The Effect of Ferrite Grain Size on the Fatigue Behavior of Ferrite-martensite Dual-phase Steels

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Abstract

The effect of ferrite grain size on the fatigue and tensile properties of dual phase steels with a 0.25 volume fraction of martensite (V_m) under different heat treatments was investigated. The heat treatments were homogenized at 1200 ^oC along with several subsequent normalizations at 910 ^oC, resulting in different microstructures and mechanical properties. After heat treatment, the obtained steels, with different ferrite grain sizes, were heat treated to obtain a dual phase ferritic-martensitic microstructure. In order to process the dual phase steels, low carbon manganese steel was used. Fatigue tests were carried out at room temperature and the fracture surfaces of the fatigue specimens were studied by SEM. The data obtained by the fatigue tests indicated that the fatigue strength at 107 cycles had a linear increase with decreasing the grain size of ferrite, while higher applied stress had a little effect on the grain size and the fatigue strength. The fracture surface of the fatigue specimens showed two distinct regions, namely, the fatigue fracture and the final fracture. Striation lines were clearly seen in the region of the fatigue failure. Furthermore, for all microstructures, the final fracture was mainly brittle.

Keywords: Dual phase steels; Fatigue; Ferrite-martensite, Grain size, Heat treatment.

1. Introduction

A recently developed class of steels known as dual phase steels is characterized by a microstructure basically consisting of a ductile ferrite phase and a high strength reinforcing martensite phase providing low yield stress, superior strain hardening rate, high tensile strength, good ductility, and good formability [1, 2]. Depending on the cooling rate, the two phases present in the microstructure of the dual phase steels may also contain retained austenite, new ferrite (epitaxial ferrite), and bainite [2–6].

In recent years, the application of high strength steels, especially dual phase steels, has had a great effect on the automotive industry. This improvement originates from the characteristics of dual phase steels [7, 8]. In the production of dual phase steels, different heat treatment procedures can be applied, resulting in different microstructures and mechanical properties due to the different obtained microstructures. The resulting microstructures consist of ferrite and martensite phases, but the volume fraction and morphology are largely varied by the quenching paths [2, 9].

The fatigue behavior and fracture toughness of two-ductile-phase alloys are complex phenomena [10, 11].

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Strain is more extensive in the softer phase and stress is higher in the harder phase at a given overall applied strain. This distribution of stress and strain has been observed for dual phase steels [12-14]. Although considerable experimental work has been carried out on these materials, there is still no theory or model that would account for the mentioned varied behavior [10]. For example, it is generally acknowledged that the introduction of retained austenite in steels can effectively benefit the combination of strength and toughness, but there is no agreement on whether retained austenite is effective for fatigue property or not [15, 16]. Ritchie [17] studied the effect of the retained austenite on the fatigue crack propagation and confirmed the positive influence of the retained austenite on the crack propagation stage. In this stage, the retained austenite blunts the tip of the crack and brings turning and branching to crack, dissipating the energy of the crack propagation and effectively hindering the crack growth. Nevertheless, the effect of the retained austenite on the crack initiation stage remains unclear. Some of the factors that influence the impact properties are morphology, distribution and carbon content of the martensite phase and the ferrite grain size. The effects of the ferrite grain size are not considerable when martensite percent is high enough to form a continuous phase [18]. On the other hand, using dual phase steels with a 0.25 volume fraction of martensite gives the best combination of the useful properties for the automotive industry [19,20]. Most of the products made from ferrite-martensite dual phase steels are exposed to cyclic forces during application. In this regard, the majority of researches have concentrated on the effect of volume fraction and morphology of martensite on the fatigue behavior of these steels. Another important parameter that affects the fatigue behavior of these steels is the ferrite grain size, which has been considerably neglected. Also, the reports on the effect of grain size on tensile properties are varied [21]. In the present research, the effect of ferrite grain size on tensile and fatigue behaviors of dual phase magnesium-containing steels was studied. Also, by examining the fracture surface, the crack nucleation site and the fracture type were identified. The previous studies have mainly focused on high-martensite dual phase steels not appropriate for use in automotive industry because of their low ductility and toughness properties. The previous works on low-martensite dual phase steels were mainly concerned with impact properties [21], but in this research, the effects of the ferrite grain size on fatigue properties as well as the tensile strength of the dual phase steels with a 0.25 V_m martensite were addressed. To substantiate this for the used C-Mn steel, the relationship between the fatigue strength and yield strength was also investigated.

2. Experimental Procedure

The composition of the initial used steel is shown in Table 1. It was supplied in the form of hot rolled plate with 10 mm thickness and a ferrite-pearlite structure along with slight banding (Fig. 1). In this Fig, the light and dark spots correspond to ferrite and pearlite, respectively.

Table 1. Chemical composition of the initial C-Mn steel.

Elements	C	Mn	Si	Cr	Ni	W	P	S
wt. %	0.130	1.360	0.233	0.063	0.032	0.014	0.014	0.009

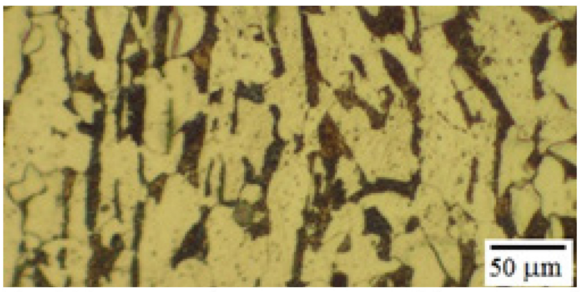

Fig. 1. Ferrite - pearlite microstructure of the as-received steel, showing the banding feature of the phases.

At the first stage, to eliminate the banding present in the initial steel, all specimens were homogenized at 1200 °C for 5 h (cooled in the furnace). Then the normalized treatment was applied to the specimens for different times with the aim of obtaining fine ferrite-pearlite sizes as listed Table 2. The volume fraction and grain sizes of the specimens were obtained by the method described in a previously published work [21].

Table 2. The heat treatment schemes used to obtain different grain sizes of ferrite for the ferrite-pearlite structure.

Sample No.	Heat treatments	No. of normalizing	Temperature (°C) & time (min) of normalizing	Cooling media	Mean ferrite length(µm)	ASTM No. of ferrite grains
1	Homogenized	-	-	-	74.3	5(4.9)
2	Homogenized & normalized	1	910-10	Furnace	29.1	8(7.6)
3	Homogenized & normalized	3	910-10	Air	9.3	11(10.9)

The used heat treatments were selected to have mini mum retained austenite in the steels. Finally, to obtain a dual phase structure, the heat treatment was done at the austenite + ferrite region. To obtain a 0.25 volume fraction of martensite, the intercritical direct annealing treatments were performed at 725 °C for 45 minutes and this was followed by quenching in brine solution. To make sure that the two phases present in the microstructure were ferrite and martensite, microhardness was applied. At least, six hardness values were taken in each sample. The soft phase had a hardness value around 200 Vickers while the harder phase had a value around 510 Vickers, showing that we had obtained a ferrite–martensite microstructure. Tensile testing of the specimens, in accordance with the ASTM standard (A370-B), was conducted at room temperature in a computer controlled Hounsfield machine using a cross head velocity of 0.50 mm/min. The general characterization of the achieved ferrite–martensite dual phase steels, such as continuous yielding, has been described in a previously published work [21].

Cylindrical cross-section specimens with a length of 54mm, parallel to the rolling direction with a gauge length of 18mm and the thickness of 8mm, were machined for fatigue tests. The specimens were prepared and loaded according to the ASTM E466 standard and their machined surfaces were polished to 1µm by a diamond-based polishing compound. A cyclic frequency of 2850 rpm was employed for all tests. The total separation of the specimen into two parts was considered as failure and the final life of the specimen. Fracture surfaces of the failed specimens were observed using a scanning electron microscope (JEOL, Model JXA 480). by a diamond-based polishing compound. A cyclic frequency of 2850 rpm was employed for all tests. The total separation of the specimen into two parts was considered as failure and the final life of the specimen. Fracture surfaces of the failed specimens were observed using a scanning electron microscope (JEOL, Model JXA 480).

3. Results and Discussion

Fig. 2 shows the morphologies of different dual phase steels. In these microstructures, martensite islands (dark phase) of irregular shape were embedded in the continuous ferrite phase.

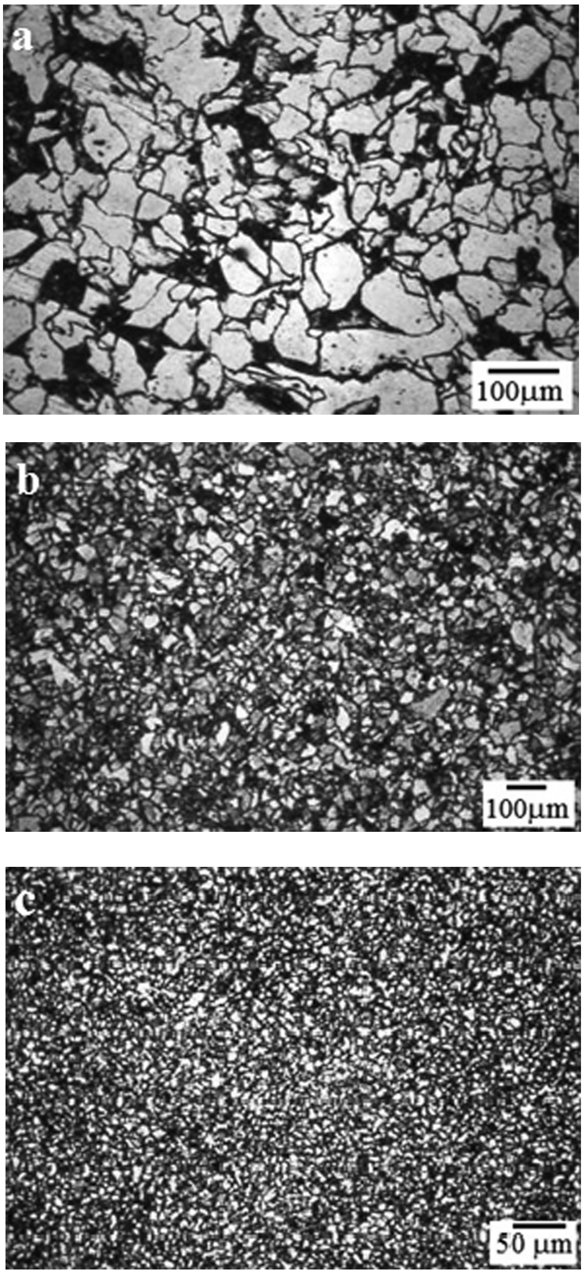

Fig. 2. Microstructure of dual phase steel achieved from the grain size of ferrite (a) 74.3 µm, (b) 29.1 µm, and (c) 9.3 µm.

Due to the fact that the ferrite phase had been principally nucleated at the austenite grain boundaries and grown into the interior of the austenite grain during cooling in the region of the intercritical temperature, the ferrite phase became a continuous phase after water quenching; so, it was regarded as the matrix phase in ferrite-martensite composites. The volume fraction of martensite (V_m) under different heat treatments was about 25 percent. The optical micrographs in Fig. 2 clearly show that the grain size of ferrite was reduced from samples (a) to (b). The effect of heat treatment on the ferrite grainsize is also presented in Table 2. The measured mean grain size of ferrite was reduced from 74.3 µm to 9.3 µm by various post heat treatments. Sample No. 2 showed the maximum rate of reduction in the ferrite grain size. It means that the first normalizing treatment had the most effect on the reduction of the grain size. The three different grain sizes of ferrite obtained from different heat treatment procedures led to various mechanical properties. From the measured tensile properties (Table 3), it could be seen that refining the ferrite grain size in all dual phase steels resulted in better tensile properties, as reported by other researchers [22, 23].

Table 3. The tensile and hardness properties.

Sample No.	Mean ferrite length (µm)	YS (MPa)	UTS (MPa)	YS/TS	Elongation	Hardness (Vickers)
1	74.3	459.3	653	0.703	25.2	123.5
2	29.1	472.1	720	0.655	20.2	140.7
3	9.3	505	840	0.601	13.7	150

As mentioned earlier [21], the dislocation concentration around the brittle martensite phase is high, causing the ferrite phase to be under stress. Refining the ferrite grains results in a higher concentration or at least, more non-uniform distribution of dislocations at the ferrite grain boundary because the locking of the dislocations is more. This concentration causes more locked dislocations, resulting in a higher tensile property. The higher YS and UTS values in Table 3 indicate that the work hardening was as a result of the locked dislocations and it was higher in more refined ferrite steels as compared to the coarser specimens.

Generally, the difference in yield and tensile strengths of this group of steels is one of their important properties. With the decrease in the ferrite grain size, the difference between yield and tensile strengths is increased, and accordingly, the YS/UTS ratio is decreased. The reason of this lowering is the increase of the work hardening of the ferrite grains. Studies have demonstrated that deformation of a completely soft phase such as ferrite with a distribution of hard constituents such as the martensite phase with very low formability results in a plastic strain slope in the soft phase, which can decrease the dislocations movement, thereby lowering the YS/UTS ratio and increasing the work hardening. The other tensile properties are given in Table 3.

Fig. 3 shows the S-N curves of the dual phase steel with different ferrite grain sizes. From the S-N curves plotted with the data obtained by the fatigue test, it could be seen that the fatigue strength was increased by 24.5 percent through decreasing the grain size of ferrite from 74.3 μm to 9.3 μm. The plots revealed that fatigue strengths were not considerably changed at high applied stress (or low cycle fatigue).

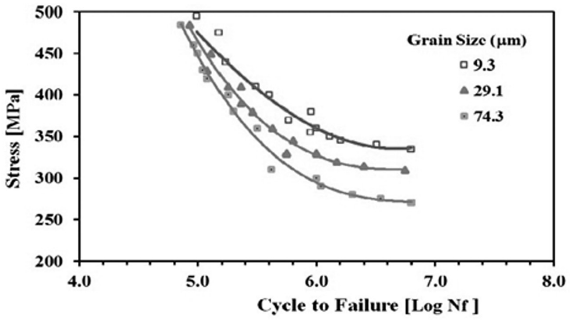

Fig. 3. Comparison of the S-N fatigue curve between different dual phase steels.

Fig. 4 shows the relationship between the fatigue limit (10^7 cycles) and ferrite grain size in dual phase steels with a constant 25%volume fraction of martensite. Furthermore, it can be observed that the fatigue limit of the ferrite grain size varied linearly. The relationship between the fatigue limit and grain size can be expressed according to Eq. (1):

$$\sigma_{10^7} = 337 - 0.98 d_f \quad \text{Eq. (1)}$$

where σ_{10^7} is the fatigue limit (MPa), and d_f is the ferrite grain size (μm).

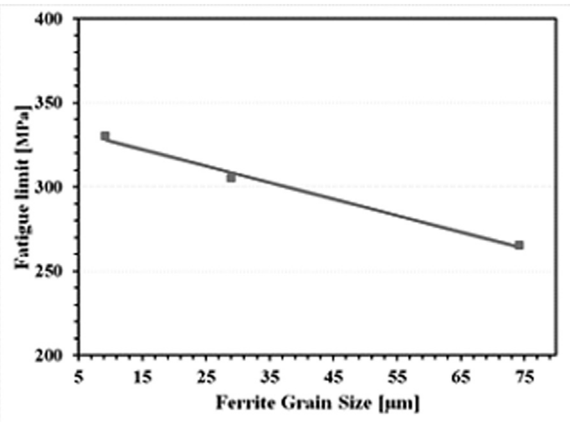

Fig. 4. The fatigue limit variation with the grain size of ferrite in dual phase steels.

In addition, yield strength and microstructure play a highly significant role in the fatigue strength. As noted by Szewczyk [7, 18)], the volume fraction of the phases is one of the important factors. Also, the specific matrix (the hard or soft phase), the grain size and the morphology of the phases, the slip character and the transformation to the hard martensite phase are highly important. For crack propagation, the texture may have a noticeable effect. It should be noted that various microstructural factors do not necessarily have the same influence on the crack nucleation and crack propagation [10,25)].

Recently, it has been reported that the fatigue strength of normalized carbon steels should be attributed to their tensile properties [26)]. To substantiate this for the used dual steels, the relationship between the fatigue strength and yield strength was investigated. Interestingly, there was a nearly linear relationship between them for the used dual steels even though some scattered data were observed. It can be understood from these results that the yield strength can directly influence the fatigue strength. An important fact is that the fatigue strength is affected by the ultimate tensile strength. Such a change in the relationship may be explained by [27)] work hardening. In this case, a low work hardening rate gives a high value for the slope of the fatigue strength and the ultimate tensile strength relationship. In this work, it was observed that the ratio between the fatigue limit with yield strength and tensile strength in this group of steels was fixed to 0.6 and 0.41, respectively.

The fractography of the fatigue specimen surfaces showed two distinct regions: fatigue fracture and final fracture. The results of this research on the nucleation of fatigue were in agreement with the presented models by others. In Fig. 5, the location of the crack nucleation along with the step of the fracture is shown. In this research, due to the application of torsion- bending method, the surface of the specimen was under more stress and this was the reason why the cracks had been initiated at the surface. Szewczyk and Gurland [25)] reported that the extensive plastic deformation of the martensite phase in a commercial dual phase steel occurred primarily in the necked region of the tensile specimens. Thus, as a result of the strain concentration in the softer phase of the two-ductile-phase materials, the fatigue crack nucleation is likely to begin at the soft phase.

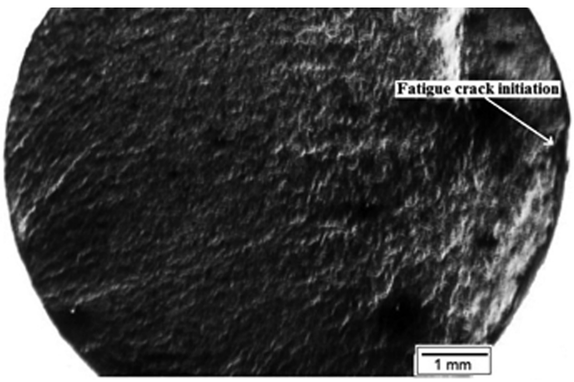

Fig. 5. Nucleation of the fatigue crack at the surface of the specimen and the fracture step of the dual phase steel with a grain size of 9.3 μm.

Fig. 6 shows the fatigue fractures of the dual phase steel with a ferrite mean grain size of 74.3 μm and 9.3 μm under an applied stress of 270 MPa and 485MPa, respectively. In both cases, the striations as well as the fatigue beach marks of the ferrite parts (ductile) and some cleavage fracture in martensite parts were clearly revealed. As can be seen, the direction of the crack growth was changed from one grain to another, due to the continuous martensite phase in this dual phase structure.

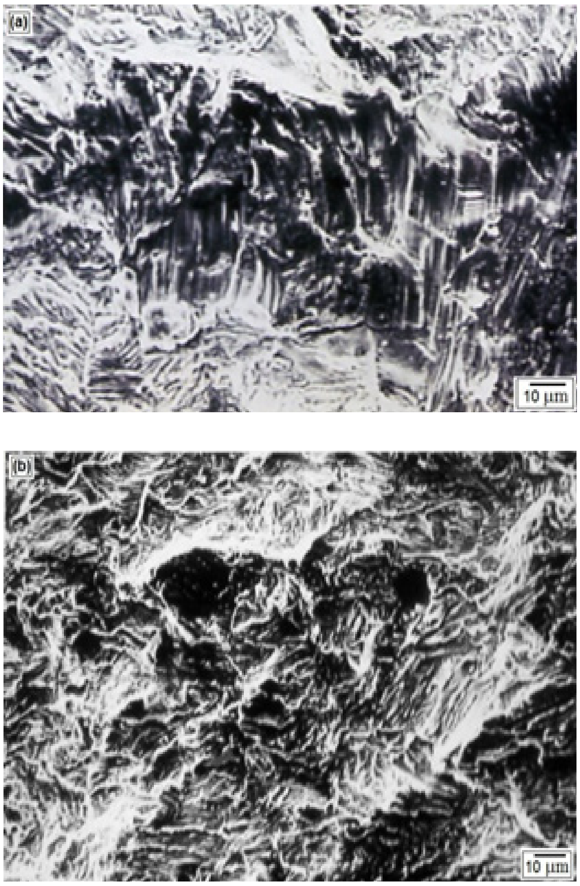

Fig. 6. Fatigue fracture surfaces of the dual phase steels with a ferrite mean grain size of a) 74.3 µm, b) 9.3 µm.

The study of the final fracture surface of the ferrite-martensite dual phase microstructure showed that in all ferrite grain sizes and in all applicable stress ranges, the fracture was brittle. The final fracture surface of the specimens with grain sizes of 74.3 and 29.1 µm at a stress of 430 and 485 µPa are shown in Fig.7. In the figure, the dark areas correspond to the ferrite phase, which has a brittle fracture, and the white sections refer to the martensite phase. The lamellar fracture in the ferrite phase could be due to the stress provided from the austenite to martensite phase transformation and also, the confinement of the plastic deformation of ferrite (due to the continuous martensite phase [16, 17]). Another reason can be the rate of the crack growth as it can cause an increase in the brittle fracture.

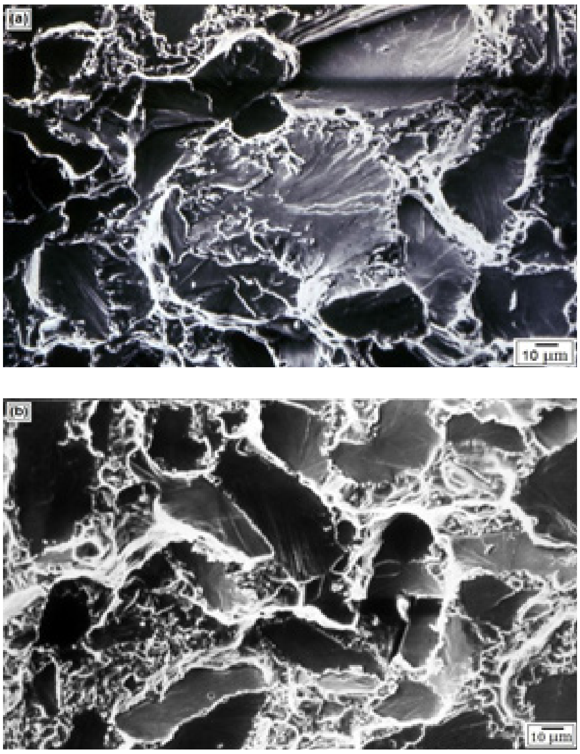

Fig. 7. Final fracture surfaces of the dual phase steels with a ferrite mean grain size of a)74.3µm and b)29 µm.

4. Conclusion

- In the direct intercritical annealing process, the martensite phase was mostly formed at the ferrite grain boundaries where with the decrease in the ferrite grain size, the martensite phase showed a bigger tendency to form continuously.
- Refinement of the structure resulted in the increase of tensile and yield strengths, the decrease of YS/UTS, and the increase of the work hardening of these steels.
- The decrease in the ferrite grain size from 74.3 µm to 9.3 µm caused a 24.5% increase in the fatigue limit.
- With the decrease in the ferrite grain sizes, the (σ_{10}^{7}/YS) and (σ_{10}^{7}/UTS) ratios were almost constant, with their values being 0.6 and 0.4, respectively.
- Fatigue crack nucleation was initiated from the surface of the samples and wavy lines were observed in the fatigue fracture surface. Also, for all ferrite grain sizes, the final fracture surfaces were mostly of the brittle type.

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