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Influence of ferrite fraction within martensite matrix on fatigue crack propagation: An experimental verification with dual phase steel

Roslinda Idris, Yunan Prawoto*

Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM, Skudai, Johor, Malaysia

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ABSTRACT

The influence of a ferrite areal fraction within a martensite matrix on fatigue crack propagation is studied experimentally. The variation of the areal fraction is achieved by means of intercritical thermal treatment, which specifically aims at optimizing the resistance to fatigue loading. Within the intercritical annealing temperature range, the areal fraction of ferrite increases with decreasing soaking temperature. Furthermore, the experiment also reveals that the highest fatigue strength was achieved when the ferrite areal fraction was approximately 65%, which in this particular test, corresponds to 748 °C. It is concluded that appropriate thermal treatment can contribute to a significant improvement of fatigue properties and strength, which was also verified by computational modeling.

1. Introduction

Recent developments in the research of dual-phase materials have shown both the importance of multi-phase materials and the progress that has been achieved [1–16]. While conventional steel always makes it impossible to obtain at the same time both good ductility and high strength, many engineering applications, especially in modern applications such as automobile industries, require economical high strength steel with good formability. Therefore, it would be ideal if multi-phase steels mostly containing ferrite and martensite phases could be obtained by a relatively simple thermal treatment process. This dream has inspired many researchers to put their effort and energy into this subject.

In general the paths to understand the characteristics of multiphase steels are multiple, e.g., microstructure, thermal treatment technique, chemical metallurgy, dislocation, etc. Below is a simple classifications of some recent papers:

- *Through observation of chemical metallurgy:* Researchers in this category study the effect of carbon content and an alloying element on fatigue strength. They typically find that the fatigue strength of dual-phase steels is significantly higher than that of as-received materials, due to the difference in its local chemical metallurgy [1,2].
- *Through observation of dislocation:* In this category researchers investigate the relationship between mechanical properties and dislocation substructures. A significant improvement of the mechanical properties of dual-phase steel can be explained by the alteration in its dislocation density [3].
- *Through thermal treatment:* Researchers in this category usually focus on the method of achieving the optimum mechanical properties they intent to obtain. These steels can be produced by annealing plain and low-alloy steels in the $(\alpha - \gamma)$ region and cooling it below the martensite start temperature at a suitable rate [4,5]. Several researchers claim to have obtained optimum results by intermediate quenching [6]. Others have obtained this by other thermal treatments, such as intercritical annealing [7,8,17,9,10]. The methods also vary from base metals to welding [11]. They are all convinced that better mechanical properties correspond to a more homogeneous and dense distribution of the fine martensite islands in the ferrite matrix obtained by thermal treatment [11]. They also agree that both the soft and ductile ferrite matrix and strong and tough martensite particles play an important role in determining the dual-phase properties, especially the continuous yielding behaviour of the steel [6,11].
- *Through microstructure research with a focus on morphology:* The main finding in this category is that the volume fraction of proeutectoid ferrite and martensite can be controlled to influence the strength and ductility [12,13]. Also, that the yield strength and the ultimate tensile strength increase with higher intercritical temperatures and cooling rates [15,16]. They also report microstructural effects on the fatigue crack growth behavior of a

* corresponding author. Tel.: +60 167 279048; fax: +60 755 66159.
E-mail address: yunan.prawoto@gmail.com (Y. Prawoto).

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micro-alloyed steel and these results allow correlating the tensile properties and crack growth resistance with microstructural and morphological features [10]. The volume fraction and morphology are also of interest for many, e.g., [14,17,18,2].

In an attempt to conduct similar research, our research group has been studying this for some time. This paper is a continuation of previously published research [5,17,18,2]. In these papers, the conceptual design, as well as the computation results and parts of the static and impact experiments, were discussed. In contrast, here the discussion is focused on the fatigue crack propagation experimental procedure and the verification of the results with computational results. In other words, this research was done to obtain an optimized sample that gains its fatigue performance from its high toughness yet possesses high tensile properties due to its tailored microstructure. Ultimately, the objective is to achieve a microstructure that resists fatigue more than the microstructures conventionally available, and in an economical manner.

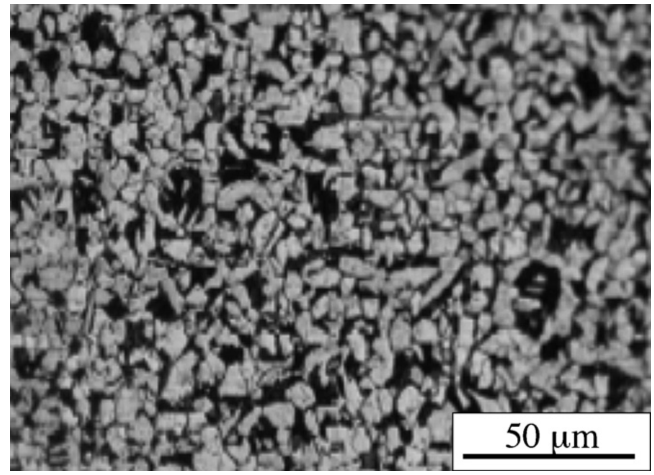

Fig. 2. Microstructure of as-received materials, low carbon steel.

2. Experimental approach

2.1. Material preparation and heat treatment

The material used for the investigation was a low carbon steel, shown in Table 1. The specimen was prepared in accordance to ASTM E647 [19] with the dimensions of $W = 25$ mm, α, or $a/W = 0.36$, and $B = 6.5$ mm, see Fig. 1. The specimens were machined using wire cut EDM (electric discharge machining) and subsequently pre-cracked using a hydraulic fatigue machine with load decreasing wave to guarantee that an excessive plastic zone does not develop in front of the crack tip.

Two successive thermal treatment processes were then applied after the specimens were machined according to ASTM E647 to obtain dual-phase material with different ferrite fractions. In the first process, the as-received specimens were annealed at different temperatures in order to get different ferrite fractions. The specimens were held in the furnace at 748 °C, 768 °C, 789 °C, 809 °C, 830 °C, and 1000 °C for 90 min, followed by water quenching (intercritically annealed). It is worth noting that traditionally, low carbon steel is tempered after heat treatment between 200 °C and 600 °C [20,21]. In this work, the tempering temperature was selected mimicking other researcher's works [7]. The second process was tempering, at a temperature of 350 °C, held for 2 h and air cooled to form tempered martensite. All the specimens are labeled MPM-xxx, where the last three letters correspond to the intercritical temperature, see also Table 2.

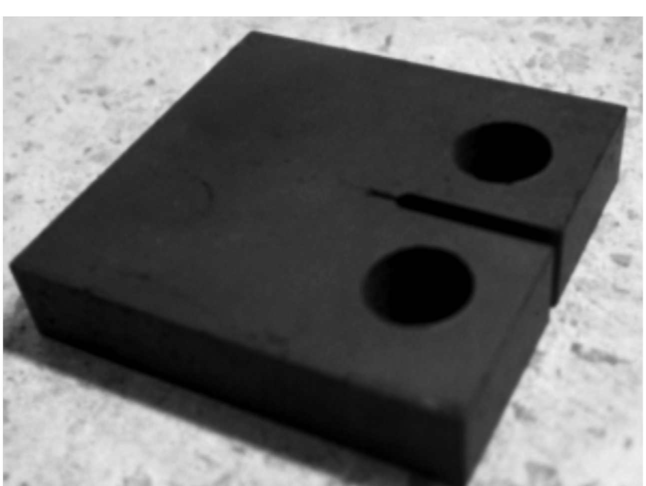

Fig. 1. Test specimen for fatigue crack propagation.

2.2. Metallographic studies

After the thermal treatment, cross-sections of the samples were ground, polished, etched with Nital (2% nitric acid in methyl alcohol), and observed by using an image analyzer to reveal the morphology of the phases. The areal fractions of ferrite were then determined by the point counting method, as done by other researchers [7,1,14].

Fig. 2 shows the microstructure of the as-received, low carbon steel consisting of ferrite and pearlite. The microstructure of MPM-748, MPM-768, MPM-789, MPM-809, MPM-830, and MPM-1000, which was intercritically annealed having ferrite contents varying between 0% and 65%, is shown in Fig. 3. Table 2 shows the areal percentage of ferrite consisting of different multi-phase materials, MPM. The arrangement of the microstructure is roughly proportional to the temperature at which the specimens were heated. In this research, temperature is the only parameter that was varied to obtain multi-phase microstructure, so it is a combination of mainly ferrite and martensite. The areal ferrite fraction estimated in the MPM depended on the soaking temperature. It was observed that the areal fraction of ferrite increases as the annealing temperature decreases. On the other hand, it was observed that the martensite volume fraction, MVF, increases with increasing intercritical annealing temperature. Similar results were obtained by other researchers [1,10,15]. the volume fraction of proeutectoid and martensite can be controlled to influence the strength and ductility. The relationship between annealing temperature and ferrite/martensite fraction are quite evident from the Fe—C equilibrium diagram [14]. According to the lever rule, increasing the temperature leads to an increase in the austenite volume fraction, which then would transform to martensite upon water quenching.

2.3. Fatigue crack propagation test

FCP (fatigue crack propagation) tests were conducted according to ASTM E647 [19] procedures using a 100 kN servo-hydraulic closed-loop dynamic testing machine, INSTRON 8801, under load control mode in constant load amplitude, ΔP conditions. The tests were performed in air at room temperature, loading at a frequency of 20 Hz with a sinusoidal waveform. The load ratio was chosen