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Original scientific paper

Correlation between Microstructure and Hardness of a Flash Butt-Welded Rail Joint

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Abstract: In this paper, the results analysis of microstructure and hardness examination of pearlite rail steel type 260 and its welded joint are presented. The relationship between the microstructure and the local hardness in different zones of the Flash Butt Welding (FBW) weld was examined, and the correlation was interpreted in terms of the quality of the examined microstructure. The main microstructural variations in the FBW weld occur within the Heat Affected Zone (HAZ). The local decrease in hardness in the zone of intercritical HAZ is caused by spheroidization of cementite. For this reason, the measured hardness values changed when advancing from the centreline of the weld towards the base metal. When moving slightly from the centreline of the weld to the maximum value across the weld in the area 1-2 mm away from the centre of the weld, the hardness value increased sharply. At the visible extent of HAZ, where the pearlite is partially spheroidized, the hardness decreased to a minimum value. Moving away from the visible part of the ZUT, the hardness gradually increased, returning to the value of the hardness of the base metal. The purpose of this paper is to present the relationship between microstructure and hardness on the longitudinal section of a flash butt-welded rail joint and to indicate their inter relationship. It has been confirmed that the altered microstructure in the welded joint of the rail leads to a change in hardness in areas of reduced hardness.

Keywords: cementite; ferrite; flash butt welding; hardness; microstructure

1 INTRODUCTION

In order to form a continuous running surface on which trains travel, it is necessary to connect the ends of the railway rails which are usually produced in lengths of several tens of meters. The ability to withstand long-term exposure to variable load, force and stress at variable temperatures and in different weather conditions, without failure over a long series of years, are the main characteristics required of rails [1]. Welded track has fewer joints compared to bolted track, resulting in reduced impact loads and reduced track maintenance costs. Welded track allows trains to move at higher speeds with less friction and less energy consumption.

FBW welded joints, despite their high reliability, still represent a discontinuity in the structure of the railway track due to the variation in microstructure, mechanical characteristics and level of residual stresses in relation to the parent rail [2]. Variability in the microstructural and mechanical characteristics of rail weld can lead to increased impact loads. For this reason, these variations can play a significant role in increasing the risk of weld failure under conditions of high cyclic shaft loading [3].

It is well known that the performance of a welded joint is determined by each component such as base metal (BM), weld metal (WM) and heat affected zone (HAZ). Especially, HAZ plays an important role in the reliability of the entire welded structure.

Correlations between microstructure and hardness in welded joints [4-6] have been established for engineering materials. However, in earlier research, there is not much information about the mechanical properties of HAZ. In particular, the quantitative distribution of hardness in HAZ has rarely been published until now [7]. Therefore, it is very important to investigate the relationship between microstructure and hardness distribution in HAZ.

Recently, the FBW welding technique has been widely used in the railway industry to produce long components such as welded rails. In this paper, some results of microstructure characterization and hardness measurements on the FBW welded joint of the new rail are reported. Hardness has been obtained by the standard hardness testing Vickers method [8]. Special emphasis is placed on the correlation between the microstructure and the hardness distribution in the rail weld zones where the hardness drop has occurred.

2 FLASH BUTT WELDING (FBW)

FBW is an electroresistance welding process where workpieces are welded together over the entire area of abutting surfaces by the heat obtained from resistance to electric current between the two surfaces, and by the application of pressure after heating is substantially completed [9]. The secondary circuit of the transformer is connected to two parts that need to be welded; by means of a clamping tool, one of them is fixed to the stationary plate, while the other part is tightly clamped to the movable plate. The term flash welding derives its name from the flash produced during the process. Flash welding was developed from resistance butt welding by accident in attempts to increase the capacity of the butt welding machines by raising the voltage and applying pressure intermittently.

The sequence of operations required for flash welding is divided into 3 steps:

Step 1 - Preheating: This first step is performed to reduce the mechanical resistance between the surfaces that will come into contact and to reduce the upsetting force required to perform the welding. Preheating contributes to reducing the cooling rate after welding and avoiding unwanted martensitic transformation.

Step 2 - Flashing: the second stage begins with a continuous movement of the workpiece at a constant speed. The workpiece held in the movable clamp is brought towards the one gripped in the stationary clamp until the two come in light contact, and as the welding current (with voltage sufficiently high) is turned on, flashing is established.

While incandescent metal particles are being expelled by flashing, the movable platen keeps on moving constantly toward the stationary one at a carefully controlled and accelerated rate.

As the flashing continues, the ends of the two workpieces burn off as they reach a higher and higher temperature until they attain the welding temperature, Fig. 1, [10].

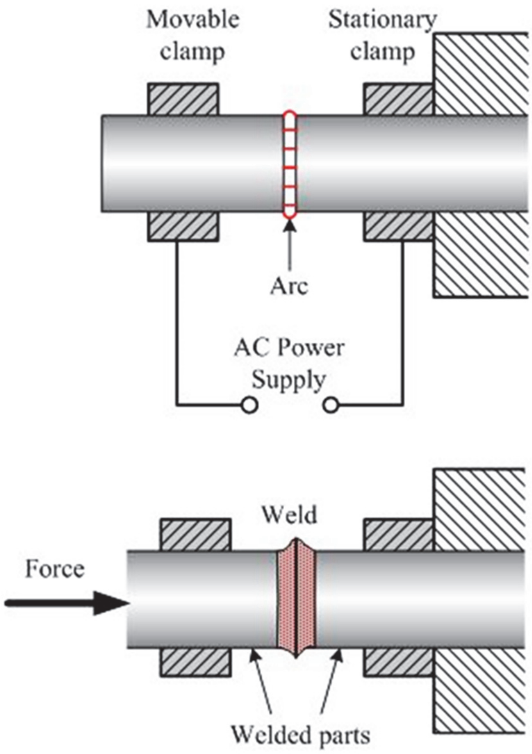

Figure 1 Schematic of the rail FBW process

Step 3 - Upsetting: At this stage, the pressure of the moving clamp is quickly and greatly increased to forge the parts together. To ensure a good quality of welding, the pressure exerted must eject liquid metals, oxides, and impurities from the interface, assuring metal/metal contact. The metal expelled forms a ragged fin which is removed later by cutting or grinding.

The removal of hot upset metal around the rail profile can be done in two ways: one of them involves the use of an automatic hydraulic stripper; another method of removing damaged metal is performed manually using pneumatic chisels, Fig. 2 [11].

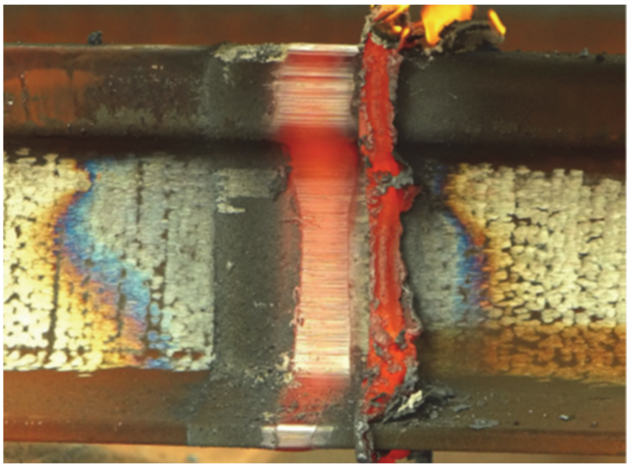

Figure 2 Flash butt weld after stripping

Three different regions were identified in the microstructural tests of FBW welds. The microstructural variations along the FBW weld, when moving from the centreline of the weld towards the base metal of the UIC 60 rail according to UIC-International Union of Railways, are shown in the schematic diagram in Fig. 3, [12].

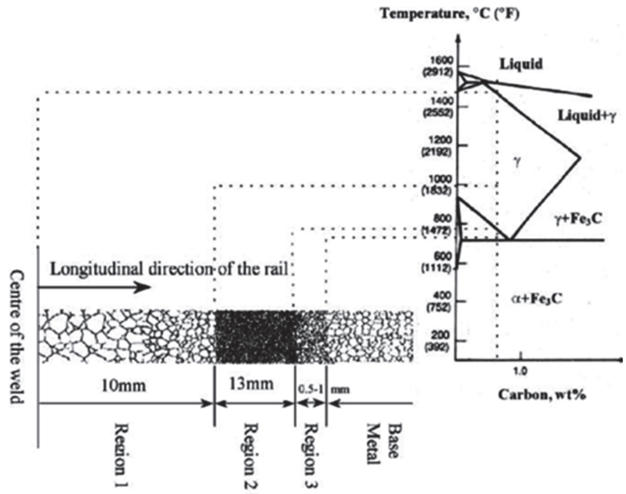

Figure 3 Schematic diagram shows the microstructural variations along the FBW weld, when moving from the centreline of the weld towards the base metal of the UIC 60 rail (dimensions not to scale)

During the upsetting operation, plastic zones are formed at the ends of the rails as a result of the rails being crushed against each other. Occurring plastic deformation leads to recrystallization that begins immediately after the rail ends are joined. The central part of the weld with the surrounding area is exposed to greater deformation and higher temperature compared to other zones of the welded joint. For this reason, these weld zones have coarse recrystallized grains (Fig. 3 - region 1). The temperature of the weld decreases by moving away from the centreline of the joint, and as the temperature decreases, the grain size also decreases (Fig. 3 - regions 2 and 3).

At the fusion line, the microstructure of the FBW joint of R260 rail shows proeutectoid ferrite at the primary austenite grain boundaries. This is considered a common microstructure in FBW welds. In the transition zone between the HAZ/base rail material pearlite is partially spheroidized, while the rest of the fusion zone shows a totally pearlitic microstructure.

The carbon content (0.62-0.80% by weight) of this steel grade is very close to that of eutectoid steel, and for this reason, as shown in the iron-carbon phase diagram [13] shown in Fig. 4, it is expected that the microstructure of the base metal of the 60E1 rail has a pearlitic microstructure.

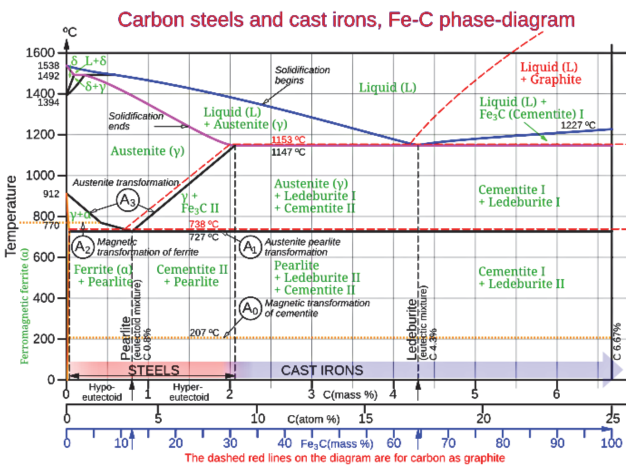

Figure 4 Phase diagram of iron-carbon

Pearlite is a two-phase lamellar structure of ferrite and cementite that develops in steels cooled in a normal fashion or isothermally transformed at a relatively high temperature. It is formed when austenite having composition same as eutectoid one is cooled below the lower critical temperature. The austenite, the eutectoid component, transformed into pearlite during the subsequent cooling process. The computed data (88.7 wt% ferrite and 11.3 wt% cementite) indicate that most of the pearlite is composed of ferrite. Hence, pearlite is the lamellar mixture of ferrite and cementite [14].

Depending on the dimensions and material of the rail, as well as the type of welding machine (stationary or mobile), the width of the HAZ of FBW weld varies between 20 and 45 mm and be resultant from the cycle of preheating and compaction. The width of the HAZ, and thus the distribution of hardness across the welded joint, varies with the height of the rail section. Hardness distribution is affected by a number of FBW parameters, including preheating, upsetting, and postweld cooling conditions.

The FBW process causes a small number of defects and metallurgical inhomogeneities in the rail weld. The FBW weld exhibits hardness levels comparable to the parent rail and also reduces the possibility of loss of smoothness of the rail head surface. The FBW process tends to produce a weld with a more uniform weld hardness profile, restricting the number of soft spots that can assist to weld deformation and ultimately failure. Therefore, the FBW process produces continuously welded rails of very high quality. The quality of rail joints is closely related to the integrity of the railway. Numerous standards (EN 571-1; EN 1290; EN 14587-1) are used to control and test rails and their welds. In order to meet the minimum criteria all FBW rail joints are tested on site. All of the welds and rails shall be inspected visually for welding, trimming, clamping or profile finishing imperfections, such as cavities, cracks, damage and thermal damage, in particular, in the electrode contact areas [15]. Welds with visible defects should be refused.

The easiest way to assess the quality of rail weld is to test the hardness along the rail weld. However, the hardness test is not adequate for the complete determination of the quality of the weld and is primarily considered complementary to other test methods. Hardness values are also used to estimate the type of microstructure and width of HAZ welds.

3 EXPERIMENTAL PROCEDURE

Rail welding was done using a mobile flash butt welding machine, see Fig. 5.

Figure 5 Mobile flash butt welding machine

This mobile rail welding machine uses the flash-butt welding method, a highly reliable process that joins rails by applying electrical resistance and forging pressure, without the need for filler material.

Base material of the rail

The material used in this study is pearlite rail steel R260. UIC 60E1 with a mass of 60.21 kg per meter is the rail type used in the tested FBW weld. Tab. 1 shows the chemical composition of the R260 rail grade according to the European standard EN 13674-1 [16].

Table 1 Chemical composition of R260 rail

Grade R260	Chemical composition (wt%) Fe is the bulk				
	C	Mn	Si	P	S
60E1	0.62-0.80	0.70-1.20	0.15-0.58	Max. 0.025	0.008-0.025

Sample preparations

For the hardness test, the sample was prepared in accordance with the EN 14587-1 standard [17]. Measuring line for testing hardness on the line approx. 5 mm below the sliding surface on the vertical longitudinal axis of the rail extending from the center line of the weld to a point on each side of the weld about 30 mm into the undamaged base rail, see Fig. 6.

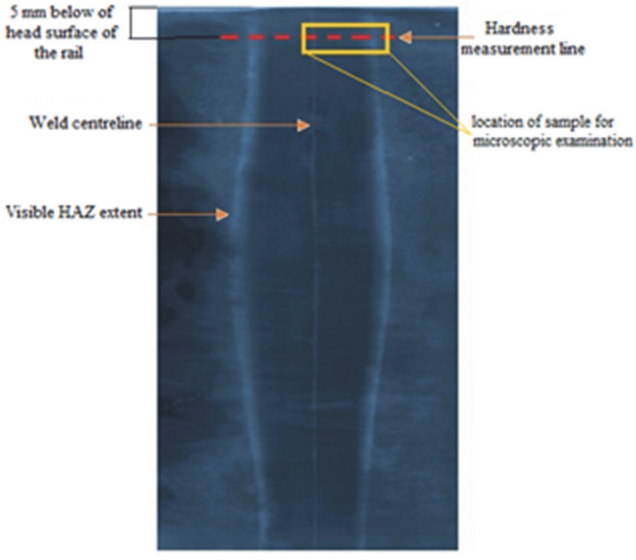

Figure 6 Macrograph of a vertical longitudinal section through the welded joint of the tested rail with the marked position of the measuring line for hardness testing and the place of sample sampling for microscopic tests. Magnification 1:2

Microscopic analysis was determined by microscopic examination also in accordance with the standard EN 14587-1. The microscopic examination was performed on a sample cut from a part of the rail head, which is marked with a rectangle in Fig. 6 and includes a measuring line for hardness testing.

A macrograph of a vertical longitudinal section through the welded joint of the tested rail with the marked position of the measuring line for hardness testing and the place of sampling for microscopic tests is shown in Fig. 6.

Sample preparation was performed without mounting, as the sample was large enough to be controlled manually.

The preparation procedure consisted of three steps to be followed in the order detailed below:

Grinding: Metallographic grinding is one of the process steps in mechanical sample preparation for subsequent microscopic examination. The principle is based on the fact that abrasive particles in successively finer grain sizes are used to remove material from the surface until the desired result is obtained [18]. The quality of the prepared surface depends on the test method. In this case, the grinding step comprised firstly coarse grinding using 240 grit, and then finer grinding was implemented with 400, 600, 800 and 1200 grit papers respectively.

Polishing: Metallographic polishing is a crucial step in preparing metal samples for microscopic examination, ensuring a true representation of the material's microstructure without distortion. It is the final stage of sample preparation, following grinding, and aims to create a deformation-free, scratch-free, and highly reflective surface [19].

In this case, pastes with diamond particles were used to remove finer scratches caused by grinding. Using 1 and 0.3 micron diamond paste sequentially, pre-polishing was achieved before final polishing using 0.05 micron colloidal silica.

Etching: Metallographic etching is a technique used to reveal the microstructure of metals by selectively removing material from a polished surface [20].

In this case, nital (3% HNO_3 + 97% ethanol) was used as an etchant. After etching, the polished test surface is cleaned with alcohol.

Hardness test

A load of 30 kg was used to obtain macro hardness results for welded rails using the Vickers method. Hardness measurements were made along the measuring line parallel to the surface of the rail head, on the longitudinal section that was previously ground. The position of the measuring line for hardness measurement was 5 mm below the sliding surface of the head, as shown in Fig. 6. The distribution of measurement points was in 2 mm intervals. A hardness testing machine model A.J. AMSLER - Switzerland was used for hardness testing.

Microstructure analysis

The pearlite microstructure of the base material of the steel rail class 60E1-R260, which consists of alternating lamellae of ferrite and cementite, is shown in Fig. 7.

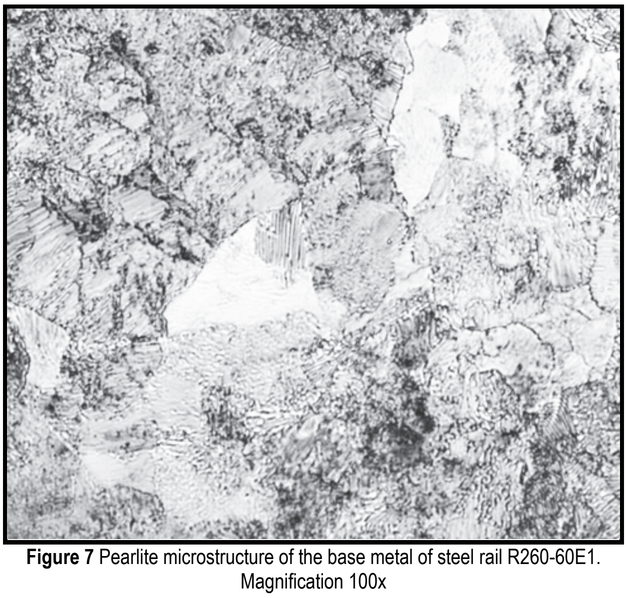

Figure 7 Pearlite microstructure of the base metal of steel rail R260-60E1. Magnification 100x

A microscopic examination of rail welds is shown in Figs. 8 to 11. The microstructural examination starts from the centre of the weld and continues towards the base metal at a distance of 5 mm below the surface of the rail head. Since FBW is solid state welding process, there is no effect of casting microstructure, such as the presence of dendrites, over the weld. Also, no martensite was observed in any weld area.

As the microstructure images show, the grain size gradually decreases away from the weld centre toward the base metal, and then increases sharply in the zone where the extent of the HAZ is visible.

The microstructure of coarse pearlite grains with ferrite at the grain boundaries, in the centre of the weld, is shown in Fig. 8. Proeutectoid ferrite at the boundaries of primary austenite grains is considered a typical structure in welded joints obtained by flash butt welding.

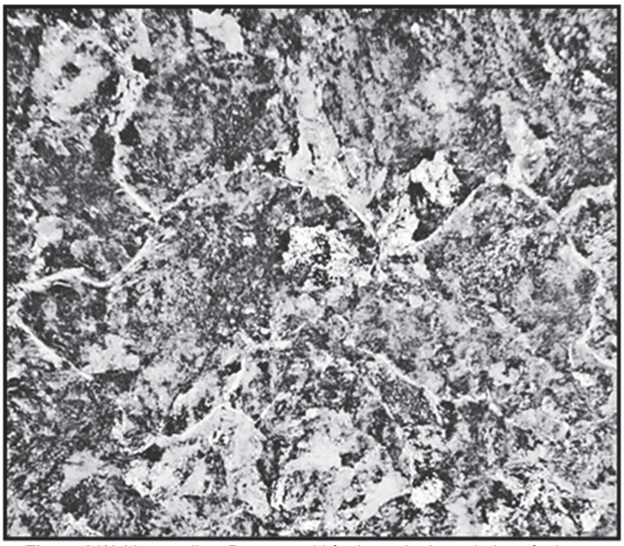

Figure 8 Weld centreline: Proeutectoid ferrite at the boundaries of primary austenite grains. Magnification 100x

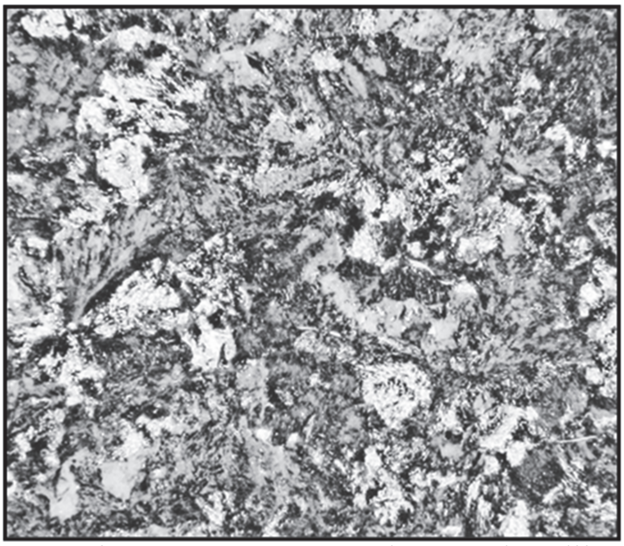

Figure 9 Coarse-grained zone: coarse grains of perlite. Magnification 100x

Within the zone that includes the centre of the weld is a coarse-grained zone with coarse pearlite grains. Fig. 9 shows the microstructure of this area. The region of fine-grained pearlite is located away from the centreline of the weld moving towards the base metal. In the intercritical zone of ZUT, at a distance of about 14 mm from the centreline of the weld, the finest grain size was observed, Fig. 10. Pearlite in this zone is partially spheroidized.

A sharp change in grain size could be clearly observed at a distance of about 15 mm from the centreline of the weld, during the transition from the intercritical to the subcritical zone. The position of the intercritical/subcritical interface is the same as the visible extent of the HAZ shown in the macrograph, see Fig. 6. The microstructure of the subcritical zone is very similar to the microstructure of the base metal, in terms of phase and grain size, Fig. 11.

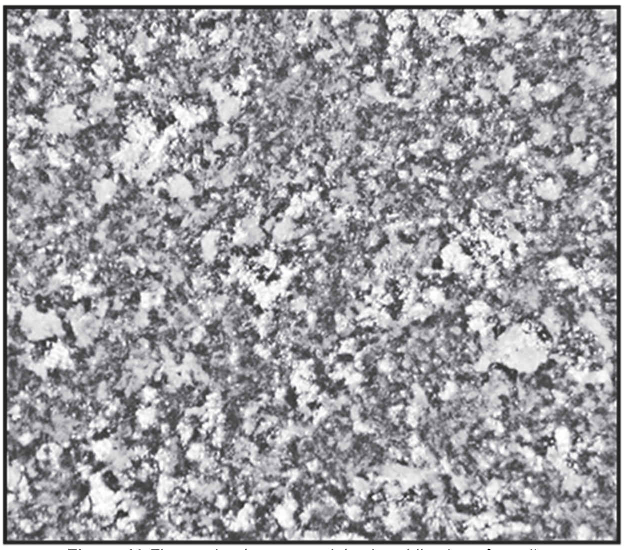

Figure 10 Fine-grained zone: partial spheroidization of pearlite. Magnification 100x

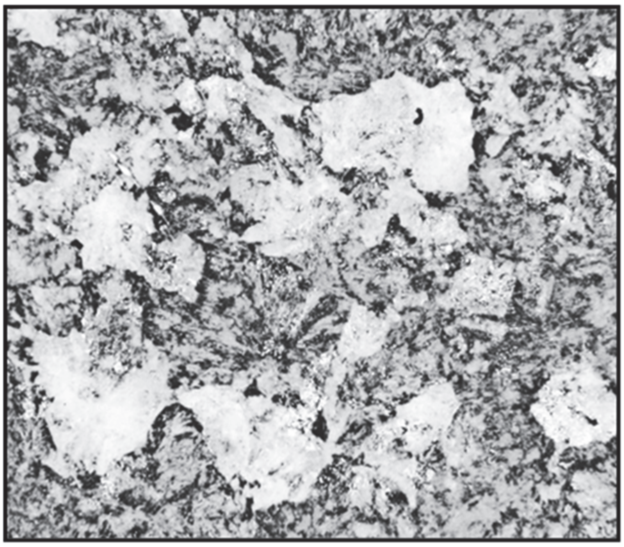

Figure 11 Subcritical zone: pearlite microstructure. Magnification 100x

Hardness distribution

Fig. 12 shows the hardness distribution along the FBW weld of rail 60E1 at a distance of 5 mm below the sliding surface. The hardness along the weld changes as it progresses from the centreline of the weld to the base metal. When moving slightly from the centreline of the weld towards the base metal, the hardness value increases sharply from 315 HV to 355 HV at a distance of 2 mm from the centreline of the weld. At a distance of 14 mm from the centre of the weld, where nearly the visible extent of the HAZ is, the hardness decreases to a minimum value of 280 HV. After this zone, the hardness gradually increases to the hardness value of the base metal.

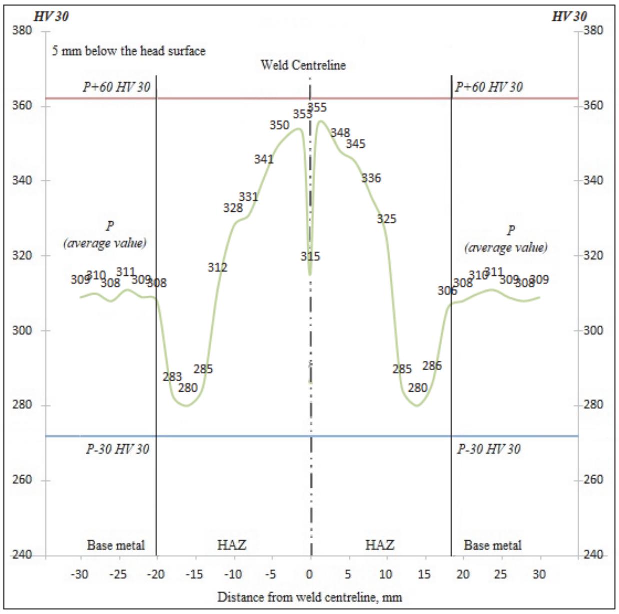

Figure 12 Hardness distribution across the rail weld at a distance of 5 mm below the working surface of the head

Correlation hardness with microstructure

The hardness of a material is strongly influenced by its microstructure. Therefore, it is important to investigate the relationship between microstructure and hardness in inhomogeneous weld zones. In this work, proeutectoid ferrite along the center line of the weld, as well as partially spheroidized cementite in the zone of fine-grained HAZ, were observed as characteristic microstructures that affect the hardness drop in the FBW weld. In flash butt weld welded rails, proeutectoid ferrite can affect weld hardness. Proeutectoid ferrite is usually formed in hypoeutectoid (low carbon) steels during the welding process. Proeutectoid ferrite is formed when the carbon content of the steel is below the eutectoid composition (see Fig. 4). During the FBW process, high temperatures and rapid cooling can lead to the formation of this microstructure [21]. Examination of the welded joint of this rail indicates the presence of pro-eutectoid ferrite along the center line of the weld, and its effect on the hardness drop to a minimum value of 315 HV (see Fig. 8). A higher volume fraction of proeutectoid ferrite causes a greater hardness drop along the center line of the FBW weld. Just after the compaction stage, the centreline of the weld is close to the melting temperature of the rail material. Proeutectoid ferrite is deposited on the austenite grain boundaries during cooling, and the relatively high cooling rate causes insufficient time for carbon diffusion through the austenite towards the proeutectoid ferrite. The presence of proeutectoid ferrite at the grain boundaries in the microstructure of the centreline of the weld depends on the peak temperature and the cooling rate. Maximum hardness values in the range of 353-355 HV were measured at a distance of 1-2 mm from the centreline of the weld. This sudden increase in hardness is possible for two reasons. The first reason may be the absence of a soft ferrite phase at the grain boundaries in the microstructure of this weld zone. In the second case, the maximum temperature that the metal reaches in this area is lower than in the area of the centre of the weld. Immediately adjacent to the centreline of the weld, the microstructure consists of large pearlite grains (see Fig. 9). Moving away from the center line of the weld, the temperature decreases and consequently leads to spheroidization within the pearlite. Spheroidized cementite, a spherical form of cementite (Fe_3C), can be found in the heat affected zone (HAZ) of FBW welded rails (see Fig. 10). This occurs due to the thermal cycle of the welding process, especially in the temperature range where partial austenitization takes place. In this case, spheroidization reduced the hardness of the microstructure to min. 280 HV, which is at the same time, the lowest measured value when testing this FBW weld. In terms of phase and grain size, the microstructure of the subcritical zone is very similar to the microstructure of the base metal (see Fig. 11). It is expected that the hardness will increase sharply in this zone, returning to the hardness of the base metal, which is confirmed here.

4 CONSLUSION

In flash butt welded rail joints, the hardness of the weld is directly correlated with its microstructure.

Fig. 12 shows the hardness distribution across the flash butt rail weld at a 5 mm distance below the running surface of the head. Changes in hardness values along the measurement line, by moving from the centreline of the weld towards the base metal are caused by a series of microstructural changes in the weld. As expected, as the microstructure changes from the weld centreline to the base metal, the hardness also changes. In general, softer microstructures such as spheroidized cementite in the intercritical zone of the HAZ or proeutectoid ferrite along the centreline of the FBW weld are associated with lower hardness.

Acknowledgment

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