Z. Odanović, V. Grabulov, M. Arsić , M. Djurdjević, B. Katavić

IZBOR OPTIMALNOG DODATNOG MATERIJALA ZA REPARATURNO ZAVARIVANJE VRATILA TURBINE HIDROCENTRALE NA LICU MESTA

SELECTION OF THE OPTIMAL FILLER MATERIAL FOR ON-SITE REPAIR WELDING OF THE TURBINE SHAFT AT THE HYDROPOWER PLANT

Originalni naučni rad / Original scientific paper

UDK / UDC: 621.791:621.224-233.1

Rad primljen / Paper received:

01.11. 2011.

Ključne reči: Vratilo turbine, reparaturno zavarivanje, dodatni materijal.

Adresa autora / Author's address:

Dr Zoran Odanović, Dr Vencislav Grabulov, Dr Miodrag Arsić, IMS Institut, Beograd, Srbija.

Dr Mile Đurđević, Nemak Linz, Linz, Austria.

Dr Boris Katavić, Institut Goša, Beograd, Srbija.

Keywords: Turbine shaft, repair welding, filler material.

Izvod

Najznačajniji delovi hidroelektrana, vratila turbina izložena su tokom rada visokim naprezanjima, puzamju, zamoru i koroziji. Zbog toga je korisno predupred iti oštećenja tokom rada, povećati pouzdanost i produžiti radni vek postrojenja. Eksploatacioni uslovi mogu da dovedu do prslina i loma u homogenom materijalu, tako da postoji potreba za reparaturom dela postrojenja. A ona može biti skupa ili dugotrajna. U okolnostima kada se reparatura izvodi na licu mesta, posebno pažljivo treba da se definiše tehnologija reparaturnog zavarivanja, parametri postupka, i izbor dodatnog materijala. U ovom istraživanju izbor dodatnog materijala je bio tema i dati su rezultati.

Vratilo je izrađeno od čeličnog liva 20Mn5 i na njemu su metodama IBR, otkrivena oštećenja tipa prslina dužine do 400 mm i dubine do 20 mm. Kako je planirano da se reparatura izvede bez demontaže vratila, primena termičke obrade nije bila izvodljiva. Analiza zavarljivosti osnovnoog materijala urađena je korišćenjem analitičkih jednačina. Rezultati su pokazali da je zavarljivost ovog čelika ograničena.

Za reparaturno zavarivanje izabran je postupak REL (111) i dve obložene austenitne elektrode sa ciljem određivanja pogodnosti za upotrebu kao potencijalnih dodatnih materijala za reparaturu. U ovom istraživanju ispitane su Fe-Ni-Cr-Mo elektroda i elektroda na bazi Ni i njihove osobine su upoređene. Ispitivanje zatezanjem, ispitivanje apsorbovane energije, ispitivanje savijanjem, merenje tvrdoće i ispiivanje osetljivosti kao što su „CTS“ i „Y“ probe, izvedeni su na ispitnim spojevima dobijenim zavarivanjem osnovnog materijala, 20Mn5, ispitivanje savijanjem, merenje tvrdoće i ispiivanje osetljivosti kao što su „CTS“ i „Y“ probe izvedeni su na ispitnim spojevima dobijenim zavarivanjem osnovnog materijala, čelika 20Mn5, sa ispitivanim dodatnim materijalima. Dobijeni rezultati su analizirani i na osnovu toga, odabrana je elektroda na bazi Ni kao pogodnija za reparaturno zavarivanje.

** Rad je prezentovan na 64. Međunarodnoj konferenciji MIZ, Chennai (Madras), India 2011.*

Abstract

The most significant components of hydropower plants are turbine shafts and generator rotors which undergo time-dependent processes such as high stresses, creep, fatigue and corrosion. It is therefore desirable to prevent in-service damages, improve reliability and extend the operational life of the plant. Plant operation can lead to cracking and failures in homogeneous materials, therefore a need for repair welding on plant components, which can be expensive and time-consuming, exists. In the circumstances when repair welding has to be carried out on site, special care has to be taken in defining repair welding technology, process parameters and selection of filler materials. In this research a selection of filler materials for repair welding on site of hydropower turbine shaft was performed and results were presented.

The shaft was made of the cast steel 20Mn5 and presence of damages in the form of cracks which were up to 400 mm long and up to 20 mm deep was detected through the use of NDT methods. As the repairing was planned to be carried out without disassembling of the shaft, application of heat treatment procedures was not feasible. Weldability analysis of the base material was performed through the use of analytical equations. Results have shown that weldability of this steel is limited.

For the repair welding a MMA (111) welding process was selected and two covered austenitic electrodes were analyzed in order to establish the feasibility of their use as potential filler material for repairing. In this research a Fe-Ni-Cr-Mo electrode and Ni based electrode were tested and their properties were compared. Tensile testing, absorbed energies tests, bending tests, hardness measurements and sensitivity tests such as "CTS" and "Y" were performed on test joints obtained by welding of base material, 20Mn5 steel, with investigated filler materials. Obtained results were analyzed and a Ni based electrode was selected as most suitable for repair welding.

UVOD

Nakon 25. godina rada jednog od agregata na hidroelektrani ,,Đerdap II" na reci Dunav u Srbiji, izvršena su detaljna ispitivanja zavarenih spojeva i osnovnog materijala vratila metodama bez razaranja (NDT), a u cilju utvrdjivanja stanja turbinskog vratila. Izvršenim ispitivanjima utvrdjeno je da u zoni prelaznog radijusa (R80) izmedju cilindričnog dela vratila i velike prirubnice, po čitavom obimu, postoji veliki broj površinskih prslina, različitih dužina i dubina. Maksimalna dužina pojedinačne prsline bila je L=430 mm, a maksimalna dubina a =20 mm. Šuplje vratilo turbine izrađeno je iz tri dela, zavarivanjem velike prirubnice i cilindričnog dela vratila i cilindričnog dela i male prirubnice. Velika prirubnica (prirubnica prema glavčini radnog kola) izrađena je od čeličnog liva 20 GSL (~20Mn5), a cilindrični deo vratila i mala prirubnica izrađeni su od čelika 20 GS.

Obzirom na prisustvo prslina odlučeno je da se izvrši reparaturno zavarivanje postojećih oštećenja. Pošto bi demontaža vratila iziskivala velike troškove, a uzimajući u obzir i konstatovana oštećenja odlučeno je da se reparaturno zavarivanje obavi na licu mesta bez demontaže vratila. Takva odluka iziskivala je posebna istraživanja u cilju definisanja optimalne tehnologije reparaturnog zavarivanja prilagodjene otežanim uslovima izvodjenja procesa. Ispitivanja prikazana u ovom radu su urađena u cilju ocene metalurške zavarljivosti livenog čelika 20GSL i odgovarajućih elektroda za zavarivanje, kao podloge za određivanje parametara zavarivanja u cilju kvalifikacije tehnologije zavarivanja.

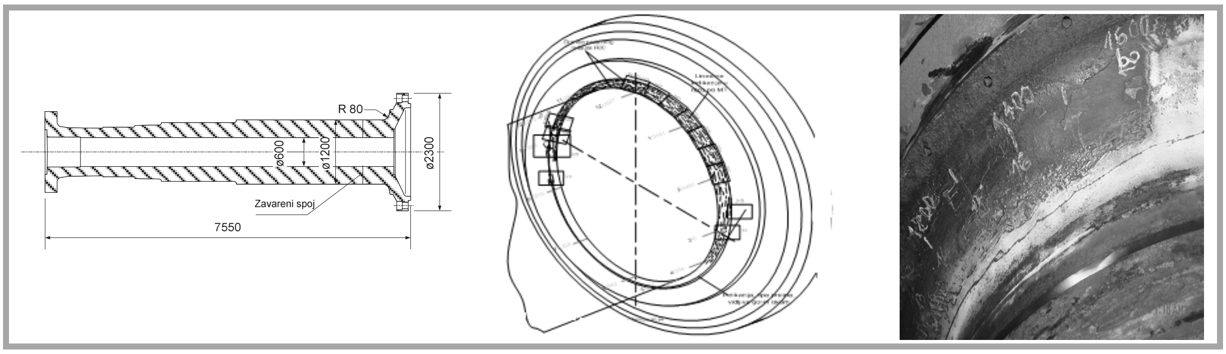
Izvršena ispitivanja grupisana su tako da definišu svaki od osnovnih pokazatelja zavarljivosti. Pri tome se vodilo računa o primeni onih metoda ili tehnoloških proba koje su karakteristične, selektivne i primenljive za ispitivanja na osnovnom metalu vratila i dodatnim materijalima za zavarivanje. Prva grupa ispitivanja odnosi se na određivanje mehaničko - tehnoloških osobina zavarenih spojeva. Pored određivanja čvrstoće zavarenog spoja, čvrstoća metala šava,

INTRODUCTION

After 25 years of operation of an hydroelectric generating set on HPP ,,Đerdap II" on Danube River in Serbia, meticulous inspections of welded joints and base material of the shaft by NDT methods were carried out in order to determine the condition of the turbine shaft. It has been determined that in the area of the transition radius (R80), between the cylindrical section of the shaft and the big flange, all along the circumference a large number of surface cracks of various lengths and depths exist. Maximum length of a single crack was L=430 mm, and maximum depth was a=20 mm. The hollow shaft consists of three parts, and has been formed by welding the big flange to the cylindrical section of the shaft at one end and small flange on the other. Big flange (positioned toward the hub of the runner) has been made of 20 GSL (~20Mn5) cast steel, while cylindrical section of the shaft and small flange have been made of 20 GS steel.

A decision has been made that, due to the presence of cracks, repair welding of existing damages should be carried out. Since the disassembling of the shaft would be very expensive, and taking into account the amount of damage, it has been decided that repair welding should be carried out on-site without disassembling the shaft. Such a decision called for special researches regarding the determination of the optimum repair welding technology, taking into account the conditions under which the process was supposed to be carried out. Tests presented in this paper were carried out with the purpose of determining the metalurgical weldability of the cast steel 20GSL and adequate welding electrodes, and serve as a basis for the obtainment of welding parameters necessary for the determination of the welding procedure.

Performed tests were grouped in such a fashion as to define every single one of basic indicators which refer to weldability. Such methods and technological tests which are characteristic, selective and applicable for



a) b) c)

Slika 1: Šuplje vratilo ispitivane hidoturbine a) shema vratila, b) prelazni radijus vratila R80 sa položajem konstatovanih prslina, c) izgled prisutnih prslina

Figure 1: Hollow shaft of the turbine: a) drawing of the shaft, b) transition radius R80 with locations of detected cracks, c) appearance of detected cracks

određivan je ugao savijanja oko lica i temena vara, energija udara i promene tvrdoće kroz presek zavarenog spoja. Cilj ovih ispitivanja je dobijanje optimalnih mehaničko strukturnih osobina repariranih mesta na vratilu hidroagregata. Druga grupa ispitivanja odnosila se na ocenu sklonosti ka pojavi hladnih i toplih prslina, primenom tehnoloških proba. Za ocenu zavarljivosti danas se u svetu koristi niz tehnoloških proba, a njihov izbor zavisi od mnogo faktora u funkciji od zahteva koji se postavljaju pred materijal. U ovom ispitivanju izabrane su tehnološke probe koje su selektivne za čelični liv prirubnice vratila i dodatne materijale koji se mogu primeniti za reparaturu zavarivanjem uslovljenom specifičnosti problema.

Analizom dobijenih rezultata na bazi obimnih ispitivanja data je ocena o zavarljivosti čeličnog liva prirubnice vratila (20GSL) i ispitivanih elektroda, koja je poslužila da se tačno definiše tehnologija reparaturnog zavarivanja prirubnice vratila.

EKSPERIMENTALNI DEO

U okviru rada obavljena su sledeća ispitivanja i aktivnosti:

- Analiza osnovnog materijala vratila
- Analiza zavarljivosti vratila na osnovu analitičkih metoda
- Izbor mogućih postupaka zavarivanja i dodatih materijala
- Izrada probnih zavarenih sučeonih spojeva
- Izrada tehnoloških proba za definisanje sklonosti ka stvaranju prslina osnovnog i dodatog materijala
- Ispitivanja mehaničko - tehnoloških osobina probnih zavarenih spojeva
- Ispitivanja u cilju ocene sklonosti ka stvaranju prslina:
  - "CTS" proba
  - Metoda japanskog društva za zavarivanje - "Y" proba

REZULTATI I DISKUSIJA

Osnovni materijal

Sheme mesta uzorkovanja iz vratila i isecanja pripremaka za izradu uzoraka prikazane su na slikama 1a i b. Usled velike mase i gabarita dostavljenog uzorka, izvršeno je sečenje komada gasnim plamenom na tri manja, iz kojih su mehaničkim sečenjem izradjivani uzorci za predvidjena ispitivanja.

Hemijski sastav

Analiza hemijskog sastava čeličnog liva prirubnice vratila obavljena je metodama odredjivanja sadr OES i XRF. Rezultati analize su prikazani u tabeli 1 [1] .

investigations regarding the base material of the shaft and filler materials were used. First group of tests refers to determination of mechanical and technological properties of welded joints. Apart from determining the strength of the welded joint and of the filler metal, the angle of bending around the face and the apex of the weld has to be determined, as well as the impact energy and change of hardness along the cross-section of the welded joint. The objective of those investigations is to obtain optimum mechanical and structural properties on repair welding locations on the shaft of the hydroelectric generating set. The other group of investigations refers to the assessment of proneness to the formation of cold and hot cracks, through the application of technological tests. Many technologial tests of this type are in use nowadays, and their selection depends on many factors which refer to requirements regarding the material. For this investigation selective technological tests have been chosen regarding the cast steel of which the shaft flange has been made of, as well as filler materials which could be applied for repair welding with respect to specific conditions.

Through the analysis of results obtained on the basis of extensive investigations the assessment regarding the weldability of cast steel (20GSL) and tested electrodes could be obtained, which served well in order to precisely establish the repair welding technology for the shaft flange.

EXPERIMENTAL

Within the scope of this research the following analyses and activities have been undertaken:

- Analysis of the base material of the shaft
- Analysis of shaft weldability based on analytical methods
- Selection of applicable welding procedures and filler materials
- Formation of welded butt joints - tests
- Formation of technological tests in order to determine the proneness to cracking for the base and filler material
- Investigations of mechanical and technological properties of test welded joints
- Investigations in order to assess the proneness to crack formation:
  - "CTS" test
  - Japan Welding Society Method - "Y" test

RESULTS AND DISSCUSION

Base Material

Sampling locations on the shaft and locations of specimen preforms are presented in figures 1a and 1b. Due to the large mass and dimensions of the obtained sample, cutting of the piece in order to obtain

Mehaničke karakteristike

U cilju ispitivanja zateznih osobina u dva pravca, iz dostavljenih uzoraka izrađene su po tri epruvete za ispitivanje zatezanjem. Epruvete su izrađene kao standardne prema zahtevima EN 10002-1:1996, prečnika mernog dela 6 mm. Ispitivanje je izvršeno na sobnoj temperaturi (T=+20°C). Rezultati ispitivanja su prikazani u tabeli 2. Iz uzorka prirubnice vratila izrađene su standardne epruvete za ispitivanje energije udara, prema zahtevima EN 10045-1. Ispitivanje je izvršeno na Šarpi klatnu opsega 0–300 J na sobnoj temperaturi (T=+20°C). Rezultati ispitivanja su prikazani u tabeli 2.

Ispitivanje tvrdoće HB 5/7500/15” je izvršeno na tri uzorka i tri merna mesta, a dobijene vrednosti su se kretale od 153 do 163 HB.

Dijagram kontinuiranog hladjenja (KH)

Kako se nije raspolagalo dijagramom kontinuiranog hladjenja za ispitivani čelični liv 20GSL, na slici 2, prikazan je dijagram za sličan čelik 20Mn5. Na dijagramu kontinuiranog hladjenja prikazane su odgovarajuće temperature transformacije, strukture i tvrdoće. Na osnovu ovih podataka može se smatrati da ovaj čelik pokazuje neke karakteristike koje se moraju uzeti u obzir pri proučavanju njegove zavarljivosti, pre svega njegova zakaljivost. Takođe, ovaj čelični liv je osetljiv na temperaturu austenitizacije i na trajanje termičke obrade.

Na osnovu prikazanih rezultata ispitivanja osnovnog materijala prirubnice vratila može se konstatovati da su vrednosti zatezne čvrstoće i izduženja na donjoj granici ili nešto niže od zahtevanih prema GOST standradu. Ostale zatezne osobine, energija udara i tvrdoća su u okviru zahteva standarda. Navedene

3 smaller pieces through the use of the gas torch has been performed, from which the samples meant for predefined tests were manufactured by mechanical cutting.

Chemical Composition

Analysis of the chemical composition of cast steel has been carried out through the use of OES AND XRF methods for content determination. Results of the analysis are presented in Table 1.

Mechanical Properties

From each of delivered samples 3 specimens were manufactured in order to carry out the testing of tensile properties in 2 directions. Specimens were manufactured in accordance with EN10002-1:1996 standard, diameter of the measurement section is 6 mm. Testing has been carried out at room temperature (T= 20°C). Testing results are presented in Table 2. From the sample of the shaft flange standard specimens for impact energy determination were manufactured, in accordance with EN 10045-1 standard. Testing has been performed through the use of the Charpy pendulum used in the range 0 - 300 J at room temperature (T= 20°C). Testing results are presented in Table 2.

Hardness testing HB 5/7500/15” has been performed on 3 samples and 3 measurement locations. Obtained values ranged from 153 to 163 HB.

Continuous Cooling Transformation Diagram

Bearing in mind that the continuous cooling transformation diagram for tested cast steel 20GSL was not available, diagram for the similar steel (20Mn5) was used, Figure 2. In the continuous cooling transformation diagram adequate transformation

Tabela 1: Rezultati hemijske analize dostavljenog uzorka u [mas. %]

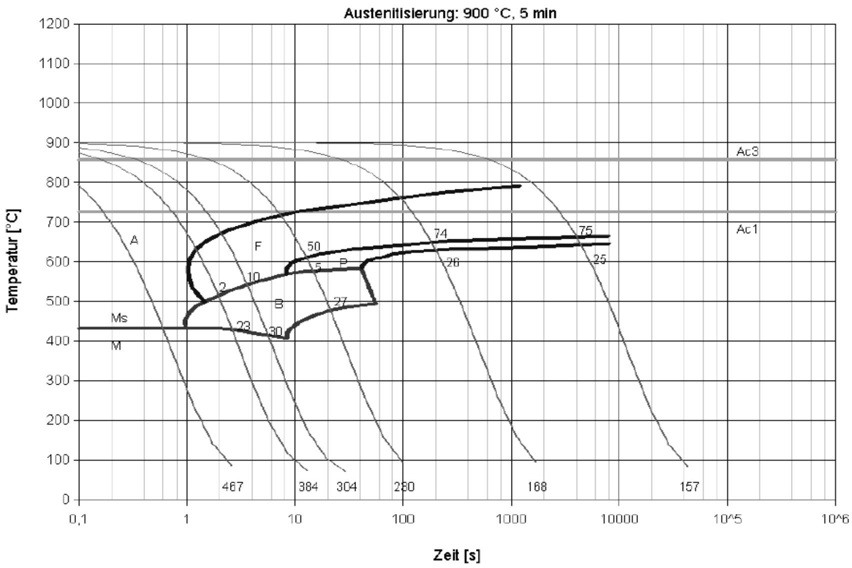
Table 1: Results of the chemical analysis of the obtained sample in [%]

Analysis method/%	C	Si	Mn	S	P	Ni	Cr	Mo	V	Al	W
OES	0,19	0,72	0,29	0,02	0,021	0,27	0,27	0,047	0,009	0,038	0,024
XRF	0,12	0,63	1,10	0,002	0,001	0,22	0,23	0,031	-	0,038	-
Chemical composition /GOST 977-88/	0,16 - 0,22	0,60 - 0,80	1,00 - 1,30	max 0,030	max 0,030	-	-	-	-		-

Tabela 2: Rezultati ispitivanja zatezanjem prema EN 10002-1 i energije udara prema SRPS EN 10045-1 [1]

Table 2: Results of tensile tests performed in accordance with EN 10002-1 standard and impact energy tests performed in accordance with SRPS EN 10045-1 standard [1]

Testing direction	Yield stress R_e (N/mm^2)	Tensile strength R_m (N/mm^2)	Elongation A_5 (%)	Contraction Z (%)	KV $_{300/2}$ (J)
transversal	322	560	21,6	54,9	49.4
longitudinal	314	525	15,3	39,2	58
Prescribed value GOST 977-88	min 294	min 540	min 18	min 30	min. 23,4 J



Slika 2: Dijagram kontinuiranog hladjenja za čelik 20GSL (20Mn5)

Figure 2: Continuous cooling transformation diagram for steel 20GSL (20Mn5)

konstatacije posebno usložnjavaju problem i zahtevaju posebnu pažnju pri izboru postupaka, tehnologija i dodatnih materijala za reparaturno zavarivanje vratila.

Ocena zavarljivosti primenom analitičkih izraza

Prvi korak ka oceni zavarljivosti, praktično pre eksperimentalnog rada je ocena zavarljivosti primenom analitičkih izraza. Pored jednačina za ekvivalent ugljenika, kada su čelici u pitanju, značajan parametar je PCM. To je parametar prslina, koj ima primenu kod proračuna parametra za pojavu hladnih prslina koji se primenjuje za niskolegirane čelike. Parametar prslina uzima u obzir samo hemijski sastav osnovnog materijala u ovom slučaju niskolegiranih čelika. Pored parametarskih jednačina za ocenu otpornosti ka pojavi hladnih prslina primenjuju se i jednačine za ocenu sklonosti prema pojavi i toplih prslina i prslina usled žarenja [2-4].

Ekvivalent ugljenika je izračunavan primenom formula [5-7] i to:

$$\mathrm{CET}: C_{ekv} = C + \frac{Mn + Mo}{10} + \frac{Cr + Cu}{20} + \frac{Ni}{40} \qquad (1)$$

$$\mathrm{CE\ \ (IIW)}: C_{ekv} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \qquad (2)$$

$$C_{ekv} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Mo}{15} + \frac{Ni}{60} + \frac{V}{10} + 5 \times B \qquad (3)$$

Sklonost prema pojavi hladnih prslina je određivana primenom formule 4, koja pored ekvivalenta ugljenika uzima u obzir i količinu difuzionog vodonika (H) i debljinu materijala s , prema [7]:

temperatures, structures and hardnesses are presented. On the basis of these data it can be considered that this steel has some properties that have to be taken into account as far as their weldability (most of all their hardenability) is concerned. This cast steel is sensitive to the austenitizing temperature and duration of the heat treatment.

On the basis of presented test results for the base material of the shaft flange it can be stated that values of tensile strength and elongation are just a bit above the lower limit or somewhat lower than values prescribed in GOST standard. Values of other tensile properties (impact energy and hardness) are within the prescribed limits. All the above mentioned makes the problem very complex, therefore special attention concerning the selection of procedures, technologies and filler materials for repair welding of the shaft is required.

Assessment of Weldability through the Application of Analytical Expressions

First step toward assessing weldability, even before experimental work, is to assess weldability through the application of analytical expressions. Apart from determining the carbon equivalent for steels, it is also important to determine PCM, which is the crack parameter applied when calculating the parameter for the occurence of cold cracks which is in use for low-alloy steels. Crack parameter takes into account only the chemical composition of the base material, in this case of a low-alloy steel. Apart from parameter equations for the assessment of resistance to cold cracking, equations for the assessment of proneness to hot cracking and cracking due to annealing [2-4] are being used. Carbon equivalent is obtained through the use of following formulas [5-7]:

$$P_C = P_{CM} + \frac{H}{60} + \frac{s}{600} \quad (4)$$

Ovde je:

P_C - pokazatelj sklonosti niskolegiranih čelika ka obrazovanju hladnih prslina,

P_{CM} - pokazatelj kojim se uzima u obzir uticaj hemijskog sastava čelika

$$P_{CM} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Mo}{15} + \frac{Ni}{60} + \frac{V}{10} + 5 \times B \quad (5)$$

H - sadržaj difundovanog vodonika u metalu šava u [cm^3/100g], s - debljina čelika u mm

Analitički izraz za ocenu sklonosti osnovnog materijala ka stvaranju toplih prslina je:

$$H.C.S = \frac{C\left(S + P + \frac{Si}{25} + \frac{Ni}{100}\right)10^3}{3 \bullet Mn + Cr + Mo + V} \quad (6)$$

Dobijeni rezultati ocene zavarljivosti primenom analitičkih izraza (1-6) i rezultata hemijske analize prikazanih u tabeli 1 dati su u tabeli 3.

Prikazani rezultati ukazuju da je predmetni čelični liv zavarljiv primenom konvencionalnih postupka zavarivanja, ali uz primenu mera predostrožnosti. Vrednosti za ekvivalent ugljenika su na nivou koji nameće predostrožnost pri zavarivanju. To znači da tokom zavarivanja treba voditi računa o brzini zagrevanja, hlađenja i o temperaturama između prolaza, odnosno obavezno predgrevanje.

Sklonost ka pojavi hladnih i toplih prslina kao i nivo ekvivalenta ugljenika koji ukazuje na mogućnost stvaranja krtih faza nameću potrebu dodatnih ispitivanja u cilju ocene sklonosti ka stvaranju toplih i hladnih prslina. Sklonost ka pojavi hladnih prslina se povećeva sa povećanjem debljine osnovnog materijala, a sklonost ka pojavi toplih prslina sa povećanjem zapremine tečnog kupatila. To znači da pored mehaničko - strukturne karakterizacije probnih uzoraka, zavarenih u cilju definisanja tehnologije zavarivanja, biće neophodno primeniti i tehnološke probe zavarljivosti.

Temperatura predgrevanja je određena primenom dve metode i to metodom koja se bazira na vrednosti parametra za hladne prsline PC po formuli [7, 8]:

$$CET : C_{ekv} = C + \frac{Mn + Mo}{10} + \frac{Cr + Cu}{20} + \frac{Ni}{40} \quad (1)$$

$$CE \quad (IIW) : C_{ekv} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \quad (2)$$

$$C_{ekv} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Mo}{15} + \frac{Ni}{60} + \frac{V}{10} + 5 \times B \quad (3)$$

Proneness to the formation of cold cracks is being determined through the use of a formula which, apart from carbon equivalent, takes into account the amount of diffused hydrogen (H) and the thickness of material s according to [7]:

$$P_C = P_{CM} + \frac{H}{60} + \frac{s}{600} \quad (4)$$

where:

PC - indicator of proneness of low-alloy steels to the formation of cold cracks,

PCM - indicator which takes into account the effect of the chemical composition of the steel

$$P_{CM} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Mo}{15} + \frac{Ni}{60} + \frac{V}{10} + 5 \times B \quad (5)$$

H - content of diffused hydrogen in the weld metal in [cm3/100g], s - thickness of steel in mm

Analytical expression for the assessment of proneness of the base material to the formation of hot cracks:

$$H.C.S = \frac{C\left(S + P + \frac{Si}{25} + \frac{Ni}{100}\right)10^3}{3 \bullet Mn + Cr + Mo + V} \quad (6)$$

Obtained results regarding the weldability assessment through the use of analytical expressions (1-6) and results of the chemical analysis from Table 1 are presented in Table 3.

Presented results indicate that this cast steel is weldable through the application of conventional welding procedures, which have to be carried out cautiously. Values of carbon equivalent call for cautiousness during the welding process. That means that special care has to be taken regarding the

Tabela 3: Analitička procena zavarljivosti čelika 20GSL (~ 20Mn5)

Table 3: Analytical assessment of weldability of steel 20GSL (~ 20Mn5)

Carbon equivalent	Value	Reference values and assessment
CET (SEW 088-93)	0,33	Weldable, preheating required
CE (BS 5135)	0,45	Weldable, preheating and annealing required
PCM (ANSI/AWS D1.1-96)	0,29	Weldable, preheating required
CEN (JIS)	0,47	Weldable, preheating and annealing required
HCS	2.15	When HCS > 4 prone to hot cracking

$$Tpr\ (C°) = 1440\ P_C - 392 \quad (7)$$

I po metodi Seferijana [11] po formuli:

$$Tpr\ (C°) = 350\ (C - 0{,}25)^{0{,}5} \quad (8)$$

gde je:

C-ekvivalentni ugljenik debljine materijala
$C = 0{,}005 \cdot s \cdot C_{ekv}$
s-debljina materijala u mm,
C_{ekv}-hemijski ekvivalent ugljenika

$$360\ C_{ekv} = 360C + 40\ (Mn+Cr) + 20Ni + 28Mo \quad (9)$$

Temperatura predgrevanja je, kao i kod ostalih parametarskih jednačina, određivana za sastav čelika 20 GSL dat u tabeli1. Dobijene su temperature predgrevanja od 150 do 200 °C.

Izbor postupka zavarivanja

Polazeći od ocene strukturno mehaničkih osobina osnovnog materijala i pretpostavljenih zahteva za kvalitet, odgovornost zavarenih spojeva i složenost izvodjenja procesa, u principu za zavarivanje čeličnih livova sa sadržajem ugljenika do 0,2%, preporučeni postupci mogu biti: metal arc welding with covered electrode (MMA - 111), metal arc active gas welding MAG (135) ili flux cored wire metal arc welding with active gas shield (FCAW/AG - 136) i submerged arc welding with wire electrode (SA-121). Na osnovu geometrijskog oblika prirubnice vratila, konstruktivnog rešenja, otežanih tehnoloških mogućnosti uslovljene mogućom reparaturom na licu mesta i rasopoložive opreme za reparaturno zavarivanje izabran je postupak metal arc welding with covered electrode (MMA - 111).

Izbor dodatnih i potrošnih materijala za zavarivanje

Izbor dodatnih materijala za zavarivanje je izvršen na osnovu sledećih kriterijuma:

- kritičnih mehaničko strukturnih osobina osnovnog materijala,
- hemijskog sastava osnovnog materijala,
- uslovljenošću izvodjenja procesa na licu mesta u turbini,
- zahteva za ograničavanje visokih vrednosti tvrdoće u metalu šava i malih unosa toplote,
- usvojenog postupaka zavarivanja,
- ocene zavarljivosti, odnosno usvojenih mera predostrožnosti pre svega zahteva za nizak sadržaj difunovanog vodonika u metalu šava.

Primenom navedenih kriterijuma izabrani su dodatni materijali za zavarivanje koji su prikazani u tabeli 4.

U tabeli 5 su dati hemijski sastavi čistog metala vara, a u tabeli 6 su date mehaničke karakteristike čistog metala vara.

heating and cooling rate and temperatures between passes, in other words preheating is obligatory.

Proneness to the formation of cold and hot cracks, as well as the carbon equivalent level which indicates the possibility of creation of brittle phases suggest additional investigations. Proneness to the formation of cold cracks increases with the increase of base material thickness, while proneness to the formation of hot cracks increases with the increase of volume of the liquid bath. That means that, apart from mechanical and structural characterization of test samples welded in order to determine the welding technology, it is necessary to carry out technological weldability tests.

Preheating temperature is obtained through the use of 2 methods, the first being the method based on the value of the cold cracking parameter PC according to the following formula:

$$Tpr\ (C°) = 1440\ P_C - 392 \quad (7)$$

The other one is the Sepherian method, preheating formula is obtained from the following formula:

$$Tpr\ (C°) = 350\ (C - 0{,}25)^{0{,}5} \quad (8)$$

where:

C - carbon equivalent of the material,
$C = 0{,}005 \cdot s \cdot C_{ekv}$
s - thickness of the material in mm
C_{ekv} - chemical carbon equivalent

$$360\ C_{ekv} = 360C + 40\ (Mn+Cr) + 20Ni + 28Mo \quad (9)$$

Preheating temperature was, as with other parametric equations, obtained for the composition of the steel 20 GSL presented in Table 1. Obtained preheating temperatures ranged from 150 to 200°C.

Welding Procedure Selection

Taking into account structural and mechanical properties of the base material and assumed quality requirements, as well as the category of welded joints and complexity of the welding process, this is the list of recommended procedures for welding of cast steels with less than 0.2% of carbon: metal arc welding with covered electrode (MMA - 111), metal arc active gas welding MAG (135) or flux cored wire metal arc welding with active gas shield (FCAW/AG - 136) and submerged arc welding with wire electrode (SA-121). Based on the geometric shape of the shaft flange, construction solution, technological possibilities conditioned by possible on-site repair welding and availability of repair welding equipment, metal arc welding with covered electrode (MMA - 111) was selected.

Selection of Filler and Expendable Materials for Welding

Selection of filler materials has been carried out taking into account the following:

Tabela 4: Kvalitet izbranih dodatnih materijala za zavarivanje
Table 4: Quality of selected welding filler materials

FILLER MATERIAL	ЭA-395/9	2222 Xuper NucleoTec
MANUFACTURER	AO SPECELEKTROD, Moscow, Russsia	CASTOLIN EUTECTIC, Vienna, Austria
CLASSIFICATION/STANDARD	ISO E16.25.6B20 GOST 9466-75	/
TYPE OF COATING	Basic	Basic
COATING CLASS	Thick Sheath	Thick Sheath

Tabela 5: Hemijski sastav čistog metala vara primenjenih dodatnih materijala (mas%)
Table 5: Chemical composition of the pure weld metal for applied filler materials [%]

Filler material / Chemical composition	C %	Si %	Mn %	Cr %	Mo %	Ni %	Fe %
ЭA-395/9	<0.12	0.35-0.70	1.20-2.80	13.50-17.00	4.50-7.00	22.00-27.00	The rest
2222 Xuper NucleoTec	<0.10	<0.50	<5.00	<15.00	<1.00	The rest	<10

Tabela 6: Mehaničke karakteristike primenjenih dodatnih materijala
Table 6: Mechanical properties of applied filler materials

Filler material / Mechanical properties	$R_{p0.2\%}$, MPa	R_m, MPa	A_5, %	A_v, J (20°C)	HB
ЭA-395/9	/	>610	30	>118	/
2222 Xuper NucleoTec	~390	620-690	40-45	~120	180-220

Mehaničko tehnološke osobine sučeonih zavarenih spojeva

U cilju definisanja mehaničkih i strukturnih osobina repariranih mesta na vratilu hidroagregata izvršena je izrada sučeonih spojeva od materijala vratila sa dva ispitivana dodatna materijala. Dva sučeona spoja su zavarena elektrodom ЭA-395/9, prečnika ϕ 3.00mm koreni zavar, a popuna je vršena elektrodom prečnika ϕ 4.00 mm. Druga dva sučeona spoja su zavarena elektrodom 2222 Xuper NucleoTec, prečnika ϕ 3.25mm koreni zavar, a popuna je vršena elektrodom prečnika ϕ 4.00 mm. Probne ploče bile su dimenzija 190x90x15mm. Oblik i dimenzije žljeba prikazani su na slici 3a), a na slici 3b) prikazan je redosled prolaza pri zavarivanju. Parametri zavarivanja prikazani su u tabelama 7 i 8.

Kod svih ploča vršeno je brušenje korenog prolaza i brušenje pre poslednjeg prolaza. Posle svakog prolaza vršeno je otkivanje metala šava pneumatskim čekićem. Tokom zavarivanja beleženi su parametri zavarivanja: napon U /V/, struja I /A/, vreme zavarivanja /s/, brzina zavarivanja /cm/s/ i odredjivana je energija zavarivanja /kJ/cm/. Elektrode su pre korišćenja sušene najmanje 2 sata na 250°C. Zavarivanje je izvedeno bez predgrevanja, sa ciljem ostvarenja oštrijih uslova zavarivanja i verovatnu nemogućnost primene predgrevanja pri izvodjenju reparature.

- Critical mechanical and structural properties of the base material,
- Chemical composition of the base material,
- Impossibility of carrying out the process anywhere outside the turbine,
- Request regarding the limiting of weld metal hardness values and heat input,
- Adopted welding procedure,
- Weldability assessment, mostly regarding the request for low content of diffused hydrogen in weld metal.

Through the application of the above mentioned criteria the filler materials presented in Table 4 have been chosen.

In Table 5 chemical compositions of the pure weld metal are presented, while Table 6 contains mechanical properties of the pure weld metal.

Mechanical and Technological Characteristics of Welded Butt Joints

In order to define mechanical and structural characteristics on repair locations on the shaft of the hydroelectric generating set, butt joints have been formed by welding the shaft material with the addition of 2 investigated filler materials. Two butt joints have been formed through the use of the 3A-395/9

Ispitivanje mehaničko tehnoloških osobina spojeva je vršeno u skladu sa standardom SRPS EN 288. Pre isecanja uzoraka za ispitivanje izvršeno je radografsko ispitivanje svih spojeva u skladu sa kriterijumima standarda EN 12517, homogenost zavarenih spojeva je zadovoljavajuća za nivo B.

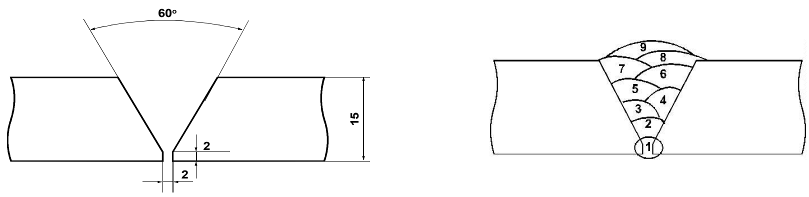
Epruvete za ispitivanje zatezanjem su izrađene kao standardne prema zahtevima EN 10002-1:1996. Ispitivanje je izvršeno na sobnoj temperaturi (T=+20°C). Rezultati ispitivanja zateznih osobina prikazani su u tabeli 9, a u tabeli 10 prikazani su rezultati ispitivanja zavarenih spojeva savijanjem.

Ispitivanje energije udara, vršeno je na standardnim epruvetama sa V zarezom od 2 mm, prema zahtevima standarda EN 10045-1 na po šest epruveta za svaki dodatni materijal. Ispitivanje je izvršeno na Šarpi klatnu opsega 0 - 300 J, na sobnoj temperaturi. Rezultati ispitivanja su prikazani u tabeli 11.

electrode, diameter of ϕ 3.00 mm root weld, while the filling has been carried out through the use of an electrode of ϕ 4.00 mm diameter.

Other two butt joints have been formed through the use of a 2222 Xuper NucleoTec electrode, diameter of ϕ 3.25 mm root weld, while the filling has been carried out through the use of an electrode of ϕ 4.00 mm diameter. Test plates were used with dimensions of 190x90x15 mm. Shape and dimensions of the groove are presented in Figure 3a, while the weld pass sequence is presented in Figure 3b. Welding parameters are presented in Tables 7 and 8.

Grinding of the root opening has been carried out, as well as grinding before the last pass. After every pass peening of the weld metal by the pneumatic hammer has been performed. During welding the following welding parameters have been recorded: voltage U /V/, current intensity I /A/, welding time /s/ and welding



a) b)

Slika 3: Shematski prikaz a) pripreme žljeba i b) redosleda prolaza pri zavarivanju

Figure 3: Schematic of: a) groove preparation and b) weld pass sequence

Tabela 7: Parametri zavarivanja sučeonih spojeva sa elektrodom ЭA-395/9

Table 7: Welding parameters for welded butt joints formed through the use of the 3A-395/9 electrode

Welded butt joint	Pass	Current intensity I (A)	Voltage U (V)	Average voltage Usr (V)	Welding time t(s)	Weld length l(cm)	Welding speed v(cm/s)	Energy E=Usr*I*t/l E(kJ/cm)	Electrode diameter (mm)
I	1K	100	25-27	26	65	17.5	0.27	9.66	ϕ 3.00
	2P-9P, mean	140	/	26	61.12	18.43	0.30	12.07	ϕ 4.0
II	1K	100	24-26	25	75.4	19.7	0.26	9.57	ϕ 3.00
	2P-9P, mean	140	/	26	61.42	18.43	0.30	12.13	ϕ 4.0

Primedba: K - koreni, P - popuna smer kretanja elektroda L ---D

Note: K - root, P - filling, direction of electrode movement L ---D

Tabela 8: Parametri zavarivanja sučeonih spojeva sa elektrodom 2222 Xuper NucleoTec

Table 8: Welding parameters for welded butt joints formed through the use of the 2222 Xuper NucleoTec electrode

Welded butt joint	Pass	Current intensity I (A)	Voltage U (V)	Average voltage Usr (V)	Welding time t(s)	Weld length l(cm)	Welding speed v(cm/s)	Energy E=Usr*I*t/l E(kJ/cm)	Electrode diameter (mm)
III	1K	100	22-25	23.5	79	19.1	0.24	9.72	ϕ 3.25
	2P-9P, mean	140	/	25.25	63.45	18.46	0.29	12.15	ϕ 4.0
IV	1K	100	22-24	23	79.8	18.5	0.23	9.92	ϕ 3.25
	2P-9P, mean	140	/	26	66.25	18.62	0.28	12.95	ϕ 4.0

Primedba: K - koreni, P - popuna smer kretanja elektroda L -- D

Note: K - root, P - filling, direction of electrode movement L -- D

Ispitivanja tvrdoće obavljena su u skladu sa preporukama standarda EN-1043. Raspodela tvrdoća kroz zavareni spoj na dva nivoa, na nivou lica i na nivou korena spoja prikazana je u tabeli 12.

Ocena sklonosti ka hladnim prslinama

Za eksperimentalnu proveru osetljivosti prema hladnim prslinama koristi se relativno velik broj tehnoloških proba. Međutim najviše pozitivnog iskustva za ocenu dodatnih materijala od C-Mn čelika ima se sa "CTS" probom (metoda kontrolisane termičke strogosti) i "Y" probom.

"CTS" proba (Control Thermal Severity)

"CTS" proba se bazira na zavarivanju dva kontrolna zavara od kojih svaki, zavisno od prostornog položaja, debljine lima i režima zavarivanja, ima svoj toplotni ciklus zavarivanja. Kontrolni šavovi, nazvani dvotermijski i trotermijski, imaju različite uslove odvođenja toplote, odnosno različite brzine hlađenja u ZUT-u. [6]. Ispitivanje tehnološke zavarljivosti po metodi kontrolisane termičke strogosti - CTS proba, vršeno je na uzorcima shematski prikazanim na slici 4.

Zavarivanje je vršeno sa elektrodama, ЭA-395/9 prečnika ϕ3.00 mm i ϕ4.00 mm i 2222 Xuper NucleoTec prečnika ϕ3.25 mm i ϕ4.00 mm, na pločama debljine 15 mm.

Uslovi zavarivanja dvo- i tro- termijskih zavara prikazani su u tabelama 13 i 14. Iz svake probe su mehaničkim putem izrezana po dva uzorka prema skici na slici 4, za ispitivanje tvrdoće HV 5 kroz zavareni spoj i za metalografska ispitivanja. Priprema uzoraka

speed /cm/s/. Welding energy /kJ/cm/ has also been determined. Electrodes were dried for at least 2 hours at the temperature of 250°C before use.

Welding has been carried out without preheating, in order to simulate severe conditions of welding and probable impossibility of preheating the repair zone during repair welding.

Investigation of mechanical and technological properties of welded joints has been performed in accordance with the standard SRPS EN 288. Before the samples were cut out, radiographic inspection of all joints in compliance with all criteria from the EN 12517 standard was performed. Homogeneity of all joints is acceptable for level B.

Specimens for tensile testing have been fabricated in accordance with EN 10002-1:1996. Testing has been carried at room temperature (T= 20°C). Testing results regarding the tensile properties are presented in Table 9, while in table 10 bending test results are presented.

Impact testing has been performed on six standard 2 mm deep V-notch specimens for every filler material, in accordance with EN 10045-1 standard. Testing has been performed through the use of the Charpy pendulum in the range from 0 to 300 J at room temperature. Test results are presented in Table 11.

Hardness tests have been performed in accordance with recommendations from the EN-1043 standard. Hardness distribution through the welded joint in 2 zones, weld face and weld root is presented in Table 12.

Tabela 9: Rezultati ispitivanja zateznih osobina sučeonog spoja

Table 9: Results of tensile tests for welded butt joints

Filler material	Specimen nr.	Rm(MPa)	Breaking point
ЭA-395/9	1	505	BM
	2	516	BM
	Mean value	510,5	
2222 Xuper NucleoTec	1	504	BM
	2	521	BM
	Mean value	512,5	

Tabela 10: Rezultati ispitivanja savijanjem

Table 10: Results of bending tests

Filler material	Specimen nr.	Bending	Angle	Result
ЭA-395/9	1	Around the face	120 o	No cracks were detected
	2	Around the root	120 o	No cracks were detected
2222 Xuper NucleoTec	1	Around the face	120 o	No cracks were detected
	2	Around the root	120 o	No cracks were detected

Primedba: Savijanje je vršeno oko trna Dt=3a=45mm;

Note: Bending has been carried out around the thorn Dt=3a=45mm

Tabela 11: Rezultati određivanja energije udara KV300/2, prema EN 10045-1

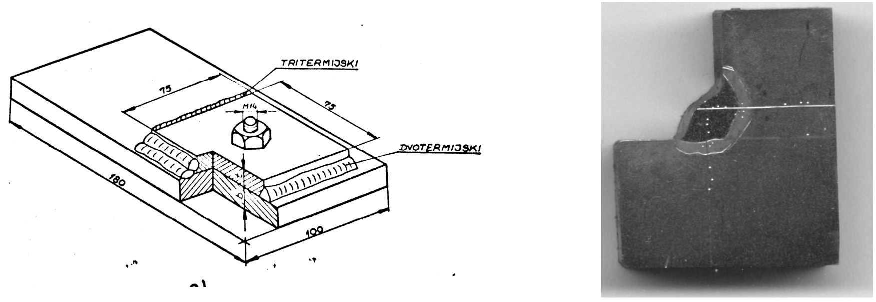
Table 11: Results of impact tests, in accordance with EN 10045-1 standard

Filler material	Notch location	Mean value KV_{300} (J)
ЭА-395/9	Weld metal	145.52
	Heat-affected zone	126.22
2222 Xuper NucleoTec	Weld metal	123.93
	Heat-affected zone	85.67

Tabela 12: Raspodela tvrdoća kroz zavareni spoj na dva nivoa, na nivou lica i na nivou korena za ispitivane elektrode

Table 12: Hardness distribution along the welded joint in 2 zones, weld face and weld root, for tested electrodes

Electrode	Connecting line	Hardness, HV 5				
		BM 1	HAZ 1	WM	HAZ 2	BM 2
ЭА-395/9	Weld face	175	286	187	238	179
	Weld root	169	234	204	221	169
2222 Xuper NucleoTec	Weld face	169	290	196	259	170
	Weld root	175	231	186	237	172



a) b)

Slika 4: "CTS" proba a) shematski prikaz uzorka za ispitivanje "CTS" probe (cover plate, base plate), b) izgled analiziranih preseka

Figure 4: "CTS" test a) schematic of the specimen (cover plate, base plate), b) appearance of analyzed cross-sections

vršena je uobičajenim postupkom poliranja i nagrizanja, a analiza mikrostruktura je obavljena na svetlosnom mikroskopu.

Ispitivanja "CTS" proba za elektrodu ЭА-395/9 prečnika ϕ3.00 mm i ϕ4.00 mm i za elektrodu 2222 Xuper NucleoTec prečnika ϕ3.25 mm i ϕ4.00 mm vršeno je 48 sati nakon zavarivanja. Priprema metalografskih uzoraka vršena je uobičajenim postupkom poliranja i nagrizanja, a analiza mikrostruktura je obavljena na svetlosnom mikroskopu. Rezultati ispitivanja tvrdoća HV5 za elektrodu ЭА-395/9, pokazuju vrednosti od 169 do 195 HV5 u metalu šava a vrednosti od 232 do 341 HV5 u ZUT što je i prikazano u tabeli 15. Vrednosti za elektrodu 2222 Xuper NucleoTec se kreću od 146 do 178 HV5 u metalu šava a vrednosti u ZUT iznose od 227 do 345 HV5, što je takodje prikazano u tabeli 15. Vrednosti tvrdoća u oblasti osnovnog metala su se kretale od 130 do 164 HV5. Makro pregledom svih uzoraka nije konstatovano prisustvo prslina ni na jednom ispitivanom uzorku.

Assessment of Proneness to the Formation of Cold Cracks

For the experimental check of proneness to the formation of cold cracks relatively many technological tests are being used. "CTS" test (method of controlled thermal severity) and "Y" test proved to be most suitable for the assessment of C--Mn steel filler materials.

"CTS" Test (Controlled Thermal Severity)

"CTS" test is based on the formation of 2 test welds which both have their own weld thermal cycle, depending on the spatial location, sheet metal thickness and welding regime. Test welds, called bithermal and trithermal, have different cooling rates in the heat-affected zone [6]. Testing of technological weldability through the use of the CTS test has been performed on samples presented in Figure 4.

Welding has been performed through the use of 3A-395/9 electrode, diameter of ϕ3.00 mm and

Tabela 13: Parametri zavarivanja "CTS" proba elektrodom ЭА-395/9, ϕ 3.00 mm i ϕ 4.00 mm
Table 13: "CTS" test welding parameters for the 3A-395/9 electrode of ϕ 3.00 mm and ϕ 4.00 mm diameters

Sample	Electrode	Current intensity Isr	Voltage, Usr	Time, T	Length, l	Energy, E	Note
	mm	A	V	Sec	cm	KJ/cm	
1	ϕ 3.00	112	26	24.3	7.5	9.43	bithermal
2	ϕ 3.00	112	28	27	7.5	11.29	bithermal
3	ϕ 4.00	150	28	26.8	7.5	15.00	bithermal
4	ϕ 4.00	150	29	29.4	7.5	17.05	bithermal

Note: E=Usr*Isr*t/l

Tabela 14: Parametri zavarivanja "CTS" proba elektrodom 2222 Xuper NucleoTec, ϕ 3.25 mm i ϕ 4.00 mm
Table 14: "CTS" test welding parameters for the 2222 Xuper NucleoTec electrode of ϕ 3.25 mm and ϕ 4.00 mm diameters

Sample	Electrode	Current intensity Isr	Voltage, Usr	Time, T	Length, l	Energy, E	Note
	mm	A	V	Sec	cm	KJ/cm	
1	ϕ 3.25	26	110	30	7.5	11.44	bithermal
2	ϕ 3.25	26	110	27	7.5	10.30	bithermal
3	ϕ 4.00	28	150	26	7.5	14.56	bithermal
4	ϕ 4.00	28	150	25	7.5	14.00	bithermal

Note: E=Usr*Isr*t/l

Metoda japanskog društva za zavarivanje - "Y" proba

"Y" proba je praktično sučeono zavarena proba sa Y oblikom žljeba. Kao kriterijum za procenu osetljivosti uzima se procentualno učešće dužine prsline u ukupnoj dužini šava, odnosno visini prsline u visini šava [7]. Šematski izgled probe sa izgledom preseka ispitnog šava prikazan je na slici 5.

Ispitivanje tehnološke zavarljivosti po metodi japanskog društva za zavarivanje, vršeno je sučeonim zavarivanjem sa elektrodama ЭА-395/9 i 2222 Xuper NucleoTec prečnika ϕ 4.00mm, jednoprolazno, na pločama debljina 15 mm i 30 mm sa zazorom od 2 mm. Za zavarivanje su korišćene samo elektrode prečnika ϕ 4.00 mm, sa ciljem simulacije oštrijih uslova za konkretnu namenu, sa većim unosom energije. Parametri zavarivanja prikazani su u tabeli 16. Na karakterističnim mestima isecani su uzorci u poprečnom pravcu za metalografsku analizu i merenja tvrdoće HV 5. Sečenje uzoraka vršeno je 72 sata nakon zavarivanja. Prikazani rezultati merenja tvrdoća, tabela 17, pokazuju da su vrednosti tvrdoća kod svih uzoraka na očekivanom nivou.

Makro pregledom ustanovljeno je prisustvo prslina, koje se mogu definisati kao tople prsline, kod uzoraka debljine 15 i 30 mm zavarenih elektrodom ЭА-395/9. Pregledom mikrostruktura uzoraka zavarenih elektrodom ЭА-395/9, na pločama debljine 30 mm, konstatovano je prisustvo i hladnih prslina u metalu šava i ZUT.

Mikrostruktura uzoraka zavarenih elektrodom 2222 Xuper NucleoTec, na pločama debljine 30 mm, pokazuje prisustvo prslina u ZUT.

ϕ 4.00 mm and 2222 Xuper NucleoTec electrode, diameter of ϕ 3.25 mm and ϕ 4.00 mm, on 15 mm thick plates.

Welding conditions regarding the bithermal and trithermal welds are presented in Tables 13 and 14. Two samples have been mechanically cut out according to Figure 4 for hardness testing along the welded joint and for metallographic investigations for each test. Sample preparation has been carried out by polishing and corrosion, while microstructure analysis has been performed using the light microscope.

"CTS" tests for the 3A-395/9 electrode of ϕ 3.00 mm and ϕ 4.00 mm diameters and for the 2222 Xuper NucleoTec electrode of ϕ 3.25 mm and ϕ 4.00 mm diameters have been subjected to testing 48 hours after welding. Sample preparation has been carried out by polishing and corrosion, while microstructure analysis has been performed using the light microscope. Hardness test results for electrode 3A-395/9 ranged from 169 to 195 HV5 in weld metal and from 232 to 341 HV5 in the heat-affected zone, as presented in Table 15.

Hardness values for 2222 Xuper NucleoTec electrode ranged from 146 to 178 HV5 in weld metal and from 227 to 345 in the heat-affected zone, which is also presented in Table 15. Hardness values of the base metal ranged from 130 to 164 HV5. Macro inspection showed that there were no cracks on inspected samples.

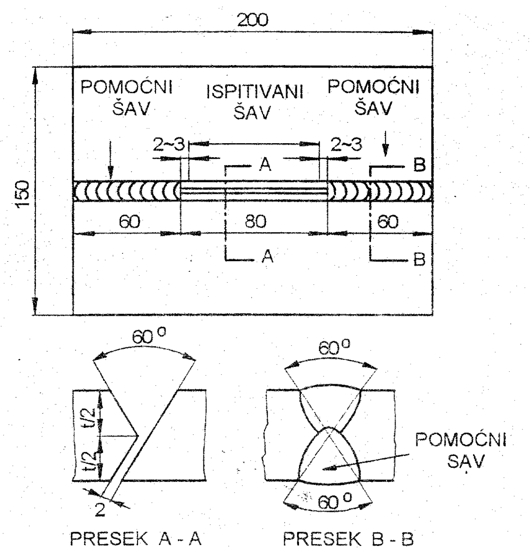
Japan Welding Society Method - "Y" Test

"Y" test is practically a butt welded test with Y-shaped groove. As a criterion for the sensitivity assessment percentage share of the crack length in the overall

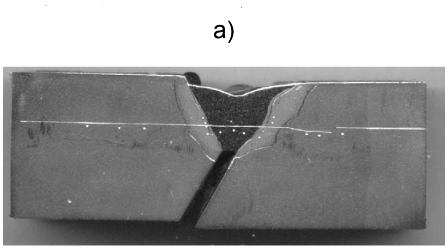
Tabela 15: Rezultati ispitivanja tvrdoće HV5 na "CTS" probama koje su zavarene sa elektrodama ЭA-395/9 i 2222 Xuper NucleoTec u zoni HAZ

Table 15: Hardness test results in the heat-affected zone for "CTS" tests carried out through the use of 3A-395/9 and 2222 Xuper NucleoTec electrodes

Electrode	Dimension	Test type	Location	Hardness values in the HAZ
ЭA-395/9	ϕ 3.00	bithermal	cover plate	286-286-299
			base plate	262-257-232
		trithermal	cover plate	303-293-283
			base plate	341-299-293
	ϕ 4.00	bithermal	cover plate	251-254-249
			base plate	321-317-271
		trithermal	cover plate	313-286-246
			base plate	246-241-254
2222 Xuper NucleoTec	ϕ 3.25	bithermal	cover plate	299-293-293
			base plate	262-280-257
		trithermal	cover plate	262-254-268
			base plate	280-293-280
	ϕ 4.00	bithermal	cover plate	260-299-280
			base plate	280-274-262
		trithermal	cover plate	341-345-341
			base plate	227-244-239



a)



b)

Slika 5: Proba "Y", a) shematski izgled, b) analizirani presek

Figure 5: "Y" test, a) schematic appearance, b) analyzed cross-section

weld length has been taken [7]. Schematic of the test is presented in Figure 5, along with the appearance of the cross-section of the weld.

Butt welding with 3A-395/9 and 2222 Xuper NucleoTec electrodes of ϕ 4.00mm diameters, on 15 and 30 mm thick plates with the root opening of 2 mm has been performed in one pass in order to test technological weldability according to the method of the Japan Welding Society. For welding only electrodes of 4.00 mm diameter have been used in order to simulate severe conditions, with the higher energy input. Welding parameters are presented in Table 16. On characteristic locations samples for the metallographic analysis and hardness measurement have been transversely cut out. Samples have been cut 72 hours after welding.

Results showed that hardness values for all samples do not deviate from expected values, Table 17. Cracks, which could be defined as hot cracks, were detected by macro inspection on 15 and 30 mm thick plates joined through the use of the 3A-395/9 electrode. Microstructural inspection of samples created through the use of the 3A-395/9 electrode on 30 mm thick plates revealed the presence of cold cracks in the weld metal and in the heat-affected zone. Microstructural inspection of samples created through the use of the 2222 Xuper NucleoTec electrode on 30 mm thick plates revealed the presence of cracks in the heat-affected zone.

On the basis of results obtained through the application of the Japan Welding Society method it

Na osnovu dobijenih rezultata ispitivanja prema metodi japanskog društva za zavarivanje - "Y" proba, pokazala se velika osetljivost ove probe na formiranje hladnih i toplih prslina. Formiranje toplih i hladnih prslina konstatovano je u metalu šava kod elektrode ЭA-395/9. Formiranje hladnih prslina u ZUT konstatovano je kod uzoraka ispitivanih sa elektrodom 2222 Xuper NucleoTec. Obzirom da su energije zavarivanja kod svih obavljenih ispitivanja bile istog reda veličine, može se predpostaviti da je formiranje hladnih prslina u ZUT više rezultat stanja osnovnog materijala, odnosno izražene poroznosti, što ukazuje da pri eventualnom reparaturnom zavarivanju materijala vratila, ova činjenica se mora uzeti u obzir.

DISKUSIJA

Ocena metalurške zavarljivosti onovnog metala vratila turbine sa elektrodama ЭA-395/9 i Castoline 2222 Xuper Tec je obavljena kroz ispitivanja mehaničko–tehnoloških karakteristika zavrenih spojeva, kao i kroz ispitivanje sklonosti prema pojavi prslina primenom niza tehnoloških proba zavarljivosti.

Detaljno ispitivanje osnovnog materijala prirubnice vratila pokazalo je da su srednje vrednosti zatezne čvrstoće i izduženja nešto niže od zahtevanih prema GOST standradu. Ostale zatezne osobine, energija udara i tvrdoća su u okviru zahteva standarda. Dijagram kontinuiranog hladjenja (KH) za ispitivani čelični liv 20GSL, sa odgovarajućim temperaturama transformacije, strukturama i tvrdoćama (slika 2) ukazuje na neke karakteristike koje se moraju uzeti u obzir pri proučavanju njegove zavarljivosti. On se odlikuje povišenom zakaljivošću, osetljiv je na temperaturu austenitizacije i na trajanje termičke obrade. Navedene konstatacije posebno usložnjavaju

could be concluded that this test is highly sensitive to the formation of cold and hot cracks, which was detected in the weld metal formed through the use of the 3A-395/9 electrode. Formation of cold cracks was detected in the heat-affected zone of samples formed through the use of the 2222 Xuper NucleoTec electrode. Taking into account that welding energy values were on the same level for all tests, it can be assumed that formation of cold cracks in the heat-affected zone was caused by the surface state of the base material (visible porosity). This fact has to be taken into account regarding the eventual repair welding of the shaft material.

DISCUSSION

Assessment of the metallurgical weldability of the turbine shaft base material with 3A-395/9 and Castoline 2222 Xuper Tec electrodes has been carried out taking into account mechanical and technological properties of welded joints, as well as proneness to the formation of cracks through performing a number of technological weldability tests.

Thoroughal investigation of the shaft flange base material showed that mean values of tensile strength and elongation are a bit lower than those listed in the GOST standard. Values of other tensile properties, such as impact energy and hardness, are within the prescribed range. Continuous cooling transformation diagram for the investigated cast steel 20GSL, with adequate transformation temperatures, structures and hardnesses (Figure 2) reveals certain characteristics which have to be taken into account regarding the weldability analysis.

Main characteristics of this material are high hardenability, sensitivity to the austenitizing

Tabela 16: Parametri zavarivanja Y proba, prečnik elektroda ϕ 4.00

Table 16: "Y" test welding parameters, electrode diameter ϕ 4.00 mm

Sample	Electrode	Plate thickness	Current Intensity, Isr	Voltage, Usr	Length, l	Time, t	Energy, E
	mm	mm	A	V	cm	sec	KJ/cm
1	ЭA-395/9	15	155	28.5	7.9	28.2	15.78
2		30	150	26.2	7.6	41.1	21.25
3	2222 Xuper NucleoTec	15	155	25	7.8	31.2	15.5
4		30	150	24.4	8.0	33.7	15.42

Napomena/Note: E=Usr*Isr*t/l

Tabela 17: Raspodela tvrdoća po preseku "Y" proba zavarivane elektrodama ЭA-395/9 i 2222 Xuper NucleoTec za debljine ploča 15 i 30 mm

Table 17: Hardness distribution along the "Y" test formed through the use of 3A-395/9 and 2222 Xuper NucleoTec electrodes and 15 and 30 mm thick plates

Electrode	Thickness	Tvrdoća HV5				
		BM 1	HAZ 1	WM	HAZ 2	BM 2
ЭA-395/9	15	151-157-146	251-299-289	172-177-185	260-262-268	151-153-142
	30	140-151-157	280-286-280	206-214-199	257-254-268	150-150-146
2222 Xuper	15	148-140-140	299-277-321	178-178-185	268-286-268	153-157-150
NucleoTec	30	145-145-138	286-280-299	190-187-187	265-293-206	147-150-148

problem i zahtevaju posebnu pažnju pri izboru postupaka, tehnologija i dodatnih materijala za reparaturno zavarivanje vratila.

Takođe rezultati ocene zavarljivosti dobijene primenom analitičkih izraza ukazuju da je predmetni čelični liv zavarljiv primenom konvencionalnih postupka zavarivanja, ali uz primenu mera predostrožnosti. Proračunate vrednosti zasnovane na hemijskom sastavu čelika su na nivou koji ukazuje ka sklonosti ka formiranju hladnih prslina, kao i mogućnost formiranja toplih prslina, posebno i zbog velike debljine (300 mm) zida vratila. Sklonost ka pojavi hladnih i toplih prslina kao i nivo ekvivalenta ugljenika koji ukazuje na mogućnost stvaranja krtih faza stvorile su potrebu dodatnih ispitivanja u cilju ocene sklonosti ka stvaranju toplih i hladnih prslina. To je zahtevalo da pored mehaničko - strukturne karakterizacije probnih zavarenih uzoraka osnovnog materijala, u cilju definisanja moguće tehnologije zavarivanja, budu primenjene i tehnološke probe zavarljivosti.

Proračuni su ukazali i na neophodnu potrebu predgrevanja i eventualnog žarenja nakon zavarivanja. Izračunata temperatura predgrevanja, za čelik 20 GSL, iznosi od 150-200 °C. Generalno posmatrajući, predmetni čelični liv spada u grupu zavarljivih čelika koji mogu uspešno da se zavaruju samo uz upotrebu selekcionisanih dodatnih materijala, primenom predgrevanja i niza drugih mera predostrožnosti.

Polazeći od ocene strukturno mehaničkih osobina osnovnog materijala i predpostavljenih zahteva za kvalitet, odgovornost zavarenih spojeva i složenost izvodjenja procesa, za zavarivanje u cilju definisanja zavarljivosti, izabran je postupak metal arc welding with covered electrode (MMA - 111). Na osnovu izabranog postupka, geometrijskog oblika prirubnice vratila, konstruktivnog rešenja, otežanih tehnoloških mogućnosti uslovljenih mogućom reparaturom na licu mesta, kritičnih mehaničko strukturnih osobina osnovnog materijala, hemijskog sastava osnovnog materijala i rasopoložive opreme za reparaturno zavarivanje izabrani su i dodatni i potrošni materijali za zavarivanje. Izabrane su elektrode: ЭA-395/9 i elektroda 2222 Xuper NucleoTec.

Eksperimentalno zavarivanje sučeonih probnih uzoraka izvedeno je parametrima zavarivanja preporučenim od strane oba proizvodjača elektroda, strujom jačine 100A za elektrode prečnika ϕ 3,00mm i ϕ 3,25mm, odnosno 140A za elektrode prečnika ϕ 4mm. Zavarivanje je vršeno bez predgrevanja, sa ciljem ostvarenja oštrijih uslova zavarivanja i verovatnu nemogućnost primene predgrevanja pri izvodjenju reparature.

Zatezna čvrstoća zavarenih spojeva, određivana na epruvetama sa paralelnim bokovima iznosi oko 510MPa za oba dodatna materijala, a mesto prekida je u osnovnom metalu, što ukazuje da su parametri zavarivanja dobro izabrani. Energija udara uzoraka iz metala šava (KV 300/2) pokazuje visoke vrednosti kod

temperature and duration of the heat treatment. The above mentioned makes the problem very complex, therefore special attention concerning the selection of procedures, technologies and filler materials for repair welding of the shaft is required.

Also, weldability assessment results obtained from analytical expressions imply that cast steel 20GSL is weldable through the use of conventional welding procedures, but certain precautionary measures have to be taken. Calculated values based on the chemical composition of steels imply a proneness to the formation of cold cracks, as well as of hot cracks, especially taking into consideration large thickness of the shaft wall (300 mm).

Proneness to the formation of cold and hot cracks and carbon equivalent value imply to the possibility of the formation of brittle phases, creating a need for additional investigations. Apart from mechanical and structural characterization of test samples of the base material, weldability tests have to be performed in order to define applicable welding technologies. Calculations showed that it is necessary to perform preheating and, eventually, annealing after welding. Calculated preheating temperature ranges from 150 to 200°C for cast steel 20 GSL. Generally speaking, cast steel 20 GSL falls into the category of weldable steels which could be successfully used for welding only through the use of selective additional materials, application of preheating and a number of other precautionary measures.

Taking into account structural and mechanical properties of the base material and assumed quality requirements, category of welded joints and welding process complexity, metal arc welding with covered electrode (MMA - 111) was selected for repair welding. On the basis of the selected procedure, geometric shape of the shaft flange, construction solution, limited technological possibilities caused by eventual on-site repair welding, critical mechanical and structural properties of the base material, chemical composition of the base material and available equipment for repair welding, additional and expendable materials have been selected too. The following electrodes were selected: 3A-395/9 and 2222 Xuper NucleoTec

Experimental formation of the welded butt joints - tests has been performed in accordance with welding parameters recommended by both electrode manufacturers. Current intensity is 100 A for electrodes of ϕ 3,00mm i ϕ 3,25mm diameters and 140 A for the electrode of ϕ 4,00mm diameter. Welding has been performed without preheating, in order to create more severe welding conditions and probable impossibility of preheating the repair zone during repair welding.

Value of tensile strength, determined on specimens with parallel sides, is approximately 510 MPa for both filler materials, while the breaking point is located in obe elektrode, preko 120 J, što je u skladu sa navodima proizvodjača. Vrednosti energije udara u ZUT-u imaju srednje vrednosti od 85 do 125 J i daleko su više od vrednosti koje su dobijene za osnovni materijal (50-60J).

To je verovatno rezultat postavljanja zareza u uskoj zoni ZUT-a, pri ispitivanju, što je rezultiralo više zahvatanjem i metala šava, čime su dobijene više vrednosti. Tvrdoća sučeonih spojeva po preseku uzoraka, pokazala je vrednosti u ZUT-u koje se kreću od 220 HV5 do maksimalno 290 HV5. Tvrdoća metala šava kod obe ispitivane elektrode je pokazala vrednosti od 190-220 HV5. Sklonost ka pojavi hladnih prslina ocenjivana je najpre preko "CTS" probe. Parametri zavarivanja ispitnih prolaza su bili u granicama preporučenih. Osnovni nalaz je bio da nije registrovana pojava inicijalnih hladnih prslina ni u dvotermijskim ni u tritermijskim šavovima ni kod jedne od ispitivanih elektroda u kombinaciji sa ispitivanim čeličnim livom. Ovo je dokaz da su ispitivane elektrode otporne na pojavu hladnih prslina za uslove koji vladaju u "CTS" probi, koja inače spada u red strogih opita.

Ocena sklonosti ka pojavi hladnih prslina proverena je i primenom i "Y"-probe, koja spada u grupu najstrožijih, kako zbog uslova hlađenja tako i zbog zazora koji egzistira. Obzirom na visok sadržaj legirajućih elemenata kod obe ispitivane elektrode, očekivana je i reakcija na pojavu toplih prslina. U cilju ocene krajnjih mogućnosti ispitivanih elektrode sa stanovišta osetljivosti ka pojavi prslina, zavarene su dve grupe uzoraka sa različitim debljinama probnih ploča, 15 mm i 30 mm. Dobijeni rezultati merenja tvrdoća pokazuju da su vrednosti tvrdoća kod svih uzoraka na očekivanom nivou. Makro pregledom ustanovljeno je prisustvo prslina, koje se mogu definisati kao tople prsline, kod uzoraka debljine 15 i 30 mm zavarenih elektrodom ЭA-395/9.

Pregledom mikrostruktura uzoraka zavarenih elektrodom ЭA-395/9, na pločama debljine 30 mm, konstatovano je prisustvo i hladnih prslina u metalu šava i ZUT-u. Mikrostruktura uzoraka zavarenih elektrodom 2222 Xuper NucleoTec, na pločama debljine 30 mm, pokazuje prisustvo prslina u ZUT-u. Za konstatovano formiranje hladnih prslina u ZUT-u, obzirom da su energije zavarivanja kod svih obavljenih ispitivanja bile istog reda veličine, može se predpostaviti da je više rezultat stanja osnovnog materijala, što ukazuje da se pri eventualnom reparaturnom zavarivanju materijala vratila ova činjenica mora uzeti u obzir.

Treba napomenuti da su sva zavarivanja vršena bez predgrevanja, sa ciljem ostvarenja oštrijih uslova zavarivanja i verovatne nemogućnost primene predgrevanja pri izvodjenju reparature.

ZAKLJUČCI

Na osnovu obavljenih ispitivanja i analize dobijenih rezultata mogu se izvesti sledeći zaključci:

the base metal, which implies that welding parameters were well chosen. Values of impact energy for samples taken from weld metal (KV 300/2) are very high for both electrodes and exceed 120 J, which is in accordance with data provided by the manufacturer. Mean values of impact energy for samples taken taken from the heat-affected zone range from 85 to 125 J and well exceed values obtained for the base material which range from 50 to 60 J, probably because the notch was located in the narrow heat-affected zone, which resulted in spreading of the heat-affected zone on account of the weld metal, thus higher values were obtained. Hardness value for butt welded joints in the heat-affected zone ranges from 220 to 290 HV5, while the weld metal hardness ranges from 190 to 220 HV5 for both investigated electrodes.

Proneness to the formation of cold cracks has been assessed through the application of the "CTS" test. Welding parameters of test passes were within the recommended range. Basically no initial cold cracks were detected neither in bithermal nor in trithermal welds formed through the use of investigated electrodes in combination with cast steel. That`s the proof that investigated electrodes are resistant to cold cracking for conditions of the "CTS" test, which is considered to be a severe test.

Assessment of proneness to cold cracking has been performed through the application of the "Y" test, which falls into the category of most severe tests due to rigid conditions regarding the cooling rate and the root opening. Taking into account that both electrodes have high content of alloying elements, the formation of hot cracks was to be expected.

In order to assess the possibilities of investigated electrodes regarding the sensitivity to crack formation, two groups of samples with different thicknesses of test plates (15 and 30 mm) were formed by welding. Results showed that hardness values for all samples do not deviate from expected values. Cracks, which could be defined as hot cracks, were detected by macro inspection on 15 and 30 mm thick plates joined through the use of the 3A-395/9 electrode.

Microstructural inspection of samples formed through the use of the 3A-395/9 electrode on 30 mm thick plates revealed the presence of cold cracks in the weld metal and in the heat-affected zone. Microstructural inspection of samples created through the use of the 2222 Xuper NucleoTec electrode on 30 mm thick plates revealed the presence of cracks in the heat-affected zone. T

aking into account that values of welding energy were on the same level for all tests, it can be assumed that formation of cold cracks in the heat-affected zone was caused by the surface state of the base material. This fact has to be taken into account regarding the eventual repair welding of the shaft material.

It`s worth noting that welding was carried out without preheating in all cases, in order to simulate severe

Obavljena su opsežna ispitivanja metalurške zavarljivosti materijala prirubnice vratila hidroturbine HE Djerdap II na reci Dunav, Srbija, izradjene od čeličnog liva 20GSL (20Mn5) sa ciljem ocene mogućnosti reparaturnog zavarivanja postojećih prslina na prirubnici vratila agregata bez demontaže vratila, on site.

Rezultati ocene zavarljivosti, dobijene primenom analitičkih izraza, ukazuju da je predmetni čelični liv zavarljiv primenom konvencionalnih postupka zavarivanja, ali uz primenu mera predostrožnosti. Proračunte vrednosti zasnovane na hemijskom sastavu čelika su na nivou koji ukazuje na sklonosti ka formiranju hladnih prslina, kao i mogućnost formiranja toplih prslina, posebno i zbog velike debljine (300 mm) zida vratila. Proračuni su ukazali i na neophodnu potrebu predgrevanja, pa je izračunata temperatura predgrevanja, koja za čelik 20 GSL iznosi od 150-200 °C.

Za probna zavarivanja u cilju definisanja zavarljivosti, izabran je postupak metal arc welding with covered electrode (MMA - 111). Na osnovu izabranog postupka, geometrijskog oblika prirubnice vratila, konstruktivnog rešenja, otežanih tehnoloških mogućnosti uslovljenih mogućom reparaturom na licu mesta, kritičnih mehaničko strukturnih osobina osnovnog materijala, hemijskog sastava osnovnog materijala i rasopoložive opreme za reparaturno zavarivanje izabrani su i dodatni i potrošni materijali za zavarivanje. Za ispitivanja su izabrane elektrode: ЭA-395/9 prizvodjača AO SPECELEKTROD, Moskva, Rusija i elektroda 2222 Xuper NucleoTec proizvodjača CASTOLIN EUTECTIC, Beč, Austrija.

Ocena metalurške zavarljivosti osnovnog metala vratila turbine sa izabranim elektrodama ЭA-395/9 i Castoline 2222 Xuper Tec je obavljena kroz ispitivanja mehaničko – tehnoloških karakteristika zavrenih spojeva, kao i kroz ispitivanje sklonosti prema pojavi hladnih i toplih prslina primenom tehnoloških proba zavarljivosti: CTS i Y proba. Zavarivanje je vršeno bez predgrevanja, sa ciljem ostvarenja oštrijih uslova zavarivanja i verovatnu nemogućnost primene predgrevanja pri izvodjenju reparature.

Ispitivana sklonost ka pojavi hladnih prslina ocenjivana je preko "CTS" probe, pokazala je da nije registrovana pojava inicijalnih hladnih prslina ni kod jedne od ispitivanih elektroda u kombinaciji sa ispitivanim čeličnim livom. Pregled mikrostruktura CTS proba, ukazao je na prisustvo poroznosti i mikroprslina u ZUT-u i na pojedinim mestima primarnih uključaka. Takodje je uočen porast zrna u ZUT-u uz liniju spoja. Navedene konstatacije posebno usložnjavaju problem i zahtevaju posebnu pažnju pri definisanju tehnologije reparaturnog zavarivanja.

Ocena sklonosti ka pojavi hladnih prslina proverena je i primenom i "Y"-probe. Obzirom na visok sadržaj legirajućih elemenata kod obe ispitivane elektrode, očekivana je i reakcija na pojavu toplih prslina. Ustanovljeno je prisustvo prslina, koje se mogu conditions of welding and probable impossibility of preheating the repair zone during repair welding.

CONCLUSIONS

On the basis of performed tests and analyses of obtained results the following conclusions can be drawn:

Extensive investigations have been undertaken regarding the metallurgical weldability of the material (cast steel 20 GSL) of which the shaft flange of the HPP Djerdap II hydro turbine on River Danube, Serbia, was made. The objective was to assess the possibility of repair welding of existing cracks on the shaft flange of the hydroelectric generating set on-site, without disassembling the shaft.

Results of the weldability assessment obtained through the application of analytical expressions imply that cast steel 20 GSL is weldable through the application of conventional welding procedures, but certain precautionary measures have to be taken. Calculated values based on the chemical composition of steel imply the proneness to the formation of cold and hot cracks, especially taking into consideration large thickness of the shaft wall (300 mm). Calculations showed that it is necessary to perform preheating. Calculated preheating temperature ranges from 150 to 200°C for cast steel 20 GSL.

In order to define weldability metal arc welding with covered electrode (MMA - 111) was selected for welding tests. Based on the selected procedure, geometric shape of the shaft flange, construction solution, technological possibilities conditioned by possible on-site repairing, critical mechanical and structural properties of the base material, chemical composition of the base material and availability of repair welding equipment, filler and expendable welding materials were selected. The following electrodes were selected for welding tests: electrode ЭA-395/9 manufactured by AO SPECELEKTROD, Moscow, Russia and electrode 2222 Xuper NucleoTec manufactured by CASTOLIN EUTECTIC, Vienna, Austria.

Assessment of metallurgical weldability of the turbine shaft base metal with selected electrodes, ЭA-395/9 i Castoline 2222 Xuper Tec, has been performed through the investigation of mechanical and technological characteristics of welded joints, as well as by assessing the proneness to the formation of cold and hot cracks through the application of ”CTS” and ”Y” welding tests. Welding has been performed without preheating, in order to simulate severe conditions of welding and probable impossibility of preheating the repair zone during repair welding.

Proneness to the formation of cold cracks has been assessed through the application of the ”CTS” test. No initial cold cracks were detected in test joints formed through the use of investigated electrodes in combination with cast steel. Microstructural inspection definisati kao tople prsline a konstatovano je i prisustvo hladnih prslina u metalu šava i ZUT-u, kod uzoraka zavarenih elektrodom ЭA-395/9. Uzorci zavareni elektrodom 2222 Xuper NucleoTec pokazali su prisustvo prslina u ZUT-u. Za konstatovano prisustvo hladnih prslina u ZUT, obzirom da su energije zavarivanja kod svih obavljenih ispitivanja bile istog reda veličine, može se predpostaviti da je više rezultat stanja osnovnog materijala, što ukazuje da se pri eventualnom reparaturnom zavarivanju materijala vratila, ova činjenica se mora uzeti u obzir. Kako je ispitivanje izvršeno na probnim pločama različitih debljina uočeno je da se broj prslina u ZUT-u uvećava sa porastom debljine ispitne ploče.

Generalni zaključak je da se materijal vratila može reparaturno zavariti uz primenu tehnologije zavarivanja koja zahteva niz mera predostrožnosti i strogo poštovanje tehnološke discipline. To znači da tehnologija zavarivanja treba da obuhvati kontrolisano predgrevanje, odnosno količinu unete energije zavarivanja i brzinu hlađenja, kao i zavarivanje sa malim količinama tečnog kupatila, uz međuprolaznu i konačno, završnu kontrolu stanja i kvaliteta oblasti obuhvaćene reparaturom što treba da bude obuhvaćeno predloženom tehnologijom reparature. Posle izvedene reparature biće neophodno metodama bez razaranja registrovati stanje zavarenih spojeva i to kasnije redovno periodično pratiti.

ZAHVALNOST

Zahvaljujemo se Ministarstvu za nauku i tehnološki razvoj Republike Srbije za finansiranje rada na ovoj temi u okviru projekta EVB: 35002-TR ,,Razvoj novih metodologija revitalizacije turbinske i hidromehaničke opreme hidroelektrana u zavisnosti od uzroka degradacije materijala“.

LITERATURA / REFERENCES

[1] Report: "TESTING OF MATERIALS AND FAILURE CAUSE ANALYSIS OF THE SHAFT OF A6 TURBINE – HPP ĐERDAP 2", IMS Study nr. 421116-147, Belgrade, 2008.

[2] Z. Odanović, V. Grabulov, S. Momčilović, B. Tasić, M. Đurđević, M. Arsić: "Investigation of the optimal parameters for repair welding of the coal mill in the fossil power station", Welding in the World, (ISSN 0043-2288), Cedex, France, Special Issue, Vol. 52 2008, pp. 347-353.

[3] Y. Ito and K. Bessyo: Weldability formula of high strength steels, related to heat-affected zone cracking. Sumitomo Search, 1 (1969), 5, p. 59 - 70, and IIW-Doc IX-631-69(1969), pp. 1-18.

[4] I. Hrivnjak: Theory of Weldability of Metals and Alloys, Elsevier Science Publishers, , ISBN 0-444-98707-X, Amsterdam, 1991

[5] Uwer, D. and H. Höhne: Characterization of the cold cracking behavior of steels during welding. IIW-Doc. IX-1630-91

[6] N. Yurioka et. al.: Study on carbon equivalents to assess cold cracking tendency and hardness in steel welding; Australian Weld. Res. Ass. Melbourne, Paper 10,1981, pp. 1-18.

[7] EN ISO 17642-2: 2005 Destructive test on welds in metallic materials – Cold cracking test for weldments (CTS)

[8] H. Granjon, Information on Cracking Tests, Document IIS/IIW-93-62

of ”CTS” tests revealed the presence of primary inclusions, porosity and microcracks in the heat-affected zone. The grain growth has been detected right beside the connecting line. The above mentioned makes the problem very complex, therefore special attention concerning the determination of repair welding technology is required.

Assessment of proneness to the formation of cold cracks has been performed through the application of the ”Y” test. Taking into account that both electrodes have high content of alloying elements, the formation of hot cracks was to be expected. The presence of cracks which could be defined as hot cracks was detected. The presence of cold cracks in the weld metal and in the heat-affected zone was also detected during the inspection of samples formed through the application of the ЭA-395/9 electrode. Testing of samples formed through the application of the 2222 Xuper NucleoTec electrode revealed the presence of cracks in the heat-affected zone.

Taking into account that values of welding energy were on the same level for all tests, it can be assumed that formation of cold cracks in the heat-affected zone was caused by the surface state of the base material. This fact has to be taken into account regarding the eventual repair welding of the shaft material. As the investigation was performed on test plates of various thicknesses, it was concluded that number of cracks increases with the increase of thickness of the test plate.

It can be generally concluded that shaft material could be welded through the use of the welding technology with a number of precautionary measures and strict compliance to the technological discipline, which means that repair welding technology should comprise controlled preheating (amount of input welding energy and cooling rate), welding with small amounts of liquid bath, interpass inspection and final inspection regarding the state and quality of the repaired zone. After the repair it is necessary to perform regular periodic inspections of welded joints by applying non-destructive testing methods.

ACKNOWLEDGEMENT

We thank the Ministry of Science and Technological Development of the Republic of Serbia for financing the work on the following theme within the EVB project: 35002-TR ,,Development of New Refurbishment Technologies Regarding the Turbine and Hydromechanical Hydropower Plant Equipment Depending on the Cause of Material Degradation“.