Fatigue test of aluminothermic welded rails

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Resumen

Este artículo recoge ensayos de fatiga efectuados sobre carriles soldados aluminotérmicamente, empleando distintas modalidades de precalentamiento. La calidad del acero aluminotérmico y excelente compacidad de las soldaduras explican los buenos resultados.

Palabras clave: Soldadura, acero aluminotérmico, carril, ensayo de fatiga.

Abstract

This work summarizes the fatigue test curves carried out from rails aluminothermic welded by different preheating procedures. Macrographic and metallographic inspection of broken specimens claims for the reliability of welding techniques and the metallurgical quality of welds as well.

Key words: Aluminothermic weld, steel rails, fatigue test.

Introduction

In previous works (1,2) aluminothermic welding of rails processes for both normal joint gap and wide joint gap (24 mm and 48 mm respectively), using different preheating methods: full-preheating and short-preheating and their variants of burners operating on oxygen/propane, compressed air/gasoline and induced air/propane, were fully described.

The draft of the European Standard for aluminothermic welds in rails, Reference CEN/TC 256/SC 1/WG 4, that is in its final steps (3), specifies for approval of a welding procedure, either the rail grade or section, the following laboratory tests: Chemical Analysis, Macro and Microstructure of the weld metal, Hardness Distribution; Slow Bend Test and Fatigue Test.

Detailed non destructive procedures such as: gammaradiography and ultrasonic testing, magnetic particle and flaw detection liquid inspection are included as Annexes of the Standard.

Testing methods

Specific requirements for the rail section UIC 60, grade 260, that is the most commonly used rail for the high-speed lines (above 200 Km/h) are as follows:

Chemical Analysis of the weld running surface must fall within the following range:

C	Mn	Si	P	S	Cr	Mo	Al	V
0.50 0.70	0.70 1.40	<0.90	<0.035	<0.030	<0.20	<0.10	<0.60	<0.10

Macro and Microstructures of the weld metal and the visible heat affected zones. Defectology:

– Distance from the rail ends to the fusion line greater than or equal to 3 mm at all vertical portions in the weld.

– Structure of the fusion zone must be 100% pearlitic (free of any bainite or martensite).

– No cracks with surface length greater than 2 mm.

– No pores with a dimension greater than 3 mm.

– No slag or sand inclusions greater than 10 mm in diameter and 3 mm in depth.

– No internal defects (porosity, inclusions, microshrink cavities) greater than 5 mm in the rail head, web or foot of the welded joint.

Hardness

The Brinell hardness tests in the weld centre of a rail grade 260 carried out according to Standard EN 3 (ISO 6506) shall fall within the range of 280 ± 20 HBW.

The hardness distribution on the heat affected zones shall be measured using the Vickers hardness test according to the Standard EN 6 (ISO 6507) starting from the weld fusion line and continuing until 20 mm of parent rail with its normal hardness (280 ± 20 HBW).

The width of the heat affected zones shall be determined (less than or equal to 20 mm, 30 mm and 40 mm, depending on the purchaser requirements) and the heat softened zones, globular pearlite, with hardness 10 HV less than average (for rail grade 260).

Slow bend test

Carried out according to the European Standard for Acceptance Tests for Aluminothermic Welding Portions, the rail sample must withstand a load of 90 Tf with a minimum deflection of 9 mm. This is equivalent to a maximum tensile bending strength of 600 MPa for the case of a rail section UIC 60, grade 260. The minimum fracture load shall be 113 Tf (750 MPa).

Fatigue test

Carried out according to the European Standard with a distance between supports of 1000 mm and applying the load on

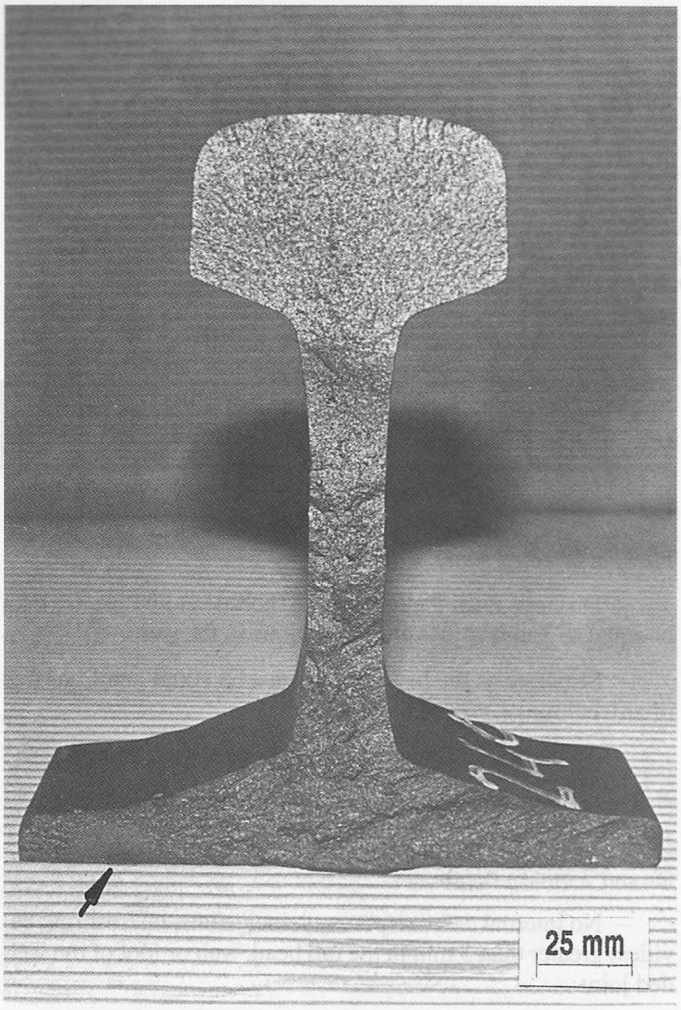

Fig.1. Surface fracture of aluminothermic weld rail broken by fatigue.

Fig. 2. Internal defects into the filler metal.

the running surface with two rolls spaced 150 mm between centres for the rail section UIC 60 (Section modulus 377 x 10^3 mm^3) rail grade 260; with an applied load range of 36 Tf and 8 Tf (equivalent to s_{max} = 220 MPa, s_{min} = 50 MPa), the minimum load cycles required without failure shall be 2 x 10^6; or the final conditions agreed during the current discussions. It is obvious that specified mechanical tests, both slow bend test (single fulcrum) and fatigue test (4-point) are the most important ones to check the aluminothermic welding processes quality and their possibilities of getting approval by the Approving Authority.

The slow bend test evidences gross defects in manufacturing: skin defects, macro and microshrink cavities, segregations, porosity due to evolving gases during the welding process, outcome from both the sand mould and the aluminothermic steel itself.

The fatigue test evidences both gross defects as well as little failures, Figures 1 & 2. The European Standard goes beyond other standards still in force (as the French Standard) that do not specify such fatigue test. Therefore, shall be more difficult to get approval under this procedure.

During the fatigue test, a small surface defect, a notch or shrinking crack due to residual stresses, changes in volume due to freezing, weld collar and rail soft-skinned zones, Figure 3, can be very important in specimen performance.

Furthermore, a faulty prepared weld collar, previously to the fatigue test, with deformations or scratches, or the sand mould geometry itself and therefore of the weld collar, can deal to that different welding processes result in a glaringly distinct results even though the welds were correctly carried out and they fulfil all the other above requirements.

In the following example, we compare the fatigue ranges of the oxygen/propane short-preheating aluminothermic weld rails calculated by two different methods.

In fact, the fatigue range comes from the fact evidenced by the experience of the statistic nature of the Wöhler curve (applied tensile strength versus cycles curve or S/N curve), which points are scattered around a middle line that is the one usually outlined, Figure 4 (4).

Scattering fits a normal distribution or Gauss distribution and depends on many different phenomena, some of them alre-

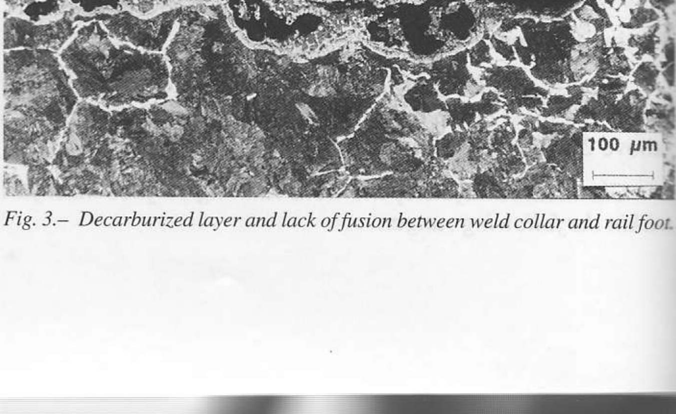

Fig. 3.– Decarburized layer and lack of fusion between weld collar and rail foot.

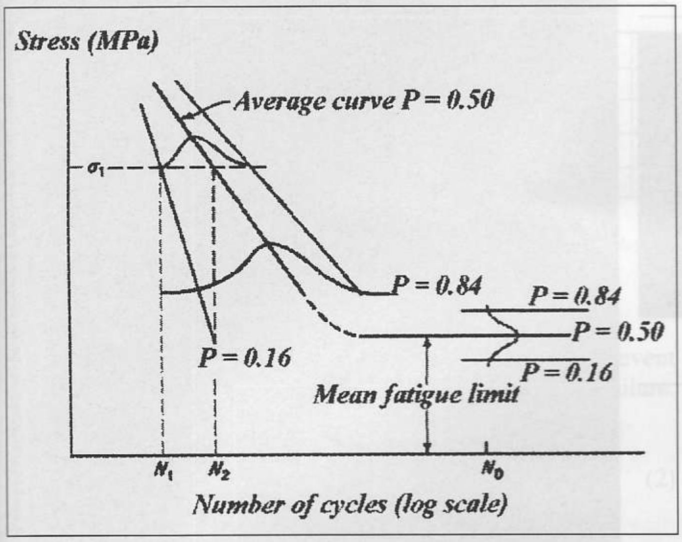

Fig. 4.– Wöhler curves stress-number of cycles. Representation of fatigue data on a probability basis.

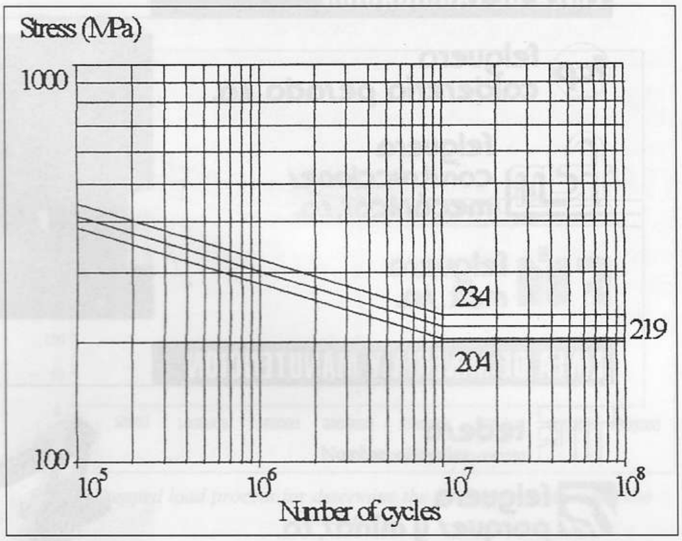

Fig. 5.– Wöhler curves of short preheated oxygen/propane aluminothermic weld rail.

ady mentioned: test method, surface quality, metallurgical state and soundness, corrosion phenomena, temperature and time, etc. All the above justify the Wöhler range representation, Figures 4 & 5, limited by:

– a lower curve, below of which only 16% of fatigue fractures should occur.

– a middle curve, the Wöhler curve really, with a failure reliability of 50% for an applied tensile strength greater than or equal to the material conventional upper fatigue limit.

– an upper curve, above of which 84% of fatigue fractures should occur.

In other words, the Wöhler curve so defined would include (for a defined number of cycles) the range m ± s in which 68% of fatigue fractures should occur, where:

m = material average tensile fatigue strength (fatigue limit).

s = standard deviation, obtained from linear regression analysis of the experimental data of the material Wöhler curve, using logarithmic coordinates.

The equations that represent the fatigue performance of the chosen aluminothermic welding process are as following (5):

- upper curve, $\sigma.N^{0.14} = 10^{3.35}$
- middle curve, $\sigma.N^{0.14} = 10^{3.32}$
- lower curve, $\sigma.N^{0.14} = 10^{3.29}$
- fatigue limit strength at 2.10^6 cycles, m = 275 MPa
- standard deviation, s = ± 19

Fatigue limit ascertainment. Results

Most common method to ascertain the fatigue limit of rails welded by aluminothermic processes are the following:

Staircase Method

As above mentioned, it is based on the statistic nature of the Wöhler curve (6,7). Using this method it is necessary to choose some tensile strength levels evenly distributed in an interval near to the standard deviation of the fatigue limit.

Samples are tested at 2.10^6 cycles using the following method: If the first sample (tested at a level near to the fatigue limit) fractures, then the next sample is tested at the maximum tensile strength right below the previous one; on the contrary the sample is tested at the maximum tensile strength right above the previous one.

The testing shall be continued, until sufficient test data to calculate the standard deviation "s", are obtained. This deviation shall be in the range 10 MPa < s < 38 MPa, when calculated according to equation (2) bellow. Note that these conditions are unlikely to be met until 8 to 12 tests have been undertaken and results are available for at least three stress range levels with results of both types (i.e. both a failure and a run-out) obtained at an intermediate level. Determine first of all whether failures or run-outs are the less frequent events. The mean failure stress is given by:

$$m = S_o + d([A/N] \pm 0.5) \quad (1)$$

where:

S_o = lowest stress range at which tests with the less frequent result were conducted (MPa)

d = 20 MPa;

N = total number of less frequent events, equal to $\sum n_i$

$A = \sum i\,.n_i$

where:

n_i = number of less frequent events at the i-th moment level above S_o

σ												
STAIRCASE												
σ_{max}	1	2	3	4	5	6	7	8	9	10	11	12
260				0		0						
240			x		x		0				0	
220		x						0		x		x
200	x								x			

Failures (0) Run - outs (x)

Fig. 6. Data obtained from a fatigue strength determination using the staircase method.

i = stress level index (i = 0 for S_o).

In the formula (1) use [A/N] + 0.5 if the less frequent event is a run-out and [A/N] – 0.5 if the less frequent event is a failure.

The standard deviation, s, is given by:

$$s = 1.62 \cdot d(\{[B.N - A^2]/N^2\} + 0.029) \quad (2)$$

where $B = \sum n_i \cdot i^2$

Figure 6 describes a method of determining the fatigue strength of a oxygen/propane pre-heated aluminothermic welds at an endurance limit of 2 million cycles using the staircase method. The results were:

5 welds fail the test (less frequent event) so, N = 5.

7 welds run-out the $2 \cdot 10^6$ cycles test.

The lowest stress range at which a failure occurs was:

S_o = 220 MPa; i = 0 for 220 MPa. Therefore:

$A = \sum i \cdot n_i = 6$; $B = \sum i^2 \cdot n_i = 10$

From the equations (1) and (2) we get:

m : fatigue limit at 50% = 220 + 20 (6/5 – 0.5) = 234 MPa

s : standard deviation = $1.62 \cdot 20 (\{[10.5 - 6^2] / 5^2\} + 0.029)$ = 19 MPa.

Locati Method

This method allows to determining the tensile fatigue limit, once known the material Wöhler curve (8). It is based in the empirical Miner´s law about the cumulative damage: ($\sum n_i / N_i = 1$), where n_i the number of cycles under maximum tensile s_i and N_i is the number of cycles to fatigue fracture under the same load conditions.

The carry out the test the sample is subjected to a stepped loads process (evenly spaced), s_i, at a steady number of cycles (usually $n_i = 10^5$). The initial load is frequently chosen slightly lower than the foreseen material fatigue limit. The test continues until fracture, Figures 7 & 8.

Then, using the Wöhler curves corresponding to 16%, 50% and 84% of the fractures, the partial damages, n_i / N_i, corresponding to the tensile levels chosen are calculated. The hypothetically cumulated damages, $\sum n_i / N_i$, are assessed for every one of the curves and displayed depending of their corresponding fatigue limits. The fatigue limit of the material should be the tensile strength, obtained from interpolating, for a cumulated damage equal to 1.

Locati method meets the following advantages: simplicity, quick-operating, very suitable (low cost) for tracking (quality control) of the aluminothermic rail welding process or to evaluate the incidence in the performance of the weld, after a modification in design geometry, operating procedure, rail steel grade, etc., at the fatigue limit.

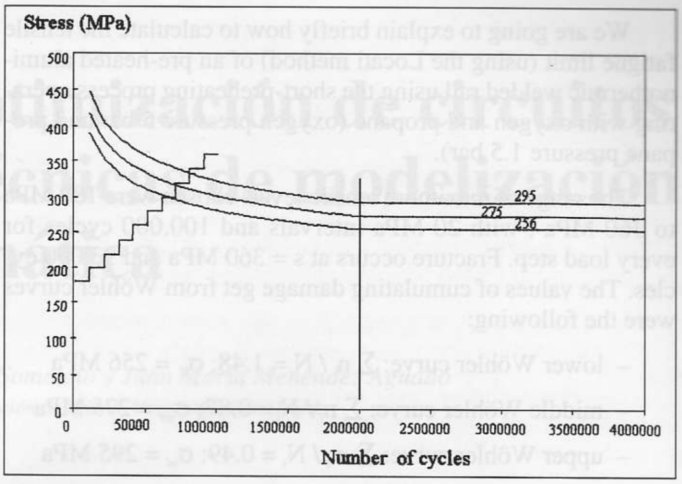

Fig. 7. Stepped load process for determine the fatigue strength using the Locati test.

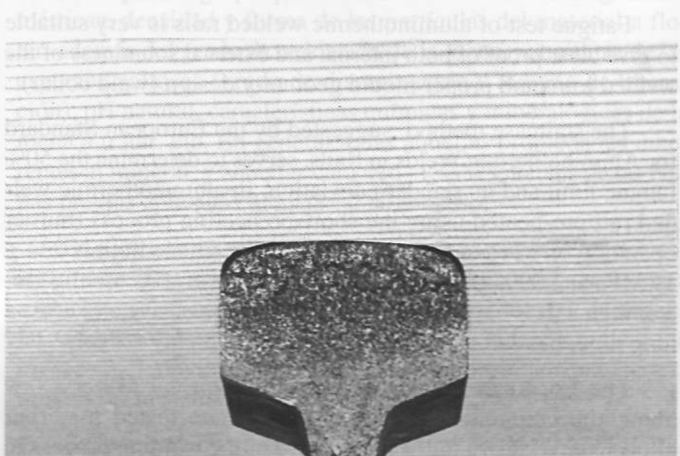

Fig. 8. Surface fracture of aluminothermic weld rail broken by fatigue. Locati test.

FATIGUE TEST ALUMINOTHERMIC WELDED RAILS

We are going to explain briefly how to calculate the tensile fatigue limit (using the Locati method) of an pre-heated aluminothermic welded rail using the short-preheating process operating with oxygen and propane (oxygen pressure 5 bar and propane pressure 1.5 bar).

The range of maximum tensile levels chosen were 180 MPa to 360 MPa , with 20 MPa intervals and 100,000 cycles for every load step. Fracture occurs at s = 360 MPa and 93,000 cycles. The values of cumulating damage get from Wöhler curves were the following:

- lower Wöhler curve: $\sum n_i / N_i = 1.48$; $\sigma_{lf} = 256$ MPa
- middle Wöhler curve: $\sum n_i / N_i = 0.87$; $\sigma_{mf} = 275$ MPa
- upper Wöhler curve: $\sum n_i / N_i = 0.49$; $\sigma_{uf} = 295$ MPa

From adjusting the above values to a second grade equation, we get: $\sigma_{mf} = 270$ MPa

This result agrees sufficiently, at 2 million cycles, with those obtained from welds carried out using the same pre-heating process.

Conclusions

Fatigue test of aluminothemic welded rails is very suitable to give clear proof of both internal and external soundness of the welded joint and proper mould geometry design (weld collar).

The staircase method, suggested by the European Standard for Aluminothermic Welds in Rails, serves to determine the 50% fatigue limit and its standard deviation. In aluminothermic welded rail pre-heated using the short-preheating process (burner operating on oxygen and propane), fatigue tensile limit is 234 ± 19 MPa at 2,000,000 cycles, needs a number of tests usually greater than 8. It is easy to see that this test is expensive and takes a long time, but due to its statistical nature is highly reliable.

The Locati method, based in the empirical Miner´s law about the cumulative damage on a fatigue tested material, allows, once known the Wöhler curve of the welding process in use to settle the fatigue tensile limit at 50% with only one test, using a reduced number of cycles. The values obtained (approximately m = 270 MPa) are very similar to those resulting from the staircase method stated in the European Standard. From our point of view and due to its ease, speediness and savings, this is the most suitable test to check the quality and compare the aluminothermic welding processes in use.

The most frequent fracture causes in aluminothemic welded rails and fatigue tested are associated to a defective design of the weld collar web-foot union zone, soft-skined zones with thickness greater than 0.5 mm, lack of fusion between rail-foot and weld collar and external defects (pores, sand inclusions, microcracks) in the lower rail-foot weld collar that is the most stressed zone during the fatigue test.

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