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Thermal response of C45 steel in high and very high cycle fatigue

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Abstract

High and very high cycle fatigue regimes are rapidly reached using an ultrasonic fatigue machine working at 20 kHz. For instance, a fatigue test up to 10^9 cycles lasts 14 hours at 20 kHz while it lasts 100 days at 100 Hz. The heating of specimen can reach several tens of degrees at 20 kHz fatigue tests. In this work, the S-N curve and the thermal response under fatigue tests at 20 kHz were investigated on normalized C45 steel. Fatigue tests at 20 kHz demonstrate than fatigue failure exists for number of cycles ranging from 10^6 to 10^{10} cycles. In addition, three stress amplitude domains were identified with regard to the specimen thermal response. These domains were correlated with failure response. For $\frac{\Delta\sigma}{2} < 200\ MPa$, the heating was < 10°C and no fracture was observed at least up to 10^{10} cycles. For $200\ MPa < \frac{\Delta\sigma}{2} < 250\ MPa$, the heating reached few hundreds of degrees. Fatigue fracture took place. The crack initiated at an internal non-metallic inclusion leading to the classical fish eye observed in very high cycle fatigue. For $250\ MPa < \frac{\Delta\sigma}{2}$, the heating reached 800°C and a ductile failure occurred.

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Keywords: Fatigue limit; Ultrasonic fatigue; Conventional fatigue, Self-heating; Ferritic-pearlitic stee; Frequency effect

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1. Introduction

Nowadays there is a growing demand for the development of fast and robust fatigue life prediction methods in the very high cycle fatigue domain. In this way, ultrasonic fatigue technique which appeared in 1950 is very interesting for manufacturers [1]. It allows to conduct tests up to a very high number of cycles in a reasonable time. However, the frequency domain of these fatigue tests facilities, typically 20 kHz, raises the issue of the frequency effects and more generally the validity of the obtained results for estimating fatigue life of structures. The objectives of this work are to investigate the thermal and failure responses of 0.45%C ferritic-pearlitic steel using a 20 kHz ultrasonic fatigue machine. The fatigue limit estimated from these experiments is compared with literature fatigue strengths obtained with conventional methods.

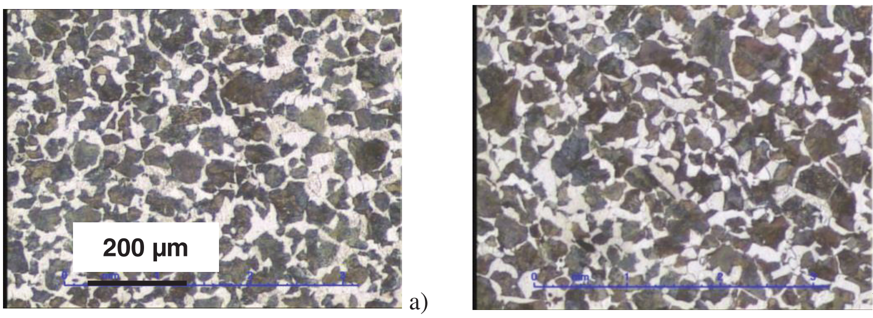
2. Materials and experimental procedures

2.1. Material

The studied material is the 0.45%C steel supplied by TyssenKrupp Materials France industrie. The chemical composition is given in Table 1. Fatigue specimens were extracted from bars. The material was rolled and heat treated via a normalizing heat treatment. The microstructures observed in the longitudinal and transverse cross section of the bar are shown in Fig. 1. The microstructure consists of ferrite (white phase) and pearlite (dark phase). The two phases are randomly distributed despite some bands of ferrite and pearlite are emphasized on the longitudinal cross section micrograph. Image analysis using the ImageJ software revealed that the mass fractions of ferrite and pearlite are 33% and 66%, respectively. These values are not far from the equilibrium values (43% and 57%, respectively). Some carbides were also observed in the microstructure.

Table 1. Chemical composition of the studied 0.45%C steel

C%	Si%	Mn %	P %	S %	Cr %	Ni %	Mo %	Al %	Cu %
0.44	0.25	0.61	0.0162	0.024	0.16	0.04	0.005	0.020	0.03



a) b)

Fig. 1. Optical micrograph of the studied 0.45%C steel – a) longitudinal cross section – b) transverse cross section - the white phase is the ferrite and the dark phase is the pearlite.

The yield strength of the material is $Re_{0.2\%} = 436\ MPa$. The ultimate tensile strength is $Rm = 617\ MPa$ and the ductility $A = 21\%$. Vickers Hardness is about 189 HV_{500g}.

2.2. Fatigue experiments and thermal measurements

To perform experiments up to a very high number of cycles in a reasonable time, ultrasonic equipment at a testing frequency of 20 kHz was used. The ultrasonic device was calibrated with a laser extensometer to obtain the relationship between the displacement amplitude at the horn edge and the input electrical signal. Hour-glass shaped cylindrical specimens were continuously fatigued up to failure at various stress amplitudes to get the S-N curve for a number of cycles higher than 10^6. Failure occurred when a crack had grown large enough to decrease the natural frequency of the system below the standard operating range (19.5–20.5 kHz) leading to a machine stop. After the fatigue test, the specimens were broken in liquid nitrogen for fracture surface examination.

In-situ temperature measurements were carried out using an Infra-Red camera. Temperature maps were recorded on a 6 mm × 9 mm area in the center of the gauge length of the specimens. The frequency acquisition of the camera is 30Hz. The temperature sets are calibrated with three scales: from 10°C to 90°C, from 50°C to 150°C, from 150°C to 350°C. Some experiments were conducted with compressed air to cool the specimen and avoid too much self-heating due to intrinsic dissipation.

Cylindrical hourglass shaped specimens were designed to run in longitudinal vibration resonance with the piezoelectric machine at 20 kHz. Its dimensions are indicated on Fig. 2. The diameter in the center of the cylindrical specimens was 3 mm. After machining, the specimens were mechanically polished. Assuming pure linear elastic behavior, the strain and stress distributions along the specimen were calculated using a one-dimensional approach in forced vibration regime. The strain R ratio defined as $\varepsilon_{\min}/\varepsilon_{\max}$ was -1. In the following, the stress amplitude rather than the strain amplitude is used to define the fatigue test. For all calculations, the Young's modulus was taken equal to 210 GPa.

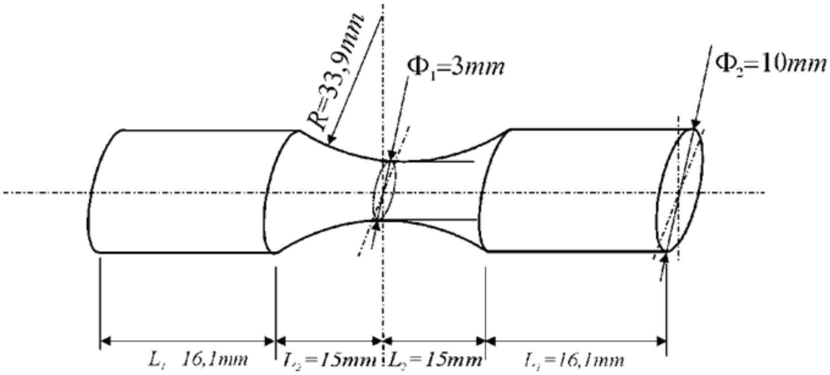


Fig. 2. Ultrasonic fatigue hour glass shaped specimen

4. Results

4.1 Untreated Stress-Number of cycles curve

Figure 3 displays the Stress-Number of cycles (S.N.) curves for 0.45%C steel loaded with and without the cooling system. The fatigue life increases with decreasing stress amplitude. No failure was observed between 2×10^5 and 2×10^8 cycles. The data are quite dispersed. No failure was observed below 259 MPa and after 4×10^9 cycles. Consequently, the fatigue strength in the very high cycle fatigue is estimated to 259 MPa and is called in the following the fatigue limit. The presence of the cooling system does not significantly change the fatigue strength.

Table 2 shows some fatigue strength values at 10^7 cycles from literature. Some of them come from experiments carried out with conventional fatigue machines working at frequencies lower than 200 Hz on normalized steels, the chemical composition and the ultimate tensile strength of which are close to the ones of the 0.45%C steel studied here [2, 3, 4]. The others were determined from models [5, 6]. They are all plotted in Figure 3. Apart from the low value found in [5], the literature values are in good agreement with our results with regard to the high dispersion of the data. However, it is worth noticing that no failure was observed between $2{\times}10^5$ and $2{\times}10^8$ cycles on the contrary to literature results. The fatigue limit is approximately 40 percent of the ultimate tensile strength as for many cast and wrought steels [2].

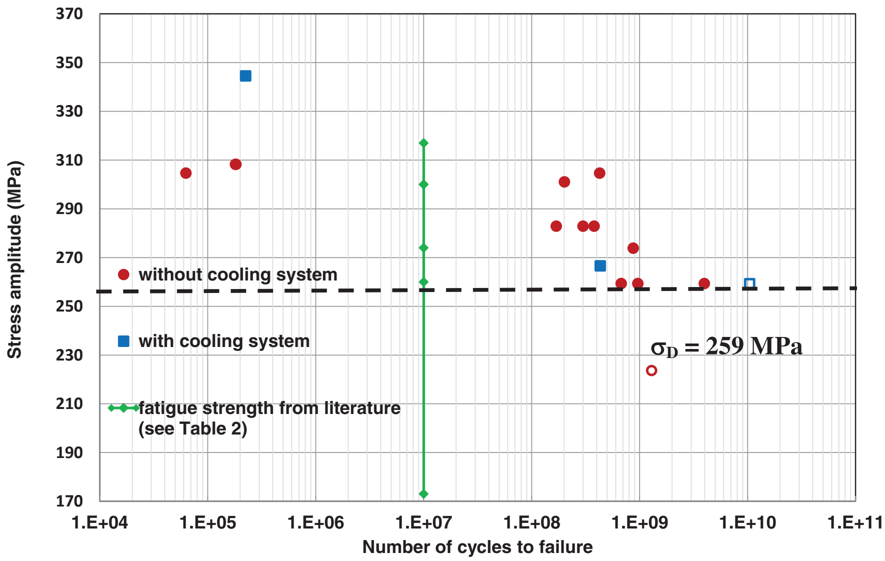


Fig. 3. Untreated Stress-Number of cycles to failure for 0.45%C steel obtained from 20 kHz ultrasonic fatigue tests (circle and square dots – the open symbols correspond to not broken specimens) and compared with literature results based on experimental results obtained from conventional fatigue machine working at <200 Hz frequencies or from models (details of literature results are given in Table 2).

Table 2. Fatigue strengths of similar ferritic-pearlitic ~0.45%C steels from literature

Materials	Fatigue strength at 10^7 cycles	Ultimate tensile strength Rm (MPa)	References
Model using a relationship between ultimate tensile strength and fatigue strength	~300 MPa		[6]
AISI 1040 normalized steel	~300 MPa ($3{\times}10^4$ cycles)	732 MPa	[2]
AISI 1040 normalized steel (Chemical composition closed to C45 studied steel)	274-317 MPa	536-650 MPa	CES Edupack
AISI 1045 as received steel –from Equation $\frac{\Delta\sigma}{2} = \sigma_f'\left(2N_f\right)^b$	173 MPa	671 MPa	[5]
AISI 1045 Steel – hot-rolled bars	~260 MPa	~705 MPa	[4]

4.2 Fracture surface

Figure 4 exhibits typical fracture surface obtained after 20 kHz fatigue loading. For $305\,MPa \leq \frac{\Delta\sigma}{2} < 350\,MPa$, the specimen fracture surface does not show any crack initiation zone. The failure comes from ductile tearing and not from fatigue. For $250\,MPa < \frac{\Delta\sigma}{2} < 305\,MPa$, the fracture surfaces exhibit fish eyes as usually observed in the very high cycle for high strength steels [1]. The fish eye observed with an optical microscope displays a whitish zone. It contains an inclusion in the center from which crack initiates. EDS analysis showed that the inclusion is rich in aluminium and oxygen.

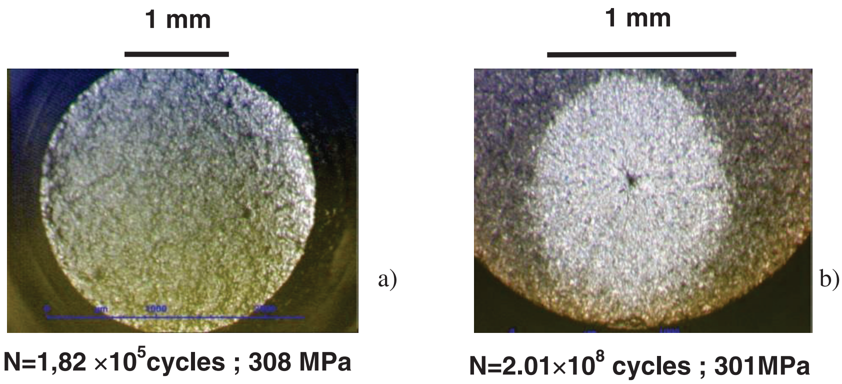


Fig. 4. Typical optical fracture surfaces obtained after ultrasonic fatigue tests on 0.45%C steel- a) for $305\,MPa \leq \frac{\Delta\sigma}{2} < 350\,MPa$ and b) for $250\,MPa < \frac{\Delta\sigma}{2} < 305\,MPa$

4.3 In-situ temperature measurements

Figure 5 shows the self-heating *ΔT* of the specimens during the 20 kHz fatigue tests for three stress amplitudes: 347 MPa, 268 MPa, 231 MPa. The three curves exhibit different thermal responses and are typical of the stress amplitude ranges identiftied from the S-N curve and the fracture surfaces.

For 347 MPa and systematically for $305\,MPa \leq \frac{\Delta\sigma}{2} < 350\,MPa$, the self-heating reached 80°C in 10^5 cycles (5 seconds). The capacity of the camera was set in the [10°C-90°C] range and so the camera cannot measure temperatures higher than 90°C. However, the specimens rapidly became red (few seconds) indicating that the temperature is above 800°C. Then, they broke by hot ductile tearing and not by fatigue.

For 268 MPa and systematically for $250\,MPa < \frac{\Delta\sigma}{2} \leq 305\,MPa$, the self-heating remained lower than 10°C for numbers of cycles ranging from 10^6 to 10^7 cycles. Subsequently, it strongly increased and reached few hundreds of degrees in few seconds up to a more or less steady, slightly decreasing temperature, up to the stop of test. The self-heating measurements were not usually conducted up to the specimen failure but all the specimens break in this stress amplitude range due to fatigue (Fig. 3). The origin of the steep and drastic self-heating and the subsequent slight decrease of the temperature are not understood at the present time and required further investigations.

For 232 MPa and systematically for $\frac{\Delta\sigma}{2} < 250\,MPa$, the self-heating still existed and gradually increased up to a steady state. It remained lower than 10°C all along the test. This self-heating change is commonly observed during ultrasonic fatigue tests [7]. The specimens loaded in this stress amplitude range do not break (at least up to 10^{10} cycles).

The cooling system does not significantly change the thermal response of Figure 5. This reveals that it is not effective enough to balance the self-heating of the specimens.

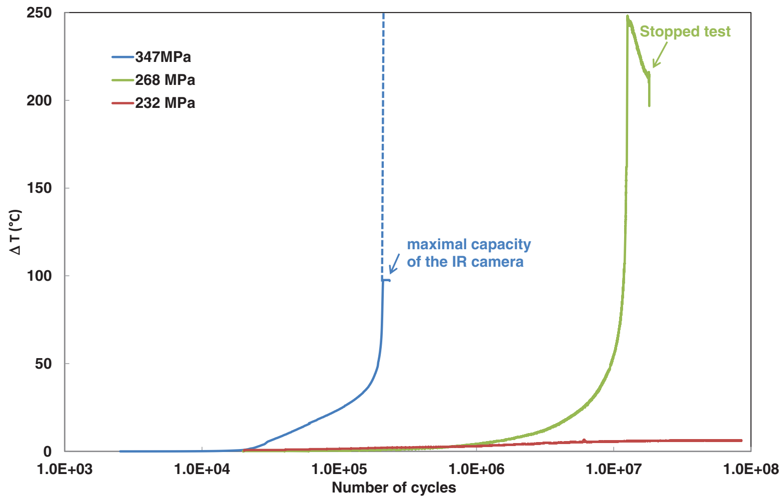


Fig. 5 Increase of temperature as a function of number of cycles for stress amplitudes of 232 MPa, 268 MPa, 347 MPa

4. Discussion and conclusions

The ultrasonic fatigue tests showed that 0.45%C normalized ferritic-pearlitic steel specimens failed between 10^5 and 10^{10} cycles despite the fact that no failure was observed 2×10^5 and 2×10^8 cycles. The fatigue limit estimated from these results is about 259 MPa. This value is consistent with the fatigue strength obtained from fatigue tests using conventional fatigue machine working at <200Hz frequencies for similar 0.45%C steel and is approximately 40 percent of the ultimate tensile strength.

However, the 20 kHz cyclic loading can produce a very strong self-heating. More precisely, three stress amplitude ranges were identified with regard to the material thermal response:

- For $\frac{\Delta\sigma}{2} < 250\ MPa$, the self-heating is < 10°C
- For $250\ MPa < \frac{\Delta\sigma}{2} \leq 305\ MPa$, the self-heating reaches few hundreds of degrees
- For $305\ MPa \leq \frac{\Delta\sigma}{2}$, the self-heating is > 800°C.

These three stress amplitude ranges correspond very well to the three types of response with regard to failure:

- For $\frac{\Delta\sigma}{2} < 250\ MPa$, no failure is observed up to 10^{10} cycles
- For $250\ MPa < \frac{\Delta\sigma}{2} \leq 305\ MPa$, fatigue failure with internal crack initiation is observed.
- For $305\ MPa \leq \frac{\Delta\sigma}{2}$, failure by hot ductile tearing is observed.

Consequently, the S-N curve of Figure 3 cannot be considered as an isothermal S-N curve as common S-N curve obtained at low frequencies. The S-N curve with the corresponding self-heating measured at 10-30% of the fatigue life is replotted in Figure 6. The tests associated with ductile tearing were removed as they did not involve fatigue rupture. The remaining dots correspond to fatigue failure with internal crack initiation. The reason why the fatigue limit obtained via the 20 kHz non isothermal fatigue tests is quite consistent with literature fatigue strength, despite the temperature difference, remains an open question.

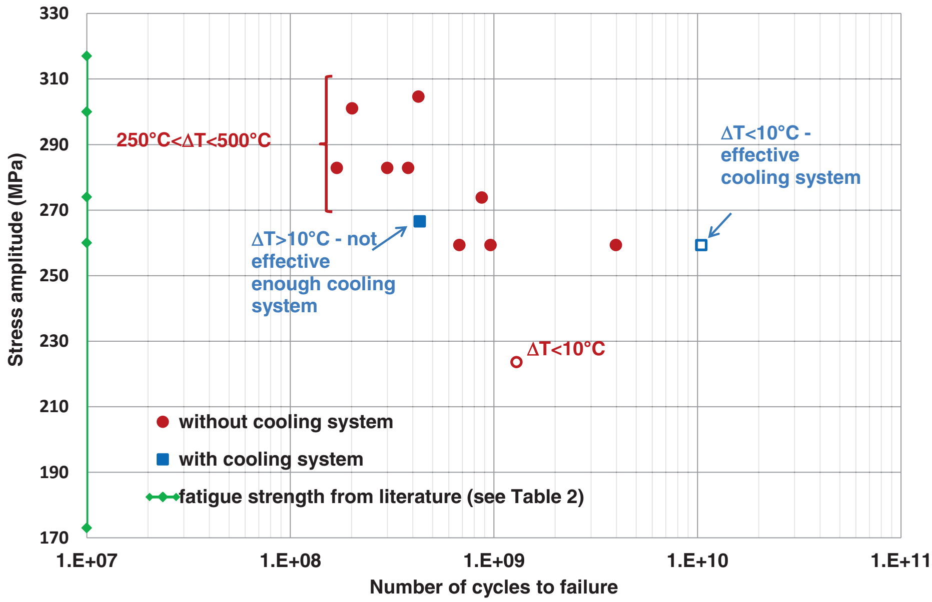


Fig. 6. Untreated Stress-Number of cycles to failure for 0.45%C steel obtained from 20 kHz ultrasonic fatigue tests (circle and square dots – the open symbols correspond to not broken specimens) and compared with literature results based on experimental results obtained from conventional fatigue machine working at <200 Hz frequencies or from models (details of literature results are given in Table 2).

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