EFFECT OF PRESTRAIN AND BAKE HARDENING HEAT TREATMENT ON THE FATIGUE CRACK GROWTH AND CRACK CLOSURE OF TWO DUAL-PHASE STEELS

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Abstract. *In this research, fatigue crack growth da/dN x DK has been studied in two dual-phase steels broadly used in the automotive industry, with 7% to 12% of martensite volume fraction. The main difference between the steels is the chemical composition: one of the steels has chromium additions while the other has silicon as an alloy element. Besides the chemical composition, the effect of 10% of prestrain followed by a bake hardening heat treatment on the fatigue resistance was verified. This thermo-mechanical treatment was used to simulate the stamping and the paint baking of the wheels. C(T) specimens with 3.80 mm thickness and 50 mm width in T-L orientation were used for the experiments. Testing frequency was 30 Hz. The experiments were performed in ambient air (approximately 25°C, R.H. = 60%), at R stress ratio of 0.1. In the near-threshold* DK_{th} *region and in the final rupture region, the fatigue behavior is different for the two steels, and also different for the two conditions considered. On the other hand, the behavior is identical in the intermediary region of crack growth. Crack closure phenomenon after prestrain and bake hardening treatment is lower than in the as received condition for both steels.*

Keywords*: Fatigue Crack Growth, Crack Closure, Dual Phase Steels.*

1. Introduction

Vehicles weight reduction has recently become a very important topic for the automotive industry due to the increasing requirements on fuel consumption efficiency, that are related to energy savings and environmental restrictions. In this context, a great effort is being made in order to develop new high strength steels that combine good formability and high tensile strength, with the aim of reducing the material thickness of the different automotive parts without resulting in a loss of performance, especially passenger safety.

At the brazilian steel producer USIMINAS, the evolution of steels for automotive applications processed in the hot strip mill, has followed this tendency (Melo et al., 1998; Souza et al., 1997; Souza et al., 2000), with the development of bainitic and ferrite-martensite dual-phase steels. ARVIN-MERITOR produces wheels made by these steels, and dominates the brazilian wheels industry (Gritti et al., 1994).

However, not only formability and high strength of these steels are important when it comes to applications. Especially in the wheel applications fatigue resistance is a major characteristic due to the applied cyclic load.

Dual-phase steels have been shown recently to display excellent resistance to fatigue crack growth, particularly at low growth rates approaching the threshold stress intensity range (DK_{th}) below which long cracks remain dormant (Cai et al., 1985; Dutta et al., 1984; Minakawa et al., 1982; Ramage et al., 1987; Sarwar and Priestner, 1999; Shang et al., 1987; Sun et al., 1995; Sudhakar and Dwarakadasa, 2000; Suzuky and McEvily, 1979; Tzou and Ritchie, 1985). Such resistance depends on the microstructure of the steel and is attributed primarily to meandering crack path morphology and associated crack closure effects.

In the present research, fatigue crack growth *da/dN* x *DK* has been studied in two dual-phase steels broadly used in the automotive industry, with 7% to 12% of martensite volume fraction. The main difference between the steels is the chemical composition: one of the steels has chromium additions while the other has silicon as an alloy element. Besides the chemical composition, the effects of 10% of prestrain followed by a bake hardening heat treatment was verified on the fatigue resistance. This thermo-mechanical treatment was used to simulate the stamping and the paint baking of the wheels.

2. Materials and experimental procedures

The chemical composition of the industrially produced steels used in this research is shown in Tab. 1. Two ferritic-martensitic dual-phase steels with different alloying additions (chromium and silicon) have been selected.

Table 1. Chemical composition of the steels (weight percent).

Specimen code	C	Si	Mn	Cr
DP-Cr	0.052	0.07	1.16	0.58
DP-Si	0.055	1.03	1.19	0.09

Prior to testing, strips were removed from the original plate and subjected to a tensile prestrain of 10%, plus a heat treatment at 170^{o}C and 20 min, to simulate industrial operations during wheels fabrication.

Metallographic specimens in longitudinal and transversal directions were prepared and observed in an LEICA optical microscopy, using the LePera's etching (LePera, 1980).

All tensile and fatigue experiments were conducted under load control on a servo-controlled, hydraulically-actuated, closed-loop MTS mechanical test machine interfaced to a computer for machine control and data acquisition. The fatigue crack growth curves and the closure measurements were made according to ASTM E647-01 Standard (ASTM, 2001). Fracture surfaces were analyzed in a JEOL scanning electron microscope.

Fatigue crack length and crack closure measurements were made by the crack mouth opening displacement method. C(T) specimens (3.80 mm thick, 50 mm wide) in T-L orientation were used for the experiments. Testing frequency was 30 Hz. The experiments were performed in ambient air (approximately 25^{o}C, R.H. = 60%), at stress R-ratio of 0.1.

3. Results and discussion

The microstructures of the dual-phase steels in the transverse direction are shown in Fig. 1(a,b) and Fig. 2(a,b), in the as-received condition and after the thermo-mechanical treatment, respectively. It's possible to see in both cases the ferrite matrix (dark) surrounding martensite islands (white). Identical microstructures are obtained in longitudinal direction, without tendency for mechanical fibering.

Quantitative metallography results, determined with an image analyzer is shown in Tab. 2. Typical room temperature mechanical properties of these materials in transversal direction are also given in Tab. 2.

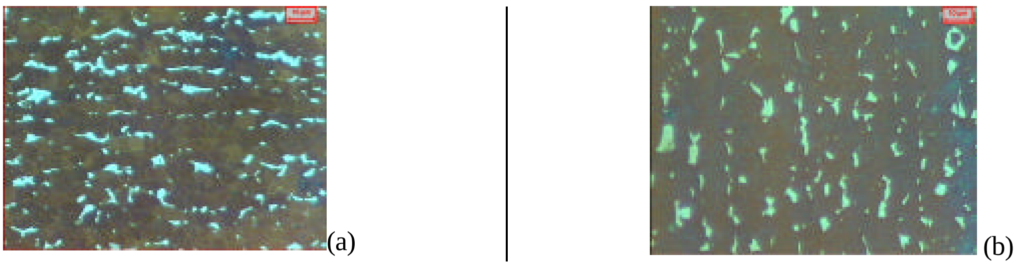

Figure 1. Optical microstructure of the DP-Cr steel, consisting of ferrite (dark) surrounding martensite (white). Transverse direction. LePera's etching. 1000X. (a) as-received condition; (b) after the thermo-mechanical treatment.

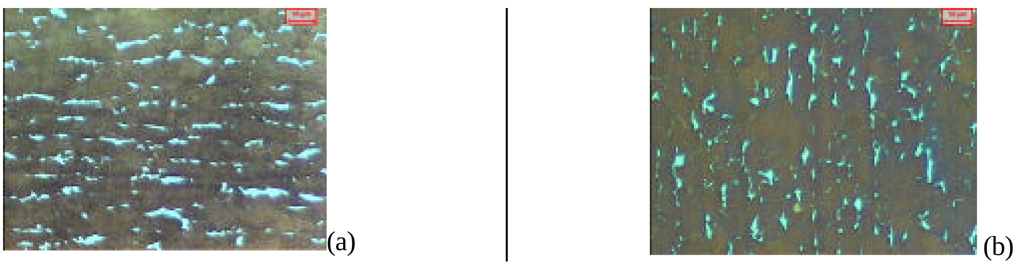

Figure 2. Optical microstructure of the DP-Si steel, consisting of ferrite (dark) surrounding martensite (white). Transverse direction. LePera's etching. 1000X. (a) as-received condition; (b) after the thermo-mechanical treatment.

The thermo-mechanical treatment did not significantly change the microstructures, but increased the mechanical strength of the steels, by the mechanisms of strain hardening (prestrain) and solid solution / precipitation hardening (bake hardening). Considerable increases in the yield and tensile strengths after prestraining and aging of dual-phase steels have also been reported in the literature (Chang, 1984a; Chang, 1984b; Davies, 1981; Fredriksson et al., 1988).

Table 2: Quantitative metallography results (20 measurements) and
tensile mechanical properties (3 specimens) in the transverse direction for the different steel grades.
AR denotes as-received condition; TM denotes after prestrain and bake hardening treatment.

Specimen Code	Ferrite Grain Size (μm)	Volume Fraction Martensite (%)	Connectivity of Martensite (%)	Yield Stress (MPa)	Ultimate Tensile Stress (MPa)	Elongation (%)
DP-Cr-AR	4,50 ± 0,22	10,56 ± 1,03	25,47 ± 7,84	406 ± 20	569 ± 8	41 ± 2,5
DP-Cr-TM	4,43 ± 0,39	11,69 ± 0,59	25,91 ± 9,13	582 ± 18	644 ± 5	28 ± 1,2
DP-Si-AR	4,62 ± 0,45	7,67 ± 0,67	23,70 ± 6,54	489 ± 24	592 ± 4	37 ± 4,7
DP-Si-TM	4,85 ± 0,33	6,97 ± 0,44	23,01 ± 7,81	653 ± 47	705 ± 44	21 ± 5,6

Fractographic analysis showed a transgranular and ductile fracture in all the steels, with a mechanism of void nucleation, growth and coalescence. Fig. 3(a,b) and Fig. 4(a,b) show these results.

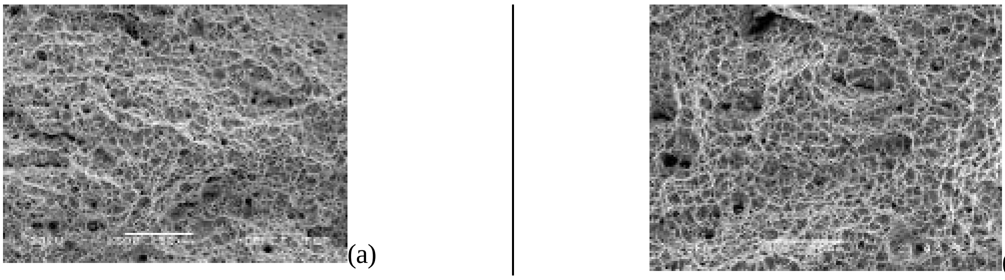
(a) (b)

Figure 3. SEM fractography of tensile surface of the DP-Cr steel, transverse direction, 500X.
(a) as-received condition; (b) after the thermo-mechanical treatment.

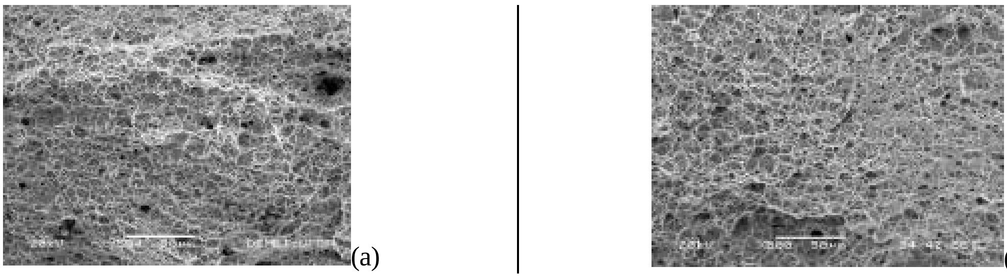
(a) (b)

Figure 4. SEM fractography of tensile surface of the DP-Si steel, transverse direction, 500X.
(a) as-received condition; (b) after the thermo-mechanical treatment.

Fatigue crack growth rate, *da/dN*, as a function of stress intensity range, *DK*, for the steel DP-Cr and the steel DP-Si, both in T-L configuration, is presented in Fig. 5, for stress ratio R = 0.1. The curves were obtained in the as-received condition and after the thermo-mechanical treatment. In the near-threshold DK_{th} region and in the final rupture region, the fatigue behavior is different for the two steels, and also different for the two conditions considered. On the other hand, the behavior is identical in the intermediary region of crack growth.

The threshold DK_{th} obtained for the steels is in accordance to results for many Fe alloys (Liaw et al., 1983; Shang et al., 1987; Dutta et al., 1984; Tzou and Ritchie, 1985). Figure 6 shows the results of this research, in comparison of those of literature. Some researchers (Sun et al., 1995; Shang et al., 1987; Ramage et al., 1987; Tzou and Ritchie, 1985; Dutta et al., 1984; Minakawa et al., 1982; Suzuki and McEvily, 1979) show more "dramatic" results ($DK_{th} \approx 20$ MPa√m), as a function of chemical composition, martensite volume fraction and connectivity, and ferrite grain size.

Values of the stress intensity at closure, K_{cl}, were obtained as function of *DK* for both steels in the near-threshold region. The results are shown in Fig. 7 in the form of the ratio of closure to maximum stress intensity, K_{cl}/K_{max}, as a function of *DK*. It is seen that the magnitude of the closure effect rapidly increases as *DK* approaches the threshold. Such results, which show the degree of closure to be at a maximum near to DK_{th} , are consistent with several recent observations for steels (Cai et al., 1985; Dutta et al., 1984; Minakawa et al., 1982; Ramage et al., 1987; Sarwar and Priestner, 1999; Shang et al., 1987; Sun et al., 1995; Sudhakar and Dwarakadasa, 2000; Suzuky and McEvily, 1979; Tzou and Ritchie, 1985). Mechanisms that have recently been used to explain the high closure levels at threshold conditions include oxide-induced crack closure, roughness-induced crack closure and crack deflection.

It is seen in Fig. 7 that the thermo-mechanical treatment leads to decreases the K_{cl}/K_{max} - *DK* relationship. Wasén and Karlsson (1989) believe that the carbide precipitation in the soft ferrite phase and the simultaneous annealing of martensite during aging have no influence on the fatigue crack growth threshold and on the crack closure. Prestraining, on the other hand, is responsible for decreases in the threshold values for materials with high ferrite content. The same dependence of DK_{th} and crack closure on prestrain is observed by Nakajima et al. (1999) in dual-phase steels in the near-threshold region.

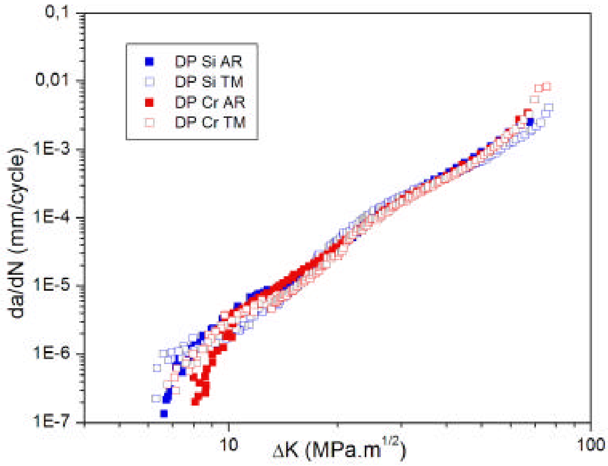

Figure 5. Variation in *da/dN* with *DK* for steels DP-Cr and DP-Si, T-L orientation, R = 0.1, as-received condition (AR) and after thermo-mechanical treatment (TM).

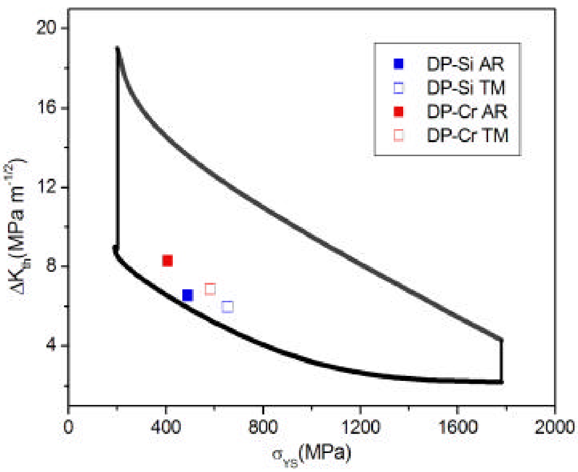

Figure 6. Dependence of threshold DK_{th} with yield stress s_{YS} for steels DP-Cr and DP-Si, T-L orientation, R = 0.1, as-received condition (AR) and after thermo-mechanical treatment (TM).

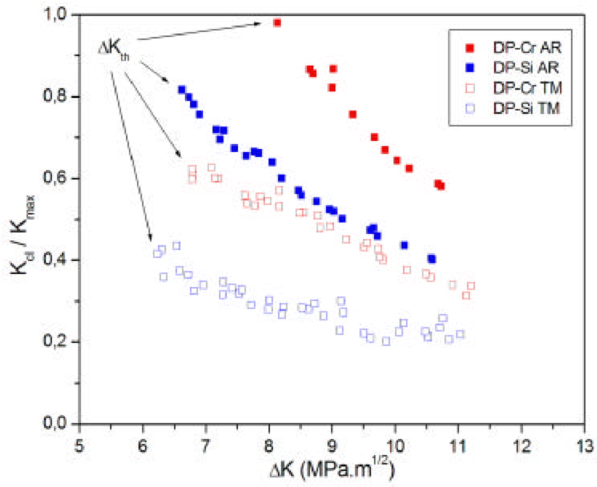

Figure 7. Experimental measurement of crack closure at near-threshold region, steels DP-Cr and DP-Si, T-L orientation, R = 0.1, as-received condition (AR) and after thermo-mechanical treatment (TM).

Fractographic analysis of the specimens at the near-threshold region showed a predominant transgranular fracture mode, with the “hill-and-valley” type appearance and shear facets, with an associated zig-zag path primarily through the ferrite. Fig. 8(a,b) and Fig. 9(a,b) show examples of this behavior, for both steels. Such fractures show high linear roughness and high crack deflection angles, characteristic of extensive crack closure induced by asperity wedging (Shang et al., 1987; Dutta et al., 1984). At higher growth rates, fracture surfaces remain transgranular, but with evidence of striations. This behavior is shown in Fig. 10(a,b) and Fig. 11(a,b) for both steels.

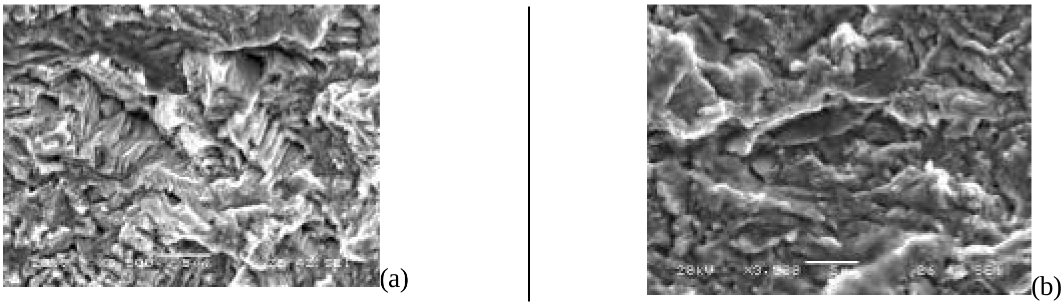

Figure 8. SEM fractography of fatigue surface of the DP-Cr steel, transversal direction, near-threshold region, 3500X. (a) as-received condition; (b) after the thermo-mechanical treatment.

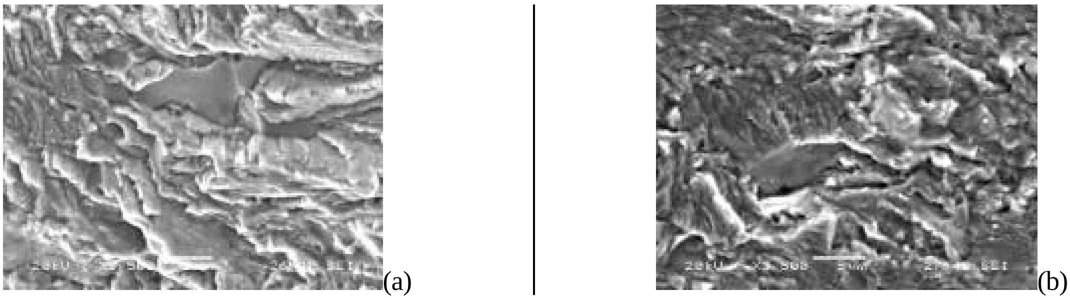

Figure 9. SEM fractography of fatigue surface of the DP-Si steel, transversal direction, near-threshold region, 3500X. (a) as-received condition; (b) after the thermo-mechanical treatment.

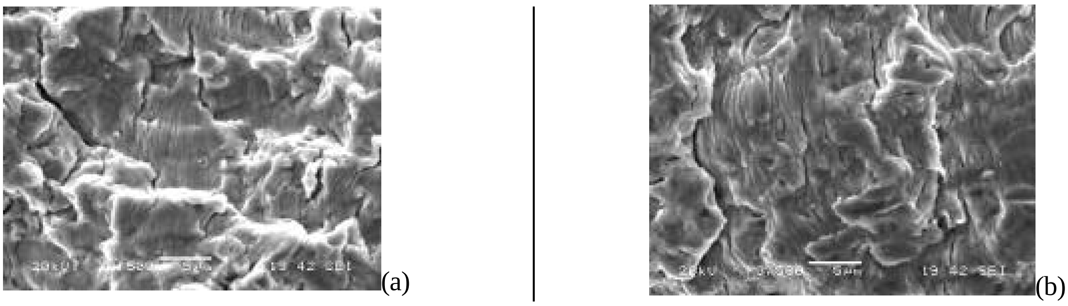

Figure 10. SEM fractography of fatigue surface of the DP-Cr steel, transversal direction, intermediate region, 3500X. (a) as-received condition; (b) after the thermo-mechanical treatment.

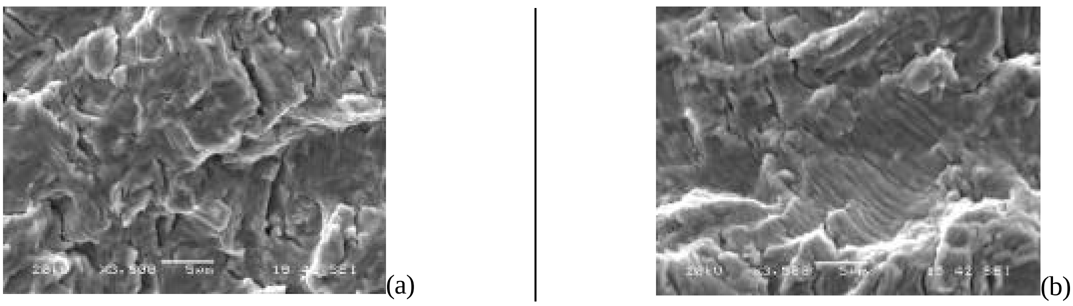

Figure 11. SEM fractography of fatigue surface of the DP-Si steel, transversal direction, intermediate region, 3500X. (a) as-received condition; (b) after the thermo-mechanical treatment.

4. Conclusions

Prestrain and bake hardening treatment did not significantly change the microstructures of the steels studied, but has increased their tensile strength. In the near-threshold DK_{th} region and in the final rupture region, the fatigue behavior is different for the two steels, and also different for the two conditions considered. On the other hand, the behavior is identical in the intermediary region of crack growth. Crack closure phenomenon after prestrain and bake hardening treatment is lower than in the as-received condition for both steels.

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