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GMA root welding of pearlitic rails using magnetic arc deflection

GMA zavarivanje korena perlitnih šina korišćenjem skretanja magnetnog luka

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Abstract

In this work optimization research for automated GMA root welds of pearlitic rails of grade R260 is presented. The important novelty of the used approach consisted of weld arc deflection via an externally applied magnetic field to increase the lateral penetration at the root of a narrow gap weld. During welding tests in laboratory an optimization of parameters was carried out, which comprised: the welding current, voltage and speed, filler wire diameter, and the strength of the external magnetic field. Results were evaluated through geometrical aspects of the weld, such as the maximum achievable lateral and diagonal root penetration, the microstructure and the hardness were evaluated. Additionally, the behaviour of the process under the influence of the external magnetic field was studied using a high-speed camera. The beneficial influence of the external magnetic field could be illustrated. It was found that best results can be obtained in high welding current spray arc mode (380-400A) with the 1,6mm wire at high welding speed (65cm/min). A high and constant magnetic flux density close to the weld arc of at least 30mT and increased welding voltage (30-31V) for a longer weld arc was found to be beneficial. Applying this approach, it was possible to weld the root layer of the used pearlitic rail foot samples with a continuously penetrated root. A smooth transition at the lower edges could be achieved. The resulting microstructure inside the heat affected zone was fully pearlitic and in comparison to the currently predominant aluminothermic (AT) rail welding, as a result of lower heat input, of finer morphology. Thus hardness drops at the transition from HAZ to BM could be avoided. Furthermore, the size of the HAZ was reduced by more than 75% in comparison to an AT rail weld.

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Rezime

U ovom radu prikazano je optimizaciono istraživanje za automatske GMA (elektrolučno u zaštiti gasa) zavarivanja korena perlitnih šina klase R260. Važna novina korišćenog pristupa sastoji se u skretanju luka zavarivačkog preko spoljašnjeg magnetnog polja radi povećanja bočnog uvarivanja u korenu uskog žljeba. Tokom testova zavarivanja u laboratoriji izvršena je optimizacija parametara, koja je obuhvatila: struju zavarivanja, napon i brzinu, prečnik žice kao dodatnog materijala i jačinu spoljašnjeg magnetnog polja. Rezultati su procenjivani kroz geometrijske aspekte šava, kao što su maksimalno ostvarivo bočno i dijagonalno uvarivanje korena, mikrostruktura i tvrdoća. Pored toga, proučavane su pojave tokom procesa pod uticajem spoljašnjeg magnetnog polja pomoću kamere velike brzine. Može se ilustrovati povoljan uticaj spoljašnjeg magnetnog polja. Utvrđeno je da se najbolji rezultati mogu postići u režimu strujnog luka (380-400A) sa visokom strujom zavarivanja sa 1,6mm žicom pri velikoj brzini zavarivanja (65c/min). Utvrđeno je da je korisna visoka i konstantna gustina magnetnog fluksa u blizini luka zavarivanja od najmanje 30mT i povećanog napona zavarivanja (30-31V) za duži luk zavarivanja. Primenom ovog pristupa moguće je zavariti koreni prolaz korišćenih perlitnih šina sa kontinuirano uvarenim korenom. Može se postići glatki prelaz na donjim ivicama . Dobijena mikrostruktura unutar zone pod uticajem toplote bila je potpuno perlitna i u poređenju sa trenutno preovladavajućim aluminotermijskim (AT) zavarivanjem šina, kao rezultat manjeg unosa toplote, finije morfologije. Tako se može izbeći pad tvrdoće na prelazu iz ZUT u OM. Šta više, veličina ZUT je smanjena za više od 75% u odnosu na AT šav na šinama.

1. Introduction

Continuously welded rail strings have become common worldwide in order to meet increased demands in safety, travelling comfort as well as to increase the lifetime of the rails and undercarriage through reduced dynamic loading and thus reduced wear and rolling contact fatigue. Welds still represent weak spots of the rail lines due to softening of the base material inside the HAZ. Furthermore, even complete failures of the rail at welds is encountered statistically reproducible more often due to weld defects [1]–[4]. In general, the weldability of the most commonly used pearlitic rails is very limited. One of the main reasons for that is these rail steels' very high carbon-content (0,8% and above). The second one is that welding in the track in remote location offers little to no infrastructure and can bear harsh environment conditions. Aluminothermic (AT) welding is for almost 120 years the preferred process for joining rails in the track accounting for about 3 Mio welds per year worldwide [5]. Due to its very small demand in equipment and thus very good practicability in remote places of little to no infrastructure and also harsh environmental conditions it still represents the state of the art for rail welding on track. Therein especially the relatively big tolerance allowance for the width of the weld gap play an important role. Furthermore, there are practically no investment costs involved, especially when compared to flash butt welding. Some disadvantages remain: A manual process depends on the welder's skills and thus always brings an uncertainty factor in quality. Reduced toughness of the weld is more likely because of the casting microstructure. Furthermore, there is an unavoidable hardness drop at the outer limits of the heat affected zone (HAZ)[6]–[8], as a result of the process' high heat input.

Gas metal arc (GMA) welding is presumably a very good alternative process to overcome the mentioned disadvantages of AT-welding. First of all, the welding parameters (including the filler material) can be adapted layer by layer. Thus the mechanical properties of the joint can be adjusted to the locally most suitable needs, such as high strength and ductility for improved fatigue strength at the root of the joint, high hardness and wear resistance at the head of the rail. If used properly many possible influencing parameters of GMAW can be used to optimize the process. Furthermore, GMA welding can be very well automatized, thus the welding results are more reliable. Still, some welding technological challenges have to be overcome in order to implement a new process for

1. Uvod

Kontinuirano zavarene trake za šine postale su uobičajene u svetu kako bi se zadovoljili povećani zahtevi u pogledu sigurnosti, udobnosti putovanja i povećanja životnog veka šina i donjeg postroja kroz smanjeno dinamičko opterećenje a time smanjeno trošenje i zamor kontaktnog kotrljanja. Zavareni spojevi i dalje predstavljaju slabe tačke pruga zbog omekšavanja osnovnog materijala unutar ZUT-a. Šta više, čak i potpuni lomovi šine na zavarenim spojevima se češće susreću a statistički se pojavljuju zbog defekata u šavu [1] - [4]. U principu, zavarljivost najčešće korišćenih perlitnih šina je veoma ograničena. Jedan od glavnih razloga za to, je veoma visok sadržaj ugljenika u železničkim čelicima (0,8% i više). Drugi je da zavarivanje na stazi u udaljenim lokacijama nudi malo ili nimalo infrastrukture i može podneti teške uslove okoline. Aluminotermijsko (AT) zavarivanje je skoro 120 godina poželjan proces spajanja šina na stazi sa oko 3 miliona zavarenih spojeva godišnje širom sveta [5]. Zbog svoje veoma male potražnje u opremi i samim tim veoma dobre praktičnosti u udaljenim mestima sa malo ili nimalo infrastrukture i oštrim uslovima okruženja i dalje predstavlja stanje tehnike za zavarivanje na železnici. Posebno važnu ulogu ima relativno velika tolerancija širine zazora. Štaviše, praktično nema troškova ulaganja, posebno u poređenju sa elektrootporskim zavarivanjem varničenjemr Neki nedostaci ostaju: Ručni proces zavisi od veština zavarivača i stoga uvek donosi faktor neizvesnosti u kvalitetu. Smanjena žilavost šava je verovatnija zbog mikrostrukture livenja. Osim toga, postoji neizbežan pad tvrdoće na spoljašnjim granicama zone pod uticajem toplote (HAZ) [6] - [8], kao rezultat visokog unosa toplote u procesu. Zavarivanje električnim lukom u zaštiti gasa (GMA) je verovatno veoma dobar alternativni proces za prevazilaženje pomenutih nedostataka AT-zavarivanja. Prvo, parametri zavarivanja (uključujući dodatni materijal) mogu se prilagoditi sloj po sloj. Tako se mehanička svojstva spoja mogu prilagoditi lokalno najpogodnijim potrebama, kao što su visoka čvrstoća i duktilnost za poboljšanu čvrstoću na zamor u korenu spoja, visoka tvrdoća i otpornost na habanje na glavi šine Ako se pravilno koriste mnogi mogući parametri koji utiču na GMAW mogu se koristiti za optimizaciju procesa. Osim toga, GMA zavarivanje se može veoma dobro automatizovati, tako da su rezultati zavarivanja pouzdaniji. Ipak, neki tehnološki izazovi za zavarivanje moraju biti prevaziđeni kako bi se implementirao novi proces zavarivanja na železnici.

rail welding. One of them is to achieve a proper geometry of the weld. This aspect is most important but due to very restricted accessibility also most difficult to achieve at the root layers. In order to obtain lateral penetration arc manipulation is necessary. Out of this background the aim of this work is defined: The root geometry for a GMA weld of pearlitic rail should be improved by applying a – to this domain - new approach. The objective is to experimentally realize a proof of concept through laboratory test welds. The focus is set to the root welding only.

2. Approach to solution

The chosen approach consists on the one side of a two pass per layer weld sequence with a detailed parameter optimization for each of the passes individually. On the other side it consists of the manipulation of the electromagnetic forces of the weld arc and also the electric current carrying droplets in transfer and melt pool by an external magnetic field. As a result, the arc and weld are laterally deflected and thus the lateral penetration improved for each section of the weld. Compared to alternative deflection methods of the weld arc by mechanically bending the tip of the filler wire this approach bears two major advantages: First, the magnetic unit is principally very simple and robust. This keeps investment costs down, no additional mechanical parts are necessary which can wear and could become faulty during intensive use. Second, through controlling the current in the magnetic coils in magnitude and direction, also the external magnetic field can be altered during the welding process and thus the weld arc can be adjusted in-situ to one's needs.

3. Experimental procedures

The used setup for the welding experiments is schematically depicted in Fig. 1. A Fronius TPS 4000 CMT® welding device and water cooled GMAW narrow gap welding torch were used. The torch was mounted in neutral position on a stationary stand together with horizontal, but slightly sidewise tilted magnetic yoke. The legs of the magnetic yoke were aligned parallel to the welding direction to create the intended parallel magnetic field and thus the lateral deflection of the weld arc. The tips of the legs were positioned symmetrically and closest possible to the tip of the filler wire.

Jedna od njih je da se postigne pravilna geometrija šava. Ovaj aspekt je najvažniji, ali je zbog veoma ograničene pristupačnosti i najteže postići na korenim slojevima. Da bi se dobilo bočno uvarivanje neophodna je manipulacija lukom.

Iz ove pozadine je definisan cilj ovog rada: geometrija korena za GMA zavarivanje perlitne šine treba da se poboljša primenom novog pristupa. Cilj je eksperimentalno ostvariti dokaz koncepta kroz laboratorijske testove zavarenih spojeva. Fokus je podešen samo na zavarivanje korena.

2. Pristup rešenju

Odabrani pristup sastoji se na jednoj strani od dva prolaza po jednom sloju zavarivanja sa detaljnom optimizacijom parametara za svaki od pojedinačnih prolaza. S druge strane, on se sastoji od manipulacije elektromagnetskih sila zavarivačkog luka, kao i od kapljica koje u spoljašnjem magnetnom polju nose kapljice pri prenosu i rastopljenoj kupki. Kao rezultat, luk i šav su bočno pomereni i na taj način je bočno uvarivanje poboljšano za svaki deo šava. U poređenju sa alternativnim metodama skretanja luka zavarivanja mehaničkim savijanjem vrha žice, ovaj pristup ima dve glavne prednosti: prvo, magnetna jedinica je uglavnom jednostavna i robusna. Time se smanjuju investicioni troškovi, ne zahtevaju se dodatni mehanički delovi koji se mogu nositi i mogu postati neispravni tokom intenzivne upotrebe. Drugo, kontrolisanjem struje u magnetnim kalemima po magnitudi i smeru, kao i spoljašnje magnetno polje koje se može menjati tokom zavarivanja i tako se luk može podesiti na licu mesta, prema potrebama.

3. Eksperimentalni postupci

Korišćena postavka za eksperimente zavarivanja shematski je prikazana na slici 1. Korišćeni su Fronius TPS 4000 CMT® uređaj za zavarivanje i vodeno hlađeni GMAW gorionik za zavarivanje. Gorionik je montiran u neutralnom položaju na stacionarnom postolju zajedno sa horizontalnim, ali blago bočnim nagibom magnetnog jarma. Noge magnetnog jarma su poredane paralelno sa pravcem zavarivanja da bi se stvorilo predviđeno paralelno magnetno polje, a time i bočno otklanjanje luka zavarivanja. Vrhovi nogu su postavljeni simetrično i najbliže moguće vrhu žice za zavarivanje.

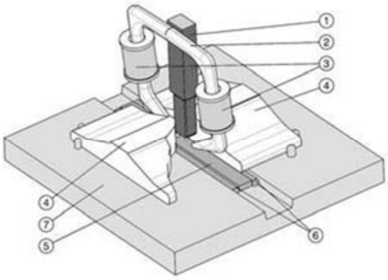

Fig. 1. *Schematic of experimental setup. 1… welding torch 2… magnetic yoke 3… coils 4… rail foot samples 5… steel strip for weld pool backing 6… ceramic tube for backing laterally penetrating weld metal 7… support plate.*
Slika 1. *Shema eksperimentalne postavke. 1… gorionik za zavarivanje 2… magnetni jaram 3… zavojnice 4… uzorci stopala šine 5… čelična traka za podlošku kupki 6… keramička cev za podlošku bočno uvarivanje metala šava 7… noseća ploča.*

The magnetic field was introduced with the help of two coils of 500 windings, which were clamped to the upper part of each of the two legs of the yoke. Electric current to the windings was supplied by a separate laboratory power unit (not depicted in Fig. 1) with adjustable DC-voltage and current. The weld sample were made of R260 60E1 rails. The nominal chemical composition of this steel is given in Table 1.

Magnetno polje je uvedeno uz pomoć dve zavojnice od 500 namotaja, koji su bili pričvršćeni za gornji deo svake od dve noge jarma. Električna struja do namotaja je snabdevena odvojenim laboratorijskim izvorom snage (koja nije prikazana na slici 1) sa podesivim DC-naponom i strujom. Uzorak zavarenog spoja je izrađen od R260 60E1 šina. Nominalni hemijski sastav ovog čelika dat je u tabeli 1.

Main alloying elements weight -%					
C	Si	Mn	P max.	S max.	Cr
0,62-0,80	0,15 -0,58	0,70-1,20	0,025	0,025	≤0,15

Table 1. *Nominal chemical composition of used rail steel according to [9]*
Tabela 1. *Nominalni hemijski sastav korišćenog čelika za šine prema [9]*

The weld flanks were vertical straight in as sawed condition with no specific preparation. To guarantee reproducible positioning, the weld samples were clamped on a dedicated support plate with alignment pins on each side. Clamping was done with standard knee levers. In order to fit the weld pool backing a clearance was milled into the support plate. A 16mm wide steel strip of S355 structural steel was placed at the bottom side of the 16mm wide weld gap to support the weld pool. Its top surface was evenly levelled to the bottom surface of the rail foot samples, so that the edges of strip and samples touched in one line one each side. The strips thickness was varied throughout the experiments from initially 1,5mm to finally 6mm. The strip was fixed to the samples with two manual TIG tack welds on the bottom surface on each side. Furthermore, on both sides of the weld gap at the bottom edges ceramic tubes were pressed into the remaining gap between steel strip, samples and support plate, in order to back the penetrating weld metal there.

Šavovi za zavarivanje su bili vertikalnog pravca u uslovima testerisanja bez specifične pripreme. Da bi se garantovala reproduktivna pozicioniranost, uzorci zavarenih spojeva su bili pričvršćeni na namenskoj nosećoj ploči, čivijama za poravnavanje na svakoj strani. Stezanje je izvršeno standardnim polugama. Da bi se podloška zavarivačke kupke uklopila u zaštitnu ploču, zazor je izbrušen u nosećoj ploči. Čelična traka širine 16 mm od konstrukcionog čelika S355 postavljena je na donju stranu zazora širine 16 mm kako bi se osigurala zavarivačka kupka. Njena gornja površina je ravnomerno poravnata sa donjom površinom uzoraka stopala, tako da su ivice trake i uzorci dotakli jednu liniju sa svake strane. Debljina traka je varirala tokom eksperimenata od inicijalno 1,5 mm do 6 mm. Traka je pričvršćena na uzorke sa dva pripoja ručnim TIG zavarivanjem na donjoj površini, sa svake strane.

Osim toga, na obe strane zazora na donjim ivicama, keramičke cevi su utisnute u preostali zazor između čelične trake, uzoraka i noseće ploče, kako bi se tamo uvario metal šava.

-Kraj 1. dela NASTAVAK U SLEDEĆEM BROJU