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Correlation of the high and very high cycle fatigue response of ferrite based steels with strain rate-temperature conditions

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ABSTRACT

The discrepancies observed between conventional and ultrasonic fatigue testing are assessed through the mechanisms of dislocation mobility in BCC metals. The existence of a transition condition between thermally-activated and athermal regimes for screw dislocation mobility is studied under fatigue loading based on infrared thermography and microstructural characterization, here in the case of DP600 dual-phase steel. Evidence is obtained regarding the microstructural sources of crack initiation, which is found to be consistent with the existence of a transition in the modes of deformation. From the analysis of the experimental data gathered in this work, guidelines are given regarding the comparison and interpretation of S-N curves obtained from conventional and ultrasonic fatigue testing. The inevitable temperature increases under ultrasonic fatigue at high stress amplitudes along with the rate dependent deformation behavior of ferrite, as a BCC structure, were found as the key parameters explaining the observed fatigue behavior and thermal response under low and ultrasonic frequencies. A transition map was produced using the experimental results for DP600 steel as well as data available in the literature for other ferrite based steels, showing the correlation between thermally-activated screw dislocation movement and the absence of failure in very high cycle fatigue.

1. Introduction

The increased demand for material fatigue characterization in gigacycle regimes has provoked further use and development of ultrasonic fatigue testing systems. Owing to a high frequency of usually 20 kHz, this loading technique allows to reach very high number of cycles up to $N = 10^9$ in a reasonable time and at lower costs compared to conventional low frequency loadings. However, this accelerated testing method has been always accompanied by a main question: are the fatigue properties obtained from ultrasonic loading similar to those measured by conventional low frequency testing? The answer has remained unclear for most metallic materials [1] and thus the so-called “frequency effect” has been controversial among researchers [2].

Generally, the influence of frequency stems from two main sources: strain rate effects and time dependent influence of environment. The former is the case for high ductility and strain rate sensitive materials such as low-carbon steels while the latter has been reported for some FCC materials such as aluminum alloys [2–5]. Low- and medium-carbon ferritic steels exhibit clear discrepancy between fatigue life and fatigue strength, obtained from ultrasonic loading and those measured from conventional fatigue tests [2]. In this case, as a general trend, ultrasonic loadings produce higher fatigue lives than low frequency tests. The elevated fatigue life and fatigue limit under ultrasonic loading has been mostly attributed to the increase of yield strength due to increasing the strain rate [2,4,6–10]. Tsutsumi et al. [6] reported that the longer fatigue life and the higher fatigue limit of low-carbon steels under ultrasonic fatigue are due to a reduction in crack tip cyclic plasticity and subsequent lower crack growth rate during ultrasonic loading. A surface-to-internal-crack initiation transition has been reported by Furuya et al. [11] as the cause of longer fatigue life of ultrafine-grain steel under ultrasonic fatigue testing.

Guennec et al. [10] attributed the higher fatigue life and fatigue strength of low-carbon steel, under ultrasonic loading to transition of crack initiation mode from the usual transgranular, often

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reported at lower loading frequencies, to intergranular crack initiation at ultrasonic frequencies. They [9,10] showed that under usual frequencies of 0.2–140 Hz, dislocation dipoles as ladder or cell structures are induced whereas in the case of 20-kHz ultrasonic loading, long segments of screw dislocations are produced. These results revealed the fact that the screw dislocations were nearly immobile during the conducted ultrasonic tests.

The effect of frequency on fatigue properties of low- and medium-carbon steels results from a particular behavior of BCC structure of ferrite grains contained in these steels. In BCC metals, the flow stress depends strongly on temperature and strain rate at low temperatures. It was first proposed by Seeger [12] that for BCC metals the flow stress, σ, can be separated into an athermal component σ_G, and a thermal or effective component σ^*, as $\sigma = \sigma_G + \sigma^*(\dot{\varepsilon}, T)$. The athermal component is the stress that a gliding dislocation requires to overcome the long range elastic interaction with other dislocations. The thermal or effective component is the stress required for screw dislocations to overcome short obstacles by thermally-activated mechanisms. This thermal component depends on temperature T, and strain rate $\dot{\varepsilon}$ and becomes negligible above a transition temperature, T_0 (or below a transition strain rate, $\dot{\varepsilon}_0$). For cyclic loading, Mughrabi et al. [13] defined two deformation regimes based on the transition temperature: (1) the thermally-activated mode ($T < T_0$) where the screw dislocations are immobile and edge dislocations move to-and-fro in a non-hardening quasi-recoverable manner (2) the athermal regime ($T > T_0$) where the mobilities of screw and edge dislocations are equivalent and screw dislocations can cross slip. In this regime, rearrangement of dislocations can take place and strain localization can occur in slip bands. The transition temperature T_0 is highly strain rate dependent and can be shifted to higher values by increasing the strain rate. Therefore, the thermally-activated regime can be reached at high temperatures providing that the strain rate is sufficiently high.

On the contrary to low and medium strength steels, high alloy and high strength steels (e.g. martensitic stainless steels) are less susceptible to frequency effects and often there is a good agreement between their fatigue life obtained from ultrasonic loadings and that measured from low frequency fatigue tests [14–18]. According to Mayer [2], why the fatigue properties of high strength steels are not sensitive to the loading frequency is due to the very small plastic strain rate involved in high-cycle-fatigue (HCF) and very-high-cycle fatigue (VHCF) loadings of these materials.

As mentioned previously, strain rate and environmental effects are considered as the main causes of frequency effects in ultrasonic fatigue loading. Because of the high frequency, significant temperature rises can occur under ultrasonic fatigue loading of metals especially at high stress amplitudes [19]. Thus, temperature can be considered as a third cause of frequency effect in ultrasonic testing [4,6]. Since heating can usually be avoided by cooling the specimen during the test or by employing intermittent loadings, temperature has not been commonly considered as an effective factor on material fatigue response but is recognized as a rather fictitious effect which should be excluded by effective cooling or measuring by pulse-pause testing. However, the effect of heat generation cannot be impeded for all materials under ultrasonic fatigue loading even by cooling the specimen and using a pulse-pause mode [20–22]. The presence of inevitable heating effects under ultrasonic tests at high stress amplitudes has been already confirmed in a previous work of the authors for ferritic-martensitic steel [23]. Peng et al. [21] stated that for structural steels with low tensile strength the specimen is prone to heating and burning at high stress amplitudes even by employing intermittent loading along with cooling systems. Yu et al. [20] affirmed that for bainite-martensite steels under intermittent ultrasonic loading, when the stress level is high, the generated heat cannot be dissipated effectively in spite of maximizing the interruption time and minimizing the oscillation time. Ranc et al. [24] reported strong temperature increase up to few hundreds of degrees for C45 steel under ultrasonic loading, in spite of using cooling systems.

In a variety of research works on fatigue loading on BCC materials, the temperature increase has been reported to be less than 100 °C, therefore the effect of temperature increase on the fatigue and deformation of the material has not been studied (see for example [4,10,24–26]). However, concerning the temperature dependent flow behavior of BCC structures, even these limited amounts of temperature increase should be taken into account. Moreover, studies involving ultrasonic frequency effects were mainly focused on the effect of frequency on fatigue lifetime, fatigue strength, crack initiation mechanisms, crack growth rate, and dislocation mechanisms. In spite of the importance of temperature on fatigue response of BCC materials, there is a lack of investigation about the mechanisms behind the temperature increase under fatigue loading and the influences which it imposes on fatigue behavior of the material.

The present work aims at explaining the high and very high cycle fatigue behavior of BCC structures accounting for strain rate and temperature effects. DP600 dual-phase steel which consists of a ferrite matrix containing martensite islands was investigated under 20-kHz ultrasonic loading as well as conventional low frequency fatigue tests. In both cases, the S-N curves were obtained and the effect of frequency on fatigue life and fatigue limit was studied. Fractography studies were conducted and effect of frequency on crack initiation and material failure was investigated. Moreover, thermographic measurements were performed and mechanisms were proposed to explain the observed abnormal thermal response of the material under ultrasonic loading and correlate it to the fatigue and deformation behavior. A strain rate-temperature transition map was developed to correlate the fatigue response of the material to deformation mechanisms by gathering the results of the present paper and data from literature for ferrite based steels.

2. Material and experiments

The material studied in this research was a commercial DP600 dual-phase steel. This ferritic-martensitic steel which contains 15 wt % martensite was received as sheets of 3.6 mm thickness from ArcelorMittal. The chemical composition and the mechanical properties of the material are presented in Tables 1 and 2, respectively. Ultrasonic and conventional low frequency fatigue tests were carried out by using a piezoelectric 20-kHz system and a 10-kN servo-hydraulic MTS machine, respectively. All fatigue tests were performed under fully reversed tension-compression conditions (R = −1). Hourglass-shaped specimens with rectangular cross section were used with the geometries shown in Fig. 1. The dimensions of ultrasonic fatigue samples were obtained by solving the vibration equations in order to reach a resonant vibration frequency of 20 kHz for the specimen. The conventional fatigue specimens were designed so that for the same displacement amplitude, the stress distribution in the neighborhood of the specimen center is equivalent to that of ultrasonic specimen [27]. Ultrasonic fatigue tests are displacement-controlled while conventional fatigue loadings are performed under load-controlled conditions. In both cases loading amplitude was low so that the

Table 1
DP600 chemical composition [28].

Alloying element	Mn	Ni	Si	Cr	C	Al	Nb
% weight	0.933	0.020	0.213	0.727	0.0748	0.039	0.0425