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Pomen varjenja pri izdelavi uparjalnikov za Jedrsko elektrarno Krško

The Role of Welding in the Manufacture of the Steam Generators for the Krško Nuclear Power Plant

Janez Tušek - Andrej Lešnjak - Borut Zorc - Jože Zorko - Franc Krošelj

V članku je opisana tehnologija zvarjanja in navarjanja, uporabljena pri izdelavi uparjalnikov za Jedrsko elektrarno Krško. Predstavljeni so najpomembnejši zvarni spoji in najpomembnejši navari. Vseh zvarnih spojev in varov pa ni bilo mogoče predstaviti, saj jih je samo v enem uparjalniku okrog 60 000. V prvem delu članka je opisano navarjanje notranje površine primarne glave uparjalnika. Uporabljeno je bilo navarjanje s tračno elektrodo pod praškom. V drugem delu je predstavljena izdelava zvarnih spojev med cevjo in cevno steno. Vseh 5428 cevi je spojenih s cevno steno na dveh koncih z obločnim varjenjem TIG ter hidravlično ekspanzijo in mehanskim uvaljanjem. Varjenje predelne stene na primarno glavo in cevno steno je opisano v tretjem delu članka. Z makro obrusom sta predstavljena oba zvarna spoja predelne stene s cevno steno in s primarno glavo. V zadnjem delu pa najdemo opis varjenja krožnih varov na plašču uparjalnika. Tu sta bila uporabljena dva različna obločna postopka varjenja. Koren vara je bil varjen z oplaščeno elektrodo, preostali vari pa avtomatsko pod praškom. Na koncu članka so podani sklepi, v katerih je navedeno, da so bile tehnologije varjenja pravilno izbrane in med izvajanjem zelo dobro nadzorovane, kar je zagotovilo, da je uparjalnik izdelan zelo kakovostno.

(Ključne besede: tehnika jedrska, uparjalniki, navarjanje s praški, varjenje TIG)

This paper describes welding and cladding technologies used in the manufacture of the steam generators for the Krško Nuclear Power Plant. The most important welded joints and claddings are treated, however, all the welded joints and claddings could not be treated because there are around 60.000 in each steam generator. First, cladding of the inner surface of the primary head of the steam generator is described. Submerged-arc cladding with a strip electrode was used for this purpose. Then the production of the welded joints between a tube and a tube sheet is described. All 5428 tubes were joined to the tube sheet, at each end, by TIG welding, preceded by mechanical rolling-in and hydraulic expansion. Welding of a partition plate to the primary head and to the tube sheet is described in the third part of the paper. Both welded joints, i.e. the one between the partition plate and the tube sheet and the one between the partition plate and the primary head, are shown as macro sections. Finally, welding of circumferential welds at the steam-generator shell is described. Two different arc welding processes were used for the purpose. The weld root was manually arc welded with a covered electrode while other welds were automatically submerged-arc welded. In the conclusions, it is stated that the welding technologies used were selected properly and well controlled during execution, which ensured the quality of the steam generator.

(Keywords: nuclear power engineering, steam generators, submerged-arc cladding, TIG welding)

0 UVOD

Kolikšen pomen ima končni izdelek, kakšna je njegova cena, kakšna sta obseg in kakovost nadzora ter preverjanja med njegovo izdelavo je v največji meri odvisno od tveganja pri njegovi uporabi.

Glede na prej omenjene kriterije je uparjalnik za jedrsko elektrarno prav gotovo

0 INTRODUCTION

The importance of the final product, its price, the extent and quality of supervision and control during its production, depend mainly on the risks involved in its exploitation.

It is clear from the above, that the way in which a steam generator is made exceptionally imizjemnega pomena, saj mora biti zanesljivost njegovega delovanja na najvišji mogoči ravni.

Uparjalnik je tlačna posoda, v kateri se ločeno pretakata dve tekočini pod visokim tlakom in pri visoki temperaturi. Na primarni strani se pretaka reaktorsko hladivo, na sekundarni strani pa voda, ki se upari in nato uporabi za pogon turbine.

Večina elementov uparjalnika (glede na celotno maso) je izdelana iz jekla za poboljšanje. Nekateri od teh elementov, predvsem tisti na primarni strani, so na notranji strani navarjeni z močno legiranim nerjavnim jeklom ali nikljevimi zlitinami (teh površin je v vsakem uparjalniku približno 35 m^2). Cevi, po katerih se pretaka reaktorsko hladivo, pa so izdelane iz zlitine niklja, kroma in železa s poslovno oznako inconel.

Posamezni deli uparjalnika so bili med seboj zvarjeni po talilnih postopkih (pod praškom, TIG), drugi z elektrouporovnim točkovnim varjenjem in tretji z mehansko silo v hladnem. Zvarne spoje sestavljajo različne vrste materialov različnih debelin in oblik. Prav zaradi uporabe različnih materialov so bili postopki varjenja izjemno zahtevni, pred varjenjem, med njim in po njem pa je bilo treba izvajati še dodatne ukrepe.

1 NAVARJANJE PRIMARNE GLAVE UPARJALNIKA

Primarna glava uparjalnika je eden od pomembnejših elementov, ki ga na vroči in hladni del loči predelna stena. V vroči del priteka reaktorsko hladivo, ki se nato pretaka prek cevnega sistema, v katerem odda toploto, v drugi, hladni del in nato nazaj v reaktor.

Na sliki 1 je shematsko prikazana primarna glava uparjalnika z označenimi navari. Ta je bila v grobem izdelana s kovanjem v vročem v temperaturnem območju od 800 do 300 °C. Celotna površina notranjosti glave je bila navarjena. Zaradi zapletenih oblik je bilo navarjanje izvedeno po več različnih postopkih. Največjo notranjo površino, ki ima obliko polkrogle z oznako 002 – slika 1, je bilo treba navariti s tračno elektrodo dimenzije 60 × 0,5 mm iz avstenitnega nerjavnega jekla. Navarjanje pod praškom je bilo treba izvesti v najmanj dveh slojih z uporabo dveh različnih dodajnih materialov. Debelina vseh slojev je morala po varjenju in brušenju navarjene površine znašati od 7,5 do 9,5 mm. Brušenje je moralo biti izvedeno, da smo dobili gladko površino. Primarna glava ima štiri odprtine. Dve (manjšega premera) sta namenjeni za vstop in nadzor ter popravilo notranjosti primarne glave, zato se tudi imenujeta odprtini za ljudi. Drugi dve odprtini pa sta priključka za dovod in odvod primarnega medija, to je pregrete vode pri visoki temperaturi in visokem tlaku. Notranjost teh štirih odprtin z oznakama 004 in 006 (sl. 1) je bila navarjena s tračno elektrodo enake sestave, kakršno je imela elektroda, uporabljena

portant, since its operational reliability has to be at the highest possible level.

A steam generator is a pressure vessel in which two pressurised media at an elevated temperature flow separately. On the primary side there is a reactor coolant, and on the secondary side there is water, which evaporates and is used for the turbine drive.

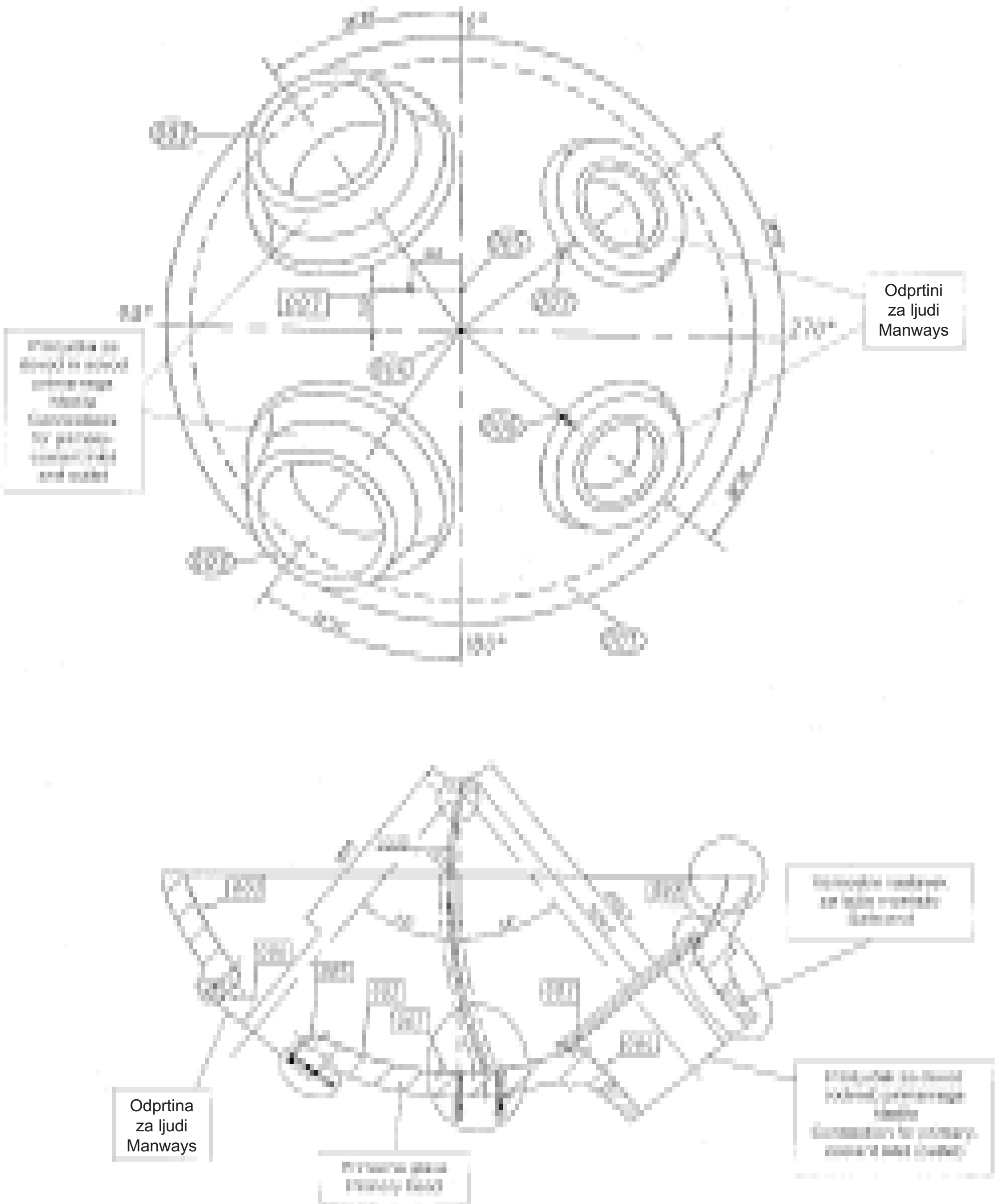
The majority of steam-generator elements, with regard to the whole mass, are made of heat-treated steel. The inside wall of some of the elements, particularly those on the primary side, are surfaced with high-alloy stainless steel or nickel alloys (an area amounting to around 35 m^2 in each steam generator). The tubes in which the coolant flows are made of a nickel-chrome-iron alloy, commercially designated as Inconel.

The individual steam-generator elements were fusion welded, i.e., submerged-arc welded, TIG welded, while others were resistance-spot welded or cold-pressure welded. These welded joints are made of different materials, and are of different sizes and shapes. Owing to the variety of materials, the welding procedures were extremely exacting and additional measures were required before, during and after welding.

1 CLADDING OF THE PRIMARY STEAM-GENERATOR HEAD

The primary steam-generator head is one of the most important elements, it is separated into a cold part and a hot part by a partition plate. The reactor coolant passes first into the hot part, after which it passes through a system of tubes where heat is discharged, and then into the second, cold, part and finally back into the reactor.

The primary steam-generation head, with the claddings indicated, is shown schematically in Fig. 1. It was roughly hot forged in the temperature range from 800 to 300 °C. The entire internal surface of the head was surfaced. Because of the intricate shapes, cladding was carried out using different procedures. The largest internal surface, having the shape of a hemisphere and designated with number 002 (Fig. 1), had to be surfaced with an austenitic stainless-steel strip electrode of 60 x 0.5 mm. Submerged-arc cladding was carried out in at least two layers using two different filler materials. After welding and grinding the thickness of all the layers should be 7.5 to 9.5 mm. Grinding should be used to obtain a smooth surface. The primary head has four openings. Two of them, the ones with the smaller diameter, are designed for entrance and control as well as repairs to the inside of the primary head, because of this, they are called manways. The other two openings are connections for supply and discharge of the primary coolant, i.e. pressurised hot water. The inside of the four openings (004 and 006 - Fig. 1) was surfaced with a strip electrode having the same composition as the elec-



Sl. 1. *Shematski prikaz primarne glave uparjalnika*
Fig. 1. *Schematic presentation of the primary steam-generator head*

za notranje navarjane površine (oznaka 002), in s prerezom 30 × 0,5 mm. Druge navare, ki so označeni na sliki 1, je bilo treba navariti ročno obločno z oplaščenimi elektrodami. Tudi te površine so bile navarjene v več slojih z oplaščenimi elektrodami različnih kemičnih lastnosti oziroma sestave.

1.1 Uporabljeni materiali

Kakor smo že omenili, je celoten uparjalnik izdelan iz različnih vrst materialov. Primarna glava

trode used for cladding the surface designated “002” and was 30 x 0.5 mm in cross-section. The other claddings indicated in Fig. 1 had to be manually arc welded with covered electrodes. Also, these surfaces were welded in several layers with covered electrodes having different chemical properties, i.e. compositions.

1.1 Materials used

The steam generator is constructed of different materials. The primary head is made of a low-je izdelana iz malo legiranega jekla za poboljšanje s kemično sestavo, navedeno v preglednici 1, in oznako SA 508 C13A.

alloy heat-treatment steel SA 508 C13A with a chemical composition given in Table 1.

Preglednica 1. *Kemična sestava osnovnega materiala za primarno glavo uparjalnika in dveh dodajnih materialov v obliki tračnih elektrod za navarjanje plasti v več slojih z oznako 002 (Fig. 1) in sestava dodajnega materiala za TIG varjenje cevi na cevno steno*
Table 1. *Chemical composition of the parent metal for the primary steam-generator head, of two filler materials, i.e. two strip electrodes, for cladding of several layers designated with number 002 (Fig. 1), and of the filler material for TIG welding of tubes to the tube sheet*

	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	V %	Nb %	Co %	Cu %
Osnovni material Parent metal	≤0,25	0,15-0,40	1,20-0,40	0,025	0,025	≤0,25	0,45-0,60	0,40-1,00	≤0,45	/	/	/
Dodajni material za prvi sloj 1st layer filler material	≤0,03	0,15-0,50	1,0-2,5	0,015	0,008	23,5-24,5	<0,30	12,0-13,0	/	0,6-1,0	≤0,05	≤0,20
Dodajni material za drugi sloj 2nd layer filler material	≤0,04	0,30-0,65	1,0-2,5	0,03	0,008	19,5-21,5	≤0,75	9,0-11,0	/	/	≤0,05	≤0,75
Dodajni material za TIG varjenje TIG welding filler material	0,05	0,08	2,9	0,005	0,001	20,25	/	71,5	/	/	0,05	0,22

S toplotnim poboljšanjem pri izdelavi primarne glave so se mehanske lastnosti osnovnega materiala močno izboljšale. Te lastnosti je bilo treba obdržati tudi po navarjanju s tračno elektrodo pod praškom. Najpomembnejši ukrep je bil tako predgrevanje varjenca pred varjenjem in vzdrževanje primerne temperature med varjenjem. Navar je bil izdelan iz več slojev nerjavnega avstenitnega jekla različne kemične sestave. Za prvi sloj je bila uporabljena tračna elektroda, s splošno trgovsko oznako CrNi 24.13 L Nb in po klasifikaciji ASME SFA 5.9 ER 309 L (Nb), proizvajalca SANDVIK, Švedska. Kemična sestava tračne elektrode za navarjanje prvega sloja je navedena v preglednici l.

Za drugi in tretji sloj je bila uporabljena tračna elektroda iz nekoliko manj legiranega avstenitnega nerjavnega jekla. Njena splošna oznaka je CrNi 19.9 L Nb in po klasifikaciji ASME SFA-5.9 ER 347. Podrobna kemična sestava je prav tako navedena v preglednici l.

S poskusi je bilo ugotovljeno, da je v obeh navarih, ki nastaneta iz zgoraj navedenih tračnih elektrod, 9 odstotkov delta ferita.

Evropski standard za dodajni material za navarjanje v obliki tračne elektrode še ne obstaja.

Strukture osnovnih in dodajnih materialov lahko določimo v Schaefflerjevem diagramu (sl. 2) z uporabo enačb:

Quenching and tempering used in the manufacture of the primary head considerably improved the mechanical properties of the parent metal. These properties should not be lost after submerged-arc cladding with the strip electrode. The most important measure was, therefore, preheating of the workpiece prior to welding and maintenance of a suitable temperature during the welding. The cladding consists of several layers of austenitic stainless steel having different chemical compositions. For the first layer the strip electrode with the trade mark CrNi 24.13 L Nb and SFA 5.9 ER 309 L (Nb), according to ASME classification, produced by SANDVIK, Sweden, was used. The chemical composition of the strip electrode for cladding of the first layer is given in Table 1.

For the second and third layers the strip electrode of a less-alloyed austenitic stainless steel was used. Its general designation is CrNi 19.9 L Nb and SFA-5.9. ER 347 according to ASME. Its chemical composition is also given in Table 1.

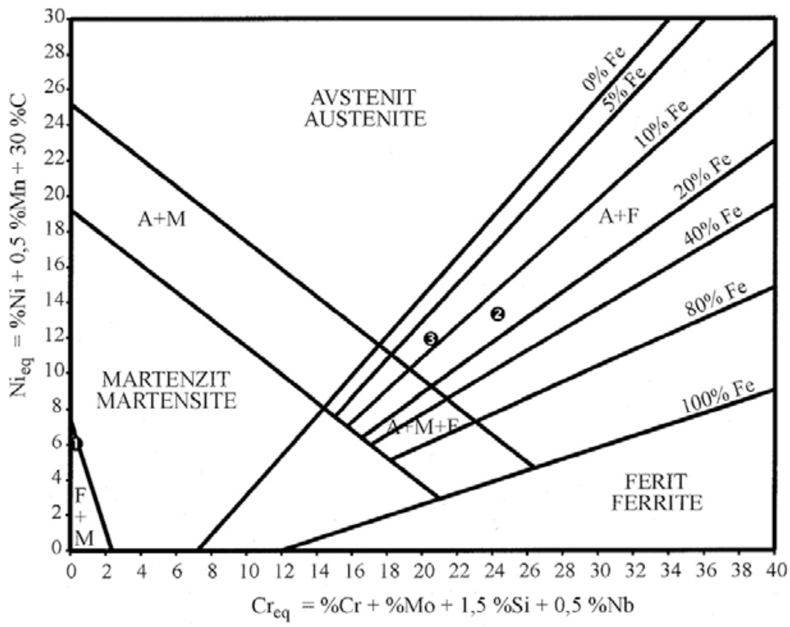
The experiments showed that both claddings made with the strip electrodes contain 9 % of delta ferrite.

There is currently no European standard for a strip-electrode filler material for cladding.

The structures of the parent metals and the filler materials can be determined in the Schaeffler diagram (Fig. 2) by means of the following equations:

$$Cr_{ekv} = \% Cr + \% Mo + 1,5 \% Si + 0,5 \% Nb \quad (1),$$

$$Ni_{ekv} = 30 \% C + \% Ni + 0,5 \% Mn \quad (2).$$



Sl. 2. *Schaefflerjev diagram z oznakami struktur osnovnega materiala in obeh dodajnih materialov za prvi in drugi sloj navara na notranji površini primarne glave*

Fig. 2. *Schaeffler diagram with indications of structures of the parent metal and the two filler materials used for the first and second layers of the cladding at the internal surface of the primary head*

1.2 Opis praktičnega navarjanja s tračno elektrodo pod praškom

Varjenje s tračno oblikovano elektrodo je znano že skoraj osemdeset let. Leta 1920 je bil namreč v Nemčiji podeljen patent št. 37008 92 za tračno oblikovan dodajni material. V praksi se postopek največkrat uporablja za navarjanje s tračno elektrodo iz avstenitnega nerjavnega jekla, kakor je to bilo tudi pri izdelavi primarne glave uparjalnikov za jedrsko elektrarno ([1] do [4]).

Dodajni material lahko uporabljamo v obliki ravnega ali pa tudi polkrožnega traku. Lahko se navarja z eno ali pa z dvema elektrodama hkrati [5]. Prečni prerezi trakov znašajo od 20 × 0,2 mm do 180 × 0,5 mm [6]. Na sliki 3 sta prikazana dva trakova 60 × 0,5 mm po ustavitvi varjenja. Takšen trak je bil uporabljen za navarjanje notranje površine primarne glave. Na spodnji strani obeh trakov je gorel en ali pa hkrati dva ali celo več oblokov. Ti so talili trak, del osnovnega materiala in del praška. Iz oblike spodnjega roba traku, kjer je gorel oblok in se je talil dodajni material, lahko pridemo do nekaterih ugotovitev.

Zanesljivo lahko trdimo, da sta v točki 1 in 2 (sl. 3) tik pred ustavitvijo procesa gorela obloka. Na levem traku pa je nazadnje oblok gorel v točkah 3, 4 in 5. V točkah l in 2 se je oblikovala kapljica, v točkah 6 in 7 pa se je kapljica ravnokar odtrgala. V

1.2 Practical trials of submerged-arc cladding with a strip electrode

Welding with a strip electrode has been known for almost eighty years. It was in 1920 that patent no. 37008 92 for a strip-shaped filler material was granted. In practice this procedure is mostly used for cladding with an austenitic stainless-steel strip electrode as was the case for the fabrication of the primary steam-generator head for a nuclear power station ([1] to [4]).

The filler material may be in the shape of a straight or semicircular strip. Cladding may be carried out with a single electrode or two electrodes simultaneously [5]. Cross-sections of the strips vary between 20 x 0.2 mm and 180 x 0.5 mm [6]. Fig. 3 shows two strips of 60 x 0.5 mm after welding. Such a strip was used for cladding the internal surface of the primary head. At the lower side of each strip one, two or even more arcs were burning at the same time. They were melting the strip, a part of the parent metal and a part of the flux. The shape of the lower strip edge, where the arc was burning and the filler material was melting, permitted us to draw a few conclusions.

It may be affirmed with certainty that at points 1 and 2 (Fig. 3) two arcs were burning immediately before the process stopped. With the left strip, the arc was burning last at points 3, 4, and 5. At points obeh primerih sta se odtrgali zelo veliki kapljici. Prav gotovo je bil premer kapljice od dva- do trikrat večji, kakor je debelina traku. Zaradi prehoda raztaljenih kapljic iz traku se dolžina oblokov stalno spreminja in oblok ali obloki se med varjenjem stalno selijo po vsej njegovi širini. Po grobi oceni se ta dolžina oblokov spreminja od nekaj milimetrov pa celo do pet milimetrov.

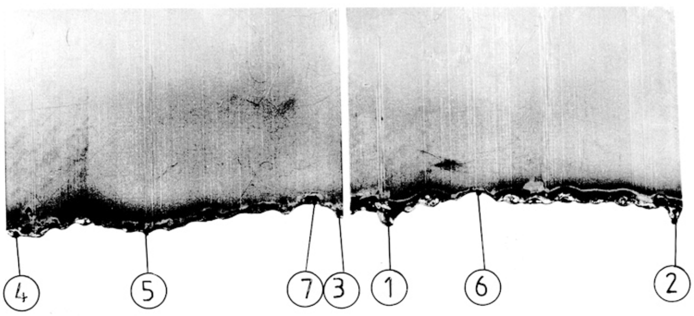
Na sliki 4 sta prikazana dva dela traku dimenzije 30 × 0,5 mm, ki sta se uporabljala za navarjanje notranjosti vseh štirih odprtin primarne glave z oznakama 004 in 006 (sl. 1).

Tudi iz teh posnetkov (sl. 4) lahko ugotovimo, da je hkrati gorelo več oblokov in da sta se sočasno lahko odtalili dve ali celo več kapljic. Na koncu traku (sl. 4 - desno) vidimo tri različno velike kapljice. Iz tega lahko sklepamo, da so tik pred ustavitvijo varjenja istočasno goreli trije obloki. Na sredini drugega traku (sl. 4 - levo) pa je nastala samo ena kapljica. Iz oblike robu pa lahko ocenimo, da se je po celotni širini traku naredilo od 5 do 7 kapljic. Kapljice so bile zaradi površinske napetosti okrogle oblike s premerom od 1 do 2,5 mm. Po klasifikaciji IIW (Mednarodni inštitut za varilstvo) lahko uvrstimo ta način

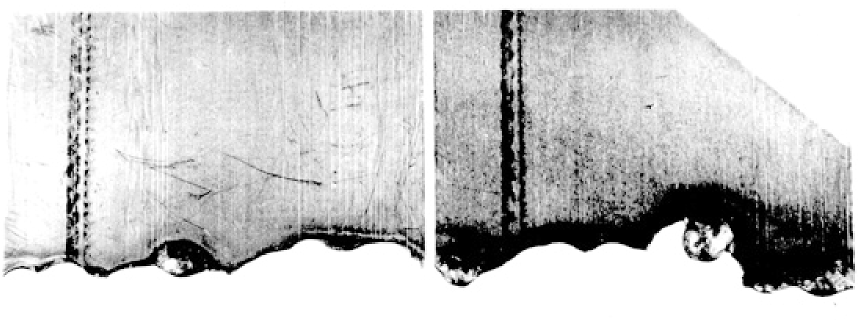
1 and 2 a droplet was formed, and at points 6 and 7 it had just detached. In both cases rather large droplets detached. The droplet diameter was at least two to three times the strip thickness. Because of the detachment of the molten droplets from the strip, the arc lengths were constantly changing, and an arc or arcs were constantly moving across its width during welding. According to a rough estimation, the arc lengths were constantly varying between a few millimetres and five millimetres.

Fig. 4 shows two parts of a strip of 30 x 0.5 mm which was used for cladding the inside of the four openings of the primary head, designated with numbers 004 and 006 (Fig. 1).

Also these photos indicate that several arcs were burning at the same time and that two or more droplets could be melted off. At the strip edge (Fig. 4, right) three droplets of different sizes can be seen. It may be concluded that immediately before the end of welding three arcs had been burning simultaneously. In the middle of the second strip (Fig. 4, left) a single droplet formed. The edge shape allows us to conclude that 5 to 7 droplets were formed along the total strip width. Because of surface tension, the droplets were round with a diameter varying from 1 to 2.5 mm. According to the IIW (International In-



Sl. 3. *Konca traku iz nerjavnega jekla (60 x 0,5 mm) za navarjanje pod praškom s spodnjima robovoma, kjer so goreli en, dva ali več oblokov, ki so se gibali po traku prečno sem in tja in talili dodajni material*
Fig. 3. *Two parts of a stainless steel strip (60 x 0.5 mm) for submerged-arc cladding showing the lower edges at which one, two or more arcs moving across the strip to and fro and melting the filler material were burning*



Sl. 4. *Konca traku iz nerjavnega jekla (30 x 0,5 mm) s spodnjima robovoma, kjer je gorel oblok za navarjanje notranjosti odprtin na primarni glavi z oznakama 004 in 006 (sl. 1)*
Fig. 4. *Two parts of a stainless strip (30 x 0.5 mm) showing the lower edges at which an arc for cladding the inside of the openings at the primary head designated by numbers 004 and 006 (Fig. 1) was burning*

prehajanja materiala v skupino 1.2.1 - usmerjen prehod [7]. Iz oblike spodnjega robu traka pa je nemogoče oceniti, ali je raztaljeni material prehajal tudi ob steni žlindre. Za razrešitev tega vprašanja bi bilo treba opraviti mnogo več raziskav in uporabiti tudi tehniko presevanja taline vara oziroma varilnega obloka, ki gori pod praškom ([8] do [12], [22]).

Poleg posameznih procesov, ki potekajo med navarjanjem s tračno elektrodo, je zelo pomembna stopnja razmešanja med dodajnim in osnovnim materialom.

Že prej je bilo omenjeno, da je treba doseči navar višine 7,5 do 9,5 mm v več slojih. Širina prekrivanja prejšnjega navara z novim znaša od 7 do 9 mm.

Jakost toka med navarjanjem I je bila približno 650 A, obločna napetost U 30 V in hitrost varjenja v_v 0,11 m/min. Vnos energije na enoto dolžine se izračuna z enačbo:

stitute of Welding) classification, this type of material transfer may be ascribed to group 1.2.1 "guided transfer" [7]. The shape of the lower strip edge does not allow us to assess whether the molten material was also transferred along the slag wall. In order to answer this question several more studies would be needed and an irradiation method should be used for the weld metal and welding arc burning in flux ([8] to [12], [22]).

In addition to the individual processes going on during strip-electrode cladding, the mixing ratio of the filler material and the parent metal is very important too.

As already mentioned, a multilayer cladding with a height of between 7.5 and 9.5 mm was to be obtained. The lap width of the previous cladding with the new one amounted to 7 to 9 mm.

The current intensity during cladding I was around 650 A, the arc voltage U 30 V, and the welding speed v_v 0.11 m/min. Energy input per unit of length can be calculated as follows:

$$E = \frac{I \cdot U}{v_v} \qquad (3)$$

in znaša 1,77 MJ/m, vnos energije na enoto površine pa po naslednji enačbi:

and amounts to 1.77 MJ/m. The heat input per unit of area can be calculated as follows:

$$E = \frac{I \cdot U}{v_v \cdot b_n} \qquad (4).$$

Navarjanje je bilo izvedeno s polom plus na elektrodi, kar je nekoliko neobičajno. Večina literature in praktikov iz industrije, kakor tudi praktične izkušnje avtorjev tega članka, priporoča, da se pri navarjanju s tračno elektrodo priključi pozitivna sponka na varjenec in negativna sponka na elektrodo ([13] do [16]). Način gorenja obloka, globina uvara in talilni učinek so namreč odvisni od polarnosti.

Katodna pega je površina na negativni elektrodi, iz katere izstopajo elektroni za vzdrževanje obloka. Elektroni skozi oblok ionizirajo nevtralno atmosfero in ustvarjajo plazmo. Površino na anodi, tj. na pozitivni elektrodi, na katero priletijo elektroni, imenujemo anodna pega.

Katodna pega je v primerjavi z anodno mnogo gibljivejša, ker po katodi išče najugodnejše mesto za izstop elektronov. Zaradi velike gibljivosti katodne pege se na negativni sponki pretali več materiala kakor na pozitivni, temperatura pa je, zaradi gibanja katodne pege, manjša na negativni sponki kakor na pozitivni. Iz povedanega izhaja, da je primerneje navarjati z negativno sponko na elektrodi, ker se pretali več dodajnega in manj osnovnega materiala.

Z negativno sponko na elektrodi pri navarjanju s tračno elektrodo je mogoče doseči ugodnejšo stopnjo razmešanja. Pri navarjanju malo legiranega konstrukcijskega jekla z nerjavnim avstenitnim jeklom se priporoča stopnja razmešanja od 12 do 15 odstotkov. Izračunamo jo z enačbo:

Cladding was carried out with a positive electrode, which was somewhat unusual. The majority of papers and practitioners in industry as well as the practical experiences of the authors recommend that in strip-electrode cladding the workpiece is positive and the electrode negative ([13] to [16]). The mode of arc burning, penetration depth, and melting rate depend on the polarity.

A cathode spot is the area at the negative electrode from which electrons for arc maintenance are emitted. The electrons passing through the arc, ionise the neutral atmosphere, and generate plasma. The anode area at the positive electrode where the electrons strike is called the anode spot.

The cathode spot is much more mobile than the anode one because it is searching for the most suitable spot for electron emission from the cathode. Because of the great mobility of the cathode spot, more material will be melted at the negative pole than at the positive pole, but the temperature will be lower at the negative pole than at the positive pole. This suggests that it is more appropriate to surface with a negative electrode since a larger volume of the filler material and a lesser volume of the parent metal will be melted.

In strip-electrode cladding it is possible to obtain a more favourable mixing ratio with the electrode negative. In cladding low-alloy structural steel with austenitic stainless steel, a mixing ratio of 12 to 15 % is recommended. It can be calculated as follows:

$$\gamma = \frac{A_0}{A_0 + A_d} \cdot 100 \quad (\%) \tag{5}$$

kjer je:

A_o – površina prečnega prereza navara –staljen osnovni material

A_d – površina prečnega prereza navara –staljen dodajni material

Pri nižjih stopnjah razmešanja lahko pride do luščenja navarjene plasti od osnovnega materiala, pri višjih stopnjah pa do nastajanja martenzitne strukture (glej Schaefflerjev diagram – sl. 2).

Poleg stopnje razmešanja sta od polarnosti odvisna tudi prigor in odgor legirnih elementov med varjenjem.

Treba je dodati, da je navarjanje z negativno sponko na elektrodi predvsem "srednjeevropski" način platiranja nerjavnega jekla na malo legirano konstrukcijsko jeklo ([14] do [16]).

Navarjanje s pozitivno sponko na elektrodi, kakršno je bilo uporabljeno pri izdelavi primarne glave uparjalnikov, pa je ameriška tehnologija navarjanja, ki jo je prevzel tudi ESAB ([15] in [17]). Za navarjanje s pozitivno sponko na elektrodi se zaradi procesov pod praškom in v talini vara uporabljajo trakovi iz nerjavnega avstenitnega jekla, ki so nekoliko močneje legirani.

Za navarjanje notranjosti primarne glave so bili uporabljeni trakovi podjetja SANDVIK in varilni praški podjetja ESAB.

Drugi navari, ki so na sliki 1 označeni s številkami 003, 005, 009 in 012, so narejeni ročno obločno z oplaščeno elektrodo. Tudi v tem primeru je prvi sloj navarjen z elektrodo s splošno oznako 24/13 in drugi z elektrodo z oznako 19/9.

Pri analizi navarjanja pod praškom je zelo pomemben dejavnik tudi produktivnost procesa. Prikažemo ga lahko na več načinov ([7], [18] do [21]). Najjasnejša pokazalnika produktivnosti sta talilni učinek in površinski učinek. Prvi je definiran s količino pretaljenega dodajnega materiala v časovni enoti, drugi pa s količino navarjene površine na časovno enoto.

where:

A_0 – area of the cross-section of the cladding - molten parent metal

A_d – area of the cross-section of the cladding - molten filler material

With lower mixing ratios, peeling-off of the surface layer from the parent metal may occur, and with higher mixing ratios, formation of a martensite structure (see Schaeffler diagram - Fig. 2).

Polarity affects not only the mixing ratio but also the pick-up and burn-off of alloying elements during welding.

It should be mentioned that cladding with a negative electrode is a Central European practice for cladding stainless steel on low-alloy structural steel ([14] to [16]).

Cladding with a positive electrode, which was used in the fabrication of the primary steam-generator head, however, is an American cladding technology, which was also taken over by the ESAB ([15] and [17]). For cladding with a positive electrode more strongly alloyed strips of austenitic stainless steel are used because of the submerged-arc and weld-pool processes.

For cladding the inside of the primary head, strips manufactured by SANDVIK and welding fluxes manufactured by ESAB were used.

The other claddings, designated with numbers 003, 005, 009, and 012 in Fig. 1, were submerged-arc surfaced with a covered electrode. In this case too, the first layer was surfaced with an electrode having a general designation 24/13, and others with an electrode having a designation 19/9.

In an analysis of submerged arc cladding, process productivity is also an important factor. It can be shown in several ways ([7], [18] to [21]). The most useful indicators of productivity are melting rate and the surface effect. The first is defined as the volume of filler material melted per unit of time, and the second as the size of the area surfaced per unit of time.

2 IZDELAVA SPOJA MED CEVJO IN CEVNO STENO

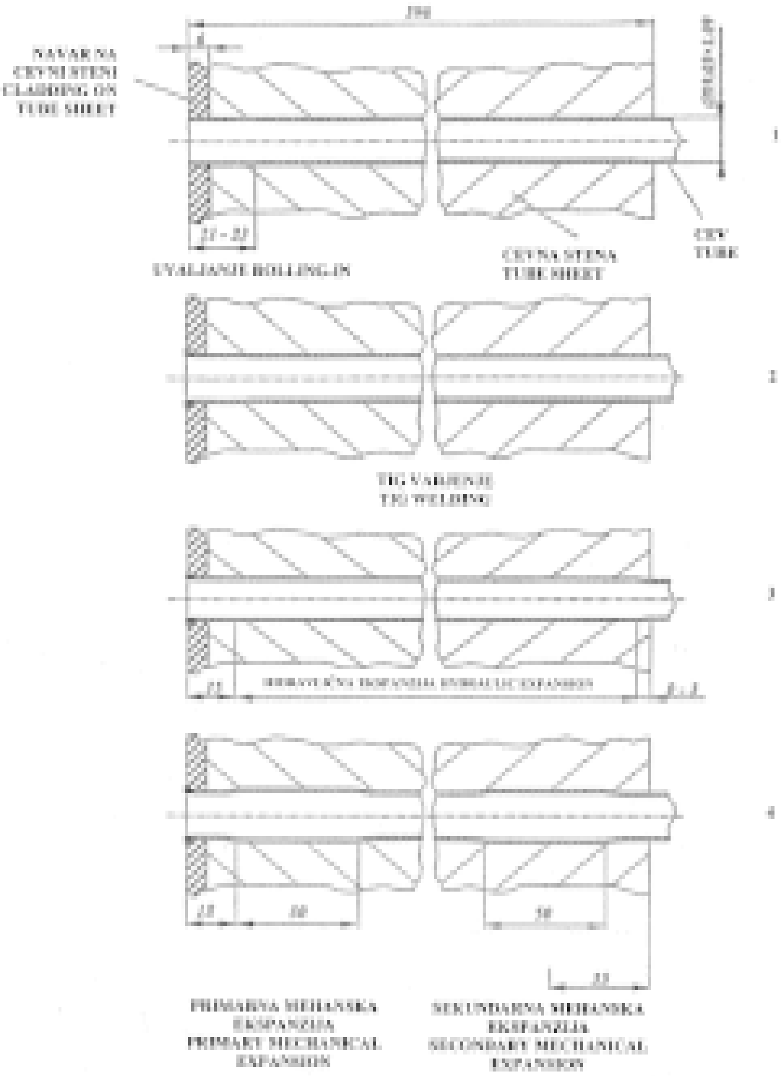
Na izbiro postopka za spajanje cevi v cevno steno najbolj vplivajo obratovalni parametri toplotnega menjalnika. Kakšna sta obratovalni tlak in temperatura? Kako je delovni medij kemično oz. korozijsko agresiven? Ali je varjenje sploh mogoče?

Če je toplotni menjalnik namenjen za obratovanje v kemično oz. korozijsko agresivnem sredstvu ob visokih temperaturah in tlaku, se priporoča izvedba spoja z varjenjem. Za izboljšanje kakovosti spoja se varjenje kombinira z ekspanzijo cevi v cevni steni ([23] in [24]).

2 JOINING THE TUBE TO THE TUBE SHEET

The choice of a procedure for joining tubes to the tube sheet is mainly affected by the operating conditions of the heat exchanger. How high are the operating pressure and operating temperature? How chemically aggressive or corrosive is the working medium? Is welding possible?

If the heat exchanger is designed for operation in chemically aggressive, i.e. corrosive, media at elevated temperatures and pressures, welding is recommended for the joint. To improve joint quality, welding is combined with tube expansion in the tube sheet ([23] and [24]).



Sl. 5. *Potek izvedbe zvarnega spoja med cevjo in cevno steno. 1 - mehansko uvaljanje; 2 - TIG varjenje; 3 - hidravlična ekspanzija; 4 - mehanska ekspanzija.*

Fig. 5. *Execution of the welded joint between a tube and the tube sheet. 1 - mechanical rolling-in; 2 - TIG welding; 3 - hydraulic expansion; 4 - mechanical expansion.*

Spoj med cevno steno in cevmi je najbolj kritičen element uparjalnika, zato se napake najpogosteje pojavljajo prav na njih. Varnost in zanesljivost uparjalnika je odvisna od kakovosti vsakega posameznega spoja med cevjo in cevno steno ([25] in [26]).

Prav zaradi čim večje varnosti in kakovosti spoja je bila izbrana kombinirana metoda varjenja in ekspanzije cevi v izvrtini v cevni steni.

Spoj je bil izveden v štirih korakih, kakor je shematsko prikazano na sliki 5.

- Najprej so bile cevi mehansko uvaljane v dolžini 21 mm od primarne strani cevne stene.
- Priprava zvarnega spoja in varjenje cevi na primarno stran cevne stene, po postopku TIG.
- Sledi hidravlična ekspanzija cevi po vsej dolžini cevne stene.
- Mehanska ekspanzija v dolžini 2x 50 mm.

The joint between the tube sheet and the individual tubes is the most critical element of the steam generator. Consequently, defects are most often found at this joint. The safety and reliability of the steam generator depends on the quality of each individual joint between the tube sheet and the tube ([25] and [26]).

It is for the sake of safety and joint quality that the combined procedure of welding and tube expansion in the borehole of the tube sheet was selected.

The joint was made in four steps as shown in Fig. 5:

- First the tubes were mechanically rolled-in to a length of 21 mm from the primary side of the tube sheet.
- Then the welded joint was prepared and the tube TIG welded at the primary side of the tube sheet.
- Then followed hydraulic expansion of the tube along the whole tube sheet length.
- Finally mechanical expansion was carried out over a length of 2 x 50 mm.

Od varjenja se zahteva, da zagotovi popolno tesnost in zadovoljivo trdnost spoja. Z dvema postopkoma ekspanzije so bile cevi enakomerno uvaljane v izvrtino cevne stene. S tem je bila zaprta špranja med cevmi in izvrtino cevne stene, kjer bi se lahko kopičili radioaktivni in korozijski produkti.

S kombinacijo dveh postopkov ekspanzije so bile, kar zadeva zaostale napetosti, dosežene najugodnejše razmere v ceveh.

2.1 Mehansko uvaljanje cevi

V cevno steno je bilo skozi podporne rešetke na sekundarni strani uparjalnika montiranih 5428 cevi U s premerom 19,05 mm in z debelino stene 1,09 mm. Premer lukenj v cevni steni je bil 19,27 mm. Cevi U so bile nato še mehansko uvaljane v dolžini 21 do 23 mm od primarne strani cevne stene. S tem postopkom so bile cevi U pritrjene v cevno steno, da se je lahko izvedla priprava zvarnega robu. Sila oprijemanja cevi U v cevno steno po mehanskem uvaljanju je bila preverjena na testnih vzorcih. Sila oprijemanja je zadostna, če se cev U ne da izvleči z roko.

S posebnim ekspanzijskim orodjem iz gume je bilo preverjeno, ali so cevi pritrjene v izvrtinah cevne stene in se ne premikajo. S to operacijo se je zaprla vrzel med cevjo U in izvrtino v cevni steni. Za doseganje optimalnih pogojev varjenja je bila oprema za mehansko uvaljanje nastavljena tako, da se cev med pripravo zvarnega robu ni mogla zasukniti. Cevi U so se med uvaljanjem relativno malo deformirale in so imele zato le relativno nizke zaostale napetosti.

2.2 Varjenje

Strojna obdelava zvarnega robu je bila izvedena s posebno frezalno napravo, ki ima tri frezalna rezila premaknjena za 120°. V sredini frezalne naprave je centrirni nastavek dolžine 100 mm, s katerim se naprava pritrdi in centrira v izvrtini, ki jo obdelujemo. Na 1 % izbranih cevi je bila izvedena dimenzionalni nadzor priprave zvarnega robu.

Varjenje cevi U v cevno steno je bilo izvedeno z uporabo avtomatskega varjenja po postopku TIG. Varilni avtomat je napravil zvar v enem prehodu z dodajanjem varilne žice, ki se je talila v obloku in skupaj s cevno steno in cevjo tvorila zvar. Skupni čas, v katerem je varilni avtomat izdelal celoten zvar, je znašal 92 sekund. Namen varjenja je bil zagotoviti popolno tesnost spoja med cevjo in cevno steno.

2.2.1 Pulzni postopek varjenja

S pulznim načinom varjenja po načinu TIG se lahko nadzira vnos toplote v zvar. Ta postopek ponuja kar nekaj prednosti pred običajnim načinom varjenja:

Welding is required to assure 100 % tightness and a satisfactory joint strength. With two expansion procedures the tubes were uniformly rolled into the tube-sheet boreholes. Thus the gap between the tube and the tube-sheet borehole, in which radioactive and corrosive products could pile up, was closed.

The combination of the two expansion procedures provided the most favourable conditions concerning the residual stresses in the tubes

2.1 Mechanical rolling-in of the tubes

5428 U tubes with a diameter of 19.05 mm and a wall thickness of 1.09 mm were mounted into the tube sheet through supporting grids on the secondary side of the steam generator. This operation is called tubing. The diameter of the tube-sheet holes was 19.27 mm. The U tubes were then mechanically rolled to a length of 21 to 23 mm from the primary side of the tube sheet. Using this procedure, the tubes were fixed into the tube sheet so that the edge preparation could be made. After mechanical rolling-in, adhesion of the U tubes was verified on test pieces. The adhesion is sufficient if a U tube cannot be pulled out by a human hand.

A special expansion tool made of rubber was used to check whether the tubes were fixed in the tube-sheet boreholes and could not be moved. Thus the gap between the U tube and the tube-sheet borehole was closed. In order to obtain optimum welding conditions, the equipment for mechanical rolling-in was set so that the tube could not turn a round during weld edge preparation. The U tubes were comparatively undeformed during rolling-in and consequently showed comparatively low residual stresses.

2.2 Welding

Machining of the weld edge was carried out by a special milling machine having three milling blades each staggered by 120°. In the centre of the milling machine there was a centring boss with a length of 100 mm with which the machine was fixed and centred in the borehole to be machined. 1 % of the selected tubes were examined as to the dimensions of the weld-edge preparation.

The U tubes were automatically TIG welded into the tube sheet. An automatic welder made a single-run weld with the addition of a welding wire which melted in the arc and constituted the weld jointly with the tube sheet and the tube. The automatic welder made the weld in 92 seconds. The purpose of welding was to achieve absolute tightness of the tube-to-tube sheet joint.

2.2.1 Pulsed-welding process

Pulsed TIG welding permits control of heat input. It offers a number of advantages over a conventional welding process, i.e.:

- možnost nadzora prostornine taline vara,
- večja globina uvara ob enakem vnosu energije,
- hitrost varjenja je mogoče nadzirati z varilnimi parametri,
- lažje razplinjevanje in s tem boljša kakovost,
- manjša obremenitev volframove elektrode.

Pulzno-tokovni način varjenja je postopek, v katerem se varilni tok zvezno spreminja med dvema nastavljenima vrednostima. V času trajanja pulznega toka potekata segrevanje in taljenje, v času pretoka osnovnega toka pa hlajenje in strjevanje taline. Vir varilnega toka samodejno preklaplja med pulznim in osnovnim varilnim tokom in obdrži želeno vrednost za določen čas. S pulznim postopkom naredimo celoten zvar s prelitjem teh posameznih delov vara, tako da se elektroda zvezno giblje po zvarnem robu. Potek jakosti toka med varjenjem je prikazan na sliki 6.

Pomembne veličine, ki jih lahko nastavimo in nadziramo, so:

- jakost pulznega toka,
- jakost osnovnega toka
- čas trajanja pulznega toka,
- čas trajanja osnovnega toka,
- oblika pulza,
- hitrost varjenja.

Viri varilnega toka za varjenje po pulznem postopku imajo možnost za natančno nastavitev teh veličin. Vrednost pulznega toka je približno 1,5 do 2–krat večja od normalnega varilnega toka za taka dela. Osnovni tok je potreben le za ohranjanje stabilnega gorenja obloka. Običajno je ta jakost nastavljena na eno četrtino vrednosti jakosti pulznega toka.

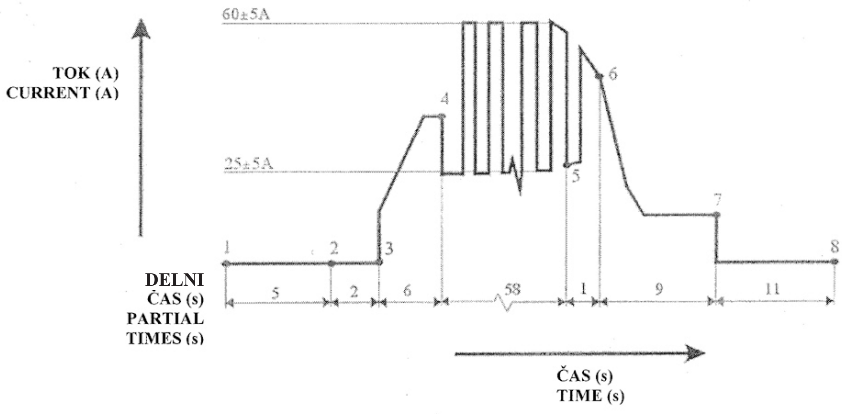
- the possibility of control over the weld metal volume,
- deeper penetration with the same heat input,
- welding speed can be controlled by welding parameters,
- better degassing and, consequently, higher quality,
- smaller load of a tungsten electrode.

A pulsed-current welding process is a method in which the welding current continuously varies between two preset values. During the pulsed-current flow heating and melting occur, and during the background-current flow cooling and weld-pool solidification take place. The welding current source will automatically switch between the pulse and the background welding currents and maintain, for a certain time, the required value. With the pulse process the weld is completed by overflowing individual parts of the weld by a continuous movement of the electrode along the weld edge. The current variation during welding is shown in Fig. 6.

Important quantities which may be set and controlled are the following:

- pulsed-current intensity,
- background-current intensity,
- pulsed-current duration,
- background-current duration,
- pulse shape,
- welding speed.

Welding current sources designed for the pulsed-current method offer the possibility of a very accurate setting for the quantities concerned. The pulsed current is approximately 1.5 to 2.0 times the normal welding current for such work. The background current is needed only for maintenance of stable arc burning. Usually this intensity is set to be one quarter of the pulsed-current intensity.



Sl. 6. *Potek jakosti toka v odvisnosti od časa med varjenjem cevi v cevno steno uparjalnika po postopku TIG. 1 - začetek procesa s pretokom plina; 2 - vključitev visoke frekvence za vžig obloka; 3 - začetek varjenja in oblikovanje taline; 4 - pričetek gibanja varilne pištole in varilne žice; 5 - začetek prekrivanja začetnega dela vara; 6 - zmanjševanje jakosti toka in ustavitev dodajanja žice; 7 - konec varilnega procesa; 8 - prekinitev dovajanja plina.*

Fig. 6. *Current variation as a function of time during TIG welding of a tube into the tube sheet of the steam generator. 1 - process start with gas flow; 2 - switching of high frequency for arc ignition; 3 - start of welding and molten-pool formation; 4 - start of gun movement and welding wire; 5 - beginning of overlap of the initial part of the weld; 6 - decrease of current intensity and stoppage of wire feed; 7 - end of welding process; 8 - interruption of gas supply*

Čas trajanja pulznega toka je nastavljen tako, da omogoča nastanek talilne kopeli z želeno globino uvara. Ta čas je po navadi nekje med 0,2 in 1 sekundo. Čas trajanja osnovnega toka je nastavljen tako, da je omogočeno delno strjevanje talilne kopeli. S pravilnimi nastavitvami je mogoče nadzirati talilno kopel, dimenzije varka in globino uvara. Varilec lahko spreminja nastavitve, za doseganje optimalnega varjenja, v odvisnosti od osnovnega materiala, debeline osnovnega materiala, lege varjenja, oblike zvarnega spoja. Dodajni material se pripelje na mesto varjenja v obliki žice, navite v kolut. Jakost toka mora biti tako krmiljena, da v času pulza iz žice v talino vara preide raztaljena kapljica.

Zvarni spoj se izvede med naslednjima dvema osnovnima materialoma:

- toplotno obdelano zlitino inconel 690, iz katere so izdelane cevi U z debelino stene 1,09 mm, in
- 6 mm debelo plastjo inconela, ki je navarjena na osnovni material cevne stene SA-508 razred 3a debeline 590 mm.

Dodajni material je žica ER Ni Cr-3 s premerom 0,6 mm. Kemične sestave osnovnih in dodajnih materialov so prikazane v preglednici 1.

Na sliki 7 je prikazan makro obrus zvarnega spoja med cevjo in cevno steno, izdelanega po postopku TIG. Z oznako (1) je označena stena cevi s premerom 19,05 mm in debelino 1,09 mm. Cevna stena je bila navarjena v več slojih, podobno kakor primarna glava, le da je bil tu uporabljen inconel kot dodajni material. Zgornji sloj je označen s številko (2). Zvar, ki tvori zvarni spoj med cevjo in cevno steno, je označen s številko (3). Zvar je bil narejen v eni potezi, toda makro obrus prikazuje mesto, kjer se je varjenje začelo in končalo, kar pomeni, da se začetek in konec vara prekrivata.

2.3 Ekspanzija cevi v cevni steni

Ekspanzija cevi v cevni steni je deformacijski proces, pri katerem se material utrjuje,

Pulsed current duration is set so as to permit the formation of a weld pool with a required penetration depth. This usually amounts to 0.2 to 1 second. The background-current duration is set so as to permit partial solidification of the weld pool. Appropriate settings make it possible to control the weld pool, weld-pass dimensions, and penetration depth. A welder may change the settings with regard to the parent metal, parent metal thickness, welding position, welded-joint shape to achieve optimum welding. The filler material used for welding is a wire in a coil form. The current intensity should be controlled so that a molten droplet is transferred from the wire into the weld pool during the pulse duration.

The welded joint was formed between the following two materials:

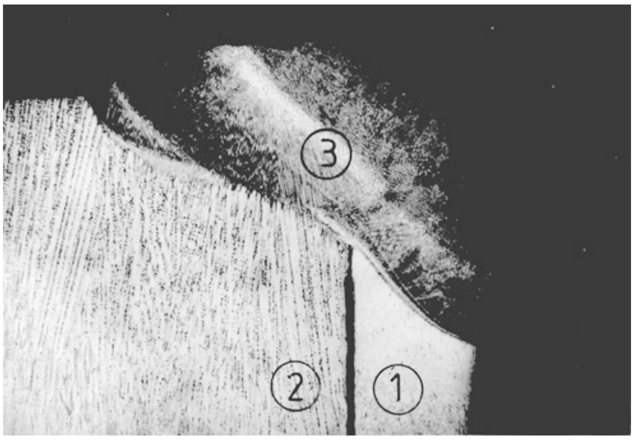
- heat-treated alloy Inconel 690, of which the U tubes with a wall thickness of 1.09 mm were made,
- 6 mm thick Inconel layer which was surfaced on the parent metal of the tube sheet SA-508 Class 3a with 590 mm thickness.

The filler material used was the wire ER Ni Cr-3 with a 0.6 mm diameter. Chemical compositions of the parent metal and the filler materials are shown in Table 1.

Fig. 7 shows a macro specimen of the TIG-welded joint between a tube and the tube sheet. Designation (1) indicates the tube with a diameter of 19.05 mm and a thickness of 1.09 mm. The tube sheet was surfaced with several layers, similar to the primary head, with the exception of the filler material which was Inconel in this case. The upper layer is designated as (2). The weld making the welded joint between the tube and the tube sheet is designated as (3). The weld was made in a single pass. The macro section, however, shows the location where welding began and finished, thus the beginning and the end of the weld overlap.

2.3 Tube expansion in the tube sheet

Tube expansion in the tube sheet is a process of deformation in which a material will harden



Sl. 7. *Makro obrus zvara zvarnega spoja cevi s cevno steno*
Fig. 7. *Macro specimen of the welded joint between a tube and the tube sheet*

kristalna zrna pa se deformirajo. Posledica tega so sorazmerno visoke napetosti in delno raztezanje cevi, kar lahko povzroči dodatne napetosti.

Osnovno načelo ekspanzije cevi je, da z velikо pritisno silo med orodjem in steno cevi presežemo mejo elastičnosti materiala cevi. Pride do plastične deformacije cevi, ki se konča, ko pride do stika med cevjo in izvrtino cevne stene. Tudi cevna stena prestane manjšo elastično deformacijo. Ko umaknemo orodje iz cevi, ta povratna elastična deformacija cevne stene povzroči trajen stik med cevjo in izvrtino cevne stene [25].

Ekspanzija cevi je bila v našem primeru izvedena v dveh korakih, in sicer najprej hidravlična, nato pa še mehanska ekspanzija. S tem je bil kar najbolj zmanjšan učinek špranje na sekundarni strani cevne stene, ki bi lahko nastala med izvrtino cevne stene in cevjo. V špranji bi se lahko kopičili radioaktivni in korozijski delci, kar bi lahko povzročalo nadaljnje korozijske procese. Varnost in zanesljivost uparjalnika je odvisna od kakovosti vsakega posameznega spoja med cevjo in cevno steno. Strukturo spoja se določi glede na zahtevani mehansko trdnost in tesnost.

2.3.1 Hidravlična ekspanzija

Hidravlično preoblikovanje je razmeroma nov postopek za ekspandiranje cevi v cevno steno. Postopek so razvili v podjetju Balcke-Dürr AG v Nemčiji, danes pa ga uporablja že veliko proizvajalcev. Z natančnim nadzorom delovnega pritiska (okoli 300 bar) lahko dosežemo manjše vrednosti zaostalih napetosti kakor pri drugih postopkih. Prav tako se skrajša čas, potreben za ekspanzijo ene cevi.

Področje hidravlične ekspanzije se je pričelo približno 10 mm od primarne strani cevne stene in se je nadaljevalo po vsej debelini cevne stene, končalo pa v območju 0 do 3 mm od roba sekundarne strani cevne stene.

Ekspandirani spoji morajo imeti gladko površino [26]. Posebej je treba paziti, da ne ekspandiramo cevi zunaj področja cevne stene, ker bi močno poškodovali cevi. Tako cev bi bilo treba začepiti in izločiti iz uporabe.

Delovni tlak vode je bil z uporabo črpalnega sistema nastavljen na 2500 bar. Na trn so bili montirani trije vrteči se valji. Skozi trn se je tlak vode prenesel na valje, ki so plastično deformirali steno cevi radialno v izvrtino cevne stene. Tlak je bil zadržan znotraj ekspandirane cevi s pomočjo elastičnega tesnila in segmentnega obroča. Hidravlični sistem je bil elektronsko nadziran.

2.3.2 Mehanska ekspanzija

Po opravljeni hidravlični ekspanziji je bila izvedena še lokalna mehanska ekspanzija z

and crystal line grains will deform. It results in comparatively high stresses and a partial tube expansion, which may produce additional stresses.

A basic principle of tube expansion is to exceed the elastic limit of the material concerned by applying a strong force, with a tool, to the tube wall. Thus plastic deformation of the tube occurs. It will end when the tube touches the tube-sheet borehole. Also the tube sheet suffers a minor elastic deformation. When the tool is removed from the tube, elastic straightening produces a constant contact between the tube and the tube-sheet borehole [25].

In our case, tube expansion was carried out in two steps, i.e., first a hydraulic expansion, then a mechanical expansion. This procedure minimised the gap effect on the secondary side of the tube sheet which might occur between the tube-sheet borehole and the tube. In the gap, radioactive and corrosive particles might accumulate and promote further corrosion processes. The safety and reliability of the steam generator depend on the quality of each individual joint between the tube and the tube sheet. The joint structure was determined with regard to the mechanical strength and the tightness required.

2.3.1 Hydraulic expansion

Hydraulic pressure forming is a new method of tube expansion in the tube sheet. It has been developed by Balcke-Dürr AG in Germany. A number of manufacturers have already introduced it into their manufacturing. An accurate supervision of working pressure (around 300 bar) allows us to obtain lower values of residual stresses than with other methods. The time required for tube expansion is shorter as well.

The zone of hydraulic pressure expansion started around 10 mm from the primary side of the tube sheet, continued through the tube-sheet thickness, and ended 0 to 3 mm from the edge of the secondary side of the tube sheet.

The expanded joints should have a smooth surface [26]. Particular attention should be paid to ensure the tubes are not expanded outside the zone of the tube sheet because the tubes could become damaged. Such a tube should be plugged and eliminated from use.

The working pressure of water is set to 2500 bar by a pumping system. Three rotating cylinders are mounted on a mandrel. Through the mandrel the water pressure is transmitted to the cylinders which plastically deform the tube wall in the direction radial to the tube-sheet borehole. The pressure inside the expanded tube is maintained by means of an elastic seal and a segment ring. The hydraulic pressure system is electronically monitored.

2.3.2 Mechanical expansion

After hydraulic pressure expansion, also local mechanical expansion is performed in order to namenom, da cevi v cevno steno še dodatno pritrdijo in se zagotovijo ugodne razmere na obeh robovih ekspandiranega področja. Dolžina mehansko ekspandiranega področja je 50 mm na obeh straneh cevne stene [27]. Za mehansko ekspanzijo uporabljamo osno vzporedne valje s hidravličnim trnom. Moment se prenaša iz ekspanzijskega stroja prek osi na trn orodja [28].

3 VARJENJE PREDELNE STENE NA PRIMARNO GLAVO IN CEVNO STENO

Predelna stena med primarno glavo in cevno steno deli primarno komoro na vroči in hladni del (sl. 1). Izdelana je iz inconela 690 in privarjena na primarno glavo in cevno steno. Zaradi zahtevnosti montaže je bila izdelana iz treh delov, ki so bili zvarjeni med montažo v primarni komori. Izdelava zvarnih spojev med predelno steno in primarno glavo ter predelno steno in cevno steno je bila izjemno zahtevna operacija zaradi različnosti materialov, medtem ko zvarjanje posameznih elementov predelne stene ni delalo posebnih težav.

Makro obrus zvarnega spoja med predelno steno in primarno glavo je prikazan na sliki 8.

Spodnji del spoja (1 – sl. 8) predstavlja primarno glavo, na kateri je bil prvi sloj varjen z avstenitnim nerjavnim jeklom 24/13 (3 – sl. 8) in druga dva z avstenitnim nerjavnim jeklom 19/9 (4 – sl. 8), kakor je opisano pod točko 1.2.

Na navar iz nerjavnega jekla je bila nato navarjena vmesna plast (5 – slika 8) iz inconela 182. Ta plast je bila navarjena ročno obločno z oplaščenimi elektrodami. Tudi predelna stena se je nato na plast namaz zvarila ročno obločno z oplaščenimi elektrodami (6 – sl. 8).

additionally fix the tube into the tube sheet and ensure favourable conditions at both edges of the expanded zone. The mechanically expanded zone is 50 mm long at each side of the tube sheet [27]. For mechanical expansion, axially parallel cylinders with a hydraulic mandrel are used. The torque was transmitted from the expansion machine via the axis to the tool mandrel [28].

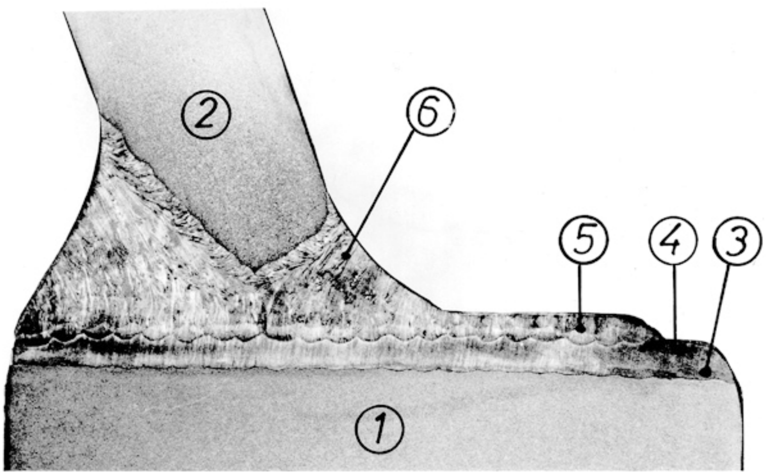
3 WELDING OF THE PARTITION PLATE TO THE PRIMARY HEAD AND THE TUBE SHEET

The partition plate between the primary head and the tube sheet separates the primary chamber into hot and cold parts (Fig. 1). It is made of Inconel 690 and welded to the primary head and the tube sheet. Because of the exacting assembly, it is made of three parts which were welded during assembly in the primary chamber. Making the welded joints between the partition plate and the primary head and between the partition plate and the tube sheet was an extremely exacting operation because of the differences in the materials used. Welding of individual elements of the partition plate, however, was not problematic.

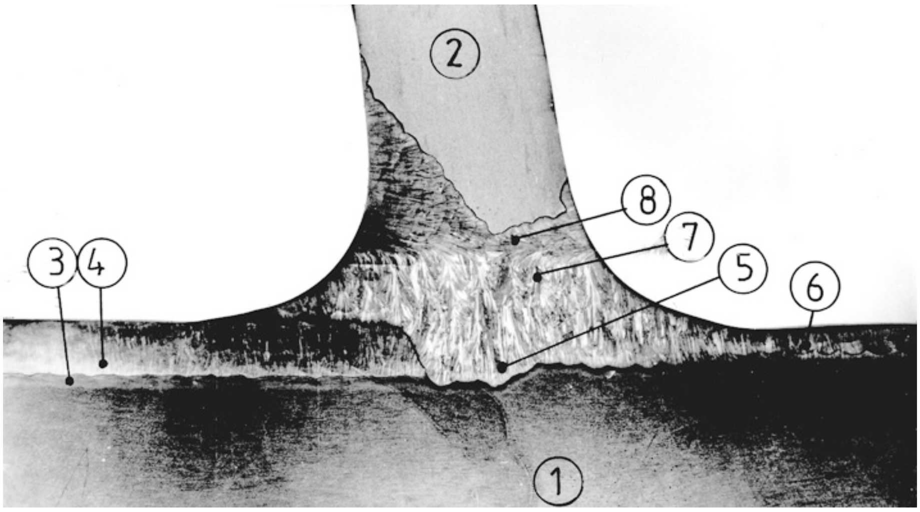
A macro specimen of the welded joint between the partition plate and the primary head is shown in Fig. 8.

The lower part of the joint (1 - Fig. 8) represents the primary head at which the first layer was welded with austenitic stainless steel 24/13 (3 - Fig. 8) and the other two with austenitic stainless steel 19/9 (4 - Fig. 8) as already described in section 1.2.

On the stainless-steel cladding an intermediate layer of Inconel 182 was then surfaced (5 - Fig. 8). This layer was manually arc surfaced with covered electrodes. Also the partition plate was then manually arc welded on the “buttering” layer with covered electrodes (6 - Fig. 8).



Sl. 8. *Makro obrus zvarnega spoja med primarno glavo in predelno steno primarne komore uparjalnika*
Fig. 8. *Macro specimen of the welded joint between the primary head and the partition plate of the primary chamber of the steam generator*



Sl. 9. *Makro obrus zvarnega spoja med predelno in cevno steno*
Fig. 9. *Macro specimen of the welded joint between the partitian plate and tube sheet*

Drugi zvarni spoj med predelno in cevno steno je bil izdelan nekoliko drugače. Makro obrus testnega odrezka za kvalifikacijo postopka vidimo na sliki 9.

Že v točki 3 smo zapisali, da je cevna stena izdelana iz enakega materiala kakor primarna glava (pregl. 1). Cevna stena (2 – sl. 9) je bila nato navarjena s trakom pod praškom, podobno kakor primarna glava, toda z nekoliko različnimi materiali. Navar v dveh slojih iz nerjavnih jekel je na sliki 9 označen s številkama 3 in 4. Zaradi čim boljše izenačitve lastnosti materialov je bila na navar iz nerjavnega jekla navarjena plast iz inconela v več slojih (5, 6 in 7 – sl. 9). V vseh primerih se je navarjalo z inconelom 182 z oplaščeno elektrodo po postopku ročno obločno varjenje. Zvar med cevno steno, ki je izdelana iz inconela 690, in navarjeno plastjo iz inconela 182 je bil izveden ročno obločno z oplaščenimi elektrodami z inconelom 182 (8 – sl. 9). Koren vara je bil varjen z elektrodo premera 3,25 mm, jakostjo toka 95 do 100 A in napetostjo obloka 25 V. Preostali varki so bili izdelani z elektrodo premera 4 mm, jakostjo toka 135 A in obločno napetostjo 26 V. Elektrode so bile pred uporabo sušene in nato skladiščene v posebni prenosni pečici, da jih je varilec jemal iz nje tik pred pričetkom varjenja.

Analiza testnega odrezka je pokazala, da je cevno steno najprimerneje navariti z inconelom brez vmesne plasti iz nerjavnega jekla. Navarjanje je bilo izvedeno s tračno elektrodo in ročno obločno z oplaščeno elektrodo.

4 VARJENJE KROŽNIH VAROV NA PLAŠČU UPARJALNIKA

Zunanji plašč uparjalnika ni enakega premera po vsej dolžini. Spodnji del ima premer 3452 mm in debelino stene 74 mm, zgornji pa premer 4474

The second welded joint, i.e., between the partition plate and the tube sheet, was made in a different manner. A macro specimen of the test coupon for procedure qualification is shown in Fig. 9.

As already mentioned, the tube sheet is made of the same material as the primary head (see Table 1). The tube sheet (2 - Fig. 9) was then submerged-arc surfaced with a strip electrode, in the same way as the primary head, but with somewhat different materials. The cladding, consisting of two stainless-steel layers, has designations 3 and 4 in Fig. 9. In order to match the properties of the materials as well as possible, a layer of Inconel was surfaced on the stainless-steel cladding in several layers (5, 6, 7 - Fig. 9). In all the cases, manual-arc cladding with Inconel 182 was carried out with a covered electrode. The weld between the tube sheet made of Inconel 690 and the surfaced layer of Inconel 182 was manually arc welded with covered electrodes of Inconel 182 (8 - Fig. 9).The weld root was welded with an electrode having a 3.25 mm diameter, a current intensity of 95 to 100 A and an arc voltage of 25 V. The other passes were made with an electrode of 4 mm diameter, current intensity of 135 A and arc voltage of 26 V. All the electrodes used were dried prior to use and then stored in a special transportable oven for a welder to take them out immediately before welding.

An analysis of the test coupon showed that it was best to surface the tube sheet with Inconel without the intermediate layer of stainless steel. Cladding was carried out with a strip electrode and manual-arc welding with a covered electrode.

4 WELDING OF CIRCUMFERENTIAL WELDS AT THE STEAM-GENERATOR SHELL

The outer shell of the steam generator does not have the same diameter along the total length. The lower part has a diameter of 3452 mm and wall mm in debelino stene 92 mm. V celoti je izdelan iz enakega materiala kot primarna glava (pregl. 1).

Vsi valjasti deli plašča so bili izdelani s kovanjem, tako da ni vzdolžnih varov. Posamezni deli plašča so bili med seboj spojeni z varjenjem s krožnimi vari.

Koren zvara na delu plašča z večjim premerom je bil najprej zavarjen ročno obločno z zunanje strani (brez prevaritve); pri tem je bila preverjena poravnava. Nato je bil z notranje strani zapolnjen žleb po ročnem obločnem postopku. Zvar je bil z zunanje strani izžlebljen, preverjeni pa so bili profili žleba. Površina zvarnega žleba je bila nato pregledana s tekočimi penetranti. Na koncu je bil zvar z zunanje strani zavarjen po avtomatskem postopku EPP.

Ročno obločno varjenje je bilo izvedeno v primeru elektrode s premerom 3,25 mm z jakostjo toka okoli 110 A, napetostjo približno 25 V in hitrostjo varjenja med 100 in 200 mm/min; v primeru elektrode s premerom 4 mm je bila jakost toka okoli 140 A, napetost približno 26 V in hitrost varjenja med 150 in 250 mm/min.

Postopek varjenja EPP je bil z jakostjo toka okoli 510 A in napetostjo približno 30 V. Hitrost varjenja je bila 0,5 m/min. Vnos energije pri postopku EPP je bil med 1,8 in 1,9 MJ/m.

Vrtenje uparjalnika okoli njegove vzdolžne osi je bilo zagotovljeno z obračalnimi valjčki. Zvarni spoj je bil ves čas ogrevan na 150 °C, tako da ni prišlo do zakaljenih struktur v toplotno vplivanem področju. Višina temperature je bila predpisana z varilnim postopkom. Ogrevanje je bilo izvedeno plamensko z dvema polkrožnima gorilnikoma z vsake strani zvara, ki sta objemala več ko polovico obsega zvara. Temperatura ogrevanja in medvarkovna temperatura sta bili preverjani s kalibriranimi pirometri vsako uro. Med varjenjem in po njem je bila skladno s popisom postopka varjenja izvedena še toplotna obdelava s pogrevanjem na 260 °C za štiri ure za zmanjšanje deleža vodika in notranjih napetosti v zvaru.

Za ročno obločno varjenje so bile uporabljene elektrode SFA-5.5 E9018-G s premerom 3,25 in 4 mm, za postopek EPP pa aglomeriran bazični prašek UV 420 TTR v kombinaciji z žico UNION S3NiMo1, EF3 po SFA A 5.23, s premerom 4 mm, ki je izdelek podjetja Thyssen.

Varjenju je sledilo vse zahtevano preverjanje, tj. VT, RT, MT, UT in brušenje zvara. Zvar je bil lokalno toplotno obdelan, tj. eno uro pri 600 °C. Toplotna obdelava zvara je bila izvedena z elektrouporovnimi grelniki, nameščenimi okoli zvara. Vsi zvari so bili po toplotni obdelavi pregledani z ultrazvokom, in sicer v prvi vrsti za odkritje morebitnih razpok.

Za potrditev ustreznosti varilne tehnologije in pripravo testnih blokov za ultrazvočne preglede

thickness of 74 mm, the upper part, however, has a 4474 mm diameter and a 92 mm wall thickness. It was made of the same material as the primary head (see Table 1).

All cylindrical parts of the shell were made by forging so that there are no longitudinal welds. Individual shell segments were joined by circumferential welds.

The weld root at the shell part having the wider diameter was first manually arc-tack welded from the outside. The alignment was checked. Then the groove was filled by manual-arc welding from the inside. The weld was grooved from the outside and the groove profiles were checked. The surface of the weld groove was subjected to a liquid penetrant examination. Finally, the weld was made from the outside by automatic submerged-arc welding.

Manual-arc welding was carried out with a current intensity of about 110 A, voltage of about 25 V, welding speed varying between 100 and 200 mm/min with an electrode diameter of 3.25 mm, a current intensity of 140 A, voltage of about 26 V and a welding speed varying between 150 and 250 mm/min with an electrode diameter of 4 mm.

Submerged-arc welding was carried out with a current intensity of about 510 A, voltage about 30 V, welding speed of 0.5 m/min and heat input varying between 1.8 and 1.9 MJ/m.

Rotation of the steam generator around its longitudinal axis was provided by rotating rolls. All the time the welded joint was preheated to 150 °C so that no through-hardened structures in the heat-affected zone occurred. The temperature was specified by the welding procedure. Flame heating was carried out with two semicircular burners from each side of the weld, which encompassed more than half of the weld circumference. Preheating and interpass temperatures were compared to calibrated pyrometers each hour. In accordance with the welding procedure specification, heat treatment with soaking to 260 °C for four hours was carried out during and after welding in order to reduce hydrogen content and internal stresses in the weld.

For manual-arc welding electrodes, SFA-5.5 E9018-G with diameters of 3.25 mm and 4 mm were used. For submerged-arc welding an agglomerated basic flux UV 420 TTR was used in combination with a wire UNION S3NiMo1, EF3 according to SFA A 5.23 with a diameter of 4 mm, produced by Thyssen, was used.

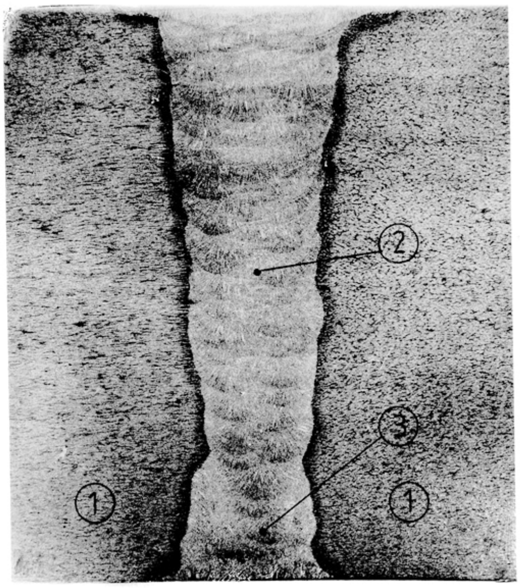
Welding was followed by the control required, i.e. visual inspection, radiographic examination, magnetic particle examination, ultrasonic examination, and weld grinding. The weld was locally heat treated for one hour at a temperature of 600 °C. The weld heat treatment was carried out with electric resistance heaters arranged around the weld. After heat treatment all the welds were examined by ultrasound, primarily in order to detect eventual cracks.

In order to confirm the suitability of the welding technology and to prepare test blocks for so bili zavarjeni testni kuponi z dolžino približno 1000 mm za vsak tip zvara posebej. Postopek izdelave in preverjanja je bil enak kakor pri varjenju na uparjalniku.

Makro obrus zvarnega spoja na zunanjem širšem delu plašča je prikazan na sliki 10. S številko 1 sta označena segmenta zunanjega plašča, s številko 2 var, ki je bil varjen pod praškom v več varkih, in s številko 3 var, ki je varjen ročno obločno z oplaščeno elektrodo.

ultrasonic examination, test coupons of 100 mm in length were welded separately for each weld type. The production and control procedures were the same as for welding the steam generator.

The macro specimen at the outside, wider part, of the shell is shown in Fig. 10. Number 1 designates two segments of the outer shell, number 2 the weld, which was multi-layer submerged-arc welded, and number 3 the weld which was manually arc welded with a covered electrode.



Sl. 10. *Makro obrus zvarnega spoja dveh delov zunanjega širšega premera plašča uparjalnika*
Fig. 10. *Macro specimen of the welded joint between two segments of the steam-generator shell with the outer, wider diameter*

5 SKLEPI

Splošno rečeno je izdelava uparjalnikov vrhunska in najzahtevnejša tehnologija na področju varjenja. To trditev lahko potrdimo s tehnološkega, metalurškega in tudi ekonomskega vidika. Dodana vrednost je izjemno visoka, zato lahko to tehnologijo prištevamo med tako imenovane zahtevne tehnologije.

Zelo velik poudarek je na kakovosti del in izdelkov. Za vsako, na prvi pogled še tako nepomembno opravilo, so bili napisani posebni postopki, po katerih so se morali ravnati izdelovalci. Za zahtevna varilska dela pa so bili izdelani tudi atesti postopkov in preverjeni atesti osnovnih in dodajnih materialov. Vsi izvajalci so morali imeti ustrezne ateste. Nadzor je bil predpisan na vseh ravneh in od različnih ustanov. Prav tako je bil zagotovljen tudi nadzor, ki je bil neodvisen od naročnika in od izvajalca.

Vse to je zagotovilo, da so bili uparjalniki za Jedrsko elektrarno Krško izdelani kakovostno, na najvišjem možnem nivoju, in da bo Jedrska elektrarna Krško tudi v prihodnje, po zamenjavi uparjalnikov, delovala tako varno in uspešno kakor doslej.

5 CONCLUSIONS

Generally it may be stated that the manufacturing of steam generators is the highest and most exacting technology in the field of welding. This statement is true from the viewpoint of technology, metallurgy as well as economy. The value added to the product is extremely high. Consequently, this technology must be considered high technology.

Great stress was laid upon the quality of work and products. For each procedure to be carried out, as unimportant as it may seem at first sight, there was a procedure specification, which should be followed by the manufacturers involved. For exacting welding work, welding procedure tests were carried out, and quality approval tests for parent metals and filler materials were verified. All the manufacturers involved should have certificates of their competence for the work. Testing is prescribed at all levels and by different institutions. Testing independent of the client and the manufacturer, was ensured as well.

This gave us the assurance that the steam generators for the Krško Nuclear Power Plant were manufactured with the required quality and that they would operate safely and efficiently.

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