An Experimental Investigation of Tensile Properties and Fatigue Crack Growth Behaviour for Dual-Phase Steel

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ABSTRACT

This paper presents the fatigue crack growth behaviour of a dual-phase steel. The fatigue strength of dual-phase steels can be influenced by their inherent microstructural phases, where hard martensitic phases are dispersed in a soft ferritic matrix. The main objective of this study is to investigate the fatigue crack growth behaviour of a dual-phase steel. The dual-phase steel was achieved by inter-critical heat treatments which specifically aimed to increase the resistance of the steel to fatigue loading. The tensile properties of dual-phase steels have been studied through tensile testing methods, while their fatigue crack growth behaviours have been experimentally investigated using compact-tension specimen under constant amplitude loading. The experimental results indicated that the fatigue crack growths in as-received steels could propagate more freely than that in dual-phase steel microstructures; thereby giving dual-phase steels a longer fatigue life compared to the as-received steels. A crack growth of about 22 % lower was observed in the dual-phase specimens compared to the as-received specimens. Finally, the variation of fatigue crack growth rate with stress intensity factor range for as-received and dual-phase steels was discussed within the Paris region. It was concluded that the presence of second hard phases (martensite) in dual-phase steel effectively retarded crack growths.

Keywords: *Dual-phase steel; Fatigue crack growth behaviour; Microstructure; Tensile properties*

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Introduction

Dual-phase steels most certainly been widely used in the automotive industry to reduce vehicle weight and enhance car safety. The dual-phase steels found major applications in the automotive structures such as longitudinal beams, cross members and reinforcements due to their combination of high strength and formability. The utilization of dual-phase steels in future automobiles will reach 80 % as predicted by the World Steel Association [1]. These steels are characterized by high strength, good ductility and high initial work hardening rates, which differentiates them from other Advanced High Strength Steels (AHSS) [2-4]. It is impossible to obtain good ductility and high strength at the same time in the conventional steels. Therefore, inter-critical heat treatment is the way to enhance the low alloy steels to dual-phase steels, which mostly contain ferrite and martensite phases with superior strength-ductility combinations.

In recent years, many researchers [5-8] found that fatigue crack growth (FCG) is effectively influenced by the distribution of the second hard phase martensite or bainite within the soft ferrite matrix. The microstructural content and morphology of the second phase would be significantly affected by the FCG rate [5, 6]. Besides that, an increase of the martensite volume fraction promotes the formation of most involving microcracks under the slip bands next to the martensite-ferrite interfaces [9]. The dual-phase steels in automotive applications are characteristically subjected to cyclic loading during use; consequently leading to catastrophic fracture after a certain period [10]. Furthermore, fatigue is one of the major causes of auto part failures. Thus, it has been of valuable importance to investigate the FCG behaviour of dual-phase steels.

This study made efforts to show that the dual-phase steels have a microstructure that resists FCG more than the microstructures of the conventionally available as-received steels. Therefore, we aim to investigate the FCG behaviour of dual-phase steels and as-received steels in terms of fatigue resistance. The as-received steels served as a benchmark for the studies on the dual-phase steels. The dual-phase steel was achieved by inter-critical heat treatments. The FCG behaviour have been experimentally investigated using compact-tension specimen under constant amplitude loading for as-received and dual-phase steels. The results derived from FCG tests reveal that the presence of second hard phases (martensite) in dual-phase steel can effectively retarded the crack growth. The martensite will hampered the crack from expanding, as shown in Figure 1. Furthermore, the FCG rate with stress intensity factor range ΔK for the as-received and dual-phase steels was discussed within the Paris region.

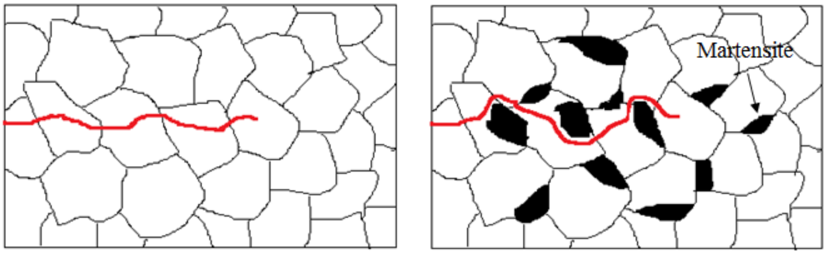


Figure 1: Schematic of crack path in ; (a) as-received steel and (b) dual-phase steel.

Materials and Methods

Materials and Specimens Preparation

In this study, the material used for the investigation was a low-carbon steel with the chemical composition shown in Table 1. This steel was selected since temperature ranges between Eutectoid temperatures, A_1, minimum temperature of austenite, and lower-bound temperature for austenite, A_3 within the iron-carbon phase diagram are classified as the largest when compared to others carbon steel. A dual-phase steel is produced by subjecting low-carbon steel samples to inter-critical annealing from temperatures above A_1 but below A_3 among the two phases (ferrite + austenite) region intended for a certain period, followed by water quenching.

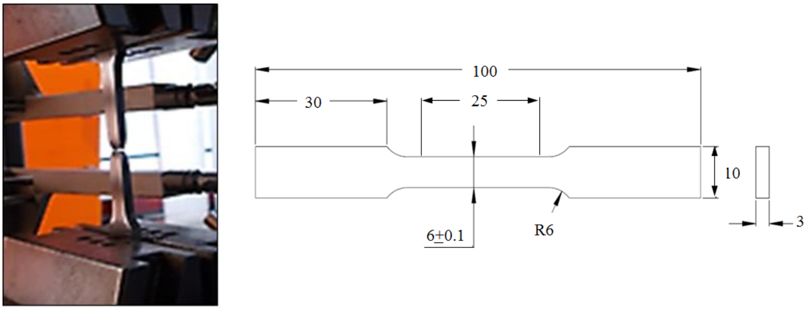
Two following heat treatment procedures were carried out to gain the dual-phase material. Initially, the as-received specimens were inter-critically annealed at 760 °C for 90 min, followed by water quenching in the first process. The temperature range was selected based on the highest fatigue strength [9]. The second process includes tempering at 400 °C, holding for 2 hours, and cooling at room temperature to eliminate residual stresses and improve toughness. This tempering temperature was selected due to the fact that conventionally, low-carbon steels are tempered just after heat treatment ranging from 200 °C and 600 °C [11-13]. All the specimens (as-received and dual-phase specimens) were mechanically polished to remove all damaged layers.

Tensile and Fatigue Crack Growth (FCG) Rate Test

The tensile specimens have been well prepared according to ASTM E8 in sub-size dimensions, with a gauge length of 25 mm, as presented in Figure 2. The tensile tests have been carried out based on ASTM E8 procedures at room temperature by using universal testing machine with a cross-head speed of 1.8 mm/min (strain rate of 0.001 s^{-1}).

Table 1: Chemical composition of the steel, wt %

Elements	C	Mn	Si	P	S	Al
wt (%)	0.192	1.61	0.384	0.0162	0.0085	0.0314



(a) (b)

Figure 2: (a) Experimental setup for tensile test, (b) Specimen geometry used for tensile testing (all dimensions are in millimeters).

The compact tension (CT) specimens have been well prepared according to ASTM E647, by having dimensions of width (W) = 50 mm and thickness (B) = 12 mm, as presented in Figure 3. Wire cut EDM (electric discharge machining) were used to cut the specimen. The residual compressive stresses that might result from the milling process [14] have been reduced by cutting a sharp notch of 4 mm wide using EDM. Prior to FCG rate tests, each CT sample was subjected to fatigue loading to acquire a pre-crack with a length of about 1.2 mm. The fatigue pre-cracking process was important to offer a sharpened fatigue crack of acceptable size and straightness, and also to remove the effect of machined starter notch. The tests were conducted under constant amplitude sinusoidal loading, with a load ratio of $R = 0.1$ and frequency 10 Hz in the ambient room temperature [4, 15]. All the CT specimens were subjected to mode I opening loading. The compliance method have been applied to measure the fatigue crack length by employing a clip gauge at the notch mouth. The experimental process flow is shown in Figure 4.

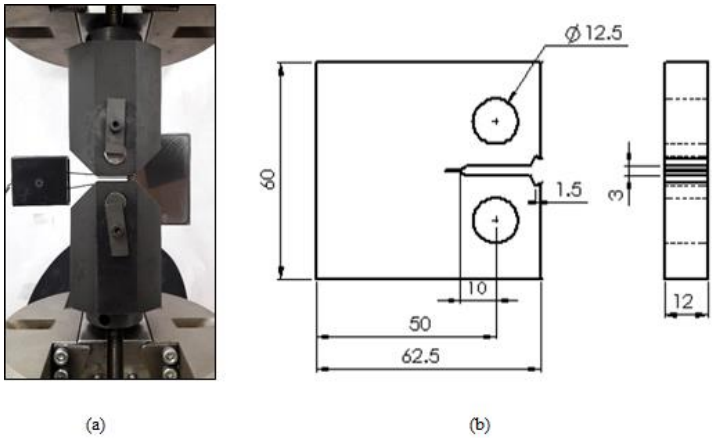


Figure 3: (a) Experimental setup for FCG rate test, (b) Specimen geometry used for FCG rate test (all dimensions are in millimeters)

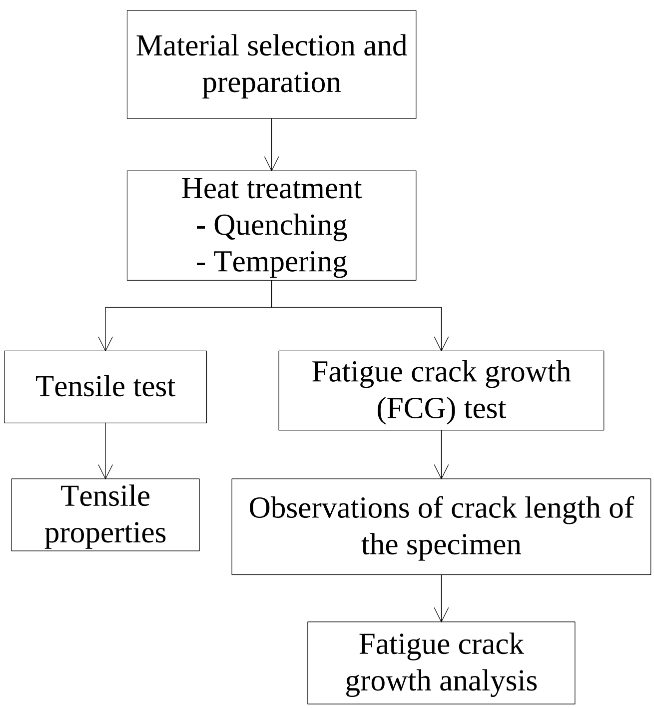


Figure 4: Process flow of the experimental procedure.

Fatigue Crack Growth Data Analysis

The FCG behaviour of the as-received and dual-phase steels was described by applying the conventional Paris model, given by Equation (1):

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

where da/dN is the FCG rate, C and m are constants that vary from materials and ΔK is the stress intensity factor range, calculated as follow;

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{2+\alpha}{(1-\alpha)^{3/2}}\left(0.886 + 4.64\alpha - 13.32\alpha^{2} + 14.72\alpha^{3} - 5.6\alpha^{4}\right) \tag{2}$$

where B and W are the specimen's thickness and width respectively, α is the relative crack length (a/W), and ΔP is the applied load range.

Results and Discussions

Tensile Properties

The heat treatment process effectively change the tensile property of the dual-phase steels when compared to the as-received steels. Table 2 presented the differences in the tensile property of the as-received and dual-phase steel specimens. Figure 5 shows the true stress - strain curves for the as-received and dual-phase steels. The yielding plateau in the as-received steel and the continuous yielding phenomenon in the dual-phase steel proved the formation of a second hard phase (martensite) in the dual-phase steel. It was found that the values of ductility for the dual-phase specimens were lower when compared with those of the as-received specimen. This artifact occurred because of the existence of harder and less ductile ferrite matrix within the microstructure of the dual-phase steel specimen. The greater ductility found in the as-received specimen was resulting from the ferrite-pearlite structures being softer as compared to the martensitic structures contained in the dual-phase steel.

It can be observed that the tensile properties significantly changed after heat treatments process. This can be proven by an increase in the yield strength and ultimate tensile strength of the dual-phase steels. The yield and ultimate tensile strength increased rapidly after heat treatments and continued up to 495 MPa and 597 MPa for the dual-phase and as-received steels, respectively. This specifies that the strength values considering the investigated dual-phase steel were higher compared to that of the as-received steel resulting from the presence of the harder second phase within the dual-phase steel [7]. However, it must be noted the fact that the strength of the martensite produced in the soft ferrite matrix might be different from the structure formed when steel was changed from austenite to 100 % martensite [16].

Table 2: Tensile properties of the steels

Properties	Measured value	
	As-received	Dual-phase
0.2 % Yield strength (MPa)	388	495
Tensile strength (MPa)	536	597
Elongation at fracture (%)	30	13
Yield ratio (%)	72	83
Young's modulus (GPa)	204	185

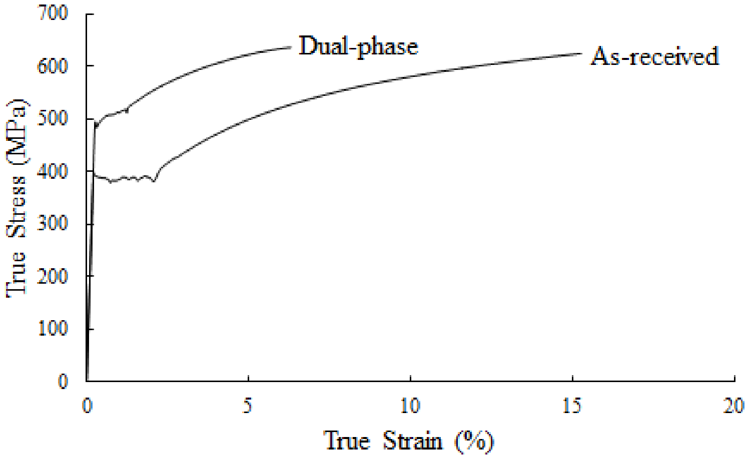


Figure 5: True stress-strain curves for as-received and dual-phase steels.

Fatigue Crack Growth (FCG) Behaviour

The fatigue crack growth process often are classified as three stages, which are the slow growing region (stage I), the stable growing region (stage II), and the rapidly growing region (stage III). In this particular study, the tests were mainly for stage II, certainly the most valued stage for fatigue life estimation. Figure 6 shows the crack length versus fatigue cycles (a-N) curves for the as-received and dual-phase steels. This figure shows that the crack initially grew from a slow rate and start accelerates as increases of the crack length after passing through many cycles. A final point for each curve is represented by means of the final fracture through the fatigue crack growth testing.

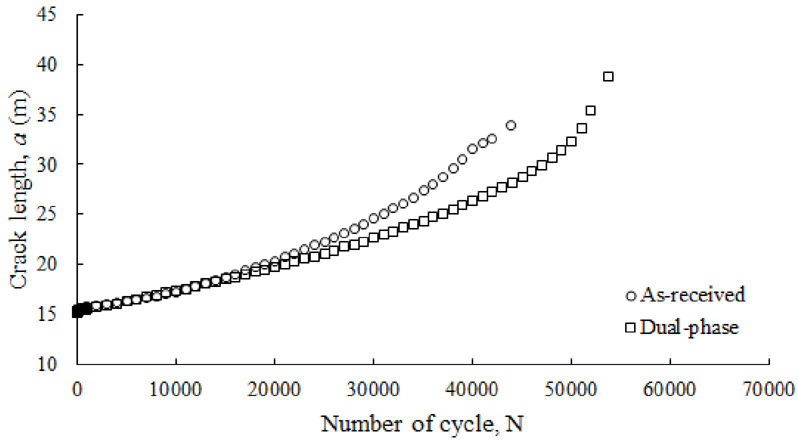


Figure 6: Fatigue life of as-received and dual-phase steels based on crack length observations.

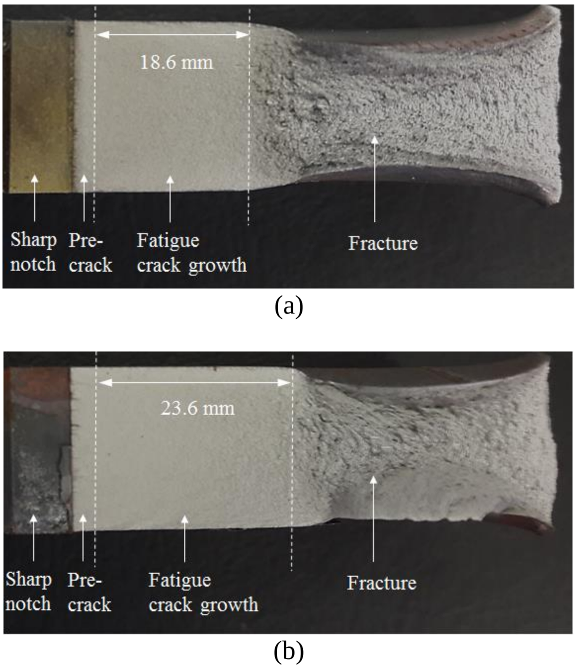


Figure 7: Fracture surface; (a) as-received specimen and (b) dual-phase specimen.

Figure 7 shows the fracture surface observation of as-received and dual-phase steels, including the sharp notch, pre-crack, fatigue crack growth and fracture regions. Note that the dual-phase specimen have the longest life at 53,674 cycles compared to the as-received specimens which have life at 43,910 cycles. This indicated that the crack growth in the dual-phase specimen was about 22 % slower than in the as-received specimen. It was clearly observed by measuring the length of the fatigue crack growth region on the fracture surface of the specimens (Figure 7). The length of the fatigue crack growth region for the dual-phase specimen was longer (23.4 mm) compared to 18.6 mm of the as-received specimen. This indicates that the longer the stable growing region (stage II) which represents the fatigue crack growth region, the longer the specimen's lifetime.

The FCG rate results in stage II for the as-received and dual-phase specimens, calculated according to the Paris model of Equation (1), and plotted together with the experimental points was presented in Figure 8. As can be seen from Figure 8, there are almost linear in logarithmic relationship between the stress intensity factor range, ΔK and FCG rate, da/dN. The results of the Paris model agreed having the experimental data, and the correlation coefficients of 0.994 and 0.995 for the as-received and dual-phase steel specimen respectively, were obtained statistically. The FCG rate of the as-received specimen was larger than that of the dual-phase specimen under the same ΔK. This happened due to the existence of harder phases (martensite) and less ductile ferrite matrix in the dual-phase microstructure. The martensite will hampered the crack from expanding. On the other hand, the cracks of the dual-phase specimen, which consists of martensite phases, expands slower than that of the as-received specimen. The increases of the martensite content increased the crack rate encounters with martensite islands. It means that the crack path was greatly much more complex, slowing down the crack propagation rate [17].

Additionally, the martensite produced at much higher austenitizing temperatures provide lower carbon, (i.e. certainly tougher), and thus, efficiently decreases the crack tip driving force through crack tip blunting and deflection. The FCG rate and da/dN in stage II for the as-received specimen ranged between 2.08 x 10^{-7} and 7.0 x 10^{-6} m/cycle respectively, while the range of ΔK varied from 27.9 to 79.7 MPa.m$^{1/2}$. The FCG rate and da/dN for the dual-phase specimen ranged between 1.14 x 10^{-7} and 9.07 x 10^{-6} m/cycle, and the range of ΔK varied from 27.3 to 80.9 MPa.m$^{1/2}$. This result indicates that the FCG rate was influenced by the microstructure.

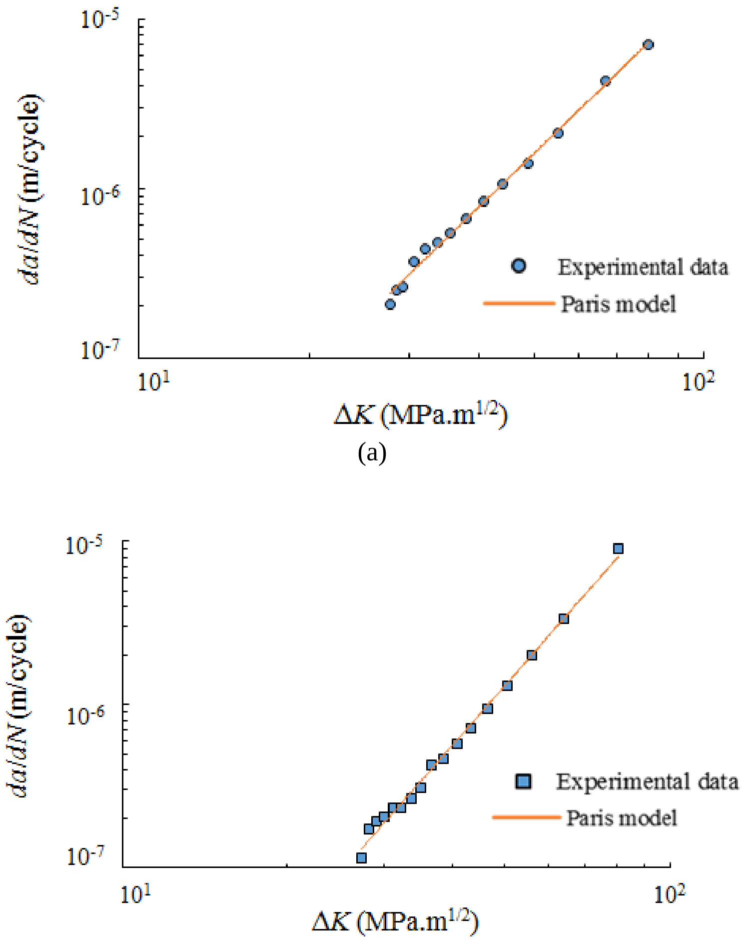


Figure 8: Fatigue crack growth curve described by the Paris model of (a) as-received and (b) dual-phase steels.

Table 3 showed the calculated *C* and *m* values, as well as the threshold value ΔK_{th} for the as-received and dual-phase specimens. The results showed that the dual-phase specimen had a higher threshold value ΔK_{th} compared to the as-received specimen. The fatigue crack in the as-received specimen propagated at a faster rate than that of the dual-phase specimen for the identical crack tip driving force, ΔK within the Paris crack growth region. The slope of a given FCG curves gained from the Paris model appeared to be equivalent to *m* which is certainly associated to the microstructure of materials. In this study, *m* for the as-received specimen was smaller than *m* for the dual-phase specimen. As stated earlier, m is certainly associated to the microstructure of materials, and in this study, $m_{as\text{-}received} < m_{dual\text{-}phase}$. This shows that the rate of FCG for dual-phase steels increases by increase of martensite content. The C and m for various materials vary, proving that almost all of those parameters are closely related towards the microstructure of materials. A higher martensite content enhances the interfacial region of ferrite and martensite; that is certainly instead of crack nucleation, so da/dN is influenced by ΔK greatly, which certainly may explain the difference in these parameters.

The fatigue behaviour of dual-phase steels is typically a part of the strain distribution involving the ferrite and martensite elements and allowing the crack to growth [9]. A noticeable growth in crack resistance of dual-phase steels was detected in this study. It could be explained that these formation related to harder phases with water quenching was accountable for this increase. The harder phases have been distribute within the softer ferritic matrix; and hence, making a possibility for the crack tends diverge from these phases and propagate mostly throughout the ferrite, which leads much more complex crack path within the heat treatment condition (annealed + quenched followed by tempering process) as shown in Figure 1. The FCG rate was found to decrease and ΔK_{th} to increase for the dual-phase specimen. The fatigue crack growth threshold was comparatively low, and the results agreed with those of other researchers who reported a decrease in the threshold value ΔK_{th} for long cracks with grain size [18].

Table 3: Fitting parameters for the Paris model

Material	C	m	Correlative coefficient	ΔK_{th} (MPa.m$^{1/2}$)
As-received	5.31×10^{-12}	3.22	0.994	17.56
Dual-phase	4.33×10^{-13}	3.82	0.995	18.12

Conclusion

This study presents a comprehensive analysis of the FCG behaviour in dual-phase steels. The dual-phase steel was produced by inter-critically heating of low carbon steel, followed by tempering processes to obtain higher fatigue strengths that will have an enhanced fatigue resistance compared to the microstructures of the conventionally available steels. The tensile and FCG rate tests were conducted to investigate the behaviour of FCG rate for as-received and dual-phase steels. It was found that the yield strength, ultimate tensile strength, and the yield ratio increased rapidly after heat treatments. The total elongation at fracture gradually decreased as a result of the existence of harder and less ductile ferrite matrix within the microstructure of a given dual-phase steel specimens. The fatigue life of dual-phase was observed to be higher than that of as-received steels. The experimental results show that the fatigue crack growth in as-received steels were propagate more freely than that in dual-phase steel microstructures, giving a longer fatigue life to the dual-phase steel compared to the as-received steel. It was observed that the FCG rate of as-received steels was higher than that of dual-phase steels, indicating that the second hard phases (martensite) efficiently retarded the crack growth. The experimental results showed that the dual-phase steels produced a higher fatigue strength, lower FCG rate, and had a microstructure with increased fatigue resistance compared to the microstructures of the as-received steels.

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