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GMA root welding of pearlitic rails using magnetic arc deflection

GMA zavarivanje korena perlitnih šina korišćenjem skretanja magnetnog luka

NASTAVAK IZ PREDHODNOG BROJA
2.deo

The entire setup was mounted on a table which was actuated by an automated linear axis and thus controlled the welding speed. By moving the sample instead of the weld torch it was possible to keep the HF-camera focused on the welding process throughout the entire length of the weld. For all experiments a standard G3Si1 wire from voestalpine Boehler Welding was used as a filler material. M21 (82% Argon, 18% CO2) shielding gas was used for all experiments at 12l/min.

The welding experiments were structured into separate series in order to sequentially optimize all necessary parameters. Throughout the first series, parameter studies were carried out to find an optimum heat input. Therefore, the welding current I_W and the welding speed V_W were systematically altered, starting from low heat input per unit of length in several one-sided single pass welds for 3 different filler wire diameters D_F. The ranges of this parameter variations are depicted in Table 2.

CONTINUED FROM PREVIOUS ISSUE
Part 2

Cela instalacija je postavljena na sto koji se aktivira po automatskoj linearnoj osi i tako se kontrolisala brzina zavarivanja. Pomeranjem uzorka umesto gorionika za zavarivanje bilo je moguće zadržati HF-kameru fokusiranu na proces zavarivanja kroz čitavu dužinu zavarenog spoja. Za sve eksperimente upotrebljena je standardna G3Si1 žica, proizvođača Voestalpine Boehler Welding. Zaštitni gas M21 (82% Argon, 18% CO2) je korišćen za sve eksperimente na 12 1/min.

Eksperimenti zavarivanja su strukturirani u odvojene serije kako bi se sekvencijalno optimizovali svi potrebni parametri. U prvoj seriji sprovedena su ispitivanja parametara kako bi se pronašao optimalni unos toplote. Zbog toga je struja zavarivanja I_W i brzina zavarivanja V_W sistematski izmenjena, počevši od unosa male toplote po jedinici dužine u više jednostranih jednostrukih zavara za 3 različita prečnika žice za zavarivanje DF. Opsezi varijacija ovog parametra prikazani su u Tabeli 2.

D_F (mm)	Iw (A)	V_W (cm.min^{-1})	preheating
1,0	200-270	19,8 - 33	no
1,2	285-360	33	no
1,6	202-400	19,8 - 69	no / 300°C

Table 2. *Welding parameter variation ranges during carried out experimental serie*
Tabela 2. *Opsezi varijacije parametara zavarivanja tokom izvedenih eksperimentalnih serija*

Welds in the first stages were evaluated by visual inspection and macrographs of at least two cross section. Based on the optimized welding parameters subsequent investigations were focused on the magnetic unit. Therein, still on-sided single pass welds were done. Parameter optimization herein included the alteration of the magnetic flux density via the coil current I_C from 1A to its maximum of 3A in 3 steps, as well as an alteration of the welding voltage from the standard characteristic to + 20%. Macrographs of cross sections and HF-camera videos were used for evaluation in this series. Although the overall welding process was stable some agitation of the weld arc and irregularities of the direction of motion

Zavareni spojevi u prvim fazama su procenjivani vizuelnim pregledom i makrografima najmanje dva poprečna preseka. Na osnovu optimizovanih parametara zavarivanja naredna istraživanja su fokusirana na magnetnu jedinicu. U tome su izvedeni i dalje jednostrani zavareni spojevi. Optimizacija parametara je uključivala promenu gustine magnetnog fluksa preko struje I_C od 1A do maksimuma od 3A u 3 koraka, kao i promenu napona zavarivanja od standardne karakteristike do + 20%. Za procenu u ovoj seriji korišćeni su makrografi poprečnih preseka i videozapisa HF kamere. Iako je celokupni proces zavarivanja bio stabilan, uočeno je mešanje luka i nepravilnosti smera kretanja kapi. Zbog toga je bilo teško of the droplet was observed. Therefore, it was difficult to measure the angle of the arc and droplets deflections directly. Alternatively, the angle α between the molten wire tip and the still solid vertical filler wire was used as a reference, s.Fig. 2.

direktno izmeriti ugao skretanja luka i kapljica. Alternativno, kao referenca je korišćen ugao između vrha rastopljene žice i još uvek čvrste vertikalne žice za zavarivanje, sl. 2.

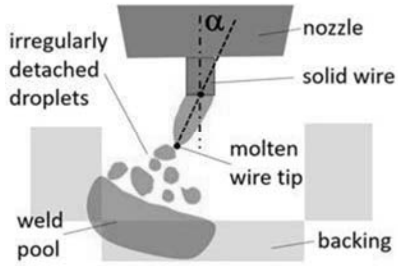

Fig. 2. *Schematic of measured angle for evaluation of magnetic deflection.*
Slika 2. *Šema izmerenog ugla za procenu magnetnog skretanja*

Finally, a fine tuning series was carried out for the optimum value of I_W for the intended two-pass-per-layer, to and fro continuous weld sequence. I_W therefore was adjusted within a narrow band of 5% from the previously defined optimum of the single sided welds. As required in the standard, samples were preheated to 300°C to avoid formation of phases other than Pearlite. During the fine tuning series a more exact evaluation of results was done based on measurement of geometrical aspects of the beads in three cross sections at ¼, ½ and ¾ of the length of each weld, see a_i and c_i in Fig. 3.

Konačno, izvršena je serija finog podešavanja za optimalnu vrednost I_W za predviđenu sekvencu sa dva prolaza po sloju, do i od neprekidnog zavarivanja. Stoga je I_W podešena u uskom pojasu od 5% od prethodno definisanog optimuma jednostrukih zavara. Kao što je zahtevano u standardu, uzorci su predgrejani na 300 °,C da bi se izbeglo stvaranje drugih faza osim perlita. Tokom serija finog podešavanja preciznija procena rezultata izvršena je na osnovu merenja geometrijskih aspekata zavara u tri preseka pri ¼, ½ i ¾ dužine svakog šava, vidi a_i i c_i na slici 3.

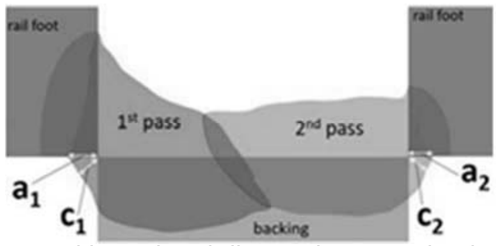

Fig. 3. *Schematic of measured lateral and diagonal penetration in evaluated cross sections.*
Slika 3. *Shematski prikaz izmerenog bočnog i dijagonalnog uvarivanja u procenjenim poprečnimpresecima*

4. Results

4.1 Welding parameters optimization

Best results were obtained if on the one side was maximized in order to increase the penetration and to have a spray arc where droplets can be deflected easily. However, on the other side it was found that the penetration did not depend on the high heat input from high I_W alone, but, rather on the ratio of I_W and the deposition rate. a_i and c_i were highest if this ratio was maximized by also increasing the welding velocity V_W highest possible. This can be explained as follows: Although an increase of V_W meant a decrease in heat input per unit length, it also meant a lower relative deposition rate. Thus the weld gap was filled slower. Hence the weld pool could penetrate the sidewall more.

4. Rezultati

4.2 Optimizacija parametara zavarivanja

Najbolji rezultati su dobijeni ako je sa jedne strane I_W maksimizira da bi se povećalo uvarivanje i da bi se dobio raspršeni (sprej) luk gde je kapljice lako skretati. Međutim, sa druge strane, utvrđeno je da uvarivanje nije zavisilo od visokog unosa toplote usled velike I_W, već od odnosa I_W i brzine deponovanja. a_i i c_i bili su najviši ako je ovaj odnos maksimiziran uz najveće moguće brzine zavarivanja V_W. Ovo se može objasniti na sledeći način: Iako povećanje V_W znači smanjenje unosa toplote po jedinici dužine, to je takođe značilo nižu relativnu brzinu deponovanja. Tako je zazor popunjen sporije. Stoga bi zavarivačka kupka mogla prodreti kroz bočnu debljinu zida i time and thus improve a_i and c_i. Therefore, when both I_W and at the same time V_W are - within the limits for a stable process - increased to a maximum, the best results could be achieved

For what concerns the optimum diameter D_F of the filler wire the best results were obtained with 1.6mm, From the comparison of the three cross sections of welds with same I_W and V_W but different D_F in Fig. 4 it can be derived that the weld pool was flatter and wider for larger D_F. Although it penetrates vertically deeper for small D_F, this maximum is reached through a narrow cone shaped weld pool, which is located too little to the side of the weld gap and therefore $c_i = 0$ and no root is formed. This fact can also be derived from the position of the weld bead inside the weld gap, which sits deeper and more to the side for larger D_F. As a result, the relative vertical position of the maximum lateral penetration, is labelled with h_P in Fig. 4 (a), (b) and (c), decreases with increasing D_F. In combination with the changed shape of the weld pool this results in a decrease of the filling of the weld gap (marked in yellow in Fig. 4 with increasing D_F. In summary this means, by using a larger filler wire D_F the location of penetration can be better pushed towards the intended location, close to the lateral edge of the root.

poboljšati a_i i c_i. Stoga, kada su I_W i istovremeno V_W - u granicama stabilnog procesa - povećani do maksimuma, mogu se postići najbolji rezultati

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Što se tiče optimalnog prečnika D_F žice zazavarivanje, najbolji rezultati su dobijeni sa 1.6mm, od poređenja tri preseka zavarenih spojeva sa istim I_W i V_W, ali različitog D_F. sa slike 4, može se izvesti da zavarivačka kupka bude ravnija i šir za veći D_F. Iako prodire vertikalno dublje kod malog D_F, ovaj maksimum se postiže kroz uski konusni oblik šava, koji je vrlo malo pomeren na stranu zazora i zato je $c_i = 0$ i nema korena. Ova činjenica se takođe može izvesti iz pozicije šava zavara unutar zazora, koji se nalazi dublje i više na strani za veći D_F. Kao rezultat, relativna vertikalna pozicija maksimalnog bočnog uvarivanja, označena je sa h_P na slici 4 (a), (b) i (c), smanjuje se sa povećanjem D_F. U kombinaciji sa promenjenim oblikom zavarivačke kupke to dovodi do smanjenja popunjenosti zazora (označeno žutom bojom na slici 4 sa povećanjem D_F. Ukratko, to znači, korišćenjem veće žice za zavarivanje D_F mesto uvarivanja se može bolje gurnuti prema predviđenoj lokaciji, blizu bočne ivice korena.

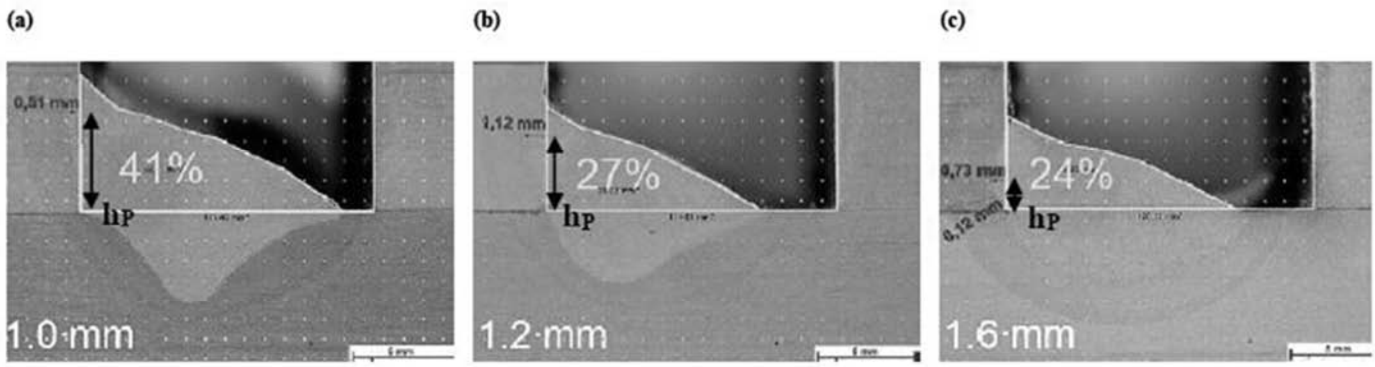
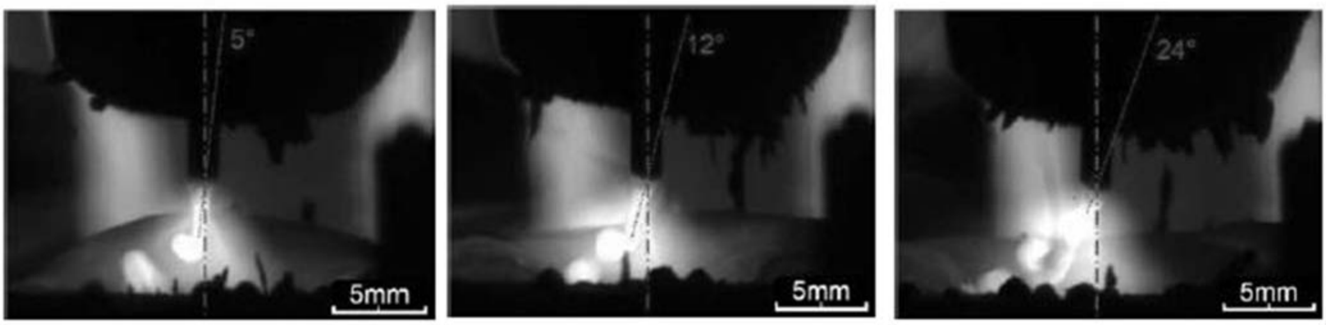


Fig. 4. *Comparison of shape of penetration and degree of filling for one-sided welds of same IW and VW, I_C and UW, but varying DF: (a)… 1.0mm (b)… 1.2mm (c)… 1.6mm .*

Slika 4. *Poređenje oblika uvarivanja i stepena punjenja za jednostrane zavarene spojeve istih I_W i V_W, I_C i UW, ali varirajući D_F: (a)… 1.0mm (b)… 1.2mm (c)… 1.6mm*

For what concerns investigation of the process behavior under an external magnetic field the following results can be presented: An almost linear correlation between the strength of the magnetic field characterized by the coil current I_C and the lateral deflection of weld arc and droplets was found, s. Fig. 5. Thus, lateral penetration can be maximized by also maximizing the strength of the external magnetic field. The only limitation to this finding resulted from the given equipment.

Što se tiče istraživanja ponašanja procesa pod spoljašnjim magnetnim poljem, mogu se prikazati sledeći rezultati: Nađena je skoro linearna korelacija između jačine magnetnog polja koje karakteriše struja zavojnice I_C i bočnog skretanja luka i kapljica, Slika 5. Dakle, bočno uvarivanje se može maksimizirati tako što se maksimizira snaga spoljašnjeg magnetnog polja. Jedino ograničenje ovog nalaza rezultuje iz date opreme.



a) b) c)

Fig. 5. *Weld arc and droplet deflection for varying strength of external magnetic field (a)… IC=1A (5mT) (b)… IC=2A (10mT) (c)…IC=3A (30mT)*

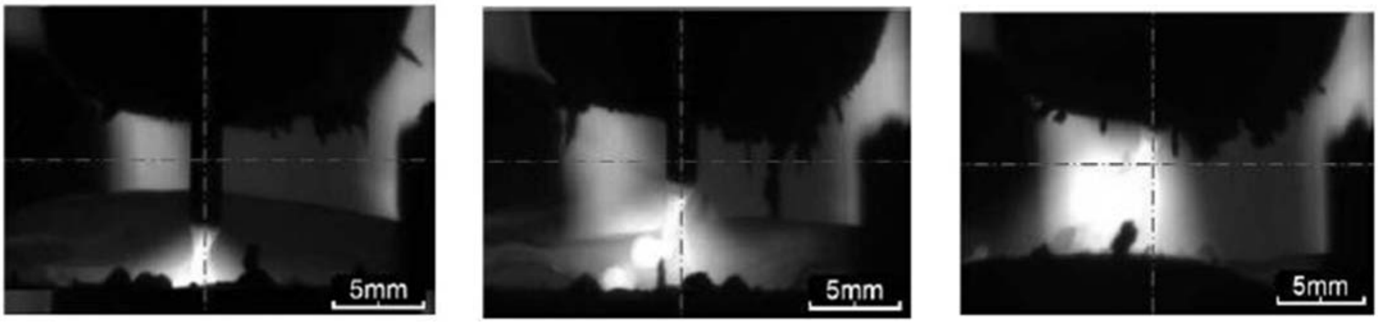
Slika 5. *Skretanje luka i kapljica za promenu jačine spoljašnjeg magnetnog polja (a)… IC = 1A (5mT) (b)… IC = 2A (10mT) (c)… IC = 3A (30mT)*

For some experiments of high I_C, the yoke adhered to the side wall of the weld sample which caused a magnetic shortcut and thus malfunction.

Furthermore, it was found that increased welding voltage U_W is beneficial in two ways. First, an increase of U_W increases the heat input und thus the penetration. Second, it also increased the length of the weld arc and therefore the length of interaction of the external magnetic field with the weld arc and droplets, s. Fig. 6.

Za neke eksperimente visoke I_C, jaram je prianjao na bočni zid uzorka zavarenog spoja koji je izazvao magnetnu kratki spoj i time prekinuo.

Nadalje, utvrđeno je da je povećanje napona zavarivanja U_W korisno na dva načina. Prvo, povećanje U_W povećava unos toplote i time uvarivanje. Drugo, takođe je povećana dužina zavarenog spoja, a time i dužina interakcije spoljašnjeg magnetnog polja sa lukom i kapljicama, sl. 6.



a) b) c)

Fig. 6. *Weld arc length for varied increase of UW (a)… standard value of UW +0% (b)… +10% (c)… 20%.*

Slika 6. *Dužina električnog luka za različito povećanje UV (a).. standardna vrednost UV + 0% (b)..+ 10% (c)..20%.*

Therefore, the droplet has a longer trajectory and thus more space and time to travel to the side of the weld gap. However, contrary to I_C, for U_W there was an upper limit at about +12% of the standard U_W for the found optimum I_W value. If U_W was too high the arc partially bounced outside from the weld gap. As a result, the weld process became unstable. This resulted in weld flaws of different types such as droplet expulsion and thus increased spatter as well as high amount of pores through disturbance of the gas flow. However, because of the beneficial influence of the increase (length of the weld arc) the best results were obtained from welds with U_W values closest possible to this limit.

The effect of the external magnetic field can be derived from the comparison of HF-camera images in Fig. 7. It can be seen that the external magnetic field not only deflects the weld arc but also the

Stoga, kapljica ima dužu putanju i time više prostora i vremena za putovanje na stranu zazora. Međutim, za razliku od I_C, za U_W je postojala gornja granica na oko + 12% od standardnog U_W za pronađenu optimalnu vrednost I_W. Ako je U_W bio previsok, luk se delimično odbijao od zazora. Kao rezultat, proces zavarivanja postaje nestabilan. Ovo je rezultovalo raznim vrstama grešaka kao što je izbacivanje kapljica i time povećano prskanje kao i velika količina pora zbog poremećaja protoka gasa. Međutim, zbog blagotvornog uticaja povećanja (dužine luka zavarivanja) najbolji rezultati su dobijeni iz zavarenih spojeva sa U_W vrednostima koje su najbliže moguće ovoj granici.

Uticaj spoljašnjeg magnetnog polja može se izvesti iz poređenja slika HF kamere na slici 7. Može se videti da spoljno magnetno polje ne samo da odbija luk nego i kapljice. Utvrđeno je da se ne menja droplets. It was found that not only the direction of the droplet is changed but also the mode of detachment. Under influence of the external magnetic field coarser droplets are formed and thus the detachment speed is less. Furthermore, droplets spin clockwise during the transition into the weld pool. The finally proposed optimum welding parameter set for the first and the second pass are given in Table 3.

samo pravac kapi, već i način odvajanja. Pod uticajem spoljašnjeg magnetnog polja formiraju se grublje kapljice, tako da je brzina odvajanja manja. Štaviše, kapljice se okreću u smeru kazaljke na satu tokom prelaska u zavarivačku kupku.
Konačno predloženi optimalni parametri zavarivanja za prvi i drugi prolaz dat je u tabeli 3.

Pass	I_W (A)	U_W (V)	V_W (cm.min^{-1})	I_C (A)
1st	400	31,1	64,5	3
2nd	380	30,7	64,5	3

Table 3. *Optimum found welding parameters for GMAW the first two passes of root welding.*
Tabela 3. *Optimalno pronađeni parametri zavarivanja za GMAV prva dva prolaza zavarivanja korena.*

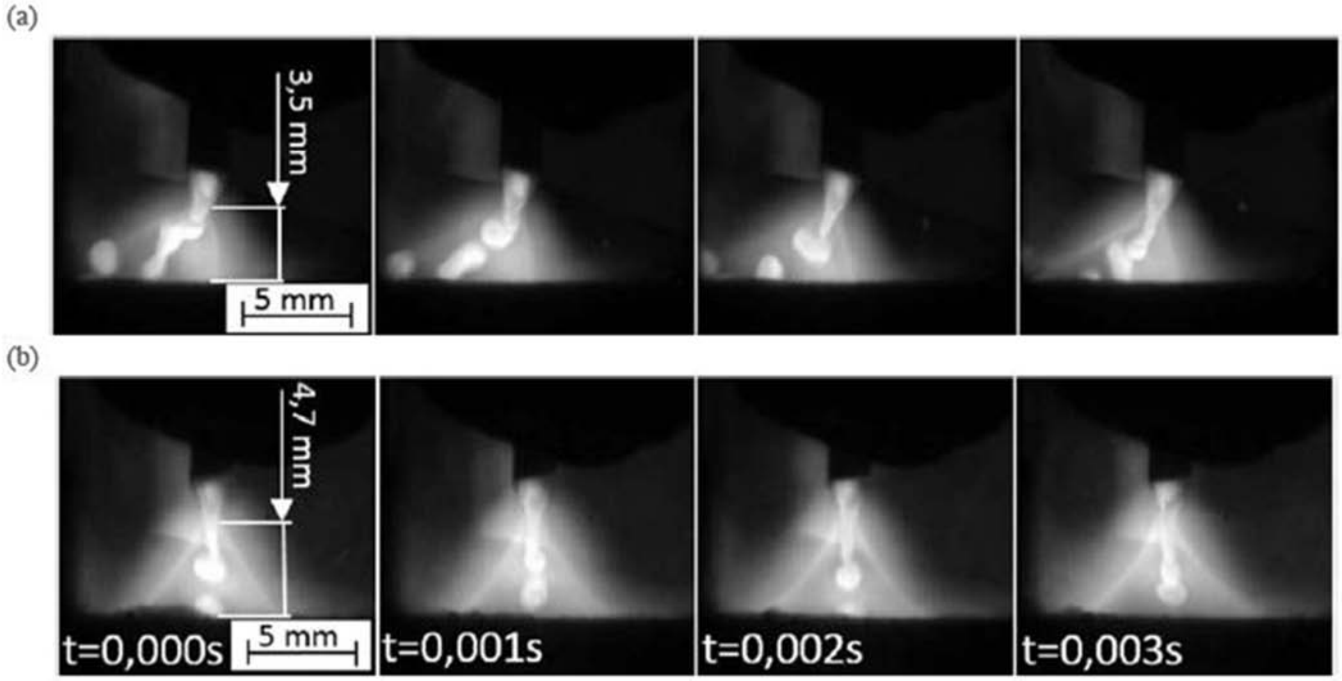


Fig. 7. *Comparison of optimized welding process . (a) with magnetic deflection IC= 3A (b) without magnetic deflection.*
Slika 7. *Poređenje optimizovanih procesa zavarivanja . (a) sa skretanjem luka IC= 3A (b) bez skretanja luka*

4.2 Optimum root weld geometry after final parameter optimizatio

The cross section in Fig. 8 represents the optimum of the achieved GMA root welding results after parameters optimization, based on the above described findings. It can be seen that a flawless weld, with good lateral penetration and a smooth collar at the transition from the base metal (BM) to the weld metal on both sides was formed. In order to illustrate the beneficial effect of the magnetic arc deflection in Fig. 9 a reference weld is presented with same parameters but not magnetic deflection is shown. It can be derived that the weld bead is located right in middle of the weld gap. The flanks of the work piece are not attained be the weld metal, thus no weld at all is formed.

4.2 Optimalna geometrija korena zuba nakon konačne optimizacije parametaran

Presek na slici 8 predstavlja optimalni rezultat postignutih rezultata zavarivanja GMA korena nakon optimizacije parametara, na osnovu gore opisanih nalaza. Može se videti da je formiran besprekoran šav, sa dobrim bočnim uvarivanjem i glatkom ogrlicom na prelazu od osnovnog metala (BM) do metala šava sa obe strane. Da bi se ilustrovao povoljan efekat otklona magnetnog luka na slici 9, prikazan je referentni šav sa istim parametrima, ali nije prikazano skretanje magneta. Može se zaključiti da se šav nalazi na sredini zazora. Na bokovima radnog komada nije postignut metal šava, pa se uopšte ne formira zavareni spoj.

4.3 Weld root geometry irregularities

Measurement results of a_i and c_i from the optimum parameter weld for the three reference cross sections are shown in Fig. 10. Irregularities in the root formation can be derived. First of all, the penetration is not uniform within one pass. Second it can be seen that in general the penetration is better for the 1st pass. Whereas the penetration continuously increases throughout the 1st pass to a_{1max}=3.5 mm, respectively c_{1max}=2.3mm, the lateral cross sections of the 2nd pass have relatively lower penetration and a_{2max}=1.8mm, respectively c_{2max}=1.4mm, is found in the center cross section. From the overview of the bottom of the weld root in Fig. 11 a qualitative assessment of the welding result over the entire length is possible. First of all it can be seen that the root is continuously formed on both sides of the weld with an exception at the beginning of the 2nd pass (s. label 7 in Fig. 11). It can be seen that within the central segment of about ¾ of the entire length of the weld the above described irregularities are valid for the entire length of the weld.

Non–uniform penetration within one pass is drawn back to within one pass non-uniform temperature field as a result of the rail geometry and the high V_W. Better results for the 1st pass are drawn back to better accessibility of the heat of the weld arc and pool when the weld gap is still fully open during the 1st pass and a not yet-fully optimized balancing of heat input in between the two passes.

4.3 Nepravilnosti geometrije korena zavara

Rezultati merenja a_i i c_i kod optimalnih parametara zavarivanja za tri referentna preseka prikazani su na slici 10. Mogu se izvući nepravilnosti u formiranju korena. Prvo, uvarivanje nije ravnomerno u jednom prolazu. Drugo se može videti da je uopšte uvarivanje bolja za prvi prolaz. Dok se uvarivanje kontinuirano povećava tokom prvog prolaza na a_{1mak}=3.5 mm, odnosno c_{1mak}=2.3mm, bočni poprečni preseci 2. prolaza imaju relativno manje uvarivanje i a_{2mak}= 1.8mm, odnosno c_{2mak}=1.4mm, nalazi se u sredini poprečnog preseka.

Iz pregleda dna korena šava na slici 11 moguće je kvalitativno ocenjivanje rezultata zavarivanja po celoj dužini. Kao prvo, može se videti da se koren kontinuirano formira na obe strane šava sa izuzetkom na početku 2. prolaza (oznaka 7 na slici 11). Može se videti da u središnjem segmentu od oko ¾ cele dužine šava gore opisane nepravilnosti važe za celu dužinu zavarenog spoja.

Nejednoliko uvarivanje u jednom prolazu povučeni su u jedno prolazno nejednako temperaturno polje kao rezultat geometrije šine i visokog V_W. Bolji rezultati za prvi prolaz povučeni su zbog bolje dostupnosti toplote luka i kupke kada je zazor za zavarivanje još uvek potpuno otvoren tokom prvog prolaza i još nije potpuno optimizirano balansiranje unosa toplote između dva prolaza.

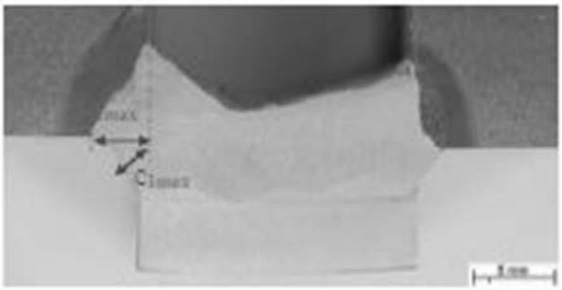


Fig. 8. *Root weld geometry after optimized parameters and magnetic arc deflection in cross section at ¾ of weld length.*

Slika 8. *Geometrija korena zavarenog spoja posle optimizovanih parametara i skretanja magnetnog luka u preseku na ¾ dužine zavarenog spoja*

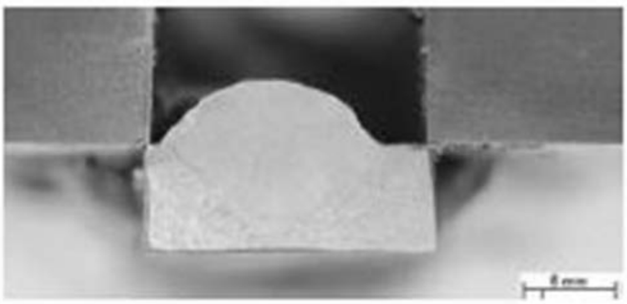


Fig. 9. *Root weld geometry of reference single pass weld without magnetic arc deflection*

Slika 9. *Geometrija korena zavarenog spoja referentnog jednostrukog prolaza bez skretanja magnetnog luka*

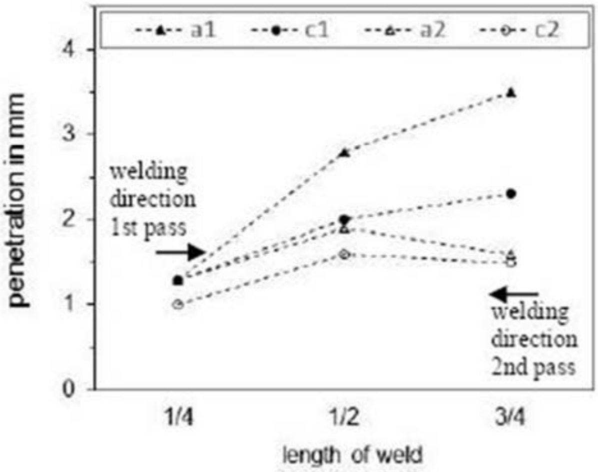


Fig. 10. *Lateral and diagonal penetration in the evaluated cross sections for 1st and 2nd pass.*
Slika 10. *Bočno i dijagonalno uvarivanje u procenjenim presecima za 1. i 2. prolaz.*

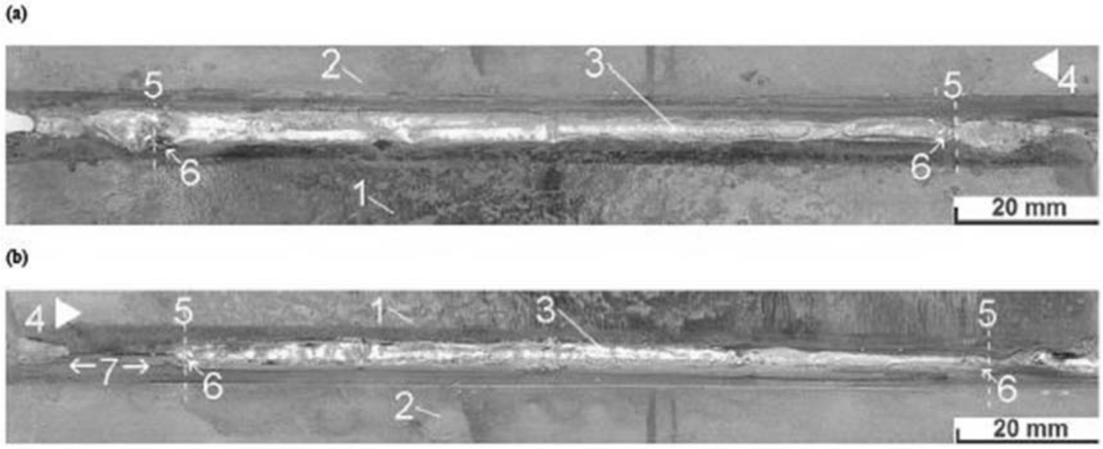


Fig. 11. *Outer appearance of root layer of GMA welded rail foot after parameter optimization. (a bottom view 1st pass (b)… bottom view 2nd pass. 1...rail foot 2... weld pool backing strip 3... Weld root 4... Welding direction 5... Sidewise run-in and run-out delimitation lines 6… TIG weld spot for fixation 7…no root*
Slika 11. *Spoljni izgled korenog sloja GMA zavarenih šina nakon optimizacije parametara. (donji pogled 1. prolaz (b)… pogled donji 2. prolaz 1 ... stopalo šine 2 ... podložna traka za zavarivačku kupku 3 ... koren zavarenog spoja 4 ... pravac zavarivanja 5 ... linije za razgraničavanje bočnih i potisnih tačaka 6… mesto TIG zavarivanje za fiksiranje 7… bez korena*

4.4 Microstructure & hardness in the HAZ

The microstructures at different areas of the HAZ (in same cross section from the optimum weld in Fig. 8) are presented Fig. 12. It can be derived that the heat affected zone (HAZ) of the rail steel consist entirely of Pearlite. Beside the fully pearlitic matrix dispersed dark elongated spots inside the HAZ, which are identified as Mn-sulfides, marked with S in Fig. 12 (b) and (f). It results from steel production and is unchanged in the HAZ. The weld metal (WM) consist of acicular ferrite, s. Fig. 12 12 (f), which is the expected microstructure of the used G3Si filler wire Within a narrow band of about 50m width along the fusion line, s. Fig. 12 (g) plate-shaped pre-eutectoid ferrite (marked with F) is found at the former austenite grain boundaries. Its formation is understood as a result of decreased carbon content caused by the high difference in carbon content between the rail steel and filler

4.4 Mikrostruktura i tvrdoća u ZUT

Mikrostrukture na različitim područjima ZUT (u istom poprečnom preseku optimalnog šava na slici 8) su prikazane na slici 12. Može se zaključiti da zona uticaja toplote (HAZ) šine u celini sadrži perlit. Pored potpuno perlitne matrice raspršene su tamno izdužene tačke unutar ZUT, koje su identifikovane kao Mn-sulfidi, označeni sa S na slici 12 (b) i (f). Oni su rezultat proizvodnje čelika i nepromenjene su u ZUT. Metal šava (WM) se sastoji od igličastog ferita, slika 12 (f), koja je očekivana mikrostruktura korišćene žice za zavarivanje. U okviru uskog pojasa širine oko 50μm duž linije stapanja, slika 12 (g) proeutektoidni ferit u obliku ploče (označen sa F) nalazi se na bivšim granicama zrna austenita. Njegovo formiranje se shvata kao rezultat smanjenog sadržaja ugljenika usled velike razlike u sadržaju ugljenika u šini i dodatnom materijalu. Iako potpuno perlitna, iz slike 12 (b) može se zaključiti metal. Although fully pearlitic, it can be derived from Fig. 12 (b) that the optical appearance of the HAZ varies. This is an indication of the changing Pearlite morphology, which for pearlitic microstructure is defined by the colony and nodule size. Inside the HAZ close from the transition from base metal (BM) these are smaller in size and thus the morphology is much refined, s. Fig. 12 (c). Further on, the morphology is gradually coarsening towards the WM. However, inside the coarse grain zone it is still finer then in the BM, compare Fig. 12 (c) top left corner and HAZ in Fig. 12 (d).

The hardness distribution over the weld is shown in (a). The hardness in the HAZ is constantly higher than the one of the BM. The hardness increases from the BM towards the WM to over 450 HV10. The hardness in the weld metal is generally on a lower level, which is a result of the used undermatching filler wire.

da optički izgled ZUT varira. Ovo ukazuje na promenu morfologije perlita, koja je za perlitnu mikrostrukturu definisana veličinom kolonije i nodula. Unutar ZUT blizu granice sa osnovnim materijalom (BM) one su manje veličine i zbog toga je morfologija sitnija, slika 12 (c). Dalje, morfologija se postepeno povećava prema metalu šava (WM). Međutim, u zoni krupnog zrna to je još finije nego u OM, uporediti sl. 12 (c) gornji levi ugao i ZUT na slici 12 (d).

Distribucija tvrdoće na zavarenom spoju prikazana je u (a). Tvrdoća u ZUT je konstantno viša nego kod OM. Tvrdoća se povećava od OM prema metalu šava na preko 450 HV10. Tvrdoća u metalu šava je generalno na nižem nivou, što je rezultat korišćene žice za zavarivanje.

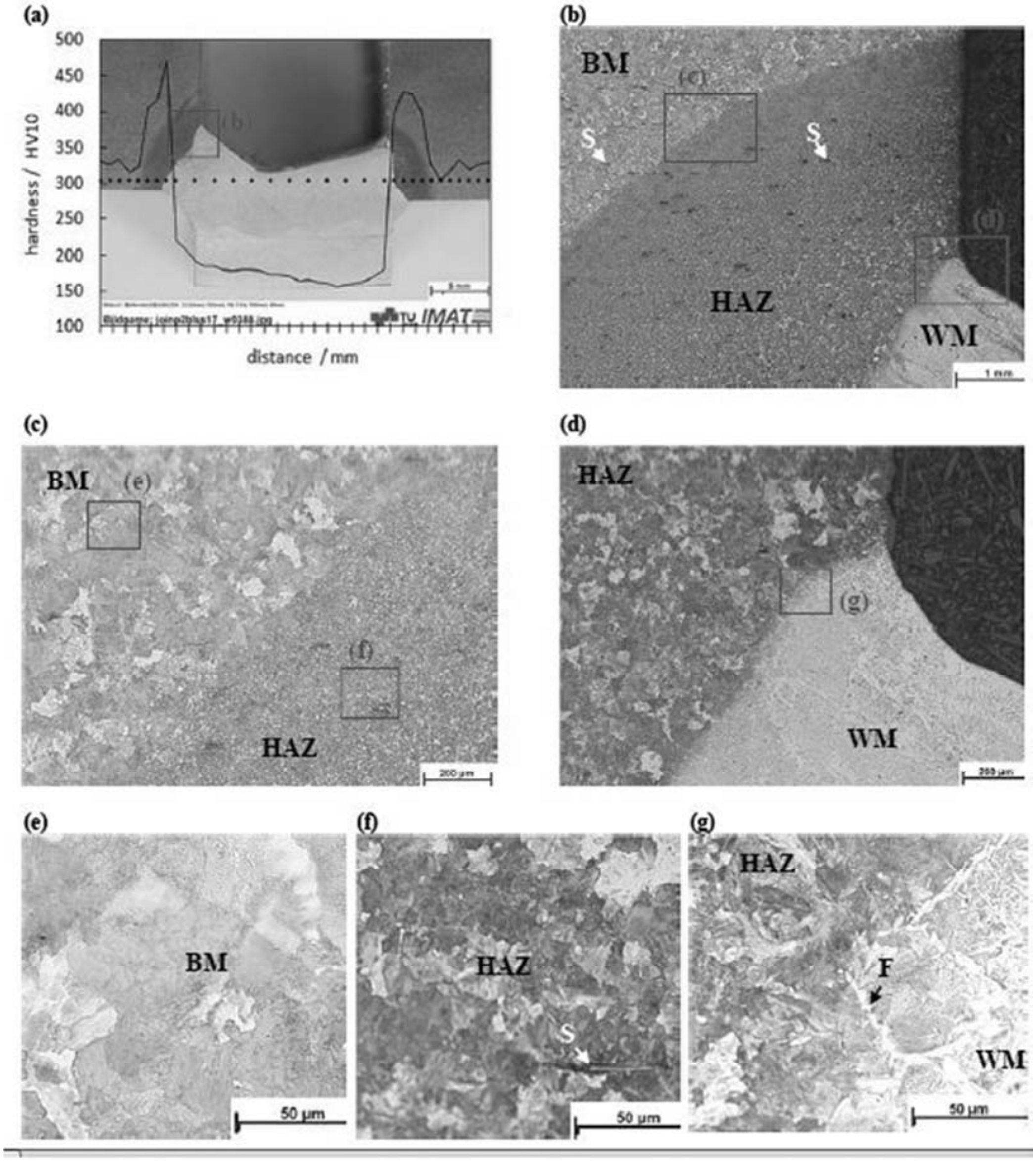


Fig. 12. *Microstructure at different areas of the optimized parameter weld.*
Slika 12. *Mikrostruktura na različitim područjima optimizovanih parametara zavarivanja*

5. Discussion

The findings of this research could in part illustrate the potential of the new approach for joining of pearlitic rails. From the comparison in Fig. 13 its advantages over conventional AT-weld can be derived: The hardness in the HAZ of the GMA welded rail is significantly and entirely above the hardness of the that of the AT-weld. Furthermore, no soft zone at the transition from BM to HAZ is observed. It can also be derived that the size of the HAZ is reduced by about 75%. If projected to the rail head, these two aspects are believed to contribute tremendously to an improvement of the wear resistanceof rail welds. Furthermore, it was shown that very good lateral penetration and smooth geometry of the collar at the weld root could be attained if all necessary parameters are well optimized. The joint in this state can surely be considered as a sound weld, providing per se sufficient bonding strength. However, penetration was not yet uniform along the weld. With regards to the applicability for in the track welding the current result are thus still questionable. For an entirely sound weld and also to overcome high gap bridging tolerances, the penetration would need to be more constant. Also the sidewise run-in in and run- out sections are not yet sufficiently weldable. The overall smaller penetration of the second pass might not be enough to achieve satisfying welds. The smooth geometry of the root furthermore opts for sufficient fatigue strength of the joint.

5. Diskusija

Nalazi ovog istraživanja mogli bi delimično ilustrovati potencijal novog pristupa za spajanje perlitnih šina. Iz poređenja na slici 13 mogu se izvesti njegove prednosti u odnosu na konvencionalni AT-šav: tvrdoća u ZUT GMA zavarene šine je značajno i potpuno iznad tvrdoće AT-zavarenog spoja. Osim toga, nije primećena nikakva meka zona na prelazu sa OM na ZUT. Takođe se može uočiti da je veličina ZUT smanjena za oko 75%. Ako se projektuju na šine, veruje se da ova dva aspekta značajno doprinose poboljšanju otpornosti na habanje šinskih zavarenih spojeva. Nadalje, pokazano je da se vrlo dobro bočno uvarivanje i glatka geometrija ogrlice na korenu šava mogu postići ako su svi potrebni parametri dobro optimizovani. Spoj u ovom stanju se sigurno može smatrati šavom bez grešaka, obezbeđujući sebi dovoljnu čvrstoću vezivanja. Međutim, uvarivanje još nije bilo ravnomerno šava. S obzirom na primenjivost za zavarivanje koloseka, trenutni rezultat je stoga i dalje pod znakom pitanja. Za potpuno zdrav šav i za prevazilaženje velikih tolerancija zazora, uvarivanje bi trebalo da bude konstantnije. Isto tako, bočni ulazi i izlazi nisu dovoljno zavarljivi. Ukupno manje uvarivanje drugog prolaza možda nije dovoljno da se postigne zadovoljavajuće zavarene spojeve. Glatka geometrija korena obezbeđuje dovoljnu zamornu čvrstoću spoja.

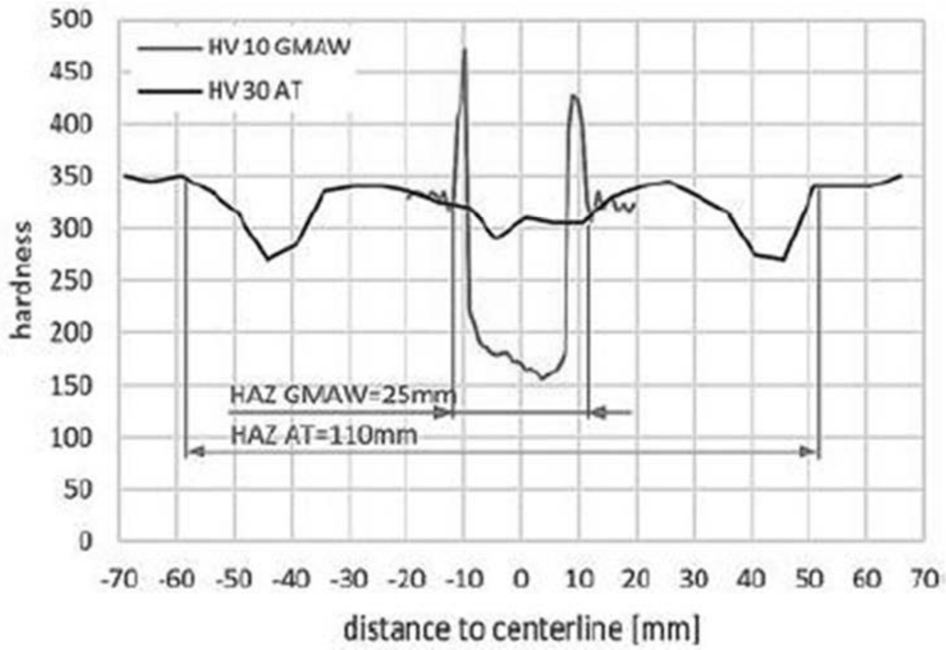


Fig. 13. *Hardness and size of HAZ: Green… GMAW from this work. Black… exemplary state of the art AT-weld of same rail steel.*

Slika 13. *Tvrdoća i veličina ZUTW Zelena… GMAV iz ovog rada. Crni… primeri najsavremenijeg AT-zavara iste šine.*

6. Conclusions

GMAW with magnetic arc deflection for the root layers of a pearlitic rails weld showed under laboratory conditions and after parameter optimization very promising results. The chosen two-pass-per layer sequence was approved to be beneficial, because it enables one to focus the weld on one side per pass, and thus adjust parameters to improve the penetration of each pass individually. In this regard, heat input optimization concluded that the highest possible ratio of the welding current I_W (~ 400A) and the deposition rate (via high welding speed V_W *~64cm/min*) for the 1.6mm filler wire showed the best results. In combination with the magnetic deflection it causes a laterally repositioned weld pool, which penetrates the BM at the root best. The present spray arc mode is also beneficial for the magnetic arc deflection. By a relative increase of the welding voltage U_W of up to about +12% the arc length is increased and the magnetic deflection further improved.

Furthermore, because of the high V_W and thus reduced heat input the microstructure in the HAZ is refined but still pearlitic. As a result of the refined pearlitic microstructure also the hardness of the HAZ is above the BM. Furthermore, because of the small heat input also the size of the HAZ is small in comparison to standard rail welding processes (75% reductions in size when compared to AT-welding). The lateral weld arc deflection by an external magnetic field works best if the field is parallel to the welding direction and the magnetic flux density at the weld is highest possible. The maximum magnetic flux density tested in this work was 30mT.

By applying these parameters, a smooth transition collar of the root and a maximum lateral penetration at the root of 3.5mm could be obtained.

The intended penetration at the root was found to be not constant over the full length of the weld. Lateral run- in and run-out with partial no root formation at the 2nd pass was found.

7. Outlook

The fundamental studies of this work have pointed out a strong potential of GMAW for pearlitic rails. However, further investigations are believed to be essential to bring the process closer to an applicability for in the track welding:

- improve results at run-in and run-out area via further optimization of welding parameters and the setup.
- equalize penetration over entire weld and in between of 1st and 2nd pass via further pass-wise parameter optimization

6. Zaključci

GMAW sa skretanjem magnetnog luka za korene slojeve perlitnih šina pokazuje u laboratorijskim uslovima i nakon optimizacije parametara veoma obećavajuće rezultate. Izabrana sekvenca sa dva prolaza po sloju je odobrena da bude korisna, jer omogućava fokus na jednostrani šav po prolazu, i na taj način podesi parametre kako bi se poboljšalo uvarivanje svakog prolaza pojedinačno. U tom smislu, optimizacijom utroška toplote je zaključeno da je najbolji mogući odnos struje zavarivanja I_W (~ 400A) i brzine deponovanja (preko visoke brzine zavarivanja V_W ~ 64cm / min) za žicu za zavarivanje od 1.6mm pokazao najbolje rezultate. U kombinaciji sa magnetnim skretanjem, on izaziva bočno premeštanje zavarivačke kupke, koja najbolje prodire u OM. Sadašnji raspršeni (sprej) luk je takođe koristan za skretanje magnetnog luka. Relativnim povećanjem napona za zavarivanje U_W do oko + 12% povećava se dužina luka i dodatno se poboljšava magnetno skretanje.

Osim toga, zbog visokog V_W i na taj način smanjenog unosa toplote, mikrostruktura u ZUT je rafinirana, ali još uvek perlitna. Kao rezultat rafinirane perlitne mikrostrukture, tvrdoća ZUT je iznad OM. Pored toga, zbog malog unosa toplote, veličina ZUT je mala u poređenju sa standardnim postupcima zavarivanja (75% smanjenja u odnosu na AT-zavarivanje). Bočno odstupanje luka skretanjem, spoljašnjim magnetnim poljem najbolje funkcioniše ako je polje paralelno sa pravcem zavarivanja, a gustina magnetnog fluksa na zavarenom spoju najveća. Maksimalna gustina magnetnog fluksa testirana u ovom radu bila je 30mT.

Primenom ovih parametara može se dobiti glatka ogrlica prelaza korena i maksimalno bočno uvarivanje u korenu od 3,5 mm.

Nađeno je da nameravano uvarivanje u korenu nije konstantna po celoj dužini šava. Nađeno je bočno neslaganje i isticanje s delimičnim formiranjem korena na 2. prolazu.

7. Perspektiva

Fundamentalne studije ovog rada ukazale su na veliki potencijal GMAW za perlitne šine. Međutim, smatra se da su dalja istraživanja od suštinskog značaja za približavanje procesa primenljivosti za zavarivanje koloseka:

- poboljšanje rezultata u oblasti neslaganja i isticanja daljom optimizacijom parametara zavarivanja i podešavanja.
- izjednačiti uvarivanje kroz ceo šav i između 1. i 2. prolaza daljom optimizacijom parametara

- redesign and optimize the magnetic unit to test the possibility to further increase lateral penetration via an increase of the magnetic flux density. This should comprise improvements to achieve higher magnetic flux densities and stronger mechanical fixation of the yoke.

To permit a future transition from the here carried out laboratory tests to in the track GMA rail welding we see these further fields of investigations are believed necessary:

- welding of entire cross sections with for each part of the rail's cross section optimization of the welding parameters, which include weld backing. This would also include a suitable design of the welding torch and magnetic unit.
- testing of mechanical properties: fatigue strength of the entire joint and wear resistance at the rail head, in order to assess if the requirements in the rail standards can be met.
- testing of gap bridging capabilities of the magnetic arc deflection.
- design and optimization of automatisation equipment and control for in track welding.

- redizajnirati i optimizovati magnetnu jedinicu kako bi se ispitala mogućnost daljeg povećanja bočnog uvarivanja povećanjem gustine magnetnog fluksa. Ovo bi trebalo da obuhvati poboljšanja za postizanje veće gustine magnetnog fluksa i jaču mehaničku fiksaciju jarma.

Da bi se omogućila budući prenos ovde sprovedenih laboratorijskih testova na GMA zavarivanje šina na železnici, vidimo da su te neophodne dalje oblasti istraživanja:

- zavarivanje celih poprečnih preseka sa za svaki deo poprečnog preseka železničke šine optimizacijom parametara zavarivanja, koji uključuju i podloške za zavarene spojeve. Ovo bi takođe uključivalo pogodan dizajn gorionika za zavarivanje i magnetne jedinice.
- Ispitivanje mehaničkih svojstava: zamorna čvrstoća celog spoja i otpornost na habanje na glavi šine, kako bi se procenilo da li se mogu ispuniti zahtevi u železničkim standardima .
- Ispitivanje mogućnosti premošćavanja zazora, skretanjem magnetnog luka.
- projektovanje i optimizacija opreme za automatizaciju i kontrolu kod zavarivanja koloseka.

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