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EFFECT OF MO AND CR ON THE FRACTURE TOUGHNESS AND FATIGUE CRACK GROWTH RESISTANCE OF A COMPLEX-PHASE C-MN-V STEEL

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Abstract. *This work shows results about J-integral resistance curves and da/dN-ΔK sigmoidal curves of a C-Mn-V steel, and compare its performance in function of 0.50%Cr and 0.25%Mo additions (mass-%). The presence of Cr or Mo in C-Mn-V steel changed its microstructure and, of course, their mechanical properties. Microstructural analysis showed the absence of pearlite on all steels, and the effect of Cr and Mo on increasing the presence of acicular ferrite, bainite and martensite. There has been an increase of martensite, rising from 30% in the C-Mn-V steel to 65% in the steel with 0.50%Cr and 70% in the steel with 0.25%Mo. It has not been verified the presence of alloying precipitates. The addition of Cr and Mo increased the tensile mechanical strength and hardness of the C-Mn-V steel. On the other hand, regarding fracture toughness, the presence of these alloying elements decreased the cracking resistance, mainly for the 0.25%Mo steel. With respect to fatigue, the presence of Cr or Mo decreased the cracking resistance in the region I of the sigmoidal curve (ΔK_{TH} region), mainly for the 0.25%Mo steel.*

Keywords: *Fracture Toughness, Fatigue Crack Growth Resistance, Complex-Phase Steels, Effect of Alloying*

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 has been made in recent decades (Auto/Steel Partnership, 1998) in order to develop and to apply 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 comfort and safety.

An international consortium called "ULSAB" met at the end of the 20th century important world steel companies, aiming to propose new steels for automotive applications. This consortium continued with the program "ULSAB-AVC" until 2004. A document published from this Program (ULSAB-AVC Program, 2001) shows the existence of numerous steels able to meet the specifications for the automotive industry. Figure 1 presents some proposed steels by this consortium and also for recent technical publications (Bleck *et al*., 2001; Wagoner, 2006; Wuppermann, 2007; Martins, 2013; Keeler and Kimchi, 2014), correlating their tensile mechanical strength with its ductility. Figure 2 shows the evolution of the use of these steels in American cars (Keeler and Kimchi, 2014). A similar change is expected to occur in the Brazilian automotive industry.

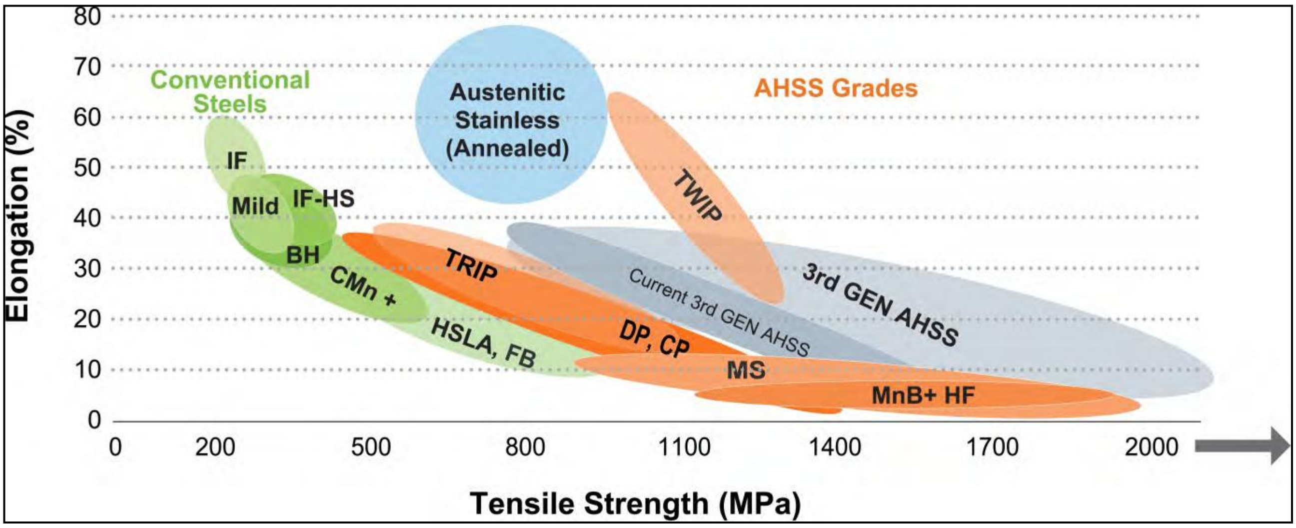


Figure 1. Global formability diagram, illustrating the range of properties available from today's AHSS grades steels (Keeler and Kimchi, 2014).

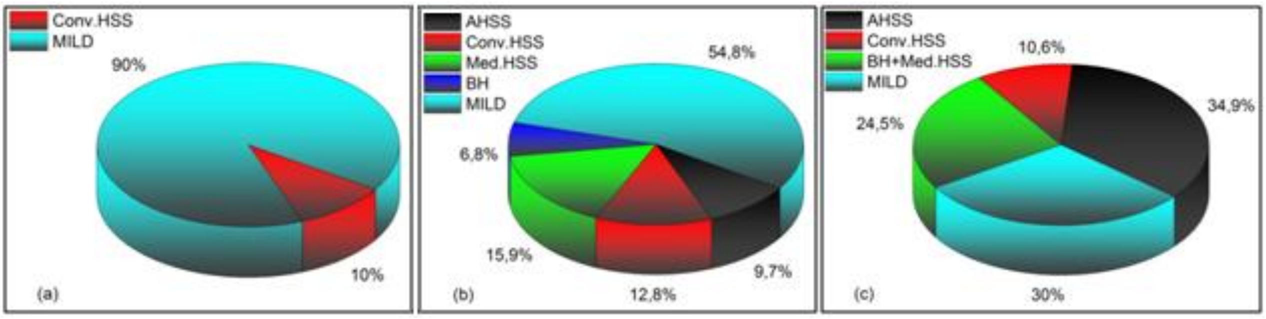


Figure 2. The use of high-strength steel (HSS) and advanced high-strength grades in the automotive industry is growing rapidly (Keeler and Kimchi, 2014). (a) 1975; (b) 2007; (c) 2015.

In the automotive industry, it is essential that the steel have good formability and weldability as well as reasonable mechanical strength, good fracture toughness and fatigue resistance. The increased carbon content increases the mechanical strength of steel, but decreases its weldability, due to increased hardenability, change of properties of the transformed phases in the heat affected zone, and increase of residual stresses in the vicinity of the weld. To have a good weldability, it is necessary to maintain the carbon content at relatively low levels. This is also desirable to have good fracture toughness. On the other hand, the decrease of carbon content decreases the pearlite volumetric fraction on steel, reducing their tensile yield stress. To resolve this dilemma, the steel industry has created high-strength and low alloy steels (HSLA) and steels with the presence of multiple phases (complex phase steels), from the choice of an appropriate chemical composition and a thermomechanical process, with the following basic characteristics:

a) austenitic grain size refining;
b) increase of dislocation density, especially through the presence of acicular ferrite and bainite;
c) precipitation of fine particles of the second phase;
d) solute atoms dissolved in ferrite.

In this context, this paper shows results obtained from fracture toughness tests (*J*-integral and J-Δa curves) and fatigue crack growth tests (da/dN-ΔK curves) with a HSLA vanadium steel, and compares its performance in function of the addition of 0.50%Cr and 0.25%Mo (mass-%). Vanadium is one of the most often used precipitate-forming elements and grain size refiner in high-strength steels; both chromium and molybdenum are solid solution strengthening elements added to avoid pearlite formation, to increase the hardenability and to promote martensite formation (Krauss, 2005; Bhadeshia and Honeycombe, 2006; Colpaert, 2008; Cooman and Speer, 2011).

This paper is a continuation of research carried out by C.A.Martins , on the occasion of his doctoral thesis (Martins, 2013). In this thesis, it was studied the effect of different additions of chromium and molybdenum on microstructure and basic mechanical properties of a C-Mn-V steel. An important conclusion from this work was that increasing the hardenability of steel became more effective from 0.50%Cr and 0.25%Mo content, hence the choice of these concentrations of alloying elements for the present study.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

All the three steels were processed by controlled rolling (pilot scale). Nominal chemical composition is presented in Tab. 1. Results of the tensile tests are shown in Tab. 2. It is interesting to note that the addition of Cr or Mo increased the mechanical resistance of the C-Mn-V steel and decreased its ductility, due to the action of these elements in solid solution and precipitation strengthening mechanisms, increase of hardenability (presence of martensite), as well as in the reduction of stacking fault energy (Vlad *et al.*, 1985; Medina and Hernandez, 1996; Lagneborg *et al.*, 1999; Woodhead, 2000; Hutchinson, 2005; Mohrbacher, 2010; Garcia *et al.*, 2011; Chatterjee *et al.*, 2011; Dong *et al.*, 2010; Salemi *et al.*, 2011).

Table 1. Steel nominal chemical composition (mass-%) (Martins, 2013).

STEEL	C	Mn	Si	P	S	Al	V	Cr	Mo	N
C-Mn-V	0.12	1.69	0.31	0.09	0.001	0.039	0.200	-	-	0.0053
0.50%Cr	0.12	1.70	0.31	0.09	0.001	0.031	0.208	0.50	-	0.0057
0.25%Mo	0.12	1.70	0.31	0.09	0.001	0.031	0.202	-	0.25	0.0062

Table 2. Steel tensile yield stress (YS), ultimate tensile stress (UTS) and total strain (STRAIN) (Martins, 2013).

STEEL	YS (MPa)	UTS (MPa)	STRAIN (%)
C-Mn-V	633	711	13
0.50%Cr	889	922	8
0.25%Mo	922	967	7

To check the chemical composition of the studied steels, samples were prepared and analyzed in an optical emission spectrometer.

Metallography samples were properly prepared and observed in a LEICA optical microscope (OM) and in a TESCAN Vega3 scanning electron microscope (SEM), using the *Nital* etching (98% of ethanol and 2% of nitric acid) to reveal the microstructure.

All mechanical experiments were conducted on a servo-controlled, hydraulically actuated, closed-loop MTS mechanical test machine interfaced to a computer for machine control and data acquisition, at room temperature. The fracture surfaces of the specimens were examined in a TESCAN Vega3 scanning electron microscope (SEM).

All specimens for fracture toughness and fatigue tests were prepared with 3.5 mm thick, which corresponds to an actual thickness of application for automotive steels. The specimens presented a C(T) type geometry, TL orientation. Figure 3 illustrates the geometry and dimensions of the specimens. In order to avoid buckling in tests, it was used stiffening plates at the grip ends.

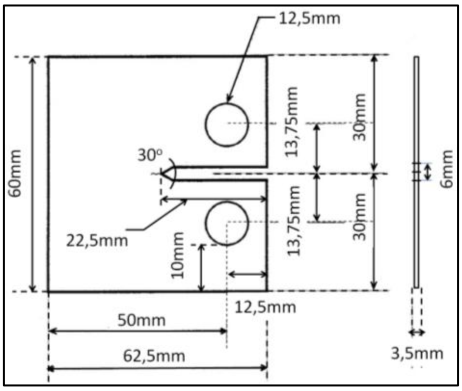
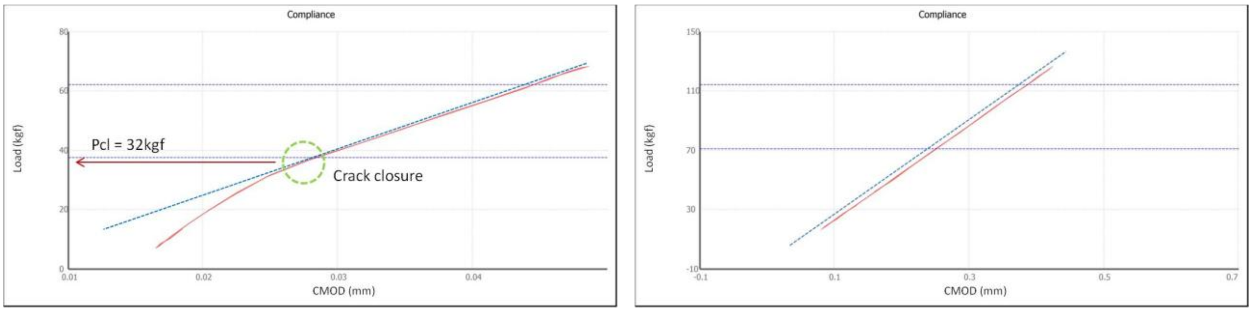


Figure 3. Specimen geometry and dimensions for mechanical experiments.

Fracture toughness tests (J-integral) were carried out using the unloading compliance technique under displacement control (ASTM E-1820-08, 2009) in specimens with an *a/W* (crack size to width) equal to 0.45, displacement intervals of 0.2 mm, 10% of unloading at each step, two stages of unloading at each step, 5 s of time interval for crack growth in each step. From the tests, the J-Δa curves were traced for the three steels and the value of J_Q (the toughness of the material near the onset of crack extension) was calculated. In this work $J_Q \neq J_{IC}$, once the thickness used for the specimens did not satisfy the standard requirement. In other words, the results are a function of the thickness considered to the specimens and J_Q is a size-dependent value of fracture toughness. Three specimens were used for each steel.

The fatigue crack growth tests were performed (ASTM E-647-08, 2009) at a frequency of 30 Hz and a stress R-ratio of 0.1. Crack size curves in function of the number of cycles have been obtained, and transformed to crack growth rate curves (*da/dN*) as a function of cyclic stress intensity factor (ΔK). Two specimens were used to obtain these curves. Closure measurements (K_{CL}/K_{max}) were calculated during the fatigue tests, through the compliance technique, where a "knee" point was formed in the applied load versus CMOD curve. Figure 4 illustrates this type of graph, with two distinct situations in terms of crack size and crack growth rate for the C-Mn-V steel.



(a) (b)

Figure 4. Load x CMOD curve (red) for the C-Mn-V steel (a) region I, *da/dN* = 3x10^{-7} mm/cycle and (b) region II, *da/dN* = 2,5x10^{-4} mm/cycle. The dashed blue line was constructed to enhance the crack closure phenomenon in situation (a) and its absence in situation (b).

3. RESULTS AND DISCUSSION

The chemical composition of the studied steels is presented in Tab. 3. Comparing this table to Tab. 1, one can observe that the steels are in accordance with the manufacturer specification.

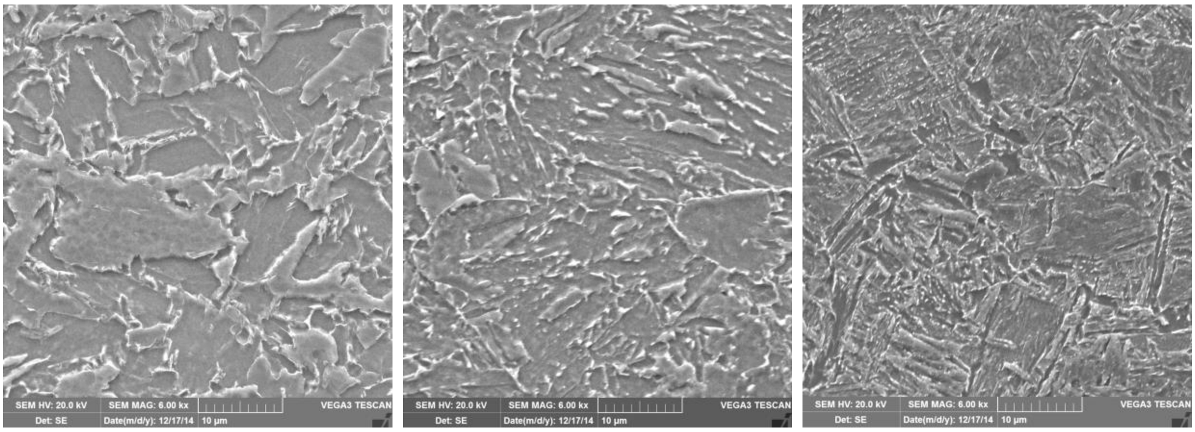
Table 3. Chemical composition of the three steels (mass-%).

STEEL	C	Mn	Si	P	S	Al	V	Cr	Mo
C-Mn-V	0.15	1.92	0.33	0.01	0.001	0.029	0.195	-	-
0.50%Cr	0.13	1.91	0.35	0.01	0.001	0.034	0.205	0.50	-
0.25%Mo	0.15	1.92	0.33	0.01	0.001	0.029	0.194	-	0.25

The microstructure of C-Mn-V steel in transverse direction is shown in Fig. 5. This figure shows also the microstructures of steels 0.25%Mo and 0.50%Cr, on same orientation. Due to the high refinement of the microstructures, the SEM images allow a better identification of the constituents.

An important result in the microstructural analysis is the absence of pearlite on all steels. This fact can be explained by the hardenability of steels and for the thermomechanical process used, including cooling rate and coiling temperature control (Lagneborg *et al*., 1999; Hutchinson, 2005; Martins, 2013). Another significant result was the effect of Cr and Mo on increasing the presence of acicular ferrite and bainite, living with martensite. This fact is known to promote an optimized combination of mechanical properties for applications in stamping process (Bhadeshia, 2001). It is also very important to note that Martins (Martins, 2013) observed an increasing volumetric fraction of martensite, from 30% for the C-Mn-V steel to 65% for the 0.50%Cr steel and to 70% for the 0.25%Mo steel, due to increasing the hardenability of steels by addition of Cr and Mo. This variation on martensite content explains the variation of tensile mechanical properties, as seen in Tab. 2. In the study of Martins (2013) it has not been verified the precipitation of alloying compounds.

The *J-Δa* resistance curves that characterize the behavior of the studied steels in terms of fracture toughness are presented in Fig. 6. Each steel is represented by a mean curve obtained among three tests. The value of J_Q, corresponding to the beginning of the stable crack growth, is presented in Fig. 7, in function of the tensile yield stress for each steel. It can be observed that the presence of chromium or molybdenum decreases the fracture toughness of the C-Mn-V steel. This fact is related to the hardener effect of alloy elements to increase the mechanical strength of the steel, and is in accordance to results found in the literature (Jacques *et al*., 2001; Godefroid *et al*., 2005; Lacroix *et al*., 2008; Salemi and Abdollah-Zadeh, 2008; Abdollah-Zadeh *et al*., 2008; Salemi *et al*., 2008; Kobayashi *et al*., 2013; Kobayashi *et al*., 2014; Martis *et al*., 2014; Lan *et al*., 2014). Fractographic analysis of the region corresponding to the value of J_Q showed ductile behavior for the three steels, even considering the low steel ductility of steels under tensile tests (Table 2). Figure 8 illustrates this behavior.



(a) C-Mn-V. (b) 0.25Mo steel. (c) 0.50Cr steel.

Figure 5. Microestruture of the three steels. Transversal direction. Nital's etching. SEM, 6000X.

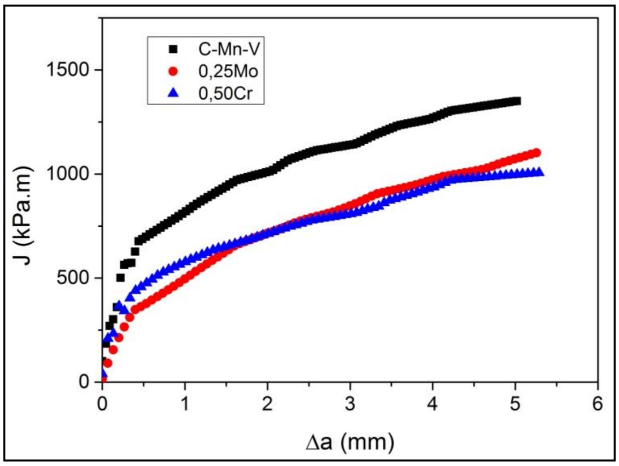


Figure 6. *J-Δa* resistance curves for the three steels.

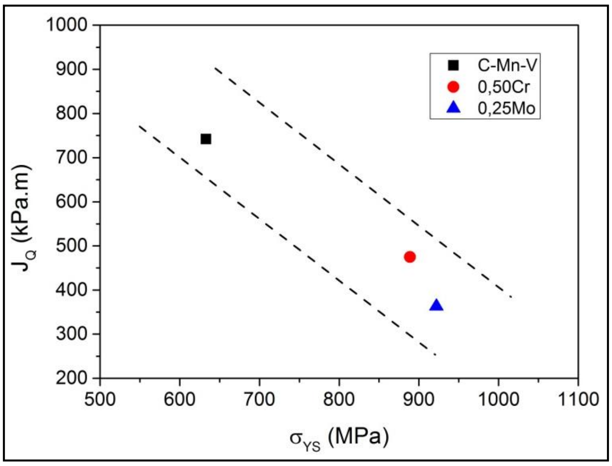
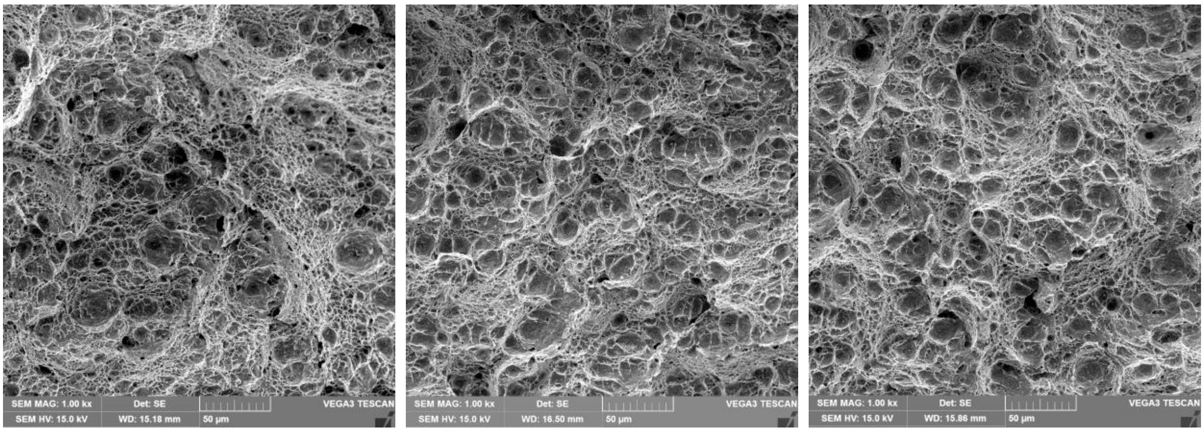


Figure 7. J_Q and σ_{YS} relationship for the studied steels.



(a) C-Mn-V. (b) 0.25Mo steel. (c) 0.50Cr steel.

Figure 8. Fracture surfaces of the studied steels, near the corresponding J_Q value, 1000X, SEM.

The traditional sigmoidal curve of fatigue crack growth rate *da/dN* in function of the driving force *ΔK* is presented in Figure 9 as comparison among the steels. One can observe a significant difference in behavior in region I of crack growth (more sensitive to microstructure), and a similar behavior in the other areas.

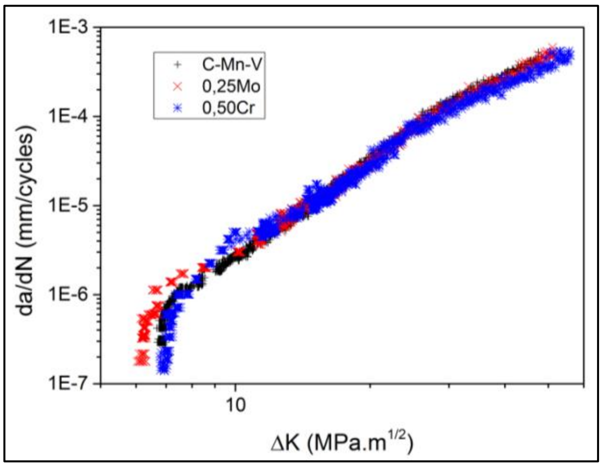


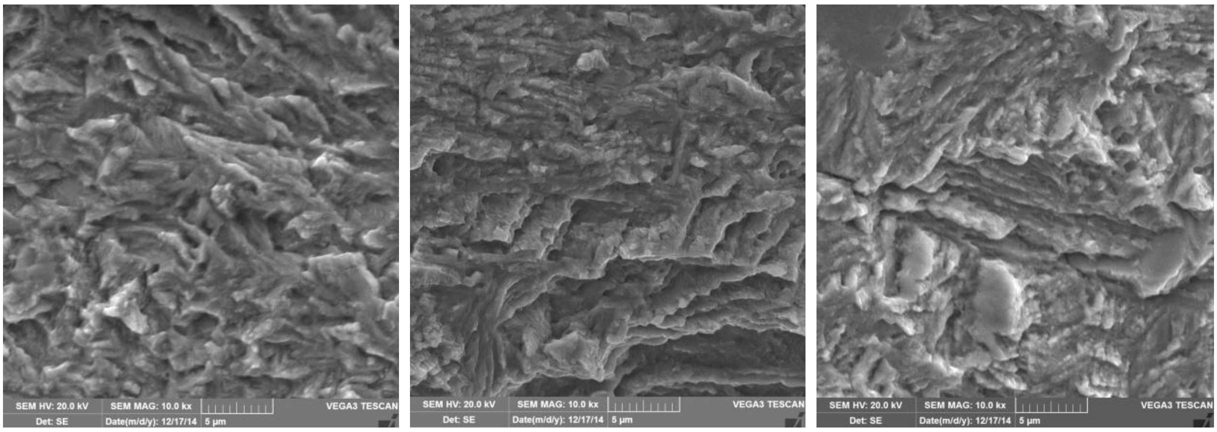
Figure 9. *da/dN* x *ΔK* for all the steels, TL orientation, R = 0.1.

Table 4 presents the value for the threshold ΔK_{TH} of the three studied steels and the constants from the Paris equation (region II). All the values are in accordance with results found in the literature for various ferrous alloys (Liaw *et al*., 1983; Dutta *et al*., 1984; Tzou and Ritchie, 1985; Shang *et al*., 1987; Gutz *et al*., 2010). This table shows an inverse relationship between ΔK_{TH} and the tensile yield stress, and a direct relation of ΔK_{TH} with K_{CL}/K_{max} (crack closure ratio) for these steels. In this context, an important parameter is the presence of martensitic phase in steel: the morphology, the connectivity (ratio between the number of ferrite/martensite boundaries and the number of total boundaries – ferrite/martensite + ferrite/ferrite) and the volumetric fraction of martensite influence the fatigue crack growth resistance (Suzuki and McEvily, 1979; Minakawa *et al*., 1982; Dutta *et* al., 1984; Wasynczuk *et al*.,1984; Cai *et* al., 1985; Tzou and Ritchie, 1985; Ramage *et al*., 1987; Shang *et al*., 1987; Chen *et al*., 1988; Sun *et al*., 1995; Sarwar and Priestner, 1999; Bag and Dwarakadasa, 1999; Sudhakar and Dwarakadasa, 2000; Sankaran *et al*., 2003; Cheng *et al*., 2008; Prawoto, 2009; Gutz *et al*., 2010; Godefroid *et al*., 2011; Idris and Prawoto, 2012; Li *et al*., 2014). There is a consensus in the literature that until certain amount of martensite (around 50%), the threshold ΔK_{TH} will increase, but will decrease with higher values of martensite, always depending on the development of oxidation-induced crack closure, roughness and crack deflection. In the case of this study, the steels with 0.50%Cr and 0.25%Mo provided a volumetric fraction of martensite that failed to develop the necessary crack closure to improve the fatigue crack growth resistance, hence the worst behavior of these steels in comparison with the C-Mn-V steel.

Table 4. Threshold ΔK_{TH} and crack closure ratio K_{CL}/K_{max} ; constants from Paris equation.

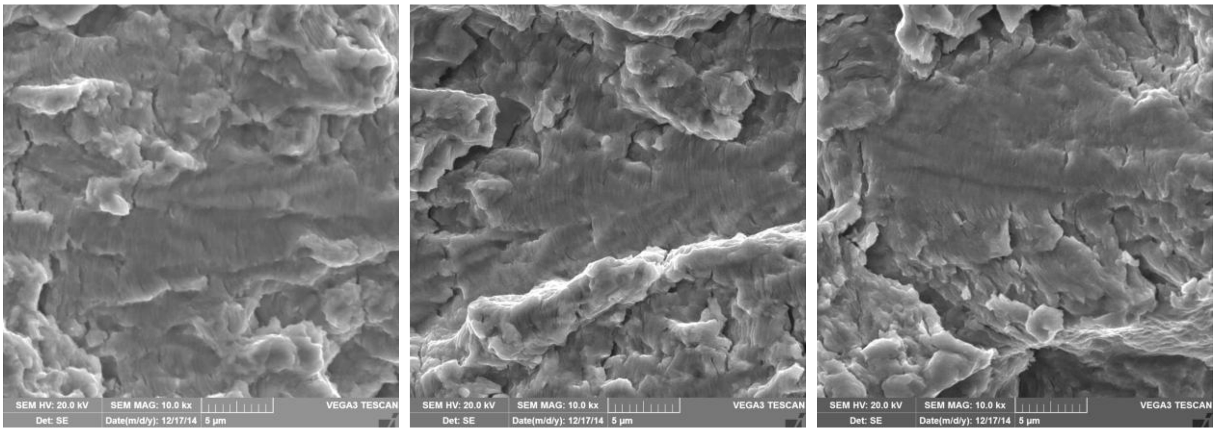
STEEL	σ_{YS} **(MPa)**	ΔK_{TH} **(MPa.m$^{1/2}$)**	K_{CL}/K_{max}	***C* *(Paris eq.)***	***m* *(Paris eq.)***
C-Mn-V	633	6.90	0.47	3,4 x 10^{-10}	3,85
0.50%Cr	889	6.80	0.46	1,4 x 10^{-8}	2,64
0.25%Mo	922	5.90	0.44	7,8 x 10^{-10}	3,54

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. Figure 10 (a,b,c) shows examples of this behavior, for all the steels. Such fractures show high roughness and high crack deflection angles, characteristic of extensive crack closure induced by asperity wedging (Gutz *et al*., 2010; Godefroid *et al*., 2011). At higher growth rates, fracture surfaces remain transgranular, but with evidence of striations. This behavior is shown in Fig. 11 (a,b,c) for all the steels.



(a) C-Mn-V. (b) 0.25Mo steel. (c) 0.50Cr steel.

Figure 10. Fracture surface of the studied steels, in the region I of crack growth, 10000X, SEM.



(a) C-Mn-V. (b) 0.25Mo steel. (c) 0.50Cr steel.

Figure 11. Fracture surface of the studied steels, in the region II of crack growth, 10000X, SEM.

4. CONCLUSIONS

This work consisted in the evaluation of fracture toughness (J-Δa curve) and fatigue crack growth (*da/dN-ΔK* curves) in complex phase C-Mn-V steel, and compared its performance depending on the addition of 0.50%Cr and 0.25%Mo. The following main conclusions were obtained:

(1) The microstructure of the three steels consisted of ferrite and martensite. The presence of Cr and Mo increased the presence of acicular ferrite and bainite, living with martensite. These alloying elements caused an elevation of volumetric fraction of martensite, from 30% in the C-Mn-V steel to 65% in steel with 0. 50%Cr and 70% in steel with 0.25Mo.

(2) The presence of Cr or Mo decreases the fracture toughness of the C-Mn-V steel, as noted in the value of the beginning of the stable crack growth (J_Q), and in the *J-Δa* resistance curves. This effect was more pronounced for the steel with 0.25%Mo. An inverse relationship was obtained between fracture toughness and tensile yield stress for the studied steels.

(3) With respect to fatigue crack growth, it was possible to observe a significant difference in behavior in region I of the sigmoidal curve *da/dN-ΔK*. The presence of Cr or Mo decreases the threshold ΔK_{TH} value of the C-Mn-V steel, primarily for the steel with 0.25%Mo. The behavior was similar among the steel in the other two regions of the fatigue curve. An inverse relationship was obtained between the threshold ΔK_{TH} value and tensile yield stress and a direct relation of ΔK_{TH} with K_{Cl}/K_{max} (crack closure ratio) for the studied steels.

(4) Under the industrial point of view and the application for the product, it should be noted that the beneficial effect of some alloying elements on basic mechanical properties of steel can harm its behavior under certain conditions. Special care must be taken in the design of chemical composition and microstructure of the steel.

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