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Effect of heat treatment on mechanical properties of FeMnAlC alloys

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Abstract

FeMnAlC alloys exhibit an attractive strength/ductility combination, low density and some of them show good oxidation behavior at high temperatures. In this paper the effect of a solubilization treatment at 1030 °C followed by aging at 550 °C on the mechanical properties of two alloys belonging to this system, has been evaluated. The results of the investigation revealed that the steel characterized by the higher quantity of Mn and Al shows, after heat treatment, the formation of intermetallic phases that make the alloy very brittle. Considering the obtained results, it is evident that optimizing the alloy chemical composition is of paramount importance to guarantee a high fracture toughness if the steel works for limited time intervals at high temperature.

Keywords: FeMnAlC alloys; Mechanical properties; Poorman steels; Steel aging.

1. Introduction

Fe-Mn-Al-C steel have an interesting combination of strength and ductility. Developed in the 1950s for replacing Fe-Cr-Ni steels, are still subject of research for their potential applications for structural parts in the automotive industry because they are lighter than other steels (Chen et al. 2017). Available research highlighted that 1%wt aluminum addition determines a density reduction of about 1.3% (Georg Frommeyer and Brüx 2006), which is an important achievement for reducing fuel consumption and CO_2 emission. Among different alloys, twinning-induced

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plasticity (TWIP) steels with up to 30 wt% Mn and > 0.4 wt% C content have shown an excellent combination of ductility and strength.

In these alloys Mn addition increases the face-centered cubic lattice parameter, moreover very high Mn and C content stabilizes the austenite, so that it can tolerate Al additions up to about 10 wt% without destabilizing the fcc structure (Ishida et al. 1990; Kalashnikov et al. 2000; Raabe et al. 2014). To produce austenite based low density steels there are many process variants. To obtain cold rolled products, with age-hardenable austenitic Fe-Mn-Al-C steels, the cold rolled strips are solution treated over the temperature range 900–1100 °C in the single austenite phase area, and then quenched. Subsequent aging treatments can be performed to produce precipitation hardening that is carried out by isothermally holding the material for 5–20 h in the temperature range 500–700 °C (Gutierrez-Urrutia and Raabe 2013; Rana 2014; Kim, Suh, and Kim 2013). For non-age hardenable austenitic Fe-Mn-Al-C steels, after cold rolling, recovery annealing in the temperature range 600- 900 °C for a short time can be performed to restore the ductility. Considering that one of the most interesting aspect of these alloys is the high reachable strength, many authors studied their strengthening mechanisms. In ferritic low-density steels, the most important strengthening mechanism is the solution hardening due to dissolution of Al in bcc iron. Aluminum creates marked solid solution strengthening in ferrite producing 40 MPa/wt% increase in yield strength (G. Frommeyer, Drewes, and Engl 2000). Austenitic low-density steels can be strengthened by means of solution hardening, work hardening, grain refinement (Etienne et al. 2014) and precipitation hardening. The latter treatment produces a significant strengthening mechanism in highly alloyed Fe-Mn-Al-C steels. This determines the precipitation of nano-scaled and homogeneously distributed κ^{I}-carbides that affect the movement and arrangement of dislocations during deformation (Song et al. 2015; Park et al. 2019; Ikarashi et al. 1992). For higher Al alloyed steels another form of precipitation is that of the α-ferrite, which can be present as fine stringers in the γ matrix (Cheng 2014).

These alloys are also studied for applications at high temperatures. Some authors reported that the oxidation rate decreases with increasing aluminum content due to the formation of a layer of $FeAl_2O_4$, and Al_2O_3 above 7% of Al (Zambrano 2018; Kao and Wan 1988). An increased oxidation resistance can be also obtained by adding 2.3% Si (Felli, Bernabai, and Cavallini 1985) . Other authors (Jackson and Wallwork 1984; Sauer, Rapp, and Hirth 1982; Pérez et al. 2002) highlighted that the steel behavior is strictly related to the alloy composition. For example, over the temperature range 600-1000 °C Fe-(5–10)%Mn-(6–10)%Al alloys develop continuous protective alumina scales and are totally ferritic. Austenite seems to be detrimental to the oxidation resistance of duplex alloys as it promotes the breakdown of the alumina scale and the growth of Mn rich oxides.

In this work two Fe-Mn-Al-C alloys, having potential interesting applications at high temperatures, have been studied in order to evaluate the effect of heat treatments on their mechanical and fracture behavior.

2. Materials and methods

For this research two kind of rolled steels having a thickness of 5 mm were considered. The two considered alloys were named B23 and B37 respectively. Their composition is given in Table 1.

Table 1. Chemical composition (wt. %) of B23 and B37 specimens.

	C	Al	Mn	Fe
B23	0.76	9.6	37	-bal.-
B37	0.96	5.6	33	-bal.-

In order to perform the tests, specimens were taken from both steels and prepared for performing tensile and aging tests. Specimens having a size of 25x25x5 mm were ground using SiC papers ranging from 80 to 2400 grit and polished using 1µm alumina suspension in order to perform metallographic analyses. In order to reveal the microstructure they were etched using Nital 2 solution.

Aging tests were performed by carrying out a solubilization treatment at 1030 °C for 60 minutes, quenching in water and aging at 550 °C for different times. Specimen hardness was measured in order to obtain the hardness as a function of time.

Tensile tests were performed on the as-received specimens and on specimens after aging at 550 °C by using an Instron 3367 machine.

In order to identify the phases before and after heat treatment X-Ray diffraction was performed by means of Philips X'pert diffractometer using a Cu (Kα) source. Fracture surfaces were analysed by using a Hitachi scanning electron microscope (SEM).

3. Results and discussions

The analysis of both the steels started with the study of their microstructure. Both B23 and B37 specimens were analyzed by using an optical microscope. Figure 1 shows the microstructure of both the alloys in the as-received state. Figure 1 highlights that both the alloys have a typical austenitic structure with visible twins.

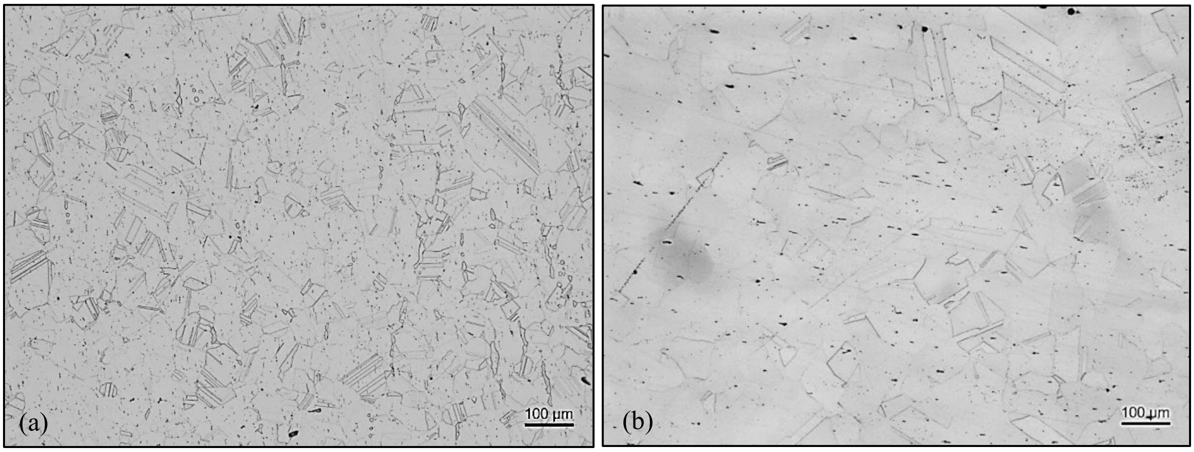

Figure 1. Optical micrographs showing the microstructure of (a) B23 and (b) B37 alloys.

In order to characterize the as received materials density measurements, performed by using the Archimedes' method, were performed: the density of B23 was 6.47 g/cm^3 and B37 is 7.08 g/cm^3. This is in accordance with the fact that B23 alloy has a higher quantity of aluminium. Vickers hardness tests gave 209 HV10 for B23 and 175 HV10 for B37 that is characterized by a lower amount of alloying elements.

Figure 2 shows aging curves obtained at 550 °C. This figure highlights that the hardness of B23 increases with time while the one of B37 is almost constant.

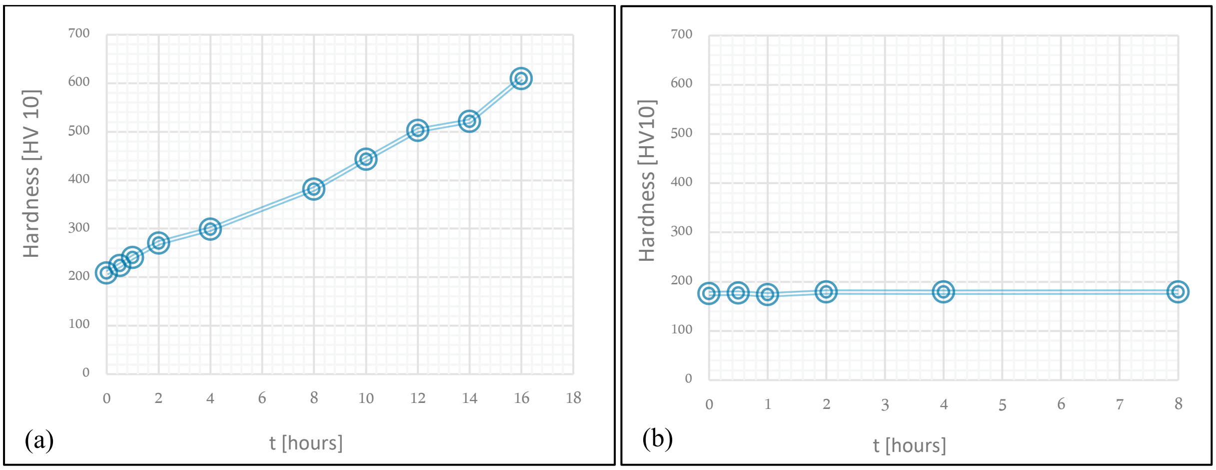

Figure 2. Hardness of (a) B23 and (b) B37 versus time during aging at 550 °C.

After solubilization and aging for 8 hours tensile test specimens of both the steels along with the ones in the as-received conditions were subjected to tensile tests. Figure 3 shows the stress-strain curves of both B23 and B37 alloys in the as-received conditions and after heat treatment.

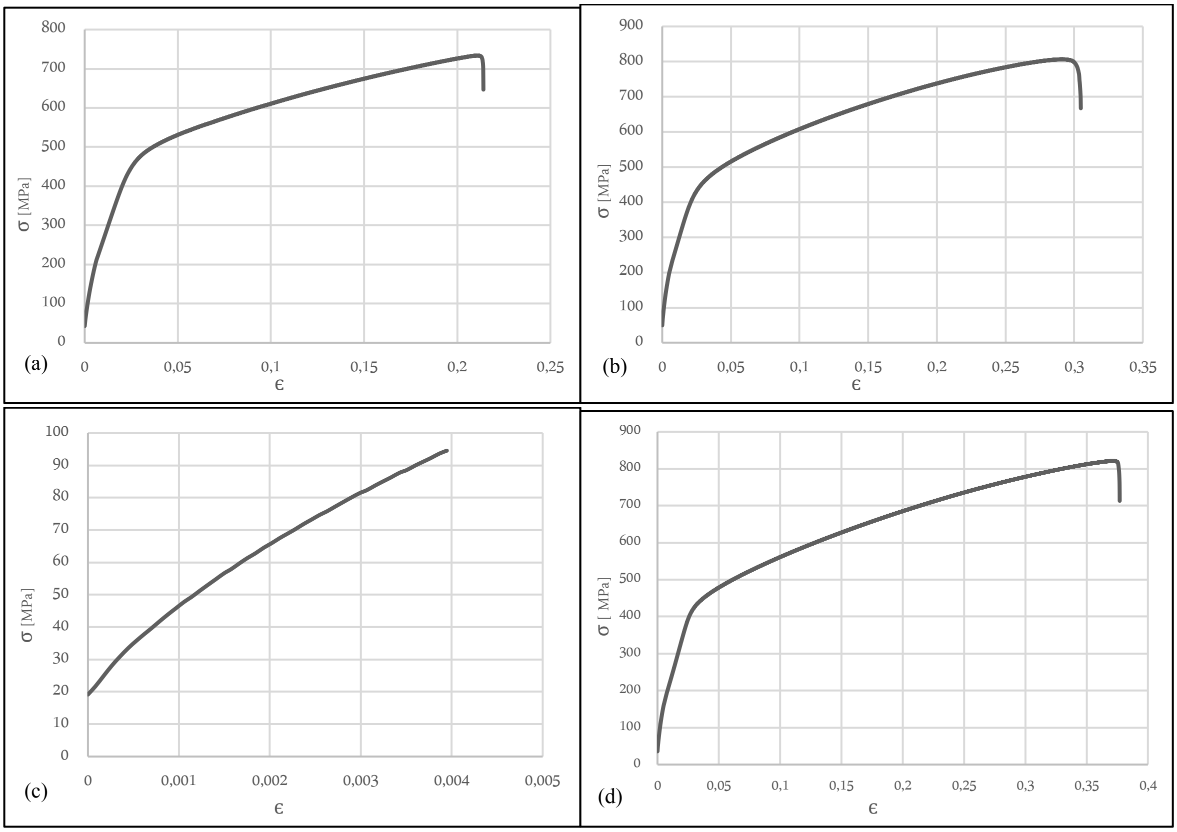

Figure 3. Stress-strain curves of (a) B23 and (b) B37 in the as-received conditions. Stress-strain curves of (c) B23 and (d) B37 after heat treatment at 550 °C for 8 hours.

For B23 in the as-received conditions the yield strength is 450 MPa with a tensile strength of 727 MPa and an elongation of 21%. For B37 the yield strength is 402 MPa with a maximum tensile strength of 801 MPa and elongation of 30%. Tensile tests performed after heat treatment showed that B37 has a mechanical behaviour very similar to the one exhibited in the as-received conditions: the yield strength was 422 MPa with a tensile strength of 817 MPa and an elongation of 37.6%. As it can be seen in Figure 3, B23 showed a very brittle behaviour after 8 hours of aging at 550 °C and broke in the elastic region.

In order to explain the different behaviour shown by the two studied alloys a microstructural analysis has been performed on the alloys after heat treatment. Figure 4 shows the microstructure of the both the alloys after 8 hour aging. It can be noticed that while B37 has the typical austenitic structure as before the heat treatment, the microstructure of B23 has completely changed and appears characterized by the presence of different phases. It must be also stressed that, after aging, B23 shows the presence of delamination defects that can affect the alloy mechanical behaviour.

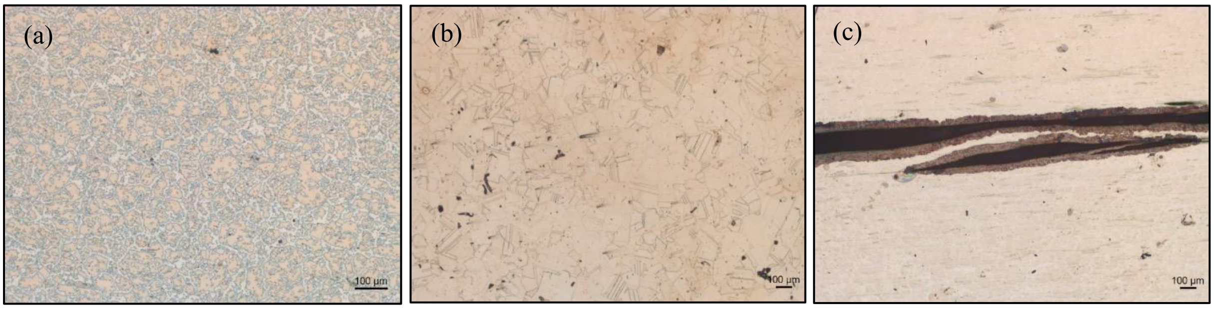

Figure 4. Optical micrographs showing the (a) microstructure of B23, the (b) microstructure of B37 and the (c) delamination defect after heat treatment in B23.

In order to explain the causes of the brittle behaviour of B23 alloy after heat treatment XRD analyses have been performed on this alloy in the as received state and in the aged conditions.

As it can be observed in Figure 5a, before heat treatment, the alloy is constituted by austenite and by a little quantity of ferrite. After heat treatment (Figure 5b) intermetallic phases, such as Al_8Mn_5, $FeMn_4$ and $FeMn_3$, are formed. Hence, this explains the change is its microstructure and its brittle behaviour during tensile test. The fracture of the alloy in the elastic region is justified by the presence of intermetallic phases, which are very brittle, and by the presence of delamination defects that act as stress intensifiers.

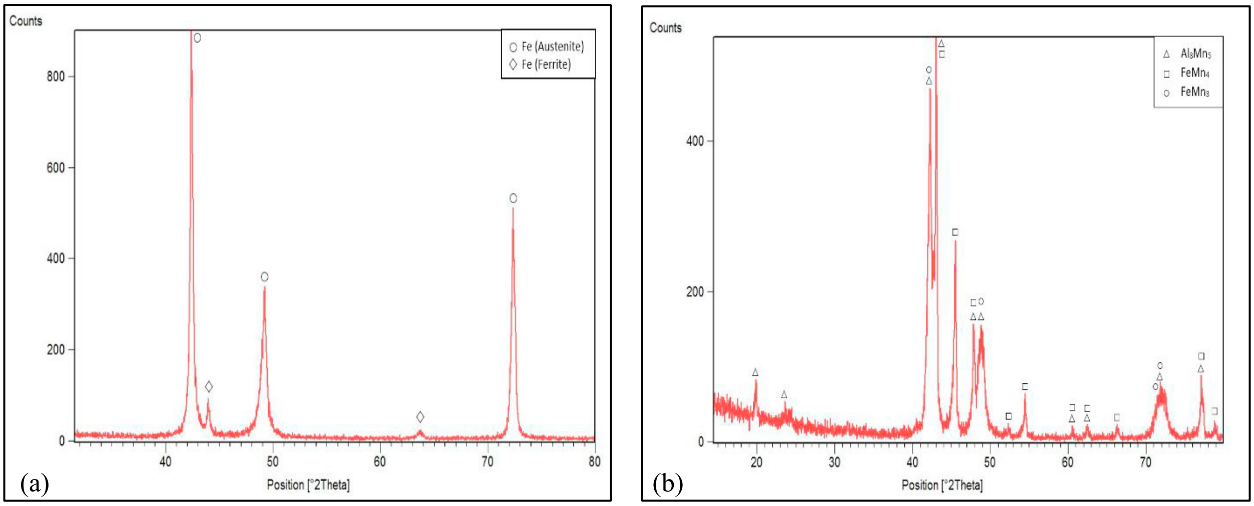

Figure 5. XRD graphs of B23 (a) before heat treatment and (b) after heat treatment.

In order to understand the fracture behaviour of the studied alloys, the fracture surfaces of both the steels were analysed by means of SEM. Figure 6 shows the fracture surfaces of both the alloys obtained from tensile test before heat treatment. Before heat treatment both the steels have similar fracture surface morphology, characterized by dimples, which is ductile in nature. After tensile tests both the specimens developed delamination layers whose presence can be attributed to the hot rolling performed in the production stage.

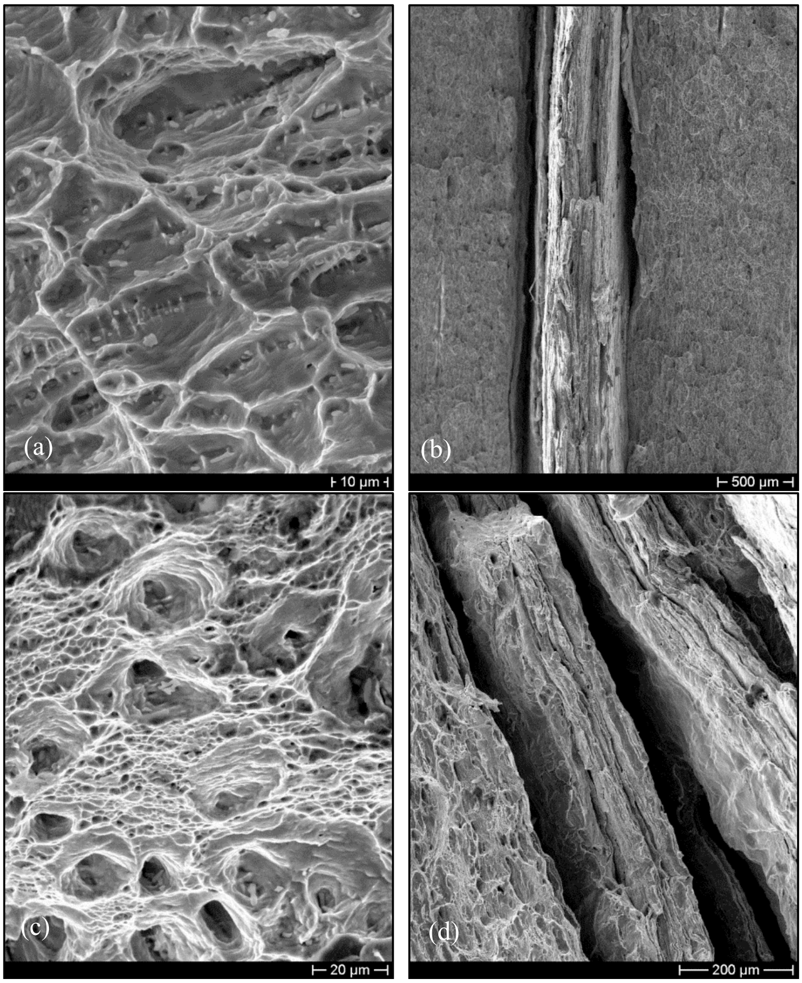

Figure 6. SEM micrographs showing (a) the fracture surface and (b) a delamination of B23 in the as-received conditions, (c) the fracture surface and (d) a delamination in B37 in the as-received conditions.

Figure 7 shows the fracture surfaces of B23 and B37 after heat treatment. By observing this figure it is evident that B37 shows a ductile facture, similar to the one observed before heat treatment, along with the delamination layers. Quite the opposite, B23 shows a brittle behaviour with a transgranular fracture characterised by the presence of secondary microcracks (Figure 7(b)).

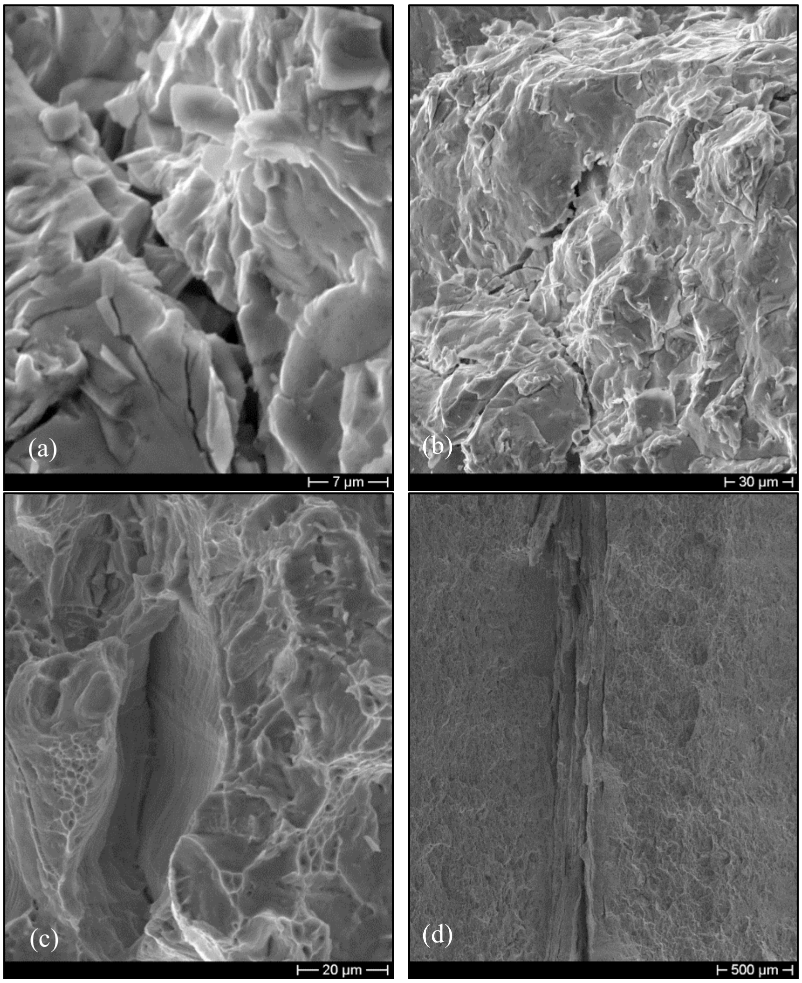

Figure 7. SEM micrographs showing (a) the facture surface (b) the fracture surface with secondary cracks in B23 after heat treatment, (c) fracture surface and (d) delamination in B37 after heat treatment.

4. Conclusions

From this research it is evident that the composition of the studied steels affects their behavior, especially when they work at a temperature above 500-600 ℃. The study carried out in this paper highlighted that the steel characterized by the higher quantity of Mn and Al shows the formation of intermetallic phases after heat treatment at 550 °C. These phases make the alloy very brittle. Based upon this observation, it must be stressed that, for FeMnAlC alloys, optimizing the chemical composition is of paramount importance to guarantee a high ductility and fracture toughness when the component is put in service at high temperature.

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