Rail aluminothermic welding. Microstructure and mechanical properties

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Resumen

Este artículo recoge los fundamentos de la tecnología de soldadura aluminotérmica "in situ" de carriles de 700, 900 y 1100 MPa de carga de rotura. Se analizan las características metalúrgicas y mecánicas de la unión soldada (zonas de fusión y afectadas por el calor, microestructura, dureza, ensayos de flexión estática y dinámica) acordes con la modalidad de precalentamiento y proceso de soldadura seguidos.

Palabras clave: Soldadura aluminotérmica, metalografía, ensayos mecánicos, aceros perlíticos.

Abstract

This work describes some process for rail welding whereby weld can be made by introducing the weld metal in one casting, on site, as a homogeneous melt. Weld characteristics (fusion zone, heat affected zone, microstructure, hardness, slow bend test and fatigue test resistance) are related with preheating modality and welding procedure of 700, 900 and 1100 MPa rail grades.

Key words: Aluminothermic weld, metallography, mechanical tests, pearlitic steels.

Introduction

The view of many modern historians is that the most important industry responsible for world-wide industrialization, after the invention and utilization of the wheel and sail, was the railway.

The two main elements of the railway, rail track and locomotives, were first developed in England. Initially, in the first stages of railway development, freight wagons were drawn across railbeds made from wooden planks. The next development was to place strips of cast iron on to wooden planks, facilitating an increase in the useful life of the rail track by dramatically increasing the load bearing capacity of the track. The main disadvantage to the use of cast iron is the material's inherent brittleness. Therefore, the cast iron rails were replaced by wrought iron rails, that, being more malleable had the advantage of greater toughness. In the mid 1860's Bessemer's steel replaced wrought iron in the manufacture of rail track. The cost of this steel was markedly higher that any other material at the time, available for the purpose of making rails, however, the initial higher financial outlay was offset by a significant improvement in rail life and load bearing capacity. The tremendous demand for this kind of steel was such that the USA had seventy rail producing plants, shortly after the development of the steel.

At the beginning of this century the Bessemer Process for producing steel was replaced by Siemens - Martin Steelmaking Process that guaranteed a tougher steel. Today rails are fabricated by Basic Oxygen Steelmaking process coupled with secondary steelmaking practices and subsequent continuous casting operations in order to provide higher quality steel products with lower levels of elements such as hydrogen, nitrogen, sulfur and phosphorus. This was introduced at the same time as a new rolling and cooling process that eliminated the problem of flakes or shattercracks in rails caused by the high hydrogen contents present in the steel.

Another important development in rail technology, that took place in the 1930's, was flash-butt welding and aluminothermic welding, used to create smooth continuous rail tracks, taking over from bolting with joint bars as a means of joining rail sections. From that time onwards, all railway companies have used the welding processes developed for joining rail sections.

It cannot be said that a steel with a high (0.7 wt%) carbon content can be considered as easy to weld, however, the reduced maintenance cost of the track, improved track stability, higher running speeds of the trains, improved passenger comfort from a continuous rail track and greater safety, justify the utilization of this process.

The rail steel is produced in 18 or 36 m sections. The fabrication of a continuous rail track has two stages, which are as follows:

1.- Rail sections are flash welded into 144 or 288 m length.

2.- The longer lengths of rail are transported to the site where they are to be laid, and welded in situ by aluminothermic welding.

The advantages of using the aluminothermic welding process are the equipment necessary for the process is simple and robust, it is in situ welding of low cost and is easily mobile, requiring no electrical power. In addition, the quality of the welding consumables is ensured by strict quality control.

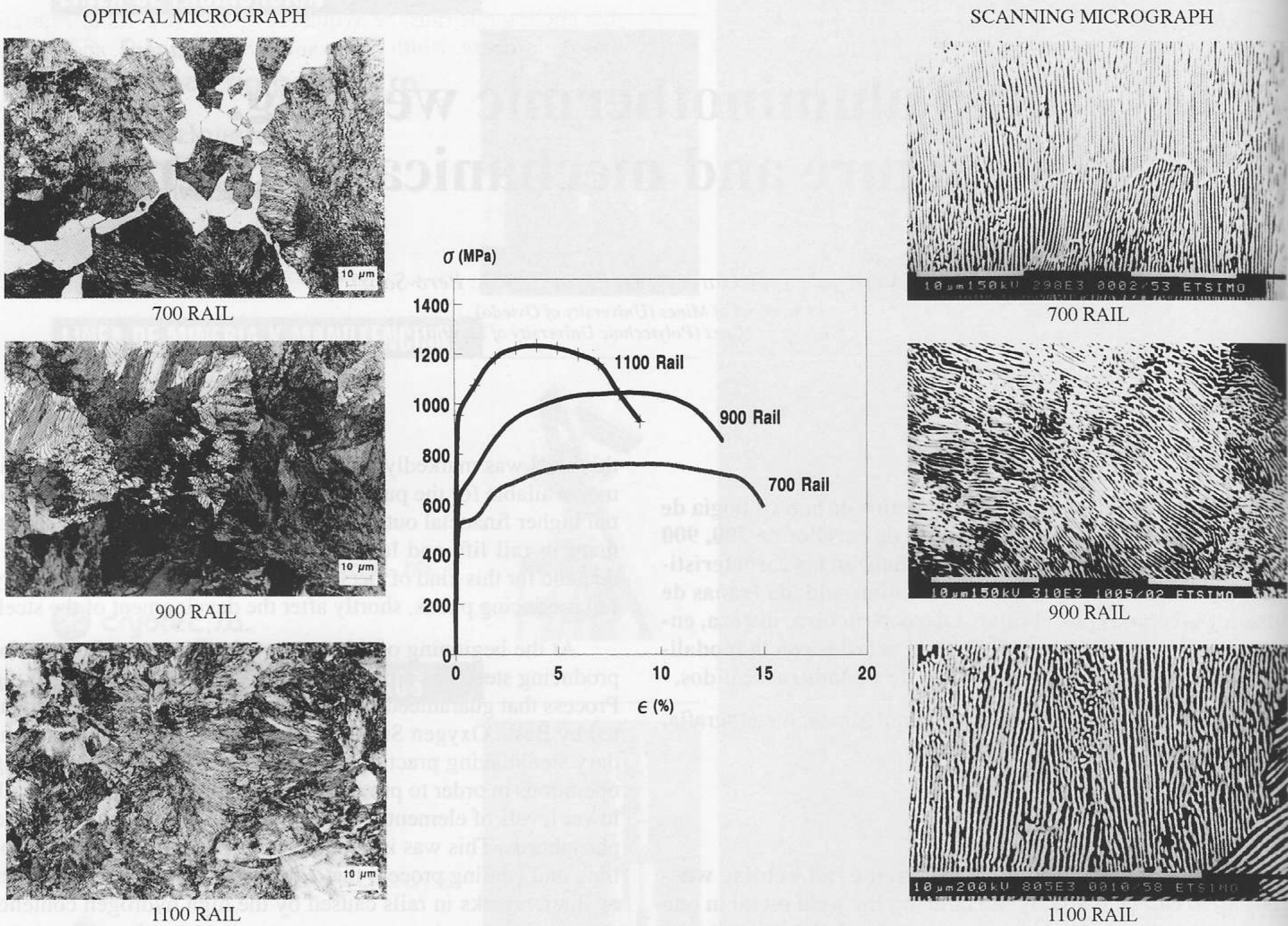


Fig. 1.–Metallography and stress-strain curves of typical rail steel grades.

Figure 1 gives the stress - strain curve, optical and scanning electron micrographs of the three rail steels usually employed in railway. The names of the rail steels also describe their relative tensile strength, i.e. RAIL 700 is a grade of steel having a tensile strength of 700 MPa (1). The yield strength, tensile strength, and hardness increase with the decrease of lamellar spacing between the ferrite and cementite in the pearlite, which in turn decreases the plasticity and elongation. The extra hard rails, 100% pearlitic, have lamellar spacing less than 0.10 microns (2).

Aluminothermic welding

The aluminothermic welding kits (from Spanish technology) consist of one aluminothermic charge, one self-tapping thimble, the mould clamps and the aluminothermic crucible (Figure 2).

The aluminothermic charges contain a powder mixture of iron oxide, aluminium and other alloys. The selection, weighing, and mixing processes need carefully control over purity (low content of P and S) and particle size distribution. Also, the physical properties and chemistry of the aluminothermic steel needs to closely match those of the parent rail.

The aluminothermic welding process is based on the reaction:

iron oxide+alloy elements+aluminium = steel+slag+heat

The aluminothermic reaction takes place in a vessel, since the thermit mixture has an ignition point in excess of 2000 ºC special means must be adopted for its ignition. The reaction immediately starts by igniting the main aluminothermic charge, which proceeds rapidly to completion (20-25 sec.). A liquid steel with alumina slag is obtained, the slag floats on the top. The steel (at a temperature greater than 2000°C) is discharged into a ceramic mould which exposes the end of the rail to the superheated steel, welding the two rails together (3).

The aluminothermic steel, must have a chemical composition, carbon equivalent (C.E.= C + Mn/6), microstructure and hardness number to match that of the rail. It is also to be noted that, the weld metal hardness can be varied over a narrow range (± 20 HBS).

Such severe tolerances in chemical composition, hardness and mechanical resistance are demanded of the aluminothermic steel that is necessary the use of special devices, and mould geometry, with the purpose of avoiding the physical faults (poro-

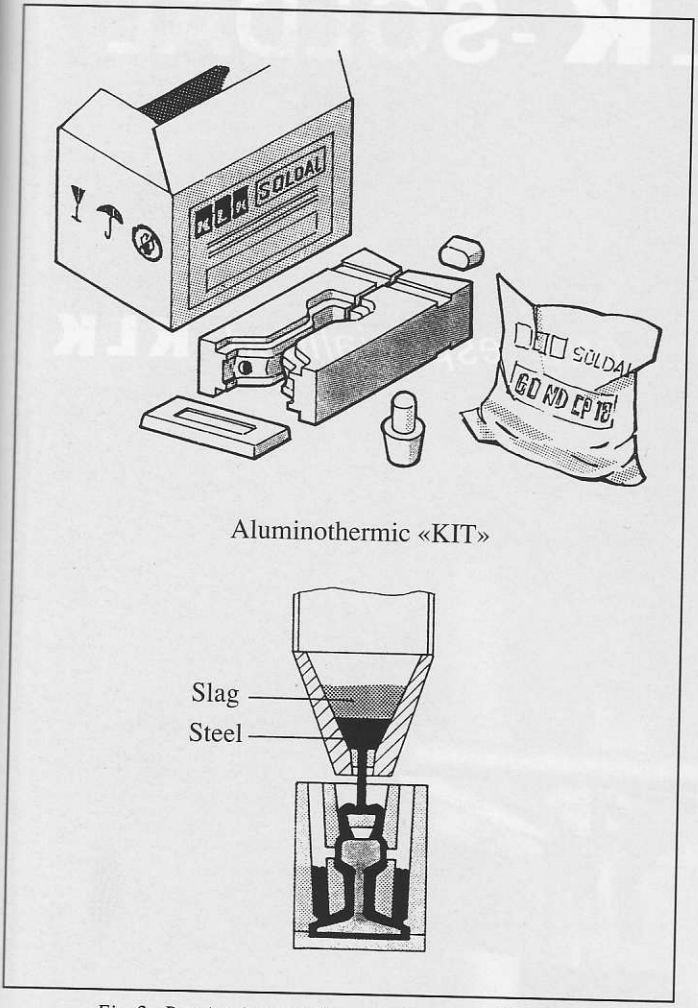


Fig. 2.–Pouring System of Aluminothermic Welding Kits.

sity and cracks) and chemical faults (micro and macrosegregations) derived from the solidification process.

It is necessary to preheat the rail ends in order to provide a slower cooling rate, as the steel has a carbon equivalent of more than 0.42 and the formation of martensite and bainite at a higher cooling rate must be avoided, Figure 3 (6). Table 1 describes the process, width of the space between rails, and preheat temperatures used by European technology. The weld quality is similar in the three processes. It is to be noted that, the full preheat treatment requires a greater degree of skill from the workers, and the heating equipment must be slower than the short preheat welding, this is to reach the temperature that is needed (850-900°C), because of this, the most Rails use short preheat welding, which does not need too much carefully by the workers, in view of the preheat is by the melt aluminothermic steel.

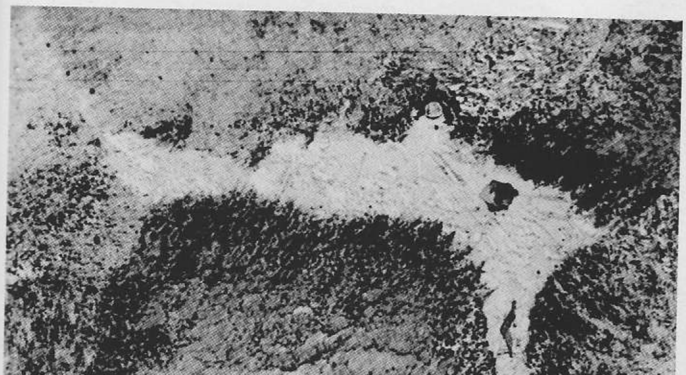


Fig. 3.–Scattered Bainite and Martensite into the weld of Pearlitic Steel Rail.

The welding kits manufactured by Spanish technology use the processes and equipment given in Table 1 and 2 (4,5).

TABLE 1

PREHEATING PROCESS AND ALUMINOTHERMIC WELD FEATURES

Type	Welding gap (mm)	Preheat Temperature (°C)	Observations
NP	18 ± 2	850-900	–
SP	25 ± 2	350-600	–
SP WG	50 ± 2	350-600	Repairs, Maintenance

TABLE 2

PREHEATING PROCESS AND TIMES

Process	Time
SP1 (propane-induced air)	5 minutes
SP2 (propane-oxygen)	90 seconds
SP3 (petrol-induced air)	3/5 minutes

European rails's regulation about aluminothermic welding

European Community, with the object of completely guaranteeing the quality and reliability of «in situ» aluminithermic, has just elaborated regulations that set out quite fully, the most

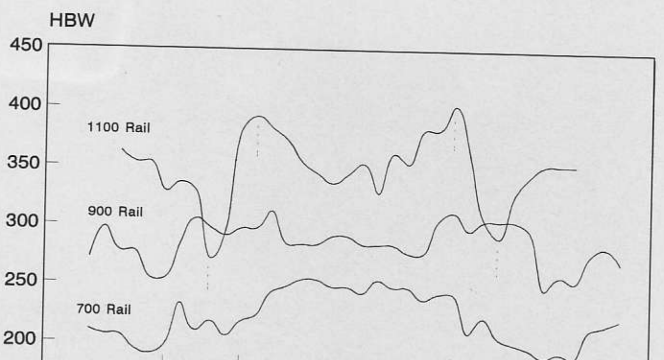


Fig. 4.–Mean Longitudinal Hardness Profile of Aluminothermic Weld Rails.

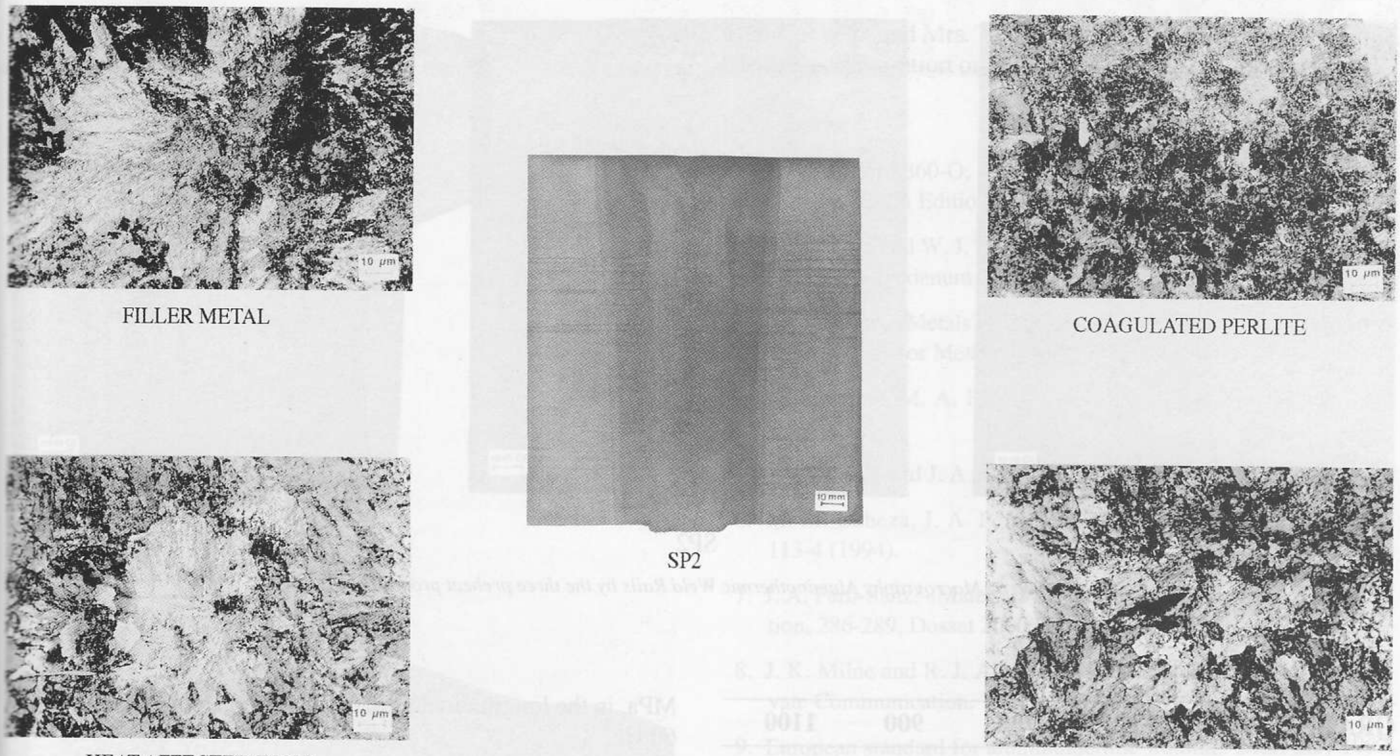


Fig. 5.–Macrography and Metallography of Aluminothermic Weld, Heat Affected Zone and Parent Rail.

to date stringent requirements, which can be summed up into sections, as follovs:

1.–Welding processes assessment.

2.–Welding kits previous reception.

3.–Welder training and assessment.

4.–In situ weld reception.

The EC Rails only allows the short preheat processes known as SP1 and SP2. The preheat treatment uses a special mixture either of propane and induced air or of propane and oxygen, utilizing equipment that is easy to operate and practically full proof.

The aluminothermic steel welded rail joints are made to mechanical and structural specifications, which are characterized by use of tests:

1.–Hardness test HBW 10/3000, arithmetical mean of 3 Brinell test: 10 mm tungsten carbide ball indentor, 3000 kgf. load. The welding hardness ranges for the various grades are given below:

RAIL	700 MPa	250 ± 20 HBW
RAIL	900 MPa	280 ± 20 HBW
RAIL	1100 MPa	350 ± 20 HBW

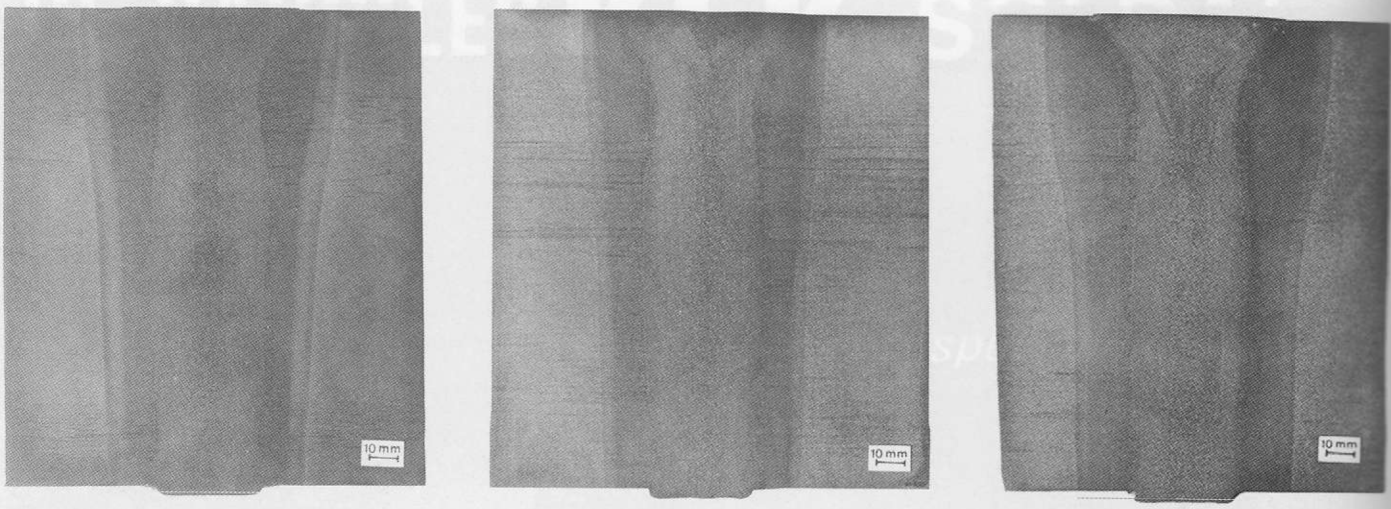
The hardness profiles of the weldment from all grades is given as Figure 4. The weldments comply with the hardness minimums. The heat affected zone (HAZ), transforms to a coarse grained pearlite without the brittle structure of martensite, Figure 5 (7).

2.–Rail structure: In the metallographic observation (magnification 700x), the microstructure is of pearlite (ferrite-pearlite in the rail grade 700) both in the filler metals and in the heat affected zones. The presence of martensite is not accepted for a rail in service. The macrographic structure of welded rail joint by the three prehet processes are given in Figure 6. In all cases the fusion zone, that is the distance from the prepared rail end to each fusion line, is greater than or equal to 3 mm at all parts of the weld; and exhibit a nominally symmetrical shape about the welding gap when welding the same rail profiles. Otherwise, the widht of the visible heat affected zone is less than or equal to 30 mm.

3.–Slow bend test, with the head of the welded rail in compression, and a maximum rate of load application 1 mm/sec. The minimum loads and deflections allowed accordind to the standards and profiles of the rail are:

	GRADE (MPa)	700	900 Loads	1100	Deflection (mm)
PROFILE	UIC 54	63	75	85	9
	UIC 60	75	90	102	9

In Figure 7, deflections (mm) vs. load (t) in three rail's standards are plotted. It is obvious that the three rail joints go beyond the minimum load and the deflection is greater than 9 mm as required. The load (t) is given as stress (MPa) for the two rail's standards:



SP1 SP2 SP3

Fig. 6.–Macrography Aluminothermic Weld Rails by the three preheat processes.

GRADE (MPa) PROFILE	700	900	1100
UIC 54	493	587	665
UIC 60	487	585	663

Also, they must support as a minimum, an equivalent stress of around 60 % of the rail's tensile strength. The tensile strenth of the welded rail joints are usually greater than that of the parent rail material. The result is a homogeneous structure weld joint throughout the rail.

4.–Fatigue test: Compliance with the required fatigue strength shall be ascertained by 4-point pulsating bending test in accordance with European regulations. The test shall be conducted within the following parameters:

– load to be applied to the running surface of the weld, the foot being subject to pulsating bending stresses, greater than 200 MPa, in the longitudinal direction at a frequency of between 5 y 60 Hz.

– ratio of maximum applied stress to minimum applied stress = 0.1.

– minimum load cycles required without failure (fracture o fatigue crack) = $2x10^6$.

– the mean value (m) and standard deviation (s) of the fatigue strength will be determine by Staircase Method or Locati Test.

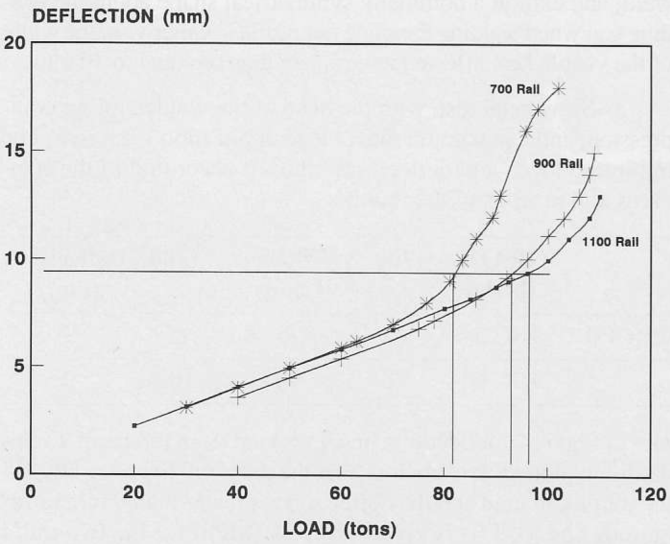


Fig. 7.–Mean deflection-load curves of aluminothermic weld rails.

Results carried out employing the SP2 process (propane-oxygen) have conducted to a fatigue strength of 234 ± 19 MPa which falls within the acceptable range established by European regulations (m > 220 MPa; 10 MPa < 2 S 38 MPa). As the SP1 process (propaine-air) is concerned we obtained an acceptable fatigue strength of 219 ± 20 MPa at $2x10^6$ cycles (8,9), a little lower than that performed by the SP2 process. Fractures, when occurred, are normally localized into the junction zone web-foot of rails, Figure 8. To avoid this a particular attention will be made to the presence of decarburization layers at the weld collar and rail end surfaces, Figure 9, and other defects inherited to the aluminothermic weld process such as microcracks, porosity and slag inclusions as well (10).

Conclusions

1.–The investigated aluminothermic Kits for the short preheat process, allow a welding methods that are easy and safe, that can be used with all the preheat equipment technology in use today and easily fulfill with the European Railroads Regulations on aluminothermic welding procedure approval (welding procedure, weld characteristics and approval procedure).

2.–The researched aluminothermic welding kits posses the chemical composition and homogeneity required by the standards namely, hardness numbers of 250, 280 and 350 HBW (± 20) for the welded rails that have a tensile strength of 700, 900, and 1100 MPa respectively.

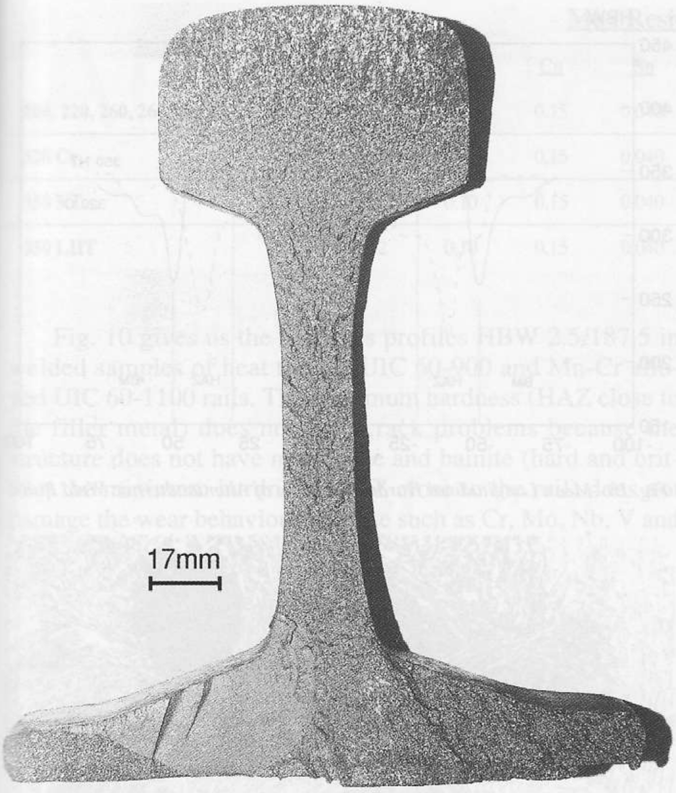


Fig. 8.–Surface fracture of aluminothermic welded rail broken by fatigue.

3.–Not only does the aluminothermic steel have a similar hardness to that of the rails, but it also results internally sound, with correct microstructure, without martensite and bainite, for which reasons they resist loads and allow greater strains as measured by slow bend test and fatigue test that those demanded by Railways.

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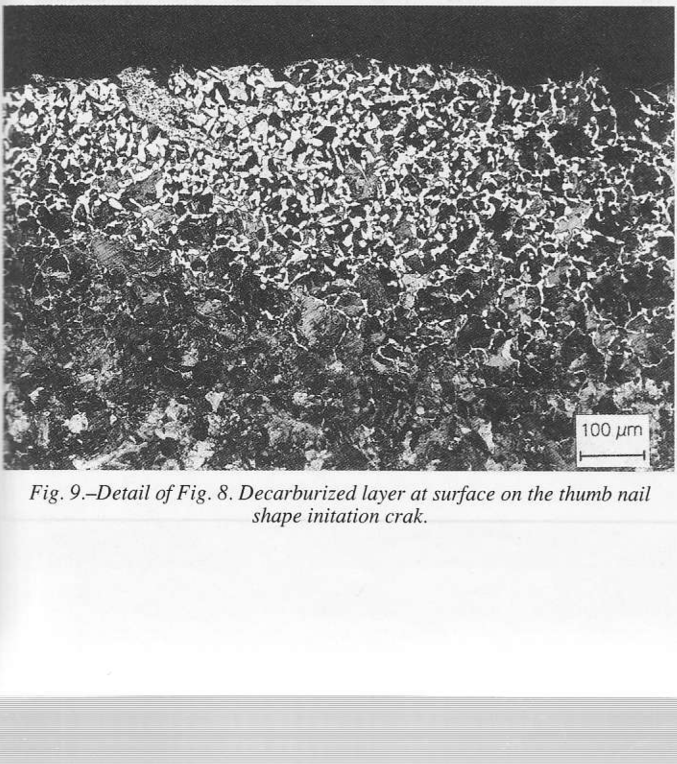

Fig. 9.–Detail of Fig. 8. Decarburized layer at surface on the thumb nail shape initation crak.

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Appendix

Aluminothermic welding of rails

The steels used to make rails materials with pearlitic structure. The most important design parameters are mechanical resistence (tensile strength, Rm) and the wear resistance (hardness, HR), together eith the minimum ductile and toughness necesary to ensure safe operation at ambient temperature.

The tensile strength of a ferritic-pearlitic steel es given by the equation:

$$Rm = f_\alpha^{1/3}\, Rm_F + (1 - f_\alpha^{1/3})\, Rm_P$$

f_α: volume fraction of ferrite.
Rm_F: tensile strength of ferrite.
Rm_P: tensile strength of pearlite.

The finest ferrite (grain size ≥ 10 ASTM) has a tensile strength $Rm_F \geq 500$ MPa and pearlite has a tensile strength $Rm_P \geq 800$ MPa, but this value depends on the lamellar spacing.

The mechanical resistance and hardness in rail steels depend, in the first place on the structural characteristic of the pearlite i.e. lamellar spacing S, and in the second place on chemistry and microstructural parameters (% Mn, % Si, volume fraction and grain size of the ferrite). The relation between hardness and lamellar spacing es:

$$HB \approx 118.5 + 2.3\, S^{-1/2}$$

S = lamellar spacing (mm) of pearlite.

We can find three grades usually used in network rails:

– Normal Rail, ferritic-pearlitic structure and coarse lamellar spacing (S ≈ 0.30 μm; Rm ≈ 700 MPa).

– Hard Rail, pearlitic structure and medium lamellar spacing (S ≈ 0.20 μm; Rm ≈ 900 MPa).

– Extra Hard Rail, pearlitic structure and thin lamellar spacing (S ≈ 0.10 μm; Rm ≈ 1100 MPa). This thin lamellar spacing es obtained by using high cooling rate with eutectic steels or normal cooling rate with Cr-Mn eutectic steel.

Tables 1 and 2 give us steel grades, chemical compositions and mechanical properties of the rails by the standard EN (CEN/TC256/SC1/WG4).

TABLE 1

STEEL GRADES

Grade [1]	Hardness range (HBW)	Description
200	200-240	Carbon-Manganese (C-Mn)
220	220-260	Carbon-Manganese (C-Mn)
260	260-300	Carbon-Manganese (C-Mn)
260 Mn	260-300	Carbon-Manganese (C-Mn)
320 Cr	320-360	Alloy (1 % Cr)
350 HT	350-390[2]	Carbon-Manganese (C-Mn) heat treated
350 LHT	350-390[2]	Low alloy, heat treated

1) See table 2 for chemical composition/mechanical properties.

2) If the hardness exceeds 390 HBW but es below 400 HBW then the rail es acceptable provided the rail microstructure is confirmed to be pearlitic.

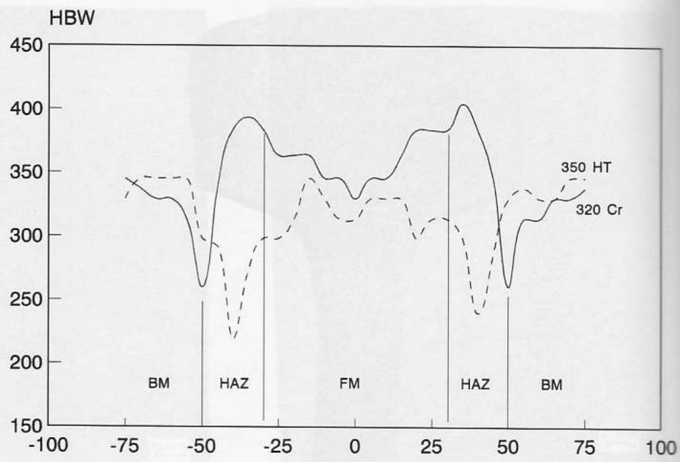

Fig. 10.–Mean Longitudinal Hardness Profile of Aluminothermic Weld Rails.

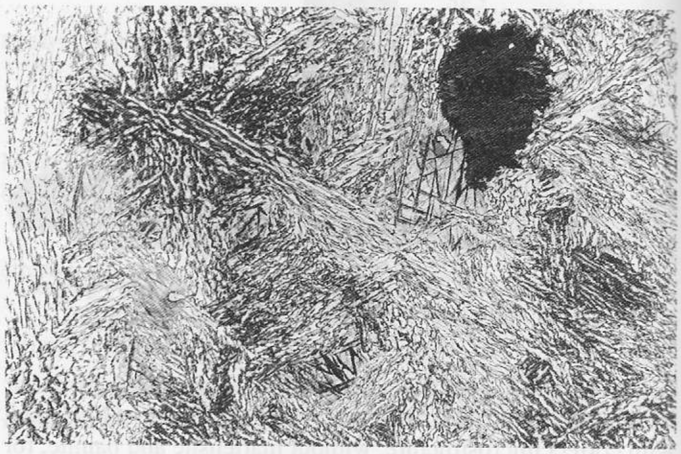

Fig. 11.–Scattered Troostite, Bainite and Martensite into the weld of Pearlitic Steel Rail. From a foreing supplier.

TABLE 2

CHEMICAL COMPOSITION/MECHANICAL PROPERTIES

Steel Sample Grade	% By Mass									P.P.M.		Rm Min N/mm	Min elong %	Centre line running surface hardness HBW
	C	Si	Mn	P	S	Cr	Al	V	N	O	H			
200 Solid	0,38/0,62	0,13/0,60	0,65/1,25	0,040x	0,008/0,040	Re	0,004x	Re	0,010x	20x	3.0x	680	14	200/240
220 Solid	0,50/0,60	0,20/0,60	1,00/1,25	0,025x	0,008/0,025	Re	0,004x	Re	0,008x	20x	3.0x	770	12	220/260
260 Solid	0,60/0,82	0,13/0,60	0,65/1,25	0,030x	0,008/0,030	Re	0,004x	Re	0,010x	20x	2.5x	880	10	260/300
260 Mn Solid	0,53/0,77	0,15/0,60	1,25/1,75	0,030x	0,008/0,030	Re	0,004x	Re	0,010x	20x	2.5x	880	10	260/300
320 Cr Solid	0,58/0,82	0,48/1,12	0,75/1,25	0,025x	0,008/0,030	0,75/1,25	0,004x	0,20 x	0,010 x	20x	2.5x	1080	9	320/360
350 HT Solid	0,70/0,82	0,13/0,60	0,65/1,25	0,025x	0,008/0,030	Re	0,004x	Re	0,010x	20x	2.5x	1175	9	350/390
350 LHT Solid	0,70/0,82	0,13/0,60	0,65/1,25	0,025x	0,008/0,030	0,30x	0,004x	Re	0,010x	20x	2.5x	1175	9	350/390

x = Maximum level Re =Residual element

Max Residual Elements

	Cr	Mo	Ni	Cu	Sn	Sb	Ti	Nb	V	Cu & 10 Sn	
200, 220, 260, 260 Mn	0,15	0,02	0,10	0,15	0,040	0,020	0,025	0,01	0,03	< 0,35	Cr + Mo + Ni +Cu + V < 0,35
320 Cr	-	0,02	0,10	0,15	0,040	0,020	0,025	0,01	-	< 0,35	Ni + Cu < 0,16
350 NT	0,10	0,02	0,10	0,15	0,040	0,020	0,025	0,03	0,03	< 0,35	Cr + Mo + Ni + Cu + V < 0,25
350 LHT	-	0,02	0,10	0,15	0,040	0,020	0,025	0,03	0,03	< 0,35	Mo + Ni + Cu + V < 0,20

Fig. 10 gives us the hardness profiles HBW 2.5/187.5 in welded samples of heat treated UIC 60-900 and Mn-Cr alloyed UIC 60-1100 rails. The maximum hardness (HAZ close to the filler metal) does not give crack problems because the structure does not have martensite and bainite (hard and brittle); the minimum hardness (HAZ close to the rail) does not damage the wear behaviour because such as Cr, Mo, Nb, V and Ti in the aluminothermic stell must be avoided. They tend to segregate in interdendritic spaces, increasing the steel hardenability and giwing non-desirable brittle constituents as already mentioned. The Fig.11 is a micrograph of a Mo-V-Ti microalloyed aluminothermic steel with bainitic structure and scattered troostite and martensite constituents: its hardness amounts 390 HBW or greater.