Available online at www.sciencedirect.com

ScienceDirect

Procedia Materials Science 3 (2014) 209 – 214

Procedia Materials Science

www.elsevier.com/locate/procedia

20th European Conference on Fracture (ECF20)

The effect of low temperatures on the fatigue of high-strength structural grade steels

Carey Leroy Walters[a]*

[a] *TNO, Van Mourik Broekmanweg 6, Delft 2628 XE, The Netherlands*

Abstract

It is well-known that for fracture, ferritic steels undergo a sudden transition from ductile behavior at higher temperatures to brittle cleavage failure at lower temperatures. However, this phenomenon has not received much attention in the literature on fatigue. The so-called Fatigue Ductile-Brittle Transition (FDBT) has been identified in the literature as the point at which the fracture mode of the fatigue cracks changes from ductile transgranular to cleavage and/or grain boundary separation. The current paper contributes to understanding this phenomenon by presenting both ductile to brittle fracture transition data and fatigue crack growth rate curves for two modern high strength steel base plate materials: S460 and S980. The data in this paper suggests that fatigue at lower shelf temperatures may have a higher rate than in the transition or upper shelf temperatures for Regions I and II of the *da/dN* versus *ΔK* curve.

Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering

Keywords: Arctic; low temperature; fatigue; transition; high-strength steel

1. Introduction

Fatigue behavior of metals is often characterized by the *da/dN* versus *ΔK* curve. This curve is typically presented in log-log coordinates and represents the crack growth per cycle (*da/dN*) on the vertical axis against the stress intensity range (*ΔK*) on the horizontal axis. An example is given in Fig. 1a. This curve is known to have three

---

* Corresponding author. Tel.: +31-888-662-832.
E-mail address: carey.walters@tno.nl

Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering
doi:10.1016/j.mspro.2014.06.037

distinct regions. Region I corresponds to low stress intensity ranges. This region contains the vertical asymptote known as the threshold stress intensity range (ΔK_{th}), below which no or negligible crack growth occurs. Region II is a region in which the relationship between the crack growth rate and the stress intensity range is approximately linear in log-log coordinates, as is often expressed in the Paris law:

$$\frac{da}{dN} = C(\Delta K)^n \tag{1}$$

Region III is the region at which the unstable crack growth is present. The current paper will focus on the threshold stress intensity range and the Paris regime because they are the most relevant to practical applications.

As ferritic steels becomes colder, they undergo a transition from a shear-dominated (ductile) fracture mode to a cleavage-dominated (brittle) fracture mode. This is measured through fracture mechanics testing, such as CTOD, K_{Ic}, Charpy, or *J*-integral testing. A similar effect has been documented for fatigue at low temperatures (e.g. Baotong and Xiulin, 1991, Moody and Gerberich, 1979, Stephens et al., 1980, Tobler and Cheng, 1985, among others) and has been called the Fatigue Ductile-Brittle Transition (FDBT). The temperature at which this transition occurs is known as the Fatigue Transition Temperature (FTT). It has been observed that lower temperatures generally cause decreased fatigue crack growth rates until the FTT is achieved. Below the FTT, the trend is reversed, and higher fatigue crack growth rates are encountered (Stephens and Chung, 1980). A more nuanced explanation is that temperatures below the FTT induce a higher slope in the da/dN versus ΔK curve, thus meaning that the fatigue crack growth rate may be lower for low ΔK values and higher for higher ΔK values than for room temperature (Stephens and Chung, 1980). This is shown in Fig. 1a for a low-carbon steel. Fig. 1b from the same source shows the slope of the da/dN versus ΔK curve (the value n from Eq. (1)) increasing until a set temperature, and then decreasing sharply thereafter. Fig. 1b also shows a number of other attributes (da/dN at $\Delta K=120$ MPa√m, cycles to failure, and critical stress intensity to fracture for fatigue) becoming more favorable as the temperature decreases, and then becoming less favorable after a certain set temperature. Clearly, this effect could become important for structures operating at low temperatures. Designers and classification societies assure safety against brittle fracture by checking that their steel has a Charpy Ductile to Brittle Transition Temperature (DBTT) below the operating temperature (plus or minus a shift to account for various factors). The FDBT should not be important for designers if this happens below their lowest design temperature or their Charpy DBTT. Therefore, there is interest in knowing the relationship between the fatigue and fracture ductile to brittle transition temperatures. Tobler and Cheng (1985) have partially answered this call by plotting the K_{Ic} fracture toughness and the Paris exponent (n) against temperature on the same plot. This plot is shown in Fig. 2a, and it shows that the slope of the da/dN versus ΔK curve increases as soon as the K_{Ic} value starts to decrease in the fracture ductile to brittle transition. However, one would expect a higher slope of the da/dN curve to occur in the lower transition or lower shelf, where the cleavage fracture is not first preceded by ductile crack growth in fracture tests. Indeed, a number of authors have observed that the FDBT occurs low in the fracture transition or even in the lower shelf. For example, it is mentioned by Baotong and Xiulin (1991) that the transition usually occurs at a lower temperature than the Fracture Appearance Transition Temperature (FATT). Furthermore, Stephens et al. (1980) indicate that the FTT tends to be lower than the Nil-Ductility Temperature or the Charpy transition temperature (though the authors leave the precise definition of Charpy transition temperature vague). Moody and Gerberich (1979) contribute by plotting the Paris exponent versus the test temperature minus the fracture DBTT. Their plot is shown in Fig. 2b. Their plot shows a clear relationship between the Paris exponent and the relative position of the DBTT over a range of the DBTT±50°C. This paper makes the first steps to resolving some of the ambiguities as to where the FDBT is relative to the fracture transition curve.

2. Materials

Two materials are considered. The first is an S980 grade plate with a thickness of 25 mm. The second is an S460 grade plate with a thickness of 40 mm. Some key properties of both materials are presented in Table 1. In both cases, the materials were assessed in the un-welded condition. The yield strength (σ_y) and ultimate tensile strength (UTS) that are presented in Table 1 came from the material certificates. The T_{27J} and FATT values are described in the following section.