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Fast Fatigue Properties Identification by “Self-Heating” Method: Application To Automotive Welded Joints

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Abstract

The welded assemblies’ high cycle fatigue properties identification for the automotive industry is a long and expensive process which has to be very efficient to perform both safety and lean design. Fatigue properties determination is a time and cost consuming process, it requires several days and specimens to be performed. The self-heating method offers the possibility to dramatically shorten the test duration. It consists in measuring the temperature of the structure under cyclic loading, and then linking it to fatigue properties. Only one specimen and few hours are required for fatigue properties identification providing important cost and time reduction. Thus, an experimental protocol is proposed to measure the rise of temperature of a lap joint welded specimen, with the use of infra-red thermography. Assuming that only self-heating and thermoelastic phenomena are responsible of the temperature evolution, self-heating temperature is extracted from experimental data. A 1D thermal model is proposed to describe the evolution of the temperature of the specimen due to self-heating. The welded joint concentrates dissipative phenomena, which corresponds to a concentrated heat source. This heat source field is then identified by fitting the model to experimental results, and its evolution with the applied loading is used to determine the welded assembly endurance limit. Self-heating method results are proven to be consistent to those obtained by classical fatigue tests.

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Keywords: Fatigue ; Welded Joint ; Steel ; Self-heating ; Thermography

1. Introduction

The determination of welded structures high cycle fatigue (HCF) properties is a prior concern in the automotive industry. Front and rear axles for instance, are seam-welded on an overall length of several meters. Such welded assemblies are expected to be designed as high-safety parts to insure the customer’s safety, but also lean design in order to reduce production costs and lead to fuel efficiency by mass. Hence, these structures properties in fatigue have to be carefully mastered. The determination of welded assemblies’ high cycle fatigue properties is usually based on the determination of mini-structures fatigue properties with classical method, i.e. applying cyclic load to

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the structure until failure or until 2.10^6 cycles [1]. In order to provide a reliable SNP curve (showing the magnitude of a cyclic stress against the number of cycles to failure with the probability of failure associated), this method has to be applied to dozens of specimens, involving:

- Time consumption: important delay are required for 10^6 cycles at 10Hz;
- Money consumption: performing 10^6 cycles costs several thousand Euros, not taking into account the price of the specimens (which usually may be expensive prototype parts).

Consequently, the use of a faster method is a key point for the industry. The self-heating method offers the possibility to dramatically shorten the test duration and the number of specimens required [2, 3, 4]. It consists in taking advantage of the temperature signal caused by intrinsic dissipation and microscopic plasticity responsible for fatigue damage. This method has been proven efficient to characterize steel sheet fatigue properties [5], and associated with a probabilistic model, to recover the full SNP curve with only few specimens and several hours of testing [6, 7]. This method has already been used on welded joint [8, 9], but no thermal model has ever been proposed to extract heat source field and then associate it to fatigue damage as a general framework.

This paper deals with the determination of welded specimen HCF fatigue properties with the self-heating method. At first, the specimen is described and a kinematical test under static load is proposed to identify the stress field of the structure: a reliable thermal model needs for it as the intrinsic dissipation heat source depends on the stress. Then, an experimental protocol is proposed to measure the temperature field of the specimen under cyclic load. This temperature field is analyzed to extract thermoelastic coupling and intrinsic dissipation. Finally, a thermal model is proposed to identify the heat source field and at last, determine fatigue properties.

2. Preliminary study

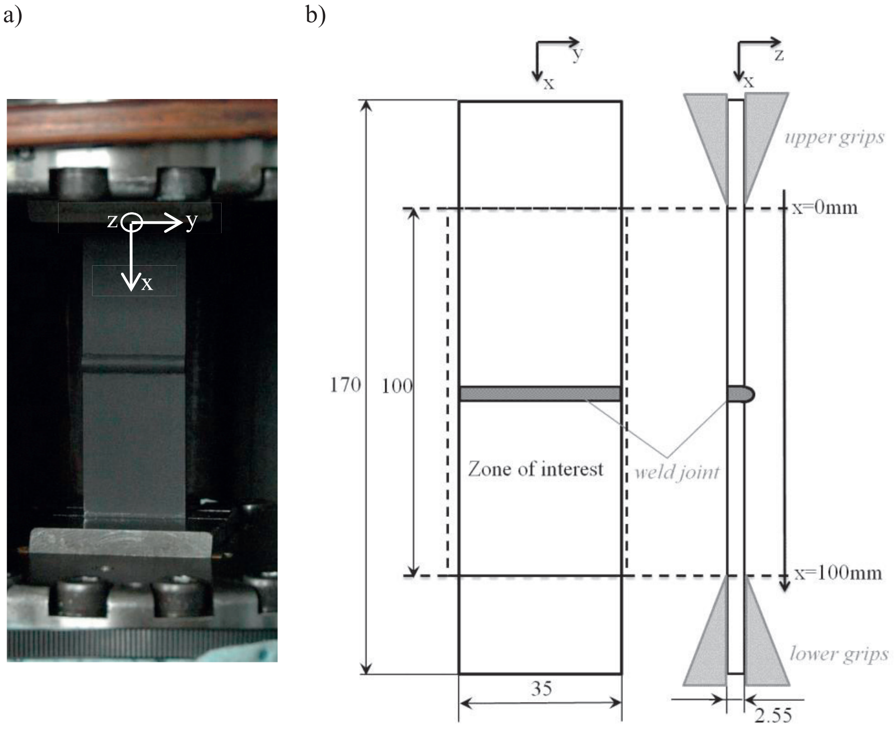

Fig. 1. Specimen (dimensions in mm)

The specimen considered in this paper is a welded joint. The standard Gas Metal Arc Welding (GMAW) process is applied on two steel sheets, 2.55mm thick, positioned one against the other (Fig. 1). The base material is a ferrite-bainite (FB) phase steel provided by ArcelorMittal. Its thermo-mechanical properties are given in Table 1. Specimens are cut with a length of 170mm centered on the welded joint and a width of 35mm. A micrography shows the diminution of the grain size in the heat affected zone and a coarse-grained structure in the joint, as usual for welded joints (Fig. 2).

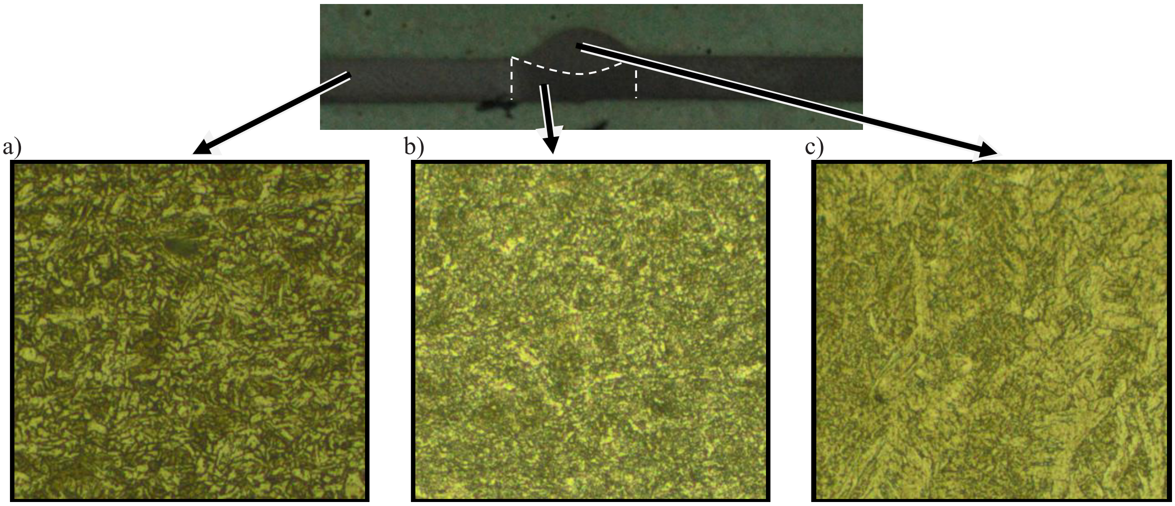

Fig. 2. Specimen micrography (x50): a) basic material; b) heat affected zone; c) welded joint

In order to identify the stress field under loading, tensile static test is applied to the specimen using a standard servo-hydraulic testing machine (Tema Concept TTC). During this test, the displacement of the specimen is measured by Stereo Digital Image Correlation (SDIC), a GOM mbH Aramis system composed of two cameras. The longitudinal x-displacement and the out of plane z-displacement being constant along the width of the specimen (y), a spacial average on y coordinate enables us to minimize the measurement noise. As shown in Fig. 3, the longitudinal x-displacement is linear along the specimen. Moreover, the out-of-plane z-displacement is negligible. Thus, we assume that the local strain field correspond to pure tension, despite of the welded joint. Beam theory leads us to a relation between the longitudinal x-displacement, Ux(x), and the macroscopic load

$$\frac{dU_x(x)}{dx} = \frac{1}{E}\frac{F}{S}, \tag{1}$$

E being the Young modulus [GPa], F the macroscopic load applied [N] and S [m²] the section of the specimen. Integration of Equation (1) leads to the x-displacement in Fig. 3. This Figure shows a good correlation between the model and experimental results, proving the hypotheses of pure tension. Thus, the stress field is given by

$$\sigma_{xx} = \frac{F}{S}. \tag{2}$$

The mechanical field being modeled, thermal test and analysis can be performed to recover the specimen fatigue properties.

Table 1. Thermo-mechanical properties of the hot-rolled FB540 steel: Young modulus, E ; Poisson coefficient, ν ; mass density, ρ ; specific heat capacity, C ; isotropic thermal conductivity, k ; yield strength, σ_y ; ultimate tensile strength, Rm ; elongation after fracture, EL.

E [GPa]	ν [-]	ρ [kg.m^{-3}]	C [J.kg-1K-1]	k [W.m-1.K-1]	σ_y [MPa]	Rm [MPa]	EL [%]
210	0.3	7800	446	47	400 - 485	540 - 610	≥18

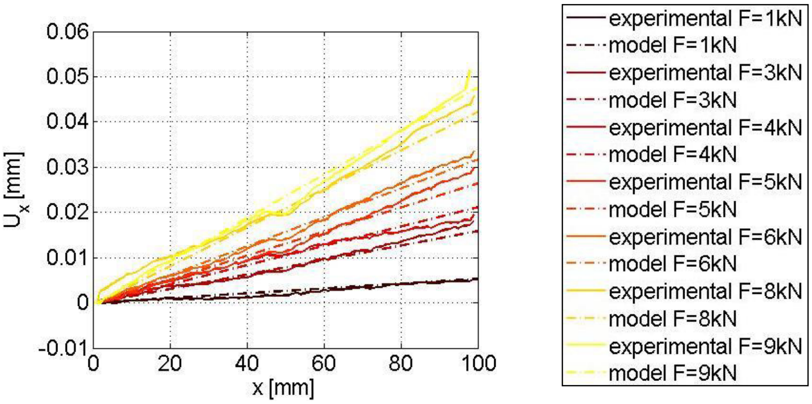

Fig. 3. Ux longitudinal displacement from F=1kN (darker color) up to 9kN (lighter color)

3. Thermal test protocol

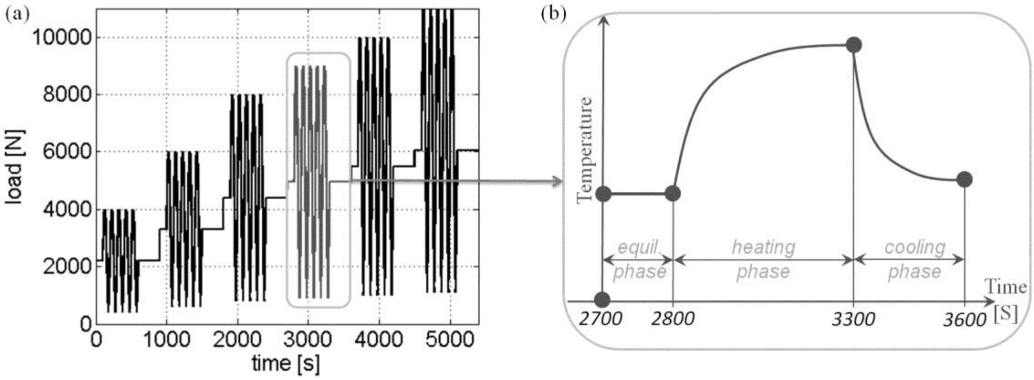

Fig. 4. (a) overall loading procedure; (b) single load level procedure

A self-heating test is now performed on the specimen. A standard self heating test consists in applying successive series of cyclic loading with constant amplitude within a series, and increasing between each series (Fig. 4). In this case, a macroscopic tensile load is applied to the specimen with the testing machine used in the previous section with a loading ratio R=0.1,

$$R = \frac{F_{\min}}{F_{\max}}, \tag{3}$$

$F_{\min}$ and $F_{\max}$ being respectively the minimal and the maximal loads applied during each series, and a loading frequency of f_{load}=30.02Hz. During all experiments, the surface temperature of the specimen is recorded with an infrared camera (Flir Systems SC700), with a matrix resolution of 640 x 512 pixels, and a recording frequency of f_{rec}=1Hz. Thus, the thermoelastic coupling is expected to be highlighted with a stroboscopic frequency of 0.02Hz.

Each loading series is divided into three phases (Fig. 4): a *waiting phase* of 100s where the average static load is applied in order to record the basic temperature of the specimen, a *heating phase* of 500s where the cyclic load is applied, 500s being sufficient to reach the self-heating steady-state temperature, and finally a *cooling phase* of 300s where the average static load is recovered.

The maximal increase in temperature being low (only several hundreds of millikelvin degrees), experimental devices are used to reduce environment perturbations, such as a closed loop water system around the grips and a dark thick clothes around the testing area.

Each series leads to a two dimension field containing 900 pictures, one every seconds.

4. Analysis

The region of interest of the specimen, as shown in Fig. 1.b, is selected for each recorded frame. Then, considering that the temperature is constant over the width of the specimen (y direction), a y-average is performed for each frame, leading to the one dimension evolution of temperature along the specimen (in the x direction) over time (Fig. 5.a).

During the first hundred seconds, the temperature is supposed to remain constant, only the average static load being applied: thus, a time average let us determine the basic temperature of the specimen, which is withdrawn from the data to get only the elevation of temperature caused by thermoelastic-coupling and intrinsic dissipation. During the next 500 seconds, as the thermoelastic coupling has been highlighted by stroboscopic effect, it is easily extracted and then withdrawn from experimental data leading to a temperature field only linked to intrinsic dissipation (Fig. 5.b).

Then, the “self-heating temperature” being extracted, the heat source associated to this evolution of temperature has to be identified, which require the use of a thermal model.

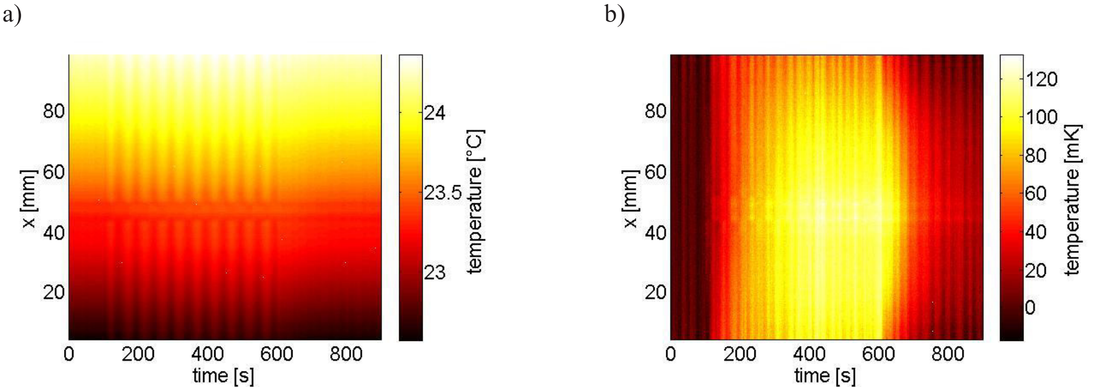

Fig. 5. (a) 1D specimen temperature over time; (b) specimen "self-heating temperature"

5. Thermal model

Due to the geometry of the specimen, and to remain consistent with the preliminary study and the experimental analysis, a one dimension model is proposed. The specimen is modeled with a simple beam of 100mm long. As the experimental temperature stabilizes after few hundred seconds for each load case, a constant heat source is assumed. Moreover, away from the welded joint, the stress is much lower than the fatigue limit of the steel used; for the maximum load case, i.e. F_{max}=13kN, the maximum stress experienced by the specimen is σ_{xx}=145MPa, much lower than the fatigue strength of the base material σ_f=400MPa. Thus, in that part of the specimen, as shown by [10], the heat source is assumed proportional to the square of the stress amplitude

$$S_{primary} = \alpha \int_S \sigma_{xx}{}^2(x)dS, \tag{4}$$

with α a material parameter to be identified. Finally, in order to take into account the dissipation of the welded joint, a concentrated heat source, C_{conc} [K/s] is assumed around the latter, leading to the heat source described in Fig. 6.

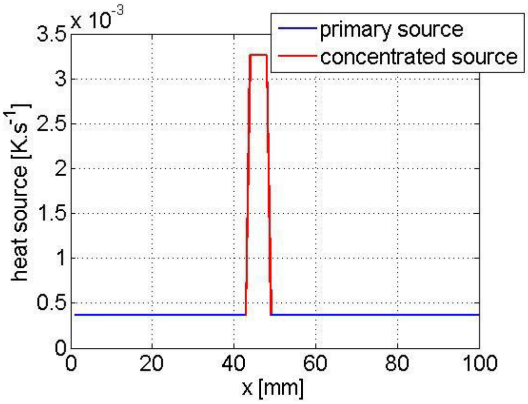

Fig. 6. Model heat source

The usual one dimension heat conduction equation [11, 12] is applied to the specimen

$$\dot{\theta}(x,t) + \frac{\lambda}{\rho C}\frac{\partial^2\theta(x,t)}{\partial x^2} + \frac{\theta(x,t)}{\tau_{eq}} = S_{heat}, \tag{5}$$

where θ(x,t) [K] is the 1D temperature elevation field, λ [W/m.K] the thermal conduction and C [J/kg.K] the specific thermal capacity, τ_{eq} [s] denotes an equivalent time scale resuming the thermal influence of natural convection around the welded joint and S_{heat} [K/s] is the heat source described previously. At extremities, Robin boundary conditions are assumed

$$\frac{\partial\theta(0,t)}{\partial x} = \frac{h_{upper}}{\lambda}\theta(0,t) \quad \& \quad \frac{\partial\theta(100,t)}{\partial x} = \frac{h_{lower}}{\lambda}\theta(100,t), \tag{6}$$

where h_{upper} and h_{lower} are two coefficients which represent the heat exchanges with the upper and the lower grips of the testing machine, respectively. These coefficients are identified by measuring the temperature and its gradient at both extremities (Fig. 7). They are proportional to the slope of the linear regression achieved in Fig. 7, leading to h_{upper}=300$\mathrm{Wm^{-2}K^{-1}}$ and h_{lower}=800$\mathrm{Wm^{-2}K^{-1}}$. The difference between these coefficients explains the lack of symmetry of the steady-state temperatures (Fig. 8). Then, the model is applied and heat source parameters (α and C_{conc}) are identified with respect to experimental steady-state temperatures. α is supposed to be constant for all load cases and thus is identified only once, e.g. on the first load case whereas C_{conc} is expected to vary for each load case, leading to the evolution of the joint concentrated heat source versus the maximal load in Fig. 9.a. As shown in this figure, the heat source increases slightly up to 9kN, and a significant change in the slope appears after this load cases. The second part of this self-heating curve leads to a fatigue limit of this mini-structure of Fmax=8.5kN, which is consistent with the few results obtained by the classical method (Fig. 9.b).

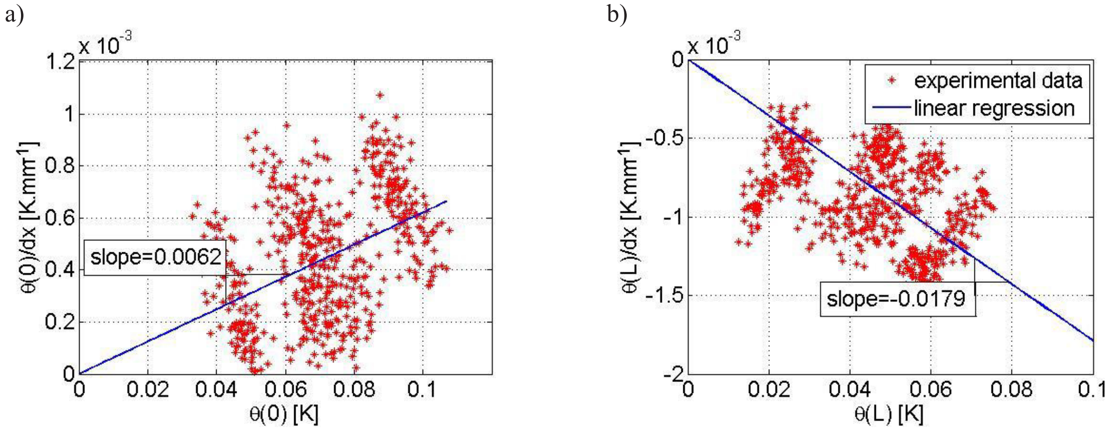

Fig. 7. Boundary condition identification: (a) x=0mm ; (b) x=100mm

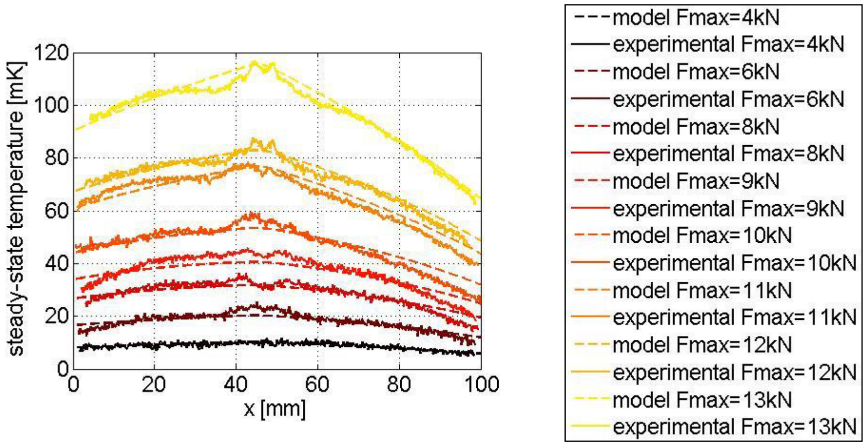

Fig. 8. Steady-state temperature from Fmax=4kN (darker color) up to Fmax=13kN (lighter color)

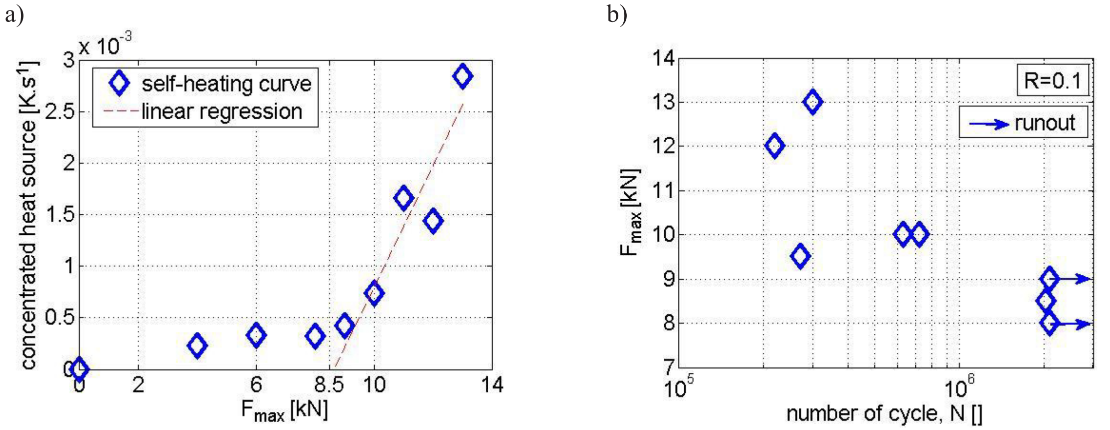

Fig. 9. a) self-heating curve; b) S-N curve (traditional method)

6. Conclusion

In this paper, the self-heating method has been applied to determine a welded joint structure fatigue properties. An experimental protocol and analysis have been proposed to extract the temperature elevation linked to self-heating. Then, a simple one dimensional model is proposed to identify the heat source caused by intrinsic dissipation into the welded joint, leading to a self-heating curve, and then recover the specimen fatigue limit, in accordance with traditional fatigue test results. Thus, this method has been proved efficient for such a structure, and investigation will continue to obtain not only the fatigue limit, but the complete SNP curve thanks to a probabilistic model.

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