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Archaeometallurgical and Comparative Study of Material Characterization and Qualities of Two Profiles of Historical Argentine Railways of Different Gauges and Their Fixing Elements

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Abstract
In the historical railway issue, few studies have been carried out, both nationally and internationally, to investigate the quality of railway material such as rails and fixings. The historical pieces of this research applied to the study of qualities of railway rail profiles are two Vignole type rails: one is the P50 wide gauge rail (1520 mm of Russian origin) that is part of the Godoy Cruz Railway Museum (Mendoza province) and the other is a narrow gauge rail (750 mm) that belongs to the Museum of the Old Patagonian Express "La Trochita" (Chubut province), and they were donated for this research. It is proposed to make a comparison of these railway and historical elements in terms of raw material, hardness, chemical composition by means of argon plasma spectrometer, analysis of macrographs and microstructures by means of binocular stereomicroscope and metallographic microscope, respectively. Through the study of these railway rails, it is possible to know the characteristics of the quality of the material, rolling or forging lines, sinks, blowholes, dendritic structures.

Keywords Rails · Fixing elements · Microstructures · Chemical composition · Hardness

Introduction

The study focuses on two Vignole type railway rail profiles: one rail is a wide gauge P50 (1520 mm, Soviet origin), and the other rail is a narrow gauge (750 mm, German origin) and a fixing element (Belgian origin). This study intends to analyze the characteristics of the materials used in the Argentine historical railways through micrographic and macrographic analysis, chemical composition, hardness measurement and make a comparison with the materials used in current railway rails. The pieces investigated are part of the railways of the provinces of Mendoza and Chubut (both in Argentina). The rails of the railway lines in a large part of Argentina are around 100 years old, so the corresponding historical revisionism is also carried out (Fig. 1).

This work is part of the Research and Development Project: "Reverse Engineering applied to the study of Historic Railways" (code: MAPPBME0008394) and which is currently being developed in the Archaeometallurgy Area dependent on the Metallurgy Laboratory, belonging to the National Technological University Mendoza Regional Faculty, Argentine.

As is mentioned in Introduction on the historical railway theme, few studies have been carried out, both nationally and

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Fig. 1 (**a**) P50 rail wide gauge 1520 mm of Sovietic origin; (**b**) 750 mm narrow gauge rail of German origin; (**c**) fixation nail of Belgian origin

internationally, to investigate the quality of railway material such as rails and fixings. To mention some of them, the thesis [1] investigated the vocabulary used in the first half of the nineteenth century to describe the properties and composition of iron and steel. The work sought to examine the vocabulary used to describe iron and steel in the context of a particular industry: railways. To determine the actual mechanical properties of nineteenth-century railway tracks, original examples from 1800 to 1860 were obtained. These rails were then subjected to mechanical testing and analysis using hardness tests, impact tests, tensile tests, light microscopy, scanning electron microscopy. They concluded from observations recorded by nineteenth-century engineers and scientists that they were accurate in terms of the general effect of material structure and composition on the properties of cast and wrought iron. It also suggests that further investigation could reveal more details about the knowledge that engineers and ironworkers possessed at the time. They also suggest that a more extensive metallurgical study of nineteenth-century rails could uncover the variations in iron casting to casting.

In another study related to the metallurgical evaluation of the Lion locomotive wheel [2], being the Lion locomotive one of the oldest steam locomotives in the world, an inspection of the manufacturing material has been carried out, starting from the replacement of worn parts and loose sections of the wheel, it was determined to be wrought iron, certified 'Best Yorshire' as its source material and likely to have been rolled and/or welded to specifications supplied by the London and North Western Railway.

The Arrival of the Railway to Mendoza

The Andean Railway arrived in Mendoza on April 7, 1885, for the event the president of the Nation Julio A. Roca arrived in Mendoza in a special train, and thus Mendoza was linked to Buenos Aires (national capital) with exit to the port located in the Atlantic Ocean and this caused a change in the economic orientation of Mendoza, which was previously economically oriented towards the Pacific Ocean. Travel time, which had taken between one to two months by wagon for 300 years, now was reduced to 48 h by train. This date was highly celebrated, and even bronze medals were awarded to those attending to the celebration (Fig. 2).

For the year 1887, the National Government transferred the Andean Railway to the company Great Western Argentine Railway; therefore, Mendoza and other neighboring towns in the region in the year 1907 became part of the Buenos Aires to Pacific Railway (BAP).

The Buenos Aires to Pacific Railway, known simply as "The Pacific", improved the services, and the new tracks ensured the circulation of freight trains that could transport greater tonnages, meaning that the Buenos Aires to Pacífico Railroad not only functioned as passenger train but also as a freight train (Fig. 3).

Fig. 2 Bronze medal commemorating the arrival of the Andean Railway to Mendoza, donation. Image provided courtesy of Benegas Station Railway Museum, Godoy Cruz. (Mendoza-Argentina)

Fig. 3 Map of the Argentine rail network in the years 1910–1911 by Buenos Aires & Pacific Railway Company Limited. Adapted from Buenos Aires and Pacific Railway Company, World Digital Library

By the year 1930, the passenger station in Mendoza capital city had a daily movement of 60 trains that ran through the most important circuits in the province of Mendoza. This intense activity ended in 1938, due to competition with the buses that traveled through Mendoza, since the paving of the roads had increased. To defend itself against this competition, the Buenos Aires & Pacific Railway created a subsidiary automotive company called International Automobile Transport Company (CITA) with the incorporation of the first buses with Leyland brand engines, which began to replace local trains [3].

The Planning of the Old Patagonian Express Railway

After World War I, the Argentine government finally decided to build the branch of the Old Patagonian Express using the economic gauge width of 750 mm. It can be said that the 600 mm narrow gauge branch lines called "Decauville" had been used frequently during this war to supply the fronts which, upon completion, played an important role in the reconstruction of the battlefields in France and Belgium. Already at the end of the conflict, the existing stock in Europe of this type of railway material was considerable and its immediate availability made it very cheap and suitable for certain purposes. In this way, the 600 mm gauge tracks, for the Decauville locomotive, were widely used in the rural areas of the prof Buenos Aires province, to transport agricultural cargo, and were a success, since they reached places where other transportations did not arrive, for its practicality and flexibility were of great importance because these rails could be lifted and moved to other more productive agricultural areas to carry out the transport of agricultural production. This caused the price of the territories to rise and the cost of transporting cargo compared to cars and trucks was greatly reduced.

In the unique post-war context, the 750-mm narrow gauge was then considered a real possibility. For passenger services, locomotives with a gauge of 750 mm were available, and this cheaper alternative was chosen for the line that would reach Esquel.

In 1921, the laying of the line connecting the town of Engineer Jacobacci (Río Negro province) with the city of

Esquel (Chubut province) was agreed (Fig. 4). This line would be called the Light Railways of Patagonia, and by November 1921 the purchase of materials for cheap railways began: some 200,000 rails were purchased from the Thyssen Industrial and Trade Company Ltd. (Thyssen was a major German steel company) and another 80,000 rails and fastening systems to Société anonymous d'Ougrée-Marihaye (Ougrée-Liege, Belgium). The first train entered the city of Esquel (Chubut province, Argentina), on May 25, 1945 [4].

However, until 1950 it was just a freight train. The first passenger service launched in 1950 connected the city of Esquel (blue circle with red point) with the capital city of Eng.Jacobacci (blue circle with white point). The passengers traveled on hard wooden benches (Fig. 5), in the case of second class cars, and all the passenger cars had a stove (salamander type), which was used to cook, and also to prepare the Mate (typical Argentine hot infusion) and primarily for heating purposes. The passenger train journey that linked Patagonia with the national capital Buenos Aires was approximately 16 h.

At the present time, only remains the branch that goes from Esquel (blue circle) to Nahuel-Pan (orange circle), making two travel weekly as touristic atractions that are highly visited by both native and international tourist.

In 1999, the government of Argentina declared the Old Patagonian Express “La Trochita" (Fig. 6) as National Hystoric Monument.

Fig. 5 Interior of the second class passenger cars of the Old Patagonian Express

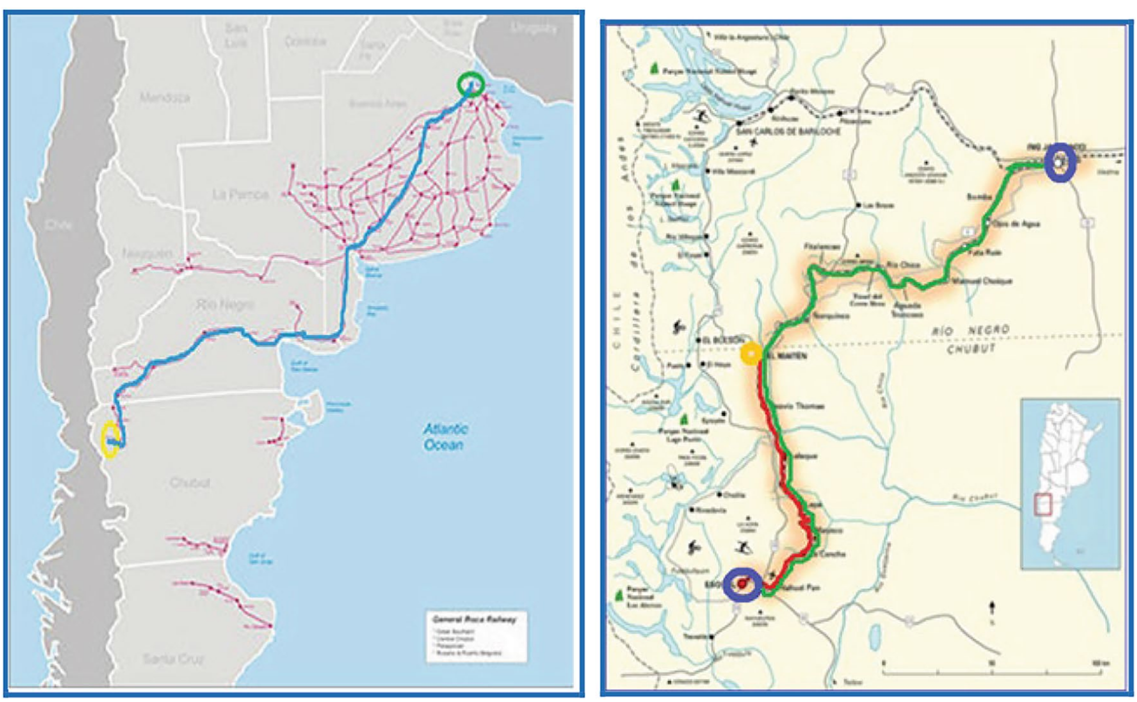

Fig. 4 (**a**) Map route of the line between Esquel (yellow circle) and Buenos Aires (green circle); (**b**) Map route of the line between Eng. Jacobacci (blue circle and Green line) and Esquel city (blue circle and red line) of the Old Patagonian Express, in Chubut province (Patagonia, Argentina)

Fig. 6 Old Patagonian Express "La Trochita"

Fig. 7 Scheme of rail profile parts

Experimental Methodology

Rails Technical Information

The rail simultaneously fulfills the functions of track, support element and guide element. The railway was the subject of detailed studies from its origin to evolve along with technological advances.

Thus, at the beginning of rail transport, the rail profiles that were used were double-headed rails, with the intention that they would be used again once the head in service reached its wear limit. Subsequently, it was observed that such an operation was not possible, given that by inverting their position, they were not suitable for traffic due to the wear caused by the sleepers on the support surface, and for this reason the current profile, called Vignole, was adopted, consisting of a wide lower face, intended to support the sleepers, and an upper face, narrower and higher, intended to guide and support the wheels [5].

The profile used is the Vignole (Fig. 7), and it is made up of three parts, which are:

• Head: it is the one used as a bearing surface and is exposed to the greatest solicitations and suffers wear. It must have a sufficient height and width, depending on the gauge of each rail.

• Web: it is the element of reduced thickness that has the function of joining the head with the foot, ensuring the transmission of loads from the head to the foot.

• Foot: it constitutes the base of the rail and it is a lower part and flat, which allows it to support the sleepers and must have sufficient width, in order to distribute the load on the sleepers.

The Studied Pieces

These pieces are the two rail profiles, one wide and the other narrow gauge and a fixation nail; these elements were provided by Railway Museums cited in two different provinces from Argentina.

Regarding the study methodology of each pieces, the first determination carried out was the determination of the chemical composition of these three pieces that make up this investigation.

Thus, the chemical composition was carried out on each rail profile and the fixing nail, with an argon plasma emission spectrometer leaves a small mark on the sample, which can then be removed in the following operations of roughing and grinding.

The metallographic preparation of the samples for the micrographic study was carried out as specified by the ASTM E407-07 standard [6].

In the roughing stage, it should be noted that the entire rail profile was worked on and, therefore, no sample was extracted or any sector included for inspection. We worked with each entire rail profile, and firstly, each rail profile was roughed with a belt sander (N° 120), and the main objective was to eliminate the marks made by the cutting tool on each profile (Table 1).

In the grinding stage, we worked with a set of water-based sandpaper ordered from the coarsest to the finest sandpaper (sandpaper used: 80, 240, 400, 600, 1200, 2000) and each larger size of sandpaper used than usual, in order to be able to work with each entire rail profile and perform the sanding operation under tap water, this operation was completely manual and with dedication to try to eliminate as much as possible the lines and scratches of rail profiles and fixing nail. It should be noted that both profiles and nail were not worked at the same time, since several days of effort were needed for each of the pieces studied in terms of grinding and polishing.

For the polishing stage of the pieces, it also represented a challenge to be able to use the metallographic polisher, instead the lathe and fine-grained polishing discs were used and the usual alumina paste.

The next stage was the chemical attack with chemical reagents, and the 2% Nital pickling reagent was used

Table 1 Chemical composition of rail P50

wt.%C	wt.%Si	wt.%Mn	wt.%P	wt.%Cr	wt.%Mo	wt.%Ni	wt.%Al	wt.%As
0.79	0.18	0.66	0.033	0.022	0.010	0.070	0.014	0.13
wt.%Zr	wt.%Bi	wt.%Zn	wt.%Fe	wt.%Co	wt.%Cu	wt.%Nb	wt.%Ti	wt.%V
0.003	0.039	0.016	97.8	0.019	0.039	0.006	0.008	0.011
wt.%W	wt.%Pb	wt.%Sn	wt.%Mg	wt.%Ca	wt.%Ce	wt.%B	wt.%S	wt.%La
< 0.040	< 0.010	0.019	0.002	0.001	0.007	0.007	0.022	0.007

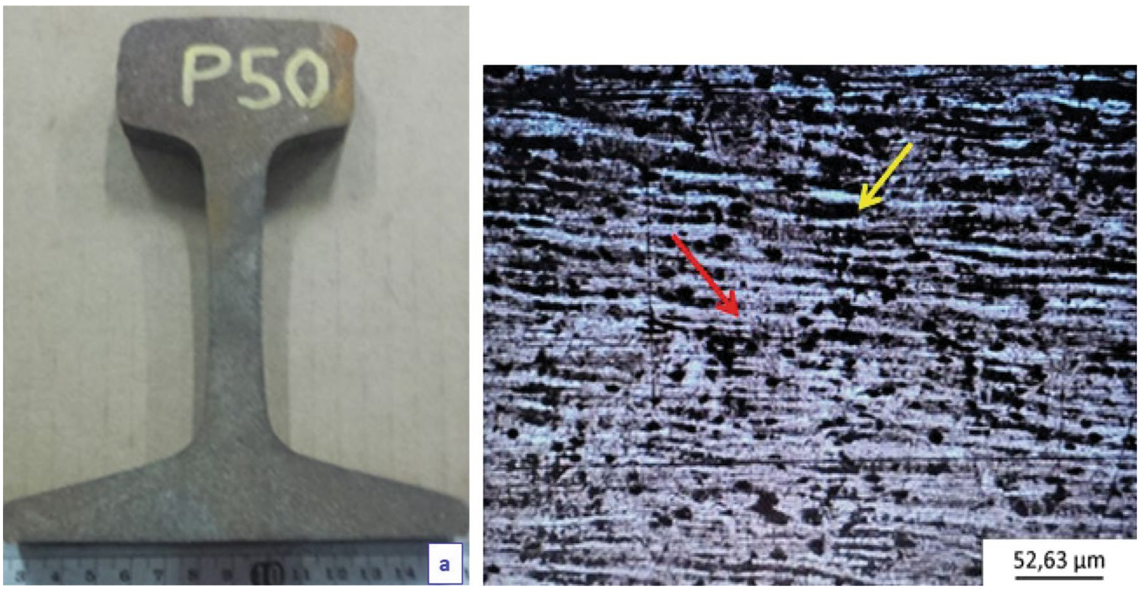

Fig. 8 Image of P50 rail, and the micrograph of P50 rail: deformed ferrite (red arrow) and deformed pearlite (yellow arrow) grains due to cold working are observed. 2% Nital

(composition: 2 cm^3 HNO_3 + 100 cm^3 95% ethanol). The images were subsequently obtained with an inverted stage metallographic microscope, working mainly with low magnifications of 50x (52.32 µm) and 100x (26.32 µm). Because we worked with the entire rail profile, higher magnifications provided blurry or out-of-focus images.

The macrographic studies were performed as specified ASTM E381 [7]. For the macrographs, the 2% Nital chemical reagent was also used, and one of the rail profiles was placed in a bucket with a sufficient amount of 2% Nital reagent so that the side of the profile that we are interested in studying was completely wet or submerged inside the bucket. This process took a couple of hours for each rail. Then, macroscopic images were obtained using a binocular stereomicroscope.

Finally, the Rockwell B (HRB) hardness measurements were made, with a 1/16″ ball and a load of 100 kgf using the bench durometer. Measurements were made for each rail, at the head in the center and on both sides, three other measurements along the web of the rail, and other measurements at the foot of each rail, located in the middle and at each end of the rail. Regarding the fixing nail, three measurements were made in each of the sectors: head, axis and tip of the fixing element.

Experimental Results

P50 Rail Micrograph

It can be seen in Fig. 8 that the rail surface has been plastically deformed and that the grain in the region is flattened, and the image shows deformed ferrite (red arrow) and pearlite grains (yellow arrow) due to cold working. Table 2 shows P50 rail hardness measurements and indicates an increase in hardness in the surface region due to cold work hardening, also an increase in hardness in web and foot of the rail. No cracks are observed in this rail profile [8].

Steels that contain less carbon than the amount needed to complete the eutectoid structure are called hypoeutectoid steels, while those that contain carbon above the eutectoid composition are usually called hypereutectoid steels. The eutectoid composition itself occurs at 0.8%C.

The material of the P50 rail, according to the chemical composition data (Table 1), is a steel with a eutectoid composition. Its composition is similar to what is now known as SAE 1080 steel. Generally, in hypoeutectoid steels there will be more ferrite than required and it is called proeutectoid (or free) ferrite. Proeutectoid ferrite can occur in several different forms, in the case of steels that approach eutectoid composition, ferrite is generally found as thick films located on what were originally austenite grains, and for this reason it is also called grain boundary ferrite.

When a metal is cold deformed, the grains elongate in the direction of the deformation and the crystallographic lattice is distorted. The crystallographic structures [9], which come from plastic deformation mechanisms, appear cloudy, since the distortion of the crystallographic lattice can raise the energy level of the grains to the value that exists at the grain boundaries, which makes differential attack difficult grain boundaries of metallographic samples, that is, they react very quickly and identification is difficult.

Table 2 Rail P50 hardness measurement

Head (HRB)	Web (HRB)	Foot (HRB)
209	175	150
220	198	157
225	208	165

P50 Rail Macrography

A macrostructure is a view of a material's structure at low magnification, usually with the naked eye or with a hand lens. Macrostructure includes features such as flow lines in rolled, wrought, welded, or extruded products and dendritic structure in cast products.

In the macrographic observation of the P50 rail (Fig. 9), according to a binocular stereomicroscope image, the fibers are observed in the laminated steel in a homogeneous way, Fig. 9a segregations (blue arrows) and some pores (red arrows) are observed and Fig. 9b (blue arrows) gaps and/or holes due to gases that have been occluded during cooling process inside the material mass are observed, and numbers 1 and 2 are pointing out segregation lines on the head of the rail, no fissures are observed whether they come from manufacturing or use such as fractures, cracks or fatigue damage. In Fig. 9c, blue arrows and number 1 are indicating central segregation line on the web side of the rail, meanwhile red arrow and number 2 is signaling contour segregation on the web side; and Fig. 9d consequently, the blue arrows are pointing some inclusions on the head of the P50 rail. On the

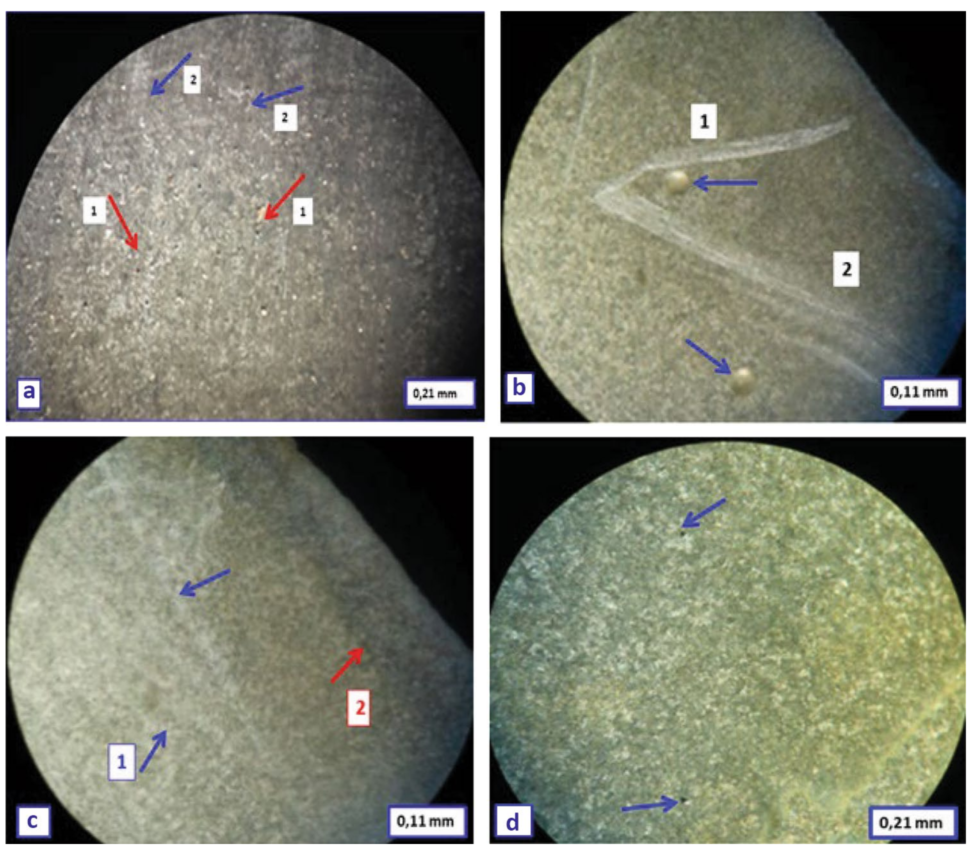

Fig. 9 Macroscopic images of the P50 rail using a binocular stereomicroscope. Segregation lines, holes due to trapped gases in the solidification process and details of some inclusions are observed

outside, the P50 rail had a layer of ferric oxide as a result of uniform corrosion that has a barrier effect. The magnification used with the binocular stereomicroscope was 10x (Scale: 0.21 mm) and 20x (Scale: 0.11 mm).

The flux lines themselves are actually regions of segregation (increased concentration of Manganese, Phosphorus, Sulfur, etc.) in the steel that follow the strain contours in the production of the product. These flow lines are an internal fingerprint of how the part was made and are observed in the macroscopy of the P50 rail, in addition to voids that come from gases contained in the structure during its cooling.

Chemical Composition and Hardness P50 Rail

"Trochita" Narrow Gauge Rail Micrograph

Ferrite is found precipitated in the form of broad needles within pearlite (Fig. 10), and may be as sections of ferrite plates that appear as a Widmanstäten pattern within pearlite, and is said to behave like a pattern, due to that its appearance is not stable or constant. This micrograph has been taken in the head's area of the narrow gauge rail. This narrow gauge rail has a low carbon composition with 0.45 wt.%C (Table 3), and this material can be comparable to current SAE 1045 steel. In Table 4 the "Trochita" Narrow Guage Rail Hardness Measurement is presented.

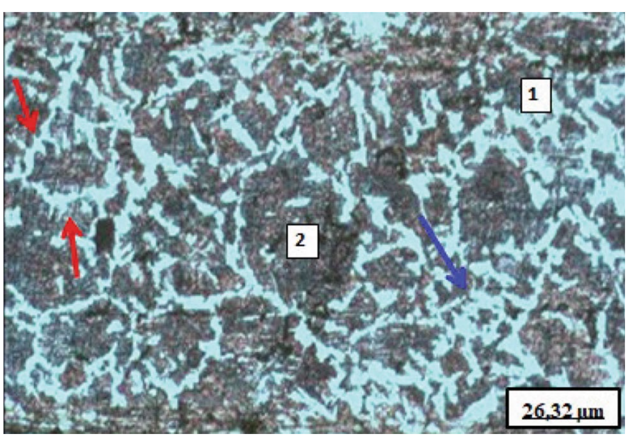

Fig. 10 Micrograph from the head zone of the narrow gauge rail, blue arrows indicate Widmanstäten side plates and red arrows indicate saw teeth in a low-carbon ferrite-pearlite steel 0.45 wt.%C. 2% Nital

The Widmanstäten transformation is a plate-like or lath-shaped structure that results from the precipitation of a new solid phase within the grains of the main solid phase. This structure also occurs as a feature that may arise incidentally in older low carbon worked or forged steels or may arise from deliberate heat treatments used during manufacturing. Very often, the Widmanstäten precipitation is only partly transported through the grains, so irregular effects occurs.

The fundamental difference between the Widmanstäten transformation and the martensitic transformation to note is that the Widmanstäten transformation involves the precipitation of a solid phase into two phases, whereas the martensitic transformation involves the quenching of the phase which produces a metastable phase on cooling [10].

Chemical Composition of "Trochita" (Little Gauge) Narrow Gauge Rail

Fixation Nail Micrograph

In the micrography of the fixation nail (Fig. 11), it has a metallographic structure of ferrite matrix (blue arrow) and islands or also called pearlite patches (red arrows). This fixation nail belongs to the narrow gauge "Trochita" (Little Gauge) Railway. The piece has been obtained from a larger piece, perhaps a billet, and through the hot forging treatment it has been hardened and this type of element would be endowed with the necessary resistance to withstand the mechanical stresses to which they would be subjected.

Since the fixing nail is a fastening piece, when it behaves elastically, therefore the Manganese (Mn) present gives it greater ductility and therefore elastic behavior, that is, the material is capable of supporting loads, flexing, without breaking, and then when the load or mechanical effort is removed, it returns to its original shape. In this way, a fixing nail transmits stress, deforms and recovers, maintaining the invariability of the track width, fixing the rails to the sleepers and the electrical insulation of the track.

The fixing nail element has a chemical composition (Table 5) of low-carbon steel (0.15 wt.%C), comparable with

Table 3 "Trochita" narrow gauge rail chemical composition

wt.%C	wt.%Si	wt.%Mn	wt.%P	wt.%Cr	wt.%Mo	wt.%Ni	wt.%Al	wt.%As
0.45	0.040	0.69	0.062	0.023	0.010	0.040	0.005	0.066
wt.%Zr	wt.%Bi	wt.%Zn	wt.%Fe	wt.%Co	wt.%Cu	wt.%Nb	wt.%Ti	wt.%V
0.005	0.030	0.019	98.3	0.024	0.051	0.008	0.014	0.012
wt.%W	wt.%Pb	wt.%Sn	wt.%Mg	wt.%Ca	wt.%Ce	wt.%B	wt.%S	wt.%La
<0.040	<0.010	0.021	0.002	0.002	0.019	0.009	0.066	0.008

what is now known as SAE 1015 steel, this type of steel being of general use, and which can be hardened by forging, carburizing and other heat treatments. In Table 6 the fixation nail hardness measurements are presented. Among its applications, low-carbon steel is currently used for motor shafts, hydraulic shafts and pump shafts, as well as in machinery parts. They would be used for such applications in a hardened surface condition. In steels of this level of carbon content, in fact, steels with 0.5 to around 0.25% C are used in the forged state, since such forgings show superior workability and machinability.

Most low-carbon steels are essentially pure iron (99.5% Fe) with small amounts of alloying elements, such as manganese, silicon, and aluminum, to improve properties. With some exceptions, ferrite is the main component of low-carbon steels and may contain alloying elements such as manganese and silicon. Due to its low carbon content, ferrite is soft and easily deformed. This means that special care must be taken to avoid cold working and scratching the sample surface during preparation [11].

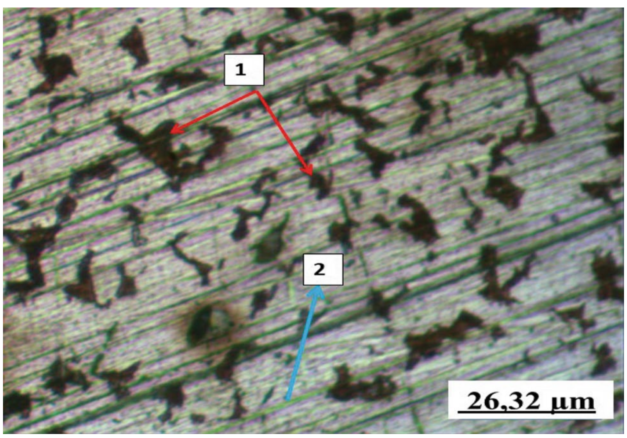

Fig. 11 The fixation nail microstructure consists in forged steel with low carbon content (0.15%C). The structure consists of islands or patches of (dark) perlite on a ferrite matrix (light). 2% Nital Reagent

Table 4 "Trochita" narrow gauge rail hardness measurement

Head (HRB)	Web (HRB)	Foot (HRB)
142	162	159
156	155	161
151	153	164

Table 6 Fixation nail hardness measurement

	Head (HRB)	Web (HRB)	Foot (HRB)
1°	62	102	110
2°	70	112	115
3°	83	105	117

Chemical Composition and Hardness Fixation Nail

Macrograph of Narrow Gauge Rail and Fixation Nail from "Trochita"

In the macrostructures, both the used rail profile and the fixing nail were sectioned longitudinally, the surfaces were prepared by conventional sanding and polished, and then both surfaces were pickled with 2% Nital reagent for 2–4 h. using a container for this purpose.

Figure 12a, b and c reveals clear and homogeneous structures, the flow lines (blue arrows) of the laminate are perfectly visualized from the head, passing through the web of the rail and going to the foot, and there are no cavities, drains or spiracles. The red arrows on the head of the narrow gauge rail point to the contour flow lines. In particular, it is observed that the dendritic structures have been conveniently eliminated, so that no cracks or fissures are observed. Generally, a minimum reduction ratio of 4 to 1, i.e.: 4 inches in the cast form to 1 inch in the rolled or forged form, is required to break the dendritic structure.

For the fixing nail (Fig. 12c), the blue arrows point to the flow lines along the piece and the red arrows also point to the flow lines but from the area of the fixation nail's head.

It should be noted that in the steel there are slight segregation regions that follow the contours of deformation in the production of the product, indicated with blue arrows in the central area of the narrow gauge rail and the fixation nail. These areas represent areas of higher concentration of some

Table 5 Fixation nail chemical composition

wt.%C	wt.%Si	wt.%Mn	wt.%P	wt.%Cr	wt.%Mo	wt.%Ni	wt.%Al	wt.%As
0.15	0.034	0.64	0.055	0.067	0.009	0.036	0.004	0.073
wt.%Zr	wt.%Bi	wt.%Zn	wt.%Fe	wt.%Co	wt.%Cu	wt.%Nb	wt.%Ti	wt.%V
0.005	0.027	0.018	98.6	0.018	0.025	0.008	0.012	0.011
wt.%W	wt.%Pb	wt.%Sn	wt.%Mg	wt.%Ca	wt.%Ce	wt.%B	wt.%S	wt.%La
< 0.040	< 0.010	0.019	0.002	0.002	0.015	0.009	0.079	0.008

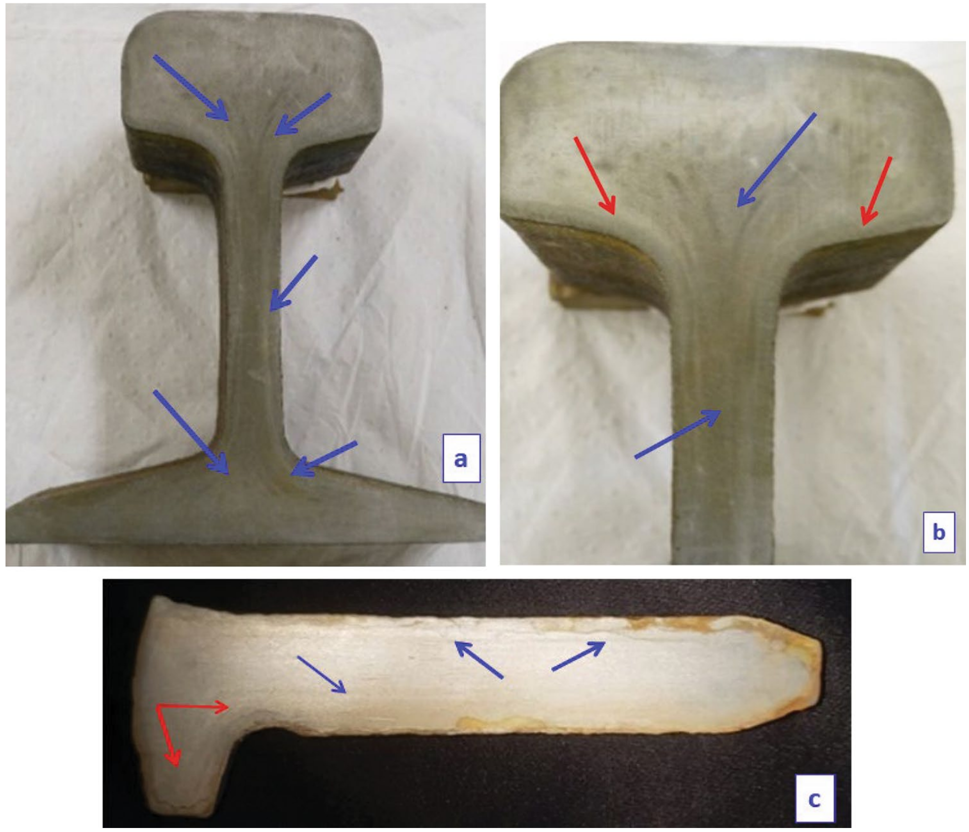

Fig. 12 (**a**) and (**b**) Macrographs of the narrow gauge rail (750 mm) and (**c**) the fixing nail, both pieces belong to the Old Patagonian Express "La Trochita" Museum

chemical elements such as: manganese (Mn), phosphorus (P), silicon (Si), sulfur (S). In liquid steel, which contains alloys, other metals and metalloids are dissolved and distributed homogeneously as normal impurities.

This homogeneity disappears when it solidifies, because the impurities (especially phosphorus and sulfur) are poorly soluble in the solid metal and are gradually repelled or "segregated" towards the liquid part as solidification progresses, being retained in the center, the last part to solidify. This accumulation of impurities in the center of the pieces is what is called segregation, as shown by the blue arrows in the narrow gauge lane. The chemical composition of the ingot presents variations: the metal is pure at the edges and at the base; unclean in the center. These rolling flow lines along with the hardness values are indicators of how the part was made [12].

The nail (Fig. 12c) would have as its main application the fastening of the rails to avoid variations in the track width. Rail fasteners are the metal products used to fasten the rails to the base track rail of the upper track structure (blocks, sleepers, bars) as well as to each other. Fixings are an important element of the track, as they provide its durability, rigidity and safety, as well as reducing the level of vibration that is transmitted from the rail to the lower elements of the track.

Discussion of Results

The first known rails date back to the Bronze Age, in the fifth century BC, appearing again as wooden rails to facilitate transport in the mines. The improvement of these in the mining sector was what led to the appearance of the first iron rails in the eighteenth century in Germany and England, to become steel rails in the nineteenth century.

The rails made of cast iron rails, which could not withstand the passage of the wheels due to their fragility, so they passed to rolled steel, while their length and duration were increased (in some situations they lasted only 3 months), while the flat foot was added after studies on the profile, and lasting up to 16 years.

Already in the nineteenth century, wheels with flanges appeared and the improvement of materials, from puddled steel, the Bessemer, Thomas and Martin systems, to the current electrical and oxygen steels, made it possible to go from axle loads of 3 to more of 30 tons, and maximum speeds of 300–500 km/h.

In relation with the results obtained from these studied pieces, the micrography of the P50 surface rail (Sovietic origin) has been plastically deformed and that the grain in the region is flattened, micrography shows deformed ferrite and pearlite grains due to cold working. Also P50 rail hardness measurements indicate an increase in hardness from the surface region through the web and into the rail foot due to cold work hardening.

In the macrographic observation of the P50 rail, the fibers are observed in the rolled steel in a homogeneous way; in addition, segregations are observed (higher concentration of manganese, phosphorus, sulfur, etc.) in the steel that follow the contours of deformation in the production of the product, in addition to holes that come from the gases contained in the structure during its cooling. There are no cracks present either from manufacturing or use such as fractures, cracks or fatigue damage.

In the case of the “Trochita” Narrow Gauge Rail micrograph (French origin), the ferrite is precipitated as broad needles within the pearlite and can be seen as sections of ferrite plates that appear as a Widmanstäten pattern within the pearlite. This micrograph has been taken in the area of the head of the narrow gauge rail. This narrow gauge rail has a low carbon composition with 0.45% C by weight; this historical material may be comparable to today's SAE 1045 steel. Widmanstäten structure also occurs as a feature that may arise incidentally in older low-carbon wrought or worked steels or may arise from deliberate heat treatments used during manufacturing. On the outside, both P50 and Narrow Gauge rails presented a layer of ferric oxide as a result of uniform corrosion that has a barrier effect.

Narrow Gauge rail macrographs reveal clear, homogeneous structures and in particular, no cracks or fissures are observed. It should be noted that in the narrow gauge rail steel there are slight regions of segregation that follow the deformation contours in the production of the product. These areas represent areas of higher concentration of some chemical elements such as: manganese (Mn), phosphorus (P), silicon (Si), sulfur (S).

The micrograph of the fixation nail (Belgian origin) shows a metallographic structure of ferrite matrix and pearlite islands. This fixing nail belongs to the Narrow Gauge railway "Trochita". The piece has been obtained from a larger piece, perhaps a billet, and through the hot forging treatment it has hardened and this type of element would be endowed with the necessary resistance to withstand the mechanical stresses to which they would be subjected as they show superior workability and machinability.

In the macrograph of the fixation nail, it is possible to observe the flow lines along the piece and the flow lines specifically in the area of the head of the fixation nail following its contour. These rolling flow lines along with the hardness values are indicators of how the part was manufactured. In the case of the fixation nail, an increase in hardness values is observed from the head of the nail towards its tip. The fixing nail, being a fastening piece, behaves elastically, so the manganese (Mn) present gives it greater ductility and therefore an elastic behavior, that is, the material is capable of supporting loads, flexing, without breaking and then when the load or mechanical stress is removed, it returns to its original shape, maintaining the invariance of the track gauge and fixing the rails to the sleepers.

This historical element, the fixing nail, has a chemical composition of low-carbon steel (0.15 wt.% C), comparable to what is now known as SAE 1015 steel, this type of steel being for general use, and which can be tempered by forging, cementation and other heat treatments. Among its applications, low-carbon steel is currently used to manufacture motor shafts, hydraulic shafts, and pump shafts, as well as machinery parts.

Historically, the rail evolved in its shape and in its metallurgical manufacturing process over the years [13]. The rails today are made of steel and in general the chemical composition of its components is as follows:

Carbon—from 0.40 to 0.82%—this increases hardness and wear resistance, but also affects brittleness. The vast majority of rails are ferritic-pearlitic.

Manganese—from 0.60 to 1.70%—influences hardness, wear resistance, and toughness (not brittle), but decreases weldability.

Silicon—from 0.05 to 0.50%—increases the hardness, wear resistance and facilitates the lamination of the rail.

Sulfur and phosphorus—less than 0.05%—they are not desirable because they weaken the steel, but their elimination is very expensive.

To improve certain characteristics of the rail, alloy elements such as Ni, Cr, Nb, V and Al are added, varying these components contents different qualities of rails are achieved according to the manufacturing process (Table 7). Depending on the manufacturing process, by rolling raw steel, bars with the required profile are obtained, which are cut into sections of 18–288 m [14].

The hardness of the rails and fixings depends on the surface treatment and the alloy chemical compositions and also impurities.

For information purposes and that could serve as a comparison between the hardness values obtained in this investigation of historical rails with the hardness values required for current rails (Table 8), where the distinction is made between normal rails and high-resistance rails, it can be observed that the difference in these hardness values expressed in Rockwell hardness (HRB) do not present a great difference, and taking into account the historical nature of these analyzed rails.

Identification of the presence and development (or growth) of defects is determined by the type of defect and the direction of growth in relation to the planes of the rail section. With due clarification that in this case a defect is one or more relevant discontinuities whose size, shape, orientation, location or properties do not meet a specified acceptance criterion and must be rejected [15].

Table 7 Materials of the rails according to their origin

Chemical composition, wt.%	Made in Europe	Made in America
wt.%C	0.4–0.57	> 0.57
wt.%Mn	0.8–1.2	< 0.8
wt.%Si	0.1–0.25	0.1–0.25
wt.%P	Maximum allowable < 0.06	Maximum allowable < 0.06
wt.%S	Maximum allowable < 0.06	Maximum allowable < 0.06

Table 8 Current rails hardness, values expressed in Rockwell Hardness (HRB)

Current rail types	Minimum	Maximum
Normal rails	107 HRB	…
High resistance rails	109 HRB	112 HRB

The type of defect refers to the characteristics of the defect, among which you can refer to the process that gave rise to it, which can be grouped into: manufacturing defects (discontinuities of primary, secondary or transformation processes), defects induced by traffic (service discontinuities, these are the most important today) and defects introduced during the assembly or maintenance (termination or installation discontinuities). Any of these defects can grow and spread through traffic.

Considering the planes in which they develop, we have: transverse defects and longitudinal defects. There are even defects that propagate in compound directions. Defects that develop primarily in a transverse plane are considered very dangerous since its transversal development cannot be visibly evaluated. This internal propagation of the defect can lead to sudden and catastrophic failure of the rail.

There is another type of classification that refers to its location on the rail, such as head defects, web defects and foot defects. The size of the internal transverse defect prior to catastrophic failure can only be fully identified by breaking the rail across its cross section (or by causing it to break in the laboratory).

High-strength properties in railway rail steel products (as raw material) are made up of superior quality steel reinforcement, which is less susceptible to corrosion. Railroad steel has a special grade in its chemical alloys, which is necessary since rail will be subjected to much higher dynamic stresses than other types of steel used in buildings and structures. Therefore, when surface rust forms on steel, it acts as a barrier to corrosion and once formed, it seals it properly and further slows down the rate of corrosion [16].

Train rail steels possess a conjoined ferritic-pearlitic microstructure, which provides a good combination of strength, toughness and ductility along with superior corrosion resistance, which is enhanced by the elements present C-Mn (carbon/manganese). Therefore, the raw material for the manufacture of railways has been of very good quality, and has been in active service for decades.

Conclusions

The quality study carried out on these historical rails has allowed us to analyze these two rail profiles, which belong to different railways in Argentina, and which are also located in provinces of the country that are very distant from each other. In addition, for these three railway elements, their diverse origins and provenances were identified through historical revisionism carried out.

From the chemical composition analysis, it can be deduced that these rail profiles could be considered as the current SAE 1080 steel for the P50 profile and as the current SAE 1045 steel for the profile belonging to the narrow gauge rail. For the narrow track rail fixing nail, according to the chemical composition analysis, it could be considered as the current SAE 1015 steel. Regarding the macrographic studies, only small defects have been found in the P50 rail, such as some segregations and gas bubbles, which were trapped during the cooling process.

The railway steels and the fixing nail have a joint ferritic-pearlitic microstructure, which provides a good combination of strength, toughness and ductility along with superior corrosion resistance, which is enhanced by the elements present C-Mn (carbon/manganese).

Evaluating the data that were acquired with these determinations made to each piece studied, and comparing what is requested for the current rails, in terms of chemical composition, hardness and metallographic structure, it is observed that these profiles of different rails meet the required quality requirements for today's railways.

Therefore, the quality of the profile of the rail referred to the raw material used for the manufacture of these historical rails has been of very good quality, and this has allowed, in the case of the province of Mendoza, a rapid recovery of these railways (currently out of service) to be used for the prompt reopening of the Mendoza-Buenos Aires route, since both the cargo and passenger trains stopped working in the 1990s.

Similar is the case of the narrow gauge railway, which once the route that connected with Buenos Aires was interrupted, this railway was reinvented by the will of the people and the Old Patagonian Express has continued to operate over the years offering two weekly tourist tours, with his locomotive internationally known as "Trochita".

In both railway networks, Mendoza province and Esquel (Chubut province), groups of friends of the railway organized themselves creating museums to keep the railway spirit alive, and longing for the train to cross the Argentine pampas and steppes again.

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