CEN WORKSHOP AGREEMENT

CWA 18107-1

May 2024

ICS 19.060

English version

Advanced fatigue testing methods - Part 1: Self-heating measurements

This CEN Workshop Agreement has been drafted and approved by a Workshop of representatives of interested parties, the constitution of which is indicated in the foreword of this Workshop Agreement.

The formal process followed by the Workshop in the development of this Workshop Agreement has been endorsed by the National Members of CEN but neither the National Members of CEN nor the CEN-CENELEC Management Centre can be held accountable for the technical content of this CEN Workshop Agreement or possible conflicts with standards or legislation.

This CEN Workshop Agreement can in no way be held as being an official standard developed by CEN and its Members.

This CEN Workshop Agreement is publicly available as a reference document from the CEN Members National Standard Bodies.

CEN members are the national standards bodies of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye and United Kingdom.

EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

Ref. No.:CWA 18107-1:2024 E

Contents

Page

European foreword

This CEN Workshop Agreement (CWA 18107-1:2024) has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements- A rapid way to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations-Part 2. It was approved by a Workshop of representatives of interested parties on 2024-02-14, the constitution of which was supported by CEN following the public call for participation made on 2023-07-31. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

The final text of CWA 18107-1:2024 was provided to CEN for publication on 2024-04-24.

Results incorporated in this CWA received funding from the European Union´s HORIZON 2020 research and innovation programme under grant agreement number 952908.

The following organizations and individuals developed and approved this CEN Workshop Agreement:

— Sergio Jiménez (Chair) — Centro Internacional de Métodos Numéricos en la Ingeniería (CIMNE)

— Lucia G. Barbu — Centro Internacional de Métodos Numéricos en la Ingeniería (CIMNE)

— Alejandro Cornejo — Centro Internacional de Métodos Numéricos en la Ingeniería (CIMNE)

— Luis Antonio Gonçalves — Centro Internacional de Métodos Numéricos en la Ingeniería (CIMNE)

— Barbara Alcayde — Centro Internacional de Métodos Numéricos en la Ingeniería (CIMNE)

— Alireza T. Fard — Centro Internacional de Métodos Numéricos en la Ingeniería (CIMNE)

— Sergi Pareda — Fundació Eurecat (EURECAT)

— David Frómeta— Fundació Eurecat (EURECAT)

— Gustaf Gustafsson — Gestamp Hardtech AB

— Peter Bailey — Instron Division of ITW Limited (INSTRON)

— Magdalena Junitkka — Research Institutes of Sweden (RISE)

Attention is drawn to the possibility that some elements of this document may be subject to patent rights. CEN-CENELEC policy on patent rights is described in CEN-CENELEC Guide 8 “Guidelines for Implementation of the Common IPR Policy on Patent”. CEN shall not be held responsible for identifying any or all such patent rights.

Although the Workshop parties have made every effort to ensure the reliability and accuracy of technical and non-technical descriptions, the Workshop is not able to guarantee, explicitly or implicitly, the correctness of this document. Anyone who applies this CEN Workshop Agreement shall be aware that neither the Workshop, nor CEN, can be held liable for damages or losses of any kind whatsoever. The use of this CEN Workshop Agreement does not relieve users of their responsibility for their own actions, and they apply this document at their own risk. The CEN Workshop Agreement should not be construed as legal advice authoritatively endorsed by CEN.

Introduction

Fast fatigue characterization methods are required to optimize the fatigue design of the components. Having accurate fast fatigue characterization becomes a key point to include a maximum information on fatigue properties of the grades, including process parameters.

In this document is presented one advanced fast fatigue characterization method. The objective is to obtain accurate prediction of the fatigue properties of materials in a very limited time, to shorten the time generally dedicated to standard fatigue characterization.

The method is based on the principle of measuring evolution of material properties under cyclic loadings of increasing stress amplitudes. It is called self-heating measurements and is based on the temperature evolution of a specimen which is representative to the progressive appearance of microplasticity leading to failure by fatigue. It has initially been developed for steels but has been applied on a wide range of materials [2] [3] [5] [6] [7] [9] [10].

The estimated endurance limit or fatigue limit and high cycle fatigue curve (S-N curve) obtained through the self-heating method align excellently with values derived from standardised tests. This document describes the experimental procedure and the limitations of the proposed approach.

1 Scope

This document provides a fast fatigue characterization method to obtain accurate prediction of the fatigue properties of materials in a very limited time. The method is based on the temperature evolution of a specimen which is representative to the progressive appearance of microplasticity leading to failure by fatigue. The document provides the guidelines for specimen preparation, testing and data post-processing as well as the limitations of the method.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1099:2017, *Metallic materials — Fatigue testing — Axial force-controlled method*

ISO/TS 21913:2022, *Temperature verification method applied to dynamic fatigue testing*

3 Symbols and abbreviations

3.1 Symbols

α	Intensity of the primary regime
δ	Intensity of the secondary regime
A	Parameter of the Stromeyer model
m	Weibull’s modulus
N	Number of active sites
P_F	Probability of failure
θ^{0D}	Mean temperature elevation
$\overline{\theta}^{0D}$	Mean steady-state temperature elevation
Σ_{∞}^{AE}	Mean endurance limit
Σ_0	Stress amplitude
S_0	Scale parameter
Σ_{max}	Maximum stress
$T_{lower\ grip}$	Temperature of the lower grip
$T_{specimen}$	Temperature registered of the specimen
$T_{upper\ grip}$	Temperature of the upper grip
V	Volume
V_0	Volume of one the site

3.2 Abbreviations

EDM	Electro-Discharge Machining
PPP	Point Poisson Process
PSB	Persistent Slip Bands
REV	Representative Elementary Volume
S-N-P curves	Amplitude stress-number of cycles to failure-probability of failure

4 General

The use of self-heating measurements allows a prediction of S-N-P curves to be done in about less than two days. 2 or 3 self-heating tests can be done to ensure the repeatability of the thermal response under cyclic loading.

Low quantity of material is needed according to the number of tests and the geometry of the specimens.

A two scales probabilistic model with two dissipative mechanisms, describing a progressive appearance of microplasticity at the origin of fatigue phenomena is proposed. With these tests and the model, several parameters are identified:

— The mean endurance limit.

— The values of α and δ, giving information about the intensity of the primary and the secondary self-heating regimes.

— The Weibull's modulus m, relating to the population of active sites in the model, and being the only parameter dedicated to the standard deviation.

With the addition of some fatigue test on standard fatigue specimens at a low number of cycles (high stress amplitude, i.e., ~100 000 cycles), the median curve of the fatigue behaviour can be identified, depending on a Stromeyer model.

5 Self-heating measurements

Self-heating measurements are based on the evolution of the temperature of a specimen under cyclic loading. This temperature elevation is caused by the mechanisms at the origin of fatigue phenomena. This method allows thus to predict the fatigue properties through this temperature evolution in a very limited time (several hours in comparison with almost one month with conventional fatigue tests).

At the origin, Stromeyer [1] used self-heating measurements (thanks to a differential temperature measuring device) to estimate the fatigue limit of a material under rotative bending. Over the years, the method has evolved, numerous materials have been tested (steels, aluminium, rubbers or composites [2] [3] [5] [6] [7] [9] [10]) and the evolution of measurement devices such as infrared cameras has open new perspectives.

In parallel, some models have been developed to account for thermal dissipation under cyclic loading with the objective to predict the fatigue properties of tested materials. A two scales probabilistic model [4] [10], developed for steels and using two dissipative phenomena, is used to this purpose.

In this section is first presented the self-heating procedure, including the geometry of the specimens and the testing device. In a second part, the two scales probabilistic model is exposed, initially developed to account for the fatigue behaviour of steel grades. In a third part, the way to identify the model's parameters is showed.

Regarding specifications for testing control, equipment or measurements consideration should be given to ISO 1099 when applicable. Additionally, when applicable, consideration should be given to ISO/TS 21913 on verification of temperature measurement systems for fatigue testing.

5.1 Self-heating procedure

In this section are presented the different necessary ingredients to be used to perform self-heating tests.

5.1.1 Geometry of the specimen

For metallic materials (sheets), the shape of the specimen is generally a strip of 10 mm width, 120 mm length and the thickness of the sheet (Figure 1). In fact, having a constant section is pertinent to consider a mean temperature of the specimen. Any geometry can be chosen but must be coherent with:

— A uniaxial stress field.

— A microstructure fine enough so that the volume can be considered as a Representative Elementary Volume (REV).

— No residual stresses induced by the machining of the specimens. For metallic materials, Electro-Discharge Machining (EDM) is used.

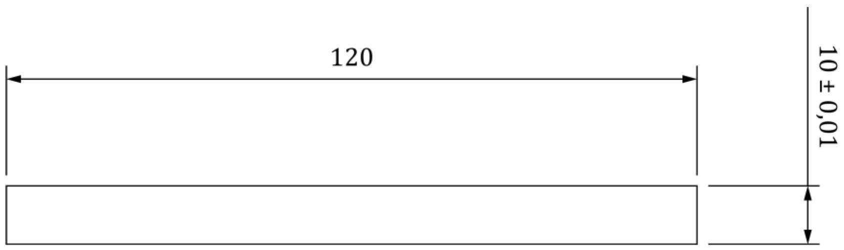

Figure 1 — Geometry of the specimen used for self-heating measurements. Dimensions are expressed in millimetres

The useful area is of about 40 mm length, the rest being inside the grips.

The tests are performed at the load ratio R = -1, which implies a compressive load. Due to the length of the specimen, buckling can occur during the test for the lowest thicknesses. An anti-buckling device, based on the one used for axial stress-controlled fatigue tests shown in ISO 1099, is used (Figure 2). It consists in 2 Aluminium reinforcement and Teflon sheets of 0,5 mm to limit friction between the specimen and the reinforcements.

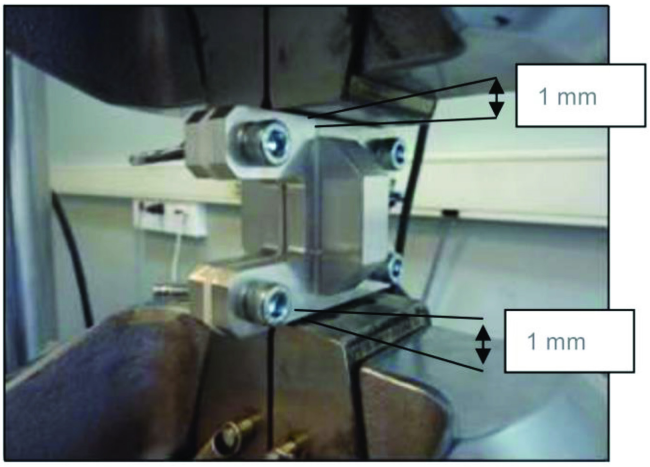

Figure 2 — Use of an anti-buckling device at R = -1

5.1.2 Temperature measurement

To account for the temperature evolution of the specimen under cyclic loading, simple thermocouples are sufficient as a mean temperature of the specimen is required. It can be attached to the specimen as shown in the Figure 3. The temperature registered for the specimen is denoted $T_{specimen}$.

Figure 3 — Thermocouple fixed at the center of the specimen

To account for the loss by conduction and by the environment, it is also necessary to fix thermocouples on each grip as shown in the Figure 4. The temperature measured on each grip is denoted T_{lower_grip} and T_{upper_grip}.

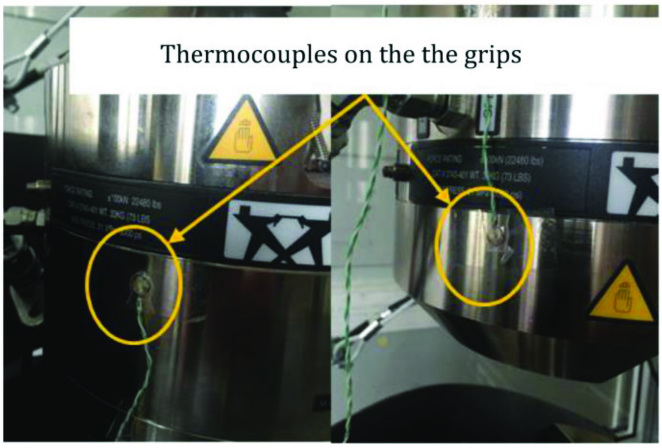

Figure 4 — Thermocouples fixed on the hydraulic grips

In the end, the temperature elevation of the specimen is denoted θ[0D] and is given by:

$$\theta = T_{specimen} - \frac{T_{lower\ grip} + T_{upper\ grip}}{2} \tag{1}$$

Temperature measurements must be performed at a frequency of 1 or 2 Hz which is the specific response time for the thermocouples.

A thermal insulation must be placed around the grips during the tests to limit disturbance of the environment (Figure 5).

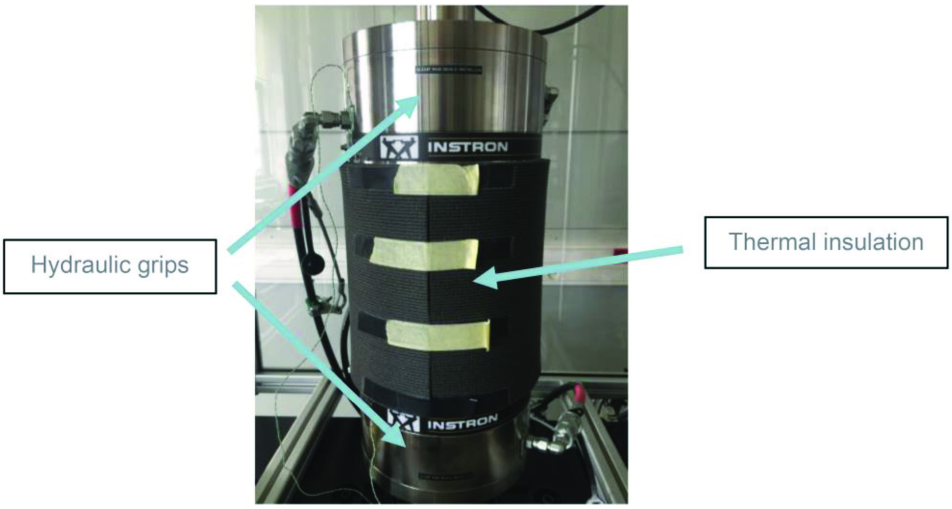

Figure 5 — Thermal insulation to avoid environmental disturbances

5.1.3 Testing protocol

The methodology employs identical loading conditions of the ISO 1099, encompassing, loading mode, control mode, frequency, waveform, stress ratio (R = -1), and gripping system. Under cyclic loading at a given stress amplitude, the temperature θ evolves to generally reach a stabilized value (6000 cycles are sufficient in metallic materials) as shown in the Figure 6. This steady-state temperature is determined for the stress amplitude of the tests. It is denoted $\overline{\theta}^{0D}$. Then, there is a return at thermal equilibrium without any loading during an equivalent time to the one for the cyclic loading.

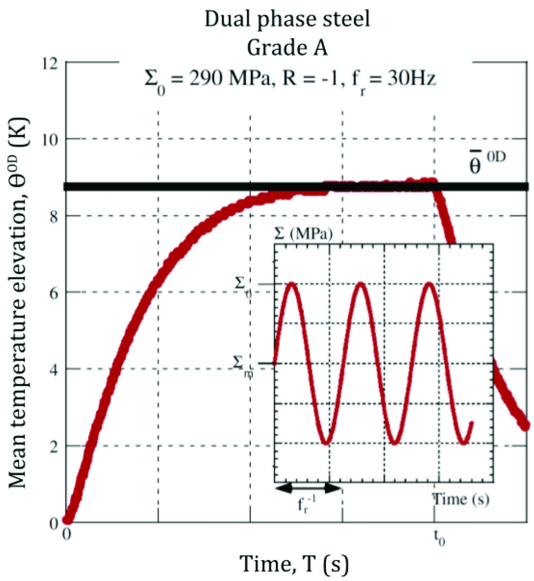

Figure 6 — Example of the evolution of the mean temperature during a loading for 6000 cycles at a given stress amplitude for a dual phase steel

For a complete self-heating test, successive series of cyclic loading with increasing stress amplitudes of 10 MPa between each successive block must be applied to the specimen. They are composed by an alternance of cyclic loadings and returns at thermal equilibrium (Figure 7).

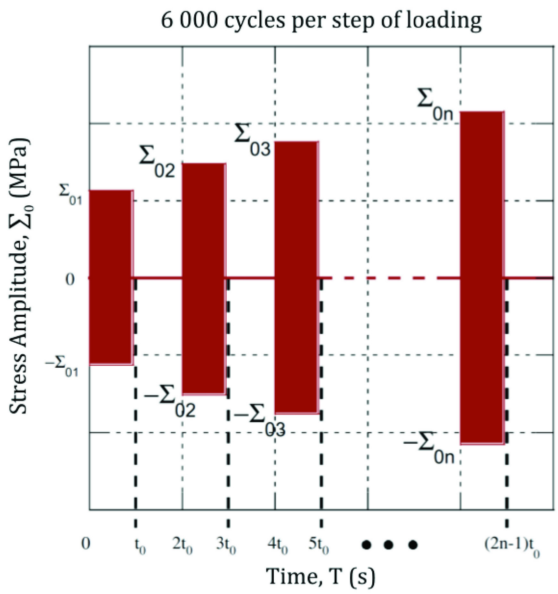

Figure 7 — Successive series of cyclic loading with increasing stress amplitude

Once the test is done, the evolution of the temperature θ can be plotted for each series, as shown in the Figure 8. There is an increase of the temperature in accordance with the increase in stress amplitude.

The test is generally stopped when the temperature is no more stabilized after 6000 cycles, or if the temperature increase is higher than 10 °C.

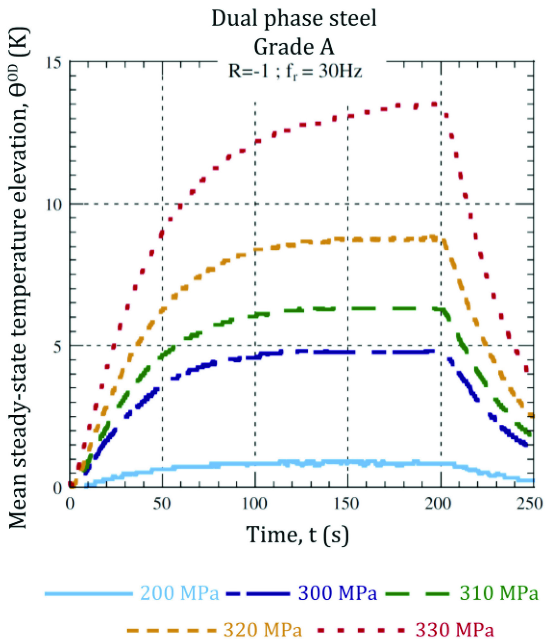

Figure 8 — Example of the evolution of the mean temperature for each series of cyclic loading for a dual phase steel

For each series, the mean steady-state temperature elevation can be determined according to Figure 6. A self-heating curve representing the mean steady state temperature elevation relating to the stress amplitude can be plotted (Figure 9).

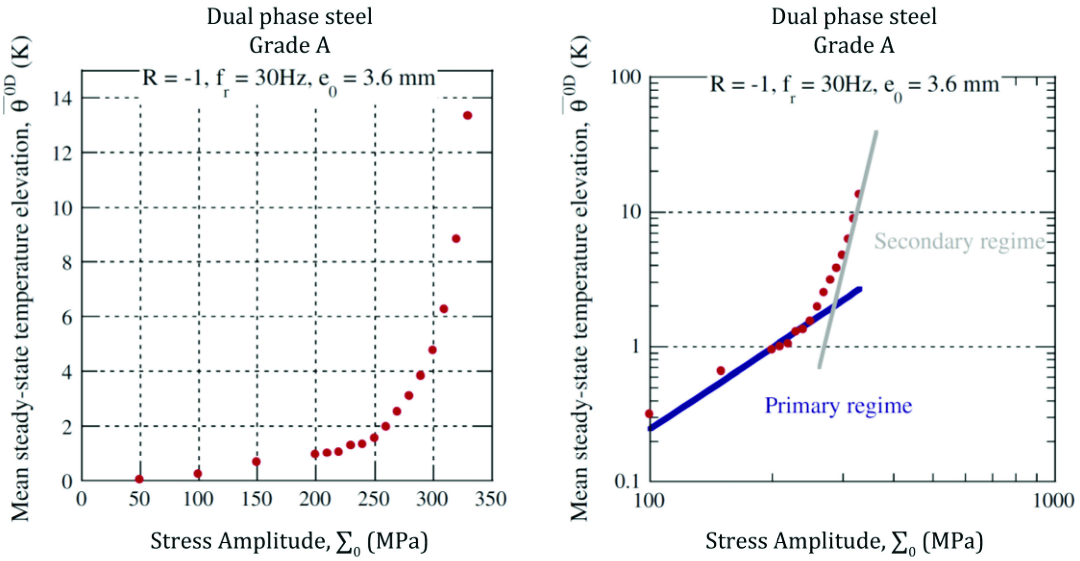

Figure 9 — Example of a self-heating curve and presence of two dissipative regimes for a dual phase steel (log-log scales for the graph at the right)

Even for low stress amplitudes, there is a non-negligible temperature evolution. Then, at about 250 MPa (example of the Figure 9), there is a more significant temperature increase. It can be put in obvious in a log-log diagram as seen in the right graph of the Figure 9. Two dissipative regimes exist, the first one being present for the lowest stress amplitudes while a second appears with the increase in stress amplitude.

For each steel grade, it has been systematically observed that the primary regime has a slope of 2 in a log-log diagram.

5.2 Determination of the mean endurance limit

Different levels of post-processing can be done with the self-heating curve. The first and the easiest consists in an empirical approach. The intersection between the asymptotic line to the end of the self-heating curve and the abscissa axis can be considered as the mean endurance limit usually defined in the range of 10^6 cycles [10]. The result is shown in the Figure 10.

The ability of this strategy to be a good estimator of the mean endurance limit has been demonstrated over the years [10] [3] [7].

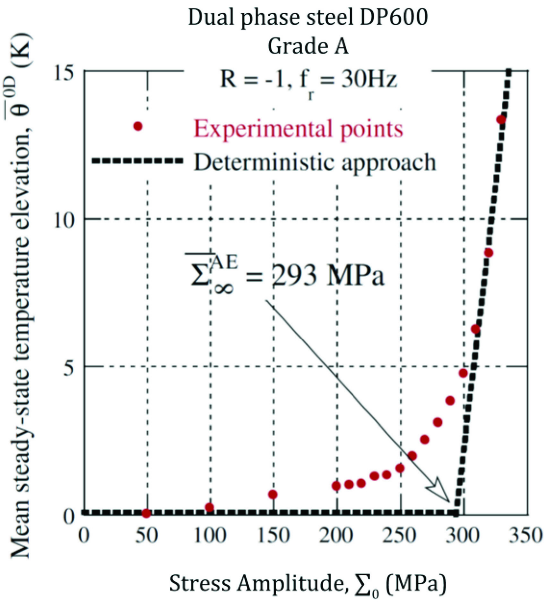

Figure 10 — Example of the determination of the mean endurance limit using an empirical approach

5.3 Two scales probabilistic model

A second level for the post-processing of the self-heating curve consists, for steels, in considering a two scales probabilistic model. The objective of this model is to account for microplasticity in steels leading to the emergence of Persistent Slip Bands (PSB) and crack initiation at the surface of the metal.

To achieve that goal, an elasto-plastic behaviour of the matrix is considered. Even below the macroscopic yield stress, some microplastic activity can be observed [11]. This behaviour accounts for the first dissipative regime observed during self-heating tests.

After a given macroscopic stress amplitude, elasto-plastic inclusions start to activate and to dissipate more energy. The activation of these inclusions follows a Point Poisson Process (PPP) [4]. This behaviour is the one which accounts for the secondary regime observe during self-heating tests and describes the progressive emergence of PSB [8] [11]. The number of active sites in the volume V is thus given by

$$N(\Omega) = \frac{1}{V_0}\left(\frac{\Sigma_0}{S_0}\right)^m \times V \qquad (2)$$

With V_0 the volume of the site, S_0 the scale parameter of the Weibull's model and m the Weibull's modulus.

The two contributions of this model are explained in the Figure 11.

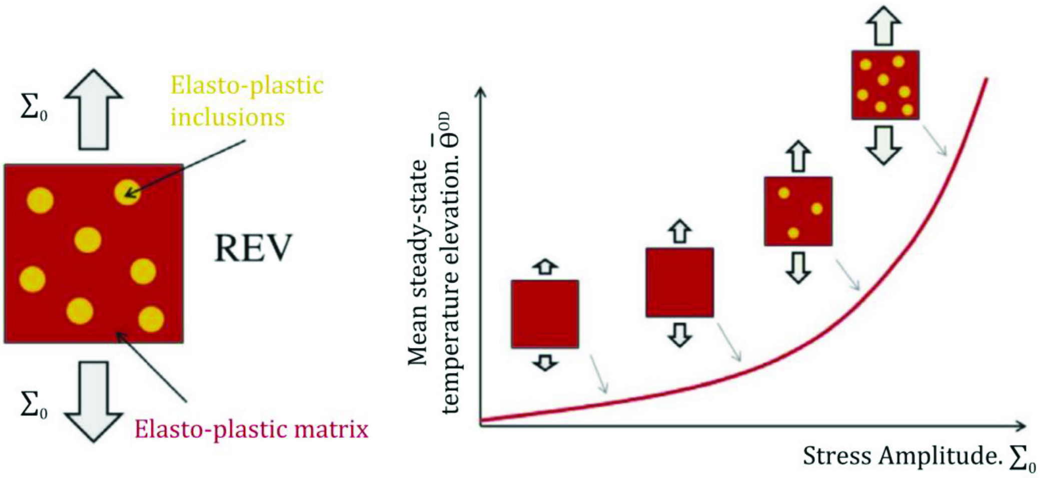

Figure 11 — Principle for the two scales probabilistic model

5.4 Identification of the model parameters

According to the two scales probabilistic model with two dissipative phenomena, the mean steady-state temperature elevation can be expressed as

$$\bar{\theta} = \alpha \times \left(\frac{\Sigma_0}{\Sigma_{max}}\right)^2 + \delta \times \left(\frac{\Sigma_0}{\Sigma_{max}}\right)^{m+2} \qquad (3)$$

With α and δ being respectively the intensity of the primary and the secondary regime. The slope of the primary regime follows a power 2 of the stress amplitude, as observed experimentally and the slope for the secondary regime is equal to m+2 in a log-log diagram.

The 3 parameters (α, δ and m) can thus be identified on the self-heating curve. The comparison between the model and the experimental self-heating curve is provided in the Figure 12. A good agreement is obtained for both dissipative regimes.

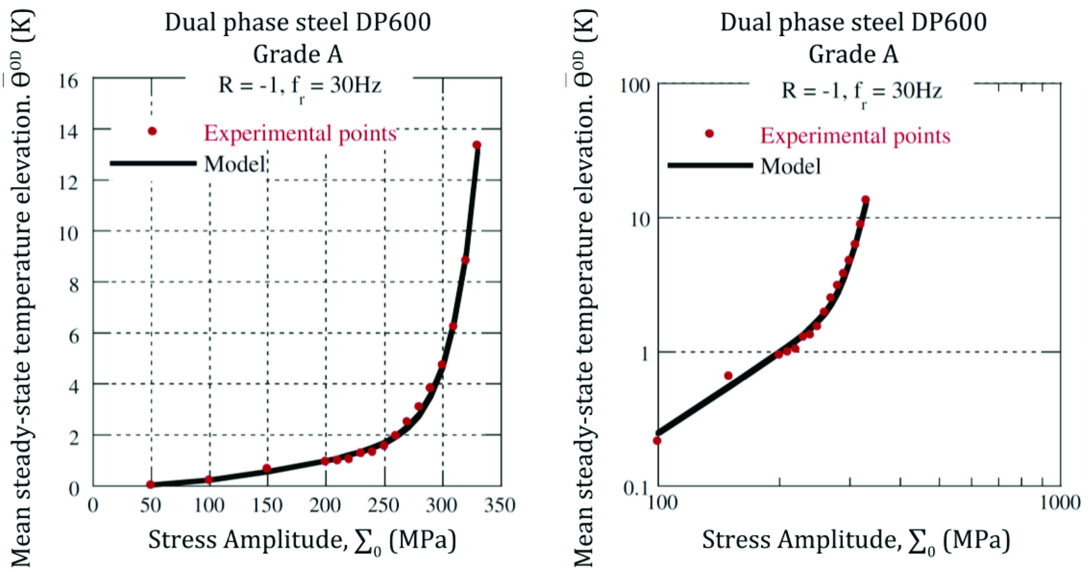

Figure 12 — Example of the identification of the model's parameters on the self-heating curve for a dual phase steel

5.5 Building of an S-N-P curve

At this stage, we have:

— The mean endurance limit (4.2).

— The parameters of the two scales probabilistic model (α, δ and m) (4.4).

To build S-N-P curves, several fatigue specimens are tested up to failure at a high stress amplitude, generally the one used at the last series of cyclic loading performed for the self-heating tests. The failure is generally obtained after about 100 000 cycles (which represents about less than one day of tests).

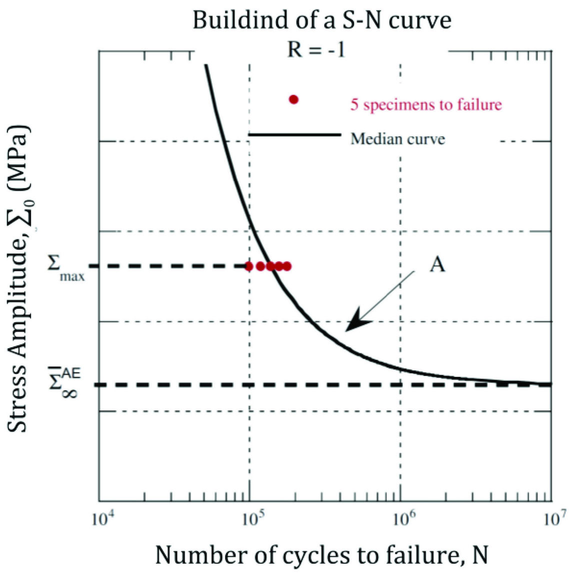

Figure 13 — Construction of the median S-N curve with the use of the mean endurance limit and several fatigue specimens to failure

With the two scales probabilistic model, by using also the weakest link theory (if one site becomes active, after a given time, the specimen will fail) and an energetic criterion, the following equation can be obtained:

$$N = \frac{A}{\Sigma_0 - \Sigma_\infty^{AE}} \quad (4)$$

It is the expression of the Stromeyer model used for standard fatigue tests. With several fatigue points to failure, the value of A can be identified.

With the two scales probabilistic model and the use of a critical dissipated energy, a given probability of failure (P_F) can be written only with a dependency to the fatigue limit obtained from self-heating measurements (giving the fatigue limit for a probability of failure of 50%) and m as follows:

$$\frac{\ln(1 - P_F)}{\ln(1 - 0{,}5)} = \left(\frac{\Sigma_\infty(P_F)}{\Sigma_\infty^{AE}} \right) \quad (5)$$

It can thus be observed that the parameter m, determined from self-heating measurements accounts for the standard deviation in fatigue. According to the values of m, if it is high, the transition between the two dissipative mechanisms is abrupt and account for a quasi-deterministic model. The standard deviation in fatigue will be low. On the contrary, a low value of m will describe a smooth transition between both regimes and account for a higher standard deviation in fatigue.

With these assumptions, the mean endurance limit for the probabilities of failure at 10 and 90% can be obtained, which authorizes to plot the iso-probabilities of failure one the S-N curve (with the same value of A than the median curve), giving S-N-P curves (Figure 14).

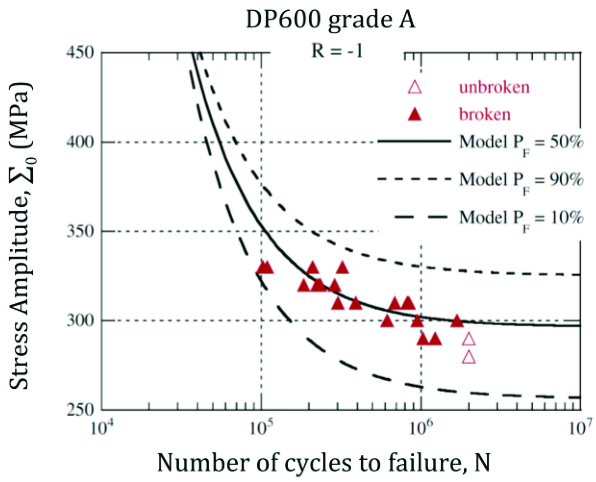

Figure 14 — Example of the construction of complete S-N-P curves from self-heating parameters for a dual phase steel

Bibliography

[1] STROMEYER C.E. The determination of fatigue limits under alternating stress conditions. *Proc. R. Soc. Lond.* 1914, **A90** pp. 411–425

[2] PEYRAC C., JOLLIVET T., LERAY N., LEFEBVRE F., WESTPHAL O., GORNET L. Self-Heating Method for Fatigue Limit Determination on Thermoplastic Composites. *Procedia Eng.* 2015, **133** pp. 129–135

[3] LA ROSA G., RISITANO A. Thermographic methodology for rapid determination of the fatigue limit of materials and mechanical components. *Int. J. Fatigue*. 2000, **22** pp. 65–73

[4] DOUDARD C., CALLOCH S., HILD F., CUGY P., GALTIER A. A probabilistic two-scale model for high cycle fatigue life predictions. *Fatigue Fract. Eng. Mater. Struct.* 2005, (3) pp. 279–288

[5] EZANNO A., DOUDARD C., CALLOCH S., HEUZÉ J.L. A new approach to characterizing and modeling the high cycle fatigue properties of cast materials based on selfheating measurements under cyclic loadings. *Int. J. Fatigue*. 2013, **47** pp. 232–243

[6] JEGOU L., MARCO Y., LE SAUX V., CALLOCH S. Fast prediction of the Wöhler curve from heat build-up measurements on Short Fiber Reinforced Plastic. *Int. J. Fatigue*. 2013, **47** pp. 259–267

[7] LE SAUX V., MARCO Y., CALLOCH S., DOUDARD C., CHARRIER P. Fast evaluation of the fatigue lifetime of rubber-like materials based on a heat build-up protocol and micro-tomography measurements. *Int. J. Fatigue*. 2013, (10) pp. 1582–1590

[8] CUGY P., GALTIER A. Microplasticity and temperature increase in low carbonsteel. In: Proceedings of the 8th international fatigue conference, vol. 1, Stockholm (Suède); 2002

[9] MAREAU C., FAVIER V., WEBER B., GALTIER A., BERVEILLER M. Micromechanical modeling of the interactions between the microstructure and the dissipative deformation mechanisms in steels under cyclic loading. *Int. J. Plast.* 2012, **32-33** pp. 106–120

[10] MUNIER R., DOUDARD C., CALLOCH S., WEBER B. Determination of high cycle fatigue properties of a wide range of steel sheet grades from self-heating measurements. *Int. J. Fatigue*. 2014, **63** pp. 46–61

[11] MUNIER R., DOUDARD C., CALLOCH S., WEBER B. Identification of the micro-plasticity mechanisms at the origin of self-heating under cyclic loading with low stress amplitude. *Int. J. Fatigue*. 2017, **103** pp. 122–135

[12] CHABOCHE J.L. Continuum damage mechanics: Part I-general concepts. *J. Appl. Mech. Trans. ASME.* 1988, **55** pp. 59–64. DOI:10.1115/1.3173661

[13] MURAKAMI S. *Continuum Damage Mechanics: A Continuum Mechanics Approach to the Analysis of Damage and Fracture*. Springer Netherlands, 2012., 10.1007/978-94-007-2666-6

[14] LEMAITRE J., DESMORAT R. *Engineering damage mechanics: Ductile, creep, fatigue and brittle failures, Eng*. Damage Mech. Ductile, Creep, Fatigue Brittle Fail, 2005, pp. 1–380., 10.1007/B138882

[15] PARAREDA S., CASELLAS D., FRÓMETA D., GARCIA-LLAMAS E., LARA A., PUJANTE J. et al. Effect of heat treatment conditions on the fatigue resistance of press hardened 22MnB5 steel evaluated through rapid testing technique, IOP Conf. Ser. Mater. Sci. Eng. 1157 (2021) 012014. https://doi.org/10.1088/1757-899X/1157/1/012014