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Understanding fatigue mechanisms in ancient metallic railway bridges: a microscopic study of puddled iron

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Abstract

Being the second oldest railway network in Europe, almost half of the metallic railway bridges in France were built before the 1900s. At the time, puddled iron was the building material of preference amongst most engineers, hot riveting was the preferred joining method.

Considering the ageing of these constructions, as well as the increasing evolution of traffic in the network, the understanding of the behaviour of this type of structures to cyclic loadings is of utmost importance. However, high cycle fatigue characterization is an expensive and time consuming process. The use of a fast characterization method through the measure of self-heating of the specimens during cycling loadings is proposed and analysed.

For homogeneous materials, like modern steel, the use of self-heating measurements to estimate fatigue-life related properties has shown good correlation to results obtained by the standard fatigue tests with the advantage of a lower time of characterization. In our case, non-metallic inclusions present in the puddled iron will have an important influence in the response of the material, and therefore the interpretation of the temperature's evolution needs a different approach.

Due to its complexity, the integrity of the structure must be analysed from a multi-scaled point of view. For this study, we focused in the quantification of the influence that the population of non-metallic inclusions have on the mechanic and thermal behaviour of a puddled iron. For this purpose, a set of specimens previously tested by the self-heating method were prepared and observed using two different tools: a classic optical microscope and a scanning electron microscope. The relationship between geometric parameters of the inclusions found in the specimens and their temperature response to cyclic loadings was shown. The hypothesis of the presence of micro plasticity (dissipative phenomenon) near inclusions was also validated through SEM observations.

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Keywords:
High cycle fatigue, railway bridge, puddled iron, non-metallic inclusions, microscopic analysis, self-heating method

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1. Introduction

Since the 1850s, the French railway network has evolved at a non-stopping pace growing in infrastructure and train capacity. As a consequence, an important part of the heritage is over one hundred years old, and therefore, developing strategies for its maintenance is an important endeavour.

Amongst all railway infrastructure, the metallic bridges are 18% of the total bridges in service. Of those, nearly 44% were built before the 1900s[1]. At the time puddled iron was the most common material used in monumental construction, hot riveting was the most common joining technique.

Between the numerous phenomena affecting the life service of a structure (*e.g. corrosion, overload, etc.*.), we will focus exclusively in high cycle fatigue. For this purpose, specimens obtained from an ancient puddled iron bridge were submitted to fatigue testing through two different methods: classical characterization (S-N curves obtained at two million cycles), and also, a method of fast characterization based on self-heating measurements. A parallel between both methods is proposed and the role of non-metallic inclusions is studied through microscopic analysis (failure profiles and description of the population).

Nomenclature

SNCF	National Society of French Railways
LBMS	Brest Laboratory of Mechanics and Systems
UBO	University of Brest, France
HCF	High Cycle Fatigue
SEM	Scanning Electron Microscope
S-N	Stress-Number of cycles
Σ	Specimen's tensile stress during self-heating test (MPa)
Σ_0	Stress amplitude of loading applied to the specimen (MPa)
θ	Specimen's temperature during self-heating test (K)
θ_{st}	Specimen's steady-state temperature (K)

2. Context : from the specimen to the structure

The failure of materials submitted to cyclic loadings under their yield stresses has being subject of study since the railway catastrophe of Meudon (1842) [1]. Due to its progressive an masked nature, the so-called "fatigue of materials" remains the source of numerous accidents and mechanical failures of components to this day (*e.g.* Eschede railway catastrophe in 1998).

Characterizing fatigue behaviour is complex and expensive. This is mostly a consequence of the need of numerous specimens to obtain a descriptive curve of the behaviour, as proposed by Wöhler in the Paris universal exposition in 1867.

Since we are interested in the behaviour of a structure, numerous difficulties will add to an already difficult problem. We will face the influence of the constructional solutions proposed by the engineers during the design of the structure, the influence of the assembly method used at the time (hot riveting), and finally, the influence of the material (puddled iron). This paper will attempt to add new elements to the understanding of the latter.

The scientific community has somewhat developed several rules of thumb to understand fatigue of most modern metals. For example, numerous authors have proposed simplified expressions to estimate the limit fatigue of steel [2]. However, it is also recognized that fatigue is a scattered phenomenon and therefore relating an endurance limit directly to a yield stress value must be taken with care. In addition, fatigue behaviour has shown to depend on the size of the specimen studied.

[1] National Society of French Railways data.

As shown in [3] and [4] puddled iron is known for having a large population of non-metallic inclusions randomly distributed. As a consequence, its mechanical behaviour (even under static loadings) will not be repeatable and it will also differentiate from modern steels due to its brittleness and anisotropy.

2.1. Case study: the bridge over the Adour river

Although largely used in the 19th century, puddled iron is no longer used in monumental construction and since the arrival of steel as a more resistant alternative, its production has been reduced to a minimum. In order to characterize the material, pieces from an already existent structure were recovered. With the logistics support of the Engineering Department of the SNCF the Eiffel bridge over the Adour river was chosen.

Built in 1862 by the Eiffel company, this structure was located in the south of France in the city of Bayonne (line Bordeaux to Irun) until its replacement in 2013. The bridge had a total span of 271.84m.

Fig. 1. Global view of the Eiffel bridge over the Adour river (photography taken in 2013).

In order to study the behaviour of the material, several pieces where obtained form the bridge before its demolition. To guarantee the quality of the recovered material, an extensive study was carried out based on the maintenance archives of the SNCF, and the advice of the team in charge of the demounting operation.

3. Experimental set-up

3.1. Fatigue characterization

As previously discussed in section 2, fatigue is a complex, masked, and scattered phenomenon. Furthermore, and also based under numerous observations such as given in [1], the existence of an endurance limit (loading amplitude from which the material will not present failure and therefore has an infinite service life) is generally admitted. However, more recent studies showed failure mechanism related to the existence of defects in materials for a very high number of cycles (10^9 - 10^{12}) [5] [6] [8]. Since puddled irons have an important population of defects and the service life of the structures is over one century, these observations must be taken into account, which means that the existence itself of a fatigue limit is not assumed *a priori* for this type of material.

3.1.1. The conventional method

Fatigue tests were carried out in tension-compression with a load frequency of 20Hz and a stress ratio of (-1). Although relatively easy to implement, the process is rather expensive (number of specimens) and time consuming. For instance, a single $2 \cdot 10^6$ cycles test at 20Hz is about 27.7 hours long.

3.1.2. The self-heating method

Given the amount of time and specimens needed to go through a conventional fatigue characterization of a material, a faster method is also proposed in this paper to accomplish this task.

Initiated by Stromeyer in 1914 [7], the determination of the fatigue limit of a metal through temperature measurements had been studied in the 1920s. First results were promising since it was possible to rely the fatigue behaviour to the thermal dissipation measured under cyclic loadings with only one specimen. For the past few decades, numerous research groups have explored the possibility to propose a model of this thermal behaviour in order to predict rapidly the fatigue behaviour of a metal [9–14]. These models are based on the hypothesis that the evolution of temperature is a consequence of micro-plasticity occurring in the material during cyclic loadings.

For these self-heating measurements, we use thermocouples (one on each grip of the machine, and one in the specimen) to measure the specimens mean temperature which reaches a steady state rapidly. Plotted as a function of the stress amplitude applied to the specimen, this steady state temperature increases significantly form some loading levels which can be explained by the assumption of micro-plasticity. Empirically, the mean fatigue limit can be estimated with the asymptotic behaviour of the last plotted points on the self-heating curve (steady-state temperature as a function of the stress amplitude), see figure 2. This method is known to give good results for fine micro-structures and homogeneous materials [15].

For the self-heating tests campaign, and since puddled iron is known to have an anisotropic behaviour, the influence of the angle between the loading axis and the inclusions was studied (α). A set of 5 specimens for each of the 6 different orientations chosen were studied (0°, 15°, 30°, 45°, 60° and 90°). For each specimen, the stable value of the mean temperature was reached rapidly (less than 7000 cycles at 20Hz).

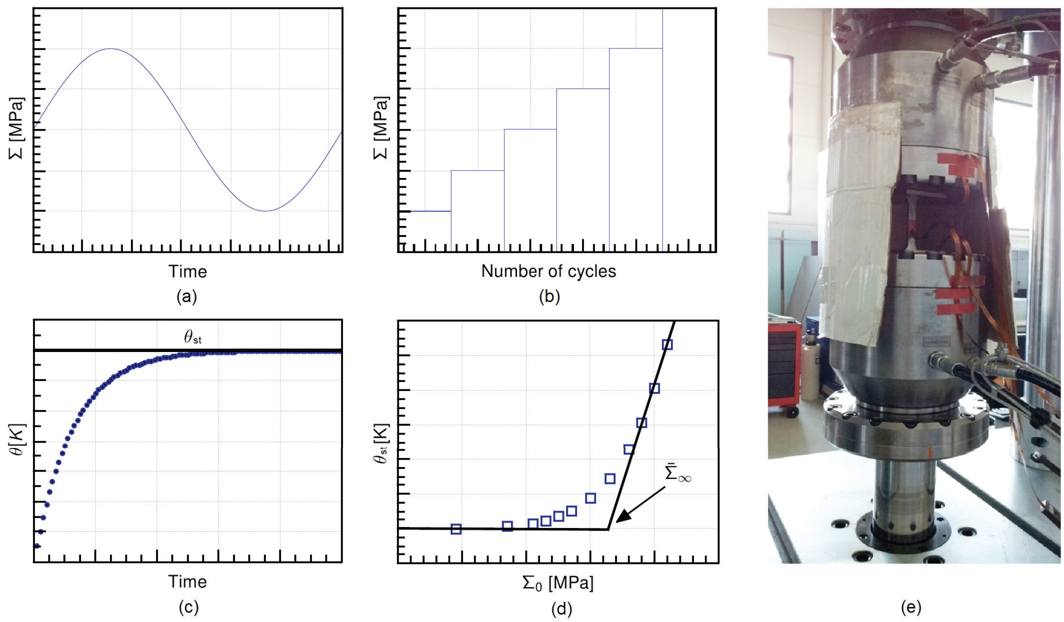


Fig. 2. the self-heating method (a) Example of a sinusoidal loading (stress vs. time); (b) Steps of charge used during a self-heating test; (c) Evolution of the temperature of the specimen during the self-heating test. (d) Empirical determination of the mean fatigue limit by the analysis of a self-heating curve. (e) Experimental set-up [4].

However, as it was illustrated in [17], some materials, particularly those with defects, do not show an easy determination of the fatigue limit through this method since thermal dissipation can also be explained by other phenomena such as crack propagation caused around the so-called defects.

For many materials with non-metallic inclusions the prediction of a fatigue limit seems particularly difficult. However, some recent works have shown that for puddled irons with fine and elongated inclusions it was possible to propose lower and higher boundaries of the fatigue limit [3]. This coming from the fact that the results of self-heating measurements for studied puddle iron specimens showed a higher scatter than those of homogeneous materials.

3.2. Microscopic observations

Since a main hypothesis of the study is the existence of a link between defects and fatigue mechanisms, fracture surfaces of the specimens were analysed after fatigue failure with a *Hitachi S-3200N* scanning electron microscope in order to find potential fatigue striations.

Each specimen tested through the self-heating method ($5 \times 10mm^2$ cross section) was cut into 5 smaller pieces polished with silicon carbide paper up to grain 4000. This was made in order to describe the non-metallic inclusions population, 44 pictures were taken for each piece (a total of 220 to 250 photos per specimen). An *Olympus CK40M* optical microscope was used for this task.

To handle properly this amount of information, a dedicated *Python* tool was developed for the purpose of assembling images for each section and through the application of a color threshold identify black (non-metallic inclusions) and white (iron matrix) patterns. The developed tool allows to count each defect in the analysed surface and get information about its shape, area, perimeter and location.

4. Results & Analysis

4.1. S-N curve

S-N curves were determined for each orientation. As an exemple, the S-N curve (stress amplitude vs. number of cycles) corresponding to the specimens with no difference between the loading axis and the inclusions orientation ($\alpha = 0$) is proposed in figure 3.

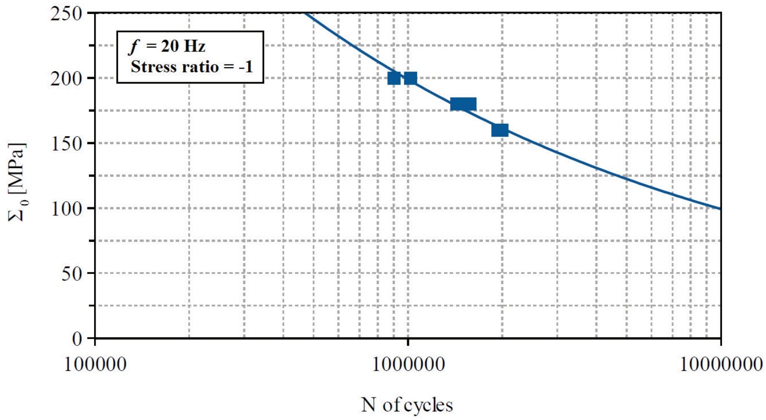


Fig. 3. Fatigue results of fatigue characterization for specimens with $\alpha = 0°$.

This figure shows that for the studied puddled iron the determination of a fatigue limit is not trivial. The five other orientations studied showed the same trend.

4.2. Self-heating measurements

As previously described, the determination of a mean fatigue limit through self-heating measurements remains difficult for materials with inclusions. As showed in figure 4 and in previous studies [3], results are scattered due to the heterogeneity of the material.

As expected, the results showed no common asymptotic behaviour which makes impossible to determine an unique fatigue limit for the material. Moreover, some curves do not show any asymptotic behaviour at all which can be

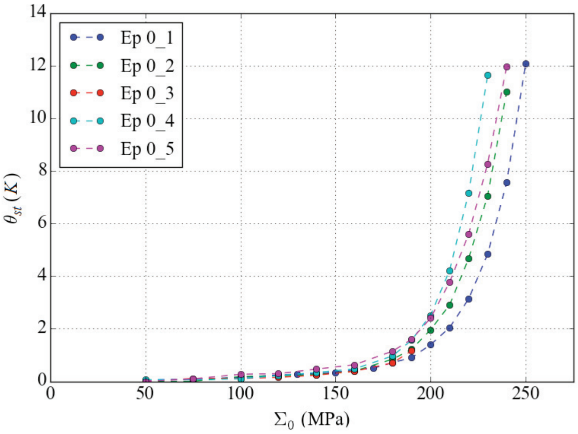


Fig. 4. Self-heating results of fast fatigue characterization for specimens with $\alpha = 0°$.

explained the brittleness of this material. Indeed, some specimens had large inclusions (in the order of several millimeters) observed in the fracture surface obtained after failure. The same behaviour was observed for every studied orientation. Furthermore, the more the value of α increases (approaching to 90°), the shorter the self-heating curves are. This observation is in line with the hypothesis of material brittleness of the material enhanced by "large inclusions". Indeed, since inclusions are oriented along the rolling direction, their projected areas will also increase as the value of α approaches to 90°.

4.3. Non-metallic inclusions characterization

Once the self-heating tests were finished, the broken specimens were recovered to observe the evidence of the phenomena involved in their failure. As shown in figure 5, smaller sized inclusions (1 to 25μm long) are surrounded by what can be identified as fatigue striations which is evidence of micro-plasticity around this defects.

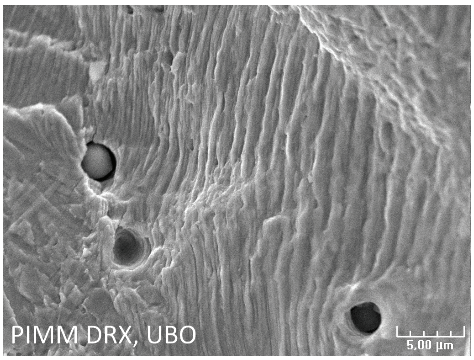
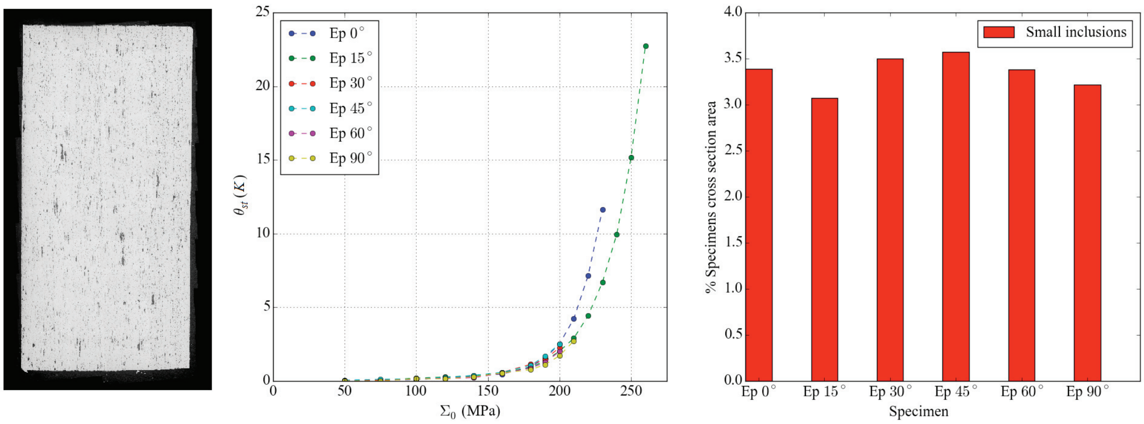


Fig. 5. SEM image obtained from a failure surface of a specimen tested through the self-heating method.

In the following figure 6, self-heating curves obtained for each specimen are confronted with a simplified description of the inclusions population.

The population of smaller inclusions remains rather constant for all studied orientations; this is logical, since the projected area of a smaller rounder defect does not evolves as much with the evolution of α as the projected area of longer, more ellipsoidal defects. This also explains the small variation of temperature values for same stresses in different specimens.



(a) (b) (c)

Fig. 6. microscopic analysis performed; (a) Example of a reconstituted surface of a cross section (5 x 10mm^2) from a specimen tested through the self-heating method; (b) Exemple of self-heating curves obtained for specimens of each orientation chosen for the study; (c) Graphical description of the mean population of “small” inclusions (5 pieces per specimen).

The brittleness (shortness in certain self-heating curves) can be explained otherwise. As the value of α increases, the probability of apparition of defects of several millimiters increase rapidly which will influence the mechanical behaviour of the specimen.

The self-heating method thus seems not suitable to determine fatigue properties of materials containing numerous defects. Nevertheless, specimens temperature evolves with the applied stress load. It appears that the hypothesis of thermal dissipation due to micro-plasticity does exists in the studied puddled iron (“small” inclusions) but the empirical determination of the mean fatigue limit is not possible because of “large” inclusions which explain the brittleness of the material.

5. Conclusions

This paper deals with the fatigue characterization of a 1862 puddled iron through two different methods; the conventional fatigue test and the measurement of self-heating during cyclic loadings. It appears that the determination of mean fatigue limits remains difficult with the conventional method, as well as for the rapid one. However, the thermal dissipation measured through the temperature signals give us information about the contribution of inclusions (defects) in the specimens.

We showed that the percentage of inclusion present in the transversal sections of the specimens is related to the temperature values observed during self-heating tests. As expected, specimens with a higher content in large inclusions presented a brittle behaviour (shorter curves).

Moreover, the origin of the thermal dissipation was investigated. As seen in section 2, this dissipation is explained by the assumption of micro-plasticity. This scenario was also verified with the studied puddled iron through SEM observations. It appears that an inclusions size threshold can be determined with the self-heating curves and the geometry analysis: big inclusions are related to brittleness and smaller to micro-plasticity.

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