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Enhancing rail performances: the Danieli RH² - Rail Head Hardening process

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In recent decades, the rail transportation sector has undergone continuous progress. To meet market demands, rail producers are improving rail strength to develop high-performance products, particularly in terms of wear resistance. Head-hardened rails offer greater resistance to wear caused by faster, more frequent trains carrying heavier loads. Building on this need, the innovative Danieli RH² - Rail Head Hardening process has been specifically designed and optimized since 2008. The RH² process involves immersing the rail head in a tank filled with a water-based polymer solution immediately after rolling. This quenchant enables a wide range of cooling rates - from those typical of oil to those of water - allowing the process to be tailored to each specific rail grade, from pearlitic to bainitic. High-quality rails produced using the Danieli RH² system feature the lowest possible transformation costs and minimal environmental impact in terms of CO₂ footprint.

Over the past five years of industrial production, extensive measurements of metallurgical and mechanical properties have been conducted on RH²-treated rails. Results demonstrate the RH² system's ability to exceed the most demanding global requirements. The foot residual stress is half the European limit. A high level of hardness uniformity is achieved at the rail head. As a result, the mechanical properties are more uniform, and the fatigue resistance is twice the minimum required by European standards.

KEYWORDS: INLINE RAIL HEAD HARDENING; PEARLITIC STEEL; FATIGUE RESISTANCE; FRACTURE TOUGHNESS; RESIDUAL STRESSES; HARDNESS; AQUEOUS SOLUTION.

INTRODUCTION

Rails account for only 1.3% of European hot-rolled steel production, amounting to 1.903 million tons in absolute terms (based on 2021 data) (1). Compared to other rolled products, the rail market is atypical due to its lower exposure to price volatility. Its customers are primarily large entities—often state-owned—that tend to favor local suppliers, provided they can meet the required quality standards. These customers typically secure multi-year purchase contracts with clearly defined quantities and prices, which are relatively insulated from the macroeconomic cycles that influence other products, such as reinforcing bars for concrete. Further highlighting this uniqueness, it's worth noting that there is no official market quotation for rail products, unlike other categories like sheets or structural profiles. However, this should not be interpreted as a lack of competition. On the contrary, the rail market is highly competitive, both technologically and commercially.

The growing volume of passenger traffic has led to a substantial and steady increase in high-speed passenger transportation in Europe (figure 1) (2). High-speed railways

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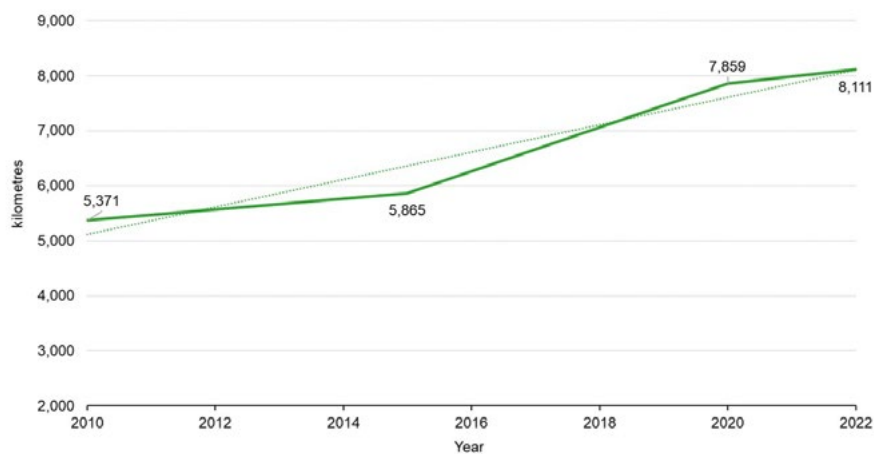
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must ensure safety, and therefore require rails with consistent geometrical tolerances throughout their service life. More frequent convoys have led to increase rail damage such as wear and Rolling Contact Fatigue (RCF) defects (3). RCF defects can appear on the rail surface or just beneath it in the form of shelling, squats and gauge corner cracks resulting from the repeated wheel-rail contact cycles. The costs to eliminate RCF defects represent a significant portion of the overall track costs due to railroad downtimes. Therefore, any improvement of rail quality contributes to reduced maintenance costs. Rails with high hardness, not only have better properties against wear but also RCF. For instance, the performance of the European head-hardened

grade R350HT compared to the standard grade R260 is approximately three times better in terms of wear resistance and twice as effective against RCF (4).

Nowadays there are two main ways to improve mechanical properties in rails, the metallurgical route (primarily through chemical composition) and the thermo-mechanical route (primarily through process control). Until 2000, rail manufacturers focused on the metallurgical route with relatively good results. More recently, thermo-mechanical methods have been investigated to further enhance the mechanical characteristics of commercial rails. One of such method is the inline heat treatment of the rail.

Dedicated high-speed railway lines with a maximum speed of 250 km/h or more in the EU



Source: Eurostat

Fig.1 - Trend of railway kilometers dedicated to high-speed in Europe. (2)

RAIL HARDENING PROCESS

Traditional rail steels contain approximately 0.7–0.8% carbon, making them nearly eutectoid. The cooling rate from the stable austenitic phase to the end of transformation de-

termines the final microstructure. The desired microstructure for this type of steel is fully pearlitic, as it minimizes wear while maintaining the same hardness (figure 2) (5).

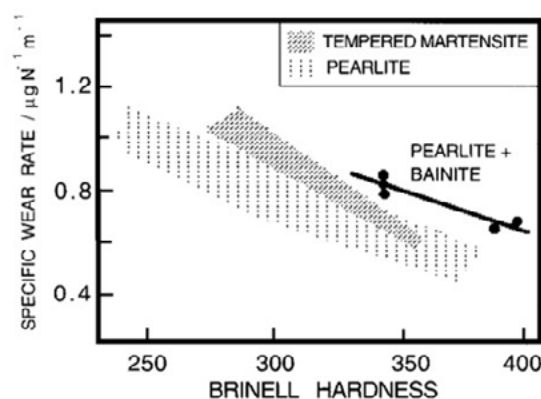


Fig.2 - Relationship between wear rate and hardness considering the microstructure (5).

The Danieli Rail Head Hardening project started in early 2008 with the aim of developing a stable and efficient technology. At the time, several rail head hardening methods were commercially available, mainly based on immersion methods (in oil or water/polymer mixture) or run-through spray systems (using compressed air, air mist or water as cooling media). A preliminary evaluation of these methods, supported by initial trials, led Danieli to select the immersion type technology using a water-based polymer solution.

A detailed study of the cooling tank's fluid dynamics was conducted to ensure a uniform cooling rate along the rail head. Various tank configurations were analyzed using CFD code Fluent® software, and the most promising solutions were tested at the Danieli Research Center (6).

In early 2010, Danieli started its experimental studies using a flexible prototype able to treat rails with different quenching media and process parameters. After careful selection an optimal polymer quenchant was identified, offering high stability throughout the cooling process. The first industrial plant was commissioned in 2013.

The key point of the heat treatment strategy is to understand and control the microstructural mechanism involved in the pearlitic transformation. The optimal process involves cooling the rail to a temperature slightly above the bainite start temperature, remaining within the pearlitic transformation range until completion, as illustrated by red line in figure 3. This process results in a fully pearlitic and fine microstructure.

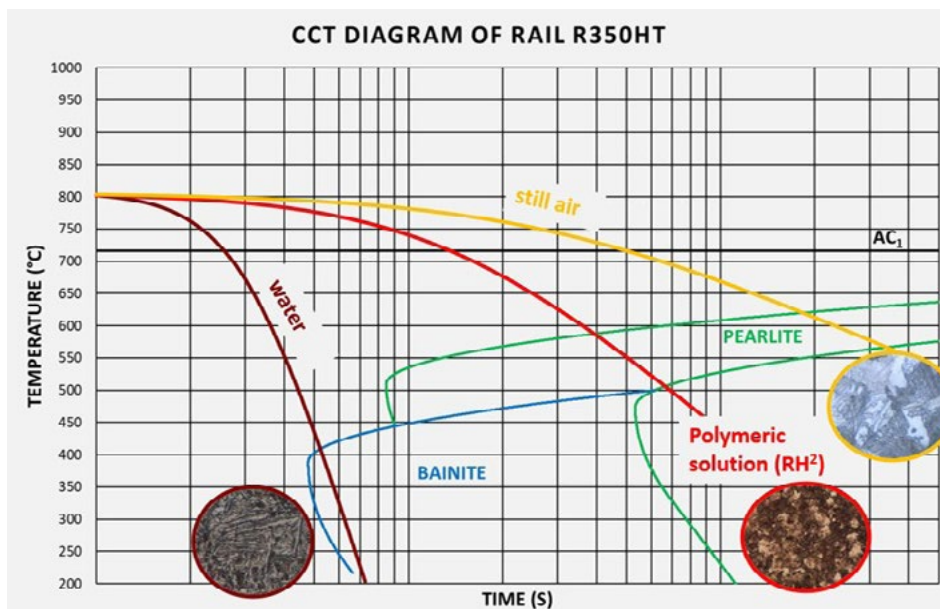


Fig.3 - Typical CCT diagram with RH² process.

The heat treatment is performed by immersing the rail head into a tank containing a water-based polymer solution. To ensure optimal and repeatable conditions, some auxiliary systems are required to control the temperature, flow rate, and polymer concentration. These systems are divided into the following main areas:

1. Recirculation circuit: Supplies the cooling fluid to the treatment tanks at the appropriate temperature and polymer concentration.
2. Regeneration circuit: Maintains the cleanliness of the solution by preventing the formation of mold and bacteria.

ENERGY COST AND CO₂ BALANCE

Nowadays, there is a growing concern about reducing CO₂ emissions. As a result, increasing attention is being paid to minimizing both emissions and production costs in the manufacturing of heat-treated rails. Figure 4 illustrates the energy cost (left) (7) and CO₂ emissions per kilowatt-hour (right) (8) across several European countries.

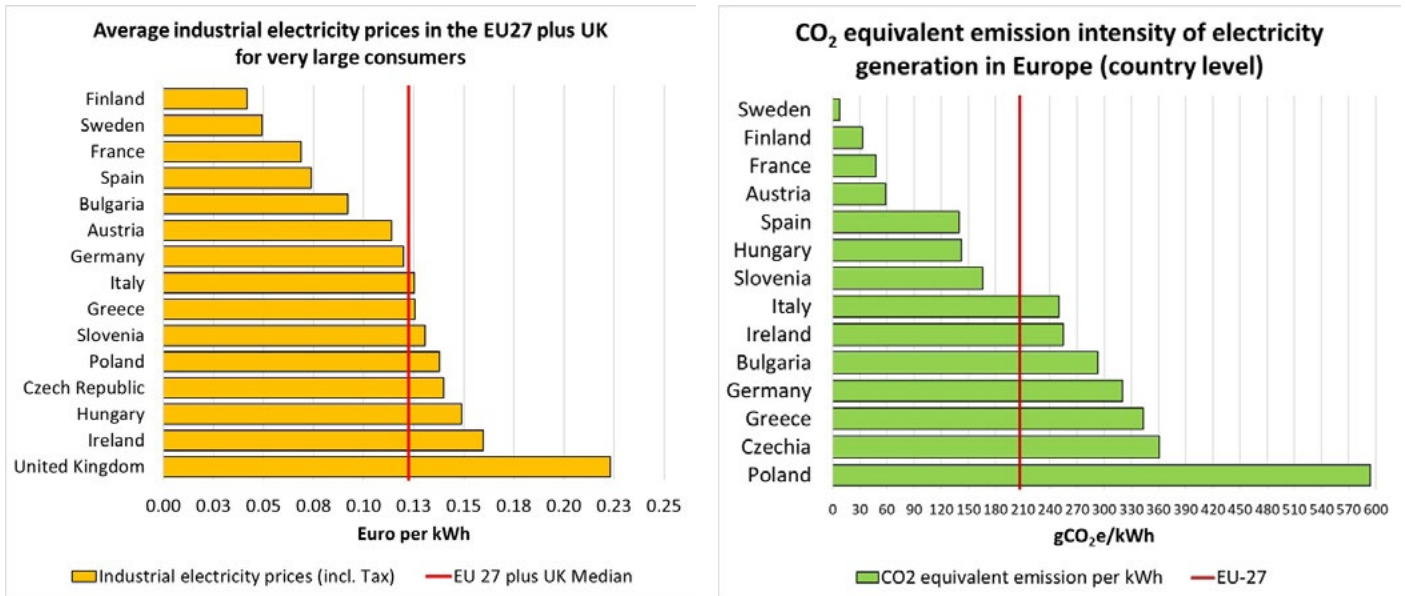


Fig.4 - Industrial electricity prices (left) (7) and CO₂ emission intensity of electricity generation (right) (8) in several countries.

Based on the data presented in figure 4 and average data from plants, a simulation was carried out to assess the production costs and gas emissions associated with the RH² process, in comparison with an alternative rail treatment technology.

The results are shown in figure 5 and figure 6. The graphs highlight that both costs and emissions depend on the specific electricity prices and emission intensity of each country. Therefore, the European average (represented by the dashed black line) was used for the simulation.

The results demonstrates that the RH² process can reduce head hardening costs by 32% and CO₂ equivalent emissions by 74% compared to an alternative technology that uses forced air as a quenchant media. Although some uncertainty remains due to assumptions and data variability, the simulation is sufficiently accurate to confirm that the RH₂ technology enables the production of rails that are both more cost-effective and environmentally friendly in the European context.

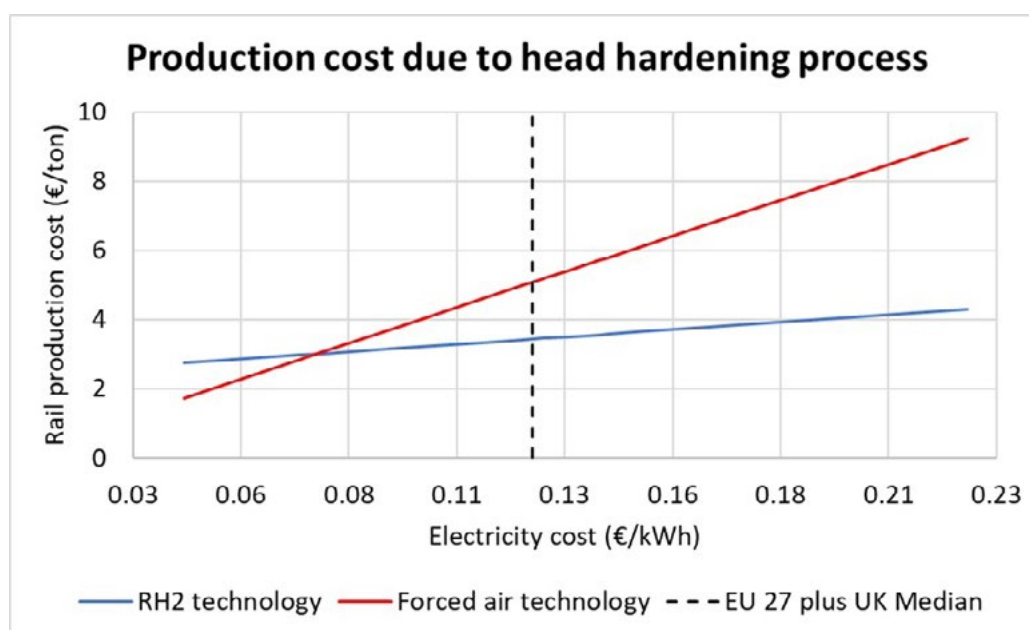


Fig.5 - Production costs of rail head hardening processes.

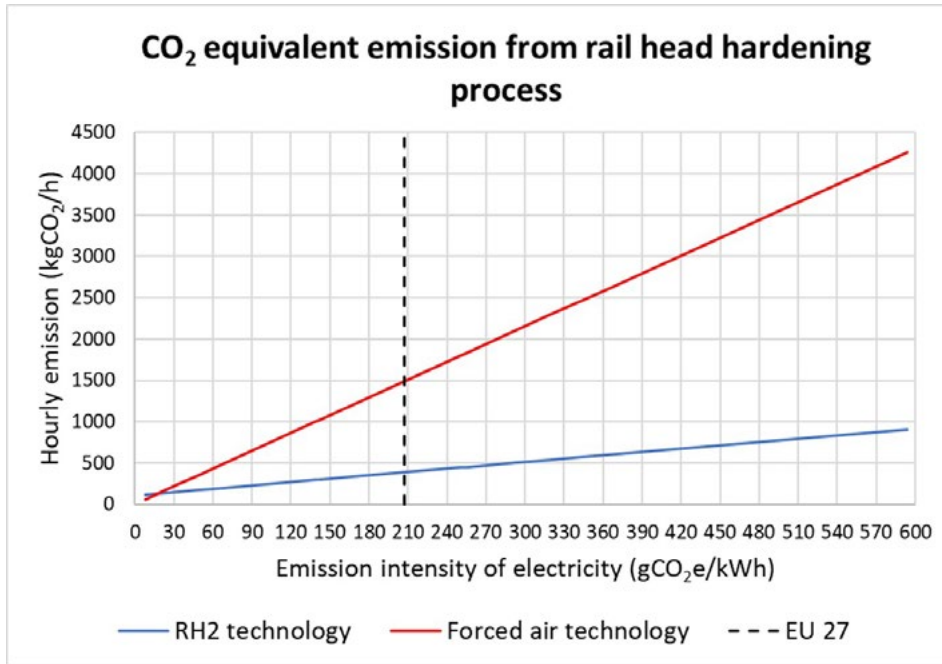


Fig.6 - CO₂ equivalent emission of rail head hardening processes.

HEAD HARDENED RAIL PROPERTIES

Hardness profile and mechanical properties

Several rail profiles were treated over the last five years of industrial production. The technological parameters of the process were optimized to ensure mechanical properties in compliance with major International Standards. Thanks to RH² technology, hardness remains uniform within the rail head. Figure 7 shows the hardness mea-

sured in the points specified by EN 13674-1:2017 (9) for three different European rails profiles. The values exceed requirements with a good safety margin. Hardness was still found to be above 360 HB at a depth of 20 mm from the running surface, where the minimum requirement by EN is 321 HB. The average standard deviation of hardness on the running surface was less than 8 HB, confirming the repeatability of system.

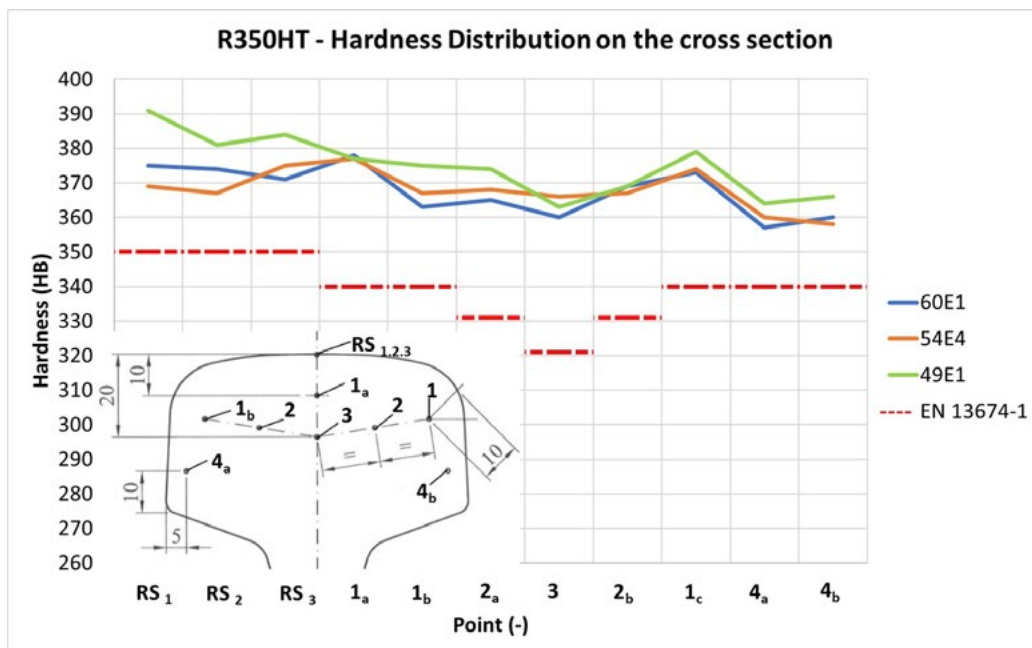


Fig.7 - Hardness distribution along section (steel grade R350HT).

An example of mechanical properties achieved on various rail profiles treated with the RH² system in industrial plant is shown below (table 1). The specimen position and testing condition are in accordance with EN 13674-1:2017 (9). An appropriate process set-up combined with

a careful choice of chemical composition enabled optimal microstructural refinement, reducing the pearlite interlamellar distance. This is clearly reflected in the tensile strength value which significantly exceeds the 1175 MPa threshold.

Tab.1 - CO₂ equivalent emission of rail head hardening processes.

MECHANICAL PROPERTIES FROM RH ²				
Rail	Rp _{0,2}	Rm	A	Z
(-)	(MPa)	(MPa)	(%)	(%)
49E1	849 ± 20	1260 ± 12	10 ± 0.27	21 ± 1.11
54E4	852 ± 11	1245 ± 9	10 ± 0.22	20 ± 0.51
60E1	861 ± 18	1255 ± 13	10 ± 0.32	21 ± 0.88
EN 13674-1	-	> 1175	> 9	-

FRACTURE TOUGHNESS AND FATIGUE RESISTANCE

Generally, increasing hardness -associated with strength - tends to reduce both toughness and fatigue life. This means that, while improved hardness can extend the rail's wear life, it may simultaneously decrease its fatigue life. However, contrary to this common assumption, the toughness test results shown in figure 8 indicate a mean fracture toughness of 38.8 MPa√m, well above the Euro-

pean requirement.

Similarly, fatigue resistance tests conducted in accordance with EN 13674-1:2017 (9) showed that all samples withstood 10⁷ cycles without failure - twice the minimum required by the European standard.

These results confirm that the RH² process positively affects fatigue life and, in fact, enables performance that exceeds standard expectations.

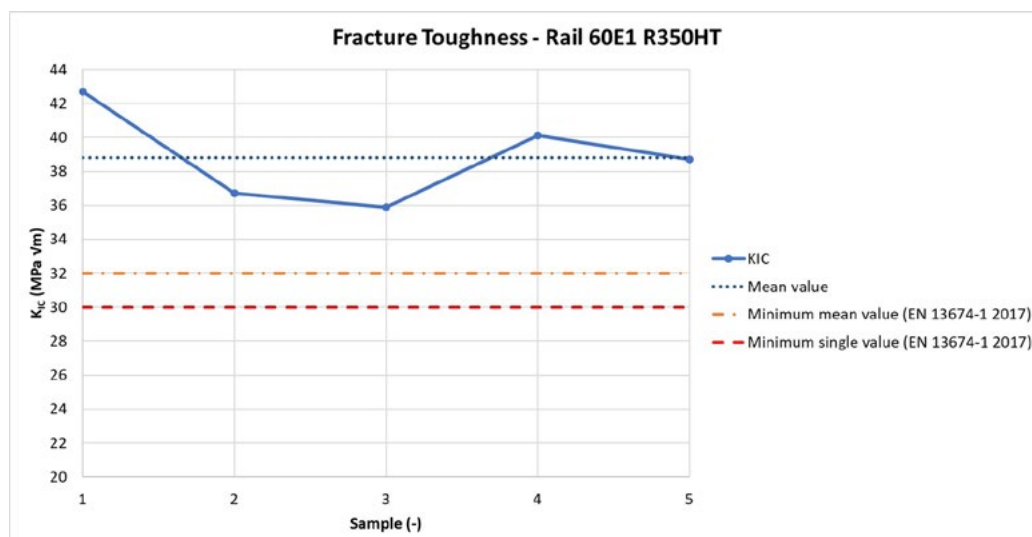


Fig.8 - Fracture toughness.

INTERLAMELLAR DISTANCE

Pearlite forms nodules composed of multiple colonies, each with parallel lamellae oriented differently from neighboring colonies. These colonies nucleate at the grain

boundaries and grow into the grain interior. New colonies form adjacent to existing ones or randomly within the grains.

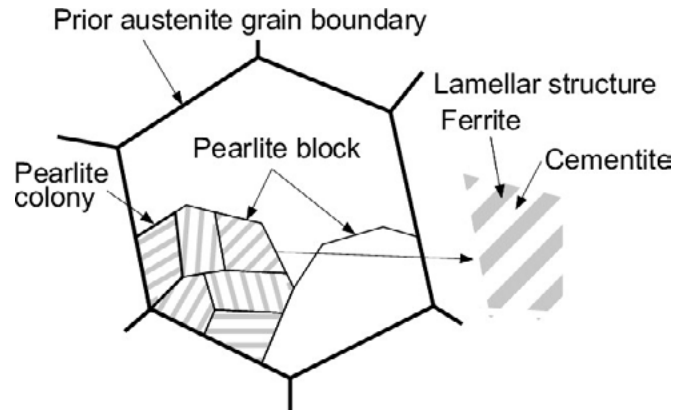


Fig.9 - Sketch of pearlite formation.

The key microstructural parameter controlling the strength of pearlitic steel is the interlamellar spacing. Finer pearlite results in higher hardness, as the cementite-ferrite interfaces act as barriers to dislocation motion. Reducing the spacing increases the density of these barriers, enhancing mechanical strength. Interlamellar spacing was measured on the treated rail

head and foot using the procedure recommended by Vander Voort (10). The results shown in Fig. 10, indicate that the interlamellar spacing is smaller and more consistent in the head than in the foot. This outcome is expected, as the head was cooled in a polymer solution and the average hardness was 367 HB, while the foot was cooled in air and the average hardness was 330 HB.

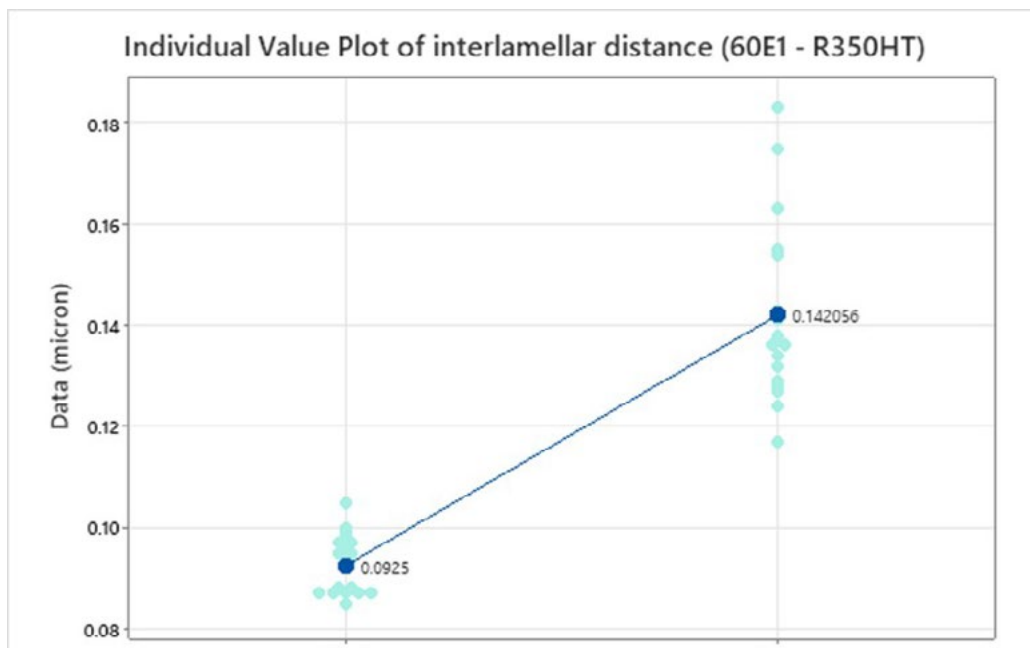
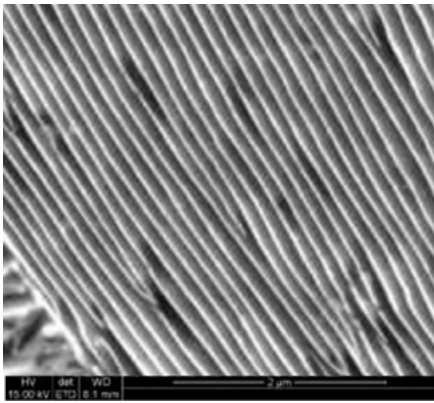
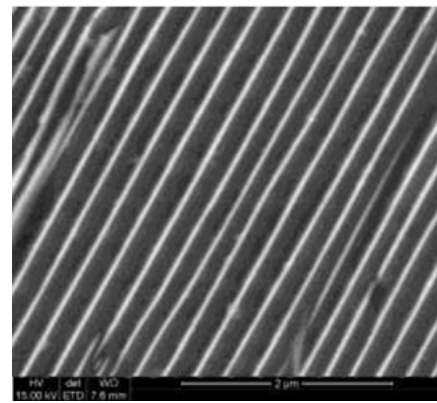


Fig.10 - Interlamellar distance of rail head and foot for heat treated rail.



SEM Image of microstructure in the area of the corner of the head (10 mm below the surface) – 60E1 – R350HT grade steel



SEM Image of microstructure in the area of the center of the foot (5mm below the surface) – 60E1 – R350HT grade steel

Fig.11

RESIDUAL STRESS

The rail profile is unsymmetrical; in fact, the head has a greater linear weight than the foot. As a result, cooling is non-uniform and phase transformations occur at different times. Uneven temperature distribution during cooling onto the cooling bed leads to thermal stresses, that can exceed the material’s yield strength at high temperatures, causing the rail to bend upon exiting the cooling bed. The bending direction depends on the rolling process: non-treated rails tend to bend toward the head, while heat-treated rails—where the head is cooler—bend toward the foot. Since heat treatment is applied to the head to achieve desired mechanical properties, controlling deformation requires

managing foot cooling. This is achieved using a series of nozzles positioned above the foot and supplied with water. However, straightness at cooling bed exit is not sufficient to meet the tolerances required by European standard. Therefore, a straightening process is necessary. Straightening introduces the highest residual stresses in rail production. If excessive, these stresses can compromise the rail quality and reduce fatigue resistance (11). Cooling the foot helps to reduce residual stresses by limiting rail bending and plastic deformation during the straightening process. Figure 12 shows results obtained from industrial practice: the average residual stress in the foot is 100 MPa - half the European limit.

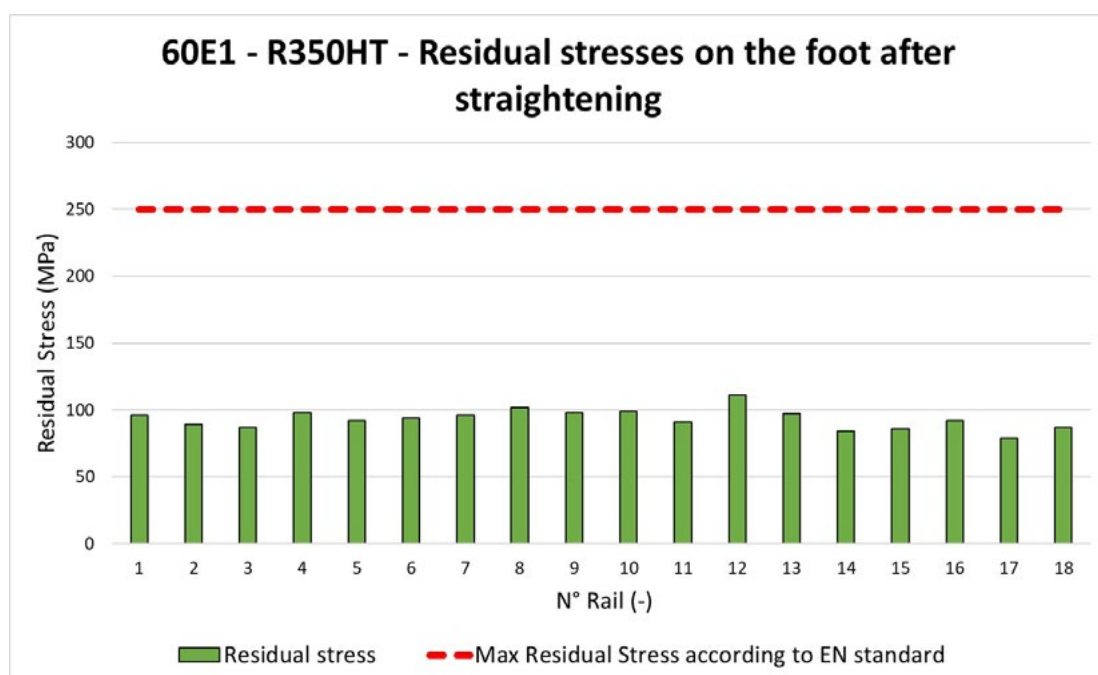


Fig.12 - Residual Stress.

CONCLUSIONS

The Danieli rail head hardening system (RH²) involves dipping the rail head in an aqueous polymer solution to enhance mechanical properties and wear resistance. The resulting values exceed European requirements with a good safety margin. Hardness remains above 360 HB at a depth of 20 mm from the running surface and tensile strength surpasses the 1175 MPa threshold by almost 100 MPa.

The primary microstructural parameter governing the strength of pearlitic microstructures is confirmed to be the pearlite interlamellar spacing. The finer pearlite, the higher hardness. After heat treatment, the average interla-

mellar spacing is less than 100 nm.

The RH² process significantly improves not only hardness and strength, but also fatigue life and toughness.

Toughness results from industrial practice indicate a mean fracture toughness of 38.8 MPa√m, well above the European requirement. Similarly, fatigue resistance tests show that all samples withstood 10⁷ cycles without failure - twice the minimum required by the European standard. These results are made possible by the low level of residual stresses. The average residual stress in the rail foot is 100 MPa - half the European limit.

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TORNA ALL'INDICE >