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Temperature-frequency evolution during 20 kHz cyclic loading of Dual-Phase 780 steel

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INTRODUCTION

Ultrasonic machine, which operates at around 20 kHz, is used to quickly get the fatigue behavior in the very high cycle fatigue domain. Cyclic loading at such high frequencies is accompanied by self-heating of the test specimen [1]–[3]. The self-heating magnitude depends on the material and cooling system. It is also accompanied by changes in loading frequency of testing. In contrast to the temperature evolution and to our knowledge, the frequency evolution during an ultrasonic fatigue test has been very little studied. In this paper, the changes in both specimen temperature and loading frequency during ultrasonic cycling for the Dual-Phase 780 steel are investigated.

EXPERIMENTAL PROCEDURE

The material studied in this research was a commercial DP780 dual-phase steel. This ferritic-martensitic steel which contains ~22 wt. % martensite was received as sheets of 3.6 mm thickness from ArcelorMittal. Table 1 shows its main mechanical properties. Ultrasonic fatigue tests were carried out by using a piezoelectric 20-kHz system. All fatigue tests were performed under fully reversed tension-compression conditions (R=-1) using a continuous loading technique. The fatigue tests were stopped when the number of cycles reaches few 10^6 cycles. Hourglass-shaped specimens with rectangular cross section were used (Fig.1). The dimensions of ultrasonic fatigue samples were obtained by solving the vibration equations in order to reach the first longitudinal tension-compression mode at about 20 kHz for the specimen were carried out at two stress amplitudes at the center of specimen: 229 MPa and 233 MPa. These values are more than twice as low as the material yield stress so that the mechanical response at the macrocsopic scale can be considered as purely linear elastic to estimate the stress amplitude. In situ infrared thermography was employed to record the mean temperature at the specimen surface. The specimens were black painted to have an emissivity close to the unit and estimate precisely the temperature. In all the presented results the temperature was estimated at the center of the gauge part of the specimen in a circular area with a diameter of ~1 mm (Fig. 2). The camera preset has to be adjusted to the measured temperature range. The loading frequency all along testing was also recorded. As the initial temperature and frequency depend on the specimen geometry and room temperature, the changes in temperature ΔT and frequency Δf over cycles were calculated by substracting the initial from current temperature and frequency, respectively. As the acquisition time was different for temperature and frequency, a data treatement was carried out to synchronized both times.

Table 1 Mechanical properties of DP780.

0.2% Yield Stress [MPa]	Ultimate Tensile Strength [MPa]	Elongation [%]	Young Modulus (GPa)
546	792	23.3	195

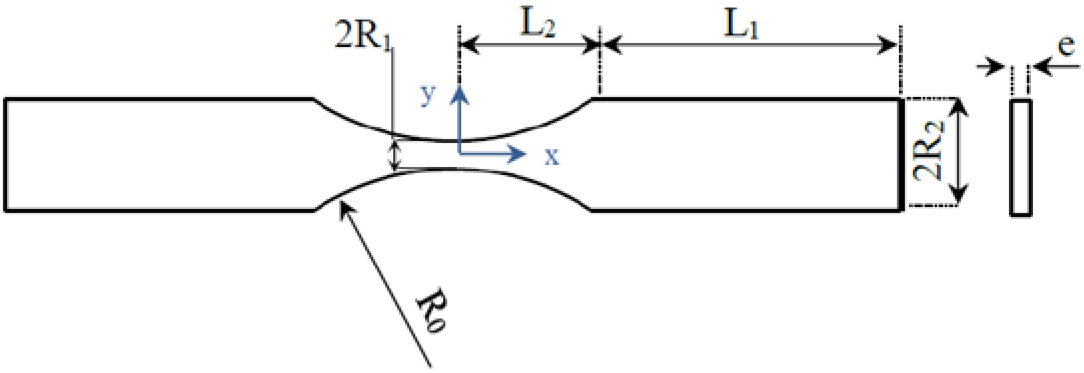

Fig. 1 Ultrasonic fatigue specimen (R_0 = 27.2 mm ; R_1 = 1.5 mm ; R_2 = 6.0 mm ; L_1 =33.0 mm ; L_2 = 15.0 mm ; e = 2.0 mm).

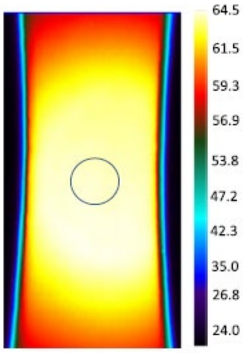

Fig. 2 Temperature map of a specimen under 20 kHz cyclic loading. The black circle defines the area in which the mean surface temperature was measured.

RESULTS

Fig.3 shows the mean self-heating ΔT evolution during ultrasonic fatigue test carried out at 229 MPa – stress amplitude. ΔT increases quite rapidly at the beginning of the test and more slowly thereafter. After 3×10^6 cycles, ΔT increases much more steeply, peaked at ~290 °C and then decreases slightly before it stabilized at ~250 °C. Interestingly, a very similar but inverse evolution for Δf was measured. Δf versus ΔT was plotted (Fig. 4). A clear linear relationship between both parameters was found. As frequency decreases with increasing temperature, the slope is negative. It can be mathematically represented by Equation 1:

$$\Delta T\ \ (°C) = \ -5.29 \times \Delta f(Hz) + 3.89 \quad \text{(Eq. 1)}$$

ΔT was recalculated using Eq. 1. A very good agreement is found between the experimental and recalculated values (Fig. 3) (comparison between red dots and blue line).

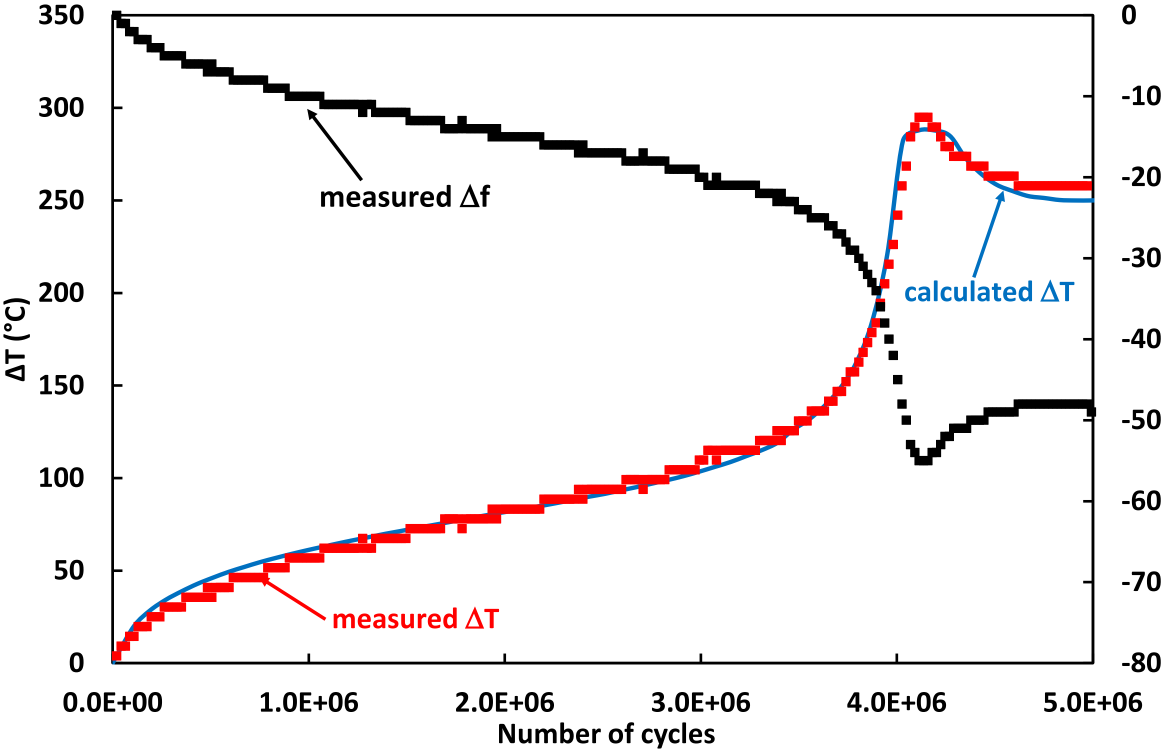

Fig. 3 Evolution of experimental ΔT (red square dots) and Δf (black square dots) during 229 MPa stress amplitude cyclic loading. Calculated ΔT from Equation 1 (blue line).

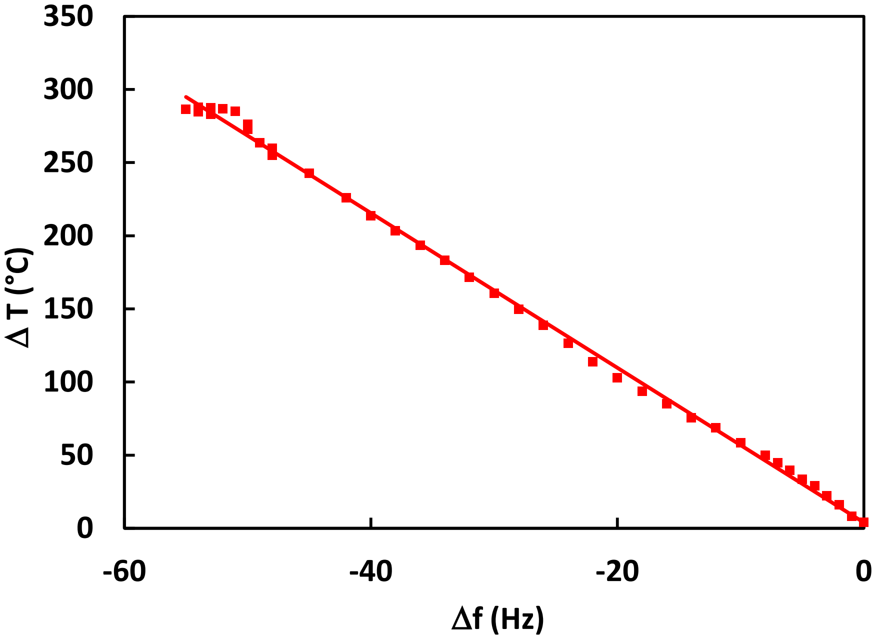

Fig. 4 ΔT versus Δf during 229 MPa stress amplitude cyclic loading.

DISCUSSION

Ultrasonic fatigue tests induce self-heating. This self-heating depends on loading conditions (with or without air cooling, pulse and pause or continuous loading) and materials [3]. In case of ferritic steels such as Dual-Phase steels or C45 steels, it can reach more than 300 °C without enough cooling and exhibit a peak [1], [2]. The origin of such thermal response was investigated in [1] [4] and is not the purpose of the present paper. The self-heating is accompanied by a simultaneous change in frequency. Fig. 3 reveals that the frequency decrease is at most equal to 60 Hz, corresponding to a relative change with the mean frequency value of 0.3%. Consequently, it is consider that, contrary to the temperature change [4], the frequency change does not impact the material response such as dissipative response (viscous and plastic strain mechanisms). Whatever this result, the frequency change is very interesting as it can be used to estimate the temperature change. Temperature measurement requires black paint and preset of the infrared camera. Black paint can deteriorate at high temperatures disturbing the measurement. In addition, the camera preset has to be adjusted to temperature ranges that is usually unknown before carrying out the ultrasonic test. On the contrary, frequency change is intrinsically shift by the control loop of the piezo electric converters to minimized the energy absorbed by the system and thus most easier to measure. Using ΔT and $\Delta \mathrm{f}$ linear relationship provides an accurate estimation of temperature as shown in Fig. 3. In the case associated with Fig. 3, the temperature was measured throughout the test. To assess the performance of the methodology that consists in using frequency measurements to estimate temperature, a new test was performed at 233 MPa stress amplitude. The infrared camera was set to measure temperature in [10°C-90°C] range. Temperature data are shown in Fig. 5 (red dots). Above ~90°C, a saturated value was measured. However, the simultaneous steep decrease in frequency suggests a steep increase in temperature. Using the first data of frequency and temperature curves, Δf versus ΔT was plotted. As for the 229 MPa case, a linear relationship was found and the associated equation was estimated. It was used to calculate missing ΔT values thereafter. The resulting curve is plotted in Fig. 5 (blue line). It reveals again a steep increase in ΔT, peaked at ~300 °C and then decreases slightly. The steep increase occurred at 1.8×10^6 number of cycles, so earlier than for 229 MPa stress amplitude loading (3.6×10^6 cycles). This result suggests that the increase in stress amplitude from 229 MPa to 233 MPa favored dissipative mechanisms occurrence such as microplasticity.

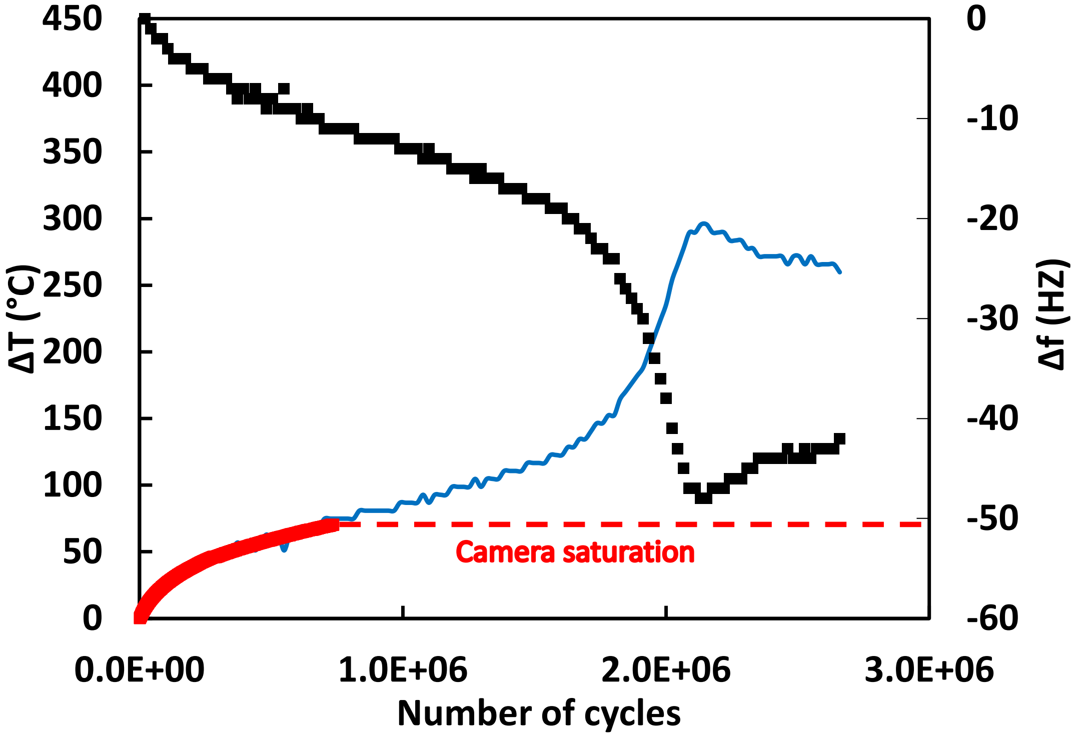

Fig. 5 Evolution of experimental ΔT (red square dots) and Δf (black square dots) during 233 MPa stress amplitude cyclic loading. Calculated from Equation 1 (blue line).

CONCLUDING REMARKS

Ultrasonic cyclic tests on DP780 steel were carried out. The in-situ specimen temperature evolution was measured using an infrared camera. The main concluding remarks of this study are:

- The increase in specimen temperature is accompanied by a simultaneous decrease in loading frequency. They both follows the same but inverse variation trend.
- A linear relationship between the temperature and frequency changes was found.
- This linear relationship can be used to estimate temperature change from frequency one when temperature data are missing.

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