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EFFECT OF MOLYBDENUM IN THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF THE DUAL-PHASE STEEL DP980

José Francisco da Silva Filho
Arcelor Mittal, São Francisco do Sul, SC, Brazil
jose.francisco@arcelormittal.com.br

Carlos Augusto Silva de Oliveira
Universidade Federal de Santa Catarina, Campus Universitário, Florianópolis, SC, Brazil, ZIP 88040-900
carlos.a@ufsc.br

Cássio Aurélio Suski
Nilceu Novicki
Instituto Federal de Santa Catarina, Itajaí, Florianópolis, SC, Brazil, ZIP 88301-360
cassio.suski@ifsc.edu.br
nilceu@ifsc.edu.br

Abstract. *High work-hardening rates in combination with excellent elongation give the Dual-Phase steels much higher formability especially with the feature of higher ultimate tensile strengths than conventional steels of similar yield strength. In this paper the investigation will address the results obtained with dual phase steels after being isothermally treated and then quenched in water. These steels differ in chemical composition according to the different Mo contents (0/ 0.15/ 0.30 and 0.45%Mo). Samples of each chemical composition were isothermally heat treated at each temperature (720/ 740/ 760/ 780/ 800/ 820/ 840/ and 860ºC). These samples were tested on tensile machine for mechanical properties and analyzed on optical/scanning electron microscope for investigating the evolution of the microstructures. Discussions were developed, mainly, on the basis in panel where pictures of the microstructures were organized in sequence of according to the temperature and Mo concentration. Supports of others techniques of analyzes such as EBSD, TEM and program Thermocal were used in order to confirm some ideas. The focus of the discussion was pointed on the phenomena of recrystallization, phase transformation and precipitates' behavior.*

Keywords: *recrystallization, phase transformation, precipitates*

1. INTRODUCTION

The sustainability and the human impact on the Earth planet have been rendered discussions ever since long time ago. The issues are addressed in different directions sometimes economically and others environmental and social. Green (2012) addressing it in the “triple bottom line” which include social, economic and environmental aspect, passed through the efficient use of materials, material life-cycle assessment, adequate material for support energy efficiency (GREEN, ESPINAL, TRAVERSA, & AMIS, 2012).

Under this context, advance of environmental and governmental laws has been pushing the automakers to continuously improve safety and fuel economy of cars with low cost. These requirements, consequently, affect design and material selection. The achievement of these goals requires a combination of high-tech materials, innovative design, advanced manufacturing processes and tight relationship among design engineers, manufacturing engineers and materials engineers (KRUPITZER & HEIMBUCH, Apr 2005). Worldwide Institutes and research centers have been spending much effort to the development of new products leading to these goals. The AHSS group (Advance High Strength Steel) has shown to be one interesting solution, in this moment. Among the steels present in this mentioned group the class of dual-phase (DP) is one that fulfills a large amount of requirement.

High work-hardening rates in combination with excellent elongation give the Dual-Phase steels much higher formability especially with the feature of higher ultimate tensile strengths than conventional steels of similar yield strength. When compared to high-strength low-alloy steels with similar yield strength, DP steels exhibit higher initial work-hardening rate than conventional ones, higher ultimate tensile strength (UTS) and lower ratio of yield strength to ultimate tensile strength. Advanced High Strength Steels are the aiming of automotive and truck manufacturers because they offer the potential for fuel economy increases through weight reduction, while maintaining an acceptable size and cost of product (DAVIES & MAGEE, 1979). Considering that the automakers are in the majority among consumers of these advanced high strength steels and that dual phase steels are one of the most popular in this category because of their ease applicability in body-structure and body-panel applications in the last years, it determines its importance in this scenario.

2. METHODS

In this section the investigation address the results obtained with Dual-Phase steels DP980 after being isothermally treated and then quenched in water. These steels differ in chemical composition according to the different Mo contents (0/ 0.15/ 0.30 and 0.45%Mo). Samples of each chemical composition were isothermally heat treated at different holding temperatures (720/ 740/ 760/ 780/ 800/ 820/ 840/ and 860ºC) resulting 32 samples. These 32 samples were tested on tensile machine for mechanical properties and analyzed on optical and scanning electron microscope for investigating the evolution of the microstructures. Figure 1 shows the microstructures of the 32heat treated samples plus 4 full hard (36 total). Mechanical properties are presented in section 3.2.

Discussions are developed, mainly, on the basis in panel (Fig. 1) where pictures of the microstructures were organized in sequence of according to the temperature and Mo concentration. Others techniques of analyzes such as EBSD, TEM and program Thermocal are used in order to confirm some ideas. Whether is necessary to present any property or effect of molybdenum, which stands out a comparison with chromium and / or silicon it will be made. The present discussion is focused on the phenomena of recrystallization, phase transformation and behavior of precipitates.

The microstructures position in panel followed the precepts of 4 columns (“a” to “d”) and 9 rows (“1” to “9). Columns a-d are the Mo concentrations 0.0, 0.15, 0.30 and 0.45%, respectively. Rows 1- 9 represent full hard and holding temperatures (room temperature, 720, 740, 760, 780, 800, 820, 840 and 860ºC), respectively. The general panel (Fig. 1) aims to provide a general viewing of the experiment; nevertheless, during the discussion of the subject, once details of a specific microstructure is necessary, a specific picture was displayed as a clear and larger size. The methodology chosen for analyzing of the microstructures is based on the scanning over all microstructures of the panel; step by step with interpretation and analysis of microstructural changes promoted by changes in temperature (axis-y) and chromium content (axis-x).

3. RESULTS AND DISCUSSION

3.1 Effect of Mo on the Microstructure

A brief overview shows that microstructures reveal significant differences. Deeper investigation over these microstructures was realized to reveal more details.

At room temperature microstructures of full hard have already shown ferrite, and C-rich structures (broken pearlite, martensite/bainite and precipitates), Figure 1 (line 1). The presence of martensite/bainite and precipitates is explained by the charging of these dual phase steels in alloying elements mainly the high level of Mn. Figure 1 (row 1) shows that the increase of Mo content in the steels from 0 to 0.45%, increases the amount of C-rich structures, mainly, the volume fraction of solid martensite.

The following discussions are carried out on the analysis of microstructures after het treatment and the written text follows the sequence of isothermal temperatures (from 720 to 860ºC). It is worth notice that Mo and Cr have, some similarities in physical characteristics and abilities in change the properties of system where they joining (lattice).

Han et al. (2010) described some abilities of Mo that affect the final microstructures such as: i) changes the position of critical point of steels (temperature, carbon content) when in solid solution; ii) increases A_3 and reduces A_4 temperatures; iii) Changes in austenite formation (during heating), austenite transformation (on cooling), martensite decomposition (on tempering) and other microstructure formation in steel; iv) delays the transformation of pearlite and bainite (Han D. , Dangsheng, Yuping , Zhingang, Gang, & Maoqiu, 2010).

Increasing the temperature from 30 to 720ºC it is observed the effect of Mo content in the microstructure of steels through the phenomena of recrystallization, phase transformation and precipitates presence. At this temperature, coarse martensite, pearlite and some kind of precipitates have already reached the advanced stage of dissolution and; it is not possible to see these aggregates as coarser as they were seen in full-hard condition. These dissolutions develop with the enrichment of carbon in austenite structure.

In terms of phase transformation, austenite grains are not observed at all, what means that the nucleation and growth phenomena are not present, significantly. Recrystallization does not show a significant difference with the addition of Mo.

Figure 2 shows that the addition of Cr is much more relevant than Mo for the acceleration of the recrystallization. So, it is noted and has to be highlighted that at 720ºC (in the Cr-added steel) the phenomenon of recrystallization prevails over the phase transformation; whereas phase transformation prevails over the recrystallization for Mo-added steels. It suggests that the Mo has lower ability than Cr for accelerating the recrystallization in the steels.

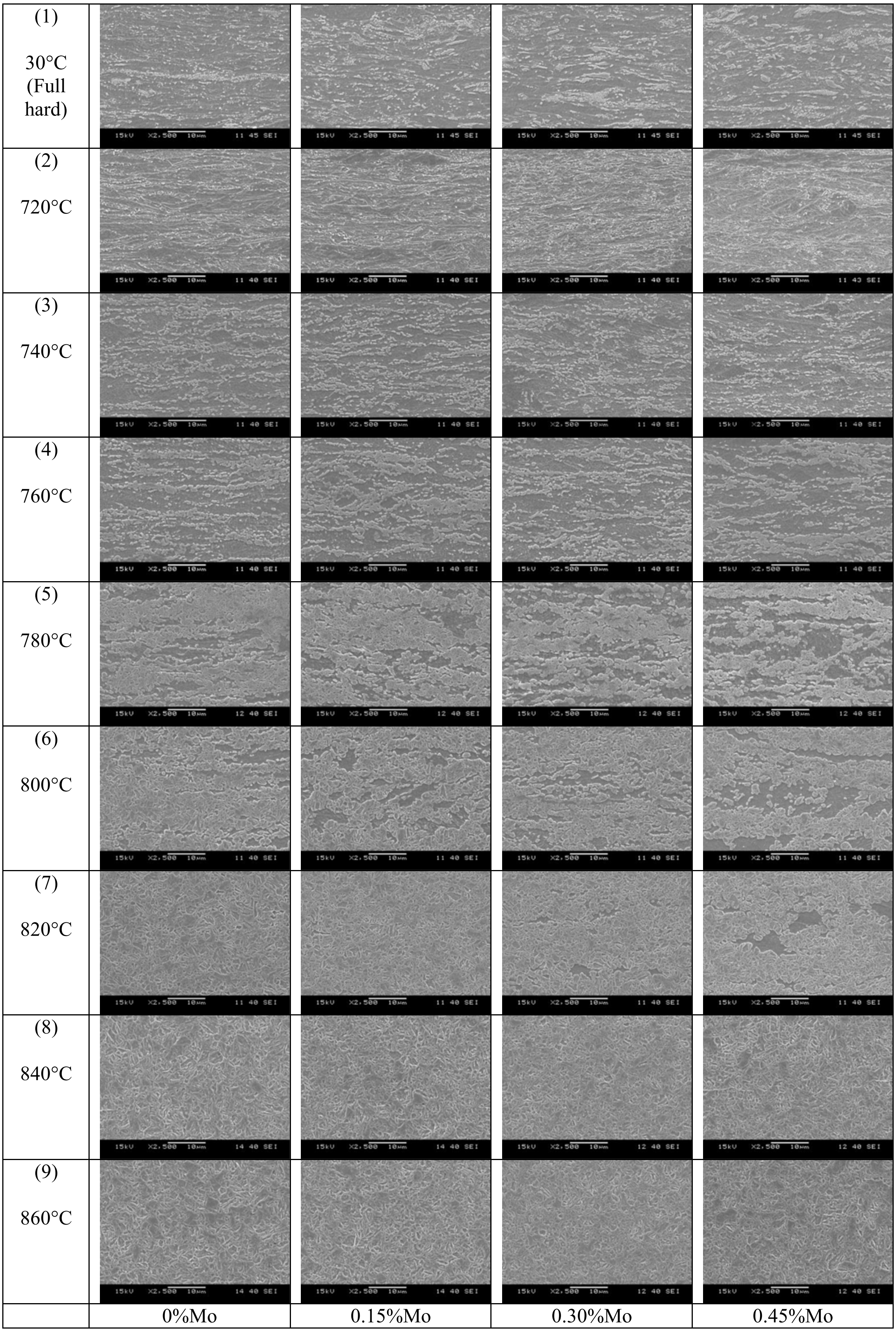


Figure 1 - Effect of molybdenum content and holding temperature on the microstructures (recrystallization, phase transformation and precipitates) of DP 600 steels.

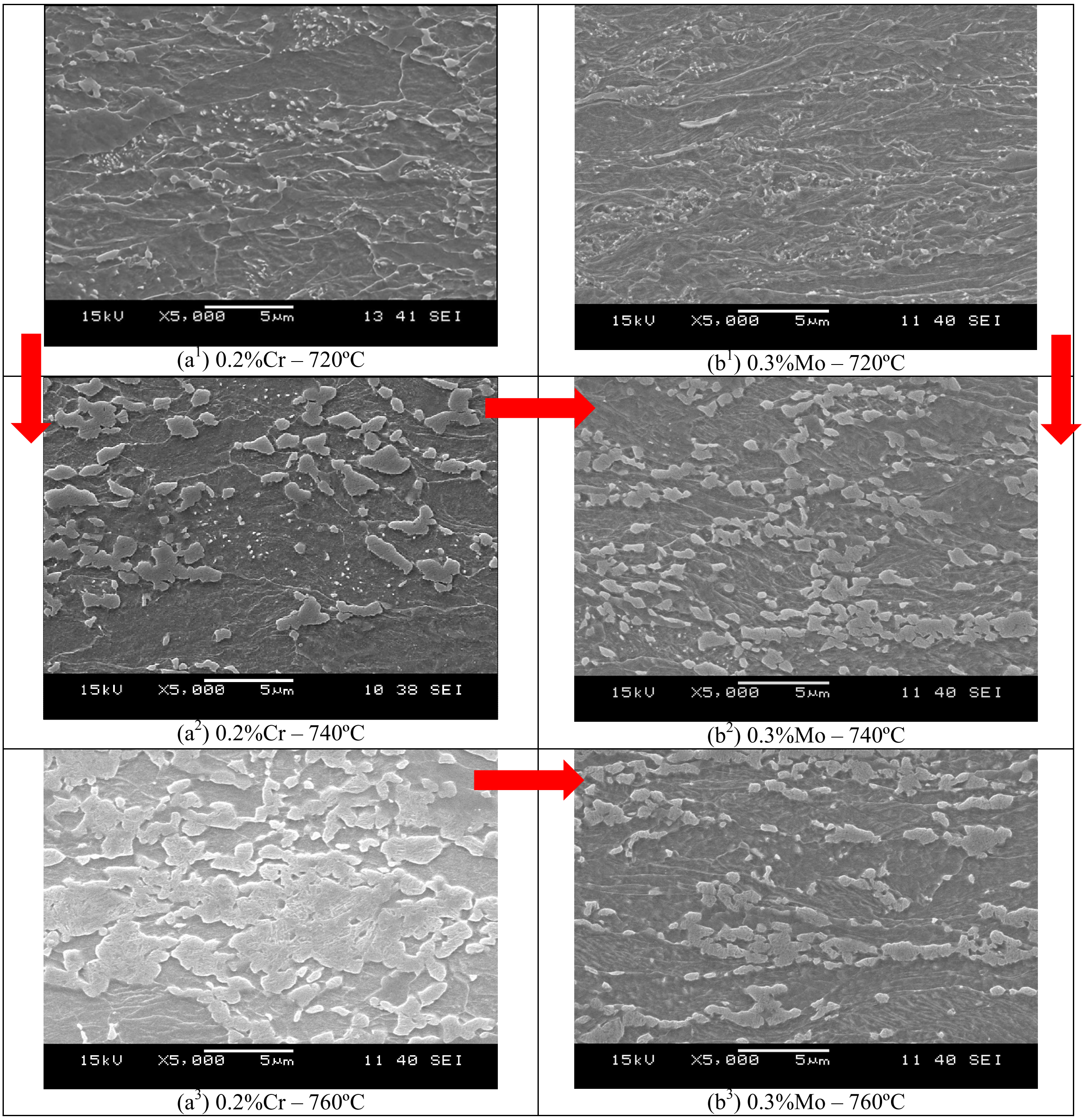


Figure 2 – Comparison between the Abilities of Cr versus Mo on the Kinetics of Recrystallization of Dual Phase Steels - DP 600

The increase in temperature from 720 to 740°C promotes changes in the microstructure of Mo-added steels. As shown in Fig. 2 (b^1 ; b^2) phase transformation develops rapidly at 740ºC; whereas recrystallization processes did not realized significantly. Increasing the temperature to 760ºC the phase transformation keeps running faster, while the recrystallization still delayed (in Mo-added steels). It suggests that the phase transformation phenomenon prevails recrystallization for Mo-added steels.

Figure 3 and table 1 show the amount of martensite as function of Mo content and temperature. Martensite percentage increases with temperature up to 820ºC for 0 and 0.15%Mo; and up to 840ºC for 0.30 and 0.45%Mo.

It is relevant to be highlighted in this analysis the amount of martensite increasing with the decreases in the content of Mo in steel from 0.45 to 0.15%. Nevertheless for the Mo-free steel the amount of martensite is placed in-between 0.45 and 0.15%Mo. It suggests that higher addition of Mo in the steels retards the kinetics of austenitization. These tendencies are shown in the curves of Mo concentrations in Figure 3.

Increasing the temperature from 760ºC to 780°C it is still possible to see non-recrystallized regions (arrows in Fig. 4). For all temperatures from 720 up to 820ºC the non-recrystallized regions appeared when Mo was added to the steel.

Therefore, under the conditions of this study, Mo acts on retarding the processes of recrystallization. At 840ºC structures are fully transformed and no more hard-ferrite is observed (Fig. 5).

Table 1 – Percentage of martensite as a function of content of Mo and Holding Temperature.

% MA Phase, Traction Test Samples – 60s - Quench Cooling								
Samples	**Temperature (ºC)**							
	720ºC	**740ºC**	**760ºC**	**780ºC**	**800ºC**	**820ºC**	**840ºC**	**860ºC**
0,0% Mo	2,50	23,89	33,52	60,64	87,92	99,37	100,00	100,00
0,15% Mo	3,04	24,40	35,74	66,26	77,28	99,33	100,00	100,00
0,30% Mo	1,04	21,62	29,64	63,02	75,87	93,62	100,00	100,00
0,45% Mo	0,92	18,97	28,85	59,21	68,20	88,79	100,00	100,00

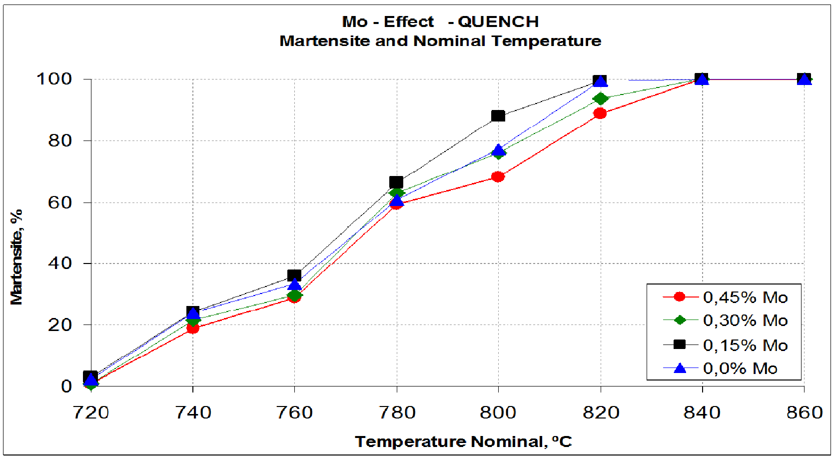


Figure 3 – Martensite Percentage as Function of Temperature for Different Mo Content Steels.

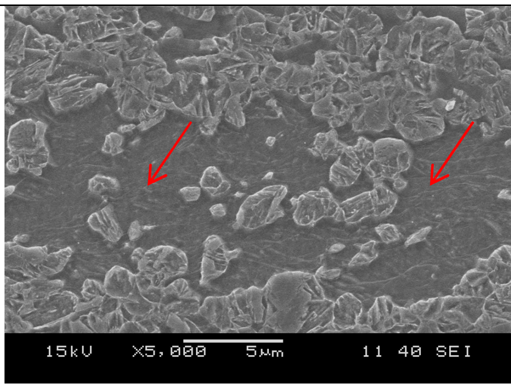
In summary, one can say that the molybdenum acted on retarding the recrystallization process, over all temperatures studied. This is consistent with the statement of Leslie and Huang et al. who explained that this phenomenon occurs due to the nucleation retarding and growth of newly recrystallized grains. They also stated that this is due to the ability of Mo for dragging the solute during the migrating boundaries ((LESLIE, 1961) ; (HUANG, POOLE, & MILITZER, 2004)).

3.2 Effect of Mo on Mechanical Properties

Figure 6 displays the behavior of tensile strength with temperature for each curve representing the amount of molybdenum. At lowest temperature (650ºC) all chemical compositions tensile strength is high due to the presence of hard structures and undissolved precipitates (carbide phases). Increasing temperature up to 720ºC the tensile strength decreases continuously due to the dissolution of carbides and evolution on the recrystallization of few phases. Above 720ºC and up to 840ºC, further tensile strength increases with temperature, for all Mo concentrations, due to the increase in volume of martensite. Moreover, the tensile strength has a direct relation with the amount of Mo.

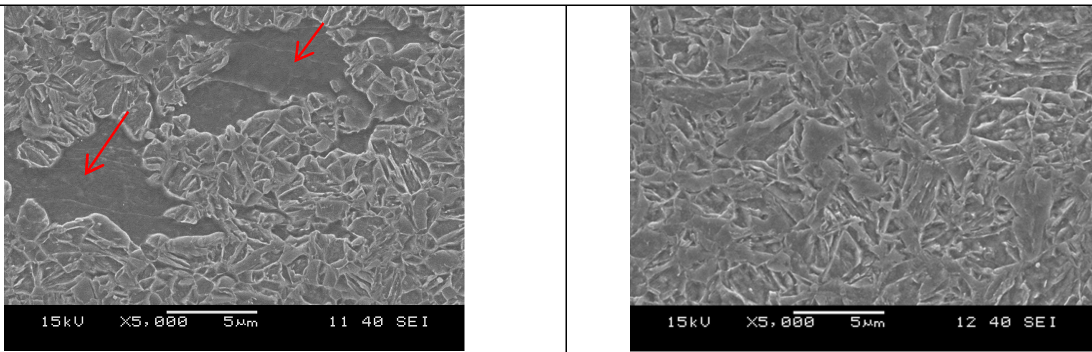
Once the amount of martensite has inverse relation with the amount of Mo, whereas tensile strength has direct ones, it means that the increasing of Mo in steels results in less volume of martensite, which in turns show higher concentration in carbon atoms. These martensites with higher carbon content enhance the strength of steels. Addition of 0.45% Mo in the steels increased the tensile strength of the 100% martensite steels on roughly 50 MPa (Fig. 6).

According to Fig. 7 at lowest temperature (650ºC) for all chemical compositions the yield strength is high due to the presence of hard structures and undissolved precipitates (carbide phases). Increasing temperature up to 760ºC the yield strength decreases continuously due to the dissolution of carbides, evolution on the recrystallization of few phases and the suppression of YPE (dual phase behavior). Above 760ºC up to 820ºC, further yield strength increases with temperature, for all Mo concentrations, due to the increase in volume of martensite. Moreover, the yield strength has a direct relation with the amount of Mo. Above 820ºC yield strength decreases smoothly probably due to martensite tempering.



0.45%Mo – 780ºC

Figure 4 – Microstructure of 0.45%-Mo Steel Revealing non-Recrystallized regions at 780ºC.



045% - 820ºC	045% - 840ºC

Figure 5 – Microstructures of 0.45%-Mo Steel (Martensite + Hard Ferrite) and (Full-Martensite) at 840ºC.

3.3 Dilatometry (CCT Diagram)

The complementary technique of dilatometric analysis was also used in this study, for investigating the effect of molybdenum additions on the microstructures and kinetics of steels. This experiment was carried out by heating the steels at the α/γ -region, holding isothermally at this region and quench at different cooling rates. These paths allow the study of phase's transformation. The analysis of CCT diagram associated to the microstructures via scanning electron microscope allowed one to obtain information concerning to the dynamic transformations developed in the structure.

Figure 8 shows more complete CCT diagram for the low-carbon dual-phase steels without (a) and with (b) Mo additions. Additions of 0.45% of Mo move the ferrite formation region to the right to slower cooling rates (from around 90 to around 1.0^{o} C/s); volume fraction of ferrite is higher in Mo-free steel after the same cooling rate from (α/γ)-region.

Lower volume of bainite is formed in Mo-added steels, therefore martensite start temperature is higher in Mo alloyed steel, especially after slow cooling rates (<10^{o}C/s). Separation of bainitic and martensitic phases after high cooling rates (>10^{o}C/s) is difficult using visual microstructure evaluation.

Figure 9 shows the effect of Mo additions in the changes of microstructure of steels. Additions of 0.45% Mo cause the suppression of ferrite formation and promote more volume fraction of martensite, refine the microstructure especially after low cooling rates.

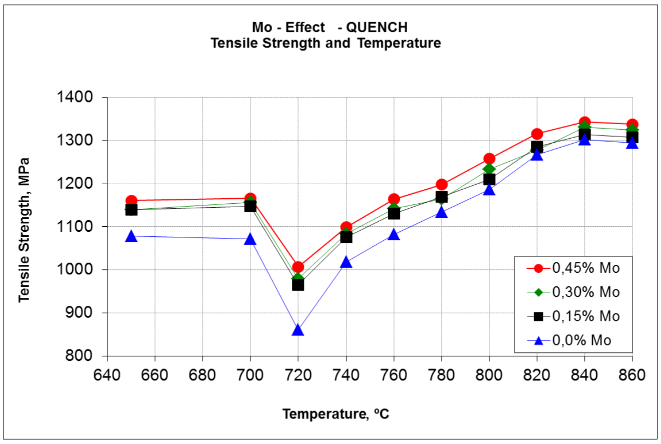


Figure 6 – Effect of Temperature on Tensile Strength for Different Mo-content Steels.

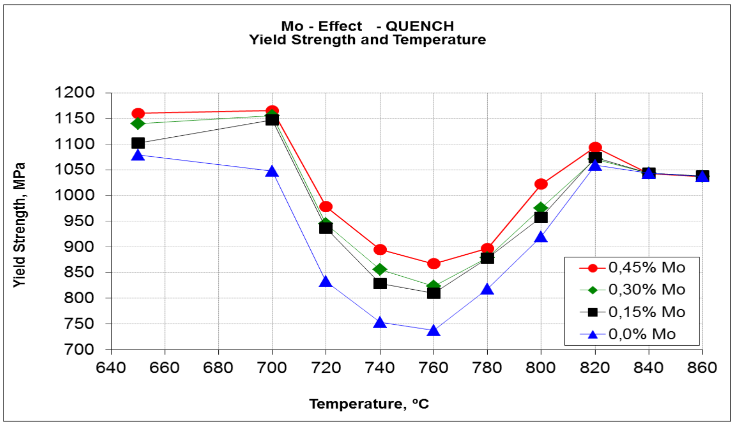


Figure 7 – Effect of Temperature on Yield Strength for Different Mo-content Steels.

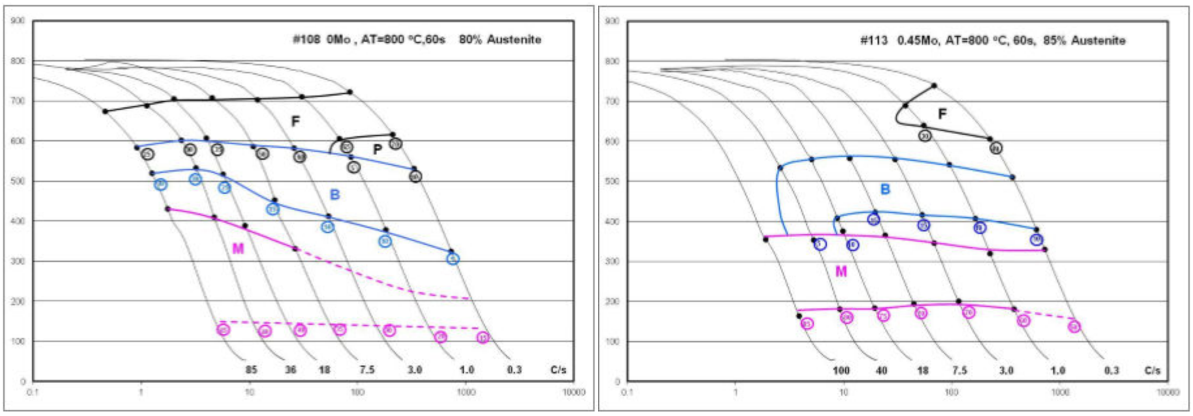


Figure 8 – CCT Diagrams showing the Influence of Mo on 0.1%C DP Steels. (a) 0% Mo (b) 0.45%Mo.

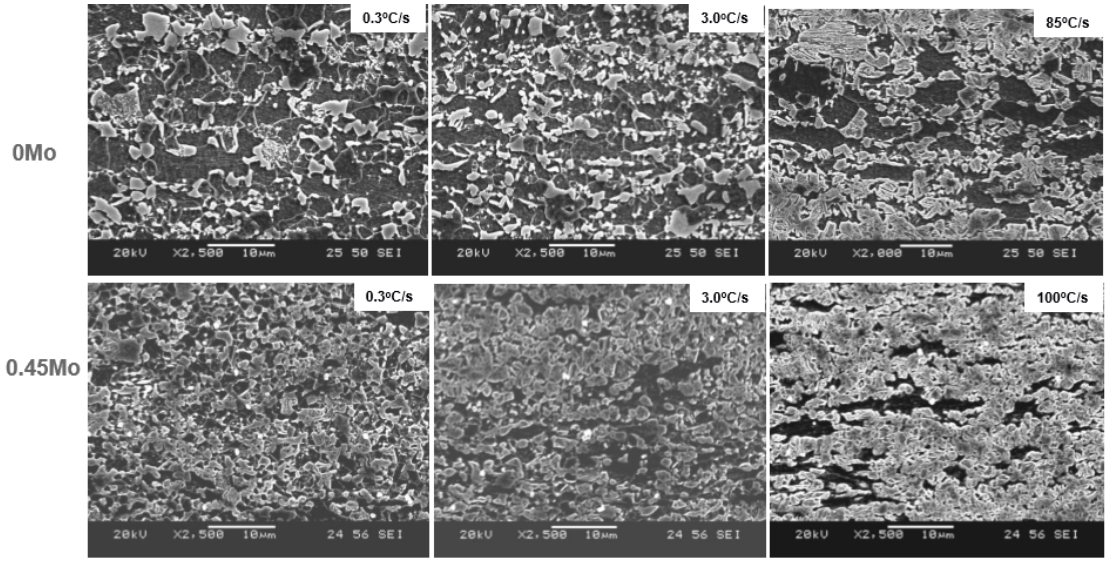


Figure 9 – Mo-Effect on Microstructures for steels cooled from (α/γ)-region.

4. CONCLUSION

- In the Mo-added steel the phase transformation prevails over the recrystallization. It suggests that the Mo has no enough ability as Cr has, for example, in accelerating the recrystallization in the steels with a matrix similar to one used in this study;
- The molybdenum acted on retarding the recrystallization process, over all temperatures studied, due to the nucleation retarding and growth of newly recrystallized grains;
- The amount of martensite increases with the decreases in the content of Mo in steel; from 0.45 up to 0.15%; nevertheless for the Mo-free steel the amount of martensite decreases a little, instead. It suggests that the addition of Mo in the steels retards the kinetics of austenitization;
- Once the amount of martensite has inverse relation with the amount of Mo, whereas tensile strength has direct ones, it means that the increasing of Mo in steels results in less volume of martensite, which in turns show higher concentration in carbon atoms. These martensites with higher carbon content enhance the strength of steels;
- The tensile strength and the yield strength increases with temperature, for all Mo concentrations, due to the increase in volume of martensite.

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