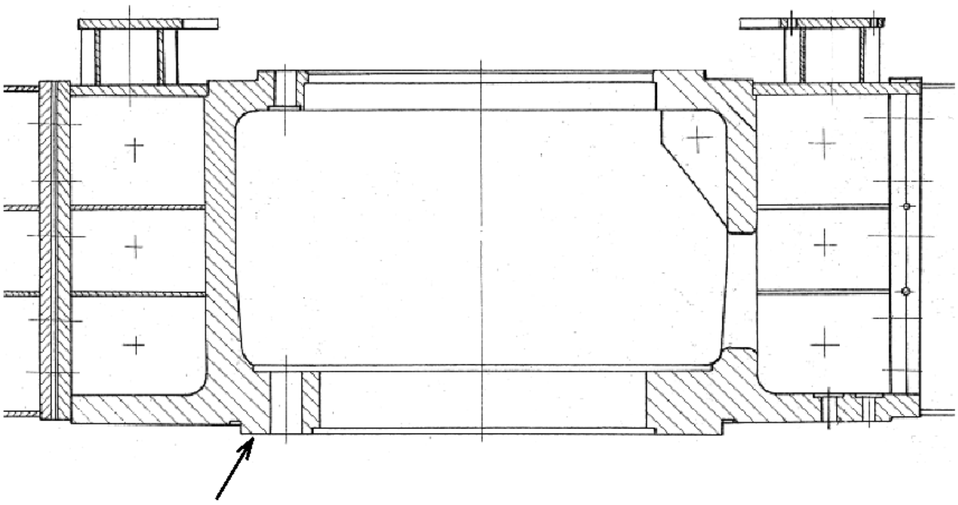


Figure 3. Generator rotor hub.

EXPERIMENTAL TESTS PERFORMED FOR DETERMINING THE STATE OF CAST HUB PART

Non-destructive tests (visual, penetrant and ultrasonic tests) are performed on the cast part of generator rotor hub in order to determine the current state of the hydroelectric generating station A4. In the area of bolts nr. 5 and 6, and in the area of bolts 19 and 20, cracks are detected 10-500 mm length and 60-100 mm depth, Figs. 4, 5 and 6. Crack indications are also detected on the surface of the opening for bolt nr.5, Fig. 4. Also, between the bolt openings repair welds are detected, created through the use of austenitic filler material during the making of the generator rotor hub.

Cracks between the openings for bolts nr. 5 and 6 are detected in the area between weld metal and base material (in the heat-affected zone) and between two repair welded joints, that are carried out with different kinds of austenitic filler material, Fig. 4. Cracks between the openings for bolts nr. 29 and 30 are detected in the weld metal of the repair weld, in the transition area between the hub and the turbine shaft, and between the hub and the axial bearing disk carrier, Figs. 5 and 6.

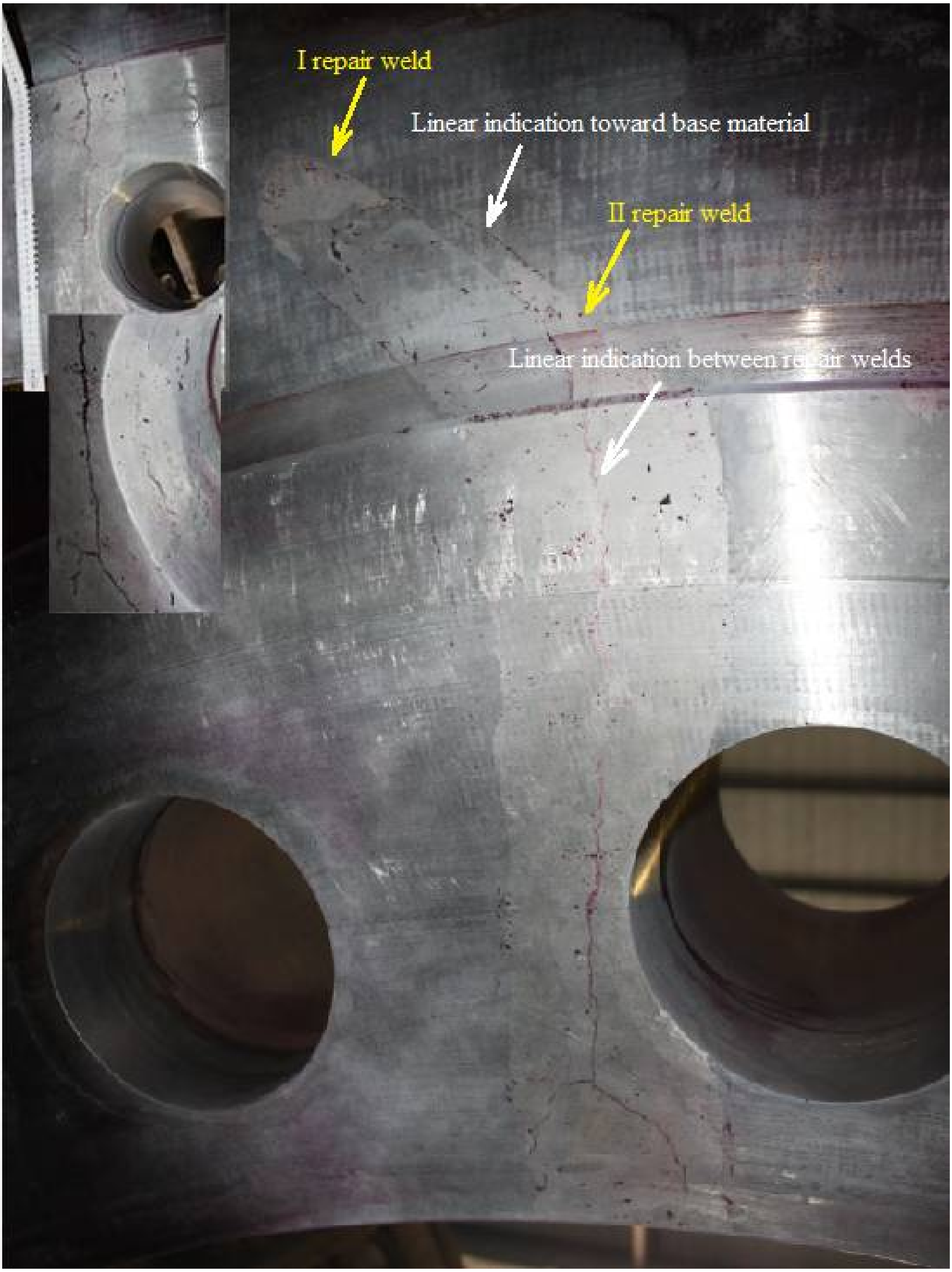


Figure 4. Cracks in the area between weld metal and base material of the hub; between two repair welds; and between openings for bolts nr. 5 and 6.

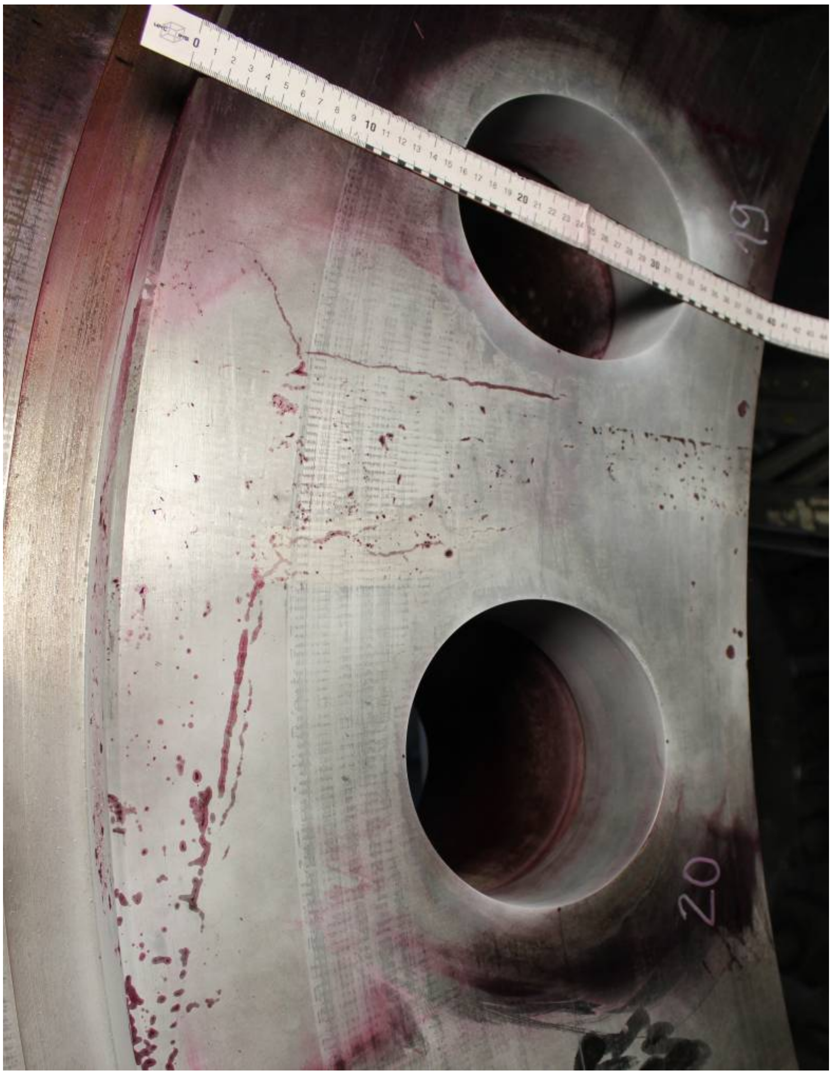


Figure 5. Cracks in the area of the repair weld (between openings for bolts nr. 19 and 20).

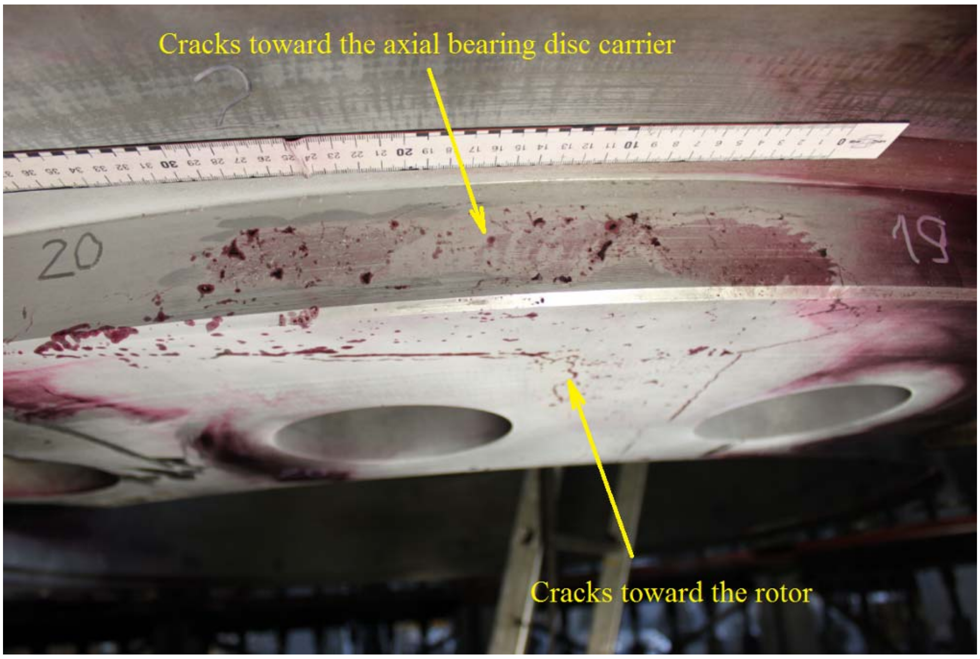


Figure 6. Cracks in the repair weld area between the hub and rotor shaft, and in the transition area from the hub toward the axial bearing (between openings for bolts nr. 19 and 20).

REPAIR WELDING TECHNOLOGY OF DETECTED CRACK ZONES

Due to the structural solution and service function of the generator rotor, the welding/surface welding repair technology of detected crack zones in the cast part of the generator rotor hub concerns a large number of details. It is necessary to carefully reconsider them and ensure that all activities are carried out with extreme care in order to enable safe operation and continuous use of the hub. Failing to notice, an underestimation, or an incorrect perception of important details may cause significant problems in the operation of the hydroelectric generating station. The paper, due to the specificity of the repair technology, contains the preparatory procedure, apart from the welding/surface welding technology.

Base material properties

Chemical composition and mechanical properties of cast steel 25L, that the cast part of the generator rotor hub is made of, are presented in Tables 1 and 2.

Table 1. Chemical composition of 25L steel material, in wt.%, from GOST 977-75, /2/.

C	Si	Mn	Cr	Ni	Cu	S	P
0.22-0.30	0.20-0.52	0.35-0.90	< 0.30	< 0.30	< 0.30	≤ 0.045	≤ 0.040

Table 2. Mechanical properties, values for normalized and annealed state of steel material 25L, GOST 977-75, /2/.

Yield stress, $R_{0.2}$ (N/mm^2)	Tensile strength, R_m (N/mm^2)	Elongation A5 (%)	Contraction Z (%)	Impact energy KCU (J/cm^2)
min. 305	min. 520	min. 21	min. 27	min. 62

Weldability analysis for cast steel 25L

According to IIW formula, Eq.(1), for values from Table 1, calculated value of carbon equivalent C_e is higher than 0.45 (limit value of good weldability), while according to Ito-Bessyo formula, Eq.(2), value of carbon equivalent C_e is above 0.3 (excellent weldability), which indicates susceptibility of material to cold cracking, and that is why it is necessary to perform repair welding/surface welding of the cast part of generator rotor hub with preheating and controlled cooling.

$$C_e = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} > 0.45\,, \qquad (1)$$

$$C_e = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Mo}{15} + \frac{Ni}{60} + \frac{V}{10} + 5B > 0.30 \qquad (2)$$

Through use of HCS (Hot Cracking Sensitivity) formula it is determined that the material is not susceptible to hot cracking, Eq.(3), because the obtained value for HCS is lower than 4 (limit value for hot cracking susceptibility in steels with tensile strength $R_m < 700$ N/mm^2).

$$HCS = 100C\frac{S + P + \frac{Si}{25} + \frac{Ni}{100}}{3Mn + Cr + Mo + V} \le 4.0 \qquad (3)$$

Due to the structural solution of the generator rotor (dimensions, mass) and conditions under which the repair is to be carried out without heat treatment, the repair welding/surface welding guidelines from Russian technical literature for steel 25L is used. According to these guidelines, when grinding depths exceed 40 mm and volumes that have to be filled are greater than 500 cm^3, the austenitic filler material has to be used. The recommended preheating temperature ranges from 100 to 150 °C, /1/, when heat treatment is not applicable.

Selection of welding procedure

Through analysis of parameters on which the selected repair welding/surface welding procedure depends (weldability of material, energy input possibilities of the welding procedure, geometric complexity of the structure, economic indicators), it is established that procedure 111 is the most suitable in this case.

Selection of filler material

Due to the large thickness of cast part of rotor hub and limited possibilities of performing preheating and heat treatment after repair welding/surface welding, the optimal solution is application of basic coated austenitic electrodes.

It is established that good properties of the weld metal and welded joints in general, when performing repair welding/surface welding on large structures and materials with low or limited weldability, are being achieved through the use of basic coated electrode ЭA 395/9 (GOST, DIN E16.25.6B20) or nickel-based electrode Castolin Xuper 2222 (EN 10204 - 2.2). Chemical compositions of pure weld metal and mechanical properties of electrode metal are presented in Tables 3-6.

Table 3. Chemical composition of pure weld metal (wt.%).

Electrode	C	Si	Mn	Cr	Ni	Mo	N	S	P
ЭA 395/9	0.09	0.50	1.60	15.5	24.5	5.70	0.12	0.009	0.020

Table 4. Mech. properties of filler metal (electrode ЭA 395/9).

Yield stress $R_{0.2}$ (N/mm^2)	Tensile strength R_m (N/mm^2)	Elongation A5 (%)	Impact energy KCU (J/cm^2)
470	690	37	210

Table 5. Chemical composition of pure weld metal, electrode Castolin Xuper 2222, values in (wt.%).

C	Si	Mn	Cr	Ni	Mo	Fe	Nb	S	P
0.024	0.17	6.13	15.9	Basic	1.03	9.26	0.009	–	–

Table 6. Mechanical properties of filler metal (electrode Castolin Xuper 2222).

Yield stress $R_{0.2}$ (N/mm^2)	Tensile strength R_m (N/mm^2)	Elongation A5 (%)	Impact energy KCU (J/cm^2)
420	673	46	130

Electrodes are dried in special furnaces before use: ЭA 395/9 electrodes at drying temperature 200-250 °C for 2 hours, while Castolin Xuper 2222 electrodes are dried at 350 °C for 2 hours. Only a single drying of electrodes is allowed, due to the possibility of coating failure because of cracking while redrying. Before use, electrodes are stored in individual cabinets at temperatures 100-120 °C.

Activities undertaken before repairs in detected crack zones

Previous repair activities in detected crack zones by repair welding/surface welding predicted the following;

- means of protection at work;
- lifting of the rotor to the height of 1.5 m from the floor of the engine room;
- first measurement of deformations of the cast part of rotor hub (planeness test) by ruler (Fig. 7) and measure controller (Fig. 8);
- marking areas where cracks are detected;
- grinding areas where cracks are detected by angle grinders until cracks are completely removed;
- final inspection of grinded areas through applied magnetic particle or penetrant testing;

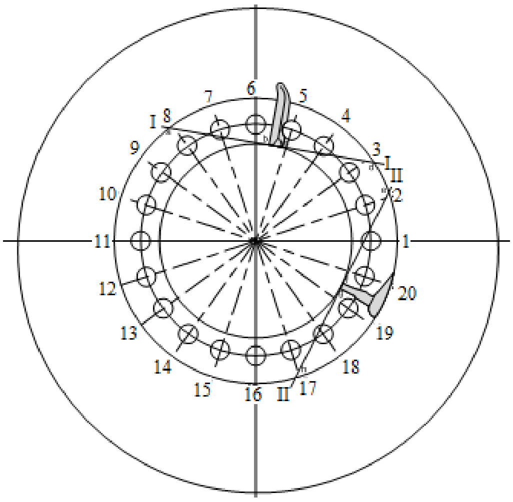


Figure 7. Planeness test for flange surface (view from below).

(a)

(b)

Figure 8. Planeness test for flange surface carried out by measure controller: a) view from below; b) side view.

- shaping grinded areas in order to remove sharp edges and prepare the surface for welding;
- specification of position, width, length, depth and volume of grinded areas;
- cleaning the surface in grinded areas and removal of anti corrosion coatings and corrosion products;
- degreasing, drying and cleaning grinded areas;
- positioning the shaped, 5 mm thick copper washer at the internal surface of the opening for bolt nr. 5;
- second measurement of deformations at the cast part of rotor hub (planeness test) by ruler.

Repair welding/surface welding operations in detected crack zones

Repair welding/surface welding in crack detected zones is performed as follows:

- positioning benchmarks for measuring deformations on generator rotor hub (planeness test);
- welding/surface welding is performed through application of austenitic filler material, along with the treatment of every layer by a pneumatic hammer with rounded top;
- shaping surface welds by flat grinders and patterns, in order to achieve a slight reinforcement (0.2-0.3 mm);
- machining surface welds by sand grinders to achieve required surface quality for non-destructive tests;
- inspection of repair welds/surface welds by magnetic particle or penetrant testing;
- welding/surface welding is repeated when necessary, until satisfactory results are achieved,
- in cases when test results are satisfactory, grinded surfaces are treated by a pneumatic hammer with rounded top (R = 5 mm) in order to reduce residual stresses in weld metal and heat affected zone;
- surface treatment is performed in zones of rotor hub flange, where surface welding is carried out, by use of abrasive material, until roughness $R_{a\,max} = 1.6$ μm is reached (allowable value of cavities and convexities is 0.03 mm);
- third measurement of deformations in cast part of rotor hub (planeness test) is performed by a ruler;
- in cases when planeness is unsatisfactory, the machining of hub flange is performed by achieving the parallelism with the surface of its coupling with the axial bearing disk carrier and with the surface of the flange, for the connection with the turbine shaft extension;
- fourth measurement of deformations in cast part of rotor hub (planeness test) is performed by a ruler.

Deformation measurement of generator rotor hub flange

Inspection of the surface condition regarding the deformations of the generator rotor hub (planeness test) is carried out before, during and after welding/surface welding, by positioning a 2 m long ruler tangentially with respect to the internal edge of the hub flange at many locations, and in areas where grinding was applied (positions I-I and II-II), presented in Fig. 7, while the planeness test carried out by measure controller is shown in Fig. 8. At measurement locations a, b, c and d for position I-I, as well as e, f, g and h for position II-II, the clearance is determined by measure controllers. Results of clearance measurement are presented in Table 7, /5/.

Table 7. Results of planeness tests carried out on flange surface (view from below).

Ruler position	Measurement location	Allowable deviation* (mm)
I-I	a	0
	b	0.03
	c	0.03
	d	0
II-II	e	0
	f	0.03
	g	0.03
	h	0
(III-III)**	i	0
	j	0.03
	k	0
(IV-IV)**	l	0
	m	0.03
	n	0

*) the turbine shaft flange connected to the rotor hub flange has allowable value of planeness deviance of 0.03 mm
**) ruler positions are not shown in Fig. 8

Repair welding/surface welding technology in detected crack zones

The repair welding/surface welding technology refers to works carried out during the repair of cast part of the generator rotor hub, at which it was necessary to perform welding/surface welding in zones where cracks are detected, depthwise and at the internal surface of the opening for bolt nr.5. The welding/surface welding technology defines all activities that are supposed to be carried out before, during and after the welding/surface welding. Cracks detected by visual, penetrant and magnetic particle tests are removed by grinding, Fig. 9.

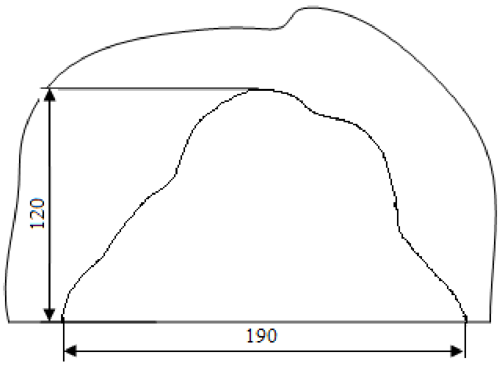


Figure 9. Appearance of the groove at location of deepest crack.

Before welding/surface welding, the grinded areas were preheated by gas flame at 120-150 °C. Butane is used for preheating, while IC thermometer is used for temperature control. After the deposition of the first weld layer, preheating was no longer necessary.

Castolin Xuper 2222 electrodes were used for welding/surface welding, diameter d = 3.2 mm, connected to the positive pole of direct current of 70-90 A. Welding/surface welding is performed by a short arc, along with the removal of slag, in the case when the width of the weld/surface weld was not higher than 2.5 × d. Welding/surface welding is carried out by depositing weld metal along the surface of ground areas with 90° change of laying direction for each layer. After the deposition, every layer is treated by a pneumatic hammer with rounded top. Grinding is performed on some of the layers in order to remove residual slag, sharp edges, pores etc. Filling of ground areas is performed through application of the overlay method with reinforcement of 1-2 layers, Figs. 11 and 12.

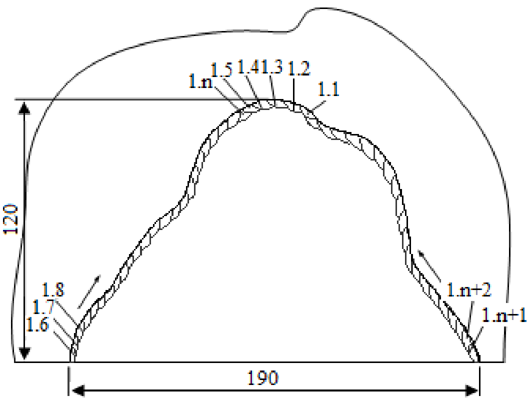


Figure 10. Welding/surface welding sequence, deposition of first layer.

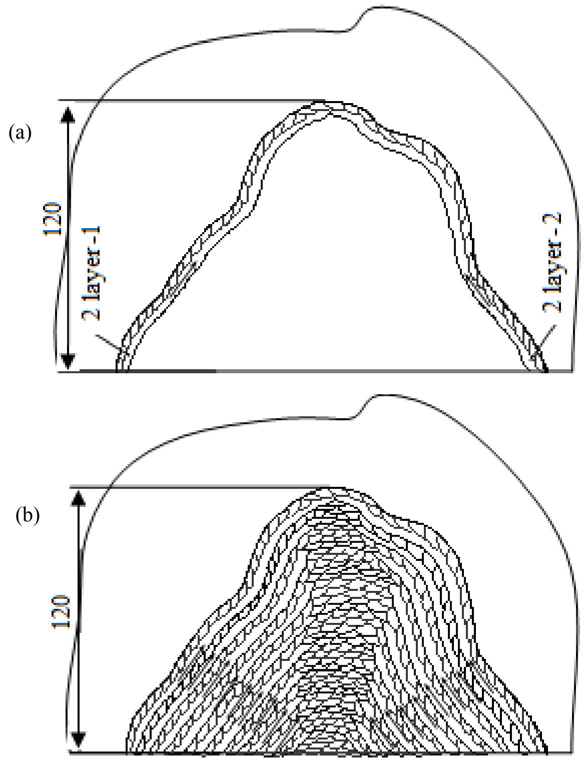


Figure 11. Deposition sequence of the second layer (a); and final appearance of the repair weld/surface weld (b).

RESULTS AND DISCUSSION

Repair welds are subjected to non-destructive testing after the repair of cast part of the generator rotor hub. Visual tests are carried out in accordance with the standard EN 970:1997, /6/, and acceptance criteria from the standard EN 5817:2007, /7/, (for class B), while penetrant tests are carried out in accordance with standard EN 571-1:2005, /8/, and acceptance criteria from standard EN 1289:2005, /9/, (for class 1). It is established that repair welding/surface welding is carried out successfully, thus enabling continued service of the generator rotor until the next revitalization of the turbine, or in other words for the upcoming period of 40 years.

CONCLUSION

Success of the applied repair technology carried out in detected crack zones on the cast part of the generator rotor hub is acknowledged by equipment manufacturer 'Силовые машины' from Saint Petersburg, Russia, because they guaranteed the safe use of rotor until the next refurbishment of the turbine, or in other words for the upcoming period of 40 years.

It should also be noted that a huge amount of money is saved, since manufacture of a new generator rotor would cost over 4 million EUR (mass of generator is over 300 tonnes), not taking into account the time needed for its making (6-12 months), which is directly related to the amount of energy a hydroelectric generating station would produce during that period.

The presented repair welding technology is also applicable for reparation of other components and structures of turbine and hydromechanical equipment subjected to various causes of damage in exploitation.

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