

# Characterisation of High-Carbon Steel Surface Welded Layer

Olivera Popović<sup>1,\*</sup> - Radica Prokić-Cvetković<sup>1</sup> - Aleksandar Sedmak<sup>1</sup> - Vencislav Grabulov<sup>2</sup> -  
Zijah Burzić<sup>3</sup> - Marko Rakin<sup>4</sup>

<sup>1</sup>Faculty of Mechanical Engineering, University of Belgrade, Serbia

<sup>2</sup>Institute for Testing Materials, Serbia

<sup>3</sup>Military Technical Institute, Serbia

<sup>4</sup>Faculty of Technology and Metallurgy, Serbia

*In this paper microstructural and mechanical properties of high-carbon steel surface welded layer obtained with self-shielded flux cored wire are presented in standard rails and crossings. The testing results of tensile characteristics, hardness, toughness via instrumented Charpy pendulum, microstructural analysis and fatigue crack growth resistance of all characteristic zones are analyzed in detail, especially from the point of view of interaction between microstructure and properties.*

*The obtained results indicate superior properties of repaired welded layers, which is due to their similarity to the new generation of bainitic steel, i.e., due to the change of microstructure from original pearlitic structure to final bainitic structure. Finally, fatigue crack growth parameters have shown that deposit layer has higher resistance than the crack growth, improving overall reliability of rails and crossings.*

©2010 Journal of Mechanical Engineering. All rights reserved.

**Keywords:** surface welding, toughness, fatigue crack growth parameters, bainitic microstructure

## 0 INTRODUCTION

High-carbon steels are widely used for rails and crossings due to their high hardness and strength. Because of their pearlitic microstructure, these steels typically have low toughness and crack growth resistance, making them prone to wear and rolling contact fatigue. This causes rails to become unfit for service due to unacceptable rail profiles, cracking, spalling and failures. Degradation of rail depends on the complicated interaction between wear mechanisms, fatigue crack initiation and growth rates, which affect rail life [1].

A few different fracture control concepts are applied in railway systems, one of them being the damage tolerance concept [2]. Within the frame of this concept, the possibility of fatigue crack growth is basically accepted. The aim is to prevent the crack to grow to its critical size during the lifetime of the component, i.e. to estimate number of cycles to a critical crack size.

Damaged parts produced from high-carbon steel can be surface welded in spite of their poor weldability. With a proper choice of welding technology, it is possible to get a microstructure with improved properties, corresponding to the new steel generation, i.e. bainitic microstructure.

In that case, surface welded layer has higher resistance than the crack growth, improving overall reliability of rails and crossings. Such technology is not only a way of reparation, but also a way of improving the initial properties of rails and crossings. Therefore, the aim of the present paper is to compare and analyze mechanical and microstructural properties of high-carbon steel as a base metal and surface welded layer, obtained by optimal welding technology.

## 1 APPLICATION OF SURFACE WELDING FOR RAIL STEEL REPARATION

For surface welding semi-automatic arc welding processes, with flux-cored and self-shielded wires are mostly used. The basic difference between them is that the first one requires an external shielding gas, and the second does not. In both cases, the core material acts as a deoxidizer, helping to purify the weld metal, generate slag formers. Also, by adding alloying elements to the core, it is possible to increase strength and provide other desirable weld metal properties [3] and [4]. These processes have slowly replaced the MMA process and are quite ideal for outdoors in heavy winds. The result of

\*Corr. Author's Address: Faculty of Mechanical Engineering, University of Belgrade,  
80 Kraljice Marije Str., 11000 Belgrade, Serbia, opopovic@mas.bg.ac.rs

flux-cored wire application is higher quality welds, faster welding and a maximization of a certain area of welding performance. Most frequently, surface welding is performed in three layers, sometimes with a buffer layer. It is necessary to obtain structural compatibility with base metal and good properties of HAZ (heat affected zone). Furthermore, by proper chemical composition of filler material it is possible to get the desirable microstructure of the final surface layer.

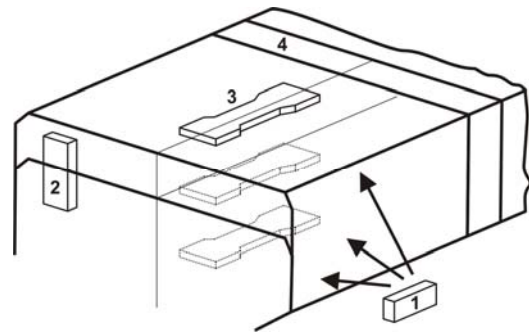
The final surface layer microstructure is the result of a complex influence of many factors: the type of filler material, heat input, mixture degree with the previous layer and post heat treatment with the next layer, because each subsequent pass alters the structure in the heated regions of the previous pass. Considering the interactions of all the mentioned parameters, insufficient literature data about the obtained results, i.e. mechanical and microstructural properties, is not surprising.

## 2 EXPERIMENTALS

The material used in present work is pearlitic steel, received in the form of rails, type UIC860 S49, which is the most common rail type on domestic railroads (Table 1). The steel is surface welded by semi-automatic process, with self-shielded wire (FCAW-S). The properties of filler material are given in Table 2.

Surface welding is carried out in three layers. Heat input during welding was approx. 10 kJ/cm and the preheating temperature was 230 °C, since the CE equivalent was 0.64. The controlled interpass temperature was 250 °C.

Specimens for further investigation were prepared from surface welded rail head, according to Fig. 1. The microstructure of the specimens was examined using an optical microscope with magnification 500-times.



- 1- specimen for toughness and crack growth resistance estimation
- 2- specimen for microstructural analysis
- 3- tensile specimens
- 4- specimen for hardness measurements

Fig. 1. Specimens from surface welded rail head

Hardness measurements were performed using a load of 100 Pa. The tensile specimens with a thickness of 2 mm, were taken from each zone and tested at room temperature. Notched specimens were also prepared. Impact testing was performed at room temperature, according to EN 10045-1, i.e ASTM E23-95, with Charpy specimens, V notched in base metal (BM), weld metal (WM) and HAZ, on the instrumented machine SCHENCK TREBEL 150 J. Fatigue crack growth tests were performed on the FRACTRONIC dynamic testing device in the FRACTOMAT system, with standard Charpy specimens, at room temperature, under the ratio  $R = 0.1$ . A standard 2 mm V notch was located in BM (specimen No. 1), and in WM and HAZ (specimen No. 2), which provides an estimation parameters for both zones. In both cases, a crack was initiated from the surface and propagated into HAZ, in accordance with previous discussion [2], enabling calculation of crack growth rate  $da/dN$  and fatigue treshold  $\Delta K_{th}$ .

Table 1. Properties of base metal

Chemical composition [%]							Tensile strength $R_m$ [N/mm <sup>2</sup> ]	Elongation $A_c$ [%]
C	Si	Mn	P	S	Cu	Al		
0.52	0.39	1.06	0.042	0.038	0.011	0.006	680-830	≥14

Table 2. Properties of filler material

Wire designation	Wire diam. [mm]	Chemical composition [%]							Hardness, HRC
		C	Si	Mn	Cr	Mo	Ni	Al	
OK Tubrodur 15.43 (self-shielded wire)	1.6	0.15	<0.5	1.1	1.0	0.5	2.3	1.6	30-40

3 RESULTS AND DISCUSSION

The hardness profile of the surface welded joint is shown in Fig. 2. The lowest hardness was found in the base metal (250 to 300 HV), which is the hardness of naturally cooled standard rails [5] and [6]. In HAZ, hardness increase was noticeable due to complex heat treatment and grain refinement. The hardness of II and III welded layer was the highest due to the influence of alloying elements in filler materials, which shift transformation points to bainitic region. Maximum hardness level of 350 to 390 HV was reached in surface welded layers and it provides improvement in mechanical properties and wear resistance [5]. Even though hardness generally has a positive effect on rail wear, higher hardness values could cause intensive wheel damage, so the final layer hardness must be a limitation for choice of the filler material. The room temperature mechanical properties (ultimate tensile strength, UTS) of the surface welded joint are shown in Table 3.

Table 3. Mechanical properties of surface welded joint

	Base metal	HAZ	Weld metal
UTS [MPa]	960	1150	1210

Total impact energy, as well as crack initiation and crack propagation energies, are

Table 4. Instrumented impact testing results of Charpy V surface welded joint specimens

	Specimen No.	Total impact energy, $E_u$ [J]	$E_u$ [J]	Crack initiation energy, $E_{in}$ [J]	$E_{in}$ [J]	Crack propagation energy, $E_{pr}$ [J]	$E_{pr}$ [J]
Base metal	1	5	5	4	4	1	1
	2	5		4		1	
	3	4.5		4		0.5	
HAZ	1	14	12	12	10	2	2
	2	13		10		3	
	3	8		7		1	
Weld metal	1	27	25	14	15	13	10
	2	20		14		6	
	3	27		16		9	

presented for all surface welded joint zones (Table 4).

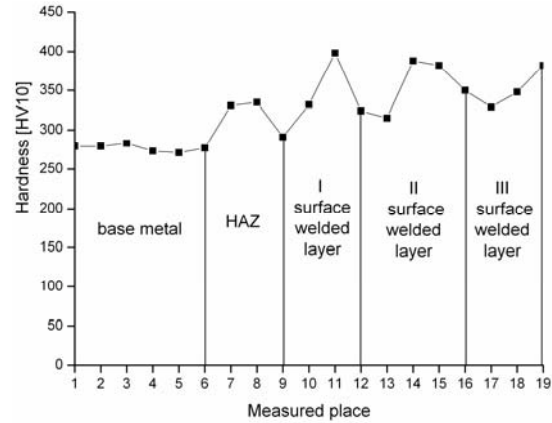


Fig. 2. Hardness profile along the joint cross-section

Special attention has to be paid to very low total energy of the base metal (5 J), due to very hard and very brittle cementite lamellae in pearlite. By surface welding, toughness of weld metal and HAZ increases, so HAZ is not a critical microstructure in welded joint. A large increase of weld metal toughness compared to base metal (5-times) results from the presence of Ni and Mn in filler material, as well as Mo, which promotes formation of needed bainitic microstructure [7].

In all surface welded joint zones, initiation energies were higher than the propagation energies (Fig. 3).

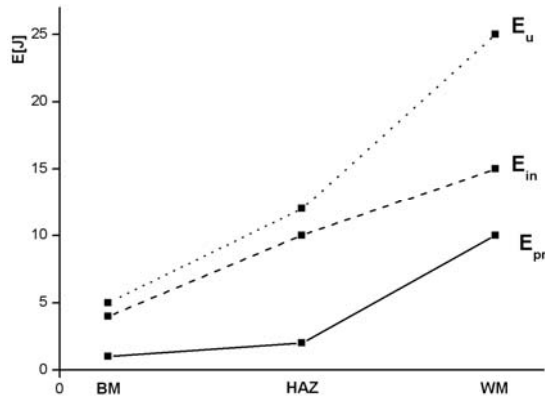


Fig. 3. Results for impact energies

The results of crack growth resistance parameters, i.e., obtained relationship  $da/dN$  vs.  $\Delta K$  for base metal is given in Fig. 4, and for weld metal and HAZ in Fig. 5. Parameters  $C$  and  $m$  in

Paris law, together with fatigue threshold  $\Delta K_{th}$  and crack growth rate values are given in Table 5 for base metal, surface weld metal and HAZ, as obtained from relationships given in Figs. 4 and 5, respectively, for corresponding  $\Delta K$  values.

In Fig. 5 a change of fatigue crack growth rate during crack propagation from WM to HAZ is clearly shown, i.e. there is an obvious transition in the curve slope (lower slope, lower crack growth rate in WM and higher slope, higher crack growth rate in HAZ). More precisely, because weld metal specimen consists of two layers (the third layer is used for V notch), two slope changes can be seen and two values of crack growth rate have been estimated. The crack growth rate in base metal is 3 to 4-times higher than in both weld metal layers, i.e. the growth of the initiated crack will be slower in weld metal layers. This means that for the same value of stress intensity factor rang  $\Delta K$ , base metal specimen needs fewer cycles of variable amplitude than weld metal specimen, for the same crack increment [8].

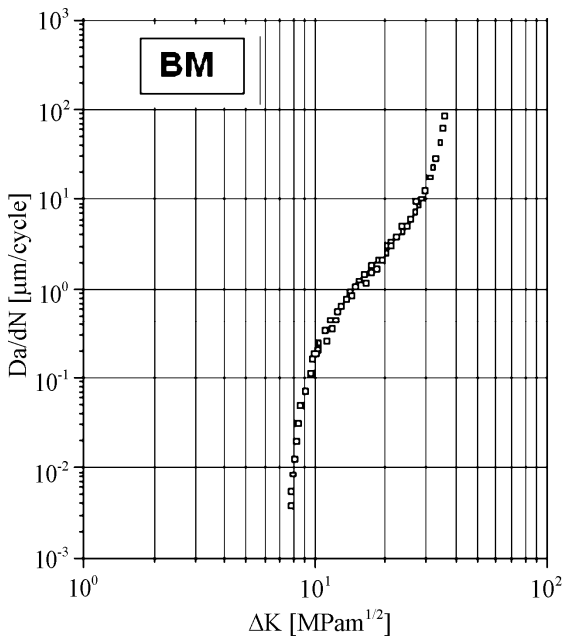


Fig. 4. Diagram  $da/dN$  vs.  $\Delta K$  for base metal

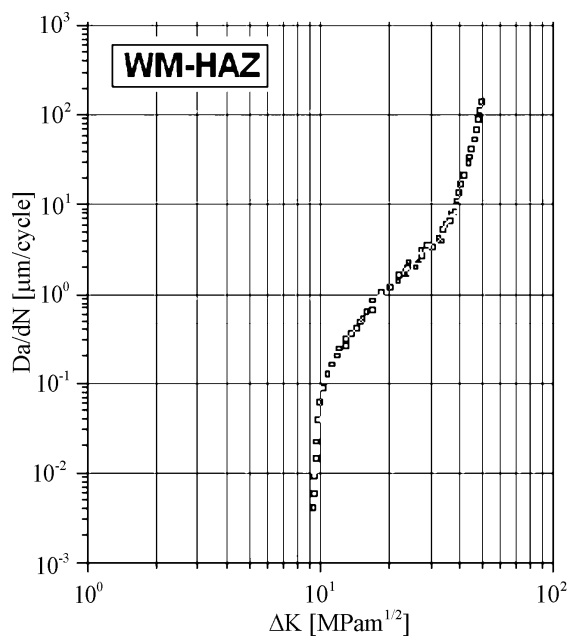


Fig. 5. Diagram  $da/dN$  vs.  $\Delta K$  for WM and HAZ

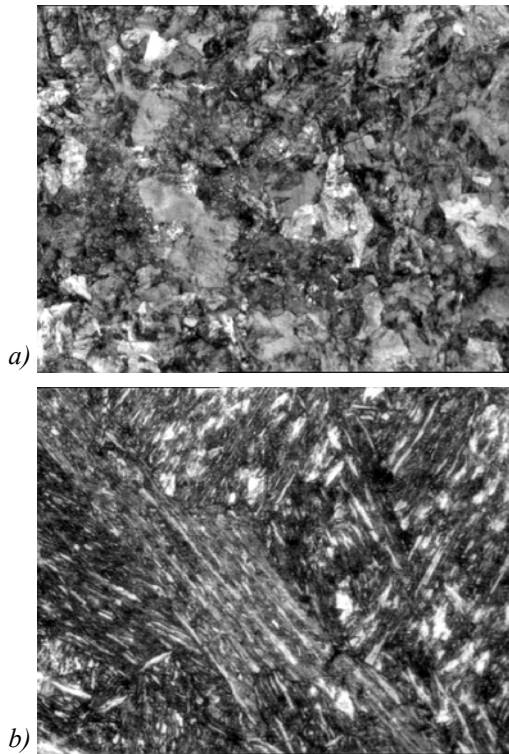


Fig. 6. Microstructure of base metal and final surface welded layer(500 x) a) a typical pearlitic microstructure with a fine lamellar aggregate of very soft and ductile ferrite and very hard carbide (cementite); b) the microstructure of final surface welded layer consists of bainite and small fractions of pearlite and ferrite.

Besides crack growth rate, fatigue threshold value  $\Delta K_{th}$  is also a representative parameter for comparison. Fatigue threshold value  $\Delta K_{th}$  in base metal ( $\Delta K_{th} = 8 \text{ MPa m}^{1/2}$ ) is lower than fatigue threshold value  $\Delta K_{th}$  in weld metal ( $\Delta K_{th} = 9.5 \text{ MPa m}^{1/2}$ ). Therefore, the crack in base metal will be initiated earlier, i.e. after less number of cycles,

than in weld metal. The values of fatigue threshold and crack growth rates correspond to initiation and propagation energies in impact testing, and in this case, good correlation is achieved [8].

Fig. 6 shows microstructures of base metal and final surface welded layer.

This microstructural observation is a final confirmation of all the previous results, i.e the fact that pearlitic and bainitic steels have been compared. Structural and mechanical properties of the obtained layers indicate that they are more similar to the new rail steel generation-bainitic steel than to the original pearlitic base metal.

#### 4 CONCLUSION

1. It has been shown that in spite of high-carbon steels poor weldability, i.e. susceptibility to welding defects, they can be successfully surface welded.
2. Maximum hardness level of 350 to 390 HV is reached in surface welded layers, compared to the hardness of base metal (250 to 300 HV). The obtained hardness values ensure a simultaneous improvement of mechanical properties and wear properties. In the case of rails, maximum hardness prevents wheel wear.
3. The most improved results are obtained for impact properties. The toughness of base metal (5 J) is five times lower than the toughness of weld metal (25 J), and more than twice lower than the toughness of HAZ (12 J). The higher crack initiation crack propagation energy is characteristic of all the zones, which should be kept in mind during the design and exploitation.

Table 5. Parameters  $C$ ,  $m$ ,  $\Delta K_{th}$  and crack growth rate values for all zones of surface welded joints

Zone of surface welded joint	Fatigue threshold [MPa m <sup>1/2</sup> ]	Parameter		Crack growth rate $da/dN$ , [m/cycle]			
		$C$	$m$	$\Delta K = 10$ [MPa m <sup>1/2</sup> ]	$\Delta K = 15$ [MPa m <sup>1/2</sup> ]	$\Delta K = 20$ [MPa m <sup>1/2</sup> ]	$\Delta K = 30$ [MPa m <sup>1/2</sup> ]
BM	8.0	$3.31 \cdot 10^{-11}$	3.28	$6.31 \cdot 10^{-08}$			
WM 1	9.5	$4.45 \cdot 10^{-13}$	3.74		$1.11 \cdot 10^{-08}$	-	-
WM 2		$3.78 \cdot 10^{-13}$	3.61		-	$1.88 \cdot 10^{-08}$	-
HAZ		$4.07 \cdot 10^{-13}$	3.79		-	-	$1.61 \cdot 10^{-07}$

4. The results show that base metal is characterized by a lower fatigue threshold than weld metal, i.e. a 3 to 4-times higher crack growth rate. This means that crack will initiate more likely in base metal, and that it requires fewer cycles to reach the critical size. Contrary to a typical welded joint, a surface welded layer is the safest place for crack initiation.
5. Testing results of base metal and surface welded layer reflect a typical behavior of two steel microstructures - pearlitic and bainitic, which has been confirmed through microstructural investigation.

#### 5 REFERENCES

- [1] Eden, H.C., Garnham, J.E., Davis, C.L. (2005). Influential microstructural changes on rolling contact fatigue crack initiation in pearlitic rail steels. *Materials Science and Technology*, vol. 21, no. 6, p. 623-629.
- [2] Zerbst, U., Madler, K., Hintze, H. (2005). Fracture mechanics in railway applications - an overview. *Engineering Fracture Mechanics*, vol. 72, p. 163-194.
- [3] Lee, K. (2001). Increase productivity with optimized FCAW wire. *Welding design & Fabrication*, vol. 74, no. 9, p. 30.
- [4] Sadler, H. (1997). Including welding Engineer, *Welding design & Fabrication*, vol. 70, no. 6, p. 74.
- [5] Singh, U.P., Roy, B., Jha, S., Bhattacharyya, S.K. (2001). Microstructure and mechanical properties of as rolled high strength bainitic rail steels. *Materials Science and Technology*, vol. 17, no. 1, p. 33-38.
- [6] Lee, K.M., Polycarpou, A.A. (2005). Wear of conventional pearlitic and improved bainitic rail steels. *Wear*, vol. 259, p. 391-399.
- [7] Aglan, H.A., Liu, Z.Y., Hassan, M.F., Fateh, M. (2004). Mechanical and fracture behaviour of bainitic rail steel. *Journal of Materials Processing Technology*, vol. 151, p. 268-274.
- [8] Popović, O. (2006). Investigation of influence of filler material and heat input on microstructure and properties of high carbon steel surface welded, Ph.D.Thesis, University of Belgrade (in Serbian).