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# Selected Properties of Welded Railway Rail Joints Made of R260 and R350HT Steel

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**Summary**

This article presents the results of studies of 60E1 profile welded railway rails joints made of R260 and R350HT steel using flash resistance welding. The study included macro- and microstructural analysis, HV30 hardness distribution in the base material, heat-affected zone, and weld line. The results indicate proper welding, no defects, and compliance of mechanical properties with standard requirements, with higher hardness for joints made of R350HT steel.

**Keywords:** flash welded rail joints, microscopic and macroscopic examination, hardness distribution

## 1. Introduction

The durability and reliability of rail joints is one of the key factors influencing the safety and operating efficiency of railway infrastructure. Rail joints are points on the track where operational stresses and degradation phenomena associated with the impact of dynamic loads accumulate. The proper assessment of their quality, including both structural and mechanical analysis, is of significant importance in both scientific and practical terms [1, 10, 13, 19].

The rail market has shown interest in R260 and R350HT rail steels for many years. R260 is a widely used grade, providing balanced strength characteristics and good weldability. When heat-treated in the head area, R350HT steel is characterised by higher hardness and wear resistance, making it suitable for heavy rail traffic applications. Nonetheless, the introduction of this grade into operational practice requires a detailed analysis of the quality of welded joints due to the possibility of structural inhomogeneities and changes in mechanical properties in the joint zones.

This paper aims to compare the properties of rail joints made of R260 and R350HT steel. It analyses the macrostructure, microstructure and hardness distribution in the various joint zones. The results of the study make it possible to determine the influence of the steel grade on the quality of the joints and may provide a basis for further optimisation of the welding processes used in the construction and modernisation of railway infrastructure.

## 2. Subject of the research

The subject of the research was welded joints of 60E1 profile rails made of steel grades R260 and R350HT. These grades belong to a group of steels used in railway tracks with high strength and wear resistance. R260 steel is characterised by a carbon content of approximately 0.6% and a perlitic structure, providing a favourable compromise between strength and ductility. It is commonly used in standard track under moderate dynamic loading conditions.

R350HT steel is subjected to additional heat treatment of the rail head for increased hardness and abrasion resistance. This material is mainly intended for high-traffic tracks and areas particularly exposed to dynamic loads, such as small radius curves or sections before turnouts. The chemical composition of the tested steels was in accordance with the guidelines given in Table 1.

The tested joints were made using flash resistance welding under industrial conditions in a stationary rail welding plant. This process involves heating the rail ends with electric current to the plasticity temperature and their subsequent pressing together, which creates a permanent metallurgical joint. Today, this is one of the most widely used rail jointing technologies, guaranteeing high quality and homogeneous joints.

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Table 1

**Chemical composition of R260 and R350HT rail steels for the fixed test according to Id-106 [5]**

| Steel grade | Chemical composition | | | | | | | | | $10^{-4}$% [ppm] | | $R_m$ min [MPa] | A5 min [%] | HBW Hardness at the running surface |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P max | S (max) | Cr | Al max | V max | N max | H max | O max | | | |
| **R260** | 0.60–0.82 | 0.13–0.60 | 0.65–1.25 | 0.030 | 0.030 | ≤ 0.15 | 0.004 | 0.030 | 0.010 | 2.5 | 20 | 880 | 10 | 260–300 |
| **R350HT** | 0.70–0.82 | 0.13–0.60 | 0.65–1.25 | 0.025 | 0.030 | ≤ 0.15 | 0.004 | 0.030 | 0.010 | 2.5 | 20 | 1,175 | 9 | 350–390 |

The main difference in the welding technology of these two rail steels is the use for R350HT of a higher number of current pulses and forced cooling at the end of the process. This operation is carried out after automatic flash removal at a temperature of 800–500°C and lasts about 70–80 seconds. Examples of the technological parameters of the fabricated joints are shown in Figures 1 and 2.

Railway rail joints are subject to qualification tests in accordance with the guidelines contained in Technical Conditions Id-112: 2013, issued by PKP PLK [6], and in standard PN-EN 14587-1: 2019 [16]; these tests are performed every five years. The guidelines were also a criterion for the quality assessment of the tested joints.

The tested joint samples were subjected to macroscopic, microscopic and hardness tests based on the guidelines given in Technical Conditions Id-112: 2013 [6] and PN-EN 14587-1: 2019 [16].

## 3. Methodology for macro- and microstructural analysis and HV30 hardness testing

The tests included macro- and microstructural analysis and Vickers hardness measurements. The procedures used made it possible to assess the quality of the joints and identify their characteristic zones, as well as to determine the distribution of mechanical properties in the area studied.

The macrostructural analysis of rail welds was carried out in accordance with PN-EN 14587-1:2019-03 on sample joints using the deep etching method as per PN-57/H-04501. The tests were carried out on the surfaces of the joints, which had been cut along the rail centreline. The joint surface was ground and etched with Fry's reagent ($CuCl_2$ + HCL + $H_2O$). Macrostructural analysis enabled the weld lines, the heat-affected zone (HAZ) and the plastic deformation zone (flow line) to be clearly identified and the quality of the joint to be assessed for the presence of defects such as cracks, porosity or inclusions.

For microstructural analysis, specimens were taken as per PN-EN 14587-1:2019-03 from the area covering the weld line and the heat-affected zone – from the head and foot of the joints. Sample preparation included grinding, polishing and final polishing with diamond suspension (1 μm). The structures were revealed by etching with 4% nital. The observations were made with a KEYENCE VHX-900F metallographic microscope at magnifications of ×100, ×500 and ×1000. The tests made it possible to identify the components of the microstructure and to assess the defects formed during the welding process.

Hardness measurements were carried out using the Vickers method in accordance with PN-EN ISO 6507 [9]. A load of 294.2 N (HV30) was applied. Measurements were made on a joint cut along the rail centreline (at a distance of 5 mm from the running surface), taking hardness impressions at 2 mm intervals. These included the parent material, the heat-affected zone and the weld line. Analysis of the hardness distribution made it possible to determine the influence of the steel grade and the welding process on the mechanical properties of the joints.

## 4. Research results

### 4.1. Macroscopic examination

The macrostructure of flash welded rail joints has a characteristic layout resulting from the joining method. Three distinct areas can be distinguished:

1. The weld (the axis of the joint), formed at the contact point between two rails that have been plasticised during welding and joined by flashing and pressing together during the upsetting. In the macrostructure, the weld is visible as a narrow line, which in reality has a finer grain size.
2. The heat-affected zone (HAZ) is directly adjacent to the weld. The size and nature of this zone depend on the welding parameters (current, spark time, pressing force).
3. Parent material — from which the rail is made.

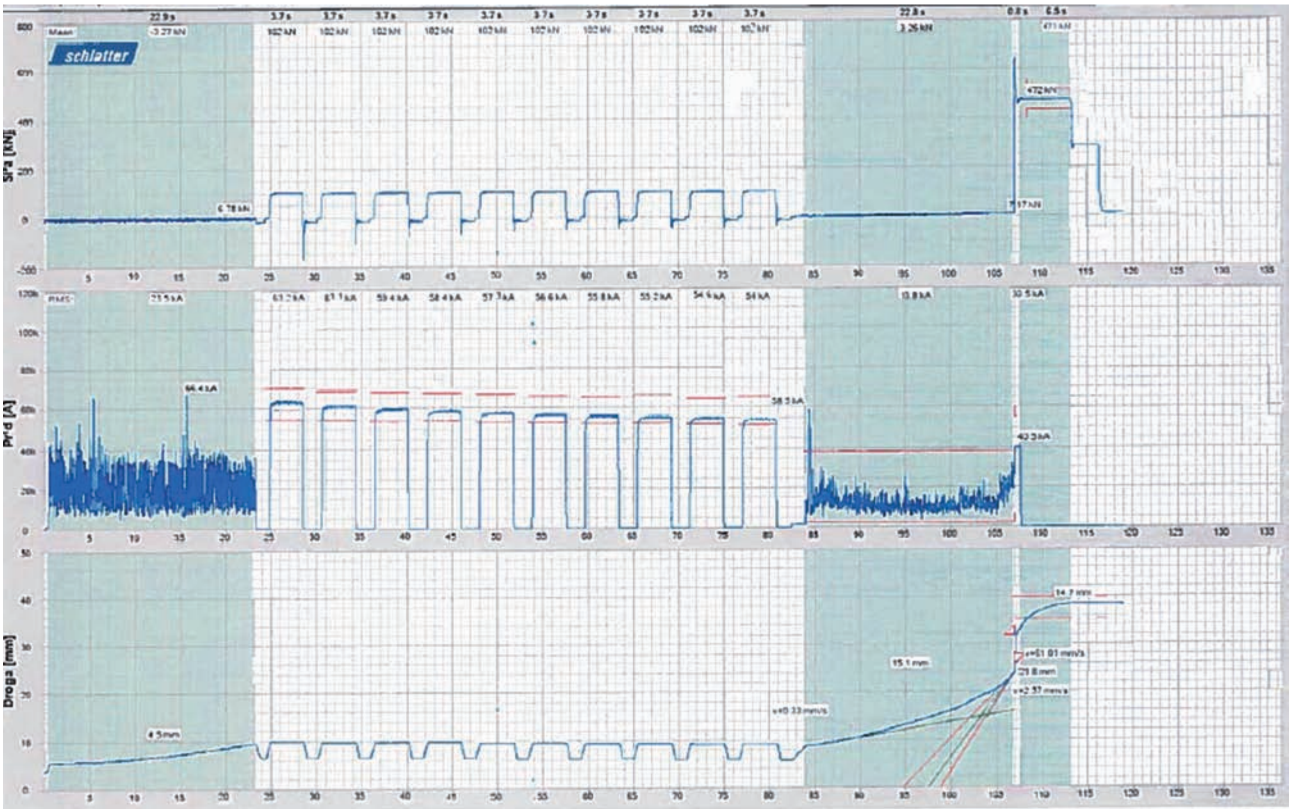


Fig. 1. Welding diagram for 60E1 rails made of R260 steel [author's own elaboration]

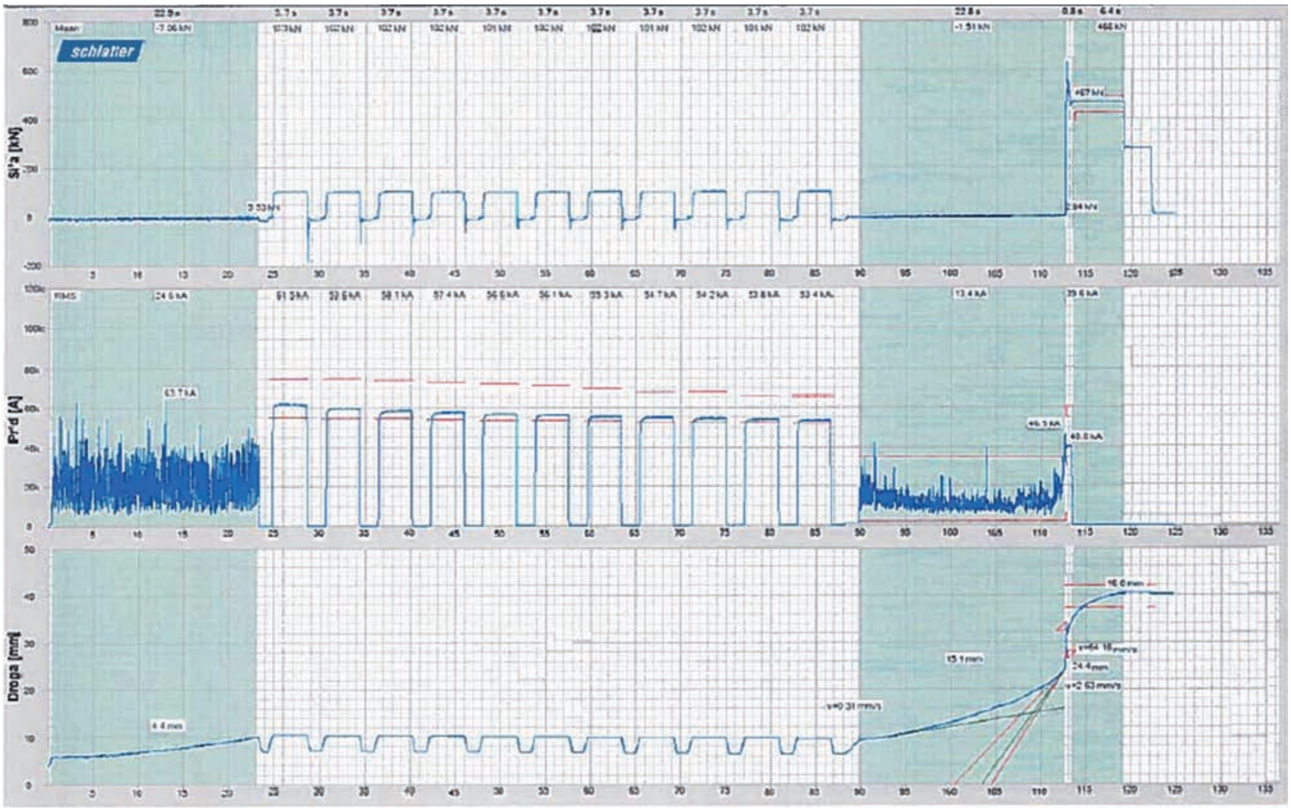


Fig. 2. Welding diagram for 60E1 rails made of R350HT steel [author's own elaboration]

The macrostructure of a flash welded joint is characterised by a narrow fine-grained zone in the weld axis, a transitional heat-affected zone and an unaltered structure of the rail's parent material, with no sharp boundaries and no defects typical of welded joints. In a rolled rail before welding, the flow lines are arranged longitudinally, along the axis of the rail, which is related to the direction of the plastic deformations introduced into the material during the rolling of the steel in the mill.

Once a welded joint has been made, the pattern of flow lines is disrupted: in the core of the rail (central part of the section), the flow lines are broken and curved close to the welding plane. They form a characteristic "fan" image, indicating displacement and plastic warping of the metal during welding and flash removal. In the transition zone on either side of the rails, they merge and bend, creating continuity, but not a straight line. In the vicinity of the welding flash, they are strongly curved and shifted towards the surface, following the direction of plastic metal flow.

This is of practical importance, as flow line continuity is a fundamental quality criterion – no gaps or discontinuities should be present. The curvature and fan shape are indicative of correct plasticisation and fusion of the material in the joint. Any abnormalities (e.g. sharp kinks, cracks, local blind spots) may indicate defects in the joint. Testing of R260 steel joints (Fig. 3) showed that the heat-affected zone is symmetrical with respect to the weld line and has a width of (28–37) mm. The deviations between the minimum and maximum heat-affected weld areas do not exceed 10 mm. No cracks, clusters of large non-metallic inclusions, undermelting or lack of fusion were found in the weld line or weld area.

Testing of R260 steel joints (Fig. 3) showed that the heat-affected zone is symmetrical with respect to the weld line and has a width of (28–37) mm. The deviations between the minimum and maximum heat-affected weld areas do not exceed 10 mm. No cracks, clusters of large non-metallic inclusions, undermelting or lack of fusion were found in the weld line or weld area.

Fig. 3. The macrostructure of the R260 steel joint [author's own elaboration]

Observations of the R350HT steel joint (Fig. 4) showed that the heat-affected zone is symmetrical with respect to the weld line and falls within an interval with a width of (25–34) mm. The deviations between the minimum and maximum heat-affected weld areas also do not exceed 10 mm. No cracks, clusters of large non-metallic inclusions, undermelting or lack of fusion were found in the weld line or weld area. For both rail steels, the flow lines had a normal pattern, although they were more pronounced for the R350HT steel.

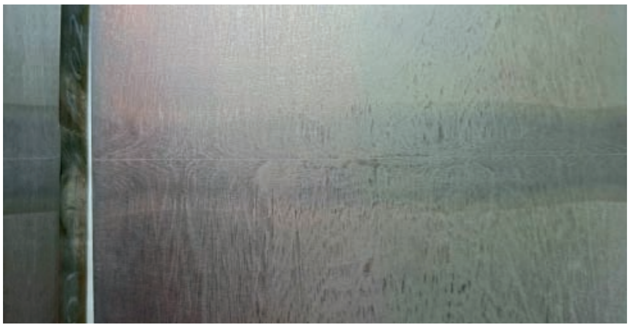

Fig. 4. The macrostructure of the R350HT steel joint [author's own elaboration]

## 4.2. Microscopic examination

The starting state (parent material) of the microstructure of both steel grades studied is perlite. Due to the heat treatment of the R350HT steel performed in the rail head area, the grain size of the perlite was finer (the scope of the study did not include grain size measurement). Three main zones were observed in the rail joints tested: the parent material, the heat-affected zone and the weld line.

The weld axis (weld line, the core of the joint) saw the greatest heating and plastic deformation of the metal during pressing. The structure in this zone is often fine-grained, resulting from complete recrystallisation. In both R260 and R350HT steel, pearlite with a small amount of ferrite was observed in the weld axis, forming a network along the primary austenite grains (Figs. 5 and 6, a and c).

The heat-affected zone is the most complex area, as the microstructure depends on the maximum temperature reached by each region during the thermal cycle. It includes the following sub-zones (going from the weld axis towards the parent material):

Supersaturation subzone (close to the weld axis) – this area is particularly sensitive to the formation of unfavourable martensitic or bainitic structures, since it is exposed to heating above the A3 temperature, i.e. austenitisation, followed by rapid cooling. This is a zone where hardness monitoring is particu-

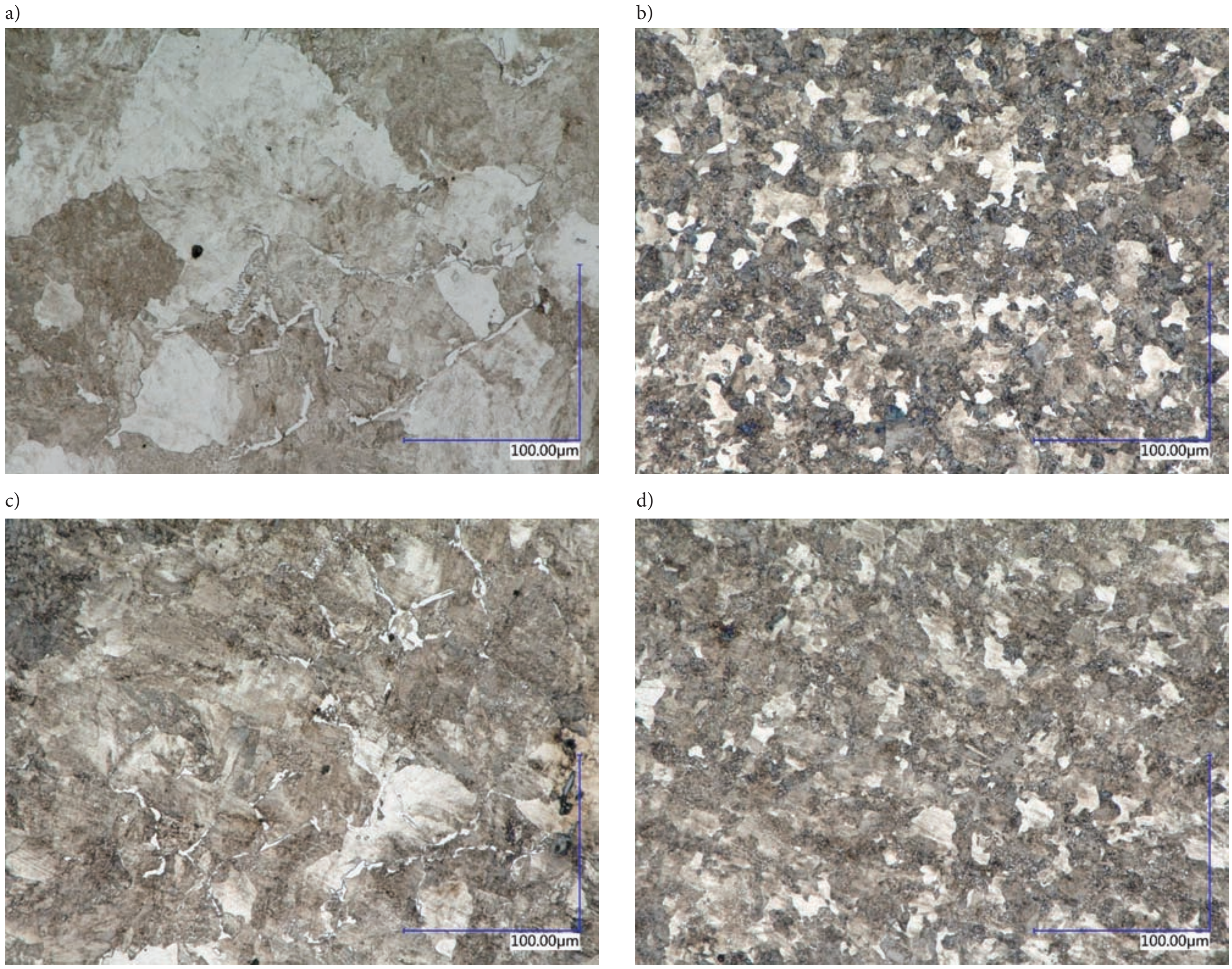


Fig. 5. The microstructure of the R260 steel specimen; (a) the microstructure in the weld line of the R260 steel specimen, in the rail head section; (b) the microstructure in the heat-affected zone of the R260 steel specimen, in the rail head section; (c) the microstructure in the weld line of the R260 steel specimen, in the rail foot section; (d) the microstructure in the heat-affected zone of the R260 steel specimen, in the rail foot section [author's own elaboration]

larly important. No bainitic or martensitic structures were found in the two steels tested at magnifications of ×100 and ×500, which was further confirmed by hardness tests.

The normalisation subzone (further away from the axis) – the area where the temperature exceeded the A3 level, but the heating time was longer and the cooling slower. In both steels tested, the perlitic structures in this area were quite homogeneous (Figs. 5 and 6, b and d).

The subzone closest to the parent material is the recrystallisation subzone, where the heating temperatures ranged from A1 to A3. This area showed the greatest changes in hardness.

The microstructure of the joint made from R260 steel consisted of pearlite and appeared relatively homogeneous. In the case of the R350HT steel, due to the prior hardening of the rail head, the structures observed within the heat-affected zone were more variable in terms of grain size; however, forced cooling, which is the fabrication step of the R350HT steel joint, apparently reduced the grain growth in the weld axis, so a more fine-grained structure was formed. Most importantly, no bainitic or martensitic structures were observed.

## 5. Hardness tests

The hardness profile for the welded rail joint made of R260 steel is shown in Figure 7.

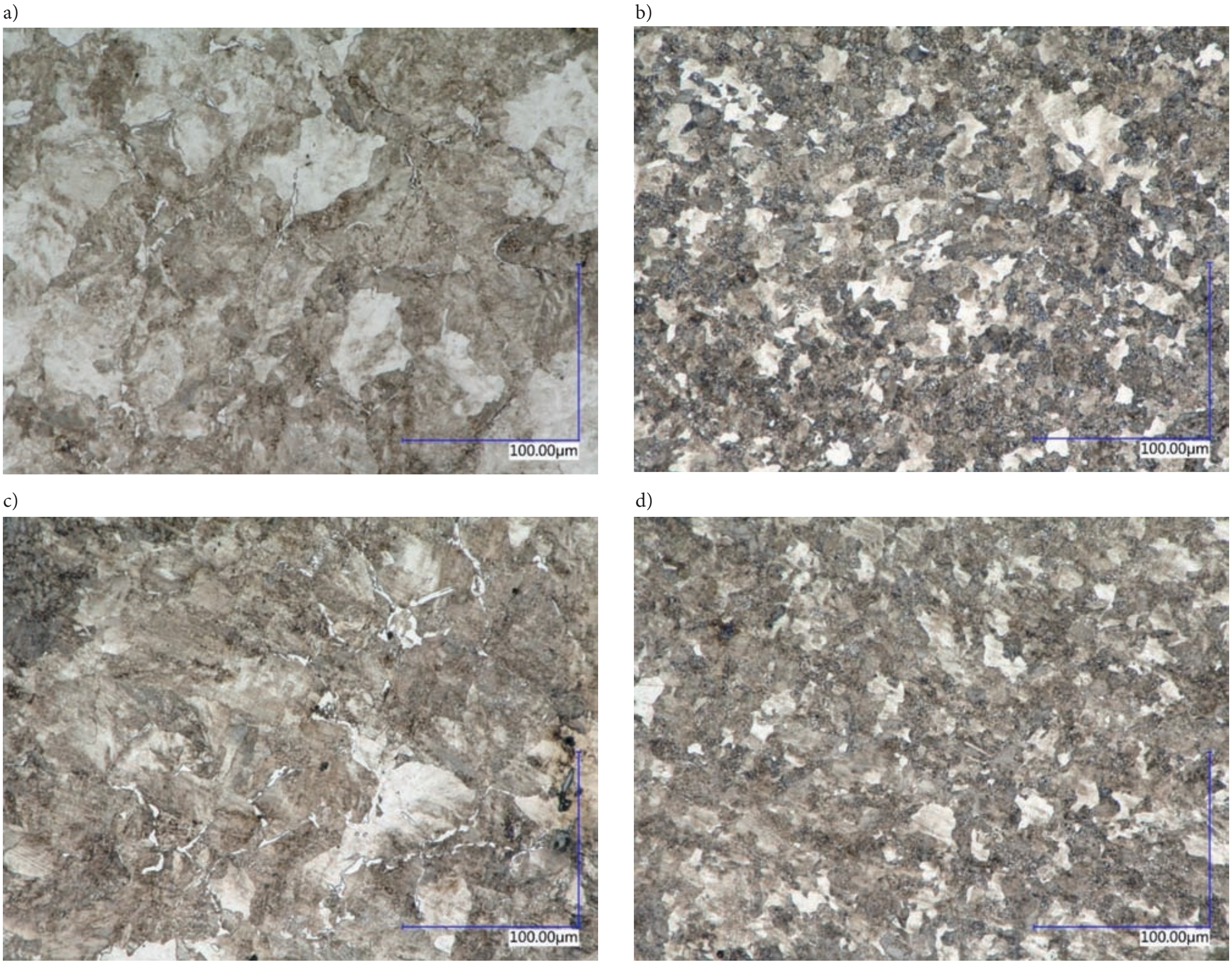


Fig. 6. The microstructure of the R350HT steel specimen; (a) the microstructure in the weld line of the R350HT steel specimen, in the rail head section; (b) the microstructure in the heat-affected zone of the R350HT steel specimen, in the rail head section; (c) the microstructure in the weld line of the R350HT steel specimen, in the rail foot section; (d) the microstructure in the heat-affected zone of the R350HT steel specimen, in the rail foot section [author's own elaboration]

The average $HV_{30}$ hardness of the tested welded rail joint was 302.2. The minimum hardness value was 280.1 $HV_{30}$ while the maximum value was 336.7 $HV_{30}$. The $HV_{30}$ hardness distribution for the tested joints is within the requirements of the standard, i.e. P + 60 HV30 and P – 30 HV30, where P is the average hardness of the joint rails. The hardness profile for the welded rail joint made of R350HT steel is shown in Figure 8.

The minimum $HV_{30}$ hardness at a distance of 10 mm from the axis of the welded rail joint was 325.0 and the maximum was 401.4, respectively. These values meet the requirements of the standard specifications. A decrease in hardness was observed at the weld axis for both tested joints.

## 6. Discussion of the results

Macroscopic analysis confirmed the correct course of the flash resistance welding process for both analysed steels – R260 and R350HT. The joints were characterised by the symmetrical shape of the heat-affected zone and the correct arrangement of the metal flow lines, which indicates proper plasticisation of the material during pressing. The absence of discontinuities, porosity or cracks demonstrates the stability of the process parameters used. The only noticeable difference was the greater clarity of the flow lines in the joints made from R350HT steel due to its higher hardness and lower susceptibility to plastic deformation.

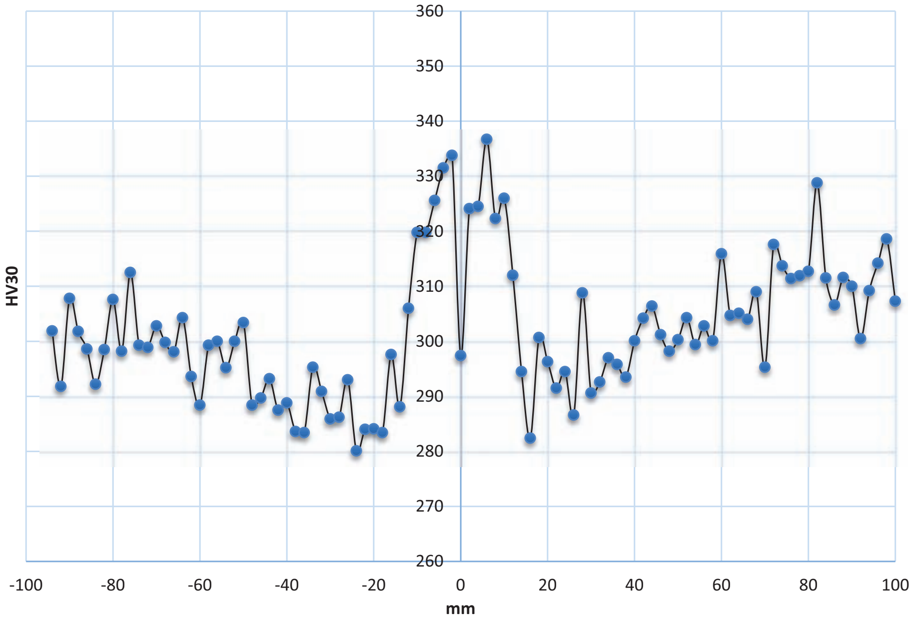


Fig. 7. The hardness profile for the welded rail joint made of R260 steel (position „0" indicates the weld axis) [author's own elaboration]

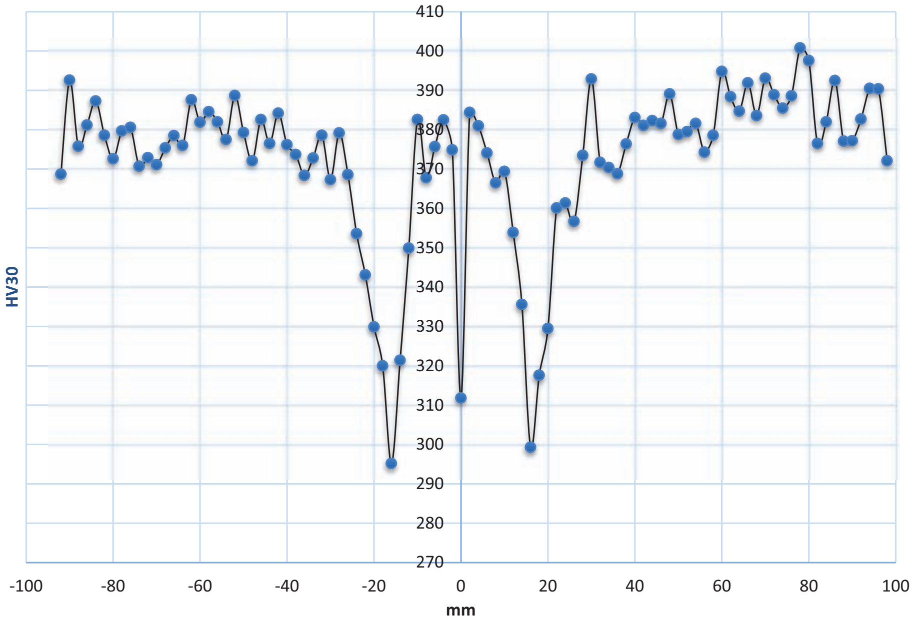


Fig. 8. The hardness profile for the welded rail joint made of R350HT steel (position „0" indicates the weld axis) [author's own elaboration]

Microstructural observations showed that a fine-grained pearlitic structure with a small amount of ferrite, resulting from full recrystallisation, formed in both R260 and R350HT steel in the welding axis. Three sub-zones were observed in the heat-affected zone — the supersaturation, normalisation and partial recrystallisation sub-zones. The nature of these zones corresponded to the temperatures reached during the heat cycle. A significant result is the absence of unfavourable bainitic and martensitic structures in both of the steels tested, indicating the correct choice of process parameters. In the case of R350HT steel, forced cooling reduced grain growth in the weld axis, favouring the formation of a more homogeneous and finer-grained microstructure.

Hardness tests showed that the results obtained were in line with the normative requirements. For R260 steel, the average hardness was 302 $HV_{30}$, with extreme values in the 280–337 $HV_{30}$ range. For R350HT steel, the joints showed higher hardness values (325–401 $HV_{30}$), which was due to the finer pearlite structure created by the earlier heat treatment of the rail head and the forced cooling after the welding process. The higher hardness of the R350HT steel indicates that it has a better resistance to wear in service, while maintaining the ductility and integrity requirements for the joint.

The results obtained are consistent with the observations of other authors studying welded rail joints [4, 9, 11, 12, 14, 21]. The literature emphasises that macrostructure quality is strongly dependent on the steel grade and technological parameters [2, 3, 8, 18–20, 22]. In the case of R260 steel, the joints are usually characterised by uniform flow lines and slight deviations in the weld zone, which was also noted in this paper. In the case of R350HT steel, more pronounced metal flow distortions are seen, as per study [1], due to the higher strain resistance and more intense phase transformations during heating.

Similar relationships were observed at the microstructural level. As indicated by previous studies [13] and the results of recent research, R260 steel retains a relatively homogeneous perlitic system after welding, with a small proportion of sub-eutectoid ferrite, which is associated with its moderate hardness and good susceptibility to thermal and mechanical processes. In contrast, R350HT steel, thanks to prior hardening, is characterised by a fine perlitic structure and, with the appropriate choice of welding technological parameters, it is possible to avoid the local occurrence of bainite, as confirmed by this study.

A comparison of the hardness values obtained in this study with data from the literature indicates their consistency. Some studies [7, 23] have highlighted that R350HT steel exhibits higher HV values in both the parent material and the joint zone, with sharper gradients in the transition region. This phenomenon, also confirmed in this study, is considered potentially unfavourable considering the fatigue service life, as it favours the initiation of cracks.

## 7. Conclusions

1. The process of flash resistance welding of R260 and R350HT steels proceeded correctly, and the joints obtained met the quality and normative requirements.
2. In the weld axis of both steels, a fine-grained perlite structure with a small amount of ferrite was observed, confirming the full recrystallisation of this area.
3. Sub-zones of supersaturation, normalisation and partial recrystallisation were noted in the heat-affected zones of both steels, but no unfavourable bainitic or martensitic structures were observed.
4. Forced cooling during the welding process of the R350HT steel reduced grain growth in the weld axis, resulting in a fine-grained structure with favourable mechanical properties.
5. The distribution of $HV_{30}$ hardness in the joints tested was within the limits specified by the standards, with joints made from R350HT having a higher hardness compared to R260.
6. Joints made from R350HT exhibit greater resistance to wear and tear, justifying the use of this steel grade on heavily-trafficked tracks and in areas particularly exposed to dynamic loads.

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