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Some comments on mechanical fatigue characterization of steel rails in Standards

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Abstract

Current Standards and recommendations on characterization of steel materials for rail production define tests for material supplying. As reported in technical literature, fatigue is the phenomenon which represent one of the main cause of rail damage and failure. Experimental testing of fatigue characterization according to Standards on different samples and with different surface roughness values, satisfying the Standard requirements, are performed. The results are then presented and discussed. Some nomenclature ambiguities are pointed out, which can lead to different loading conditions for fatigue testing.

Keywords: Fatigue; rails; Standard; Roughness

1. Introduction

Current international standards and recommendations on acceptance and qualification of materials for railway applications, and in particular for rails EN 13674-1 (2010), describe tests to characterize material and components supplies. Different Standards sometimes agree, sometimes do not and in some parts are ambiguous.

In these standards both the supplying requirements and testing are described.

For example in ASTM A1 (2010) dealing with material acceptance, chemical characterization and hardness measurements are required.

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In qualifying tests more requirements are prescribed.

The Standard EN 13674-1 (2010), defines the qualification requirements about the number of specimens, geometry and dimensions, where specimens are to be obtained in rail volume, test procedure and result processing. They consist in fracture toughness, fatigue crack growth rate, fatigue tests, residual stress measurements, geometrical parameters, hardness measurements, tensile strength and elongation, chemical parameters and surface quality.

The Standard ASTM A1 (2010) is referred to T steel tee rails. The requirements are limited to chemical composition, internal status, hardness and geometrical parameters. Control techniques are optical checks, hardness tests and ultrasounds.

Standard ISO 5003 (2016) indicates terms and definitions, dimension tolerances, technical requirements, inspection rules, identification, certification, for as-rolled and heat-treated steel rails for railways and is similar to EN 13674-1 (2010).

It must be noted that neither in AREMA (American Railway Engineering & Maintenance-of-Way Association) specifications AREMA (2010) nor in ASTM, specific Standards were found related to fatigue resistance of materials for railway applications, while these requirements are well defined for European Standards, even if in AREMA (2010), Lewis and Olofsson (2009) and other documents it is well documented that fatigue is one of the main cause of failure and damage of rails. In particular rolling contact fatigue, friction, thermal fatigue, wear are mentioned as the main failure causes for rails.

In Lewis and Olofsson (2009) it is described how rail fatigue and wear depend on the repeating contact loads. According to the authors, the main factors differentiating wear and fatigue of rail-wheel contact from failures in other mechanical components are that the cyclic loads are compressive. With gears, rails share highly concentrated non-conformal contacts, and the surfaces experience combined rolling and sliding relative motion.

Topic of this paper is pointing out some critical hints present in fatigue qualification tests Standards for rails.

Aim of the paper is to propose some modification to avoid ambiguities in interpretation and to improve qualifications of the materials for what concerns the definition of surface finish of specimens undergoing fatigue loading and the corresponding definitions of fatigue loading parameters.

2. Standards review

The first hint related to the EN 13674-1 (2010) is in the definition of qualification fatigue tests procedures: the nomenclature used in the definition of testing procedure is not univocal. The first point consists in that EN 13674-1 (2010) asks for "constant amplitude fatigue tests" to be "carried out in accordance with ISO 1099" (that is ISO 1099 (2006)) while a few lines later it states that " the control variable shall be axial strain amplitude" requiring for a defined "total strain amplitude" to be applied to specimens. Actually, ISO 1099 (2006) requires stress controlled fatigue testing and defines how to apply stress to the specimen.

In EN 13674-1 (2010) neither the term "constant amplitude fatigue tests" is defined nor the term "total strain amplitude" and in the list of reference Standards no reference is given for the corresponding definitions. In ISO 1099 (2006) more definitions are available.

In §3.9 ISO 1099 (2006) the stress amplitude is defined as "one-half the algebraic difference between the maximum stress and the minimum stress in a stress cycle", while in §3.10 ISO 1099 (2006) the stress range is defined as "arithmetic difference between the maximum and minimum stress". The Standard then reports a figure which is not coherent with these definitions. On the other hand, these definitions correspond to the ones of ASTM E1823 (2013).

The ambiguity related to the definition of "constant amplitude" fatigue tests can be clarified thanks to §4.1 ISO 1099 (2006) where, in stating the general outline of tests, the Standard lists the possible test aims in which the "fatigue life at a specified stress amplitude" is reported.

To further clear the ambiguities related to the terms "amplitude" and "total strain" let us refer to other Standards about fatigue testing of steels.

ASTM standards gather many definitions in ASTM E1823 (2013) helping to clarify some terms.

For example, constant amplitude fatigue loading is defined as "a loading (straining) in which all of the peak forces (strains) are equal and all of the valley forces (strains) are equal." Also force (load or strain) fatigue amplitude

are defined as "one half of the range of a cycle (also known as alternating force)" and correspondingly the stress range is defined as "the difference between the maximum and minimum stresses."

To solve the point related to strain or stress controlled testing in case of high cycle fatigue, the ASTM E 606/E606M (2012) is dedicated to the determination of fatigue properties of homogeneous materials by means of uniaxial testing, when the magnitudes of time-dependent inelastic strains are on the same order or less than the magnitudes of time-independent inelastic strains, that is in case of Low Cycle Fatigue. The practice is intended for strain controlled fatigue testing, but later it provides "useful information for load-controlled or stress-controlled testing."

In this standard many definitions can be found. First of all for what concerns the interpretation of the "total strain" of EN 13674-1 (2010), in ASTM E 606/E606M (2012) the instantaneous strain ε is defined as the sum of elastic ε_e and inelastic ε_{tv} contributions and the corresponding terms are defined in the following. In ASTM 2368 (2004) which deals with termo-mechanical testing which are tests usually performed in strain control due to large amounts of inelastic strains, the total strain is defined as "the strain component measured on the test specimen, and is the sum of the thermal strain and the mechanical strain". In isothermal conditions the two definition of total strain coincide as the thermal train is defined as the strain component due to a change in temperature under free expansion conditions, measured on the test specimen, and the mechanical strain, as the strain component measured when the free expansion thermal strain (as measured on the test specimen) is subtracted from the total strain.

From these references it can be derived that the term "total strain" in isothermal conditions can be assumed as the strain measured by the extensometer which, in elastic stress conditions, corresponds to the elastic strain contribution.

For what concerns the term "amplitude", Standard ASTM E 606/E606M (2012) nomenclature refers to ASTM E1823 (2013) definitions. In these standards it is stated that: "Total axial strain amplitude is the most commonly utilized control variable in a low-cycle fatigue test. Total axial strain is often controlled continuously throughout each fatigue cycle in a manner prescribed."

In ASTM E 606/E606M (2012) the definition of total strain amplitude is given as the sum of elastic and plastic strain amplitudes, corresponding to mechanical strain amplitude definitions, where the elastic term is defined as half the ratio between the $\Delta\sigma$ is the true stress range and the Young's modulus.

This allows to confirm that the strain range is the difference between the maximum and the minimum strain values and the amplitude is the absolute value of the difference between the maximum (or minimum) and the mean value, according to ASTM E1823 (2013) for what concerns definition to EN 13674-1 (2010), for the definition but not for the corresponding schematic drawing.

Also in other Standards Systems, coherent definitions can be found. In Standard JIS 7083 (1993) the range of a parameter (load, stress, strain..) is defined as the difference between the maximum value and minimum value of the alternating parameter and the amplitude as the half of the range or the absolute value of the difference between the maximum (or minimum) and the mean value.

In JIS 7083 (1993) the corresponding scheme of is coherently reported. ASTM E466 (2015), EN 1993-1-9 (2006), SAE J1099 (2002) show definitions coherent with ASTM E1823 (2013).

Form a testing point of view another critical hint can be pointed out in the Standard.

It is well known that fatigue resistance is related to surface finish (ASTM E466 (2015), Roushdy and Kandeil (1996), Kuroda et al (2006), Murakami (2002), Itoga et al (2002)).

It must also be taken into account that there are coupling effects between surface finish, environmental conditions, temperature, kind of fatigue loading, material properties (e.g UTS) and fatigue resistance.

Standards EN 13674-1 (2010), ISO 1099 (2006) requirements on surface finish are related to mean roughness (*Ra*) only. The surface finish and residual stresses appear to be parameters which strongly affects the results of testing and Standards ISO 1099 (2006), ASTM E 606/E606M (2012), ASTM E466 (2015) recommend also how to avoid the influence of this parameter from testing results by means of definite specimen manufacturing procedures, including a final polishing stage. In AREMA (2010) recommendations, grinding of rail is indicated as preventive approach for rail maintenance, to control wear phenomena in rolling contact fatigue crack propagation, to maintain optimal rail profiles matching and to control rail corrugation and weld dipping.

Average surface roughness *Ra* suggested for preventive rail grinding ranges 10-12 μm.

For what concerns the recommended value of *Ra* for rail fatigue testing, the qualification tests defined in EN 13674-1 (2010) define Ra roughness requirements to surface finish for fatigue specimens. In Figure 1 the fatigue

specimen design according to EN 13674-1 (2010) is reported. It can be observed that the required Ra value is 1.6 μm, while in the referenced ISO 1099 (2006) it is recommended a Ra value of 0.2 μm. According to technical drawing agreements, the indicated value is a maximum allowed value, while the minimum value is not specified. According to the following experimental results, surface finish with such an elevated range of variation can give different results in fatigue characterization. If the aim of qualification tests is to characterize the material obtained from the bulk of the rail it makes sense, to avoid any surface effect and residual stress effect, to fulfil the surface finish requirements of ISO 1099 (2006) for rail specimens and in ASTM E 606/E606M (2012) and ASTM E466 (2015) for general purpose tests, as an example. Else the different roughness surface range can allow non/qualification results as indicated in the following case study.

If the aim of qualification tests is obtaining information on the influence of surface finish, in ISO 1099 (2006) for example, a different procedure to obtain specimens is indicated. In case the surface condition in which the metal will be used in actual application are relevant, as it is for rails according to AREMA (2010), Lewis and Olofsson (2009), ISO 1099 (2006) indicates that at least one surface of the test section of the test piece should remain unmachined.

Other standards were checked. For example Standard ASTM E466 (2015) refers, among others, to ASTM E1823 (2013) and ASTM E 606/E606M (2012).

This Standard is indicated for constant amplitude high cycle fatigue tests and it is recommended to carry on also measurements of hardness, surface finish, residual stresses. In particular ASTM E466 (2015) indicates that the results of the axial force fatigue test are suitable for application to design only when the specimen test conditions realistically simulate service conditions or some methodology of accounting for service conditions is available and clearly defined.
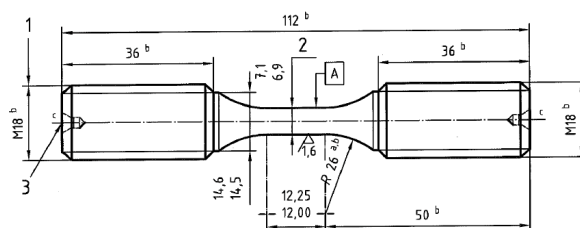
Fig. 1. Fatigue specimen design according to EN 13674-1 (2010).
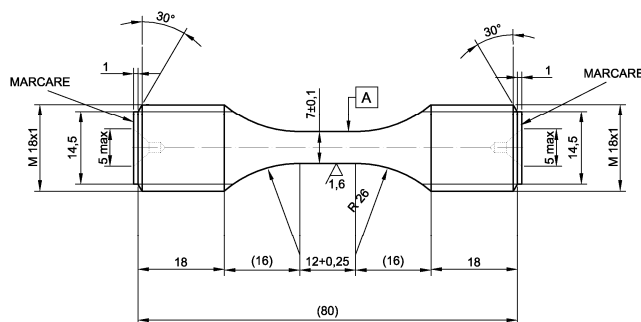
Fig. 2. Specimen geometry (dimensions in mm).

3. Materials and methods

Specimens were obtained from 7 different Vignole rails, all supposedly compliant to the R260 (EN 13674) rail steel grade. The examined rails were designated with letters, from A to G.

The chemical composition of the examined rails, which is reported in Table 1, is very similar and is consistent with the stated grade and standard. The steel microstructure, Figure 3 as an example, was almost fully pearlitic, with

rare traces of pre-euctectoid ferrite at prior austenitic grain boundaries.

The tensile and fatigue samples were obtained from the sampling positions specified in EN 13674-1 (2010), i.e. their loading axis was parallel to the longitudinal axis of the rail, and it was located 10 mm below the surface of the fillet between the running surface and the side of the rail head. Specimens were obtained by means of turning and grinding. In Figure 2 the fatigue specimen geometry is reported. The geometry, different from EN 13674-1 (2010), was required for the testing machine gripping system. Surface finish requirement are compliant with EN 13674-1 (2010).

Table 1. Sample chemical composition.

|		C	Si	Mn	P	S	Cr	Al	V	N
		%	%	%	%	%	%	%	%	%
R260	min	0.6	0.13	0.65	0	0	0	0	0	0
(EN 13674 tab 5)	max	0.82	0.6	1.25	0.03	0.03	0.15	0.004	0.03	0.01
A	med.	0.732	0.275	1.098	0.021	0.012	0.041	0.002	0.001	0.0062
	dev.	0.018	0.007	0.006	0.001	0.002	0	0	0	0.0004
B	med.	0.676	0.276	1.072	0.015	0.019	0.043	0.001	0.001	0.0064
	dev.	0.014	0.003	0.004	0.001	0.003	0	0	0	0.0002
C	med.	0.724	0.288	1.078	0.02	0.015	0.041	<0.001	0.002	0.0066
	dev.	0.017	0.004	0.004	0.001	0.003	0	0	0	0.0004
D	med.	0.726	0.298	1.079	0.02	0.018	0.039	0.001	0.001	0.0062
	dev.	0.016	0.002	0.004	0.001	0.001	0	0	0	0.0003
E	med.	0.73	0.251	1.071	0.019	0.014	0.043	0.002	0.001	0.0069
	dev.	0.021	0.003	0.005	0.001	0.002	0	0	0	0.0003
F	med.	0.716	0.282	1.081	0.016	0.016	0.03	0.001	0.001	0.0066
	dev.	0.018	0.004	0.003	0.001	0	0	0	0	0.0006
G	med.	0.708	0.271	1.083	0.022	0.013	0.037	0.001	0.002	0.0062
	dev.	0.006	0.003	0.005	0.001	0.002	0	0	0	0.0002
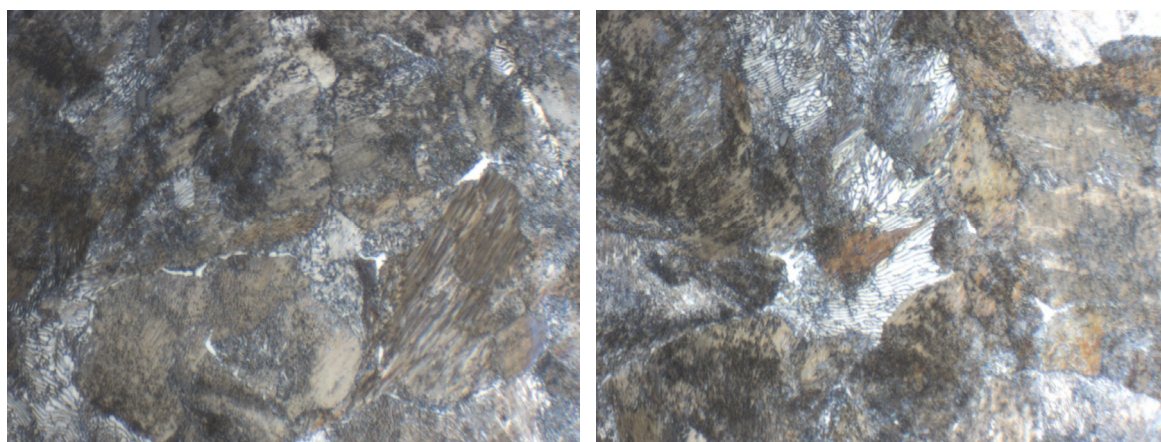
Fig. 3. Microstructures of rails B (left) and C (right). Pearlite, traces of pre-euctectoid ferrite. Optical microscopy after Nital etching, 700 x.

Monotonic tensile testing specimens were obtained according to EN 13674-1 (2010) for what concerns geometry

and surface roughness. For all the fatigue specimens *Ra, Rt, Rz* and *Rq* values were acquired. Roughness measurements were obtained by means of a ALPA TL90 instrument, cutoff 0.25 mm and measurement length 1.25 mm.

A second set of fatigue specimens was prepared with a better surface finish, obtained by means of turning and grinding. The first set was identified with the subscript I while the second by the subscript II, the roughness values are also reported in Table 2. Three specimens for each sample were used for uniaxial monotonic tensile characterization.

Tensile monotonic tests were run by means of a servohydraulic universal Instron testing machine 8801, load cell 100 kN, in displacement control. The average elastic modulus was calculated for each sample and it was used to calculate the stress required for fatigue testing as the Standard EN 13674-1 (2010) requires to run fatigue tests in strain control, with a loading ratio R=-1 and a defined strain amplitude. Three specimens need to be tested at the same strain amplitude and all three specimens shall survive 5 millions loading cycles.

Fatigue tests were run on a Amsler HFP 100 resonance testing machine, equipped with a 100 kN load cell.

Since the maximum required stress was lower than the elastic limit, the tests were run in stress control and the stress amplitude was calculated corresponding to the required strain amplitude multiplied for the average elastic modulus of each rail, as obtained from the tensile tests.

Strain gauges were set on selected specimens to verify the strain amplitude to fulfill the Standard requirement.

For all specimens the fatigue frequency was about 110 Hz.

Table 2. average roughness measurements results for turned specimens.

		Ra	Rq	Rt	Rz
AI	average	1.214	1.472	8.106	6.195
	std dev	0.252	0.296	1.726	1.217
BI	average	1.201	2.707	14.764	11.010
	std dev	0.273	0.463	4.425	1.963
CI	average	1.114	1.170	8.154	6.083
	std dev	0.426	0.428	3.450	2.403
DI	average	1.201	1.488	7.947	5.771
	std dev	0.116	0.131	1.065	0.491
EI	average	1.196	2.056	13.019	9.579
	std dev	0.243	0.385	3.022	1.530
FI	average	0.774	0.849	5.394	3.549
	std dev	0.321	0.408	2.809	1.800
GI	average	1.184	1.864	7.140	12.128
	std dev	0.443	0.510	1.638	1.910
BII	average	0.387	0.508	3.810	2.672
	std dev	0.069	0.110	1.181	0.445
EII	average	0.429	0.561	4.068	2.905
	std dev	0.123	0.174	1.847	0.894
GII	average	0.292	0.375	2.866	2.101
	std dev	0.074	0.099	0.929	0.410

4. Results and discussion

Monotonic uniaxial test results are reported in Table 3, while the stress-strain curves are reported in Figure 5 for

sample C as an example.

For this set of specimens, average roughness parameter values were elevated but still in the range allowed by the Standard (Table 2).

In Table 4 fatigue tests results are reported. In the first column the specimen designation, in column 2 the results of the test, in column 3 the corresponding normalized applied stress. In column 2, the symbol "X" means that the specimen failed while the symbol "O" means that the specimen survived 5 millions of cycles. All the failures happened for less than 1 million cycles. Highlighted specimens are the grinded ones.

Table 3: tensile monotonic testing results

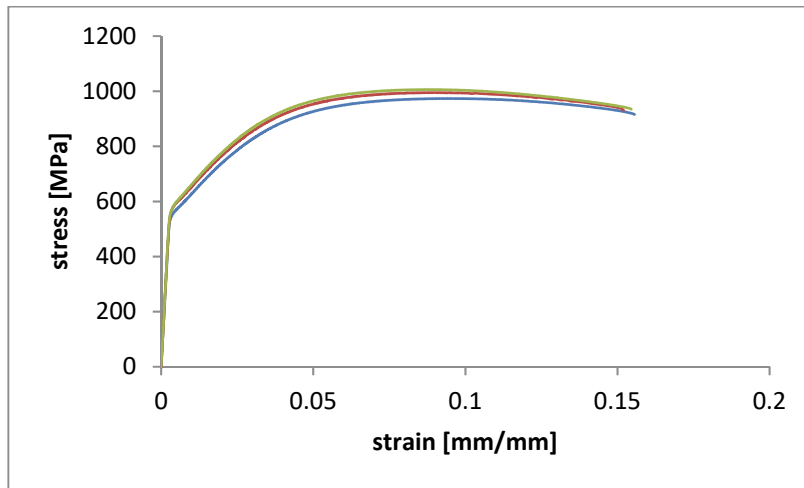|	E [MPa]	Rm [MPa]	Rp02 [MPa]
A	201618	1005	592
B	198063	958	576
C	202827	992	587
D	203807	990	597
E	204397	972	579
F	198171	973	577
G	205164	990	594

Fig. 4. Tensile monotonic testing curves for sample C.

Fatigue testing results showed that specimens B, E and G which resulted compliant for roughness requirements, did not pass the fatigue testing. The same material, if specimens were manufactured with a finer surface roughness passed the fatigue testing.

5. Conclusions

An overview of standard related to fatigue testing show a general coherence in terminology and definitions.

Standard EN 13674-1 (2010) nomenclature requires revision for what concerns the terms strain range and amplitude. Also the testing procedures requires to be reviewed for what concerns the testing control parameter.

Generally speaking the surface roughness parameter *Ra* requires a more accurate definition to allow qualification results to be univocally interpreted.

Table 3: Fatigue testing results

	cycles to failure	result	maximum stress [MPa]
A1		0	272
A2		0	
A3		0	
B1	457097	X	267
B2		0	
B3		0	
B4 II		0	
B5 II		0	
B6 II		0	
C1		0	274
C2		0	
C3		0	
D1		0	275
D2		0	
D3		0	
E1		0	276
E2		0	
E3	460275	X	
E4	659684	X	
E5 II		0	
E6 II		0	
E7 II		0	
F1		0	268
F2		0	
F3		0	
G1	180229	X	317
G2		0	
G3	179302	X	
G4		0	
G5 II		0	
G6 II		0	
G7 II		0	

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