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RELATIONSHIP BETWEEN MICROSTRUCTURE, MECHANICAL PROPERTIES AND DISLOCATION SUBSTRUCTURES IN A MULTIPHASE STEEL

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ABSTRACT

This paper discusses the formation of microstructures with different volume fractions, as an outcome from a specific heat treatment, with the following phases: ferrite, martensite, bainite and retained austenite. For the microstructure characterization we developed a chemical etching that allows us to distinguish the phases by optical microscopy. The process was also accomplished by scanning electron microscopy with the objective of analyzing the active mechanisms of fracture and transmission electron microscopy with the aim of determining the dislocation substructures formed during the fatigue test. The evaluation of the mechanical properties is carried out based on the results of the tensile and fatigue tests. The experimental results show that appropriate heat treatments can contribute to a significant improvement of the mechanical properties of the steel. In this process it is essential to control the volume fraction, phases morphology, and grain size.

1. INTRODUCTION

During the 1970's energy crisis, a new kind of steel named as dual phase steel was developed. This type of steel exhibited a microstructure which was constituted basically on ferrite and martensite [1]. They could provide a high mechanical resistance and better ductility than the HSLA steels [2]. They are very important for the automobile industry since they reduce weight and costs. And they also improve the fatigue life of products of many car parts such as wheels, radiator support, doors, springs support, etc [2-4]. Dual phase steels are important in many other application fields, specially in areas related to structural applications [5-7]. When looking for new ways to improve the levels of the toughness properties of this steel, we could replace the martensite phase for the bainite phase. Nowadays ferritic-baintic steels have been applied in low temperature pipelines [8].
Multiphase steels are produced with the main purpose of exploiting the several phases combinations, according to the demands of the project. Modifications of their chemical composition, termomechanical or heat treatments allow microstructures formation with different morphologies, grain size and volume fractions of the phases, improving their mechanical properties to be used in many industrial applications [9-11].

2. EXPERIMENTAL PROCEDURE

The sample used in this investigation was a low-carbon steel supplied by Usina Metalúrgica de Minas Gerais S.A. - USIMINAS. The chemical composition of the material is shown in tab.1.

Table 1 - Chemical Composition of the steel, wt%

Elements	C	Si	Mn	P	S	Al	Nb	N
wt %	0.11	0.01	0.51	0.02	0.009	0.031	0.024	0.0039

The specimens used in the tensile test were machined under specified ASTM E 8 standard and the specimens for the fatigue test under the ASTM E 466 standard. Initially all the specimens were annealed in order to reduce the effects of rolling. They were divided in 4 sets of tensile and fatigue tests. These sets were heated at 920°C for 12 minutes and quenched in cold water (5°C). After that each specimen set received a specific heat treatment, as described in Figs.1a and 1b.
The tensile and fatigue tests were carried out on a MTS hydraulic machine, model 810.23M. For the fatigue test a frequency of 25Hz was used with the stress ratio equal to zero.
The volume fractions of ferrite, bainite and the M.A. (martensite + retained austenite) phases are obtained through the image analysis of the samples etched with the modified reagent LePera [12-13]. The volume fraction of retained austenite is obtained through the evaluation of images of the samples etched with a 10% sodium metabisulphite solution. The martensite volume fraction is calculated by subtracting the retained austenite to the total M.A.
The dislocation substructures formed after the tests are studied by transmission electron microscopy (TEM). The surfaces fracture analyses are performed by scanning electron microscopy (SEM) in low vacuum to identify the active failure mechanisms.

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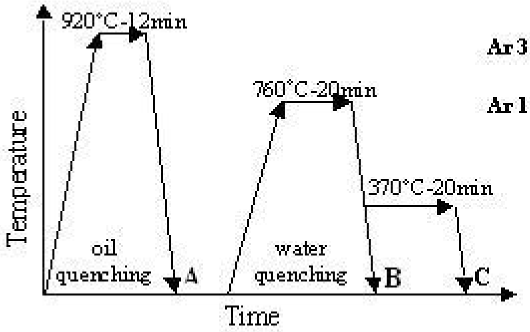

Figure 1a - Thermal cycles utilized: heat treatments A, B and C.

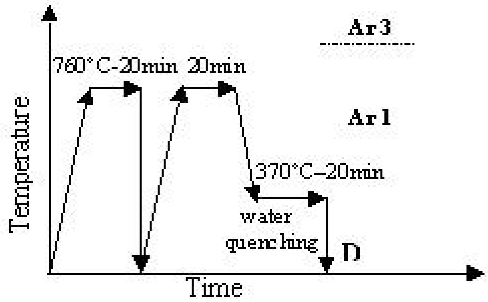

Figure 1b - Thermal cycles utilized: heat treatment D.

3. RESULTS AND DISCUSSION

The heat treatment A produces a multiphase microstructure with fine granulation, according to Fig. 2.

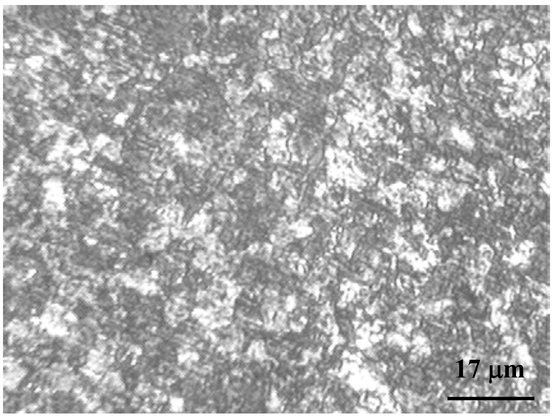

Figure 2 - Light optical micrograph. With the phases: gray - ferrite, dark - bainite and white - MA. Etching: modified LePera

Heat treatment B also produces a multiphase microstructure, however, with different morphology, where the ferritic matrix is filled with martensite or bainite islands. The micrograph in Fig.3 shows the general aspect of the microstructure obtained. Micrograph of Fig.4 shows the general aspect of the microstructure etched with the adapted reacting LePera, in order to reveal the bainitic phase (dark - **b**). Microstructure in Fig.5, etched with sodium metabisulphite, highlights the areas of the retained austenite (clear). Heat treatment C, presented in Fig.6, forms a similar microstructure to treatment B, basically a ferritic matrix with second phase islands. However, maintenance in the isothermal temperature (370°C) allows a bainite formation in order to reduce the martensite volume fraction.

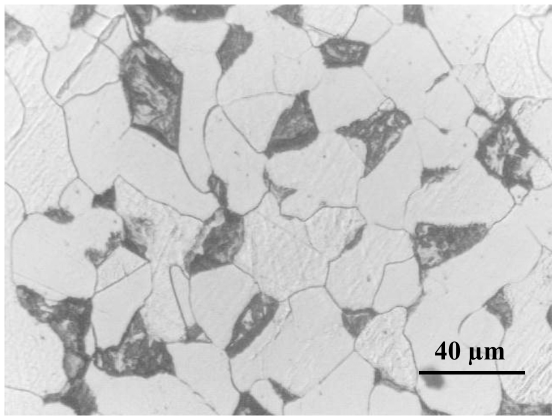

Figure 3 - Light optical micrograph showing the general aspect of the microstructure obtained in the heat treatment B. Ferrite (clear), martensite and bainite (dark). Etching: nital - 2%

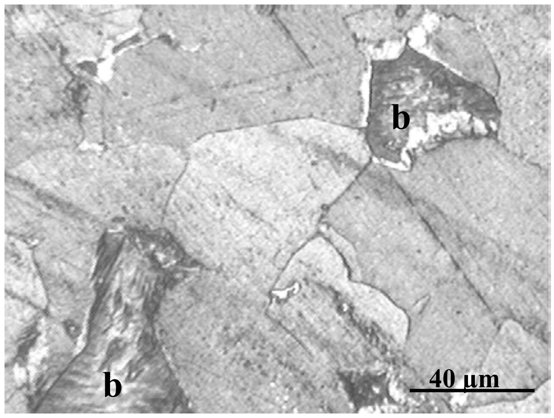

Figure 4 - Light optical micrograph showing the phases: ferrite (matrix-gray), bainite (islands - b) and constituent MA – white. Etching: Modified LePera.

Microstructure formed by the heat treatment D consisted basically of a ferritic matrix with bainite islands. However, the maintenance of the steel at an intercritical temperature (760°C) provides two interesting effects: the formation of small inserted grains, as branches of bainite and MA (martensite + retained austenite) in some areas and the growth at the ferritic grains.

Tab.2 shows the volume fraction of the steel phases for all the microstructures obtained by the heat treatments A, B, C and D studied in this paper.

It is important to observe that in heat treatment A the fast cooling rate has favored the formation of the phases of martensite and bainite, in comparison with the other treatments. The microstructure obtained in heat treatment

B presents a similar second phase volume fraction in comparison to the microstructure obtained in treatments C and D.

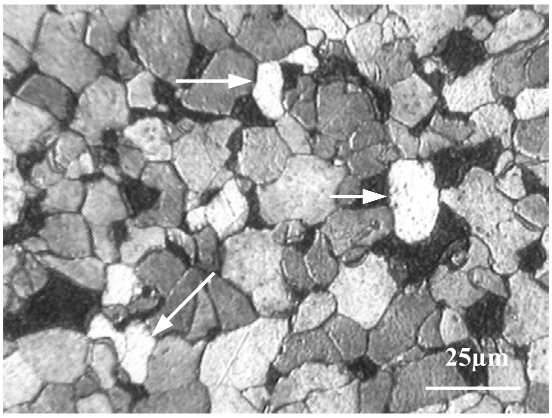

Figure 5 - Light optical micrograph highlighting the retained austenite present (clear). Etching: sodium metabisulphite - 10%.

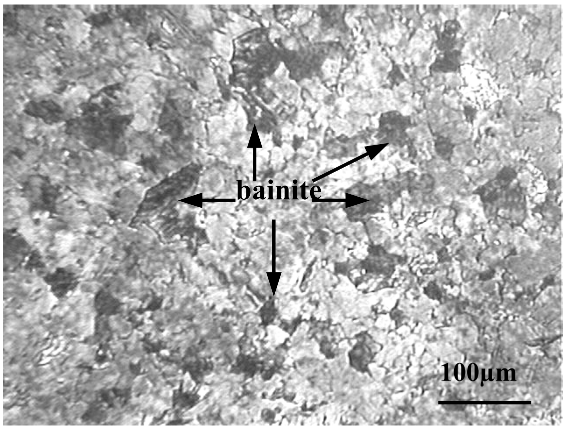

Figure 6 - Light optical micrograph showing the typical microstructure consisting of ferrtic matrix (gray) with bainitic islands prevalent (dark). Etching: modified LePera.

It is observed that the martensite volume fraction obtained in heat treatments C and D is quite reduced. The volume fraction of the martensite, obtained by the heat treatment B, is favored by the high cooling rate applied in the quenching, after the intercritical heat treatment.

Table 3 shows the average size of the grain in the ferritic phase. It is observed that increase in time at an intercritical temperature (760°C) increases the grain size. Table 4 shows the microhardness of the phases when the heat treatment is applied.

Heat treatment A is appropriate for the production of a microstructure with refined grains, while treatment D promotes excessive grain growth. It becomes interesting to reduce the residence time at the intercritical temperature [14]. Since the grains are quite refined in condition A and in a granular region in condition D it becomes impossible to measure the microhardness of each phase.

It is observed in Table 4 that the microhardness of the ferritic phase was smaller for the ones that remained at the isothermal temperature (370°C). The same phenomenon is observed inside the bainite phase, showing that the bainite formed under a continuous cooling (treatment B) presents a larger microhardness as compared to the one obtained in the isothermal temperature (treatments C and D). Table 5 shows the results obtained in tensile tests.

The reduction of the strength values observed in the steel C and D is associated, among other factors, to the decrease of the volume fraction of the second phase, a small quantity of martensite presented, and the reduction of the microhardness values in the ferritic phase. The reductions of the yield strength and tensile strength values of the steel in condition D are worsened by the increase of the ferritic grains (size effects).

Steels samples in conditions C and D, although not presenting the best tensile strength values, had a low relationship for the yield rate (σ_y/σ_t). So they are suitable for processes involving cold forming. Kumar et al [17] found similar results - σ_y/σ_t between 0.66 and 0.75 - considering these samples suitable for a series of industrial applications.

Graphic of the Fig. 7 shows the fatigue curves for each microstructural condition studied.

The microstructure produced by heat treatment B presents the best fatigue performance when compared with the microstructure obtained in treatment A. It can be said that the morphology produced in B is more suitable for the improvement in fatigue properties. Particles of a second phase act as barriers to the growth of the crack, delaying or deviating it [18]. Suzuki and McEvely [19] also observed a similar fact.

Table 2 – Volume percentages of the phases

Heat treatment	Volume Fractions %								
	Bainite	$\overline{\sigma}$	Ferrite	$\overline{\sigma}$	Constituet M.A.	$\overline{\sigma}$	Retained Austenite	$\overline{\sigma}$	Martensite (estimated)
A	20.64	3.60	63.22	3.60	16.32	3.60	6.58	1.21	9.74
B	13.69	2.31	75.16	2.31	11.15	2.31	5.20	2.14	5.95
C	15.18	1.56	77.78	1.56	7.04	1.56	6.21	2.11	0.83
D	19.65	1.83	76.22	1.83	4.13	1.83	3.06	1.70	1.07

Table 3 – Average grain size (ferrite).

Heat treatment conditions	Average diameter of the grains (μm)	Grain size (ASTM E 112)	
		Number	(μm)
Rolled	7.8	G-11	7.9
Annealed	15.2	G-9.5	13.3
A	6.1	G-12	5.6
B	25.8	G-7.5	26.7
C	27.7	G-7.5	26.7
D	45.3	G-6.0	44.9

Table 4 - Microhardness of the phases.

Heat treatment	Microhardness (HV)			
	Ferrite	Martensite	Bainite	Granular region
Annealed	160	-	-	-
A	-	-	-	192*
B	174	453	292	-
C	134	-	230	-
D	132	-	226	182

* average value of the microhardness

Comparing the steel produced in condition B, with the one produced in the conditions C and D, some contributing factors are related to the improvement of their fatigue properties e.g.: higher microhardness of phases, presence of the martensitic phase, and more homogeneous distribution of the islands of the second phase in the ferritic matrix.

Table 5 - Tensile properties.

Heat treatment	σ_y (MPa)		σ_t (MPa)		(%)	
	Yield strength	$\overline{\sigma}$	Tensile strength	$\overline{\sigma}$	Elongation	$\overline{\sigma}$
Annealed	293	05	350	04	38	2
A	401	10	515	03	19	2
B	402	21	587	07	16	3
C	277	15	447	23	21	3
D	264	11	432	16	28	3

The performance in fatigue presented by the steel produced in condition D is worse than the steel produced in condition C. This fact is mainly due to the increase of the mean size of the ferritic grains and the heterogeneity of the microstructure obtained in C: areas with small bainite grains, retained austenite and a gradient of the ferritic grain size being quite close to areas of larger concentration of a second phase. These factors improve the appearance of the local stresses during the process of recurrent deformation and they help in the nucleation of the microcracks.

Microstructure formed in treatment A presents higher tensile and fatigue properties than the ones formed in conditions C and D. This fact is justified by the presence of reduced grain size and higher bainite and martensite volume fractions [20,21].

Microscopic analysis, for all conditions studied, reveals that the main micromechanisms fractures are activated by dimple formation. Fig.8 shows a typical fracture surface.

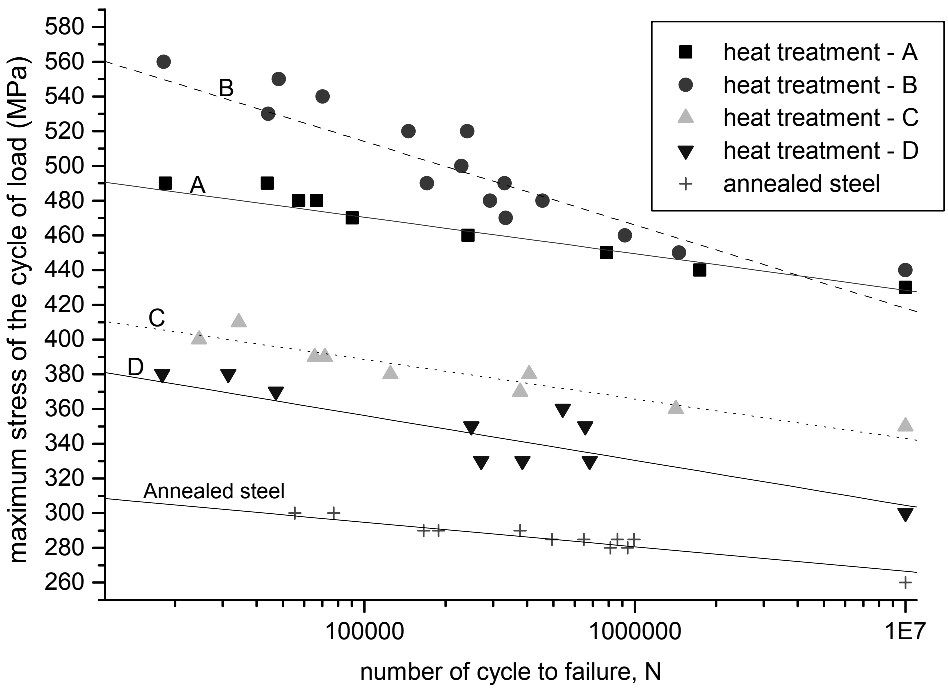

Figure 7 - Fatigue curves for the microstructural conditions investigated.

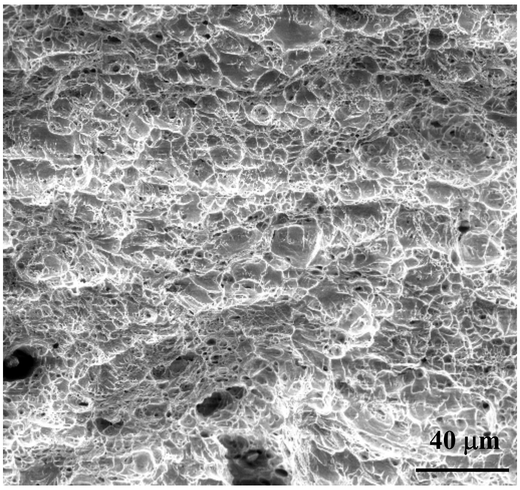

Figure 8 - Scanning Electron Micrograph (SEM) showing aspects of fracture in steel under condition D - surface covered of dimples with rare occurrence of quasi-cleavage.

The micrograph of Fig.9 shows a typical dislocation substructure formed in the ferrite phase in a steel treated in condition C and D. Subgrain formation is observed.

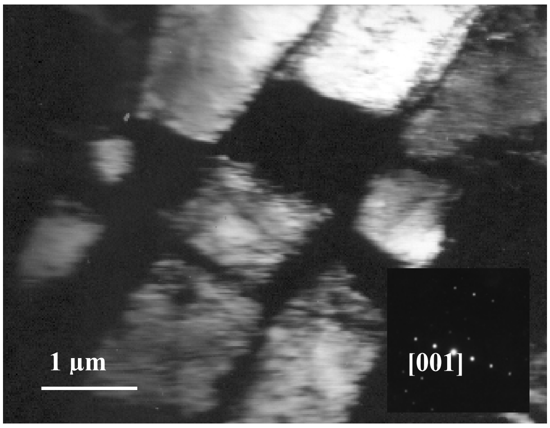

Figure 9 – Transmission Electron Microscopy (TEM) micrograph showing typical dislocation arrangements and subgrains formed in a steel sample treated in conditions C and D.

The increase in the microhardness of the ferritic phase in a sample treated in A and B condition improves the mechanical properties of the steel and modifies the configuration of the dislocation substructures. The new cellular arrangement is shown in Fig.10. This arrangement permits that, during the test, the material supports higher stresses and strains without collapsing.

4. CONCLUSION

1. The microstructure of the steel sample formed in condition B presents better mechanical properties than others. In spite of presenting a larger grain size and smaller bainite and martensite volume fractions than the ones treated in the condition A, it reaches higher tensile strength and a higher fatigue life. This fact is related to the morphology of the phases with martensite or bainite islands distributed by the ferritic matrix and to the high values of the microhardness reached in ferritic phase due to the fast cooling end.
2. Microstructures formed by heat treatment A present a larger volume fraction of second phase and smaller grain sizes than the ones obtained in other treatments. These characteristics ensure (steel obtained in condition A) a better performance in fatigue and tensile tests than microstructures obtained in conditions C and D.
3. Microstructure obtained in heat treatment C presents better mechanical properties than the steel obtained in condition D. The steel obtained in condition D, in spite of containing a larger bainite volume fraction than the steel in condition C and similar microhardness of the phases, presents smaller mechanical property levels due to the heterogeneity of the microstructure and to the excessive growth of the ferritic grain size.
4. For all the microstructures obtained in this work, the macroscopic analysis of the fracture surfaces present ductile characteristics (deformations). The microscopic analysis reveals that the main fracture micromechanism is actived by dimple formation with a few occurrences of the quasi-cleavage facets.

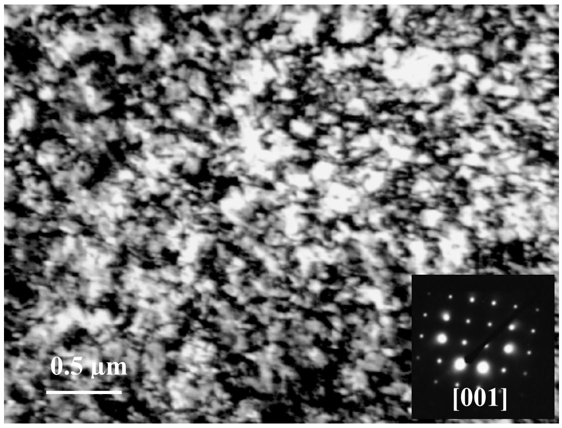

Figure 10 – Transmission Electron Microscopy (TEM): micrograph showing a typical cellular dislocation substructure formed in a steel treated in conditions A and B.

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