# METODOLOGIJA REPARATURNOG ZAVARIVANJA PRSLINA NA LIVENOM DELU GLAVČINE ROTORA GENERATORA AGREGATA A4 NA HIDROELEKTRANI ĐERDAP 1

# METHODOLOGY OF REPAIR WELDING IN ZONES WHERE CRACKS WERE DETECTED ON THE CASTED PART OF THE GENERATOR ROTOR HUB OF THE HYDROELECTRIC GENERATING SET A4 AT HYDRO POWER PLANT DJERDAP 1

**Miodrag Arsić[1], Brane Vistać[1], Vencislav Grabulov[1], Srđan Bošnjak[2], Zoran Savić[1]**

[1]*Institute for materials testing, Bulevar vojvode Mišića 43, Belgrade, miodrag.arsić@institutims.rs*
[2]*Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, sbosnjak@mas.bg.ac.rs*

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***Keywords:*** *hydroelectric generating set, generator rotor hub, crack, repair technology*

**Sažetak:**

U toku revitalizacije agregata A4 na hidroelektrani Đerdap 1, u cilju utvrđivanja stanja izvršena su eksperimentalna ispitivanja metodama bez razaranja svih njegovih delova. Tako su na livenom delu glavčine rotora generatora, u zoni prirubnice prema vratilu turbine, utvrđene greške tipa prsline, dužina od 10 do 500 mm (ispitivanja magnetnim česticama) i dubina prostiranja od 60 do 100 mm (ispitivanja ultrazvukom). Predmetni deo glavčine rotora generatora izrađen je od čeličnog odlivka oznake 25L, prema standardu GOST 977 – 75.

Metodologijom reparaturnog zavarivanja/navarivanja prslina na livenom delu glavčine rotora generatora je, zbog konstrukcijskog rešenja i funkcije u eksploataciji rotora generatora, trebalo veliki broj detalja precizirati, pažljivo razmotriti i koordinisano izvršiti u cilju sigurnosti za ponovno korišćenje glavčine, jer ukoliko se samo neki od njih previde, podcene ili nepravilno sagledaju mogu nastati značajni problemi u radu agregata kao celine. U radu je, zbog specifičnosti sprovedene metodologije za sanaciju prslina, pored tehnologije zavarivanja/navarivanja data i procedura pripremnih radova.

Posebno treba istaći i veliki finansijski efekat koji je ostvaren, jer samo izrada konstrukcije novog rotora generatora koštala bi više od 4.000.000 € (masa generatora je veća od 300 t), ne računajući vreme potrebno za njegovu izradu (od 6 do 12 meseci) što je u direktnoj vezi sa količinom hidro energije koju bi jedan agregat proizveo u tom periodu. Izneta metodologija reparaturnog zavarivanja primenljiva je i za sanaciju drugih delova i konstrukcija turbinske i hidromehaničke opreme izloženih različitim uzrocima oštećenja u eksploataciji.

**Abstract**

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

The repair methodology by welding / surface welding in zones where cracks were detected at the casted part of the generator rotor hub has to, due to the structural solution and function in service of the generator rotor, embrace a large number of details, carefully reconsider them and

ensure carrying out of all activities with extreme care in order to enable the safe operation and continuous use of the hub. Overlooking, underestimation or incorrect perception of important details could cause significant problems during the operation of the hydroelectric generating set. This paper, due to the specificity of the repair methodology, contains the preparatory works procedure apart from the welding / surface welding technology.

It should especially be noted that a huge amount of money was saved, because the making of the new generator rotor would cost more than 4.000.000 € (mass of the generator is larger than 300 t), not taking into account the time needed for its making (6 – 12 months), which is directly related to the amount of energy a hydroelectic generating set would produce during that period. This methodology of repair welding is also applicable for the reparation of other components and structures of turbine and hydromechanical equipment subjected to various causes of damage during exploitation.

## 1. INTRODUCTION

Vertical Kaplan turbines are installed in 6 hydroelectric generating sets at "Djerdap 1", nominal power 200 MW, that were made in Russia [1]. They have been designed for the service life of fourty years due to the structural solution, or in other words because of the impossibility of performing periodic inspections and state analyses. Basic components of the hydroelectric generating set A4 turbine are presented in figure 1, generator rotor is presented in figure 2, while casted part of the rotor hub with the marked area where cracks were detected is presented in figure 3.

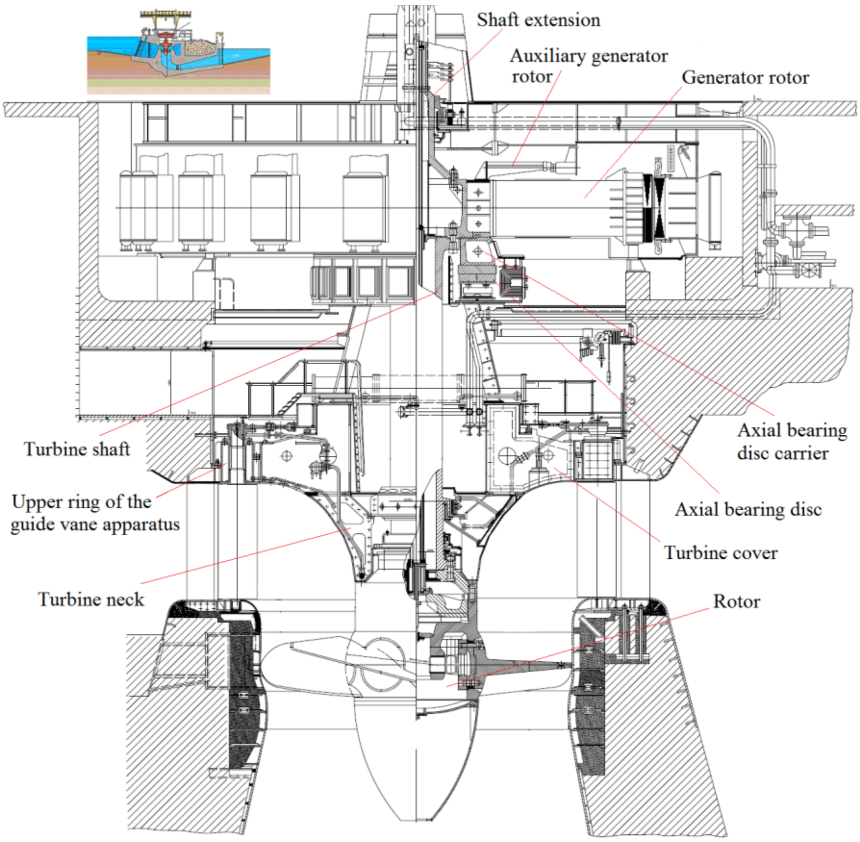
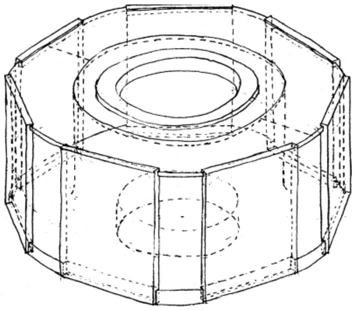
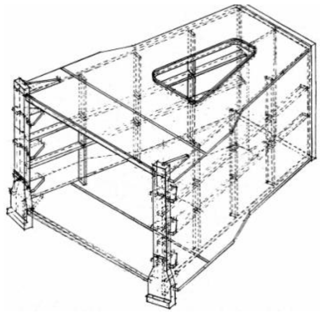



***Figure 1**. Appearance of the vertical Kaplan turbine, nominal power 200 MW*

*a) Part of the generator rotor*



*b) Part of the generator rotor hub*



*c) Generator rotor arms*

***Figure 2**. Generator rotor*

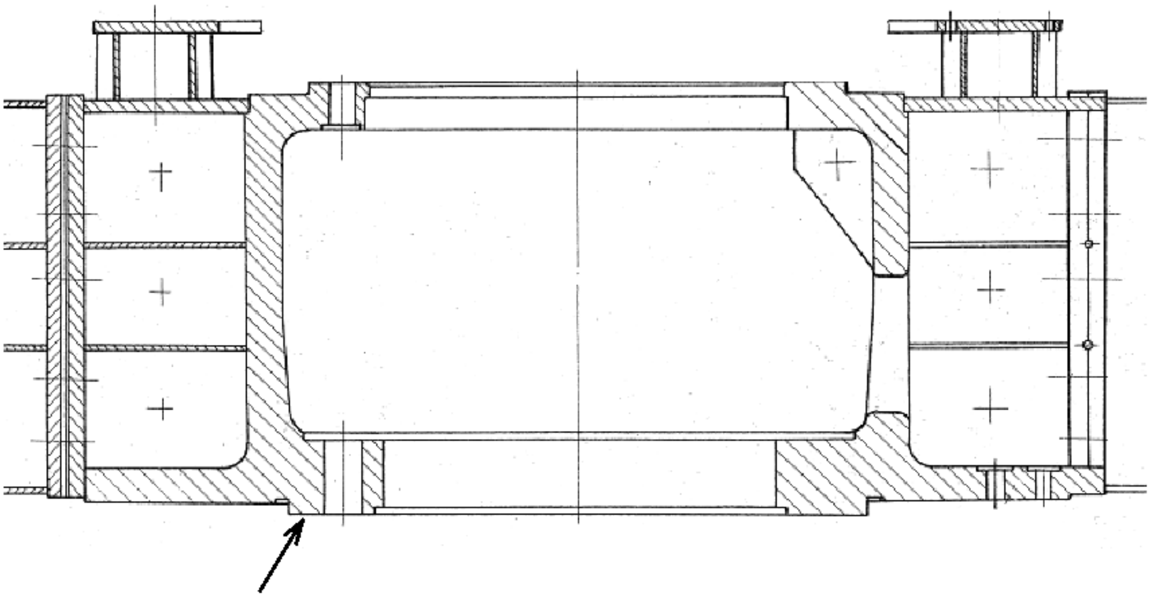



***Figure 3.** Generator rotor hub*

## 2. EXPERIMENTAL TESTS PERFORMED IN ORDER TO DETERMINE THE CURRENT STATE OF THE CASTED PART OF THE HUB

Non-destructive tests (visual testing, penetrant testing and ultrasonic testing) were performed on the casted part of the generator rotor hub in order to determine the current state of the hydroelectric generating set A4. In the area of bolts nr. 5 and 6, as well in the area of bolts 19 and 20, 10 – 500 mm long and 60 – 100 mm deep cracks were detected, figures 4, 5 and 6. Crack indications were also detected at the surface of the opening for the bolt nr. 5, figure 4. Also, between the bolt openings repair welds were 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 were detected in the area between weld metal and base material (in the heat-affected zone) and between two repair welded joints, carried out by using different kinds of austenitic filler material, figure 4. Cracks between the openings for bolts nr. 29 and 30 were detected in 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 disc carrier, figures 5 and 6.

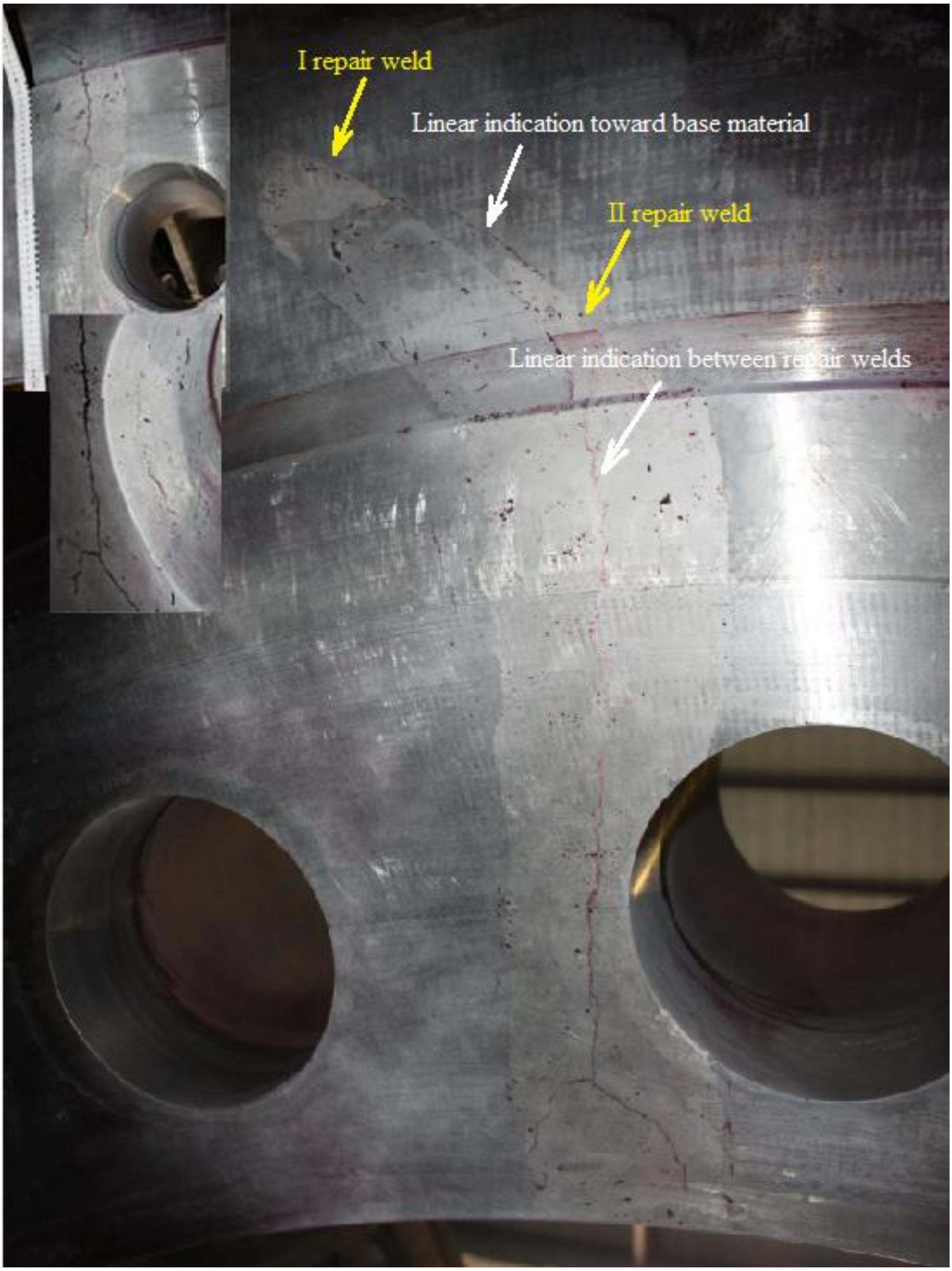



***Figure 4.*** *Cracks in the area between weld metal and base material of the hub, between two repair welds and between openings for bolts nr. 5 and 6*

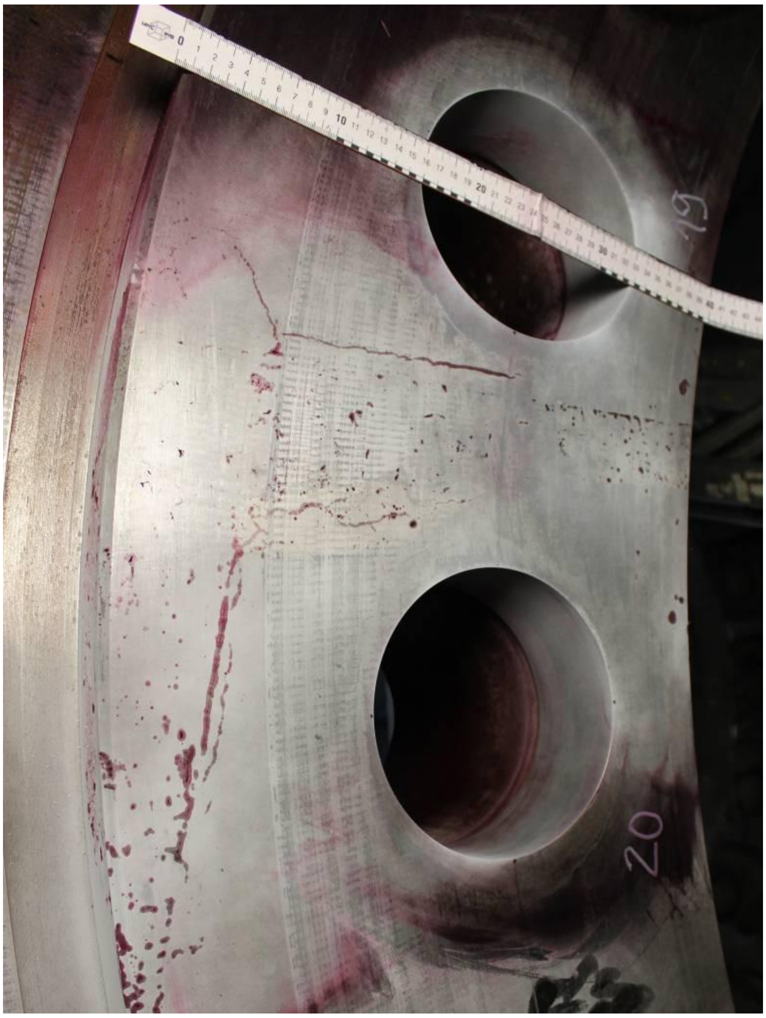



***Figure 5.*** *Cracks in the area of the repair weld (between openings for bolts nr. 19 and 20)*

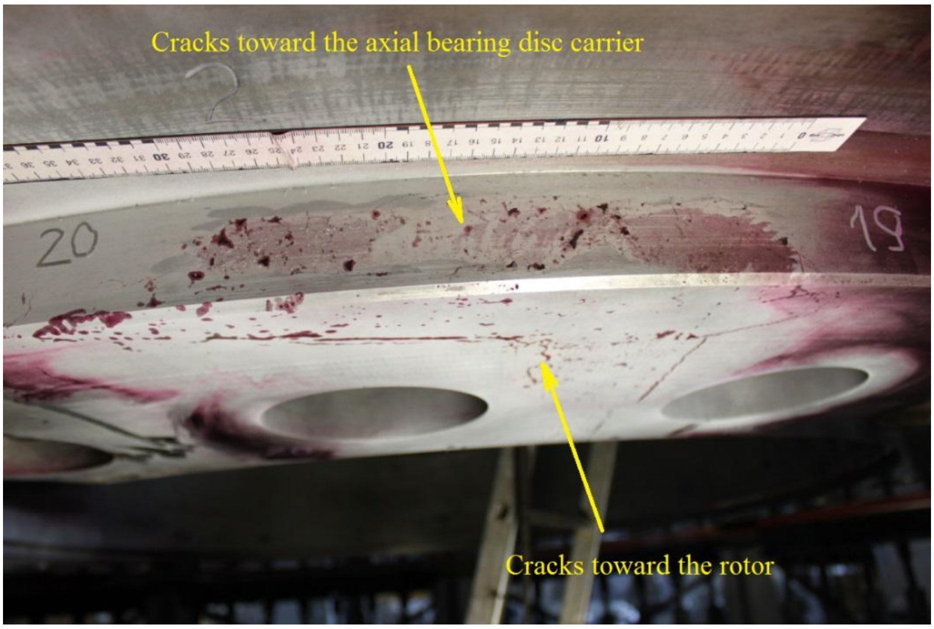



***Figure 6.*** *Cracks in the repair weld area between the hub and rotor shaft, and in the transition area from the hub toward the axial bearing (between openings for bolts nr. 19 and 20)*

# 3. METHODOLOGY OF REPAIR WELDING/SURFACE WELDING IN ZONES OF THE CASTED PART OF THE GENERATOR ROTOR HUB OF THE HYDROELECTRIC GENERATING SET A4 WHERE CRACKS WERE DETECTED

The repair methodology by welding/surface welding in zones at the casted part of the generator rotor hub where cracks were detected needs to, due to the structural solution and service function of the generator rotor, embrace a large number of details, carefully reconsider them and ensure carrying out of all activities with extreme care in order to enable the safe operation and continuous use of the hub. Overlooking, underestimation or incorrect perception of important details could cause significant problems during the operation of the hydroelectric generating set. This paper, due to the specificity of the repair methodology, contains the preparatory works procedure apart from the welding/surface welding technology.

**Properties of Base Material**

Chemical composition and mechanical properties of cast steel 25L, of which the casted part of the generator rotor hub was made, are presented in tables 1 and 2.

***Table 1.*** *Chemical composition, values in [%], according to GOST 977-75 [2]*

| Material | C | Si | Mn | Cr | Ni | Cu | S | P |
|---|---|---|---|---|---|---|---|---|
| 25L | 0.22 - 0.30 | 0.20 - 0.52 | 0.35 - 0.90 | $< 0.30$ | $< 0.30$ | $< 0.30$ | $\leq 0.045$ | $\leq 0.040$ |

***Table 2.*** *Mechanical properties, values for normalized and annealed state, GOST 977-75 [2]*

| Material | Yield stress $R_{0.2}$ [N/mm$^2$] | Tensile strength $R_m$ [N/mm$^2$] | Elongation A5 [%] | Contraction Z (%) | Impact energy KCU [J/cm$^2$] |
|---|---|---|---|---|---|
| 25L | min 305 | min 520 | min 21 | min 27 | min 62 |

**Weldability Analysis for Cast Steel 25L**

According to IIW formula (equation 1), for values given in 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 (equation 2), value of carbon equivalent $C_e$ is higher than 0.3 (value of excellent weldability), which indicates the proneness of material to the occurrence of cold cracks, and that's why it is necessary to perform repair welding/surface welding at the casted part of the generator rotor hub with preheating and controlled cooling.

$$Ce = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 > 0.45 \quad (1)$$
$$Ce = C + Si/30 + (Mn + Cu + Cr)/20 + Mo/15 + Ni/60 + V/10 + 5B > 0.30 \quad (2)$$

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

$$HCS = 100C\,(S+P+Si/25+Ni/100) / (3Mn+Cr+Mo+V) \leq 4.0 \quad (3)$$

Due to the structural solution for the generator rotor (dimensions, mass) and conditions under which the repair is supposed to be carried out without heat treatment, for repair welding/surface welding the recommendation from the russian technical literature for steel 25L was used. According to that recommendation, when depths of grindings exceed 40 mm and volumes which have to be filled are greater than 500 cm$^3$, austenitic filler material has to be used. Recommended preheating temperature ranges from 100 to 150ºC [1] when heat treatment is not applicable.

## Selection of Welding Procedure

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

## Selection of Filler Material

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

It was established that good properties of weld metal and welded joints in general when performing repair welding / surface welding at large structures and on materials with low or limited weldability are being achieved through the use of the 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 4 – 7.

The electrodes were dried before use in special furnaces, ЭA 395/9 electrodes at a drying temperature of 200 – 250 $^o$C for 2 hours, while Castolin Xuper 2222 electrodes were subjected to the drying temperature of 350$^o$C for 2 hours. Only one drying of electrodes is allowed, due to the possibility of coating failure because of cracking during the redrying. Before being used, electrodes are being stored in individual heaters (wallets) at temperatures ranging from 100 to 120 $^o$C.

Through welding qualifications it was determined that welded joints formed through the use of Castolin Xuper 2222 electrodes are less deformed than those formed through the use of ЭA 395/9 electrodes, figure 7 [3, 4].

***Table 4.*** *Chemical composition of pure weld metal, values in [%]*

| 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 5.*** *Mechanical properties of filler metal*

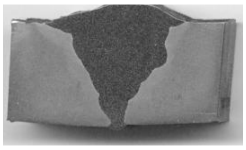
| Electrode | Yield stress $R_{0.2}$ [N/mm$^2$] | Tensile strength $R_m$ [N/mm$^2$] | Elongation A5 [%] | Impact energy KCU [J/cm$^2$] |
|---|---|---|---|---|
| ЭA 395/9 | 470 | 690 | 37 | 210 |

***Table 6.*** *Chemical composition of pure weld metal, values in [%]*

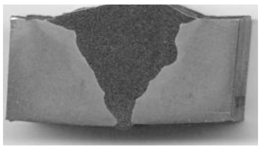
| Electrode | C | Si | Mn | Cr | Ni | Mo | Fe | Nb | S | P |
|---|---|---|---|---|---|---|---|---|---|---|
| Castolin Xuper 2222 | 0,024 | 0,17 | 6,13 | 15, 9 | Basic | 1,03 | 9,26 | 0,009 | – | – |

***Table 7.*** *Mechanical properties of filler metal*

| Electrode | Yield stress $R_{0.2}$ [N/mm$^2$] | Tensile strength $R_m$ [N/mm$^2$] | Elongation A5 [%] | Impact energy KCU [J/cm$^2$] |
|---|---|---|---|---|
| Castolin Xuper 2222 | 420 | 673 | 46 | 130 |



*a) Welding electrode ЭА 395/9*



*b) Welding electrode Castolin Xuper 2222*

***Figure 7***. *Macrographic images of welded joints*

### Preparatory Works Undertaken before Repairs in Zones Where Cracks Were Detected

Preparatory works for repairs in zones where cracks were detected by repair welding/surface welding predicted the following;

Means of protection at work,

Lifting of the rotor at the height of 1.5 m from the floor of the engine room;

Performing of first measurement of deformations at the casted part of the rotor hub (planeness test) by a ruler (figure 8) and measure controller (figure 9);

Marking of areas where cracks were detected;

Grinding in areas where cracks were detected by angle grinders until the cracks are completely removed;

Final inspection of grinded areas through the utilization of magnetic particle testing or penetrant testing;

Shaping of 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 of the surface in grinded areas and removal of anticorrosion protection and corrosion products;

Degreasing, drying and cleaning of grinded areas;

Positioning of the shaped, 5 mm thick copper washer at the internal surface of the opening for the bolt nr. 5;

Performing of second measurement of deformations at the casted part of the rotor hub (planeness test) by a ruler.

### Order of Operations During Repair Welding/Surface Welding in Zones Where Cracks Were Detected

Repair welding/surface welding in zones where cracks were detected was performed as follows;

Positioning of benchmarks for the measurement of deformations of generator rotor hub (planeness test);

Welding/surface welding was performed through the application of austenitic filler material, along with the treatment of every layer by a pneumatic hammer with the rounded top;

Shaping of surface welds through the utilization of flat grinders and patterns, in order to achieve a slight reinforcement (0.2 – 0.3 mm;

Machining of surface welds by sand grinders in order to achieve required quality of surfaces for non-destructive tests;

Inspection of repair welds/surface welds by the magnetic particle testing method or penetrant testing method;

Welding/surface welding was repeated when necessary, until satisfactory results were achieved, In cases when test results were satisfactory, grinded surfaces were treated by a pneumatic hammer with the rounded top (R = 5 mm) in order to reduce residual stresses in weld metal and heat affected zone;

Surface treatment was performed in zones of rotor hub flange where surface welding was carried out through the use of abrasive material, until machining quality $Ra_{max}$ = 1,6 μm was reached (allowable value of cavities and convexities is 0.03 mm);

Third measurement of deformations at the casted part of the rotor hub (planeness test) was performed by a ruler;

In cases when planeness was unsatisfactory, the machining of hub flange was performed by achieving the parallelness with the surface of its coupling with the axial bearing disc carrier and with the surface of the flange for the connection with the turbine shaft extension;

Fourth measurement of deformations at the casted part of the rotor hub (planeness test) was performed by a ruler.

## Deformation Measurement at the Generator Rotor Hub Flange

Inspection of surface condition regarding the deformations of the generator rotor hub (planeness test) was carried out before, during and after welding / surface welding, by positioning 2 m long ruler tangentially with respect to the internal edge of the hub flange at many locations and in areas where grinding occurred (positions I – I and II – II), which is presented in figure 8, while planeness test carried out by the measure controller is shown in figure 9. 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 was determined by measure controllers. Results of clearance measurement are presented in table 8 [5].

***Table 8***. *Results of planeness testing carried out on flange surface (view from below)*

| | | Date of measurement | | | | Allowable deviation*) [mm] |
|---|---|---|---|---|---|---|
| Ruler position | Measurement location | First measurement | Second measurement | Third measurement | Fourth measurement | |
| 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 |
| *) | For the turbine shaft flange, which is being connected with the rotor hub flange, allowable value of planeness deviance is 0,03 mm. | | | | | |
| **) | Ruler positions are not shown in fig. 8 | | | | | |

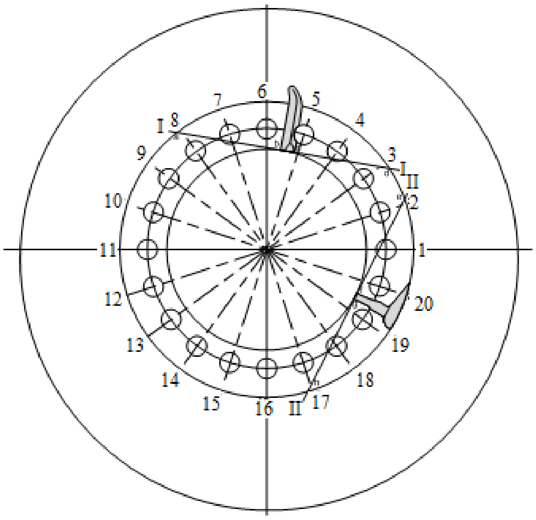
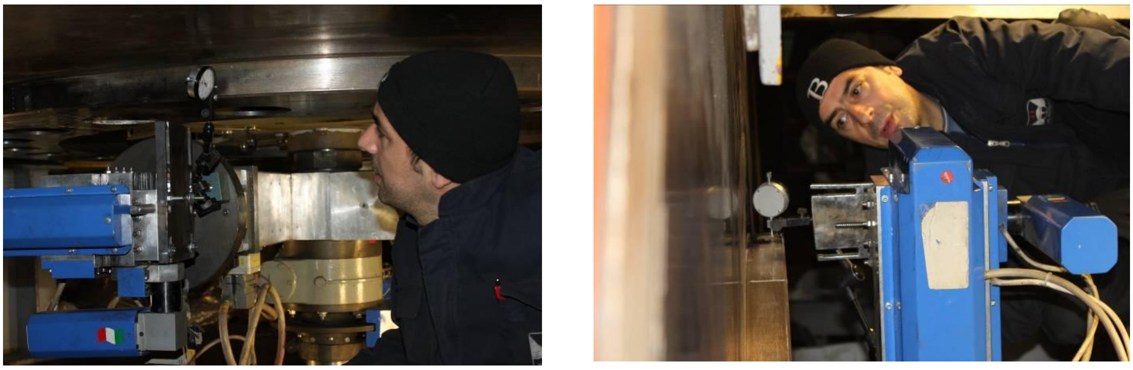



***Figure 8***. *Planeness test for flange surface (view from below)*



*a) View from below* *b) Side view*

***Figure 9.*** *Planeness test for flange surface carried out by measure controller*

**Technology of Repair Welding / Surface Welding in Zones Where Cracks Were Detected**

This technology of repair welding/surface welding refers to works carried out during the repair of the casted part of the generator rotor hub, at which it was necessary to perform welding / surfaace welding in zones where cracks were detected, depthwise and at the internal surface of the opening for the bolt nr. 5. Technology of welding/surface welding defines all activities that are supposed to be carried out before, during and after welding/surface welding. Cracks detected by visual testing, penetrant testing and magnetic particle testing were removed by grinding, figure 10.


***Figure 10.*** *Appearance of the groove at the location where the deepest crack was detected*

Before welding/surface welding, areas where grinding occurred were preheated by a gas flame at temperatures ranging from 120 $^{o}$C to 150 $^{o}$C. Butan was used for preheating, while IC thermometer was 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 with intensity of 70 – 90 A. Welding/surface welding was 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 x d. Welding/surface welding was carried out by depositing weld metal along the surface of grinded areas with the change of laying direction of 90 $^{o}$ for every layer. After the deposition, every layer was treated by a pneumatic hammer with the rounded top. Grinding was performed on some of the layers in order to remove residual slag, sharp edges, pores etc. Filling of grinded areas was performed through the application of the overlay method with the reinforcement of 1 – 2 layers, figures 11 and 12.

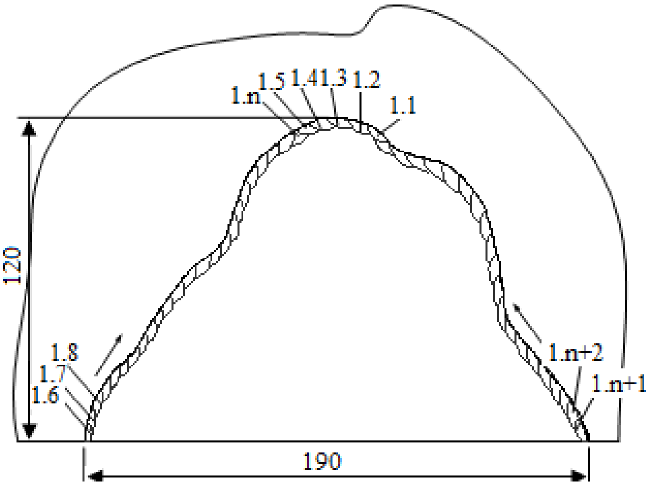
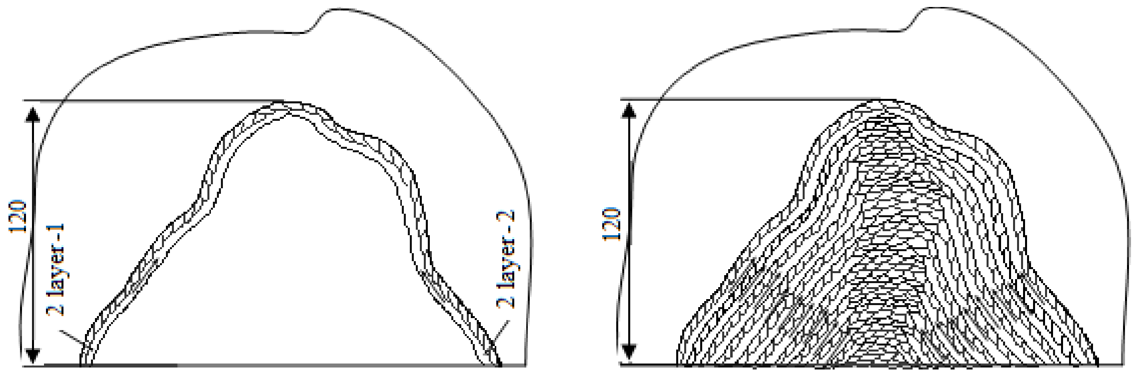



***Figure 11.*** *Sequence of welding/surface welding, deposition of the first layer*




*a) Sequence of deposition of the second layer*

*b) Appearance of the repair weld/surface weld*

***Figure 12.*** *Sequence of deposition of the second layer and final appearance of the repair weld/surface weld*

## 4. RESULTS AND DISCUSSION

Repair welds were subjected to non-destructive testing after the repair was performed at the casted part of the generator rotor hub. Visual testing was 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 testing was carried out in accordance with the standard EN 571–1:2005 [8] and acceptance criteria from the standard EN 1289:2005 [9] (for class 1). It was established that repair welding/surface welding has been carried out successfully, which enables the continuous service of the generator rotor until the next refurbishment of the turbine, or in other words for the upcoming period of 40 years.

## 5. CONCLUSION

Successfulness of the repair methodology carried out in zones where cracks were detected at the casted part of the generator rotor hub has been acknowledged by the equipment manufacturer „Силовые машины" from Saint Petersburg, because they guaranteed that rotor could be safely used 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 was saved, because the making of the new generator rotor would cost more than 4.000.000 € (mass of the generator is larger than 300 t), not taking into account the time needed for its making (6 – 12 months), which is directly related to the amount of energy a hydroelectic generating set would produce during that period.

Presented methodology of repair welding is also applicable for the reparation of other components and structures of turbine and hydromechanical equipment subjected to various causes of damage during exploitation.

## 6. ACKNOWLEDGEMENT

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