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# ARC WELDING MAINTENANCE OF RAILWAY COMPONENTS

# ODRŽAVANJA ŽELEZNIČKIH KOMPONENTI PRIMENOM PROCESA ELETROLUČNOG NAVARIVANJA

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## Abstract

The service performance and life of rail components are subjected to the following wear mechanisms: metal to metal or adhesive wear; fatigue; plastic flow and defects in rail and welds. Standard and head hardened rail grades made of high carbon steel as well as crossing made of austenitic manganese steels require permanent in field as well as workshop maintenance. Arc welding has been widely used for the repair and maintenance of rail components. This paper focuses on repairs of railway components using flux cored arc welding as a process with higher productivity, reliability, quality and increased service life of the repaired components. The paper addresses metallurgical aspects of the rail components welding, development of welding procedures, welding filler materials selection, heat input and temperature control, dilution and distortion control, weld, heat affected zone and parent material properties.

## Rezime

Performanse i vek železničkih komponenti su diktirane sledećim mehanizmima: adhesivno i abrazivno habanje; zamor (kotrljajuci); plastična deformacija i nedostaci/defekti u šinama i varovima. Standardne (normalizovane) i površinski kaljenje/očvrsle železničke šine napravljene su od visoko ugljeničnog čelika kao i razdvojnice uglavnom su napravljene od austenitičkih manganskih čelika i zahtevaju trajno održavanje na terenu, kao i u radionicama. Zavarivanje električnim lukom je široko korišćeno za popravku i održavanje železničkih komponenti. Ovaj rad se fokusira na popravke železničkih komponenti koristeći elekrolučno zavarivanje/navarivanje korištenjem žice punjene praškom, kao proces sa većom produktivnošću, pouzdanošću, kvalitetom i povećanim radnim vekom popravljenih komponenti. Rad se bavi metalurškim aspektima zavarivanja železničkih komponenti, razvojem procedura zavarivanja, izborom dodatnih materijala za zavarivanje , unosom toplote i kontrolom temperature, faznim transformacijama, kontrolom vitoperenja i razlučivanja, zonom uticaja toplote i svojstvima osnovnog materijala.

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## 1. Introduction

The service performance and life of rails in track (carbon manganese as well as austenitic manganese rail steels) is determined primarily by:

- Metal to Metal Wear;
- Fatigue;
- Plastic Flow and
- Defects in rail and welds.

Tables 1 and 2 are providing summary information regarding the causes of the rail defects and failures, and Figures 1 to 4 are illustrating some of the defects.

***Table 1**. Causes of rail defects [1]*

***Tabela 1.** Uzroci oštećenja šina [1].*

| Railway | First | Second | Third | Fourth |
|---|---|---|---|---|
| Rail track (99/00) | Squats 21.7% | Vertical/transverse 20.1% | Horiz./longitudinal 12.5% | Bolt holes 9.6% |
| SNCF (1999) | Squats 23.4% | Internal fatigue 11.5% | Shells 8.4% | Thermite welds 4.7% |
| HSPC (1999) | Thermite welds 31.5% | Wheel burns 17.2% | Horizontal split webs 13.3% | Bolt holes 11.3% |
| NS (1997) | Insulated Joints 59.4% | Transverse defects 18% | Thermite welds 15% | Fatigue Failure 5.2% |
| DB (1996) | Thermite welds 29% | Sudden fracture 18% | Fatigue Failure 16% | Electric bonds 4% |
| Banverket* (1998) | Transverse fracture 55.1% | Welded joint 32.7% | Horizontal defect 6.1% | Vertical split 2.0% |
| HH1 (1999) | Vertical split heads 34.7% | Thermite welds 20.3% | Detail fractures 13.1% | Bolt holes 12.2% |
| HH2 (1999) | Transverse defects 23.6% | Thermite welds 15.5% | Wheel burns 13.2% | Shells 9.6% |

***Table 2.** Causes of rail fractures [1]*

***Tabela 2**. Uzroci loma šina [1].*

| Railway | First | Second | Third | Fourth |
|---|---|---|---|---|
| Rail track (99/2000) | Vertical/transverse 39.5% | Thermite welds 22.4% | Bolt holes 14.9% | Horiz./longitudinal 7.4% |
| SNCF (1999) | Thermite welds 35.3% | Internal fatigue 18.6% | Squats 8.8% | Rail manufacture 6.1% |
| Banverket* (1998) | Transverse fracture 44.1% | Vertical split 19.4% | Welded joint 19.4% | Horizontal defect 17.2% |
| HH2 (1999) | Transverse defects 37.9% | Thermite welds 35.6% | Bolt holes 5.8% | Flash welds 5.6% |


***Figure 3.*** *Rail shell development*

***Slika 3****. Oštećenja glave šine u obliku “školjki”*

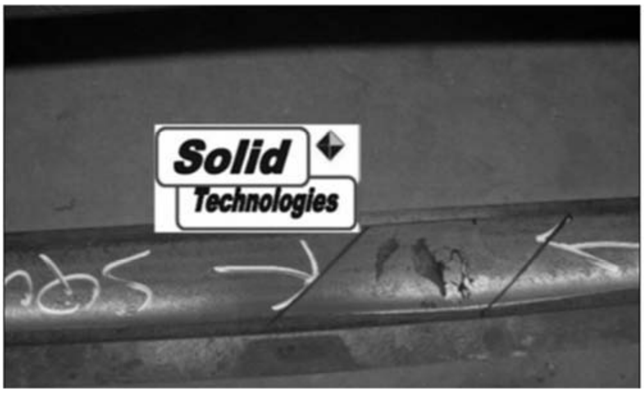



***Figure 4.*** *Rail squat*

***Slika 4.*** *Oštećenja uzrokovana zamorom metala usled kontakta pri kotrljanju*


***Figure 5.*** *Thermit weld defect*

***Slika 5.*** *Oštećenja aluminotermijski zavarenog spoja*

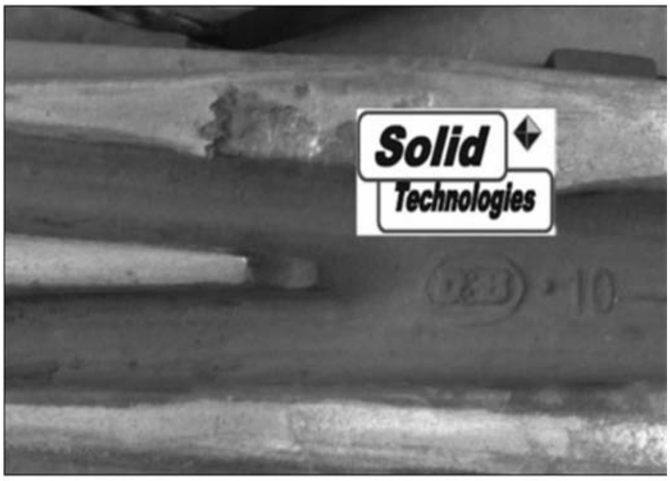



***Figure 6.*** *Rail crossing defect*

***Slika 6.*** *Oštećenja na železničkom prelazu*

## 2. Steels used in railroads

The main railroad steels are carbon manganese alloys with main alloying elements in the range of 0.6 to 0.8% carbon and 0.65 -1.3% Mn. The hypereutectoid grade steels are also used with the chemical composition consisting of carbon in the range of 0.85-1.00 % and Manganese 0.95-1,35% (Tables 3 and 4).

***Table 3.*** *Rail mechanical properties [4]*

***Tabela 3****. Mehanička svojstva šina [4]*

| Nominal rail size | | 0.2% Proof stress MPa, Min. | Tensile strength MPa, Min. | Elongation %, Min. | Surface hardness HB |
|---|---|---|---|---|---|
| All rail | 31 kg, 41 kg | – | 700 | 8 | — |
| | 50 kg, 60 kg, 68 kg | 420 | 880 | 8 | 260 |
| Head-hardened rail | 50 kg, 60 kg, 68 kg | 780 | 1130 | 9 | 340 |

***Tabela 4.*** *Hemijski sastav ugljenično - manganskih čelika [5-6]*

***Table 4.*** *Chemical compositions of carbon manganese steels [5-6]*

| | C | Mn | Si | P | S | Cr | AL | V | N | Mo | Sn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| UIC 860 Classificatio | % | % | % | %max | %max | %max | %max | %max | %max | %max | %max |
| 700 | 0.40-0.60 | 0.80-1.30 | 0.10-0.40 | 0.050 | 0.050 | | | | | 680 | |
| 800 | 0.45-0.65 | 0.80-1.20 | <0.50 | 0.045 | 0.045 | | | | | 770 | |
| 900A | 0.60-0.80 | 0.80-1.30 | 0.10-0.50 | 0.040 | 0.040 | | | | | 880 | |
| 900B | 0.55-0.75 | 1.30-1.70 | 0.10-0.50 | 0.040 | 0.040 | | | | | 880 | |
| 1100 | 0.60-0.82 | 0.80-1.30 | 0.30-0.90 | 0.030 | 0.030 | 0.80-1.30 | | | | 1080 | |
| EN13674-1 Classification | | | | | | | | | | | |
| R200 | 0.38-0.62 | 0.65-1.25 | 0.13-0.6 | 0.040 | 0.040 | 0.15 | 0.004 | 0.03 | 0.01 | 680 | 200-240 |
| R220 | 0.50-0.60 | 0.65-1.25 | 0.20-0.60 | 0.025 | 0.030 | 0.15 | 0.004 | 0.03 | 0.08 | 770 | 220-260 |
| R260 | 0.60-0.82 | 1.00-1.25 | 0.13-0.60 | 0.030 | 0.030 | 0.15 | 0.004 | 0.03 | 0.01 | 880 | 260-300 |
| R260Mn | 0.5-0.77 | 0.65-1.25 | 0.13-0.62 | 0.025 | 0.030 | 0.15 | 0.004 | 0.03 | 0.01 | 880 | 260-300 |
| R320Cr | 0.58-0.82 | 1.25-1.75 | 0.48-1.12 | 0.025 | 0.025 | 0.75-1.25 | 0.004 | 0.02 | 0.01 | 1080 | 320-360 |
| R350HT | 0.70-0.82 | 0.65-1.25 | 0.13-0.60 | 0.025 | 0.025 | 0.15 | 0.004 | 0.03 | 0.01 | 1175 | 350-390 |
| R350LHT | 0.70-0.82 | 0.65-1.25 | 0.13-0.60 | 0.025 | 0.025 | 0.3 | 0.004 | 0.03 | 0.01 | 1175 | 350-390 |
| R370CrHT | 0.68-0.84 | 0.65-1.15 | 0.38-1.02 | 0.025 | 0.025 | 0.35-0.65 | 0.004 | 0.03 | 0.030 | 1280 | 370-400 |
| R400HT | 0.88-1.07 | 0.65-1.35 | 0.18-0.62 | 0.025 | 0.025 | 0.30 | 0.004 | 0.030 | 0.030 | 1280 | 400-440 |

Austenitic Manganese Steels (AMS) are usually used in the form of castings for crossings applications with typical chemistry of 0.9 -1.4% C and 10 -14% Mn. A numerous variety of Hadfield's original compositions are available. Key chemical elements are listed in Table 5. [7].

***Table 5.*** *Key alloying elements of austenitic manganese steels in (mass. %).*

***Tabela 5.*** *Osnovni legirajući elementi austenitnih manganskih čelika u (mas. %)*

| C | Mn | Si | P | Fe |
|---|---|---|---|---|
| 1-1.3 | min. 12 | max. 1 | 0.07 | rest |

Increased cooling rate in the range from 871 °C to 315 °C during quenching is important to surpass detrimental carbides precipitation from austenite. This is very important for manufacturing as well as welding repair of AMS.

## 3. Arc welding repair maintenance of railtrack defects

Flux Cored Arc Welding (FCAW) is a semi-automatic process where a continuous flux/powder-filled tubular electrode is used. The consumable electrode is usually made of a low carbon steel or stainless steel tubular sheath with the core filled with fluxing and alloying materials (Figure 8.). Flux cored arc welding consumables are available in two forms tubular consumable - gas shielded and tubular consumable – self shielded (FCAWSS). The FCAWSS process offers considerable flexibility and is more economical than the MMAW process.

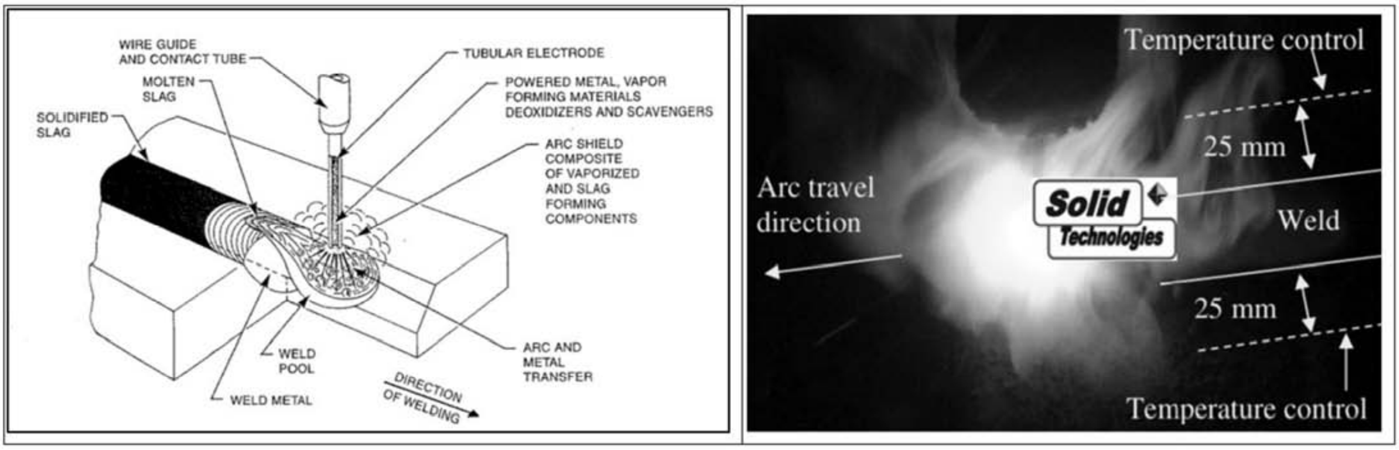



***Figure 8.*** *Semi automatic Flux Cored Arc Welding Self Shielded (FCAWSS) process*

***Slika 8.*** *Poluautomatski proces zavarivanja punjenom žicom sa samozaštitom (FCAVSS)*

### *Filler metals - consumables for the repair of rail components*

Filler metals for repairing railway defects are listed in Table 6. and Table 7. for carbon manganese and austenitic manganese steels, respectively.

***Table 6.*** *Chemical composition of the filler materials suitable for repairing defects on carbon manganese steels in (mass. %)*

***Tabela 6.*** *Hemijski sastav dodatnih materijala koji su pogodni za popravku oštećenja na ugljenično manganskim čelicima u (mas. %)*

| Weld Alloy description | Weld developed Microstructure | C | Mn | Ni | Mo | W | Cr | Fe | Applicable to |
|---|---|---|---|---|---|---|---|---|---|
| Pearlitic/ Ferritic steel | Predominantly acicular ferrite. Minor proportions of grain boundary ferrite and bainite may be present | 0-0.3 | Total of these elements: 5% max | | | | | rest | All rail standard rail surface hardness 260 HB (Table 3) |
| Low carbon bainitic steel | Predominantly low carbon bainite | 0-0.4 | Total of these elements: 6% max. | | | | | rest | Head hardened rail; surface hardness 340 HB (Table 3) |

***Table 7.*** *Chemical composition of the filler materials suitable for repairing defects on austenitic manganese steels in (mass. %)*

***Tabela 7****. Hemijski sastav dodatnih materijala koji su pogodni za popravku oštećenja na austenitno manganskim čelicima u (mas. %)*

| Weld alloy description | Weld developed microstructure | C | Mn | Ni | Mo | W | Cr | Fe | Applicable to |
|---|---|---|---|---|---|---|---|---|---|
| Austenitic manganese | Austenite with isolated particles of carbide at grain boundaries | 0.6-1.3 | 10-20 | - | - | - | - | rest | Austenitic Manganese Crossings |
| High carbon austenitic steel | Complete or incomplete networks of carbide and austenite eutectic in austenite | 0.9-1.7 | 1-4 | - | - | - | 3-10 | rest | |
| | | 0.4-0.9 | 10-18 | - | - | - | 19-18 | rest | |

Reviewing the as welded microstructures of Flux Cored Self Shielded Arc Welding weld deposit and development of Al and C equivalents Dumovic and Dunne [8] developed diagram as illustrated in Figure 9., for prediction of the weld metal microstructures/phase fields relative to the relevant wear resistance mechanisms.

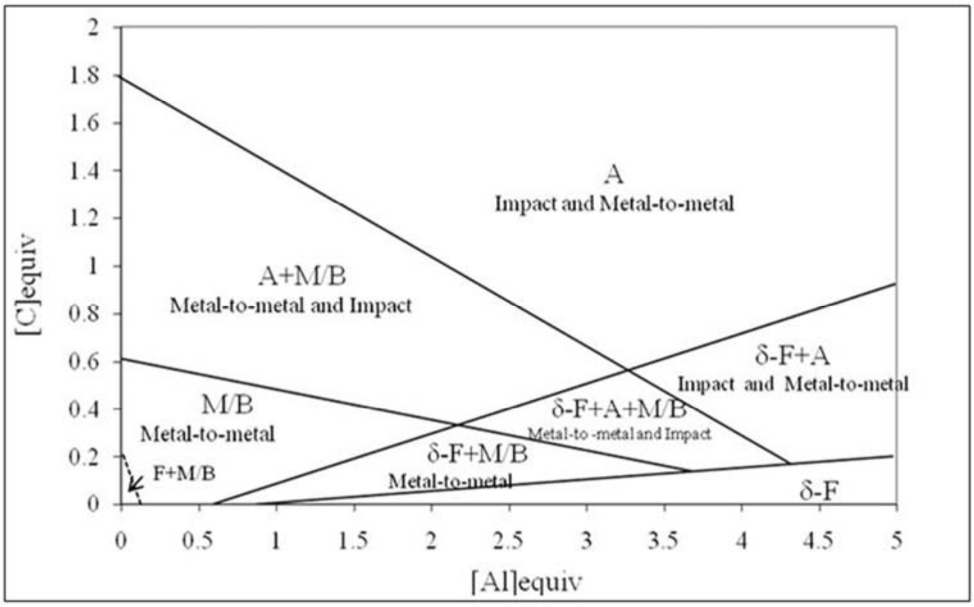



***Figure 9.*** *Diagram for predicting the weld metal microstructures/phase fields for FCAWSS weld deposits, and the corresponding wear resistance mechanisms. A represents austenite, M is martensite, F refers to $\alpha$ ferrite, and $\delta$-F is ferrite that forms at high temperatures and B is bainite [8]*

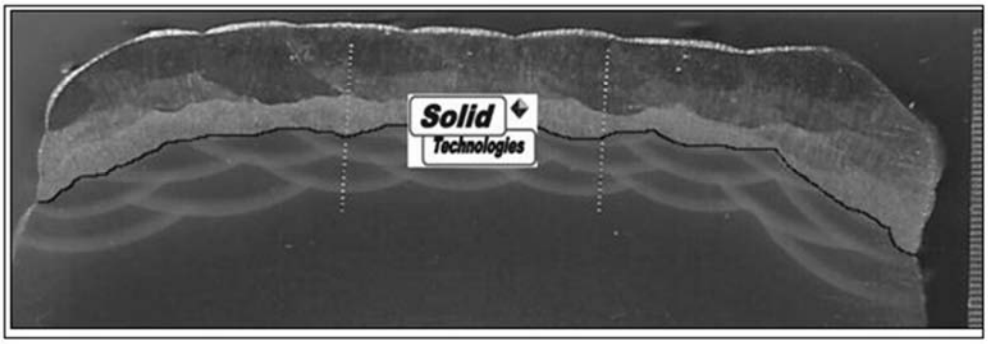
***Slika 9.*** *Dijagram za predviđanje mikrostrukture metala šava/faznih polja za FCAVSS prolaze šava i odgovarajući mehanizmi otpornosti na habanje. A predstavlja austenit, M je martenzit, F se odnosi na $\alpha$ ferit, a $\delta$-F je ferit koji se formira na visokim temperaturama, a B je bainit [8].*

Equivalents of Al and C were calculated according to equations:

$$[Al]_{eq} = wt\%\ Al + 0.5wt\%\ Mo + 0.43wt\%\ Si + 0.075wt\%\ Cr + 0.016wt\%\ W + 0.625wt\%\ V + 0.79wt\%\ Ti \quad (1)$$

$$[C]_{eq} = wt\%\ C + 0.018wt\ \%\ Mn + 0.04wt\%\ Ni \quad (2)$$

Cross-section of one welded joint with characteristic transformation temperatures, measured line hardness and welding conditions for material R35L3 on the first welded layer are presented are presented in Figure 10.




| R35L3 | $A_1$ [°C] | $A_3$ [°C] | Ms [°C] | Mf [°C] | $B_S$ [°C] | CE IIW | Hardness [HV] | WFS [“/min] | I [A] | U [V] | TS [mm/min] | HI [KJ/mm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lay. 1. | 735 | 873 | 379 | 164 | 451 | 1.04 | 425 p4 | 350 | 130 | 28 | 345 | 0.51 |

***Figure 10.*** *R35 weld deposit Layer 1 phase transformations.*

*HV10 (Preheat >Ms ) = 353.1 x CE(IIW) – 2.051 (3)*

*HV10 (Prehat <Ms) = 291.6 x CE(IIW) + 81.24 (4)*

***Slika 10.*** *Makro izgled navara sa karakterističnim temperaturama transformacije, uslovima navarivanja i izmerenim tvrdoćama*

*HV10 (predgrevanje >Ms ) = 353.1 x CE(IIW) – 2.051 (3)*

*HV10 (predgrevanje <Ms) = 291.6 x CE(IIW) + 81.24 (4)*

In Figure 11. the martensitic start temperature (MS) as function of carbon equivalent CE(IIW) and in dependence of welding layer is presented [9].

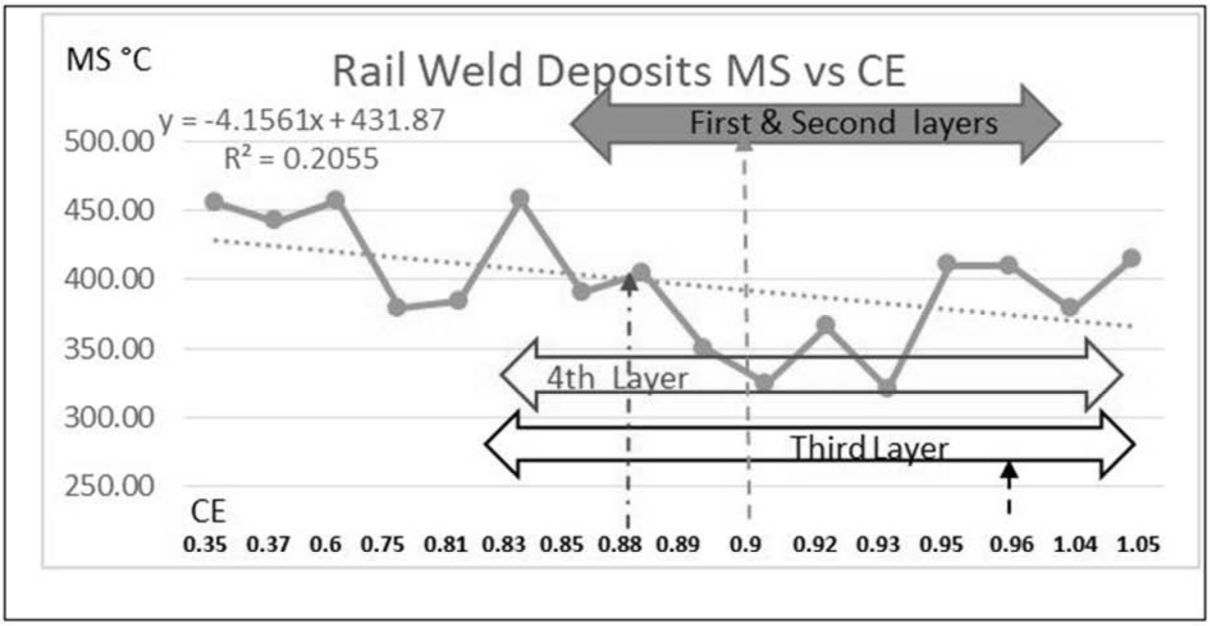



***Figure 11.*** *Martensitic Start temperature as function of CE(IIW) [9]*

***Slika 11****. Temperatura početka martenzitne transformacije MS u funkcija CE(IIV) [9]*

An example of the austenitic manganese weld with grain boundaries carbides and degradation of crossing in service along grain boundaries of weld repair is presented in Figure 12. [13]. In Figure 13, a failure analysis of broken rail revealed development of undesired martensitic phase in the weld overlay on high carbon head hardened rail [10].

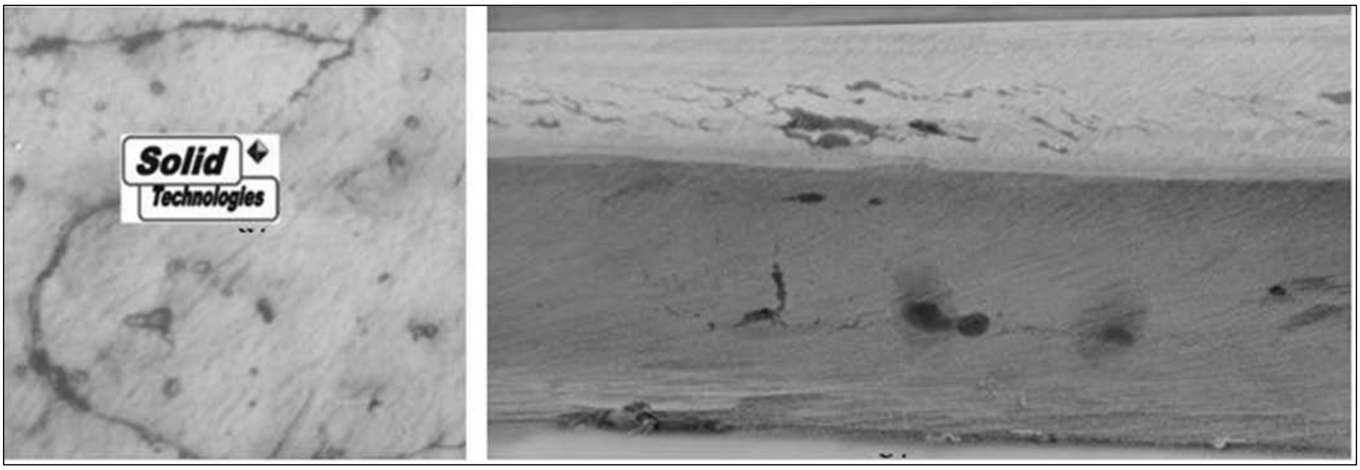



***Figure 12.*** *Austenitic manganese weld with grain boundaries carbides a) and degradation of crossing in service along grain boundaries of weld repair b)[13]*

***Slika 12***. *Austenitntno manganski var sa karbidima po granicama zrna a) i oštećenja duž granica zrna na repariranom šavu nastala tokom eksploatacije b) [13]*

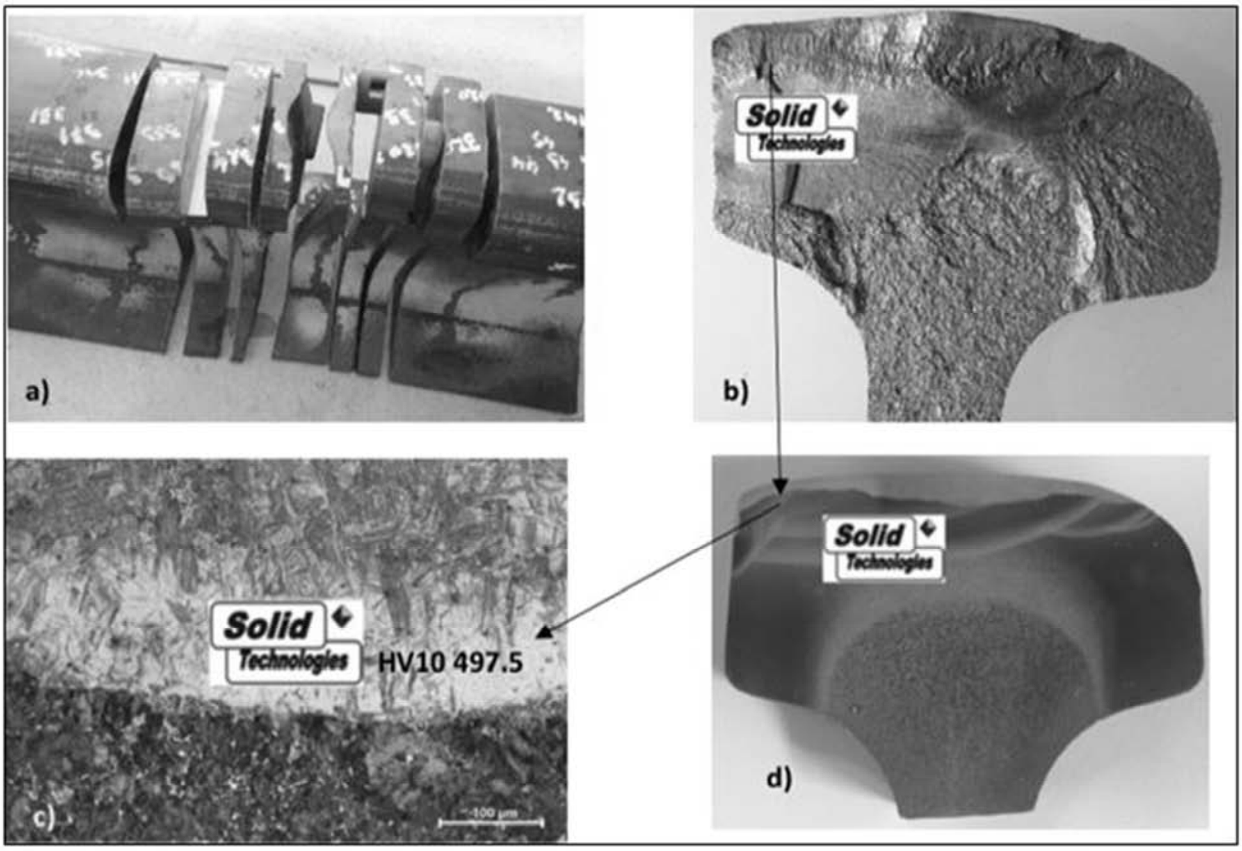



***Figure 13.*** *Failure analysis of broken rail revealed development of undesired martensitic phase in the weld overlay on high carbon head hardened rail [10]*

***Slika 13.*** *Analiza loma slomljene šine pokazala je nastanak i razvoj neželjene martenzitne faze u navarenom sloju šava kod otvrdnute glave visokougljenične šine [10]*

Welding procedure specification (WPS) for repair welding of carbon steel rail by the Flux Cored Self Shielded Arc (FCAWSS) welding process in Figure 14 is presented, and in Figure 15, another sample of the weld repairing is presented for the case of Termit weld which was overlayed with Solid Rail 30 weld deposit. Based on hardness measurements it is evident that HAZ is softened zone.

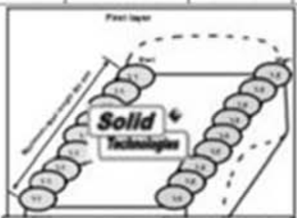
## WELDING PROCEDURE SPECIFICATION (WPS) [11]

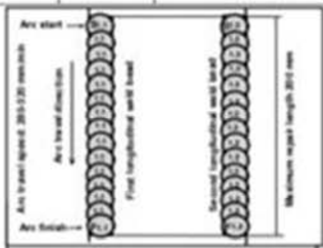
| | |
|---|---|
| PROJECT Weld Surfacing Repair of Wheel Burns, Squats, Thermit/Flush but dips, Rail Ends | WPS #: ST-RHC-1408-12 / DATE : |
| CLIENT: | WELDING CODE/ Applicable standards: N/A guidelines AS/NZS 2576, DIN 8555, EN 14700, AS 1085.20, AWS D15.2 |
| RAIL MAT. SPEC.: Carbon Steel Rail AS 1085.1, Standard and H. H. Rail | MATERIAL THICKNESS MAX 170 mm; THISCKNESS RANGE: All |
| REFERENCE: NATA: LS14-0530-03- VT; LS14-0530-03 MPI; LS14-0530-02 and | PREHEAT/MIN. INTERPASS TEMP.:350 °C; DON'T WELD BELOW 350 °C; Temp Verification: Infrared Thermometer and crayons. Temperature control 75-100 mm from the end of weld prep. |
| PWHT: NA; PREHEAT METHOD: Oxy-fuel. | MAX. INTERPASS TEMPERATURE:450 °C; DO NOT EXCEED 450 °C |
| JOINT TYPE/ POSITION: Flat weld overlay; 1G | Soaking Time at preheating temperature of 350 °C: 10 minutes |
| WELDING PROCESS: Flux Cored Arc Welding Self Shielded | Welding wire: Solid RAIL 30; P.N.: 1430B7D1205 |
| **OPERATORS: Solid Technologies**: | **POWER SOURCE, WIRE FEEDER:; CV or CC:** CV; **WELDING GUN:** |

NOTICE Prior to welding remove grease, rust and dirt. 100% NDT inspection dye-penetrants or magnetic particle inspection. For thermit weld dips prepare app. 90 mm each side from the centre of the thermit weld. Use grinding or air arc/plasma gouging. Establish defects (squats, wheel burns etc.) wear, defect pattern, size and estimate reference points for the surfacing depth, width and length (200 mm length and max 20 mm deep).

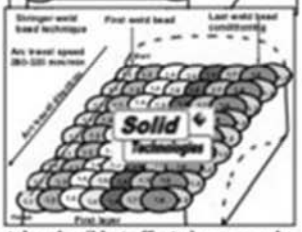
| Layer No. | Weld Bead (max. 10 weld beads per layer) | | WIRE: RAIL 30 SIZE (mm) | WIRE: RAIL 30 ESO (mm) | ± DC AC | CV or CC | WFS (mm/min) | Current (Amps) | VOLTS | TRAVEL SPEED (mm/min) | Heat Input kJ/mm |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 to 7 | 1.1 / 7.1 | 1.8 / 7.8 | 1.2 mm | 25 | DC+ | CV | 200-450 | 80-300 | 15-35 | 150-400 | 0.6-0.93 |

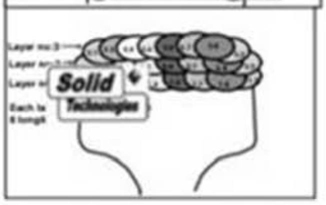

**Rail surface preparation details**




**Temp. control min 350 Max 450 °C**




**Bead sequence placement. Overlapping weld bead to commence in the toe of previous weld bead. Stringer Weld bead technique. Weld bead 1 is placed on one edge and weld bed 2 is placed on the opposite edge of the rail head, providing deposited metal and rail hat affected zone crack free and desired structure and properties.**


**75 to 90 °, drag angle, pull technique. To minimise spatter use 90 ° angle.**

**Weld Bead 1.1**


**Weld Bead 1.2**

**INTER-RUN CLEANING**: remove slag by chip/wire brush;
**DRESSING AND GRINDING AFTER WELDING:** After welding, excess metal shall be removed and the running surface finished by grinding.

**VISUAL INSPECTION AFTER WELDING**: No regions of under-fill, cracking, slag inclusions, lack of fusion, roll over, gas prosody, crater porosity, grinding burns or arc –strike, melted edges.

**AUTHORISED AND APPROVED BY:** Dr Milo Dumovic, Managing Director
Solid Technologies Pty. Ltd.
ABOBE PROCEDURE DETAILS ARE GUIDE ONLY

***Figure 14.*** *Welding procedure specification (WPS) for repair welding of carbon steel rail by the Flux Cored Self Shielded Arc Welding process*

***Slika 14.*** *Specifikacija postupka zavarivanja (WPS) za reparaturno zavarivanje šine od ugljeničnog čelika postupkom sa punjenom žicom sa samozaštitom*

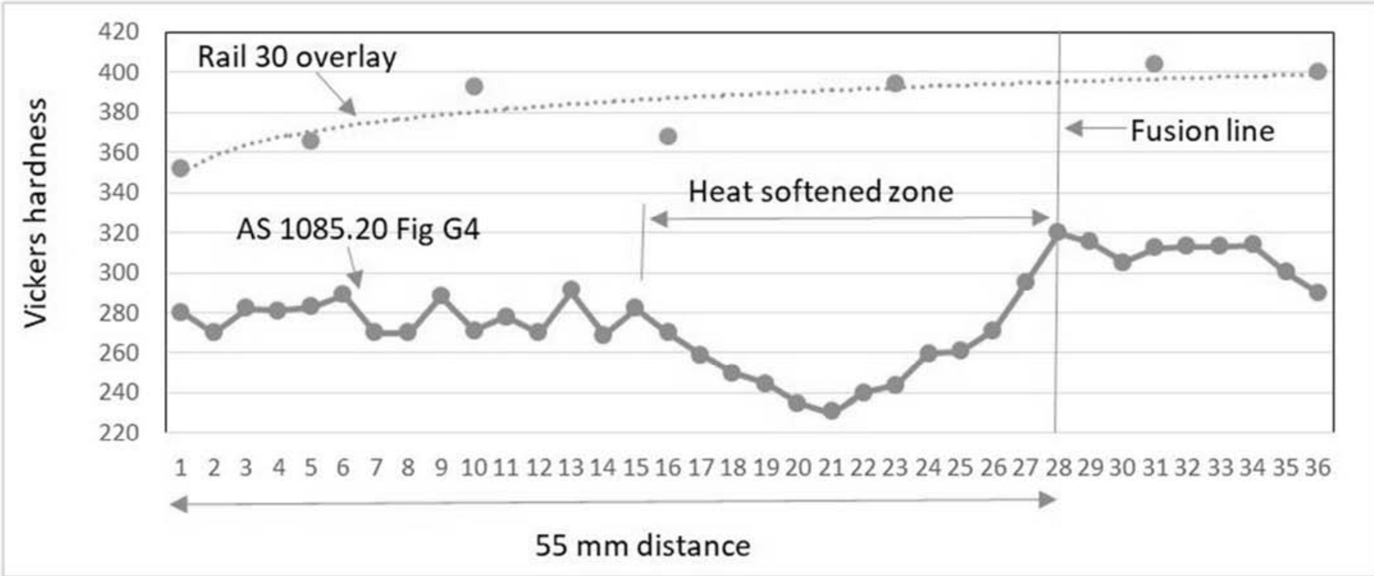



***Figure 15.*** *Soft HAZ of thermit weld overlayed with Solid Rail 30 weld deposit [12]*

***Slika 15.*** *Omekšana zona uticaja toplote (ZUT) aluminotermijski zavarenog spoja šine koji je navaren sa slojem Solid Rail 30 dodatnim materijalom [12]*

## 4. Conclusions

Flux cored semi-automatic arc welding maintenance of railroads and its components require complex metallurgical approach and solutions. High Carbon Rail steels require use of consumables which will develop pearlitic/ferritic weld deposits for standard rail; and bainitic weld deposits for head hardened rail. Dilution, distortion and phase transformations must be considered in order to avoid developments of undesired microstructures that could lead to catastrophic failure. While most of the standards are focused on the HAZ and its cracking, particular attention needs to be made to the first layer of weld deposit and in particular close to the fusion line up to 0.5 mm where carbon pick up from the rail parent material can cause formation of brittle structures. With austenitic manganese steels maximum weld interpass temperature is established at 260°C in order to avoid brittle carbide formation that could cause disintegration of the casting components. Wide varieties of alloys are available and development of proper Welding Procedure Specifications is essential to successful repair of the rail defects.

## 4. Zaključci

Održavanje pruga i njenih komponenti poluautomatskim elektrolučnim zavarivanjem sa punjenom žicom zahteva kompleksan metalurški pristup i rešenja. Čelici za šine sa visokim sadržajem ugljenika zahtevaju upotrebu dodatnog materijala koji će razviti perlitno/feritne slojeve navarivanja za standardnu šinu; i bainitne slojeve navara za glavu kaljene šine. Rastvaranje, distorzija i fazne transformacije moraju se uzeti u obzir kako bi se izbeglo stvaranje neželjenih mikrostruktura koje bi mogle dovesti do katastrofalnog kvara. Dok je većina standarda fokusirana na zonu uticaja toplote (ZUT) i njeno pucanje, međutim posebna pažnja treba da se posveti prvom sloju navara, a posebno blizu linije spoja do 0,5 mm gde porast sadržaja ugljenika iz osnovnog materijala šine može prouzrokovati formiranje krtih struktura. Kod austenitnitno manganskih čelika maksimalna temperatura međuprolaza pri zavarivanju je preporučena na 260°C, kako bi se izbeglo stvaranje krtih karbida koji bi mogli izazvati dezintegraciju komponenti spajanja. Veliki broj različitih dostupnih varijanti dodatnih materijala i razvoj odgovarajućih specifikacija procedura zavarivanja (WPS) je od suštinskog značaja za uspešnu popravku defekata šine.

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