Fatigue behavior of DP600 dual-phase steel under ultrasonic and conventional low frequency cyclic loadings

Noushin Torabian[a], Véronique Favier[b], Justin Dirrenberger[c], Frédéric Adamski[d], Saeed Ziaei-Rad[e], Nicolas Ranc[f]

a. Laboratoire PIMM, Arts et Métiers Paris Tech, CNAM, CNRS, Paris 75013, France. noushin.torabiandehkordi@ensam.eu

b. Laboratoire PIMM, Arts et Métiers Paris Tech, CNAM, CNRS, Paris 75013, France. veronique.favier@ensam.eu

c. Laboratoire PIMM, Arts et Métiers Paris Tech, CNAM, CNRS, Paris 75013, France. Justin.DIRRENBERGER@ensam.eu

d. Laboratoire PIMM, Arts et Métiers Paris Tech, CNAM, CNRS, Paris 75013, France. Frederic.ADAMSKI@ensam.eu

e. Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran. szrad@cc.iut.ac.ir

f. Laboratoire PIMM, Arts et Métiers Paris Tech, CNAM, CNRS, Paris 75013, France. Nicolas.RANC@ensam.eu

Abstract

Fatigue behavior of DP600 dual-phase steel was investigated in high- and very-high-cycle fatigue regimes by conducting ultrasonic 20-kHz fatigue loadings as well as conventional low frequency fatigue tests. Fractography studies and microscopic observations on specimen's surfaces were carried out to study the fracture and deformation mechanisms under low and ultrasonic frequencies. The S-N curves were determined from ultrasonic 20-kHz fatigue loadings and conventional tests with a frequency of 30 Hz. fatigue life was found to be higher in the case of ultrasonic fatigue whereas the fatigue strength was the same for both cases. Moreover, in situ infrared thermographic studies were carried out and it was observed that the dissipated energy per cycle was much higher under conventional fatigue tests than ultrasonic loadings.

Keywords : ultrasonic fatigue ; dual-phase steel ; frequency effect

1. Introduction

An evaluation of the fatigue properties in high-cycle and recently in very-high-cycle regimes (beyond 10^7 cycles) is of significant importance for researchers and industrial companies. Owing to the development of ultrasonic fatigue test systems working at very high frequencies (20-30 kHz), it has been possible to investigate the fatigue behavior of materials up to a large number of cycles in a reasonable testing time 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 been remained unclear for most metallic materials [1] and thus the so-called "frequency effect" has been a controversy among the researchers [2]. The present work aims to reconfirm the presence of such frequency effects on fatigue properties as well as thermal response of bcc metals with complex microstructures. 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 was studied. Moreover, fractography studies were conducted and effect of frequency on crack initiation and material failure was investigated. In addition, the influence of frequency on dissipated energy per cycle was studied at low stress amplitudes and the mechanisms behind these effects were discussed.

2. Results and Discussions

2.1 Thermal response of material

In situ infrared thermography was employed to study the thermal response of the material under ultrasonic and low frequency fatigue tests. Under ultrasonic 20-kHz loading an abnormal temperature evolution was observed at stress amplitudes above 247 MPa. Two deformation regimes were distinguished and discussed based on the transition between the thermally activated deformation mode and the athermal deformation mode for the ferrite phase [3]. In athermal regime high mobilities of screw and edge dislocations leads to energy dissipations much higher than that under low-temperature regime which stems from to- and fro glide of edge dislocations. Below 247 MPa, a quadratic evolution of the dissipated energy per cycle as a function of stress amplitude, σ_a, was determined, as shown in Figure 1. The to-and-fro glide of the edge dislocations was considered to be the main dissipative mechanism. This motion is quasi-recoverable and leaves a quasi-constant dislocation structure (no cyclic hardening). Above 247 MPa, a strong increase in temperature was observed as a consequence of the expansion of strong dissipative zones throughout the specimen width. The temperature decreased slightly to a more or less steady-state during cycling. The presence of strong dissipative zones was attributed to the fact that the transition temperature between the thermally activated deformation mode and the athermal deformation mode was reached because of self-heating. Therefore, the dislocation mobility increased strongly leading to strong dissipated energy in those zones. The higher mobility of dislocations also resulted in a multiplication of dislocations and cyclic hardening. At ~300-350°C, dynamic strain aging was assumed to operate as an extra hardening mechanism.

The dissipated energy per cycle measured at low stress amplitude ranges was much higher in the case of conventional low frequency tests than ultrasonic loadings. This is because of the deformation mode which was athermal under low frequency tests while under ultrasonic loading at low stress amplitudes material deformation occurred in low-temperature mode. In athermal regime high mobilities of screw and edge dislocations leads to energy dissipations much higher than that under low-temperature regime which stems from to- and fro glide of edge dislocations.

2.2 S-N properties and deformation mechanisms

A clear difference was observed in the S-N curves obtained from conventional 30-Hz fatigue tests and that of ultrasonic 20-kHz loadings. The fatigue life was higher under ultrasonic frequency tests; however, the fatigue limit was nearly the same for both cases. The higher fatigue life was attributed to the dynamic strain aging which resulted from the high temperature increases at high stress amplitudes. However, why the fatigue limit was the same for both cases remains as an open question.

In both ultrasonic and low frequency tests transgranular cracking along the slip bands was observed and no intergranular crack was detected. Surface fracture initiation was observed in low and high cycle regimes under conventional tests. Under ultrasonic loading, a transition from surface initiation in high cycle regime to internal inclusion-induced initiation in gigacycle regime was revealed. However, some cases of surface initiation at very high number of cycle were observed.

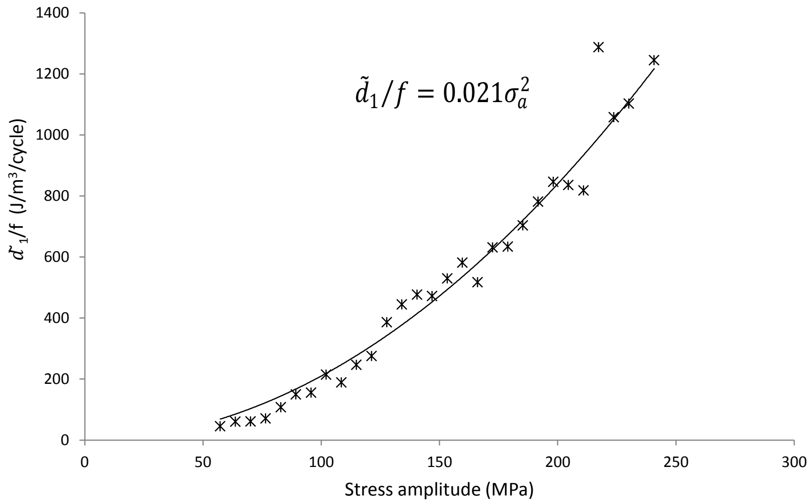

Figure 1. *Mean dissipated energy per cycle versus stress amplitude, for DP600 steel under ultrasonic loading.*

3. Conclusion

The behavior of ferritic-martensitic dual-phase steel was studied in high and very high cycle regimes by conduction ultrasonic 20-kHz and conventional low frequency tension-compression fatigue tests along with temperature measurements and microscopic observations. A clear difference was observed in the fatigue lifetime as well as the intrinsic dissipation per cycle between ultrasonic and conventional fatigue loadings. The rate dependent flow behavior of the ferrite phase, as a bcc structure, was found to be a decisive parameter explaining the effects of frequency on fatigue and thermal response of the material. Moreover, the significant temperature increase under ultrasonic fatigue loading at high stress amplitudes was found to play an important role in the observed phenomena.

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