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Experimental and simulation study of phase transformation in thermite welded railway steel heat-affected zone regions

Proučavanje faznih transformacija u zoni uticaja toplote aluminotermijski zavarenih čelika za šine eksperimentalnim metodama i simulacijom

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Abstract

Rail transportation has been an emerging and promising transportation method for economic development in Thailand and several countries. Thermite welding is one of the major welding and joining processes used to weld rail steel both during construction and maintenance. Unlike most welding processes in which heat is generated by electrical energy, thermite welding use heat generated during the chemical reactions between iron oxide and aluminum or other metallic compounds to create the weld. The amount of heat generated is thus depended on the composition and ratios of iron oxide, aluminum, as well as other metallic compounds mixed in the thermite powder. In addition, the size, shape, and material used for thermite mold could also play an important role in the heat transfer process during thermite welding of rail steel. In this research, SYSWELD software developed by ESI Group is used to perform thermal-mechanical-metallurgical welding simulation during thermite welding of rail steel. The current article presents that research methodology used to formulate the prediction of microstructure developed in the heat-affected zone regions of thermite welding of railway steel. It is noted that this work attempts to evaluate how preheat, heat generation during chemical reaction, and possible post-weld heat treatment could be performed to controlled the microstructure of pearlitic rail steel using SYSWELD software. The results of this on-

Rezime

Prevoz železnicom je obećavajući način transporta značajan za ekonomski razavoj Tajlanda i još nekih država. Aluminotermisko zavarivanje (Termit) je jedan od glavnih procesa spajanja i zavarivanja šina, kako pri izgradnji, tako i pri održavanju železničkih pruga. Za razliku od većine procesa zavarivanja koji toplotu generišu primenom električne enrgije, aluminutermisko zavarivanje koristi toplotu koja se generiše tokom hemijske reakcije između železnih oksida i aluminijuma ili drugih metalnih komponenti, da bi se dobio zavareni spoj. Količina generisane toplote zavisi od sastava i odnosa železnih oksida i aluminijuma ili drugih metalnih komponenti koje su izmešane u prahu za zavarivanje. Takođe, veličina i oblik materiala koji se koristi za kalup za proces Termit, takođe imaju značajan uticaj na proces prenosa toplote za vreme zavarivanja čelika šina. U ovom istraživanju softver SYSWELD, razvijen od strane ESI Grupe, je primenjen za simulaciju termičkio – mehaničkih – metalurških pojava za vreme aluminutermiskog zavarivanja čelika za šine. Ovaj rad prikazuje metodologiju istraživanja radi formulisanja predviđanja nastalih mikrostruktura u oblastima zone uticaja toplote aluminutermisko zavarenog čelika za šine. Ovaj rad pokušava da proceni kako predgrevanje, generisnje toplote za vreme hemijske reakcije i moguća termička obrada posle zavarivanja, može da vrši kontrolu mikrostrukture perlita čelika za šine, primenom

going research will be used as the baseline for future development of structural integrity program for improving joining of rail steel such as the design and selection of welding processes and materials involved for rail construction, especially when appropriate grades and welding procedures of rail steels must be chosen and developed to withstand the actual loading conditions.

1. Introduction

Thermite welding is the the welding process widely used in construction and repair of railway steel due to its portability and no electrical power source required. During thermite welding, two rails are joined together by exothermic chemical reaction called aluminothermic reaction between metal oxide and aluminum in thermite powder. This produces molten metal that fills the mold and the gap between two rails and welds them together. It is important to provide sufficient preheat in the range of 800oC to 1 000oC to avoid fast cooling rate which produces hard and brittle microstructure in the weld metal and heat affected zones [1- 2]. Additional preheat would be necessary to remove excess moisture and contaminant in the environment to perform welding. It is also very important to properly select preheat time, preheat temperature, liquid temperature, and weld gap size to minimize shrinkage cavity, cold-lap and centerline defects during thermite welding of railway steel [3].

Myers, et al. [1] investigated microstructure and properties of thermite welds in rails of composition 0.75- 0.76C, 0.80-0.93Mn, 0.17-0.74Si (wt.%). They found that the peak hardness in the heat affected zone (HAZ) regions is always adjacent to the weld metal, while the lowest hardness is almost always in the outer extremity of the HAZ in the partially spheroidized pearlite microstructure. Also preheat time hardly influences the width of the HAZ regions in thermite welds. Wang, et al. [2] studied mechanical properties and fracture roughness of thermite welded rail steels of composition 0.72C, 1.21Mn, 0.22Si and 0.77C, 0.95Mn, 0.62Si (wt.%) at low temperature. They found that the impact toughness values of the weld metal were much lower than those of rail steels with rail steel of composition 0.72C, 1.21Mn, 0.22Si performed better at low temperature. Chen, et al. [3] investigated weld defect formation in rail thermite welds including cold-lap defect, shrinkage cavity, centerline defect, and distributed microporosity. They reported that with current thermite welding practice, shrinkage cavities can be avoided, while cold-lap and centerline defect likely form. With

SYSWELD softvera. Rezutati ovog istraživanja će se koristiti kao osnova za budući razvoj programa za unapređenje spajanja čelika za šine, kao što je projektovanje i izbor procesa zavarivanja i materijala koji se koriste u železničkim konstrukcijama, posebno za postojeće kvalitete i procedure zavarivanja čelika za šine koje bi morale da se razvijaju za postojeće uslove opterećenja.

1. Uvod

Aluminotermisko zavarivanje (Termit), je process zavarivanja široko primenjivan pri izgradnji i popravci čelika za železnice, zbog njegove mobilnosti i ne zahtevanja izvore električne energije. Za vreme termit zavarivanja, dve šine se spajaju ekzotermnom reakcijom koja se zove aluminotermijska reakcija između metalnog oksida i aluminijuma u termit prahu. Tako nastao tečni metal ističe u kalup i međuprostor između dve šine i zavaruje ih. Važno je da se obezbedi dovoljno predgrevanja u oblasti od 800^{o}C do 1 000^{o}C da bi se izbegla velika brzina hlađenja koja daje tvrde i krte mikrostrukture u metalu šava i zoni uticaja toplote [1-2]. Da bi se izvršilo zavarivanje neophodno je dodatno predgrevanje da bi se uklonio višak vlage i štetni sastojci iz okruženja. Takođe je vrlo važno da se pravilno odredi trajanje predgrevanja, temperature predgrevanja, likvidus temperatura i veličina zazora između šina, da bi se izbegle šupljine usled skupljanja, nalepi i centralne greške za vreme zavarivanja čelika za železnice [3].

Myers i dr. [1] su ispitivali mikrostrukturu i osobine aluminutermisko zavarivanih šina sledećeg hemiskog sastava: 0.75-0.76C, 0.80-0.93Mn, 0.17-0.74Si (zapr. %). Oni su našli da je naviša tvrdoća u zoni uticaja toplote (ZUT) u oblastima uz metal šava, dok je skoro uvek najniža tvrdoća na spoljnjoj starani ZUTa, u delimično sferoidizovanoj perlitnoj mikrostrukturi. Takođe, vreme predgrevanja značajno utiče na širinu oblasti ZUTa u zavarenom spoju. Wang i dr. [2] ispitivali su mehaničke osobine i udarnu žilavost aluminutermisko zavarivarenih čelika za šine sledećeg hemiskog sastava: 0.72C, 1.21Mn, 0.22Si and 0.77C, 0.95Mn, 0.62Si (zapr.%) na niskim temperaturama. Chen, i dr. [3] su ispitivali stvaranje zavarivačkih grešaka i raspodelu mikroporoznosti. Oni su pokazali da pri postojećoj praksi pri aluminutermiskom zavarivanju, šupljine usled skupljanja se mogu izbeći, dok se hladni nalepi i centralne greške teško izbegavaju. Sa produženjem vremena predgrevanja, povišenjem temperature tečnog metala i veličinom zazora, ove greške se mogu smanjiti. Za razliku od increasing of preheat time, liquid temperature and weld gap size, these two defects can be reduced. Unlike other defects, microporosity cannot be eliminated during thermite welding.

In terms of modeling and simulation of thermite welding of rail steel, only one paper was found. Chen, et al. [4] performed thermal modeling of rail thermite welding using FIDAP, which is a finite-element package available in Fluent. They also mentioned the difficulty of including all physical phenomena involved in thermite welding in one model and they only performed the heat conduction model which is the dominant heat transfer that influences the temperature evolution during thermite welding. In their work, temperature evolution, width of weld metal, and width of HAZ regions were calculated for different welding conditions. Based on their summary, weld gap size was reported to be the most significant factor in determining thermal condition in thermite welding. Other related modeling works include simulation of pearlite formation during flash-butt welding of R350HT rail steel with composition 0.72-0.80C, 0.70-1.20Mn, 0.15-0.58Si (wt.%) by Weingrill, et al. [5]. They used interlamellar spacing as main parameter to obtain mechanical properties of pearlitic rail steel such as strength, hardness, and wear-resistance. Their thermo-metallurgical numerical simulation utilizes MATLAB routines in combination with SYSWELD. First, they obtained a TTT-diagram of R350HT rail steel from JMatPro based on the chemical composition and austenitization condition. Next, the CCT diagram was obtained using dilatometry experiment. During their flashbutt welding experiments, thermocouples were attached in the HAZ at the rail head at different distances from the weld centerline. The Johnson-Mehl-Avrami-Kolmogorov (JMAK) and Koistinen-Marburger kinetics models for non-isothermal diffusion-controlled transformation were performed on MATLAB. Finally, all determined parameters were input into SYSWELD metallurgical database to perform thermometallurgical simulation of flash-butt welding of R350HT rail steel [5]. In their subsequent work of multi-layer GMAW of R350HT rail steel [6], they also used SYSWELD to perform a 3D multilayer thermo-metallurgical simulation using SYSWELD to calculate temperature evolution as well as phase transformation in the HAZ of multi-layer GMAW welds. They also simplify their model to reduce the model complexity and simulation time by using a symmetry model in the y-z plane along the centerline of the weld path to lower the element numbers. In addition, they also neglect the motion

drugih grešaka, mikroporoznost se ne može izbeći za vreme aluminutermiskog zavarivanja.

Iz oblasti modeliranja i simulacije aluminutermiskog zavarivanja čelika za šine, pronađen je samo jedan rad. Chen, i dr. [4] su izvršili termičko modeliranje primenom FIDAP programa, koji predstavlja proračunski paket zasnovan na metodi konačnih elemenata, koji je u okviru programskog paketa Fluent. Oni su takođe napomenuli da je problem uključivanje svih fizičkih fenomena koji se javljaju kod aluminutermiskog zavarivanja čelika za šine u jedan model i oni su primenili samo model provođenja toplote koji je dominantan pri prenosu toplote i koji utiče na formiranje temperatura tokom aluminutermiskog zavarivanja. U njihovom radu, raspodela temperature, širina metala šava i širina oblasti ZUTa su izračunavani za razlčite uslove zavarivanja. Na osnovu njihovih zaključaka, navedeno je da je veličina zazora najznačajniji faktor pri određivanju termičkih uslova pri aluminutermiskom zavarivanju. Drugi slični radovi uključuju simulaciju formiranja perlita pri sučeonom elektrootpornom zavarivanju čelika za šine R350HT, sa sledećim hemijskim sastavom: 0.72-0.80C, 0.70-1.20Mn, 0.15-0.58Si (zapr. %), što je prikazano u radu Weingrill i dr. [5]. Oni su koristili međulamelarno rastojanje kao glavni parameter za dobijanje mehaničkih osobina perlitnog čelika za šine, kao što su čvrstoća, tvrdoća i otpornost na habanje. Njihova termo – metalurška numerička simulacija koristi MATLAB rute u kombinaciji sa programom SYSWELD. Prvi korak je dobijanje IR dijagrama za čelika za šine R350HT uz pomoć programa JMatPro zasnovano na hemijskom sastavu i uslovima austenitizacije. Sledeće je izrada KH dijagrama primenom dilatometrijskih ispitivanja. Za vreme eksperimenata sučeonog zavarivanja, termoparovi su postavljeni u ZUTu, glave šine na različitim rastojanjima od centralne linije zavarenog spoja. Kinetički modeli Johnson-Mehl-Avrami-Kolmogorov (JMAK) i Koistinen-Marburger model za ne - izotermalnu difuzijom kontrolisanu transformaciju, su primenjeni u programu MATLAB. Konačno, tako određeni parametri su unešeni u SYSWELD metaluršku bazu podataka da bi se izvršila termo – metalurška simulacija sučeonog zavarivanja čelika za šine R350HT [5]. U njihovom daljem radu na višeprolaznom zavarivanju čelika za šine R350HT postupkom MAG [6], gde je takođe primenjen program SYSWELD da bi se izvršila 3D simulacija termmičkih i metalurških procesa radi dobijanja temperaturne istorije, kao i faznih transformacija u ZUTu višeprolaznog MAG zavarenog spoja. Oni su of welding torch as well as using the simplified spherical shape of Goldak heat source (16 mm width and length, power ratio of 1.0 and length ratio of 0.9) as compared to the actual pulsed mode GMAW process.

Regarding the modeling of mechanical property of rail steel, Boonsukachote, et al. [7] performed mechanical property modeling of pearlitic rail steel of composition 0.747C, 0.782Mn, 0.298Si (wt.%). Their experimental tasks involves the tensile test, charpy impact test, and metallurgical analysis. Next, they used the microstructure based RVE models to evaluate the effects of each single phase on the mechanical property, i.e. performance of rail steel. Different amount of bainite were predicted using their 3D RVE simulations and the relationships between strength (yield strength and tensile strength) and bainite volume fraction were obtained.

In this research, SYSWELD software [8] is used to perform thermal-mechanical-metallurgical simulation during thermite welding of rail steel. This article mainly discusses the research methodology that will be used to formulate the prediction of the microstructure evolution in the heataffected zone regions of thermite welding of railway steel. It is noted that the aim of this research work is to simulate and evaluate how preheat, heat generation during chemical reaction of thermite welding and possible post-weld heat treatment affect the microstructure evolution as well as the mechanical property of thermite welded railway steel. The output and the outcome of this research will be used as the baseline for future development of structural integrity program for improving the welding procedure of railway steel including the design and selection of welding processes and materials involved for repair and maintenance of railway steel tracks, which undergo several loading conditions. The following sections discuss the preliminary experimental studies and how it will be used to perform SYSWELD simulation, which will be the focus of our on-going research.

pojednostavili model da bi smanjili kompleksnost modela i vreme simulacije, primenom simetrije modela prema y-z ravni duž centralne linije spoja, čime je smanjen broj elemenata za koje se vrši proračun. Takođe je zanemareno kretanje gorionika primenom pojednostavljenog sferičnog oblika za opis izvora toplote prema modelu Goldaka (16mm širine i dužine, odnos snage 1.0 i dužina 0.9) u poređenju sa aktuelnim pulsirajućim MAG procesom.

Što se tiče modeliranja mehaničkih osobina čelika za šine Boonsukachote i dr. [7] su izvršili modeliranje mehaničkih osobina perlitnih čelika za šine sledećeg hemijskog sastava: 0.747C, 0.782Mn, 0.298Si (zapr.%). Njihovo eksperimentalno istraživanje obuhvatalo je ispitivanje zatezanjem, ispitivanje energije udara po Šarpiju i metaluršku analizu. Zatim su primenili mikrostrukturne RVE modele, da bi ispitali efekte svake pojedinačne faze na mehaničke osobine čelika za šine. Različiti udeli beinita su predpostavljeni u njihovoj 3D RVE simulaciji i dobijena je zavisnost između čvrstoće (granice razvlačenja i zatezne čvrstoće) i zapreminskog udela beinita.

U ovom radu SYSWELD softver [8] je primenjen da bi se izvršila termičko – mehanička – metalurška simulacija procesa aluminutermiskog zavarivanja čelika za šine. U ovom radu se najviše razmatra istraživačka metodologija koja će biti primenjena da bi se predvidelo nastajanje mikrostruktura u oblastima zone pod uticajem toplote pri aluminutermiskom zavarivanju čelika za šine. Istaknuto je da je cilj ovog istraživačkog rada simulacija i procena kako predgrevanje, generisanje toplote za vreme hemijske reakcije aluminutermiskog zavarivanja i moguća termička obrada posle zavarivanja, utiču na mikrostrukturu i mehaničke osobine aluminutermiski zavarenog spoja čelika za šine. Dobijeni rezultati ovog istraživanja će biti korišćeni kao osnova za budući razvoj programa integriteta konstrukcija za unapređenje procedura zavarivanja čelika za šine, uključujući projektovanje i izbor procesa zavarivanja i materijala koji se koriste za popravku i održavanje železničkih pruga, koje podnose različite uslove opterećenja. Naredna poglavlja razmatraju preliminarna eksperimentalna istraživanja i način kako mogu da se primene u SYSWELD simulacijama, što će biti focus tekućih istraživanja.

2. Experimental works

Rail steel grade R260 (0.62-0.80C, 0.70-1.20Mn, 0.15- 0.58Si, wt.%) was used in the current phase of the study. Thermite welding of R260 rail steels was performed at the Rail Welding Section, Production and Repair Center, Civil Engineering Department, State Railway of Thailand as showed in Fig. 1. The experimental procedures were explained in our previous works [9-10]. In our former works the effect of preheat and cooling rate during thermite welding were investigated. Our results reported that thermite welding of rail steel grade R260 with slower cooling rate would result in slightly softer pearlite, i.e. coarser pearlite in the heat affected zone region in the rail head section [9]. In addition, the soundness and quality of the weld were tested using slow-bend test and ultrasonic testing. The results showed improved performance and lower weld defects when higher preheat was performed during thermite welding.

Next, the microstructure evoluation at different cooling rate was performed using Jominy End Quench Test method on rail steels of two different grades [11]. It was later proved using the mass spectroscopy technique to analyze the chemical composition of one of the two steel to be in the specification of R260 steel and another with lower carbon and manganese contents which results in softer and haas less hardness. The chemical composition of R260 steel used in this work was found to be 0.725-0.735C, 1.195-1.231Mn, and 0.238-0.253Si, wt.%. Fig. 2 displays the hardenability curves of rail steel grade R260 for data No. 1 and data No. 2, which were heat treated at different temperatures before quenching. It was found that austenitizing temperature at higher temperature of 950oC for 1 hour resulted in lower

2. Eksperimentalni rad

Čelik za šine kvaliteta R260 (0.62-0.80C, 0.70-1.20Mn, 0.15-0.58Si, zapr.%) je primenjen u ovoj fazi ispitivanja. Aluminotermisko zavarivanje čelika za šine kvaliteta R260 je izvršeno u Rail Welding Section, Production and Repair Center, Civil Engineering Department, State Railway of Thailand, kao što je prikazano na Slici 1. Eksperimentalna procedura je prikazana u našim prethodnim radovima [9-10]. U prethodnim radovima ispitivan je efekat predgrevanja i brzine hlađenja za vreme aluminutermiskog zavarivanja. Dobijeni rezultati pokazuju da aluminutermisko zavarivanje čelika za šine kvaliteta R260 sa nižim brzinama hlađenja rezultuju stvaranjem mekšeg perlita, na primer grubog perlita u oblasti zone uticaja toplote u delu glave šine [9]. Zatim je vršeno ispitivanje homogenosti i kvaliteta zavarenog spoja primenom ispitivanja sporim savijanjem i ispitivanje ultrazvukom. Rezultati su pokazali poboljšane osobine i manje zavarivačkih grešaka kada je primenjeno predgervanje na višim temperaturama pri aluminutermiskom zavarivanju.

Ocena mikrostruktura pri različitim brzinama hlađenja je vršena primenom Jomini proba na čeliku za šine na dva kvaliteta [11]. Kasnije je dokazano primenom tehnike masene spektroskopije za analizu hemijskog sastava, da je jedan od dva čelika po specifikaciji čelik R260, a drugi sa nižim sadržajem ugljenika i mangana koji je mekši i pokazivao je nižu tvrdoću. Hemijski sastav čelika R260 koji je korišćen u ovom istraživanju je bio: 0.725-0.735C, 1.195-1.231Mn i 0.238-0.253Si (zapr.%). Slika 2 prikazuje krive otvrdnjavanja čelika za šine R260 za podatke Br. 1 i Br. 2. koji su termički obrađeni na različitim temperaturama pre kaljenja. Nađeno je da temperatura austenitizacije na višoj temperature od 950^0C za 1 sat rezultuje nižom tvrdoćom u

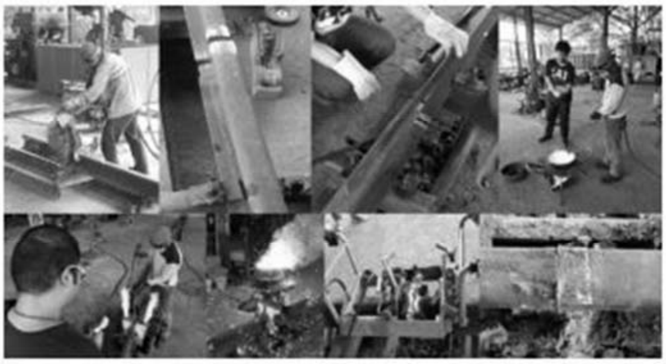

Figure 1. *Thermite welding of rail steels*

Slika 1. *Aluminotermisko zavarivanje (Termit) čelika za šine* hardness as compared to austenitizing temperature at lower temperature of 850oC for 1 hour.

Next, the rail steel grade R260 specimens were sectioned at different hardness to obtain their representative microstrucutre evolutions at different cooling rates from Jominy End Quench tests performed. The microstructure at 1000X magnification obtained from opical microscope is provided in Fig. 3 below. It can be seen that the microstructure that corresponds to high hardness of 59-60 HRC is mainly consists of martensite phase. At hardness levels of 53-56 HRC, the microstructure is mixture of martensite, bainite and pearlite phases. For hardness levels at 37-42 HRC, microstructure is a little difficult to distinguish and is possibly mixture of martensite, bainite, and pearlite. At further distance, the hardness levels of 31-33 HRC display mainly pearlite structures. In order to validate this further, similar approach to Weingrill, et al. [5-6] is necessary to obtain TTT and CCT diagrams for R260 rail steel. Our plan is to use Electron Backscatter Diffraction (EBSD) to quantify the phase fractions, size, and volume fraction of martensite, bainite, and pearlite in different regions of rail steels subjected to different heating and cooling conditions. It is important to obtain microstructure characterization of representative thermite welding experimentally similar to those already obtained from Jominy End Quench test in order to validate the SYSWELD simulation of thermite welding of R260 rail steels.

poređenju sa temperaturom austenitizacije na nižoj temperaturi od 850^{0}C za 1 sat.

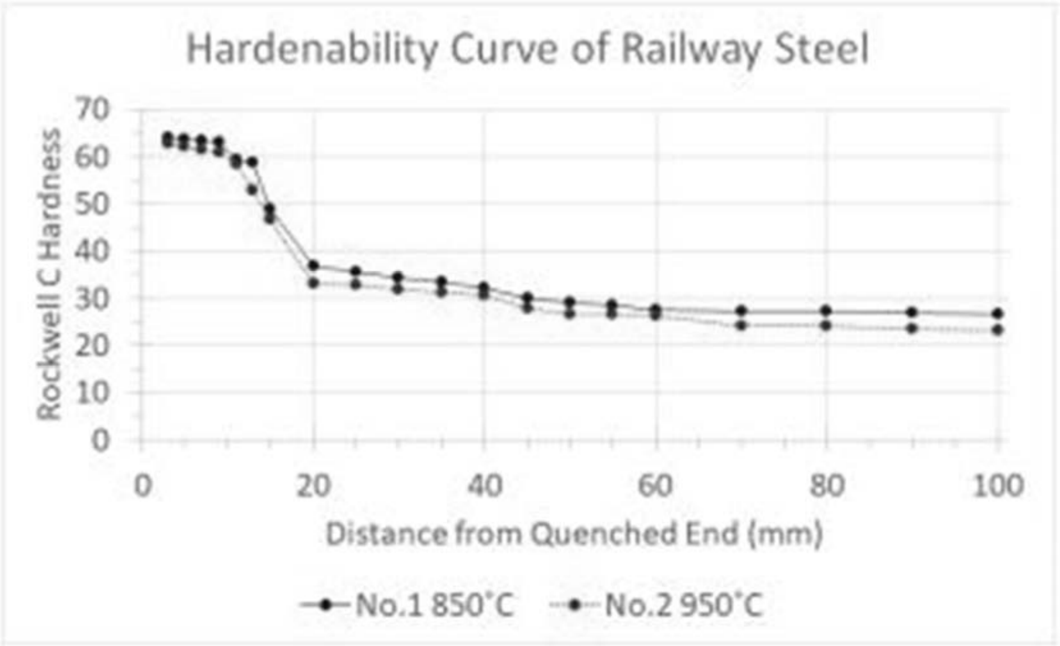

Figure 2. *Hardenability curves of railway steels*

Slika 2. *Krive otvrdnjavanja čelika za šine*

Uzorci čelika za šine kvaliteta R260 su isecani na mestima različitih tvrdoća, da bi se dobile reprezentativne mikrostrukture pri različitim brzinama hlađenja sa Jomini testa. Mikrostrukture pri uvećanju od 1000 puta dobijene na svetlosnom mikroskopu prikazane su na Slici 3. Može se videti da na uzorcima sa tvrdoćom koja odgovara visokoj tvrdoći od 59-60 HRC, mikrostruktura se uglavnom sastoji od martenzitne faze. Pri tvrdoćama od 53-56 HRC, mikrostruktura je mešavina martenzitne, beinitne i perlitne faze. Za nivoe tvrdoća od 37-42 HRC, teško je izdvojiti pojedine faze, pa je verovatno mikrostruktura mešavina martenzita, beinita i perlita. Na većim rastojanjima od centralne linije spoja, gde je nivo tvrdoće 31-33 HRC, javlja se uglavnom perlitna struktura. Da bi ovo potvrdili, primenjen je sličan pristup kao u radu Weingrill, i dr. [5-6], pa je bilo neophodno da se dobiju IR i KH dijagrami za čelik za šine R260. Naš plan je da se primeni elektronska povratna difrakcija - Electron Backscatter Diffraction (EBSD), da bi se kvantifikovali udeli faza, veličina i zapreminski udeli martenzita, beinita i perlita u različitim oblastima čelika za šine, koji su podvrgnuti različitim uslovima zagrevanja i hlađenja. Važno je dobiti karakteristične mikrostrukture dobijene eksperimentalno pri aluminotermijskom zavarivanju, slične onim koje su dobijene Jomini testom, a da bi se potvrdila simulacija aluminotermijskog zavarivanja čelika za šine R260.

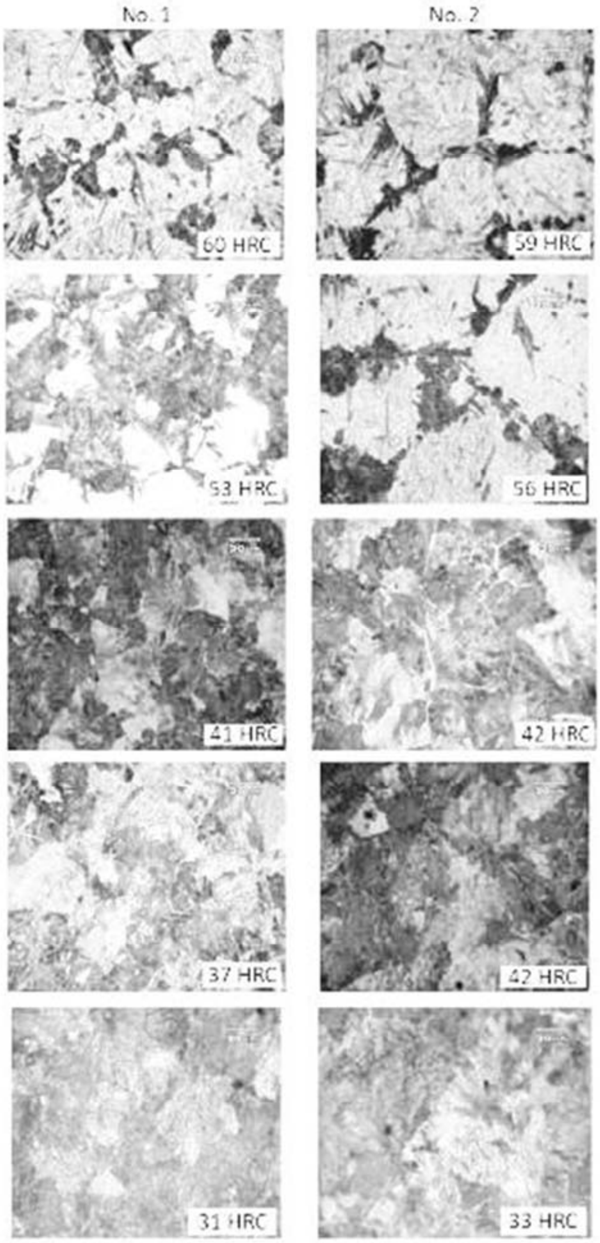

Figure 3. *Microstructure of R260 rail steel at different cooling rates*

Slika 3. *Mikrostrukture čelika za šine R260 pri različitim brzinama hlađenja*

3. Simulation works

The effects of cooling rate during thermite welding was simulated using SYSWELD software. Fig. 4 displays calculation example from ESI Group's SYSWELD software [8] on the application of heat treatment analysis during Jominy End Quench Test of Steels. In our work, we will start with validating the simulation with experimental Jominy End Quench Test results discussed in previous section. After that, the thermite welding simulation will be performed using simplified symmetry along the centerline to calculate both the temperature evolution with different liquid or molten temperature, which will be used to determine the

3. Simulacija procesa

Efekti brzina hlađenja za vreme aluminotermijskog zavarivanja su simulirani primenom SYSWELD softvera. Na Slici 4 prikazan je primer proračuna SYSWELD softverom ESI Grupe [8], primenjenom na analizi termičke obrade za vreme Jomini testa. U ovom radu započeto je sa potvrdom simulacije sa ekperimentalnim rezultatima Jomini testa, što je diskutovano u prethodnom odeljku. Nakon toga simulacija aluminotermijskog zavarivanja će biti vršena primenom pojednostavljene simetrije duž centralne linije spoja, da bi se proračunale temperature na obe strane sa različitim temperaturama tečne i microstructure and hardness in the heat affected zone of thermite welded R260 railway steel. It is noted that the simulation work is not included in this article and will be explained in our future work.

rastopljene faze i koje će biti iskorišćene za određivanje mikrostruktura i tvrdoća u zoni uticaja toplote aluminotermijsko zavarivarenog čelika za šine R260. Naglašeno je da rad na simulaciji procesa nije prikazan u ovom radu i da će biti izložen u našem budućem radu.

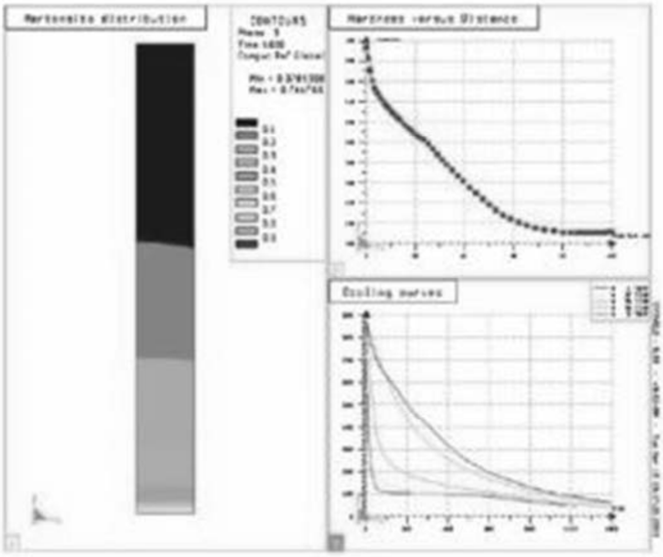

Figure 4. *Example of SYSWELD calculation of Jominy End Quench Test [8]*

Slika 4. *Primer SYSWELD proračuna Jomini testa zakaljivanja [8]*

4. Summary

This paper discusses the experimental and simulation study of thermite welding of R260 rail steel. The effect of preheat temperature and cooling rate has already been performed experimentally and discussed in this paper. The simulation work using SYSWELD is explained in the literature review and how it will be utilized to simulate the thermite welding of rail steel. To validate the simulation, Jominy End Quench Test was used to quantify the cooling rate and microstructure evolution in R260 steel. Further details on the models will be available in future publication.

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4. Zaključak

Ovaj rad razmatra eksperimentalno istraživanje i simulaciju aluminotermijskog zavarivanja čelika za šine R260. Efekti temperature predgrevanja i brzine hlađenja su praćeni eksperimentalno i diskutovani su u radu. Simulacija primenom programa SYSWELD je objašnjena u pregledu literature, kao i način kako će on biti iskorišćen za simulaciju aluminotermijskog zavarivanja čelika za šine. Za potvrdu simulacije primenjen je Jomini test prokaljivanja, da bi se kvantifikovale brzine hlađenja i mikrostrukture koje se formiraju kod čelika R260. Više detalja modela će biti prikazani u budućim publikacijama.

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