

Comparison of the quality of rail steel from the nineteenth century converter processes and the modern oxygen-converter process

Research Article

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Abstract: This article presents the results of comparative tests for rails produced at the end of the nineteenth century using the steel production processes used at that time in relation to currently produced rails in the standard, not heat-treated R260 steel grade, and heat-treated high-hardness R350HT steel grade. Detailed results of steel quality assessment are presented, including oxide cleanliness tests and macro- and microstructure analyses for each rail. The influence of the main elements on the morphology of the microstructure of individual rails is discussed, illustrating the description with numerous photos. An analysis of the chemical composition of each steel grade is provided, analysing the differences in the chemical composition of rails from different manufacturing processes. The results of hardness measurements in the rail head as an indicator of the rails' abrasion resistance are also presented. The article also discusses the steel production processes used since the mid- nineteenth century, taking into account their positive and negative features in relation to the currently used steel production process.

Keywords: Railway rail • Steel production process • Chemical composition • Steel cleanliness • Mechanical properties

1. Introduction

The breakthrough in the production of high-quality steel was made by Henry Bessemer, the inventor of the famous Bessemer process announced in 1856 [1,2]. It involved the use of a completely new converter process for freshening pig iron in a liquid state. The patented solution was a significant technical improvement over the time-consuming puddling process, where solid pig iron was heated with exhaust gases, and ore was necessary to initiate the oxidation process. The Bessemer process involved blowing liquid iron with a strong stream of air in a special converter, which had the shape of a cylindrical container covered with steel and lined with refractory bricks [3]. Blowing air into the molten pig iron not only cleaned the pig iron but also increased its temperature, which made it easier to pour into appropriate moulds or ingot moulds. The increase in the temperature of the pig iron was the

result of the reaction of oxygen with silicon and carbon. As a result of blowing, carbon, silicon, and manganese were removed in a short time, which allowed obtaining steel free of impurities and which could then be easily processed plastically. This enabled the production of cheap steel of relatively high quality, which made possible, among other things, the creation of transcontinental railway networks. A major drawback of this process was that the steel contained large amounts of sulphur and phosphorus. Bessemer used an ore without phosphorus, but other producers used ores rich in phosphorus and sulphur. In the puddling process, phosphorus was removed at a low temperature, while in the converter process, unremoved phosphorus caused the steel to become brittle. This feature made the ore containing phosphorus, found mostly in continental Europe, unsuitable for the Bessemer method, but perfectly suitable for the puddling process [3]. Improvement in this area was brought only by the method of removing sulphur and phosphorus from pig iron, patented in 1877 by Sidney Thomas. It differed from the Bessemer process in that the refractory coating of the converter was made of tar-burned

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dolomite, which made it alkaline. However, the lining of the Bessemer converter was acidic (silica) [1,4]. Thanks to Thomas's improvement, phosphorus migrated from iron to slag, allowing better quality steel to be obtained. An additional benefit was that phosphates used as fertilizers were obtained as a derivative of the process. A negative feature of both converter processes was a high concentration of dissolved nitrogen in the steel as well as low deoxidation, resulting in a high content of oxides in the steel, which negatively affected the functional properties of the products. The solution to this problem was the invention by Pierre-Émile Martin in 1865 of a furnace with a heated blast of air and gas [5,6]. This method allowed for the smelting of steel from pig iron and scrap with a significantly reduced content of elements such as carbon, sulphur, phosphorus, manganese, and silicon to the level required for steel. This process also assisted in the removal of excess gases (hydrogen and nitrogen), making the steel smelted in this process weldable. Open-hearth furnaces with both alkaline and acid lining were used. However, it was a very energy-intensive process and also time-consuming due to the extended smelting time. Attempts were made to improve the efficiency of the open-hearth process by increasing the charge weight up to 600 Mg [7]. Currently, oxygen converters are used to produce steel, enabling the blowing of not only oxygen but also inert gases like nitrogen or argon and fluxes, and post-furnace processing of steel is carried out in an argon treatment station, in a ladle heating furnace (LHF), and in a device for vacuum degassing of steel RH (the Ruhrstahl Heraeus process). The argonizing station is equipped with an argon lance, measuring devices (measuring temperature, oxygen activity, and FeO + MnO content in the slag), and an installation for argonizing the heat through gas-permeable fittings built in the bottom of the casting ladle. The main tasks of processing at the argon treatment station include homogenization and correction of the chemical composition of steel, correction of oxygen activity in steel and slag, and acceleration of the flow of non-metallic inclusions into the slag.

The LHF is equipped with a metal heating installation, an argonizing installation, a ferroalloy feeding system, and measuring and testing devices (measuring the temperature, oxygen activity, and FeO + MnO content in the slag). Heating steel is a basic process carried out on LHF. Temperature regulation is done by heating the steel in a ladle and blowing argon through the steel. The correction of the chemical composition of steel is made by specifying ferroalloys precisely, which allows for obtaining narrow ranges of the content of individual elements. Before transporting the ladle, insulating powder is placed on the steel surface to reduce heat loss. The LHF is used to correct the steel temperature (preheat), deoxidize the steel, and correct

the chemical composition. The continuous steel casting process enables melts to be delivered to the continuous casting machine (CCM) at a precisely defined temperature at a precisely designated time, which is particularly important in sequential steel casting [8].

The RH steel vacuum degassing device is equipped with replaceable vacuum vessels (chambers), an alloy additive dosing system, and a sampling system for chemical composition analysis and temperature measurement. A vacuum pump is used to create a vacuum. The purpose of vacuum degassing of steel is to reduce the content of gases, i.e. hydrogen, nitrogen, and oxygen in liquid steel. To remove hydrogen, it usually takes four changes (circulations) of steel in the chamber (10–12 min) at a pressure below 3 mbar. The transport gas is argon, which is supplied to the suction port through nozzles [8].

The tasks of vacuum treatment include reduction of hydrogen and nitrogen content in liquid steel, vacuum deoxidation, and improvement of the degree of steel cleanness (homogenization of non-metallic inclusions). As a consequence of the vacuum degassing operation, the level of hydrogen in rail heats cannot exceed 2.5 ppm in accordance with the European standard EN13674-1 [9], oxygen 20 ppm and nitrogen 90 ppm. This means that the process of vacuum removal of gases, especially hydrogen, protects the manufactured rails against the occurrence of hydrogen flakes.

The input in the casting process on a CCM is rail steel after post-furnace treatment and vacuum degassing operations, and the starting material is blooms intended for rolling. The technological materials used in the casting process are insulating powder for the tundish, insulating and lubricating powder for the continuous casting mould, inert gas (Ar with a minimum purity of 99.98%) supplied to protect the steel against secondary oxidation, ceramic materials (ladle sliding gate valve and refractory shrouding tube protecting the steel against secondary oxidation between the casting ladle and the tundish, stopper rods, and submerged nozzles protecting the steel against secondary oxidation on the way between the tundish and the mould). Rail steel produced in the basic oxygen furnace (BOF) process is characterized by a narrow and stable chemical composition of basic elements, low levels of residual elements, and low levels of gases. For example, in 2021, rail heats in the R260 grade produced at ArcelorMittal Poland S.A., the division in Dąbrowa Górnicza [10], were characterized by the following statistical distribution of the main elements: C content – average 0.72% (min. 0.68%, max. 0.79%), Mn content – average 1.09% (min. 1.02%, max. 1.15%), Si content – average 0.32% (min. 0.29%, max. 0.37%), P content – average 0.011% (min. 0.005%, max. 0.019%), S content – average 0.014% (min. 0.008%, max. 0.021%), and Al content – average 0.0024%

(min. 0.001%, max. 0.004%). All analysed rail heats also contained low content of residual elements, indicating slight contamination with undesirable elements in the R260 rail steel. The produced steel also had slight contamination with non-metallic oxide inclusions, expressed by the K3 index. For 97.83% of the tested samples, the K3 index was less than or equal to 10 (for 85.87% of the samples, K3 = 0), and for 2.17% of the samples the results were up to K3 = 20.

The modern rail steel production process allows us to ensure appropriate quality and properties of the rail, which should be characterized by [11]:

- high uniformity of chemical composition,
- low content of harmful elements,
- high metallurgical cleanness,
- appropriate macrostructure (Baumann print),
- high level of mechanical properties within a narrow range,
- appropriate level of fracture toughness, fatigue strength, and fatigue crack growth rate,
- low level of residual stresses.

The issues of rail steel quality and issues related to the operation of railway rails are widely published in the scientific and technical literature, which can be conventionally divided into the following issues, including the classification of contact-fatigue defects and their formation mechanisms [12–15], selection of steel grades for the planned track load and operating conditions [16,17], diagnostics of the railway surface, and monitoring of changes occurring on the running surface of rails [18–20], which directly affect the safety of rail transport. There are also numerous publications presenting the results of research on rail heat treatment technologies and their impact on

the microstructure and properties of rails [21–26]. However, these works did not analyse the cleanness of steel and the mechanical properties of rails from various technological processes of melting rail steel. The analysis of the literature regarding the quality of rail steel did not include any items presenting the results of tests performed on rails from historical steel production processes compared to tests carried out on rails from a contemporary, modern converter-oxygen process. The comparative form of various rail steel production processes presented in this article is intended to illustrate the progress that has been made in the production of railway rails and the increase in requirements for modern rails.

Current transport trends include the desire to increase the speed of passenger transport and increase the axle loads of wagons in freight transport while maintaining a high level of safety. Transport economics and its competitiveness with other means of transport in transporting people and goods increase the requirements for railway products. Market expectations come down to the possibility of purchasing and installing railway rails with a long service life under all operating conditions. Heat-treated rails are characterized by greater wear resistance, resulting in extended rail service life in unfavourable conditions such as track curves, high axial loads or high speeds, and increased resistance to brittle fracture, which ultimately makes the product more durable and safer.

2. Materials for testing

Sections of rails produced at the end of the nineteenth century and modern rails manufactured in two types of steel grades – R260 and heat treated R350HT – were obtained for testing. Table 1 shows the rail manufacturer and year of production. All rails from the nineteenth century are light rails with an estimated height after the production process of 105–130 mm. These rails were used on tracks, with clearly visible loss of material on the rail head and plastic

Sample no.	Manufacturer	Year of production	Steel grade	Height of the rail (mm)	Width of the rail foot (mm)
1	Dortmunder Union	1875	Low carbon steel	101*	93
2	Phoenix West	189?	Medium carbon steel	130*	116
3	Aachener Hütte	1879	Low carbon steel	117*	109
4	KRUPP	1894	Medium carbon steel	127*	100
5	ArcelorMittal Poland S.A.	2024	R260	149	125
6	ArcelorMittal Poland S.A.	2024	R350HT	149	125

*Measurement after operation in the axis of symmetry of the rail.

Table 1. Summary of the description of research samples.

deformation of their running surface as a result of long-term operation; their condition at the time of delivery for testing is shown in Figures 1–4. Modern 49E1 type rails with a nominal height of 149 mm were selected for comparison due to the most similar shape. Samples of the 49E1 rail were delivered for testing after rolling and heat treatment processes; their illustration is given in Figures 5 and 6.

3. Scope of research

The scope of research carried out included the following:

- chemical composition analysis,
- testing of the microstructure and hardness on the cross-section of the rail head,
- macroetching in HCl solution,
- assessment of sulphur distribution in the Baumann print,
- assessment of K3 oxide cleanness.

4. Research methodology

4.1 Chemical composition analysis

The results of control analysis of the chemical composition of the main elements and residual elements are presented



Figure 2. Phoenix West rail.

in Tables 2 and 3, respectively. Type 49E1 rails manufactured by ArcelorMittal Poland S.A. from 2024 are marked with number 5 for the R260 steel grade and number 6 for the R350HT steel grade, respectively. For comparison purposes, Tables 4 and 5 present the ranges of main and residual elements permissible in the EN13674-1:2011 + A1:2017 [9] standard for the standard steel grade R260 and heat-treated R350HT.

Upon analysing the chemical composition of nineteenth century rails marked with numbers 1–4, it can be



Figure 1. Dortmunder Union rail.



Figure 3. Aachener Hütte rail.



Figure 4. KRUPP rail.



Figure 5. ArcelorMittal Poland S.A. rail in steel grade R260.

seen that the carbon content in rail numbers 1 and 3 is at a similar level in the range of 0.17–0.20%, and the same can be said in relation to the carbon level in rail numbers 2 and 4, where the level of this element is in the range of 0.42–0.46%. The manganese content in samples 1, 2, and 4 is at a similar level, and only sample number 3 has a significantly lower manganese content of 0.22%. The silicon content in samples 2 and 3 is an order of magnitude lower than that in samples 1 and 4. The level of sulphur



Figure 6. ArcelorMittal Poland S.A. rail in steel grade R350HT.

content in samples 1–4 is similar and ranges from almost 0.05 to 0.07%. Greater differences in the percentage by mass occur for phosphorus; for samples 1 and 3, it is approximately 0.1%, while for samples 2 and 3 the average phosphorus content is 0.07%. Based on chemical analysis, it is difficult to clearly state by which process the rails come from, but it can be assumed, taking into account the phosphorus content in the steel, that the Dortmunder Union and Aachener Hütte rails came from the Thomas process. Noteworthy is the high nitrogen content in sample number 1, in relation to the current requirements of the standard [9] for the maximum nitrogen content, the concentration being more than three times higher than the standard values. In terms of the main elements C, Mn, and Si, the level of their content in samples 1–4 is even several times lower than the requirements for the standard grade R260. An opposite relationship is observed for harmful elements such as phosphorus or sulphur. The phosphorus content in samples 1–4 was over 2.5–4.2 times higher than the standard requirements [9], while the sulphur content exceeded the standard requirements for the R260 grade by 1.8–2.8 times. These differences translate into the level of hardness and cleanness of the steel and thus into the functional properties of the rails. Some information regarding the origin of ores for the production of nineteenth century rails is provided by the level of arsenic, which was the highest in sample numbers 1 and 2. Arsenic occurs in some rich iron ore deposits, e.g. in the study of Karczew or Lorraine [27]. Due to the lower affinity of arsenic than iron for oxygen, its total content is transferred to the steel, and its effect on its properties is similar to that of phosphorus. In the

Sample no.	Mass %								
	C	Si	Mn	P	S	Cr	Al	V	N
1	0.173	0.53	0.589	0.105	0.06	0.008	0.002	0.013	0.0332
2	0.46	0.011	0.418	0.064	0.07	0.009	0.007	0.001	0.0051
3	0.20	0.034	0.222	0.096	0.045	0.007	0.002	0.006	0.0121
4	0.422	0.19	0.69	0.075	0.046	0.010	0.003	0.01	0.0112
5	0.71	0.31	1.04	0.0073	0.014	0.008	0.003	0.003	0.0070
6	0.79	0.38	1.12	0.011	0.013	0.07	0.004	0.002	0.0057

Table 2. Chemical composition of individual samples for the main elements.

Sample no.	Mass %								
	Cu	Ni	Sn	As	Nb	Ti	Mo	B	Cu + 10Sn
1	0.149	0.014	<0.001	0.038	0.001	0.001	<0.001	0.0005	0.159
2	0.135	0.027	0.002	0.038	0.001	<0.001	<0.001	0.0003	0.155
3	0.009	0.013	<0.001	0.019	0.001	<0.001	<0.001	0.0004	0.019
4	0.08	0.01	<0.001	0.023	0.001	<0.010	<0.010	0.0003	0.09
5	0.02	0.014	0.0006	0.001	0.001	0.0009	0.003	0.0004	0.026
6	0.03	0.016	0.002	0.001	0.001	0.0009	0.006	0.0005	0.05

Table 3. Chemical composition of individual samples for residual elements.

range of up to 1%, arsenic increases the strength and hardness of mild steels while reducing their ductility. The higher the As content in the steel, the greater the impact on mechanical properties.

4.2 Microstructure studies

Samples for assessing the microstructure from rails 1–4 were taken from the side of the rail heads from the place closest to that specified by the standard [9] for assessing the microstructure of heat-treated rails. For non-heat-treated rails, the standard does not require microstructure testing. For steel grades R260Mn, R320Cr, R350HT, R370CrHT, and R400HT, the standard defines that the structure should be fully pearlitic with no martensite or bainite precipitation at

the grain boundaries. Photos of microstructures taken at various magnifications from samples from nineteenth century rails are shown in Figures 7–10.

The microstructure of rails produced by Dortmunder Union (Figure 7) and Aachener Hütte (Figure 9) containing 0.17–0.2% C revealed ferritic precipitates, while in the microstructure of Phoenix (Figure 8) West and Krupp (Figure 10) rails with a higher C content in the range of 0.42–0.46% showed visible perlite colonies, especially at higher magnification. For comparison, Figure 11 shows the microstructure of a modern rail in the non-heat-treated R260 grade, whereas Figure 12 shows the microstructure of a heat-treated rail in the R350HT grade. The microstructure of R260 steel, due primarily to the higher carbon and manganese contents, is fully pearlitic with the distance of the cementite lamellas in the pearlite of

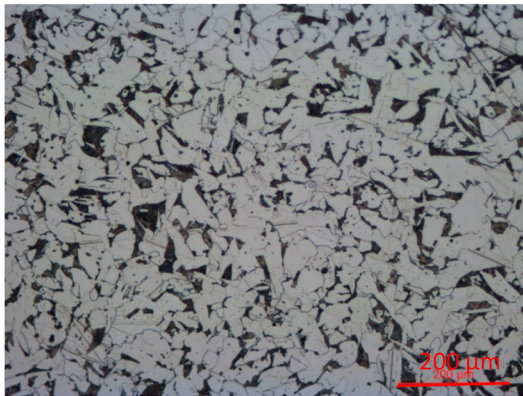
Steel grade	Mass %								
	C	Si	Mn	P max	S max	Cr	Al max	V max	N max
R260*	0.62–0.80	0.15–0.58	0.70–1.20	0.025	0.025	≤0.15	0.004	0.030	0.009
R350HT*	0.72–0.80	0.15–0.58	0.70–1.20	0.020	0.025	≤0.15	0.004	0.030	0.009

*The requirements are given for steel in the liquid state.

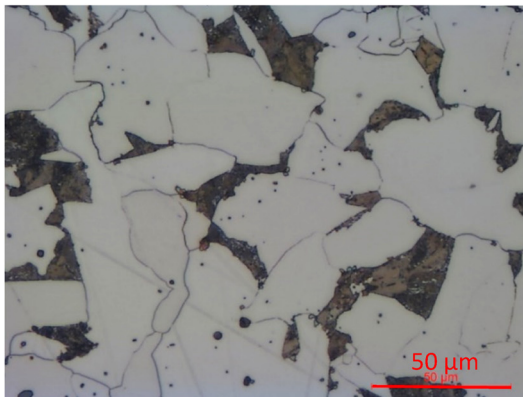
Table 4. Range of chemical composition of the R260 and R350HT grades for the main elements.

Steel grade	Mass %								
	Cu	Ni	Sn	As	Nb	Ti	Mo	B	Cu + 10Sn
R260	0.15	0.10	0.030	—	0.01	0.025	0.02	—	0.35
R350HT	0.15	0.10	0.030	—	0.04	0.025	0.02	—	0.35

Table 5. Range of chemical composition of the R260 and R350HT grades for residual elements.

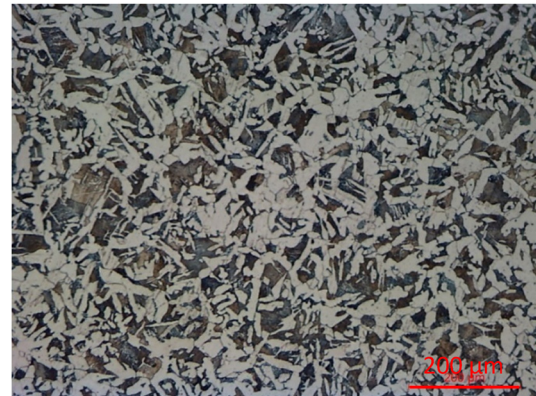


a)

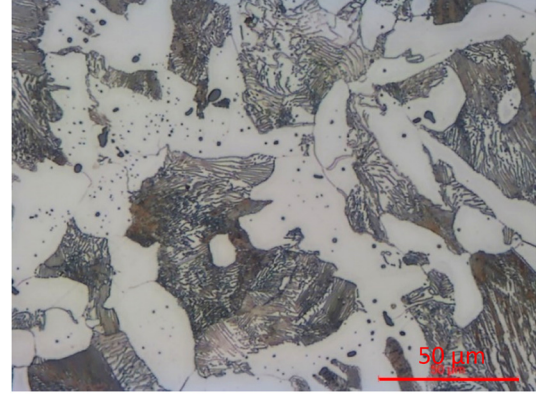


b)

Figure 7. Images of the ferrite-pearlite microstructure of the Dortmund Union rail. a) magn. 100x, b) magn. 500x.



a)

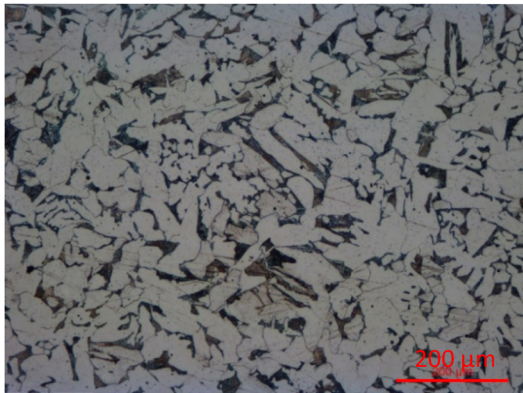


b)

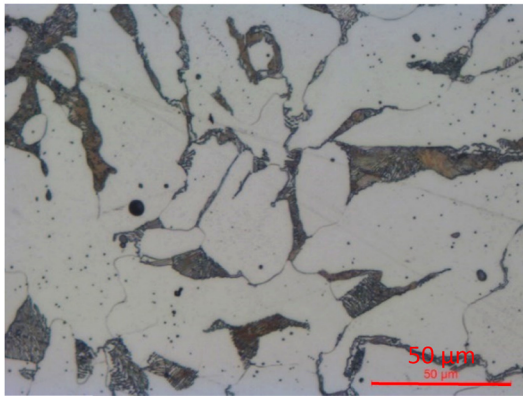
Figure 8. Images of the ferrite-pearlite microstructure of the Phoenix West rail. Coarse-plate perlite is visible. a) magn. 100x, b) 500X.

0.2–0.25 μm ; an example image of the microstructure of R260 steel is shown in Figure 13a. For R350HT steel, we observe greater pearlite fragmentation, which reduces the distance of cementite lamellas in the pearlite to 0.05–0.15 μm while maintaining a fully pearlitic structure (Figure 13b). The distances between the lamellas depend on the heat treatment parameters used, especially dedicated to each type of rail steel with different hardness requirements. The following relationship occurs: the smaller the interlamellar distance in pearlite, the higher the hardness and the higher the level of mechanical properties; therefore, in order to obtain higher hardness, a deeper modification of the pearlite morphology is necessary.

The wear resistance of rails is a property resulting from microstructural parameters, in particular the distance between the cementite lamellas in the pearlite, the thickness of the cementite lamellas, and the size of the pearlite colonies. The essence of the rail heat treatment process is the modification of the pearlite microstructure in order to extend the rail service life, especially in track curves with a small radius, in the case of intensive track use, or in the case of high unit pressures. The appropriately modified pearlite microstructure improves the fatigue strength and increases resistance to brittle fracture expressed by the critical stress intensity factor K_{Ic} , as well

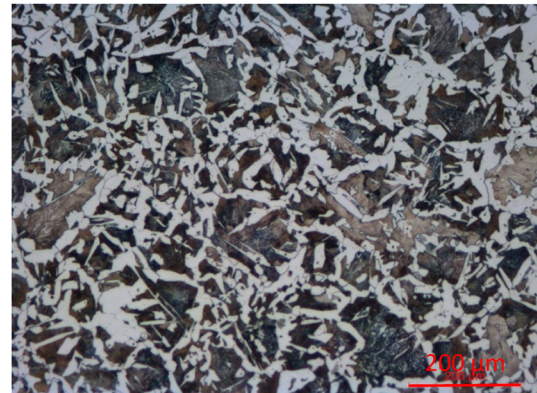


a)

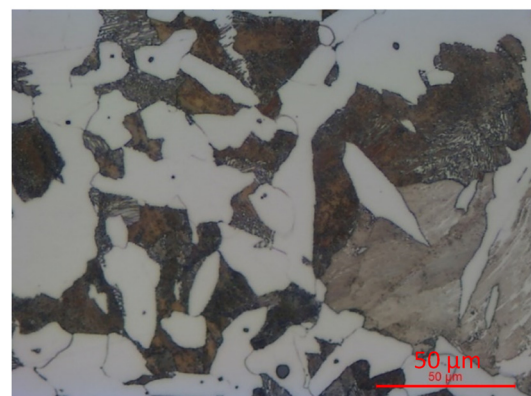


b)

Figure 9. Images of the ferrite-pearlite microstructure of the Aachener Hütte rail. a) magn. 100x, b) magn. 500x.



a)



b)

Figure 10. Images of the microstructure of the ferrite-pearlite Krupp rail. a) magn. 100x, b) magn. 500x.

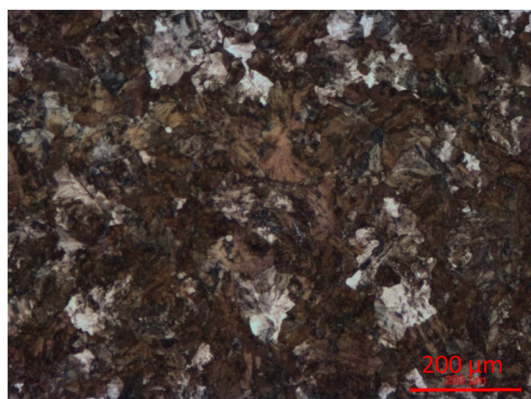
as resistance to contact-fatigue defects, which means an increase in the safety standard for both passenger and freight transport as a result of minimizing the risk of uncontrolled rail cracks in the track [28].

Table 6 shows the measured hardness values for all tested rails. The hardness measurement was made in the centre of the rail head, differently from the requirements of the standard [9], which for not heat-treated rails requires measurement on the running surface after removing the 0.5 mm decarburized layer, and additionally, for heat-treated rails, on the cross-section of the head. This approach results from the need to ensure comparability of hardness measurements due to the fact that rails 1–4 had significant wear characterized by large losses of material and deformation of the head shape resulting from the plastic flow of the material during the operation of these rails. This allowed the elimination of the influence of the strengthened material on the running surface of rails 1–4 on the measured hardness. For comparison purposes, the hardness in the centre of the head was measured for rails 5 and 6.

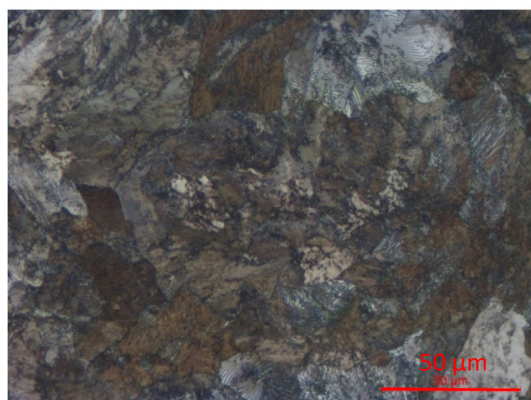
4.3 Macrostructure study

The Baumann print assesses the distribution of sulphur in the form of sulphides on the tested surface of steel products. Baumann prints were made to illustrate the sulphur distribution on the cross-section of the tested rails, which are presented in Figures 14–19.

Samples 1 and 2 show point-like subsurface sulphide concentrations around the perimeter of the rail head and foot. The distribution of sulphides on the rail cross-section, especially sample No. 2 is uniform. However, for samples 3 and 4, large sulphide concentrations are observed, both spotty and banded, in all areas of the rail, i.e. in the head, web and foot. According to Annexure D of the standard [9], and the Baumann test is assessed using patterns marked D1–D12, whereby patterns D1–D7 being acceptable. Assigning Baumann's print to one of the other patterns results in a negative assessment of the sample. All Baumann prints made on samples 1–4 are outside the standard grading scale [9]. Baumann's prints made from modern rails were rated D2 for sample no. 5 and D4 for sample no. 6.

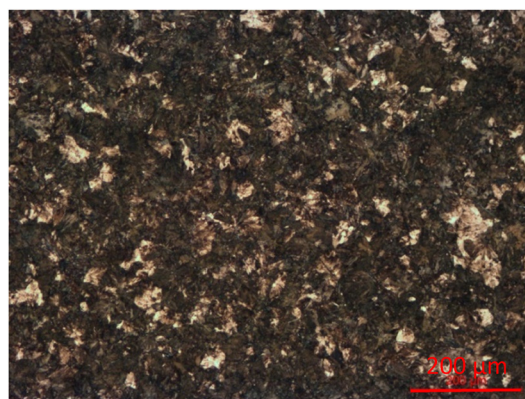


a)

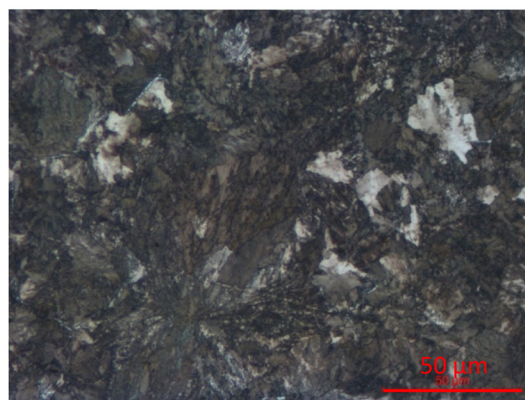


b)

Figure 11. Images of the microstructure of a fully pearlitic rail from ArcelorMittal Poland S.A. in the R260 grade. a) magn. 100x, b) magn. 500x.



a)



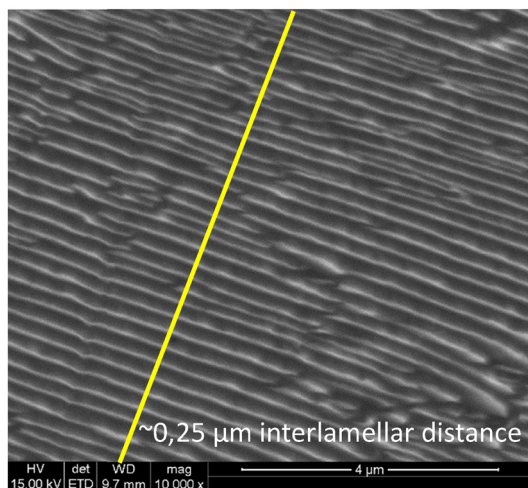
b)

Figure 12. Images of the microstructure of a fine-plate perlite rail of the ArcelorMittal Poland S.A. in the R350HT grade. a) magn. 100x, b) magn. 500x.

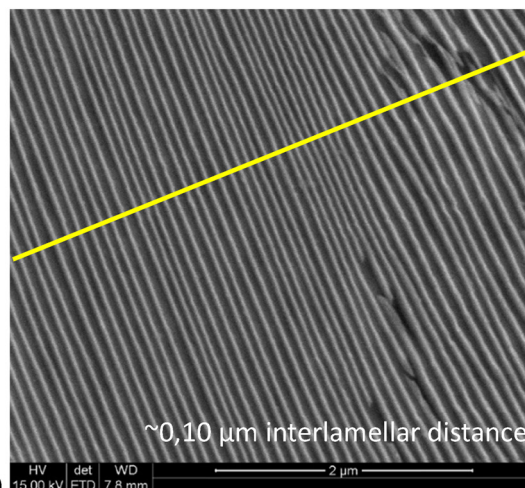
Figures 20–25 show photographs of rail templates from a macroetching test with a concentrated HCl solution.

Deep etching reagents intensively etch non-metallic inclusions and widen various types of macroscopic discontinuities

in the metal matrix. Therefore, it is possible to reveal various types of defects, such as porosity, pin holes, clusters of non-metallic inclusions, cracks, as well as overlaps and forging laps. It is also possible to assess the primary structure, zones



a)



b)

Figure 13. Images of the microstructure of (a) steel grade R260 and (b) steel grade R350HT (b).

Sample no.	Manufacturer	Steel grade	Hardness in the centre of the head, HBW				Hardness on the running surface, HBW
			1	2	3	mean	
1	Dortmunder Union	Low carbon steel	204	192	189	195	—
2	Phoenix West	Medium carbon steel	168	171	165	168	—
3	Aachener Hütte	Low carbon steel	153	140	146	146	—
4	KRUPP	Medium carbon steel	198	205	198	200	—
5	ArcelorMittal Poland S.A.	R260	274	271	279	275	Avg. 285
6	ArcelorMittal Poland S.A.	R350HT	387	385	382	385	Avg. 374

Table 6. Hardness values for individual rails (HBW 2.5|187.5).

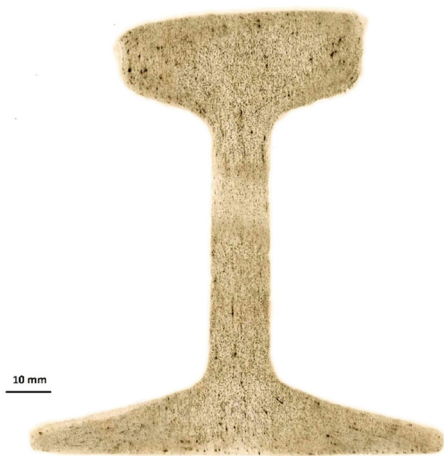


Figure 14. Baumann print, sample no. 1.

of segregation and dendritic structure. On sample No. 2, this test revealed a crack on the rail foot in an advanced form, propagating from the lower surface of the rail foot, and areas of significant peripheral decarburization in the form of a light rim (Figure 21). Non-metallic inclusion of particularly large size was observed for sample no. 3 (Figure 22). Figure 26 shows an image of an example inclusion. SEM/EDS microanalysis in the area of discontinuity showed the presence of elements such as Fe, O, Si, and Al (Figure 27). The chemical composition indicates a two-phase structure composed of silicon oxides SiO_2 and aluminium oxides Al_2O_3 . The image of sample No. 1 after deep etching shows a peripheral decarburization zone and segregation, which is more intensely observed on sample No. 4 along with large clusters of non-metallic precipitations. Sample Nos 5 and 6 show the correct macrostructure without defects with visible traces of sulphur



Figure 15. Baumann print, sample no. 2.



Figure 16. Baumann print, sample no. 3.



Figure 17. Baumann print, sample no. 4.

segregation occurring in the node at the transition between the rail web and the rail head.

4.4 Oxide cleanness

Testing the oxide cleanness of steel, expressed using the K3 index, is one of the mandatory acceptance tests specified in the EN 13674-1 standard [9]. The degree of cleanness (K3

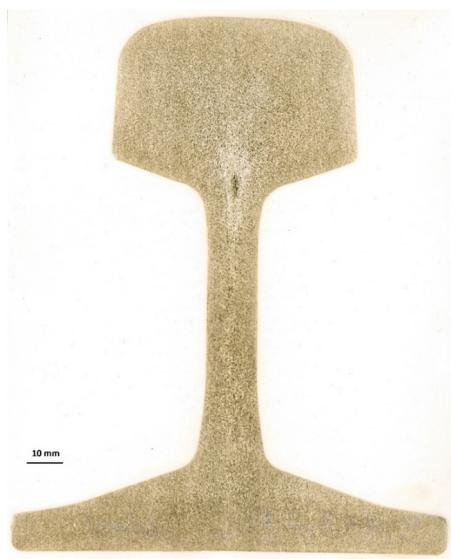


Figure 18. Baumann print, sample no. 5.



Figure 19. Baumann print, sample no. 6.

index) is a value indicating the content of non-metallic inclusions in the product in the form of oxide inclusions. It illustrates the content of these oxides by determining the percentage of non-metallic inclusions in the structure. The result is the sum obtained by counting the inclusions present on a 1,000 mm² reference surface, which are weighted based on their area, starting from the specified dimension upwards. The evaluation criteria are as follows: for orders less than 5,000 tons, only one sample with a K3 value greater than 10 but less than 20 is allowed. The following limits must be taken into account:

Total index $10 < K3 < 20$ – for a maximum of 5% of the samples



Figure 20. Etching test, sample no. 1.

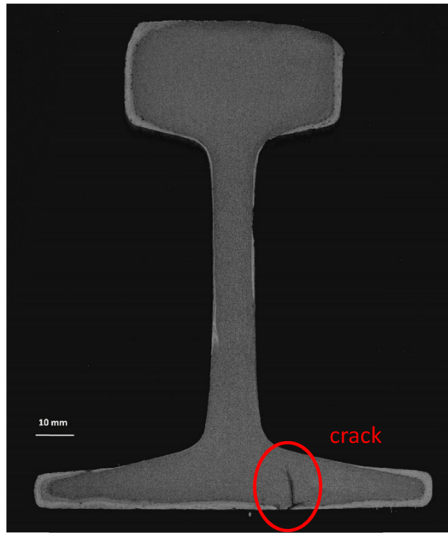


Figure 21. Etching test, sample no. 2.

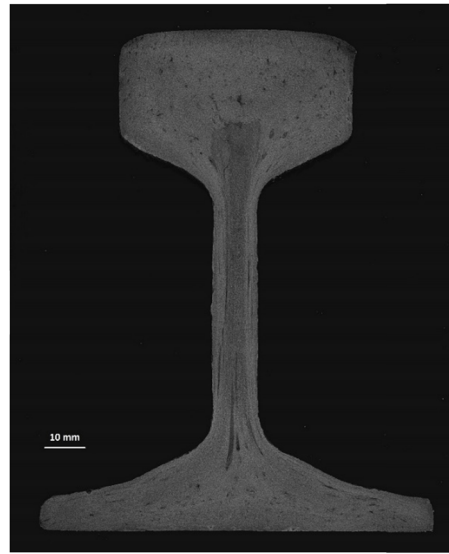


Figure 23. Etching test, sample no. 4.

$K3 < 10$ —for a minimum of 95% of the samples

The place of sampling for determining the K3 index is defined on the side of the rail head in accordance with Figure 28.

The detailed procedure for assessing oxide cleanness is described in Annexure F of the standard [9]. The following types of inclusions are distinguished:

- OA inclusion type: oxide inclusions of fragmented type (aluminium oxides);

- OS inclusion type: oxide inclusions of elongated type (silicates);

- OG inclusion type: oxide inclusions of globular type.

Table 7 presents the assessment of the oxide cleanness test for all samples.

All samples from rails 1–4 were assessed as negative, i.e. they did not meet modern criteria for oxide cleanness. A particularly high K3 index was recorded on sample No. 3, where a high intensity of non-metallic inclusions was observed in the macrographic examination. Samples 5 and 6 from

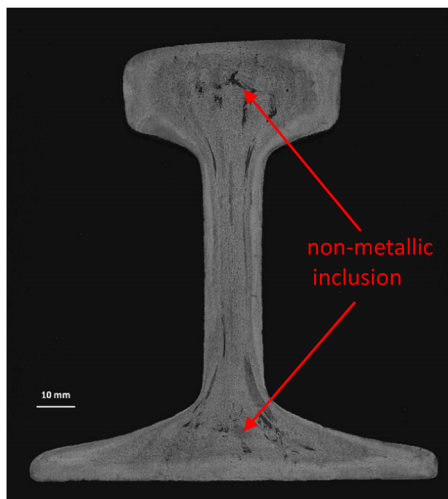


Figure 22. Etching test, sample no. 3.



Figure 24. Etching test, sample no. 5.



Figure 25. Etching test, sample no. 6.

rails manufactured in 2024, both in the R260 and heat-treated R350HT grades, were characterized by high oxide cleanness for all types of inclusions OA, OS, and OG; zero number of inclusions was recorded for each classification number, which translated into the final value coefficient $K3 = 0$. For samples 1–4 had a hardness in the range of 150–200 HB, while the average hardness of sample No. 5 was 285 HBW and that of sample No. 6 from the heat-treated rail reached 374 HBW. The difference in hardness is the result of much lower levels of the



Figure 26. Image of a non-metallic inclusion – low carbon steel (Aachener Hütte), sample No. 3.

5. Summary

This comparative research on rails from the nineteenth century and rails currently produced in terms of the quality of rail steel and the level of properties illustrated the progress made in the production of rail steel and the increase in requirements imposed on modern rails. Samples 1–4 had a hardness in the range of 150–200 HB, while the average hardness of sample No. 5 was 285 HBW and that of sample No. 6 from the heat-treated rail reached 374 HBW. The difference in hardness is the result of much lower levels of the

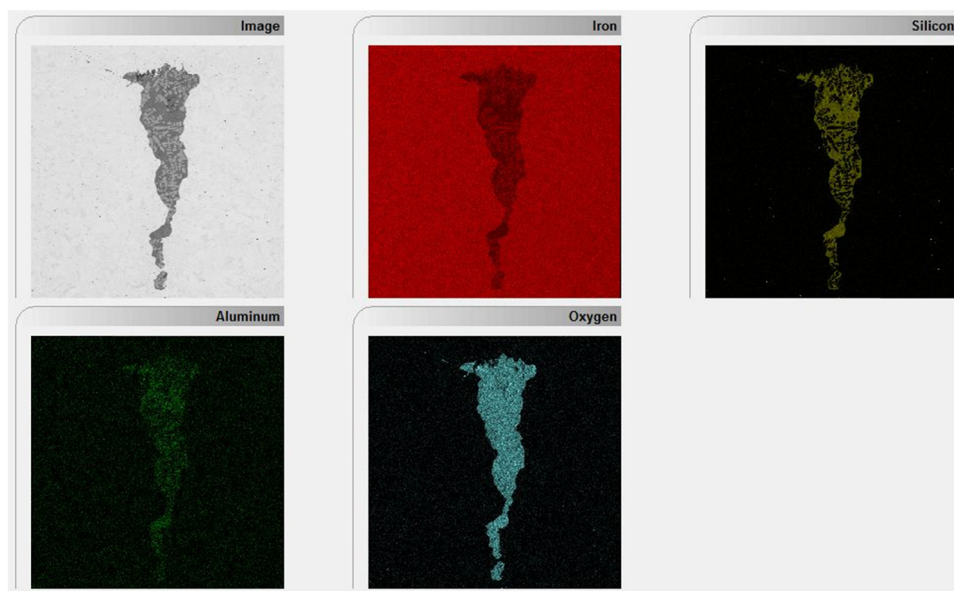


Figure 27. Mapping in the area of discontinuity – low carbon steel (Aachener Hütte), sample No. 3.

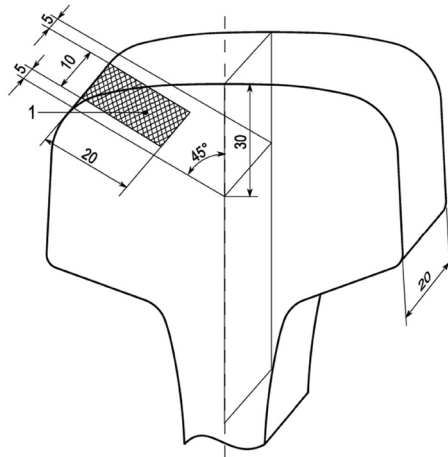


Figure 28. Location of the sample for assessing oxide cleanness in the rail head [9].

content of the main elements, i.e. C, Mn, and Si, and the lack of additional rail head hardening treatments for rails 1–4; however, it reflects well the increase in requirements regarding the operational properties of rails. It is assumed that hardness



Figure 29. R260 steel with MnS inclusions.

is a measure of the abrasion resistance of the pearlitic structure, and each increase in the rail hardness by 40 HBW increased the abrasion resistance by an index of 1.75. Therefore, increasing the hardness from 200 to 280 HBW allowed the abrasion resistance to be increased by 3.5 times. However, the low hardness of rails 1–4 allowed the abrasion

Sample no.	Area of the assessed surface (mm ²)	Type of inclusions	Number of inclusions determined by the classification number						First subtotal	K3
			3	4	5	6	7	8		
			Factor f_g							
			0.5	1	2	5	10	20		
1	200	OA	1	0	0	0	0	0	0.5	60
		OS	0	0	0	0	0	0	0	
		OG	15	2	1	0	0	0	11.5	
2	200	OA	0	0	1	0	0	0	2	42.5
		OS	0	0	0	0	0	0	0	
		OG	5	0	2	0	0	0	6.5	
3	200	OA	0	0	0	0	0	0	0	120
		OS	2	3	0	0	0	1	24	
		OG	0	0	0	0	0	0	0	
4	200	OA	0	0	0	0	0	0	0	25
		OS	2	2	1	0	0	0	5	
		OG	0	0	0	0	0	0	0	
5	200	OA	0	0	0	0	0	0	0	0
		OS	0	0	0	0	0	0	0	
		OG	0	0	0	0	0	0	0	
6	200	OA	0	0	0	0	0	0	0	0
		OS	0	0	0	0	0	0	0	
		OG	0	0	0	0	0	0	0	

Table 7. Assessment of oxide cleanness.



Figure 30. R350HT steel with MnS inclusions.

process of the running surface to precede the development of contact-fatigue defects. No surface defects such as Squat, Head Checking, Shelling, or Tache Oval were observed on the running surface of any samples 1–4. The quality of the steel used in rails 1–4, in particular the high content of undesirable steel impurities in the form of phosphorus and sulphur compounds and the low oxide cleanness expressed by the K3 index, did not allow meeting the requirements of the modern standard [9] in any of the assessed acceptance test criteria. Nevertheless, rails made of steel obtained in the nineteenth century processes fulfilled their role and constituted an important element in the development of the railway network and rail transport. Obviously taking into account the fact that the rails from the nineteenth century worked under completely different operating conditions, especially taking into account the maximum axle loads, the transported tonnage, and the maximum speed of the trains. The improvement in the steelmaking process and the technology for the production of railway rails as well as the use of heat treatment made it possible to meet the increasingly higher requirements for railway rails set by modern railway companies, leading to the creation of highly hard grades of R350HT rail steel with hardness in the range of 350–390 HBW, which are more than four times higher than that of nineteenth century rails in terms of abrasion resistance, up to ultra-hard grades of R400HT type with a hardness range of 400–440 HBW on the running surface.

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Author contributions

Sylwester Żak – contribution 60%; Tomasz Ropka – contribution 40%.

Conflict of interest statement

Authors state no conflict of interest.

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