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Resistance Welding of High-Manganese Cast Steel with Unalloyed Steel Rails

E. Tasak [a]*, A. Ziewiec [a], L. Tuz [a]
[a] Faculty of Metals Engineering and Industrial Computer Science, AGH, University of Science and Technology,
al. A. Mickiewicza 30, 30-059 Cracow, Poland
* Corresponding author's e-mail: tasak@agh.edu.pl

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Abstract

The paper presents the influence of resistance welding parameters on the mechanical properties and structure of joints of the unalloyed steel rail and high-manganese crossover. As the spacer Cr-Ni austenitic cast steel with decreased austenite stability was used. The results show, that the austenitic cast steel with metastable structure of austenite provide to high strain hardening of spacer deformation during operation. The high increase of hardness is the result dislocation hardening and the transition of austenite into martensite. The content of ferrite δ and martensite was measured by metallographic method and verified by X-ray diffraction phase analysis. Moreover, it was shown that to high welding parameters causes the cracks in HAZ of manganese iron cast and in the spacer near to fusion line with unalloyed cast steel. The reparation of cracks can be made by welding methods.

Key words: Crossovers welding, Hadfield cast steel, Austenitic spacer, Dissimilar metals welding

1. Introduction

The rail frogs and crossovers are currently produced of a high-manganese cast steel (GX120Mn13 Hadfield steel). Welding of austenitic high-manganese cast steel and unalloyed steel rails brings nonapplicable quality of joints. For that reason, the high-manganese cast steel and rails wielding process is carried out with the use of resistance welding method with austenitic chromium-nickel cast steel or steel spacer [1]. The process is covered by patents [2-5]. Moreover, the patent [2] covers the welding technology and the X10CrNiTi18-9, X10CrNiNb18-10, X5CrNiNb18-10 steels for the spacer. In the home patent [3], instead of the resistance welding of spacer, the pad welding process of austenitic Cr-Ni steel on the unalloyed steel were applied. Such performed spacer was resistance welded with high-manganese cast steel. The disadvantage of joints according to patents [2, 3] is lower wear resistance of austenitic Cr-Ni spacer. On the running surface in the spacer place the cavity may occur even after relatively short operation time. This causes the rapid wear of adjacent regions of high-manganese cast steel crossover and the unalloyed steel rail. In order to eliminate this phenomenon, in the patents [4, 5] involved the application of new material for spacer, such as austenitic or semiaustenitic cast steel. During operation the self-hardening is proceeded what caused the extend lifetime of joint.

2. Materials and research methods

The material tested were steel rails made of the R350HT grade welded with high-manganese GX120Mn13 cast steel. Chromium-nickel austenite cast steel with a lower austenite stability with the chemical composition of X5CrNi17-7 steel was used as the spacer [4]. The chemical composition of the steel is selected in such a way that it provides the austenitic-ferritic-martensitic structure. During operation, when the wheels are in contact with the rail head, in addition to work hardening, there is a further phase transformation of the austenite to martensite. This causes the increase of the spacer hardness to the level of a hardened high-manganese cast steel. In comparison to the previously applied solutions, this phenomenon should provide a better stability of the welded joint.

The welding was performed on an industrial Schlatter welder. An example of welded joint and the longitudinal cross-section of joints are presented in Figures 1 and 2 respectively. The tests were carried out for the joints made with used the various length of austenitic spacer and process parameters.

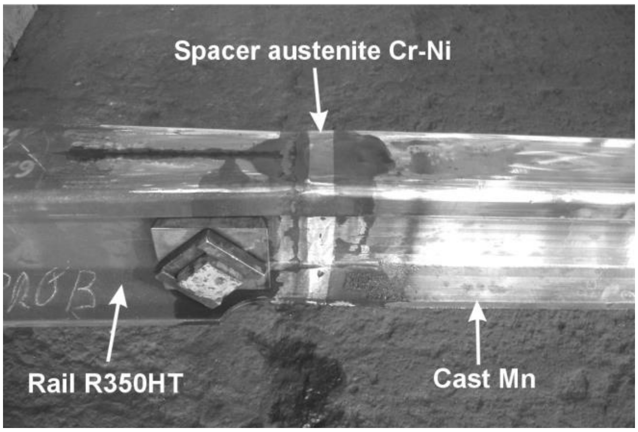


Fig. 1. The high-manganese cast steel with wing rails resistance welded joint with the austenitic Cr-Ni spacer

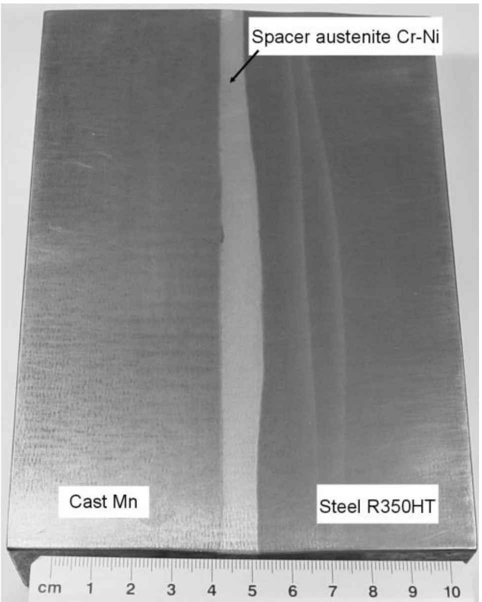


Fig. 2. The longitudinal cross-section of resistance welded joint with ca. 5 mm width spacer

For the above mentioned welds the following tests were carried out:

- technological static bending test of joint,
- non-destructive and visual testing,
- microscopic tests,
- X-ray diffraction phase analysis and metallographic quantitative analysis,
- hardness measurements,
- simulations of hardening and structural transformations during the surface deformation of the rail head,
- welding defects regeneration.

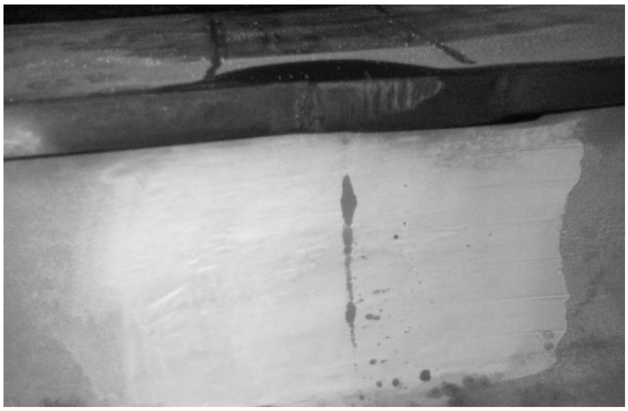
3. Tests results

3.1. Technological static bending test

The quality of welded joint acc. to PN-EN 14587:2013 standard is assessed by static bending test. The section of the welded rails with the length of 1150 mm is mounted on supports and bent on a press. The pressure mandrel should be placed in the area of the weld. The criteria for evaluation are the values of deflection and the bending force at which the crack is obtained. In the analysed sample, the cracking of joints occurred with the load of 1170 kN and the deflection of 21 mm. The criterion acc. to PN-EN 14587:2013 for welded joints of R350HT steel rails with austenitic spacer is the minimum breaking force equals 850 kN.

3.2. Non-destructive and visual testing

The penetration testing of joints made with the low and medium values of welding parameters did not disclose any defects. However, those made with high values disclose the metal discontinuity (crack) in the heat affected zone (HAZ) on the high manganese cast steel side (Fig. 3).



Fig, 3. Crack in the heat affected zone (HAZ) on the high manganese cast steel side

3.3. Microscopic testing

The microscopic testing was carried out on the good joints and with defects such as pores and cracks. The microstructure of 17-7 type cast steel spacer is presented in Figure 4. In the austenitic microstructure of spacer are visible also ferrite δ and martensite α' formed during cooling the steel after welding. The martensite presence indicates that the martensitic transformation temperature M_s is above the room temperature. The dilatometric test of spacer [7] shows that the temperature of beginning austenite into martensite transformation M_s equals ca. 160°C. The literature provides various equations for Ms calculation based on the chemical composition, but the results for analysed spacer have very wide range, from –84°C to +145°C. Only the temperature M_s=145°C calculated from the equation presented in [8]:

$$M_s [K] = 764,2 - 302,6(\%C) - 30,6(\%Mn) - 16,6(\%Ni) + \\ - 8,9(\%Cr) + 2,4(\%Mo) - 11,3(\%Cu) + 8,58(\%Co) + 7,4(\%W) + \\ - 14,5(\%Si)$$

is similar with those obtained by dilatometric test.

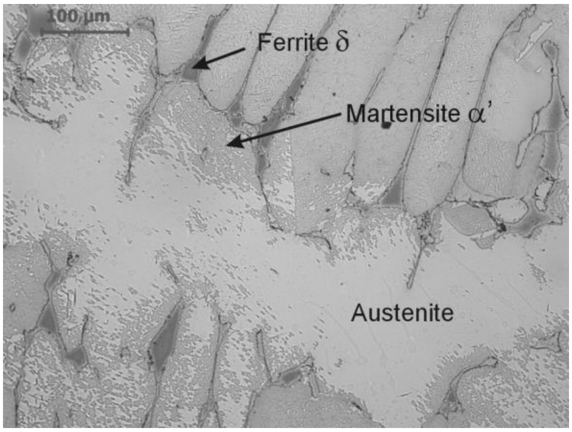


Fig. 4. Microstructure of X5CrNi17-7 cast steel spacer. Ferrite δ (dark) and martenzite α'on the background of austenite. Visible the segregation influence in the interdendritic regions on the austenite stability

The volume fractions of ferrite δ and martensite α' were determined by X-ray diffraction phase analysis and metallographic quantitative analysis. The ferrite δ percentage measurement by the second method consisted in an analysis of a dozen of microstructure photographs taken in randomly selected areas followed by their analysis with the use of the Sigma Scan Pro computer program. The evaluated content of ferrite δ is equal 8,3% and martensite α' from 15% to 46%. Such a wide range of martensite α' content is a result of various austenite stability observed in the sample selected from different places in the rail. Due to nickel segregation, the martensite α' content in the samples from the middle is lower than in those from near to surface. X-ray diffraction phase analysis show the total content ferrite δ and martensite α' from 25% to 55%. The obtained results are similar for both testing methods.

The microstructure evaluation of weld on the perlitic steel does not show defects such as slag, inclusions, lack of fusion either. Only, in the process with high value of parameters the molten metal and stirring of the spacer with unalloyed steel were occurred (Fig. 5). The molten and stirred metal was not removed during squeezing. It caused the occurrence the martensitic microstructure with the Knoop' microhardness of 939 HK0.05 (ca. 970 HV) [9]. The melting of grain boundaries in the perlitic steel causes to high temperature of welding process.

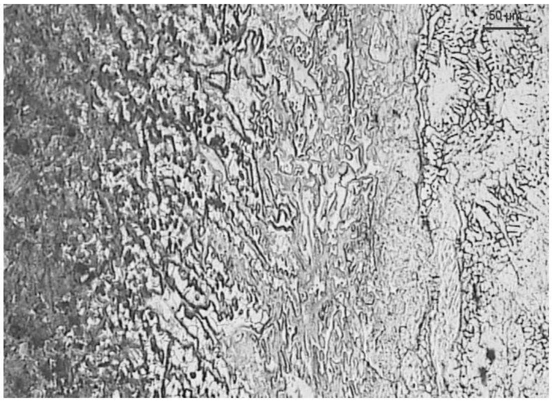


Fig. 5. Microstructure of region near to fusion line between spacer and rail. Visible stirred metals near to fusion line and disadvantageous martensitic microstructure

Microstructure of weld at the high-manganese cast steel side is presented in Figure 6. Austenitic microstructure is observed in the high-manganese cast steel. Near to fusion line the segregation or deformation bands are observed. Detailed analysis of those regions obtained the phase ε (martensite ε) bands and martensite α' in the bands crossing. Those phases underwent from manganese austenite with decreased stability in the cooling process. The martensite presence are proved by magnetic testing with the use of the microscopic magnetic phase identification station [7].

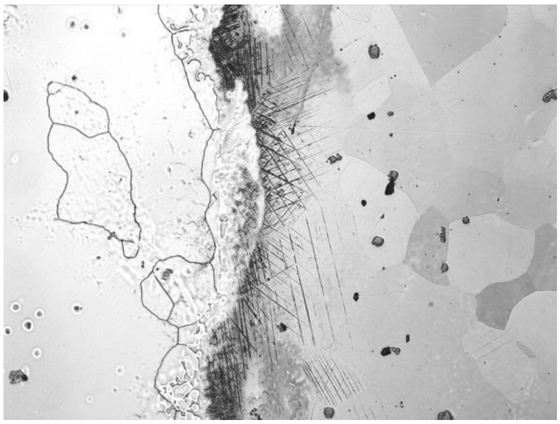


Fig. 6. Microstructure of the region near to fusion line between spacer and high-manganese cast steel

The explanation of those phases is following. The liquid metals occurred in the welding process is not removed during squeezing. The slowly cooling of this region caused the carbon and manganese diffusion to the austenitic spacer. The manganese austenite, depleted of carbon and manganese in the cooling process undergoes transformation to ε phase and martensite α'. Those phases are disadvantageous due to their location in the plane and caused the brittle cracking.

3.4. Hardness distribution and rail surface hardening ratio testing

The hardness distribution on the cross-section of joint after welding process and simulated operation is presented in Figure 7. The obtained hardness values are following: in the austenitic high-manganese cast steel ca. 230 HV10, in the austenitic Cr-Ni spacer ca. 210 HV10 and in the rail steel w HAZ near to fusion line ca. 370 HV10. The hardness after simulated operation increased in the spacer to ca. 510 HV10, and in the high-manganese cast steel to ca. 600 HV10.

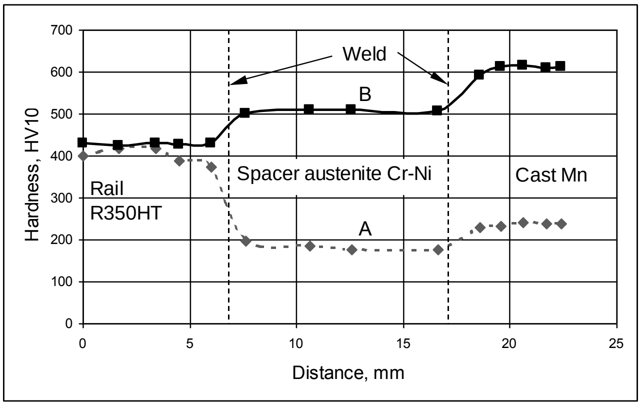


Fig. 7. Hardness distribution in the cross-section of welded joint with the GX5CrNi17-7 cast steel spacer; A – after welding, B – after surface hardening

The hardness measurement results comparison showed that the Cr-Ni with metastable austenite cast steel spacer deformation caused the hardness increase by 2.5 times in the spacer and by 2.6 times for the he high-manganese cast steel surface. The strong hardening is the result of dislocation reinforcement and the phase transformation of austenite into martensite α' in the spacer and dislocation reinforcement, the twinning and the phase transformation of austenite into martensite ε and α' in the high-manganese cast steel (Hadfield).

The strong hardening degree in the rail head of high-manganese cast steel rail and X5CrNi17-7 with metastable austenite cast steel spacer should guarantee good wear resistane of welded joints.

The application of this welding technolology and new material for spacer in KZN Bieżanów is resulted over 30 joints of rail steel R350HT with the high-manganese cast steel. Joints have been manufactured in rail crossovers for national railways since 2012. Periodic service of the crossovers occurs very good properties in the operation.

3.5. Welding defects regeneration

The cracks in the fusion lines were obtained by the penetration testing. The microscopic testing of cracks obtained their propagation in the high-manganese cast steel in the distance of 1 to 2 mm from fusion line and in the austenitic spacer in the region of stirred metals either. The applicable method of regeneration of short cracks was grinding and welding. It was prepared the welding process specification (WPS) including the placement of defects. Figures 8 and 9 present the scheme of regeneration of welded joints in the rail head with cracks in the unalloyed steel and in the high-manganese cast steel.

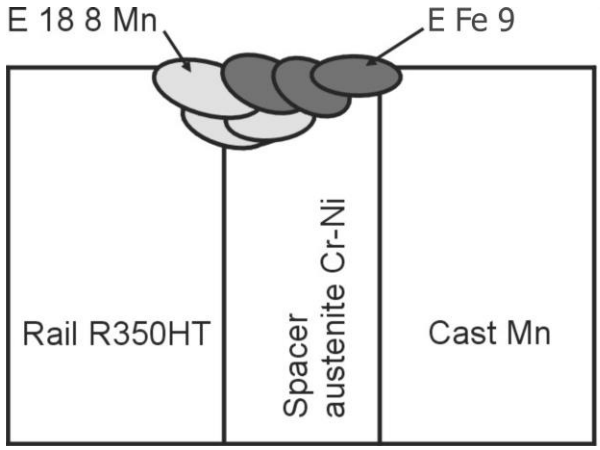


Fig. 8. The method of regeneration of weld defect in the rail head on the R350HT steel rail

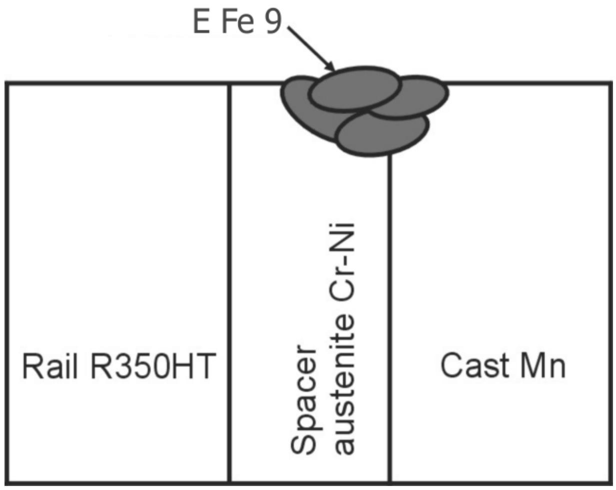


Fig. 9. The method of regeneration of weld defect in the rail head on the high-manganese cast steel rail

The main problem occurring in the regeneration of high-manganese cast steel is susceptibility to hot cracking in weld and HAZ. The cracks in HAZ are caused by manganese cementite presence in the austenite grain boundaries. Even thin layer of cementite in the grain boundaries cased the equilibrium melting [10] and further cracking. An example of crack is presented in figure 10.

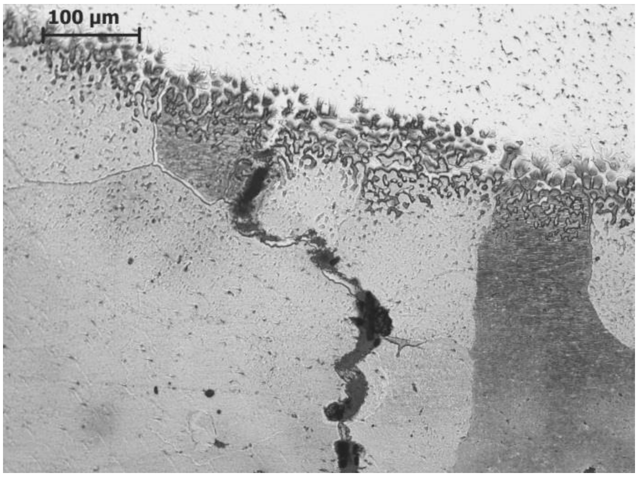


Fig. 10. Microstructure in the fusion line region on the high-manganese cast steel. Visible crack cased by the equilibrium melting of austenite grain boundaries

4. Conclusions

The main conclusions are listed as follow:

- The macro- and microscopic tests on a joint with a plate made of austenitic cast steel of a lower austenite stability showed correct joint geometry. The welding line, both at the side of the manganese cast steel and of the rail steel, does not demonstrate welding defects. This is proven by the high value of the deflection, the required level of break force of the joint during the bending tests and the localization of the fracture in the R350HT steel.
- The structure of the plate consists of austenite, ferrite δ and martensite α'. During the operation of the wheel with the head surface, further austenite $\rightarrow$ martensite α' phase transformation takes place, causing self-hardening of the spacer, which prevents the creation of a cavity on the surface of the rail head in the area of the austenitic spacer.
- The deformation of the rail head in the joint area by the hammering method, which simulates joint reinforcement during operation, confirmed the course of the austenite $\rightarrow$ martensite α' phase transformation in the austenitic X5CrNi17-7 cast steel spacer and the increase of hardness up to the level of 510 HV10. In a manganese cast steel rail, surface reinforcement, as a result of hammering, causes a hardness increase up to 600 HV10. Such a high degree of plate reinforcement guarantees high wear resistance of the welded joint.
- The metallographically measured percentage of δ ferrite in the austenitic steel spacer is 8,3%.
- The martensite content depends on the measurement placement and in the middle of cast is ca. 15% whereas near to surface is even 46%. The total content of ferrite and martensite in the hardened layer determined by the X-ray phase analysis equals about 55%. The measurement results for the ferrite and martensite α' amounts performed metallographically and by the method of an X-ray phase analysis are thus similar.
- The tests on the joint of high-manganese cast steel welded with a R350HT steel rail by means of an austenitic cast steel spacer fully confirmed the assumptions and expectations with regards to the rail crossover joints with rails. The application of a austenitic cast steel with decreased austenite stability spacer makes it possible to obtain a joint with similar reinforcement of manganese cast steel and spacer caused increased wear resistance in the operation process.
- In case of the welding defects occurrence applicable is regeneration by welding methods. There is need to consider of possibility of hot crack occurrence in the austenitic microstructure of weld metal or in the HAZ of high-manganese cast steel.

Acknowledgement

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