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Introduction of a New Term - Ferrite Number Density (FND) to Measure the Ferrite Number of Welds on Thin 300 Series Stainless Steel Sheets

Uvođenje novog termina – Gustina feritnog broja (FND) za merenje feritnog broja zavarenih spojeva na tankim limovima od nerđajućeg čelika serije 300

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Abstract

Delta-ferrite content in austenitic steel welds is a crucial parameter to control, since a number of properties depend on this. A FeritScope® is commonly used commercially to measure the Ferrite Number (FN) of the welds which takes advantage of the fact that the retained delta-ferrite phase at room temperature is magnetic whereas austenite is not. However, the readings obtained from the FeritScope® are influenced by a number of constraints such as sheet thickness, weld clad thickness, etc. Although some correction factors have been introduced by the FeritScope® manufacturer to account for these influential conditions, some other geometrical features of the welds were also found to influence the measured FN; for example, despite being a major influential parameter, there is no factor introduced to correct the measurement inconsistencies associated with smaller weld crown widths. In addition, the results obtained on measuring the FN using a FeritScope® contradicted the trends that were expected considering the literature. This research introduces a term called Ferrite Number Density (FND) to represent the ferrite content, in which the measured FN is further proportioned with the cross-sectional area of the weld bead, thus eliminating its dependency on the geometrical size of the weld. It has been established from this research that for welds completed on sheets thicker than 2.4 mm, the FN can be directly used as an indicator of the ferrite content in the weld; however, for thinner sheets, the FND must be used to indicate the ferrite

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Key words: Ferrite Number, welding of thin sheets, Ferrite Number Density, FeritScope®, FGAB1.3-Fe probe, aspect ratio

Rezime

Sadržaj delta-ferita u zavarenim spojevima od austenitnih čelika je presudni parametar za kontrolu, jer od toga zavisi niz svojstava. FeritScope® se obično komercijalno koristi za merenje feritnog broja (FN) zavarenih delova koji koristi činjenicu da je zaostala delta-feritna faza na sobnoj temperaturi magnetna, dok austenit nije. Međutim, očitavanja dobijena FeritScope®-om utiče niz ograničenja kao što su debljina lima, debljina plakature i sl. Iako je proizvođač FeritScope® uveo neke faktore korekcije da bi objasnio ove uticajne uslove, neke druge geometrijske karakteristike zavarenih spojeva takođe utiču na izmereni FN; na primer, uprkos tome što je glavni uticajni parametar, nije uveden faktor koji bi ispravio neusklađenosti merenja povezanih sa manjim širinama vrhova zavarenih spojeva. Pored toga, rezultati dobijeni merenjem FN-a upotrebom FeritScope®-a bili su u suprotnosti sa trendovima koji su bili očekivani uzimajući u obzir literaturu. Ovo istraživanje uvodi termin nazvan Gustina Feritnog broja (FND) da bi predstavio sadržaj ferita, u kome je izmereni FN dodatno proporcionalan sa površinom poprečnog preseka zavara, čime se eliminiše njegova zavisnost od geometrijske veličine zavara. Iz ovog istraživanja utvrđeno je da se za zavare izrađene na limovima debljim od 2,4 mm, FN može direktno koristiti kao pokazatelj sadržaja ferita u šavu; međutim, za tanje limove FND se mora koristiti za označavanje sadržaja ferita u zavarivanju, ako se upotrebljava FeritScope® sa sondom odmerene veličine, npr. u ovom slučaju



content of the weld, if a FeritScope® with an apportioned size probe is used, e.g. in this case an FGAB1.3-Fe probe. Use of FND eliminated all the contradictions obtained between experimental data and literature for thin sheet welds.

1. Introduction

Generally, austenitic stainless steel welds are expected to have a dual-phase microstructure to eliminate deleterious imperfections from forming within the weld microstructure in austenite-to-ferrite proportions ranging between 95/5 to 90/10 respectively. The amount of retained delta-ferrite in the weld depends mainly on the chemical composition of the materials being joined [1], filler material (if used) and the cooling rate of the weld pool [2]. The amount of retained delta-ferrite in the welds is measured using a Ferrite Number (FN) scale, which has been defined in various internationally accepted standards such as ISO 8249 and AWS A4.2M. In austenitic stainless steels, the presence of small amounts of ferrite is known to have beneficial effects on the weld properties [3]. One of the most significant benefits of retaining these small amounts of delta-ferrite during solidification is that it increases the weld's resistance to solidification cracking, especially in presence of sulphur and phosphorous impurities [4]. However, having larger quantities of delta ferrite (>10 FN) can lead to the formation of the brittle sigma phase within the weld on exposure to high temperatures (425°C to 550°C) for extended times. This influence of delta-ferrite on weldments makes it necessary to measure the ferrite content of austenitic stainless steel welds. Various methods and instruments have been developed in order to measure either the ferrite content (in percentage) or the FN of austenitic steel welds, either destructively or non-destructively. The destructive tests include image analysis of etched metallographic specimen, electrochemical examination [5], etc. The non-destructive methods take advantage of the fact that delta-ferrite at room temperature is magnetic, in a non-magnetic austenite matrix. Although a number of instruments are commercially available for measuring the FN of the welds, one of the most commonly used is a FeritScope®, developed by Fischer Scientific. The FeritScope® measures the FN using a magnetic induction method, consequently measuring all the magnetic phases within the weld including the delta-ferrite as well as any strain-induced martensite that may have formed during large deformation processes. Most of the alloying elements present in austenitic stainless steel can be classified into austenite-promoting and ferrite-promoting elements [6]. The

sonda FGAB1.3-Fe. Upotrebom FND-a otklonjene su sve kontradikcije dobijene između eksperimentalnih podataka i literature za zavarene tanke limove.

1. Uvod

Uopšteno, očekuje se da će austenitni zavareni spojevi imati dvofaznu mikrostrukturu radi eliminisanja nastajanja štetnih nesavršenosti unutar mikrostrukture šava, u proporcijama austenit-ferit između 95/5 do 90/10. Količina zaostalog delta-ferita u šavu uglavnom zavisi od hemijskog sastava osnovnih materijala [1], dodatnih materijala (ako se koristi) i brzine hlađenja zavarivačke kupke [2]. Količina zaostalog delta-ferita u šavovima se meri korišćenjem skale feritnog broja (FN), koja je definisana u raznim međunarodno prihvaćenim standardima, kao što su ISO 8249 i AWS A4.2M. Poznato je da prisustvo malih količina ferita u austenitnim nerđajućim čelicima ima blagotvoran uticaj na svojstva šava [3]. Jedna od najznačajnijih prednosti zadržavanja tih malih količina delta-ferita tokom očvršćavanja je ta što povećava otpornost šava solidifikacione prsline, posebno u prisustvu nečistoća sumpora i fosfora [4]. Međutim, veće količine delta ferita (> 10 FN) mogu dovesti do stvaranja krte sigma faze unutar šava izloženog visokim temperaturama (425 ° C do 550 ° C) tokom dužeg vremena. Ovaj uticaj delta-ferita na zavarene spojeve čini neophodnim merenje sadržaja ferita u zavarenim spojevima od austenitnih nehrđajućih čelika.

Razvijene su različite metode i instrumenti za merenje sadržaja ferita (u procentima) ili FN austenitnih zavarenih spojeva, bilo sa ili bez razaranja. Ispitivanja sa razaranjem uključuju analizu slike nagriženog metalografskog uzorka, elektrohemijsko ispitivanje [5] itd. Kod metoda bez razaranja, koristi se činjenica da je delta-ferit na sobnoj temperaturi magnetičan, u nemagnetičnoj austenitnoj matrici. Iako je komercijalno dostupan veliki broj instrumenata za merenje FN zavarenih spojeva, jedan od najčešće korišćenih je FeritScope®, koji je razvio Fischer Scientific. FeritScope® meri FN metodom magnetne indukcije, mereći sve magnetne faze u šavu, uključujući delta-ferit, kao i martenzit izazvan deformacijom koji se može formirati tokom procesa velikih deformacije.

Većina legirajućih elemenata prisutnih u austenitnom nerđajućem čeliku može se svrstati u elemente koji promovišu austenit i ferit [6]. Elementi koji promovišu austenit, kao što su nikel (Ni), ugljenik (C), azot (N) i bakar (Cu), ubrzavaju stvaranje austenita u zavarivačkoj kupki tokom očvršćavanja.



austenite-promoting elements such as nickel (Ni), carbon (C), nitrogen (N) and copper (Cu) accelerate the formation of austenite in the weld pool during solidification. They have been collectively quantified as nickel equivalent (N_{ieq}) in the WRC-1992 Ferrite Number prediction diagram. Likewise, the ferrite promoting-elements, that include chromium (Cr), molybdenum (Mo) and niobium (Nb), have been collectively termed as chromium equivalent (C_{req}). It has been reported by [6] while developing the WRC-1992 diagrams that the relative quantities of C_{req} and N_{ieq} determine the amount of delta-ferrite that will be retained in the solidified weld when the arc welding process is used. As mentioned earlier, apart from the chemical composition, the weld pool cooling rate is also believed to significantly affect the amount of delta ferrite retained. A number of researchers have reported a shift in solidification mode from primary ferrite to primary austenite at extremely high cooling rates, such as in case of laser [7] and electron beam welding [8]. Still, at low to moderate cooling rates, typically obtained in TIG welding, the weld pool is expected to solidify primarily as ferrite (depending on the chemistry of the materials), known as FA type of solidification [6]. In this type of solidification mode, the amount of retained delta-ferrite increases with an increase in the cooling rate. This is because at high cooling rates, the diffusion controlled ferrite to austenite transformation is suppressed owing to insufficient time. In the present research, the influence of weld bead geometry on measured FNs using a FeritScope® for thin sheets (< 2.4 mm) has been investigated. The measured FNs show results contradicting those reported in literature such as the effect of cooling rate on the retained delta-ferrite. It is believed that in addition to the influential parameters mentioned in the FeritScope® user manual [9], the weld bead width and consequently the weld cross-sectional area can have a significant effect on the measured FNs. A new term, Ferrite Number Density (FND) has been introduced, which can be a better indicator of the ferrite content in a solidified weld by eliminating the influence of these geometrical features, especially in thin sheet joints. Using the FND instead of FN also eliminated the contradictions obtained when experimental results were compared to the literature.

2. Methodology

2.1 Experimental Procedure

A number of 304L stainless steel sheets having various thicknesses were welded using an automated tungsten inert gas (TIG) welding process. The sheet thicknesses used for the

Oni su zajednički kvantifikovani kao ekvivalent nikla (N_{iek}) u dijagramu predviđanja feritnog broja WRC-1992. Isto tako, feritni promotivni elementi, koji uključuju hrom (Cr), molibden (Mo) i niobijum (Nb), zajedno su nazvani hromovim ekvivalentom (C_{iek}). Saopšteno je [6] tokom izrade dijagrama WRC-1992. da relativne količine C_{iek} -a i N_{iek} -a određuju količinu delta-ferita koja će se zadržati u očvrslom šavu pri elektrolučnim postupcima zavarivanja. Kao što je ranije spomenuto, osim hemijskog sastava, veruje se da i brzina hlađenja kupke značajno utiče na količinu zaostalog delta ferita.

Brojni istraživači su izvestili da je prelazak u režimu očvršćavanja sa primarnog ferita na primarni austenit, pri ekstremno visokim brzinama hlađenja, kao što je slučaj u slučaju laserskog [7] i zavarivanja elektronskim snopom [8]. Ipak, pri niskim do umerenim brzinama hlađenja, koje se obično dobijaju pri TIG zavarivanju, očekuje se da kupka očvršne prevashodno kao ferit (zavisno od hemije materijala), poznat kao FA vrsta očvršćavanja [6]. U ovom načinu očvršćavanja, količina zaostalog delta-ferita raste sa porastom brzine hlađenja. To je zato što se pri visokim brzinama hlađenja difuziona transformacija ferita do austenita potiskuje zbog nedovoljnog vremena.

U ovom istraživanju je istražen uticaj geometrije zavara na izmerene FN-ove pomoću FeritScope®-a za tanke limove (<2,4 mm). Izmereni FN pokazuju rezultate suprotne onima koji su navedeni u literaturi, kao što je efekat brzine hlađenja na zaostali delta-ferit. Veruje se da pored uticajnih parametara navedenih u korisničkom priručniku FeritScope® [9], širina zavara i posledično područje poprečnog preseka šava mogu imati značajan uticaj na izmerene FN. Uveden je novi termin Gustina feritnog broja (FND), koji može biti bolji pokazatelj sadržaja ferita u očvrslom šavu, eliminišući uticaj ovih geometrijskih karakteristika, naročito na spojevima tankih ploča. Korišćenjem FND-a umesto FN-a takođe su eliminisane kontradikcije dobijene prilikom uspoređivanja eksperimentalnih rezultata sa literaturom.

2. Metodologija

2.1 Postupak eksperimenta

Brojni limovi od nerđajućeg čelika 304L raznih debljina zavareni su automatskim TIG postupkom zavarivanja. Debljina lima korišćena za eksperimente bila je 0,7 mm, 0,9 mm, 1,5 mm, 2,0



experiments were 0.7 mm, 0.9 mm, 1.5 mm, 2.0 mm and 2.4 mm. The chemical composition of all these sheet materials is mentioned in Table 1. Sheets thinner than 1.5 mm were welded autogenously i.e. without any filler material. This ensured that the weld pool chemistry remained unaltered, except in the cases where nitrogen gas was deliberately added to the weld pool through the shielding gas, which has been explained later in this section. Sheets thicker than and including 1.5 mm were welded using a 308LSi filler wire, the chemistry for which is also mentioned in Table 1. The parameter ranges for every thickness were established from trial experiments that give full penetration of the joint in most cases. High purity argon (99.995%) was used as a shielding gas, however, for some experiments nitrogen gas was added to the shielding gas in order to validate the results and modify the phase distribution in the weld pool, as N₂ is known to be a strong austenite promoting element. The gas compositions used for these experiments utilised 2.5% or 5% or 10% nitrogen in argon. Irrespective of shielding gas composition, high purity argon was used as the backing gas for all the experiments. The shielding gas flow rate was maintained at 8 l/min, whereas the backing gas flow rate was maintained at 5 l/min. The arc length was kept constant at 2.5 mm, which ensured that the arc voltage and the power density remained constant for a particular welding atmosphere. All experiments were done using a pulsed current waveform. Consequently, for the autogeneous welds, peak welding current (I_p), torch travel speed (S), duty cycle (δ) and the nitrogen content (N₂) in the shielding gas could be varied between experiments in order to cover a wide range of heat inputs and the cooling rates of the weld pool. For the sheets that were heterogeneously welded (welded using filler materials), among the parameters mentioned above, the duty cycle was kept constant at 50%, but the filler wire feed rate (R) and the filler wire diameter (D) could be varied in order to alter the chemical composition of the weld pool. In addition to this, the pulsing frequency (f) was also varied between experiments, although it has no direct influence on the heat input to the weld pool. The minimum and maximum values of the parameters used in case of autogeneous and heterogeneous welds are mentioned in Table 2 and Table 3 respectively.

In order to develop a suitable design of experiment, among all the parameters mentioned above, I_p, S, δ, f and R were considered as continuous parameters. Due to the limitation on the materials

mm i 2,4 mm. Hemijski sastav svih ovih limova naveden je u Tabeli 1. Limovi tanji od 1,5 mm su zavareni autogeno, tj. bez ikakvog dodatnog materijala. Ovo je osiguralo da hemija zavarivačke kupke ostaje nepromenjena, osim u slučajevima kada je gas azot namerno dodat u kupku kroz zaštitni gas, što je objašnjeno kasnije u ovom odeljku. Limovi deblji od i uključujući 1,5 mm zavareni su dodatnim materijalom žicom 308LSi, čija hemija je takođe navedena u Tabeli 1. Parametri opsega za svaku debljinu su utvrđeni iz eksperimentalnih pokušaja koji u većini slučajeva daju potpuno uvarivanje spoja. Argon visoke čistoće (99,995%) korišćen je kao zaštitni gas, međutim, za neke eksperimente, dodat je azot u zaštitni gas da bi se potvrdili rezultati i modifikovala fazna raspodela u zavarivačkoj kupki, jer je poznato da je N₂ snažan element za promociju austenita. Sastavi gasnih mešavina korišćenih za ove eksperimente su sa 2,5% ili 5% ili 10% azota u argonu. Bez obzira na sastav zaštitnog gasa, argon visoke čistoće korišćen je kao osnovni za sve eksperimente. Brzina protoka zaštitnog gasa je održavana na 8 l/min, dok je protok povratnog gasa održavan na 5 l min. Dužina luka je održavana konstantnom na 2,5 mm, što osigurava da napon luka i gustina struje ostaju konstantni za određenu atmosferu zavarivanja. Svi eksperimenti su rađeni korišćenjem talasnog pulsog oblika struje. Shodno tome, za autogene zavare, vršna struja zavarivanja (I_p), brzina kretanja gorionika (S), radni ciklus (d) i sadržaj azota (N₂) u zaštitnom gasu mogu se menjati između eksperimenata kako bi se pokrивao širok raspon unosa toplote i brzine hlađenja kupke. Za limove koji su heterogeno zavareni (zavareni upotrebom dodatnog materijala), među gore pomenutim parametrima, radni ciklus je bio konstantan na 50%, ali brzina dodatnog materijala žice (R) i prečnik žice (D) mogu se menjati u cilju izmene hemijskog sastava zavarivačke kupke. Pored toga, frekvencija pulsiranja (f) takođe je varirala između eksperimenata, mada nema direktan uticaj na dovod toplote u zavarivačku kupku. Minimalne i maksimalne vrednosti parametara koji se koriste u slučaju autogenih i heterogenih zavarivanja navedeni su u tabeli 2 i tabeli 3.

Da bi se razvio odgovarajući dizajn eksperimenta, među svim gore pomenutim parametrima, I_p, S, d, f i R su razmatrani kao kontinuirani parametri. Zbog ograničenja raspoloživih materijala i opreme, D i N₂ su smatrani diskretnim parametrima. S obzirom na mogućnost nelinearne zavisnosti zaostalog delta-ferita od parametara zavarivanja, korišćen je konvencionalni centralni kompozitni dizajn (CCD)



and equipment available, D and N₂ were considered as discrete parameters. Considering the possibility of a non-linear dependence of retained delta-ferrite on the welding parameters, a conventional central composite design (CCD) of experiments scheme was used. Consequently, for every combination of discrete parameters, with four continuous parameters, 31 experiments were required at each thickness. In order to reduce the total number of experiments, only some of these were repeated for other combinations of the discrete parameters. For example, for a 0.7 mm thick sheet, 31 experiments using the CCD scheme were performed using pure argon, from which only 17 random experiments were repeated for every level of nitrogen concentration (2.5%, 5% and 10%) in the shielding gas. Consequently, nearly 85 experiments were performed at every thickness, for all of which, the Ferrite Number, bead geometry and the cross-sectional area was measured as explained in the following sections.

eksperimentalne šeme. Shodno tome, za svaku kombinaciju diskretnih parametara, sa četiri kontinuirana parametra, potreban je 31 eksperiment u svakoj debljini. Da bi se smanjio ukupan broj eksperimenata, samo su neki od njih ponovljeni za druge kombinacije diskretnih parametara. Na primer, za lim debljine 0,7 mm izvedeno je 31 eksperimenta po CCD shemi pomoću čistog argona, iz kojih je ponovljeno samo 17 nasumičnih eksperimenata za svaki nivo koncentracije azota (2,5%, 5% i 10%) u zaštitnom gasu. Shodno tome, izvedeno je gotovo 85 eksperimenata u svakoj debljini, za koji je meren feritni broj, geometrija zavara i površina poprečnog preseka kao što je objašnjeno u sledećim odeljcima.

Thickness (mm)	C	Cr	Mn	N	Ni	P	S	Si
0.7	0.019	18.290	1.130	0.064	8.250	0.035	0.001	0.310
0.9	0.023	18.140	1.750	0.090	8.180	0.041	0.003	0.200
1.5	0.026	17.795	2.000	0.100	8.120	0.025	0.001	0.497
2.0	0.015	17.685	1.669	0.071	8.075	0.033	0.001	0.320
2.4	0.0186	18.200	1.434	0.0378	8.050	0.0306	0.0037	0.401
Filler 308LSi	0.010	20.000	1.800	0.000	10.000	0.015	0.015	0.800

Table 1. Chemical Composition of materials used for the experiments

Tabela 1. Hemijski sastav materijala korišćenih u eksperimentima

2.2 Ferrite Number Measurement

A Fischer FeritScope® FMP30 with an FGAB1.3-Fe probe was used to measure the FNs of the welds obtained from the experiments. The FN for every weld was taken as an average of 10 readings at different locations along the length of weld. Since the sheets used for the experiments were thin, the measured FNs were required to be multiplied by a correction factor corresponding to that particular thickness and measured FN, the guidelines for which have been mentioned in the user manual [9] of the FeritScope®. However, in the manual, the correction factor curves are plotted only for a few discrete values of FNs, from which others required values being obtained through interpolation. The true FNs were obtained from the measured FNs using Equation (1).

$$(FN)_{true} = (FN)_{observed} * Correction Factor \quad (1)$$

2.2 Merenje feritnog broja

Fischer FeritScope® FMP30 sa FGAB1.3-Fe sondom korišćen je za merenje FN-a šavova dobijenih eksperimentima. FN za svaki šav uzet je u proseku 10 očitavanja na različitim lokacijama duž dužine šava. Pošto su limovi korišćeni za eksperimente tanki, trebalo je da se mereni FN umnože korekcijskim faktorom koji odgovara toj određenoj debljini i izmerenom FN, prema smernicama koje su pomenute u korisničkom priručniku [9] FeritScope®. Međutim, u priručniku su krive korekcijskog faktora prikazane samo za nekoliko diskretnih vrednosti FN-a od kojih se interpolacijom dobijaju druge potrebne vrednosti. Pravi FN su dobijeni iz izmerenih FN pomoću jednačine (1).

$$(FN)_{true} = (FN)_{observed} * Correction Factor \quad (1)$$



Figure 1 shows the difference between the true and measured FNs when the correction factors were applied to some of the readings obtained from those 0.7 mm thick sheet welds as an example. It can be clearly seen that the true FNs are considerably higher than the measured FNs. In all the subsequent sections in this paper, the term FN refers to the true FNs and not the measured values. Similarly, the correction factors for the curvature of the specimen being measured have also been mentioned in the user manual of the FeritScope®. This correction factor is required only if the radius of curvature of the specimen for which the FN is measured is less than 50 mm. Consequently, for the welds done heterogeneously, this correction factor was taken into account along with the correction factor for the thickness, depending on the radius of the crown determined from macrographic examination.

Metallographic samples were taken from all the welds in order to measure their cross-sectional area. These samples were etched using the acetic-glyceria (5 ml glycerol, 15 ml hydrochloric acid, 10 ml nitric acid and 10 ml acetic acid) solution, in order to be able to distinctly see the delta-ferrite dendrites within the austenite grains in the microstructure. A Leica DM2700 microscope was used to capture the images of the weld microstructure. The ferrite content of the welds was also quantified by applying the image analysis technique on the microstructural images obtained. ImageJ software was used to measure the ferrite content, which has been detailed in the later sections.

2.3 Heat Input and Cooling Rate Calculations

For all the welds, the heat input and the cooling rate of the weld was calculated using the analytical expressions derived by [10]. This was done in order to understand the effect of cooling rate on the residual delta-ferrite content. However, the results obtained contradicted the trends available in the literature, which led to the belief that some other factors, apart from the ones mentioned in the FeritScope® user manual must be influencing the measured FNs.

2.3.1 Heat Input Calculations

In general, for an arc welding process using a pulsed waveform, the heat input to the weld pool is a function of effective welding current, the torch travel speed and the voltage across the arc (which is defined by the arc length and the welding atmosphere). The heat input, neglecting thermal efficiency (η) is expressed in J/mm and is calculated using Equation (2).

Na slici 1 prikazana je razlika između pravih i izmerenih FN-ova kada su korektivni faktori primenjeni na neke od očitavanja dobijenih iz tih zavarenih spojeva na 0,7 mm debelim limovima. Jasno se vidi da su pravi FN-ovi znatno veći od izmerenih FN-ova. U svim narednim odeljcima ovog rada, termin FN se odnosi na prave FN-ove, a ne na izmerene vrednosti.

Slično tome, korektivni faktori za zakrivljenost uzorka koji se mere su takođe navedeni u korisničkom priručniku FeritScope®. Ovaj korekcionni faktor potreban je samo ako je poluprečnik zakrivljenosti uzorka za koji se meri FN manji od 50 mm. Shodno tome, za heterogeno zavarene spojeve, uzet je u obzir i ovaj korekcionni faktor, zajedno sa korekcionim faktorom za debljinu, u zavisnosti od radijusa vrha, određenih makrografskim pregledom.

Uzeti su metalografski uzorci svih šavova kako bi se izmerila njihova površina poprečnog preseka. Ovi uzorci su nagriženi rastvorom kiselina u glicerinu (5 ml glicerina, 15 ml hlorovodonične kiseline, 10 ml azotne kiseline i 10 ml sirćetne kiseline) kako bi se mogli jasno videti delta-ferritni dendriti unutar zrna austenita u mikrostrukturi. Za snimanje mikrostrukture korišćen je mikroskop Leica DM2700. Sadržaj ferita u šavovima je takođe kvantifikovan primenom tehnike analize slike na dobijenim mikrostrukturnim slikama. Softver Image J je korišćen za merenje sadržaja ferita, što je detaljno opisano u kasnijim odeljcima.

2.3 Proračun unete toplote i brzine hlađenja

Za sve šavove, unos toplote i brzina hlađenja šava izračunata je korištenjem analitičkih izraza dobijenih sa [10]. Ovo je urađeno da bi se razumeo uticaj brzine hlađenja na zaostali sadržaj delta-ferita. Međutim, dobijeni rezultati su u suprotnosti s trendovima dostupnim u literaturi, što je dovelo do uverenja da neki drugi faktori, osim onih koji se spominju u FeritScope® korisničkom priručniku, moraju uticati na izmerene FN.

2.3.1 Izračunavanje umete toplote

Uopšteno, za neki elektrolučni postupak zavarivanja uz upotrebu pulsirajućeg talasnog oblika, unos toplote u kupku je funkcija efektivne struje zavarivanja, brzine kretanja gorionika i napona duž luka (što je definisano dužinom luka i atmosferom zavarivanja). Unos toplote, zanemarujući toplotnu efikasnost (η), izražava se u J / mm i izračunava se pomoću jednačine (2).



$$H=(I_e*V)/S \tag{2}$$

where,
 H is the heat input (J/mm)
 V is the arc voltage (V)
 S is the torch travel speed (mm/s)
 I_e is the effective current (A), which in the case of a pulsed waveform is calculated using

$$I_e=\sqrt{(I_p^2)*\delta + (I_b^2)*(1-\delta)} \tag{3}$$

where,
 I_p is the peak current,
 I_b is the base current
 δ is the duty cycle.

The heat source power (q) which is required to obtain the cooling rate was calculated using Equation (4).

$$q=I_e*V \tag{4}$$

The reason for neglecting the thermal efficiency (η) within this study is that the value of 0.6 applied to the TIG process in the standard EN1011 is an average and could skew comparative studies completed by any future researchers wishing to assess this work.

$$H=(I_e*V)/S \tag{2}$$

gde je,
 H je unos toplote (J / mm)
 V je napon luka (V)
 S brzina kretanja gorionika (mm / s)
 tj. Efektivna struja (A) koja se u slučaju pulsnog talasnog oblika izračunava koristeći

$$I_e=\sqrt{(I_p^2)*\delta + (I_b^2)*(1-\delta)} \tag{3}$$

gde je,
 I_p vršna struja,
 I_b osnovna struja
 d radni ciklus

Snaga izvora toplote (q) koja je potrebna za postizanje brzine hlađenja izračunata je pomoću jednačine (4).

$$q=I_e*V \tag{4}$$

Razlog zanemarivanja toplotne efikasnosti (η) u okviru ove studije je taj što je vrednost 0,6, koja se primenjuje na TIG postupak u standardu EN1011, prosečna i može da iskrivi uporedne studije koje bi završili bilo koji budući istraživači koji žele da procene ovaj rad.

Sheet Thickness →	0.7 mm		0.9 mm	
Parameter	Minimum	Maximum	Minimum	Maximum
Peak Welding Current (A)	50	70	60	80
Torch Travel Speed (mm/s)	4	6	4	6
Duty Cycle (%)	40	60	40	60
Pulsing Frequency (Hz)	4	8	4	8
Nitrogen content in shielding gas (%)	0	10	0	10

Table 2. Parameter ranges used for autogenous welds
Tabela 2. Opseg korišćenih parametara za autogene šavove

Sheet Thickness →	1.5 mm		2.0 mm		2.4 mm	
Parameter	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Peak Welding Current (A)	60	120	60	160	90	160
Torch Travel Speed (mm/s)	2	4	1	6	1	3
Pulsing Frequency (Hz)	1	6	1	10	1	6
Filler Wire Feed Rate (mm/min)	100	700	100	900	150	700
Filler Wire Diameter (mm)	0.8	1	0.8	1	0.8	1
Nitrogen content in shielding gas (%)	0	10	0	10	0	10

Table 3. Parameter ranges used for heterogeneous welds
Tabela 3. Opseg korišćenih parametara za heterogene šavove

Therefore the heat input and the heat source power was calculated for all the welds using Equation (1), (2) and (3), following which the cooling rates were obtained from the expressions shown below.

2.3.2 Cooling Rate Calculations

The cooling rate of the weld pool was calculated using either the 2-D or the 3-D cooling rate expression since the welds obtained were a mixture of full and partially penetrated fusion profiles. The

Stoga su ulazna toplota i snaga izvora toplote izračunati za sve šavove pomoću jednačine (1), (2) i (3), nakon čega su brzine hlađenja dobijene iz izraza prikazanih dole.

2.3.2 Izračunavanje brzine hlađenja

Brzina hlađenja kupke je izračunata korišćenjem ili 2-D ili 3-D izraza brzine hlađenja, jer su dobijeni šavovi bili mešavina potpuno i delimično uvaranih



expressions for 2-D and 3-D cooling rates used are shown in Equation (5) and Equation (6) respectively.

$$R_{2D} = 2\pi K \rho C_p \left(\frac{(S/10)t}{q} \right)^2 (T' - T_0)^3 \quad (5)$$

$$R_{3D} = 2\pi K \left(\frac{(S/10)t}{q} \right)^2 (T' - T_0)^2 \quad (6)$$

where,

R_{2D} and R_{3D} is the 2-D and the 3-D cooling rate respectively ($^{\circ}\text{C}/\text{s}$),

K is the thermal conductivity ($\text{W}/\text{cm}^{\circ}\text{C}$),

ρ is the density (g/cm^3),

C_p is the specific heat ($\text{J}/\text{g}^{\circ}\text{C}$)

S is the torch travel speed (mm/s),

t is the thickness (cm)

q is the heat source power (watts)

T' is the temperature at which the cooling rate is calculated ($^{\circ}\text{C}$)

T_0 is the initial plate temperature

Table 4 summarizes the values of the constant parameters used in Equations (5) and (6) for the calculation of the cooling rate of the weld. These values are the same as those used by [11] to estimate the cooling rate for the prediction of Ferrite Numbers. Whether a 2-D cooling rate

profila stpanja. Izrazi za korišćene 2-D i 3-D brzine hlađenja prikazani su u jednačini (5) i jednačini (6).

$$R_{2D} = 2\pi K \rho C_p \left(\frac{(S/10)t}{q} \right)^2 (T' - T_0)^3 \quad (5)$$

$$R_{3D} = 2\pi K \left(\frac{(S/10)t}{q} \right)^2 (T' - T_0)^2 \quad (6)$$

gde je,

R_{2D} i R_{3D} su 2-D i 3-D brzina hlađenja, respektivno ($^{\circ}\text{C}/\text{s}$),

K je toplotna provodljivost ($\text{W}/\text{cm}^{\circ}\text{C}$),

ρ je gustina (g/cm^3),

C_p je specifična toplota ($\text{J}/\text{g}^{\circ}\text{C}$)

S brzina kretanja gorionika (mm/s),

t debljina (cm)

q je snaga izvora toplote (vati)

T' je temperatura pri kojoj se izračunava brzina hlađenja ($^{\circ}\text{C}$)

T_0 je početna temperatura ploče

U tabela 4 sumirane su vrednosti konstantnih parametara korišćenih u jednačinama (5) i (6) za proračun brzine hlađenja šava. Ove vrednosti su iste kao i one koje koristi [11] za procenu brzine hlađenja za predviđanje feritnih brojeva. Da li se primenjuje dvosmerna brzina hlađenja

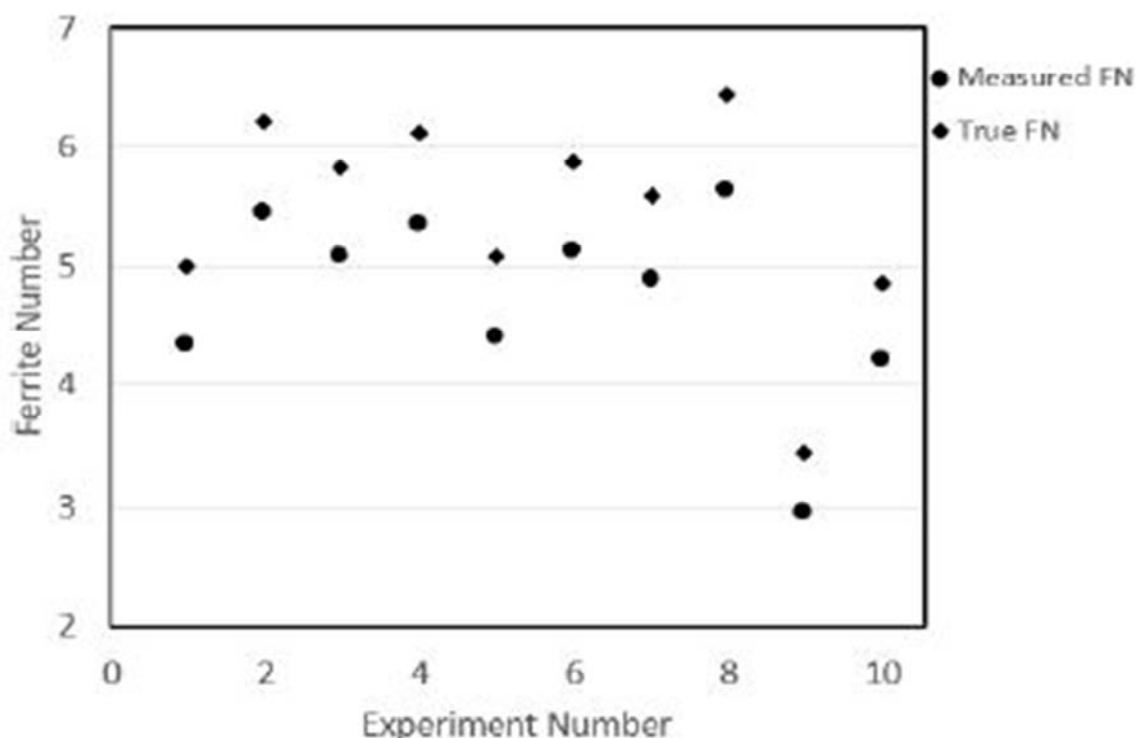


Figure 1. Difference between True FN and measured FN for 0.7 mm thick sheet welds

Slika 1. Razlika između stvarnog FN i izmerenog FN za šavove od lima debljine 0,7 mm

or a 3-D cooling rate applies depends on the relative plate thickness (τ), which can be estimated using Equation (7) as mentioned in the ASM Welding Handbook [12].

ili trosmerna brzina hlađenja zavisi od relativne debljine lima (t), koja se može proceniti pomoću jednačine (7) kao što je spomenuto u ASM priručniku za zavarivanje [12].



$$\tau = t * \sqrt{(\rho C_p V (T' - T_0) / q)} \quad (7)$$

According to the Welding Handbook, if $\tau < 0.6$, a 2-D cooling rate expression must be used, but if $\tau > 0.9$, the 3-D cooling rate expression must be used. However, [2] found that this criteria was not optimal and modified it such that, a 2-D cooling rate expression was used when the value of τ was less than 1.5, and a 3-D cooling rate expression was used when the value of τ was greater than 2.0. For values in between these, an average of 2-D and 3-D cooling rates was considered. This cooling rate was used as one of the input parameter to predict the FN in the Oak Ridge Ferrite Number (ORFN) model. In this research, the criteria used by [2] is applied to calculate the cooling rates, since the FN values obtained from experiments could then be compared to the values predicted by the ORFN model.

3. Results and Discussion

From the results obtained, the influence of the cooling rate on the FN was studied. Figure 2 shows plots of measured FNs against the cooling rates calculated for the welded joints of various thickness sheets.

It can be seen from Figure 2 that as the cooling rate is increased, the amount of retained delta-ferrite is decreased for welds completed on the 0.7 mm, 0.9 mm, 1.5 mm and 2.0 mm thick sheets. The 2.4 mm thick sheet did not show such a trend, the possible reason for which is explained in the later sections.

$$\tau = t * \sqrt{(\rho C_p V (T' - T_0) / q)} \quad (7)$$

Prema Priručniku za zavarivanje, ako je $t < 0,6$, mora se koristiti 2-D izraz brzine hlađenja, ali ako je $t > 0,9$, mora se upotrebiti 3-D izraz brzine hlađenja. Međutim, [2] utvrđeno je da ovaj kriterijum nije optimalan i modifikovan je tako da je korišćen 2-D izraz brzine hlađenja kada je vrednost τ manja od 1,5, a 3-D izraz brzine hlađenja je korišćen kada je τ bio veći od 2,0. Za vrednosti između ovih, razmotrene su prosečne vrednosti 2-D i 3-D hlađenja. Ova brzina hlađenja korišćena je kao jedan od ulaznih parametara za predviđanje FN u modelu Oak Ridge Feritnog broja (ORFN). U ovom istraživanju, kriterijumi koje koristi [2] se primenjuju za izračunavanje stepena hlađenja, pošto se vrednosti FN dobijene eksperimentima mogu uporediti sa vrednostima predviđenim ORFN modelom.

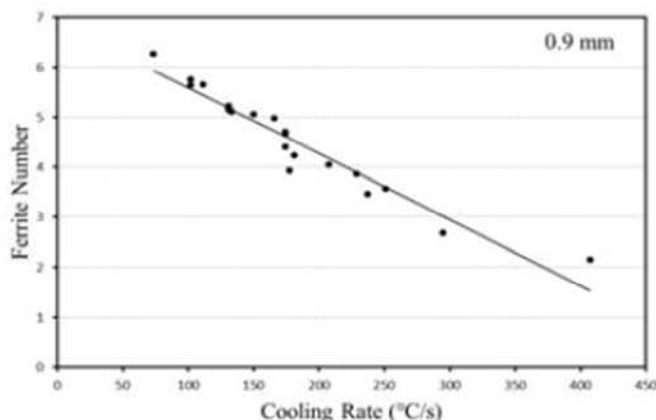
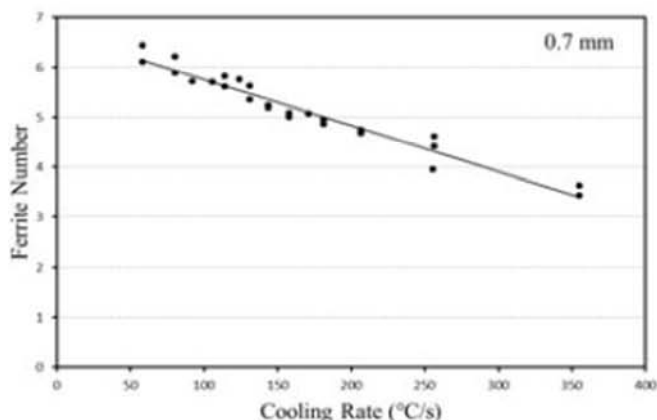
3. Rezultati i diskusija

Na osnovu dobijenih rezultata proučavan je uticaj brzine hlađenja na FN. Na slici 2 prikazane su grafički podaci izmerenih FN-a prema brzini hlađenja izračunatoj za zavarene spojeve limova različite debljine.

Na slici 2 se vidi da se s povećanjem brzine hlađenja količina zadržanog delta-ferita smanjuje za zavarene spojeve na limovima debljine 0,7 mm, 0,9 mm, 1,5 mm i 2,0 mm. Lim debljine 2,4 mm nije pokazao takav trend, čiji je mogući razlog objašnjen u kasnijim odeljcima.

Parameter	Value
K(thermal conductivity)	0.28 W/cm-°C
ρC_p (density*specific heat)	4.6 J/cm ³ -°C
T' (temperature at which cooling rate is calculated)	1450°C
T ₀ (ambient temperature)	25°C

Table 4. Values of constant parameters used to calculate the cooling rate of the welds
Tabela 4. Vrednosti konstantnih parametara za izračunavanje brzine hlađenja zavarenih spojeva



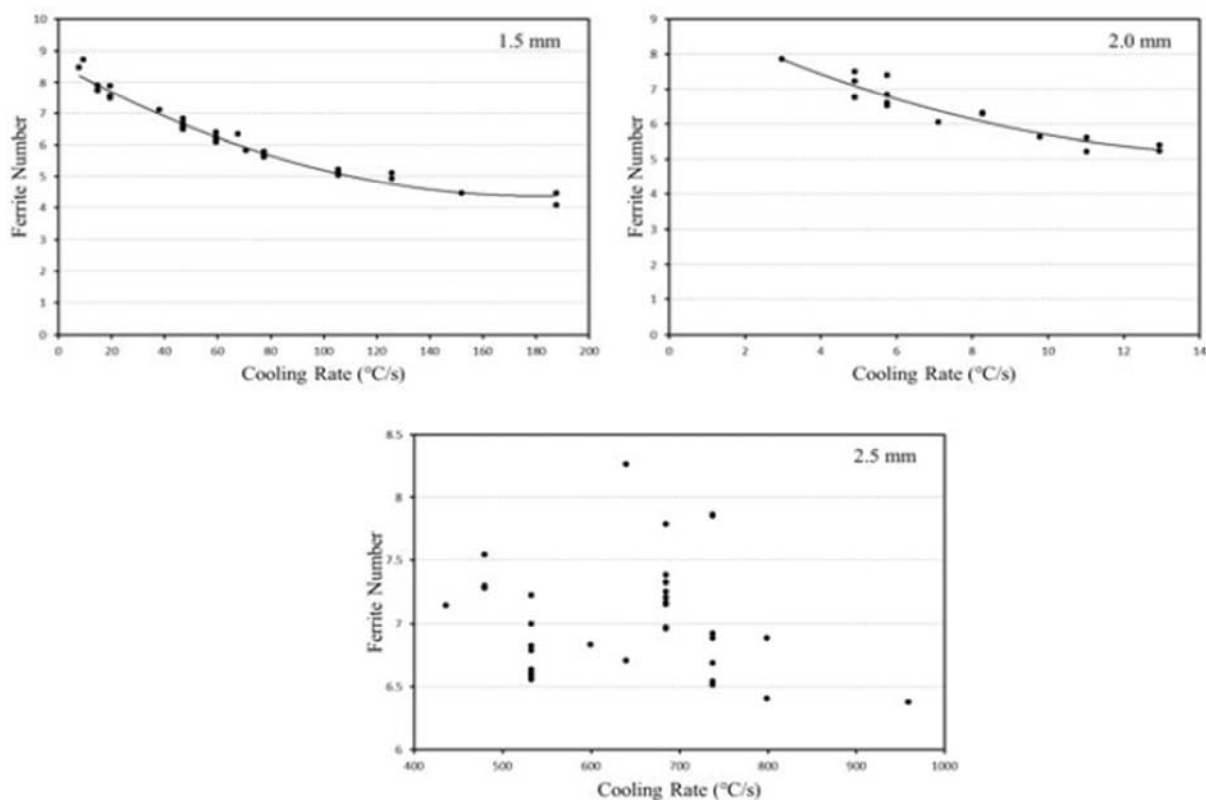


Figure 2. Plots illustrating dependence of retained delta ferrite content on the cooling rate of the weld pool for various thickness sheets

Slika 2. Grafikoni koji prikazuju zavisnost sadržaja zaostalog delta ferita od brzine hlađenja zavarivačke kupke za limove različite debljine

This reduction in retained delta-ferrite on increasing the cooling rate of the weld is in contradiction to what was expected. Considering the chemical composition of the sheet materials, and comparing the microstructures of the weld pool (shown in the later sections) to the microstructures shown in [4], it is evident that the weld pool has undergone an FA type of solidification. In this type of solidification, the weld pool primarily solidifies as delta-ferrite, following which a conversion to austenite takes place through a diffusion controlled reaction. In such cases, if the cooling rate is increased, the amount of residual delta-ferrite is expected to increase, owing to the fact that the conversion to austenite is suppressed due to insufficient time available. The data in Figure 2 is plotted on a logarithmic scale of cooling rate in Figure 3. The curves for predicted FN's plotted against logarithms of cooling rates using the ORFN model developed by [2] using the chemistry of 0.7 mm and 0.9 mm thick sheets used for the experiments are shown in Figure 4. It can be clearly seen that for the experiments performed using the parameter ranges mentioned in Table 2, which lead to the logarithms of the cooling rates to vary between 1.70 and 2.60 for 0.7 mm and between 1.85 and 2.60 for 0.9 mm thick sheets, the FN must increase with increasing cooling rates.

Ovo smanjenje zaostalog delta-ferita povećanjem brzine hlađenja šava je u suprotnosti sa očekivanjem. Uzimajući u obzir hemijski sastav materijala i upoređujući mikrostrukture kupki (prikazanih u kasnijim odeljcima) sa mikrostrukturama prikazanim u [4], očigledno je da je zavarivačka kupka podvrgnuta FA očvršćivanju. U ovoj vrsti očvršćavanja, zavarivačka kupka prvenstveno očvrstne kao delta-ferit, nakon čega se vrši konverzija u austenit reakcijom sa difuzionom kontrolom. U takvim slučajevima, ako se povećava brzina hlađenja, očekuje se da će se povećati količina preostalog delta-ferita zbog činjenice da je pretvaranje u austenit ugušeno zbog nedovoljnog raspoloživog vremena. Podaci na slici 2 prikazani su na logaritamskoj skali brzine hlađenja na slici 3. Krive za predviđene FN-e iscrtane prema logaritmima stepena hlađenja pomoću ORFN modela razvijenog od strane [2] koristeći hemiju limova debljine 0,7 mm i 0,9 mm za eksperimente prikazani su na slici 4. Jasno se može videti da za eksperimente izvedene korišćenjem raspona parametara navedenih u tabeli 2, koji dovode do toga da logaritmi brzina hlađenja variraju između 1,70 i 2,60 za 0,7 mm i između 1,85 i 2,60 za limove debljine 0,9 mm, FN mora da se povećava sa povećanjem brzine hlađenja.

-Kraj 1. dela NASTAVAK U SLEDEĆEM BROJU