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ZNAČAJ PRSLINA U ZONI UTICAJA TOPLOTE ČELIKA ZA POVIŠENE TEMPERATURE

SIGNIFICANCE OF CRACKS IN THE HEAT-AFFECTED-ZONE OF STEELS FOR ELEVATED TEMPERATURE APPLICATION

Originalni naučni rad / Original scientific paper
UDK /UDC: 621.791.051:669.14
Rad primljen / Paper received: 21.5.2008.

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Ključne reči
- prsline tipa IV
- čelik P91
- područja HAZ
- puzanje

Izvod

Oštećenje i lom zavarenih spojeva klasifikuju se prema položaju prslina. Prsline IV grupe javljaju se u zavarenim spojevima čelika otpornih na puzanje, zbog povećane brzine formiranja šupljina u prisustvu čestica krupnozrnih karbida u finozrnim i interkritičnim žarenim područjima zone uticaja toplote. Akumulacija oštećenja puzanjem izaziva prevremeni otkaz komponente. Zbog toga je za ocenu preostalog veka opreme za rad na povišenoj temperaturi u termoelektranama i u procesnoj industriji potrebna analiza ponašanja materijala u dokritičnom režimu i u režimu puzanja.

Pojava prslina IV grupe je uočena kod čelika sa 9–12% hroma. Problem se može eliminisati termičkom obradom – ponovnom austenitizacijom i otpuštanjem, ali je to retko izvodljivo i zato se komponente moraju projektovati tako da se uzme u obzir smanjenje čvrstoće puzanja i veka.

UVOD

Termodinamičko iskorišćenje parne turbine u proizvodnji električne energije u elektrani na fosilno gorivo može da se poveća ako se povećaju temperatura i pritisak pare na ulazu u turbinu. Zbog toga se razvijaju čelici za teže radne uslove, koji su potrebni za efikasnu proizvodnju energije. Dugoročni cilj Nacionalnog instituta za nauku o materijalu iz Japana je da razvija čelike za superkritične uslove rada, temperatura pare 650°C i pritisak od 350 bar, a tome teži i Evropska Unija, /1/.

Feritni čelici sa sadržajem 1–12% hroma (Cr) i 0,5–1% molibdena (Mo) se koriste u savremenim elektranama na fosilno gorivo, koje rade na temperaturama ispod 600°C. Sa povećanjem temperature pare iznad 600°C, može da se poveća stepen iskorišćenja, a emisija štetnog ugljendioksida (CO_2) smanji. Konvencionalni Cr-Mo čelici nemaju zahtevanu čvrstoću puzanja i otpornost na oksidaciju na temperaturi iznad 600°C. Stoga se u novije vreme razvijaju i već ugrađuju u novim modernim elektranama visokohromni čelici (P92 i P122), u kojima je Mo delimično ili potpuno zamenjen volframom (W). Njihovom primenom temperatura pare može da se poveća na 650°C ili više, tako da se efikasnost postrojenja poboljšava i smanjuje emisija CO_2 u odnosu na postojeće elektrane, /2/.

Keywords
- type IV cracks
- P91 steel
- HAZ regions
- creep

Abstract

Damage and failure of welded joints are classified according to the crack position. Type IV cracking occurs in welded joints in creep-resistant steels, due to enhanced rate of creep void formation in the presence of coarse grained carbide particles in fine-grained and intercritically annealed regions of the heat-affected zone. Creep damage accumulation causes premature failure. So, the evaluation of residual service life of equipment operating at elevated temperatures in power plants and in process industry requires analysis of material behaviour in subcritical and in creep regime.

The occurrence of type IV cracks is observed in 9–12% chromium steels. The problem can be solved by reaustenitisation and tempering heat treatment, but this is a rare practical option, and components have to be designed taking into account reduced creep strength and life.

INTRODUCTION

Thermodynamic efficiency of steam turbines in electric power production in fossil-fired plants could be increased if temperature and pressure of steam inlet into the turbine are increased. Therefore, steels for severe working conditions are being developed that are required for efficient power generation. The long-term task of the National Institute for Material Science in Japan is to develop steels for supercritical working conditions, steam temperature 650°C and pressure 350 bar, and it is an objective of the European Union, /1/.

Ferritic steels with 1–12% chromium (Cr) and 0.5–1% molybdenum (Mo) have been used in modern fossil-fired power plants, operating at temperatures below 600°C. By increasing the steam temperature above 600°C, the efficiency can be increased, and emission of harmful carbon dioxide (CO_2) reduced. Conventional Cr-Mo steels do not have required creep strength and oxidation resistance above 600°C. Hence, high-chromium steels (P92 and P122) in which Mo is partly or completely replaced by wolfram (W) are recently developed and applied in new modern power plants. Applying them, steam temperature may be increased to 650°C or more, so plant efficiency can be improved, while CO_2 emissions can be reduced, compared to the existing power plants, /2/.

MATERIJAL

Prvi visokohromni feritni čelici pojavili su se u Evropi sredinom 60-ih godina prošlog veka, /1/. Čelik 9Cr-2Mo, razvijen je u Francuskoj prvenstveno za cevovode kao EM12. Imao je dvofaznu mikrostrukturu sa δ-feritom, što je uslovljavalo lošu udarnu žilavost. U isto vreme u Nemačkoj je razvijen čelik 12Cr-1Mo, oznake X20CrMoV12-1, koji se širom sveta koristi za cevovode i parovode. Dobra strana ovog čelika je njegova martenzitna mikrostruktura, ali zato ima manju čvrstoću puzanja nego EM12 na temperaturama preko 520°C i, zbog velikog sadržaja ugljenika, uslovi za njegovu zavarljivost su složeni.

Posle oko 10 godina, Nacionalna laboratorija Ouk Ridž (ORNL) u SAD je razvila modifikovani 9Cr-1Mo čelik, što je konačno dovelo do T91/P91 čelika, radi zamene čelika EM12 i X20CrMoV12-1. U osnovi, legura 9Cr-1Mo ima mikrostrukturu otpuštenog martenzita, stabilizovanu karbidima $M_{23}C_6$, sa daljim ojačavanjem Mo u čvrstom rastvoru i finom raspodelom taloga karbonitrida MX, bogatih vanadijumom (V)/niobijumom (Nb).

Dalja, pouzdana poboljšanja čvrstoće puzanja postignuta su razvojem čelika kao što su NF616 i HCM12A, kod kojih volfram (W) povećava dugoročnu čvrstoću puzanja ojačavanjem u čvrstom rastvoru i usporava ukrupnjavanje karbida $M_{23}C_6$ koji stabilizuju lamelarnu strukturu martenzita. Međutim, pri koncentracijama većim od 2%, nastanak krupne laves faze (Fe_2W) može da dovede do pogoršanja osobina puzanja. Sem toga, W pospešuje formiranje δ-ferita, pa njegovo korišćenje mora da bude uravnoteženo, bilo smanjivanjem sadržaja drugih rastvora–aktivatora ferita, poput Mo, bilo dodavanjem stabilizatora austenita kao što je kobalt (Co).

Martenzitni čelik, oznake P 91, koji je predmet ove analize, je mikrolegiran vanadijumom, niobijumom i azotom. Prihvaćen je 1983. godine ASTM standardom A213 kao čelik T91 za tankozide cevi, a 1984. standardom A335 kao čelik za debelozide cevi P91, /3/.

Na sl. 1 su upoređene potrebne debljine zida cevi različitih čelika za iste konstrukcijske uslove.

Prednosti ugradnje novih materijala veće čvrstoće, kao što je čelik P91, se iskazuju smanjenjem debljine zida, što smanjuje troškove zavarivanja, zagađenje okoline, troškove transporta komponenata, uz smanjeni termički zamor i gradnju kompaktnijih konstrukcija. Tanjim komponentama se smanjuje sklonost ka termomehaničkom oštećenju, jer se za kraće vreme dostiže termička ravnoteža. Toplotni gradijent po debljini zida je manji kod tanjih zidova.

Pa ipak, dobre osobine ovih poboljšanih čelika često ne dolaze do izražaja, jer u zoni uticaja toplote (HAZ) zavarenih spojeva može doći do prevremenog otkaza zbog fenomena koji se naziva lom zbog prslina tipa IV.

Prsline u zavarenim spojevima se klasifikuju prema položaju (sl. 2). Prsline I grupe javljaju se u metalu šava (WM); prsline II grupe mogu da iniciraju u metala šava i da rastu unutar WM, ili izvan WM, u HAZ; prsline III grupe se javljaju u krupnozrnoj zoni HAZ (CGHAZ). Prsline tipa IV javljaju se samo kod zavarenih spojeva čelika otpornih na puzanje.

MATERIAL

The first high chromium ferritic steels appeared in Europe in the mid 1960s, /1/. Steel 9Cr-2Mo was developed primarily for pipelines in France as EM12. It was of duplex microstructure containing δ-ferrite that produced poor impact toughness. At the same time, in Germany, the 12Cr-1Mo steel, designated as X20CrMoV12-1, was developed, that is used throughout the world for pipelines and steam lines. Advantage of this steel is its martensitic microstructure, but it is of inferior creep strength compared to EM12 at temperatures above 520°C and, primarily due to high carbon content, the condition for its weldability are complex.

About ten years later, the Oak Ridge National Laboratory (ORNL) in USA developed modified 9Cr-Mo steel, what finally led to T91/P91 steel, for replacing EM12 and X20CrMoV12-1 steels. Basically, the alloy 9Cr-1Mo is of tempered martensitic microstructure, stabilized by $M_{23}C_6$ carbides, with further strengthening by Mo in solid solution and fine distribution of vanadium (V)/niobium (Nb) rich carbonitride MX precipitates.

Further reliable improvements of creep strength have been achieved by development of steels such as NF616 and HCM12A, where the wolfram (W) has enhanced the long-term creep strength through solid solution hardening and retarded the coarsening of $M_{23}C_6$ carbides that stabilized the martensite lath structure. Anyhow, at concentrations higher than 2 wt-%, the formation of coarse laves phase (Fe_2W) may cause the deterioration of creep properties. In addition, W enhances the formation of δ-ferrite, and therefore its use has to be balanced, either by lowering the concentration of other ferrite promoting solutes such as Mo, or by adding the austenite stabilizers such as cobalt (Co).

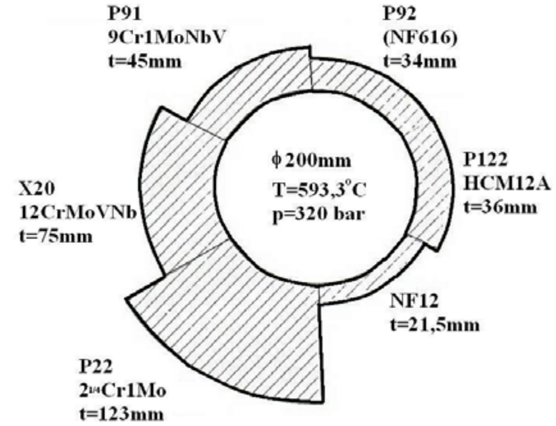
Martensitic steel, designated P91, which is the subject of this analysis, is micro alloyed with vanadium, niobium and nitrogen. It is accepted in 1983 by ASTM standard A213 as T91 steel for tubing, and in 1984 by standard A335 as piping steel P91, /3/.

In Fig. 1 necessary tube wall thicknesses of different steels for the same design conditions are compared.

The advantages of applying new materials of higher strength, as P91 steel, are manifested by reduced wall thickness, reducing welding costs, environment pollution, component transportation costs, and by lower thermal fatigue and more compact structures. Thinner components shorten the time of thermal balance, and the susceptibility to thermo mechanical damage is reduced. Thermal gradient through wall thickness is lower in thinner walls.

Nevertheless, the performance of the improved steels is often not expressed because in the heat-affected-zone (HAZ) of welded joints premature failure can occur due to phenomenon termed type IV cracking.

Cracks in welded joints are classified according to crack position (Fig. 2). Type I mode groups occur in weld metal (WM); type II mode may initiate in WM and propagate within WM, or outside WM, in HAZ; type III mode appears in the coarse grained region of HAZ (CGHAZ). Type IV cracks occur only in welded joints of creep-resistant steels.



Slika 1. Poređenje debljine zida za različite čelike pri istim konstrukcionim uslovima
Figure 1 The comparison of required wall thicknesses in different steels under the same conditions.

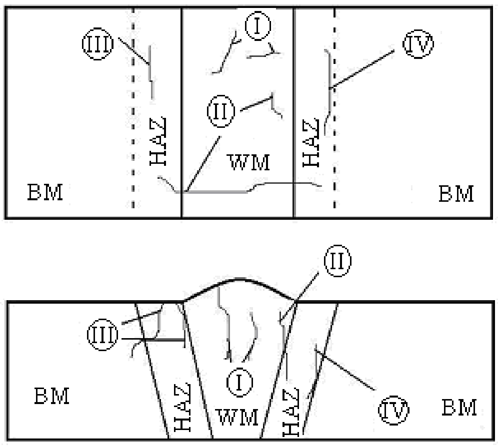
Pojavu prslina tipa IV karakteriše povećana brzina formiranja šupljina puzanja u finozrnom području (FGHAZ) i interkritičnom žarenom području (ICHAZ), što dovodi do otkaza ranije nego kod istog ali nezavarenog materijala. Ova područja sadrže čestice krupnijih karbida koje dovode do smanjenja čvrstoće puzanja; ove čestice takođe dovode do nastanka šupljina. Pri ispitivanju poprečnog preseka zavarenog spoja, najslabije područje tipa IV je između osnovnog metala veće čvrstoće i krupnozrnog HAZ, /4/.

Prsline tipa IV su posebno uočene kod čelika sa 9–12% Cr. Kako je njihova pojava povezana sa heterogenošću mikrostrukture HAZ, one se mogu otkloniti reaustenitizacijom i termičkom obradom otpuštanjem. Međutim, to je teško ostvarljivo. Stoga se pri projektovanju to uzima u obzir smanjenjem čvrstoće puzanja $\Delta\sigma$ ili odgovarajućim smanjenjem veka, /5/. Vrednost čvrstoće puzanja $\Delta\sigma$ zavisi od hemijskog sastava, termičke obrade i naponskog stanja, te se mora eksperimentalno odrediti pri svakoj primeni, što očigledno predstavlja ograničavajući faktor u postupku projektovanja. Zahvaljujući neuralnim mrežama kao fleksibilnim nelinearnim funkcijama, danas je moguće razviti kvantitativni model fizičkih fenomena na osnovu postojećih eksperimentalno dobijenih podataka o karakteru i ponašanju materijala bez poznavanja unutrašnjih mehanizama /4, 5/.

OŠTEĆENJE IZAZVANO PRSLINAMA TIPA IV

Oštećenje izazvano prslinama IV grupe, završeno lomom puzanjem u finozrnom području HAZ, obično nastaje u unutrašnjosti debljine zida cevi, gde je naponsko stanje složenije nego na površini cevi, /6/. Stoga je teško odrediti preostali vek komponente metodama ispitivanja bez razaranja (IBR), koje se primenjuju za ispitivanje spoljnje površine cevi, kao što je metoda replika.

Posle nekoliko otkaza u elektranama, mnogi istraživači su počeli da proučavaju oštećenja tipa IV. Oni su zaključili da do oštećenja dolazi zbog toga što je u FGHAZ čvrstoća puzanja manja u poređenju sa čvrstoćom puzanja u CGHAZ u metalu šava i u osnovnom metalu.



Slika 2. Klasifikacija prslina u zavarenim spojevima (BM–osnovni metal; HAZ–zona uticaja toplote; WM–metal šava)
Figure 2. Classification of cracks in welded joints (BM–parent metal; HAZ–heat-affected-zone; WM–weld metal).

The occurrence of type IV cracking is characterized by higher rate of creep void formation in fine-grained region (FGHAZ) and intercritically annealed region (ICHAZ), what leads to earlier failure than in the same, but unwelded steel. These regions contain coarse carbide particles causing the reduction of creep strength; these particles also contribute to nucleate void formation. In testing of welded joint cross-section, the weakest type IV region is found between stronger parent metal and coarse-grained HAZ, /4/.

Type IV cracking is especially observed in steel with 9-12 wt-% Cr. Since its occurrence is associated with heterogeneous HAZ microstructure, it may be eliminated by reaustenitization and heat treatment by tempering. However, it is hard to accomplish. Therefore, the design must take this into account reduced creep strength $\Delta\sigma$ or equivalent reduction of life, /5/. The value of creep strength $\Delta\sigma$ depends on chemical composition, heat treatment and the stress state, so it should be experimentally determined for each application, what is apparently a limiting factor in any design process. Owing to neural networks as flexible, nonlinear functions, it is currently possible to develop quantitative model of physical phenomena based on the existing experimentally obtained data on the character and behaviour of material without knowing the underlying mechanisms, /4, 5/.

DAMAGE CAUSED BY TYPE IV CRACKING

The damage caused by type IV cracking, ending in creep failure in the fine-grained HAZ, usually appears in the interior of the wall thickness, where the stress state is more complex than at the surface, /6/. Therefore, it is difficult to evaluate the remaining life by non-destructive techniques (NDT) that are applied for testing outer pipe surfaces, such as the replication method.

After several incidences of failure in thermal power plants, type IV damage has been the issue of study by many experts. They concluded that the damage was caused by lower creep strength of FGHAZ, compared to that of CGHAZ in weld metal and parent metal.

Otkriveno ja da se čvrstoća puzanja smanjuje zbog sledeća dva fenomena:

– smanjenja otpornosti na puzanje koje je povezano sa smanjenjem gustine dislokacija i promenom strukture karbida, izazvanom starenjem;
– ubrzanog nastanka i rasta šupljina na granicama zrna, izdvajanjem nečistoća.

MEHANIZAM OŠTEĆENJA ZVOG PRSLINA TIPA IV

Pre analize mehanizna stvaranja i širenja prslina tipa IV, treba ukratko navesti u kojim zonama zavarenog spoja se one javljaju, /7/: svi feritni čelici imaju manju vrednost tvrdoće u interkritičnom području HAZ (sl. 3), kao i malu čvrstoću puzanja; nema izražene promene mikrostrukture osnovnog metala, jer se položaj prslina tipa IV opisuje često kao mesto koje se nalazi u osnovnom metalu, na leđnoj strani vidljivo tarnsformisane HAZ; u izvesnoj meri se javljaju u svim zavarenim spojevima feritnih čelika. Prsline puzanja tipa IV se javljaju u interkritičnom području HAZ posle 40 000–80 000 sati rada.

Ispitivanjem sučeono zavarenih spojeva cevi od čelika P91, uočavaju se oštećenja tipa IV u HAZ, /7/. Pomoću skening elektronskog mikroskopa (SEM) utvrđeno je da su mikroprsline i mnoštvo poligonalnih šupljina raspoređene po bivšim granicama austenitnih zrna. Na isti način su raspoređena i fina martenzitna zrna okružena krupnim karbidima i šupljinama puzanja (sl. 4).

Pomoću transmisionog elektronskog mikroskopa (TEM) moguće je uočiti guste taloge karbida (DPC), sl. 5. Zbog sličnog oblika, veličine i raspodele, DPC se smatraju osnovnim uzročnikom pojave šuplina i prslina. Moguće je da je heterogenost sadržaja ugljenika na granicama bivših austenitnih zrna izvor pojave DPC.

Slika 6 prikazuje pretpostavljeni mehanizam nastanka i razvoja oštećenja tipa IV. Neki karbidi se pre zavarivanja raspoređuju po granicama prethodnih austenitnih zrna osnovnog metala, sl. 6a, gore.

It has been found that the creep strength is being reduced on account of two phenomena:

– reduction of creep resistance associated with decreasing dislocation density and changing carbide structure, caused by aging;
– acceleration of void formation and growth at grain boundaries by segregation of impurities.

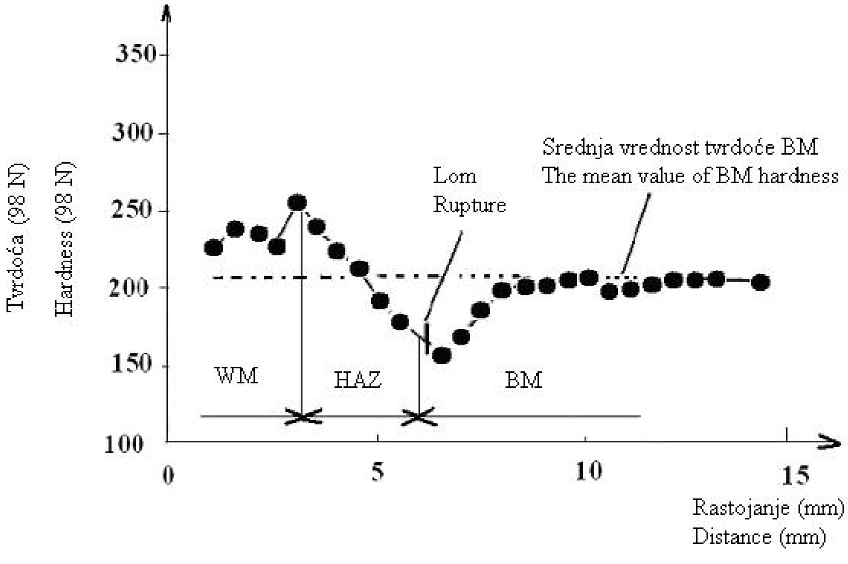
MECHANISM OF TYPE IV DAMAGE

Before analysing type IV cracking mechanism formation and growth, let us refer shortly to the zones of welded joints they appear in, /7/: all ferritic steels have lower hardness value in intercritical HAZ region (Fig. 3), as well as poor creep strength; there is no marked change of parent metal microstructure, because type IV crack position is often described as lying in the parent metal at the back of visibly transformed HAZ; to some extent, they appear in all ferritic steel welds. Type IV creep cracking occurs in the intercritical HAZ region after 40 000–80 000 hours of service.

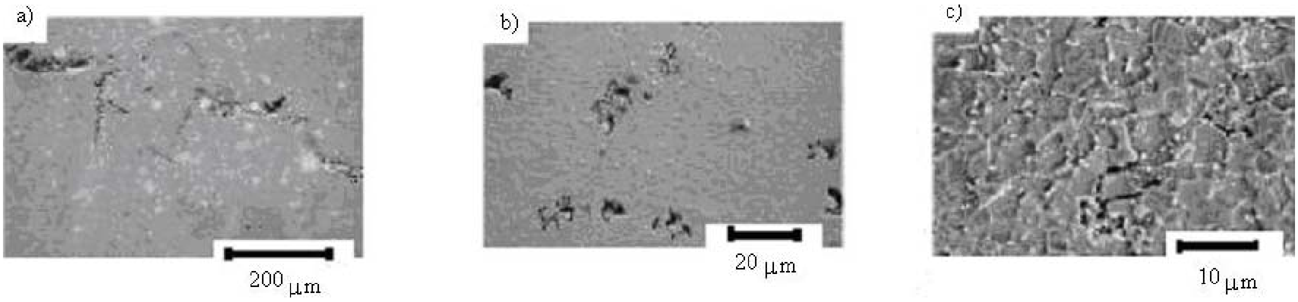
Testing of seam-welded joints of the pipes made of P91 steel revealed type IV damage in the HAZ, /7/. Scanning electron microscopy (SEM) showed that the micro-cracks and many polygonal voids were arranged along the former austenite grain boundaries. In the same manner are also distributed fine martensite grains surrounded by coarse carbides and creep voids (Fig. 4).

Transmission electron microscopy (TEM) allows for visualization of dense precipitations of carbides (DPC), Fig. 5. Due to similar shape, size and distribution, DPC are considered as basic cause of the voids and cracks. It is possible that the heterogeneity of carbon content at the former austenite grain boundaries is the origin of DPC.

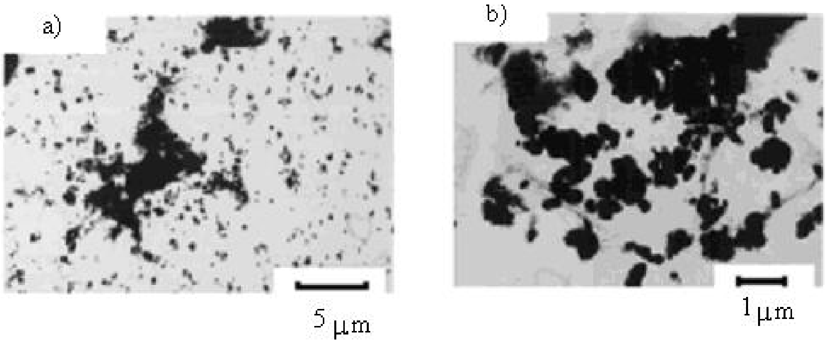
Figure 6 presents the presumed mechanism of initiation and propagation of type IV damage. Before welding, some carbides are distributed at prior austenite grain boundaries of the parent metal, Fig. 6a, above.



Slika 3. Raspodela tvrdoće i mesto najniže tvrdoće gde dolazi do pojave prsline tipa IV u poprečnom preseku zavarenog spoja čelika T91 na temperaturi T = 600°C pri naponu od 147 MPa
Figure 3. Hardness distribution and location of lowest hardness where type IV cracks occur in the cross-section of T91 steel welded joint at temperature 600°C and stress of 147 MPa.



Slika 4. Skening elektronski mikrografi (SEM) područja finozrne strukture HAZ (FGHAZ)
a) mikroprsline; b) šupljine; c) fina martenzitna zrna okružena krupnim karbidima i šupljinama puzanja, /7/
Figure 4. Scanning electron micrographs (SEM) of fine-grained HAZ (FGHAZ)
a) microcracks; b) voids; c) fine martensite grains surrounded by coarse carbides and creep voids, /7/.



Slika 5. Transmisioni elektronski mikrografi (TEM) gustih taloga karbida (DPC) (a), i područja finozrne strukture HAZ (FGHAZ) (b)
Figure 5 Transmission electron micrographs (TEM) of dense precipitations of carbides (DPC) (a), and fine-grained HAZ region (FGHAZ) (b).

U toku zavarivanja fina zrna nastala u neposrednoj blizini karbida apsorbuju veće količine ugljenika na visokoj temperaturi. S druge strane, fina zrna koja su nastala daleko od karbida ne apsorbuju ugljenik. Zbog toga su fina martenzitna zrna s viškom ugljenika raspoređena kao što je prikazano na sl. 6a, dole. Na granicama i unutar finih martenzitnih zrna s viškom ugljenika se talože velike količine karbida, a tokom starenja u eksploataciji se formira DPC, sl. 6b. Pločasta gusto pakovana mikrostruktura se pojavljuje na granicama zrna s kritičnom količinom karbida. Na granici kritično naraslog karbida i matrice pojavljuju se šupljine puzanja u relativno ranoj fazi rada. S obzirom na pločasti oblik, šupljine se lako međusobno povezuju i zato se granice martenzitnih zrna se odvajaju, sl. 6c. Kako su šupljine bile raspoređene po granicama prethodnih austenitnih zrna, one se međusobno povezuju i obrazuju mikroprslinu cik-cak oblika, sl. 6d, /7/.

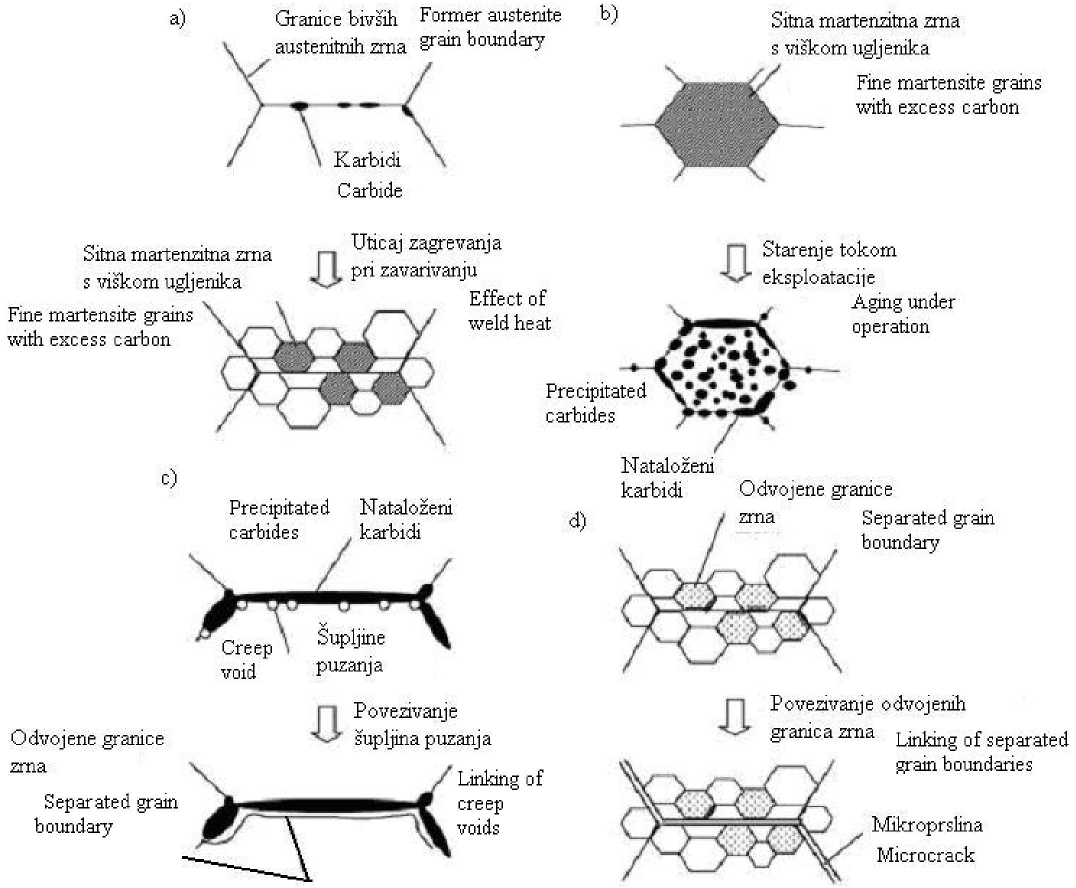
POSTUPCI ZAVARIVANJA

Feritni čelici sa 9–12% Cr za elektrane se isporučuju u normalizovanom i otpuštenom stanju. Osobine P91/T91 čelika najviše zavise od mikrostrukture otpuštenog martenzita i odgovarajućeg rasporeda i veličine taloga očvrslih u toku puzanja. Pažljiva kontrola postupaka zavarivanja i termičke obrade je od suštinskog značaja za pouzdan rad zavarenih komponenata od P/T91 čelika. Predgrevanje, temperatura međuprolaza i termička obrada posle zavarivanja (PWHT) su važni faktori koji se moraju vrlo pažljivo kontrolisati da bi se izbegao prevremeni otkaz zavarene konstrukcije.

During the welding, fine grains formed in the vicinity of carbides absorb a large quantity of carbon at high temperature. On the other hand, fine grains formed remotely from carbides do not absorb carbon. Hence, fine martensite grains with excess carbon are distributed as shown in Fig. 6a, below. On boundaries and inside fine martensite grains with excess carbon, a large amount of carbide is precipitated, and DPC is formed during aging in service, Fig. 6b. A plate-like close packed microstructure appeared on the grain boundaries with ultimate amount of carbide. On the boundaries of so grown carbide and the matrix, creep cavities should be manifested in relatively early phase of usage. Due to the plate-like form, cavities are connected easily and so the martensite grain boundaries are separated, Fig. 6c. As the cavities were distributed on the boundaries of the prior austenite grains, they are inter-connected and constitute a micro crack of zigzag form, Fig. 6d, /7/.

WELDING PROCEDURES

Ferritic steels with 9–12% Cr for power plants are delivered in normalized and tempered condition. Properties of P91/T91 steel mostly depend on the microstructure of tempered martensite and corresponding distribution and size of creep strengthening precipitates. Careful control of welding and heat treatment procedures are of key importance for reliable operation of welded components of P91/T91 steel. Preheating, interpass temperature and post weld heat treatment (PWHT) are significant factors that have to be controlled very carefully in order to avoid premature failure of the welded structure.



Slika 6. Predloženi mehanizam stvaranja i razvoja oštećenja tipa IV u područja finozrne strukture HAZ (FGHAZ).
a) rastvor karbida na granicama prethodnih austenitnih zrna i formiranje finih martenzitnih zrna sa visokim sadržajem ugljenika;
b) formiranje gustih taloga karbida (DPC) u finim martenzitnim zrnima s visokim sadržajem ugljenika starenjem u toku radnog ciklusa;
c) formiranje šuplina puzanja, njihovo spajanje i odvajanje granice zrna; d) formiranje mikroprslina.

Figure 6. Proposed mechanism of initiation and propagation of type IV damage of of fine-grained HAZ region (FGHAZ).
a) solution of carbides on the prior austenite boundaries and formation of fine martensite grains with high carbon content; b) formation of dense precipitations of carbides (DPC) in high carbon fine martensite grains by aging under the operation cycle; c) formation of creep voids, their coalescence and separation of grain boundary; d) formation of microcracks.

Preporučuje se da se posle zavarivanja izvede otpuštanje da bi se, što više, reprodukovala otpuštena martenzitna struktura i da bi se otpustili zaostali naponi od zavarivanja. Da bi se izbegle hladne prsline, komad se pre zavarivanja predgreva posle čega se prirodno hladi do temperature nešto ispod temperature završetka martenzitne transformacije, M_f. Tipične temperature koje se koriste za zavarivanje čelika P91 date su na sl. 7.

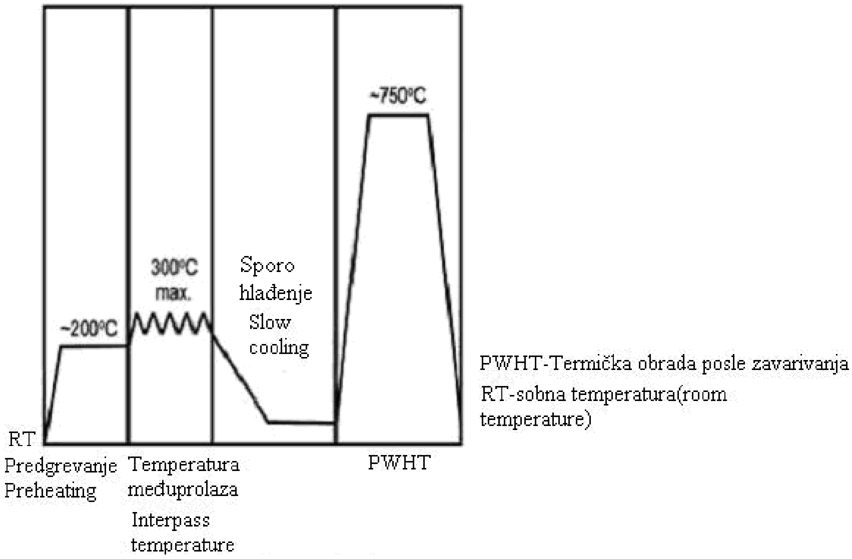
Mogu se koristiti uobičajeni postupci zavarivanja, /1, 6/:

- Zavarivanje netopljivom volfram elektrodom u zaštiti argona (TIG): sa malom unetom toplotom se zavaruju tankozidne cevi, cevi i prirubnice i koreni prolazi debljih spojeva sa ispunom ručnim eletrolučnim (SMAW) ili zavarivanjem pod praškom (SAW). Za koreni prolaz važno je da se sa donje strane najmanje tri sloja zaštite argonom.
- Ručno eletrolučno zavarivanje (SMAW) za popravku.
- Zavarivanje pod praškom (SAW) se koristi za spajanje pojedinačnih cevi u duže segmente; odlikuje se produktivnošću i kvalitetom; veća količina unete toplote može da izazove veću tvrdoću i manju žilavost šava.
- Zavarivanje punjenom žicom (FCAW).

Tempering is recommended after the welding process in order to reproduce, as much as possible, the martensitic structure and relieve residual stresses induced by welding. To avoid cold cracks, the work piece is preheated before welding and subjected to natural cooling to the temperature, slightly below martensite finish temperature, M_f. Typical temperatures used for welding of P91 steel are given in Fig. 7.

Usual welding procedures may be applied, /1, 6/:

- Inert gas tungsten arc welding (TIG): by low heat input it is used for welding of thin-wall tubes, tube-to-header stub welds and root runs in thicker joints when filling passes are completed by shielded metal arc welding (SMAW) or submerged-arc-welding (SAW). It is important that at least three runs of the root pass weld are shielded by argon gas.
- Shielded metal arc welding (SMAW-for repair purposes).
- Submerged arc welding (SAW) is used for assembling pipes into segments; typical for productivity and quality with high material volume deposition; higher heat input may cause high hardness and low toughness of welds.
- Flux cored arc welding (FCAW).



Slika 7. Tipične temperature za izradu zavarenih konstrukcija od čelika P91
Figure 7. Typical temperatures for manufacturing welded structures of P91 steel.

Dodatni materijali za zavarivanje čelika sa 9–12% Cr moraju da odgovaraju radnoj čvrstoći puzanja osnovnog metala. Idealno je da dodatni i osnovni metal imaju istu žilavost na temperaturi okoline, jer su zavareni spojevi izloženi promenljivim naponima pri zaustavljanju postrojenja. Kako metal šava ne može da ispuni oba zahteva, elektrode se projektuju tako da je sastav sličan osnovnom metalu, čvrstoću puzanja odgovarajuća, a žilavost manja.

O pojavi prslina grupe IV dostupno je malo podataka o uticaju unete količine toplote pri zavarivanju i temperature predgrevanja na puzanje zavarenih spojeva. Svrha izbora odgovarajuće temperature predgrevanja je da se izbegne nastanak i širenje prslina u toku hlađenja posle zavarivanja. Nanošenjem više slojeva povećava se žilavost šavova.

Detalji o zoni uticaja toplote

Na sl. 8 shematski su prikazane mikrostrukture koje se javljaju u zavarenom spoju čelila sa 9–12% Cr, prema klasifikaciji Manan i Laha, /8/:

- Krupnozrno područje (CGHAZ): u toku zavarivanja metal blizu linije stapanja dostiže temperaturu iznad A_{C3} tačke; svi karbidi koji predstavljaju glavnu prepreku u rastu austenitnih zrna se rastvaraju, a kao posledica nastaju krupna zrna austenita. U čelicima sa 9–12% Cr, ovako dobijen austenit se pri hlađenju transformiše u martenzit.
- Finozrna oblast (FGHAZ): udaljena od linije stapanja, maksimalna temperatura T_p je još uvek iznad A_{c3} tačke; rast austenitnih zrna ograničen je nepotpunim rastvaranjem karbida; stvara se sitnozrni austenit koji se u 9–12% Cr čelicima kasnije transformiše u martenzit.
- Interkritična oblast (ICHAZ): ovde je $A_{C1} < T_p < A_{C3}$, a rezultat je delimičan povratak u austenit pri zagrevanju. Novi austenit nastaje na granicama prethodnih austenitnih zrna i na granicama lamela martenzita, dok je ostatak mikrostrukture otpušten. Austenit se u čelicima sa 9–12% Cr, pri hlađenju transformiše u neotpušteni martenzit.
- Područje u kome je T_p ispod A_{C1}, zbog čega je prvobitna mikrostruktura materijala izložena daljem otpuštanju.

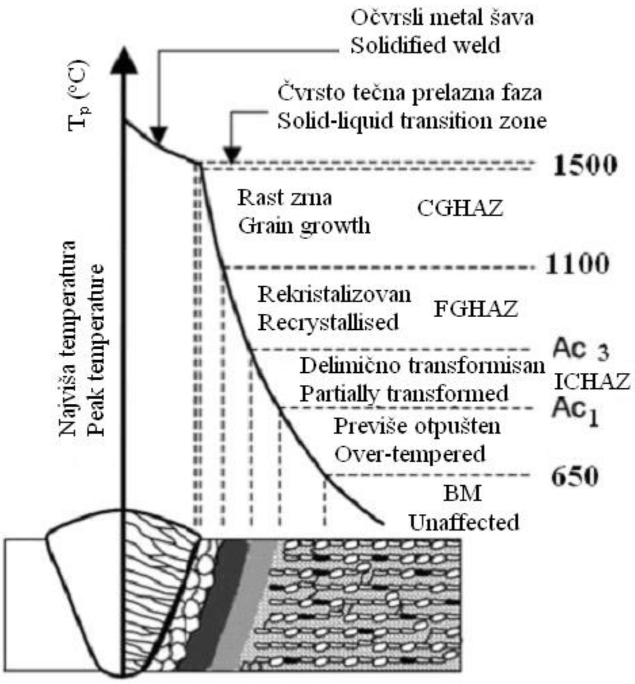
Consumables for welding 9–12% Cr steel have to match parent metal creep strength in service. It is perfect if consumables and parent metal have the same toughness at environmental temperature, since welded joints are exposed to variable stresses at plant shut-down. As weld metal can not meet both requirements, the electrodes are designed to have composition like the parent metal, appropriate creep strength, but lower toughness.

Regarding type IV cracking occurrence, there are scarce data on heat input and preheat temperature affecting welded joint creep. The purpose of adequate preheat temperature selection is to avoid initiation and propagation of cracks during post-weld cooling. Depositing multiple layers increases the weld toughness.

Details about heat-affected-zone

Figure 8 shows microstructures manifested in 9–12% Cr steels which are categorized by Mannan and Laha, /8/, in the following way:

- Course grain region (CGHAZ): during welding, the metal close to the fusion line reaches temperature above A_{C3}; all carbides presenting the major obstacle to austenitic grain growth are dissolved, and as a consequence, course austenite grains are formed. In 9–12% Cr steels, the so formed austenite is during cooling transformed into martensite.
- Fine grain region (FGHAZ): remote from the fusion line, maximal temperature T_p is still above A_{C3}; austenitic grain growth is limited by incomplete dissolution of carbides; fine grain austenite is formed and subsequently transformed into martensite in 9–12% Cr steels.
- Intercritical region (ICHAZ): here is $A_{C1} < T_p < A_{C3}$, and the result is partly reconversion back to austenite during heating. The new austenite nucleates at prior austenite grain boundaries and martensite lath boundaries, while the rest of the microstructure is tempered. Upon cooling, austenite is transformed into untempered martensite in 9-12% Cr steels.
- Over-tempered region: T_p is below A_{C1} and the initial material microstructure is subjected to further tempering.



Slika 8. Tipične mikrostrukture HAZ, čelika P91, nastale tokom zavarivanja
Figure 8. Typical microstructures HAZ, of P91 steel, formed during welding.

Termička obrada posle zavarivanja (PWHT) otpušta novonastali martenzit, stvoren toplotnim ciklusom zavarivanja. Međutim, mehaničke osobine ostaju nepromenjene i posle PWHT na nekoliko milimetara od linije stapanja.

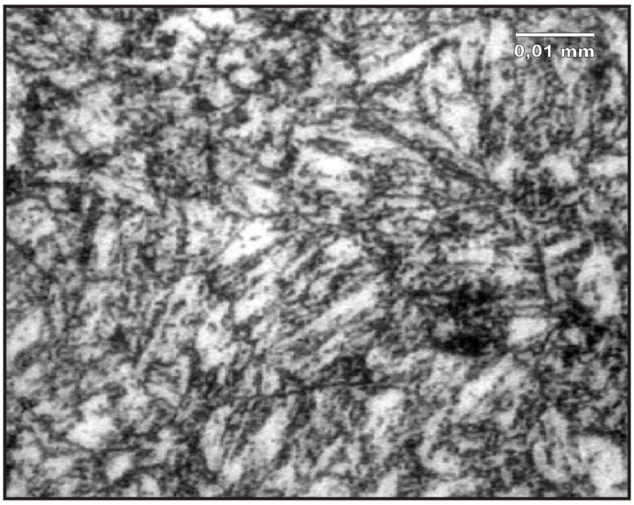
U /9/ je ispitivana simulirana HAZ čelika P91. Strukturu BM predstavlja otpušteni lamelarni martenzit, sl. 9.

Na sl. 10, prikazana je mikrostruktura HAZ, simulirana na 925°C, za koju je u utvrđeno da predstavlja oblast u kojoj se u uslovima puzanja mogu pojaviti prsline tipa IV, /9/.

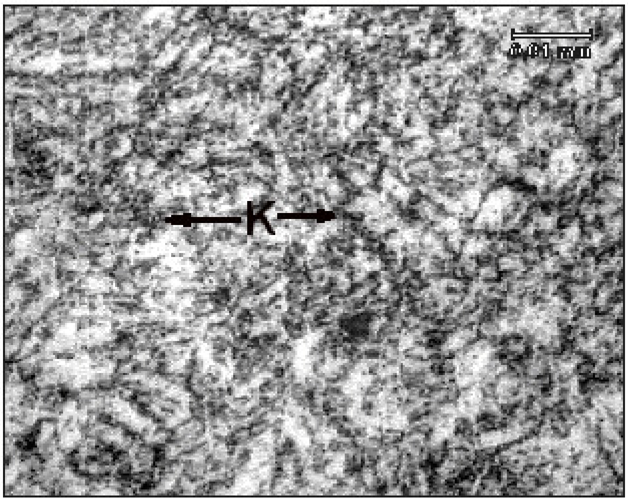
Post weld heat treatment (PWHT) has tempered newly formed martensite, induced by the welding thermal cycle. However, mechanical properties do not change even after PWHT, over several millimeters from the fusion line.

In /9/, the simulated HAZ of P91 steel is inspected. The BM tempered lath martensite structure is shown in Fig. 9.

Figure 10 shows microstructures of the simulated HAZ region (925°C), proved to represent the region in which Type IV cracks may occur in the state of creep, /9/.



Slika 9. Osnovni metal (sredstvo za nagrizanje VILELLA), /9/
Figure 9. Parent metal (etching agent VILELLA), /9/.



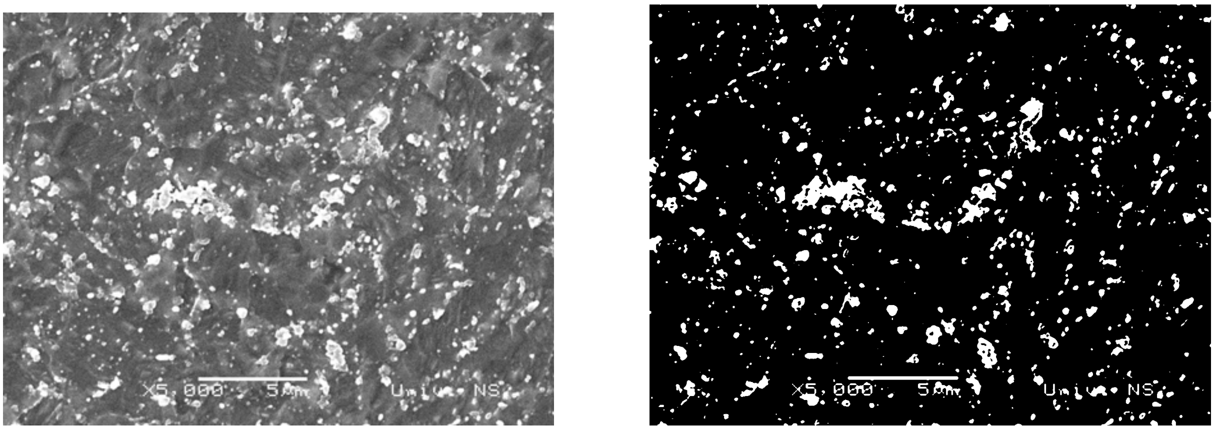
Slika 10. Mikrostruktura uzorka simuliranog na T_p = 925°C
Figure 10. Microstructure of sample simulated at T_p = 925°C.

Mikrostruktura koja odgovara temperaturi austenitizacije od 925°C, sl. 10, je otpušteni martenzit sa slabije izraženim lamelama martenzita. Na pojedinim granicama prethodnih austenitnih zrna, na svetlosnom mikroskopu je uočeno prisustvo izdvojenih krupnih karbida većih od 1 μm.

The microstructure corresponding to austenitisation temperature of 925°C, Fig. 10, consists of martensite with less prominent martensite laths. On some boundaries of previous austenitic grains, the presence of isolated coarser carbides exceeding 1 μm is observed.

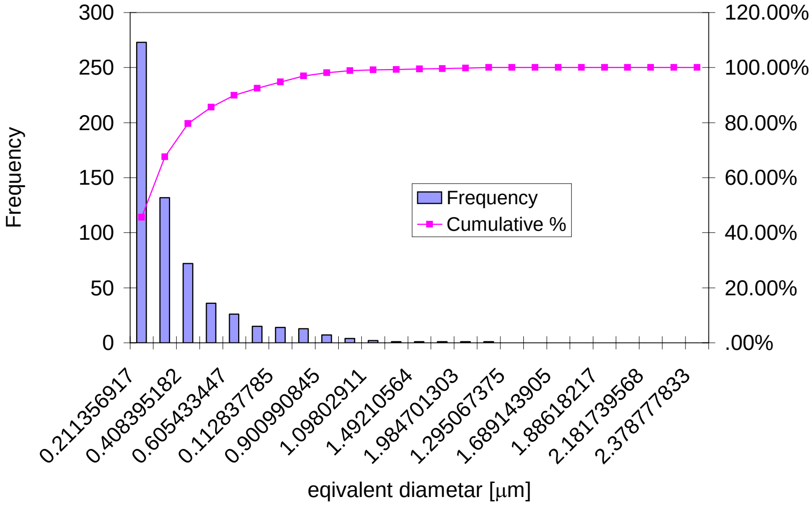
Primenom SEM, moguće je detaljnije analizirati raspored i veličinu karbida tipa $M_{23}C_6$ koji se najčešće izdvajaju po granicama bivših austenitnih zrna i po granicama lamela martenzita. Na sl. 11a, vidi se da su karbidi tipa $M_{23}C_6$ krupniji na granicama bivših austenitnih zrna u odnosu na one izdvojene na granici subzrna ferita. Raspodela karbidne faze $M_{23}C_6$ posle digitalne obrade sl. 11a, prikazana je na sl. 11b, a rezultati merenja raspodele površine karbida na sl. 11c, /9/.

Application of SEM enables more detailed analysis of the distribution and size of $M_{23}C_6$ type carbides that most frequently precipitate along boundaries of prior austenitic grains and along martensitic lath boundaries as well. In Fig. 11a, $M_{23}C_6$ carbides are coarser on boundaries of prior austenitic grains than those along ferritic subgrain boundaries. After digital image processing Fig. 11a, the carbide phase $M_{23}C_6$ distribution is shown in Fig. 11b, and carbide surface distribution measurement results in Fig. 11c, /9/.



a) T_p = 925°C

b) T_p = 925°C–raspodela karbida (carbide distribution)



c) T_p = 925°C–raspodela ekvivalentnog prečnika karbidne faze (distribution of equivalent diameter of carbide phase)

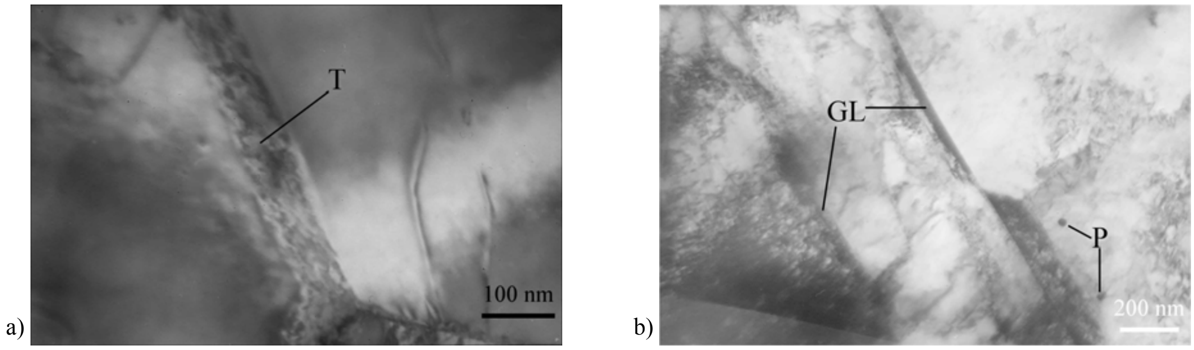
Slika 11. Mikrostrukture simuliranih uzoraka sa SEM, /9/
Figure 11. Microstructure of simulated samples on SEM, /9/.

Od metoda za karakterizaciju mikrostrukture radi ocene upotrebljivosti datog stanja čelika, jedino je pouzdana transmisiona elektronska mikroskopija (TEM), jer ona dokazuje prisustvo taloga po granicama zrna za stanje 925°C sa PWHT, sl. 12a. Taj talog utiče na proces plastične deformacije po granici zrna, koja se odigrava pri puzanju, jer povećava otpornost prema plastičnoj deformaciji po granici zrna i time povećava otpornost ka pojavi puzanja.

Kod epruveta simuliranih na 925°C, bez PWHT, sl. 12b, nije uočeno prisustvo taloga po granici zrna, pa je otpornost prema plastičnoj deformaciji na granici zrna niža. Zbog toga je čelik u ovom stanju manje pogodan za upotrebu u uslovima puzanja.

Transmission electron microscopy (TEM) is the only reliable microstructural method for the characterisation of the present state of steel in the fitness-for-service assessment. This method reveals presence of the precipitates along grain boundaries for specimen simulated at 925°C, with PWHT, Fig. 12a. The precipitate influences creep plastic deformation along the grain boundary by increasing resistance to plastic deformation at boundaries, and apparently to creep.

The specimen simulated at 925°C, without PWHT, Fig. 12b, had no precipitations along grain boundaries, so the resistance to plasic deformation on the grain boundary is lower. Therefore, the steel in this state is less convenient for service in creep conditions.



T–talog po granicama zrna (T–precipitates along grain boundaries);
GL–granice lamela martenzita (GL–martensite lath boundaries); P–talozi (P–precipitates)

Slika 12. Struktura uzorka simuliranog na 925°C, a) sa PWHT i b) bez PWHT, /9/
Figure 12. Microstructure of simulated samples on TEM, a) 925°C with PWHT i b) 925°C without PWHT, /9/.

SPREČAVANJE OŠTEĆENJA TIPA IV

Pre svega je važno postići homogeni sadržaja ugljenika na granicama prethodnih austenitnih zrna. Pretpostavlja se da veliki karbidi ostaju nerastvoreni i da su izvor pojave prslina grupe IV, iako je osnovni metal dva puta zagrevan iznad tačke A_{C3} pre zavarivanja. Da su veliki karbidi uneti u rastvor pre zavarivanja, izbegla bi se fina martenzitna zrna s viškom ugljenika, formiranje DPC i izbeglo bi se oštećenje tipa IV.

Da se krupni karbidi ne bi potpuno uveli u rastvor, u ovom postupku treba koristiti duže vreme normalizacije. Međutim, duže vreme normalizacije snižava mehanička svojstva materijala ispod zahtevanih za dati kvalitet.

Najbolje je izvesti odgovarajuću obradu normalizacijom, sa trajanjem istim kao pri termičkoj obradi. Potrebna je dvostruka ili trostruka normalizacija, jer bi veliki karbidi nestali bez smanjivanja mehaničkih osobina i bez znatnijh troškova. Predloženim postupcima karbidi bi savršeno bili uneti u rastvor pre zavarivanja, i mehanizmi oštećenja zbog prslina iz IV grupe ne bi bili mogući.

TYPE IV DAMAGE PREVENTION

Primarily, it is important to acquire homogeneous carbon content along the boundaries of prior austenite grains. It is assumed that large carbides remain undissolved and are the source of type IV crack occurrence, although parent metal is heated above A_{C3}, two times before welding. If large carbides are added into the solution before welding, fine martensitic grains with excess carbon, and both the DPC formation and type IV damage all would be avoided.

In order to evade these carbides to be fully added to the solution, longer normalization time should be used in this procedure. However, longer normalization time decreases mechanical properties of material, below specified values.

The best option is to perform appropriate normalization treatment, with times equal to heat treatment. Double or triple normalization is necessary for eliminating large carbides without reducing mechanical properties at no substantial expenses. The proposed procedures perfectly introduce the carbides into the solution prior to welding, and type IV crack damage mechanisms are not be possible.

ZAKLJUČAK

Sudeći po objavljenim podacima, prsline IV grupe preovlađuju kada je napon loma manji od 100 MPa, /4/.

Nije uočeno da na vrednost napona loma, zbog prslina tipa IV, utiče količina toplote unete tokom zavarivanja, što omogućava primenu drugačijih parametara zavarivanja, te tako optimizuje produktivnost zavarivanja.

CONCLUSION

According to published data, type IV cracks prevail if the fracture stress is below 100 MPa, /4/.

It has not been noted that fracture stress, due to type IV cracks, is affected by welding heat input, enabling the use of different welding parameters, and accordingly, optimising welding productivity.

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