EFFECT OF STRESS CONCENTRATION ON THE FATIGUE RESISTANCE OF TWO DUAL-PHASE STEELS

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Abstract. *In this research, fatigue crack resistance has been studied in two dual-phase steels broadly used in wheels for 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. Both steels are pre-strained and heat treated, to simulate the industrial operations of stamping and paint baking of the wheels. Load controlled constant amplitude axial fatigue tests (S-N curves) are conducted in specimens of 3.50 mm thickness, frequency of 30 Hz, at R stress ratio of 0.1. The effect of stress concentration was evaluated, by putting opposite U-shaped notches in some specimens, to simulate the irregular geometry of the wheels. Silicon dual-phase steel showed superior behavior than chromium dual-phase steel. Notched specimens showed a significant decrease in the fatigue life.*

Keywords*: Stress concentration, Fatigue resistance, 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, which 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 initiation (Advanced Mat. & Processes, 2001; Aichbhaumik, 1979; Borsa, 2002; Cai et al., 1985; Fredriksson et al., 1988; Kunio and Yamada, 1979; Mediratta et al., 1985a; Mediratta et al., 1985b; Melo et al., 1998; Mizui et al., 1984; Mizui and Takahashi, 1991; Nagase and Kanri, 1992; Quesnel and Meshhii, 1977; Ramage et al., 1987; Shang et al., 1987; Sherman, 1975; Sherman and Davies, 1979; Sperle, 1985; Tosal-Martinez et al., 2001) and to fatigue crack growth (Cai et al., 1985; Dutta et al., 1984; Godefroid et al., 2005; Minakawa et al., 1982; Nakajima et al., 1999; 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; Wasén and Karlsson, 1989). Such resistance depends on the microstructure of the steel and is controlled by ferrite grain size, martensite connectivity and martensite volume fraction.

In the present research, fatigue crack resistance (S-N curves) has been studied in two dual-phase steels broadly used in the automotive industry, with a mixture of 7% to 12% martensite in a ferrite matrix. The main difference between the steels is the chemical composition: one of the steels has chromium additions (DP-Cr) while the other has silicon as an alloy element (DP-Si). Besides the chemical composition, the effects of 10% of prestrain followed by a bake hardening heat treatment were verified on the fatigue resistance. This thermo-mechanical treatment was used to simulate the stamping and the paint baking of the wheels. The effect of stress concentration was evaluated, by putting opposite U-shaped notches in some specimens, to simulate the irregular geometry 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.

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 (stamping and paint baking).

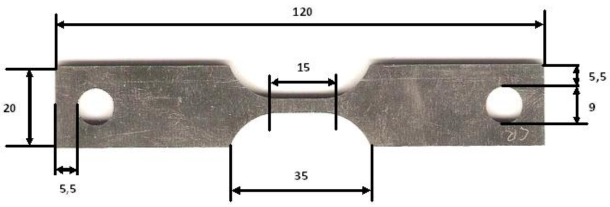
Metallographic specimens in longitudinal and transversal directions were prepared and observed in an LEICA optical microscopy, using the LePera’s etching (LePera, 1980).

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

Steel grade	C	Si	Mn	Cr
DP-Cr	0.052	0.07	1.16	0.58
DP-Si	0.055	1.03	1.19	0.09

All mechanical tests 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. Fracture surfaces were analyzed in a JEOL scanning electron microscope.

Fatigue tests were conducted using a frequency of 30 Hz. The experiments were performed in ambient air (approximately 25^{o}C, R.H. = 60%), at stress R-ratio of 0.1. The fatigue strength was determined in the life range of 10^4 to 10^7 cycles. Specimens of 3.50 mm thickness/width were used in T-L orientation. Figure 1a shows the geometry of specimens. Opposite U-shaped notches were considered in some specimens to simulate the irregular geometry of the wheels and to verify the effect of stress concentration in the fatigue life, Fig. 1b. According to Pilkey (1997), the stress concentration factor K_{tn} (= $\sigma_{max}/\sigma_{nom}$; nominal stress based on net area) for this configuration is 2.8.



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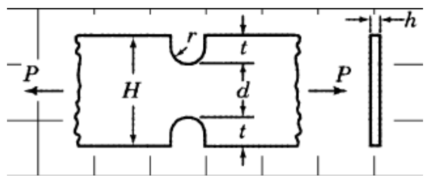


(b)

Figure 1. (a) Geometry and dimensions (in mm) of specimens for fatigue tests
(b) Details of the U-shaped notch: H = 3.5 mm; d = 2.5 mm; t = 0.5 mm; r = 0.25 mm; h = 3.5 mm

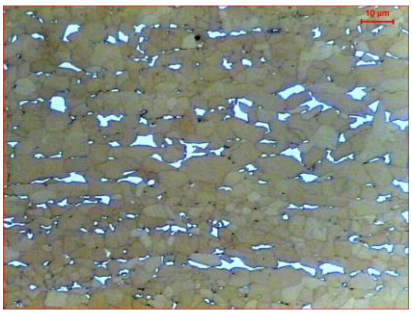
3. RESULTS AND DISCUSSION

The microstructures of the dual-phase steels in the transverse direction are shown in Fig. 2(a,b), after the thermo-mechanical treatment. 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 metallographic results, determined with an image analyzer are shown in Tab. 2. It can be seen that the two steels are typical dual-phase steels, consisting of a relative low mixture of martensite in a fine grained ferrite matrix, suitable for stamping and wheels production.

Room temperature mechanical properties of these materials in transversal direction are given in Tab. 3. The thermo-mechanical treatment is responsible for 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 been reported in the literature (Chang, 1984a; Chang, 1984b; Davies, 1981; Fredriksson et al., 1988).

Fractographic analysis showed a transgranular and ductile fracture in all the steels, with a mechanism of void nucleation, growth and coalescence.



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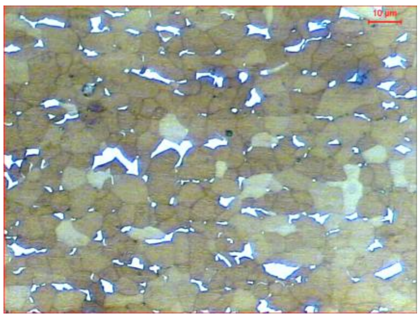

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Figure 2. Optical microstructure of the two dual-phase steel, consisting of ferrite (dark) surrounding martensite (white)
Transverse direction. LePera's etching. 1000X. (a) DP-Cr steel; (b) DP-Si steel

Table 2. Quantitative metallography results (20 measurements) in the transverse direction for the different steel grades

Steel grades	Ferrite Grain Size (μm)	Volume Fraction Martensite (%)	Connectivity of Martensite (%)
DP-Cr	4,4 ± 0,4	11,7 ± 0,6	25,9 ± 9,1
DP-Si	4,8 ± 0,3	7,0 ± 0,4	23,0 ± 7,8

Table 3. Tensile mechanical properties (3 specimens) in the transverse direction for the different steel grades

Steel grades	Yield Stress YS (MPa)	Ultimate Tensile Stress UTS (MPa)	Yield Ratio YS/UTS	Elongation (%)
DP-Cr	582 ± 18	644 ± 5	0,9	28 ± 1,2
DP-Si	653 ± 47	705 ± 44	0,9	21 ± 5,6

Results of fatigue tests on smooth specimens are presented in Fig. 3 for the two steels studied. Three specimens are tested for each load level considered. In this figure the fatigue strength for 10^7 cycles is shown (the fatigue limit FL without fracture). It can be seen that the dual-phase steel with silicon clearly offers the best fatigue performance throughout all the life range tested.

Fractographic analysis showed a similar aspect in both steels, even considering the different mechanical behavior of the steels. During the period of fatigue life it's seen a flat fracture surface, indicating the absence of an appreciable amount of plastic deformation. The micromechanism of failure is divided in four parts: crack initiation at a corner of the rectangular section (Fig. 4a, Fig. 5a), irregular crack growth by crystallographic facets (Fig. 4b, Fig.5b), crack growth by striations (Fig. 4c, Fig. 5c) and final ductile rupture.

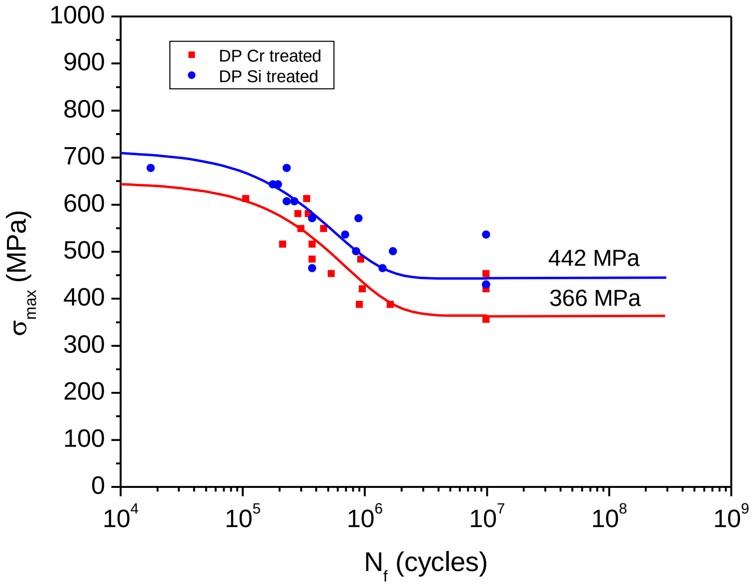
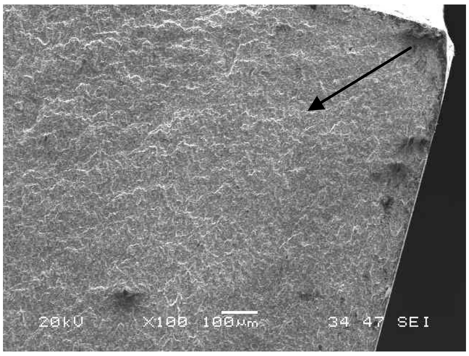


Figure 3. S-N curves for the two steels treated (prestrained and baked), smooth specimens



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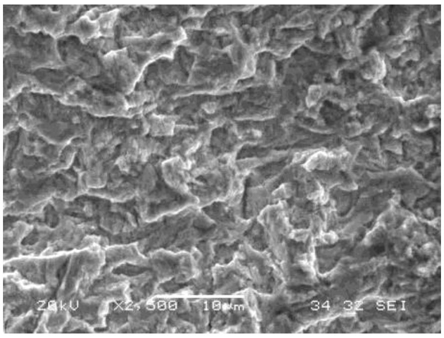

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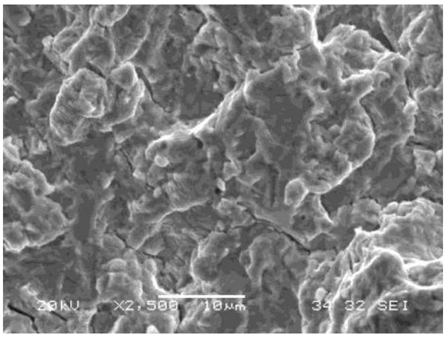

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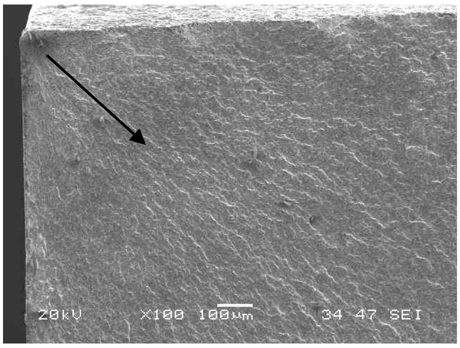
Figure 4. SEM fractography of fatigue surface from the DP-Cr steel, (a) general view, 100X; (b) crack origin and crack growth by facets, 2500X; (c) crack growth by striations and secondary cracks, 2500X; arrow indicates the crack growth direction



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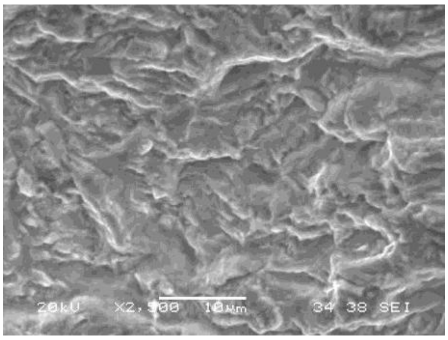

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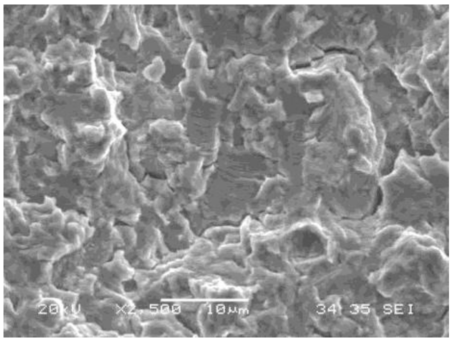


(c)

Figure 5. SEM fractography of fatigue surface from the DP-Si steel, (a) general view, 100X; (b) crack origin and crack growth by facets, 2500X; (c) crack growth by striations and secondary cracks, 2500X; arrow indicates the crack growth direction

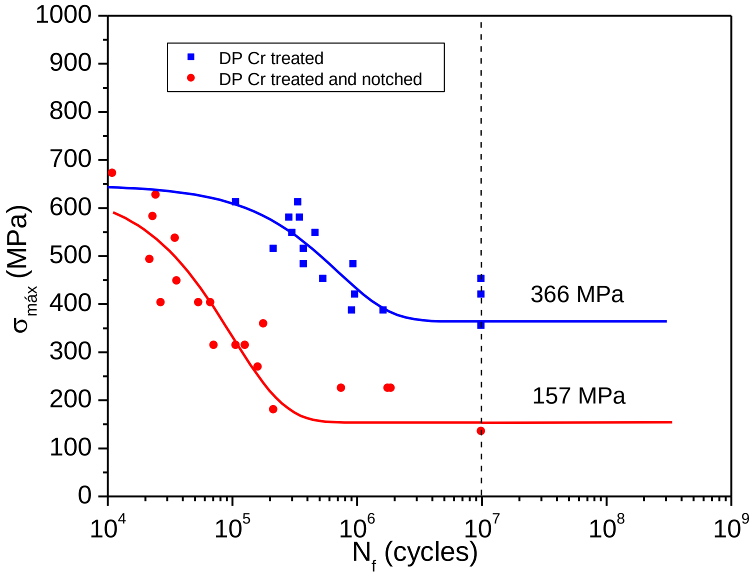
Results of fatigue tests on notched specimens are compared with smooth specimen data in Fig. 6(a,b) for the two steels studied. All stresses given refer to the net cross-section. Three specimens are tested for each load level considered. In this figure the fatigue strength for 10^7 cycles is shown (the fatigue limit FL, without fracture). It is possible to see that both dual-phase steels have lost its fatigue resistance.

The values of the notch strength reduction factor (K_f = the ratio of fatigue strength of smooth and notched specimens) and notch sensitivity ($q = (K_f - 1)/(K_{tn} - 1)$) are presented in Table 4. The value of *q* reflect the effectiveness of the notch in reducing fatigue life; q = 1 indicates full notch sensitivity since $K_f = K_{tn}$ and q = 0 ($K_f = 1$) indicates the material is completely insensitive to notches. This leads to the confirmation that both dual-phase steels have high notch sensitivity.

Fractographic analysis of notched specimens showed a similar aspect in both steels, with crack nucleation at the tip of the two opposite notches, crack growth more pronounced in one side of the specimens and final ductile rupture.

Table 4: Notched fatigue properties

Steel grade	K_f (K_{tn} = 2,8)	q
DP-Cr	2,3	0,7
DP-Si	2,2	0,7



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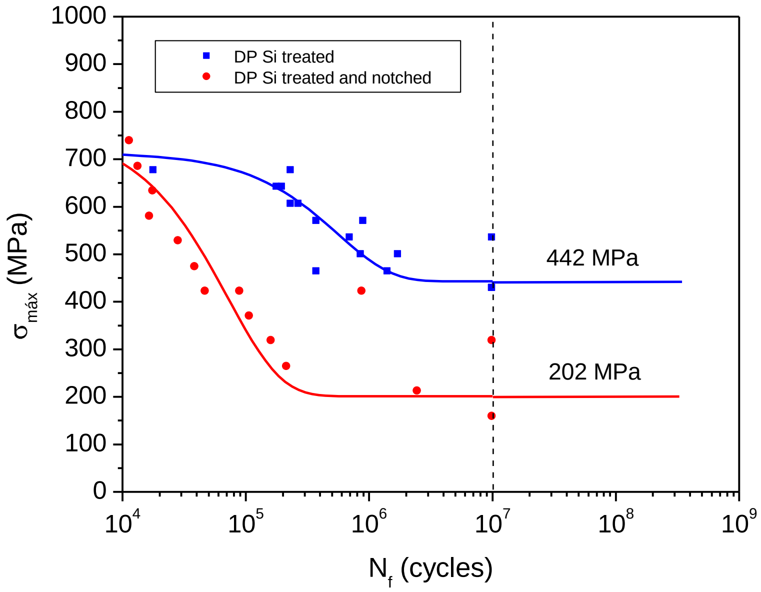

(b)

Figure 6. S-N curves for (a) DP-Cr steel and (b) DP-Si steel prestrained and baked, smooth and notched specimens

The fatigue strength on smooth material specimens is closely related to the monotonic yield strength and ultimate tensile strength (Hertzberg, 1989; Schijve, 2001). This relationship is attributed to the direct influence of the mechanical strength to the fatigue crack initiation process, and can explain the results of this investigation and the best fatigue performance of the DP-Si steel. According to Sherman and Davies (1979) and Sperle (1985), results for notched specimens follow the same overall pattern as smooth specimens, although yield ratio (= YS/UTS) has an important influence. It is found that notch sensitivity tends to increase with yield ratio. They have also observed that dual-phase steels with high yield ratio, like the two steels studied here, are more susceptible to cyclic softening. This reflects the fact that the two dual-phase steels have lost their fatigue resistance.

4. CONCLUSIONS

The fatigue strength in tests on smooth specimens of the two dual-phase studied in the life range of $10^4 - 10^7$ cycles is closely related to the monotonic yield strength of the steels. The notch sensitivity of the steels is high. Due to cyclic softening, the fatigue strength in tests on notched specimens is related to the yield ratio as well as to the yield strength.

5. ACKNOWLEDGEMENTS

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