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ABSTRACT

Usually bainitic microstructures exhibit good toughness and austempering is typically the preferred heat treatment when toughness is the primary requirement of the component. Several reports have shown such characteristics when compared to tempered martensite. High-carbon steel may exhibit brittle characteristics but it is a good steel with respect to mechanical properties and wear resistance. The objective of this study was to compare the impact properties of AISI O1, a high-carbon tool steel, designated VND in Brazil. This was done by comparing Charpy impact strength under different heat-treatment cycles. Steel test specimens were quenched from 820°C and tempered at 450°C to obtain tempered martensite, then austenitized, cooled, and held at 350°C to obtain bainite by holding at temperature for 20, 40, and 60 min. Because hardness influences impact behavior, comparative studies were performed at the same surface hardness level. The austempered samples with bainite microstructures obtained at a constant temperature and, by varying holding times, exhibited lower impact properties as compared to the quenched and tempered condition.

Keywords

bainite, tempered martensite, impact properties

Introduction

High-carbon steels are used for many applications because of their superior mechanical properties. Toughness is important because a component should resist the formation of cracks that may exist in brittle materials. Therefore, heat treatment must be well defined to produce an adequate microstructure for the required application.

It is well known that bainitic microstructure produced by austempering exhibits better impact performance than tempered martensite. High toughness exhibited by bainite was shown previously by comparison at the same hardness with an identical component subjected to conventional quenching and tempering [1]. Many reports published since have agreed with this result. However, similar results have also been reported when comparing impact results from tempered martensite and bainite [2]. One objective of the work reported here is to compare recent experimental work with other previously reported studies.

Austempering is an isothermal heat treatment performed by austenitizing and holding in the temperature range 250°–400°C, although some upper bainite may be obtained at temperatures of approximately 500°C. Upper and lower bainite are classifications based on the morphology resulting from the different temperatures at which they are formed. The mechanical properties of upper and lower bainite are typically different. Austempering is used because lower bainite exhibits better mechanical properties than upper bainite and it is also better compared with quenched and tempered martensite. Austempering also reduces warping and cracking potential, whereas achieving improved dimensional stability because austempering also reduces residual stress before bainite formation [3].

Recent results have shown that mechanical properties of austempered components possess a strong dependence on austempering temperature and holding time [4–10]. Austenitizing temperature effects on the formation of hard bainite are reported in the literature [4]. High carbon steel samples (0.91 %C, 1.45 %Si, 0.48 %Mn, and 0.99 %Cr) were subjected to austenitizing temperatures in the range: 880°C–1000°C for 20 min and held for different times in an oil bath at 200°C–280°C and then water cooled. One conclusion from this work was that austenitizing temperatures noticeably affect transformation kinetics. Bainite formation shifted toward lower a temperature and shorter soaking times with increasing austenitizing temperatures producing microstructural changes as well. Maximum hardness (810 HV) was obtained with an austenitization temperature of 980°C.

Most of the reported works are related to SAE 52100 steel; however, high-speed steel [6] and low carbon steel [5,7] microstructures containing bainite and retained austenite obtained after austempering have exhibited attractive mechanical properties when austempering is performed at a suitable time and temperature. Duplex microstructures, bainite and martensite, obtained by a combination of austempering and quenching, is also promising in terms of tensile strength, impact toughness, and hardness [8,9].

Higher austempering temperatures and higher holding times usually promote coarsening of the bainitic microstructure leading to worsening of toughness. Bainite becames stronger with finer grain size, high carbide precipitation, and high dislocation density, which increases as the tempering temperature decreases [5,7,10]. Results from Ref 9, using SAE 52100 showed that using the optimum austempering temperature of 270°C and holding time of 30 min followed by water quenching produced austenitic and martensitic microstructures.

Interesting work was performed with SAE 52100 steel austempered at approximately 300°C, 275°C and 250°C and holding times of 15 min, 30 min and 60 min as process parameters [8]. Bainite, martensite, and retained austenite were obtained. The total amount of retained austenite decreased with increasing holding time. Lower hardness and better impact performance were obtained for the highest temperature and longest holding time. The conclusion was that austempering temperatures are more effective than austempering holding time for controlling the volume fraction of bainite for AISI 52100 steel.

On the other hand, tempered martensite can exhibit good toughness when the tempering temperature is carefully chosen. Embrittlement can be found in tempered steels and it occurs when the tempering temperature is close to 350°C. Tempered martensite embrittlement (TME), also called temper embrittlement (TE), is associated with slow cooling in the range 370°C–565°C. In both cases, they lead to poor impact properties. There are two characteristics involving TME: segregation of minor elements (mainly P) to austenite grain boundary, and the formation of deleterious carbide morphology from thin layers of retained austenite during tempering [3]. This indicates that, if tempering was performed in this tempering temperature range, low impact performance will result. Studies have been conducted with spring steel that show that this embrittlement is associated with TME [11].

There are limited reports comparing tempered martensite and bainite microstructure because there is a common belief that achieving a bainitic microstructure is preferred. However, recent works have reported different conclusions [3,12]. Santos et al., using results based on SAE O1 steel, demonstrated that modified martempering is a better heat treatment than austempering when impact properties are considered [12]. Aksu [13] also studied toughness and impact properties using different austempering parameters and comparing the results to conventional quenching and tempering. In this study, samples from DIN 35NiCrMoV12.5 steel were subjected to different isothermal temperatures (300°C, 325°C, and 350°C) and also different holding times (1 min, 10 min, 1 h, 10 h). All of the samples were austenitized for 1 h at 850°C. Austempering was performed in a salt bath with subsequent cooling in water. For conventional quenching and tempering process, no details were provided except that tempering was performed at 400°C to obtain 44 HRC. The conclusion was that although higher toughness values for bainite microstructure was expected, fracture toughness tests of the austempered samples revealed structures with lower toughness than conventionally treated samples. Such results are consistent with Bowen et al. [14], who reported that the coarsest cementite particles were found in the tempered microstructure. With these results, toughness was found to follow the order: upper bainite < lower bainite < tempered martensite. Such results are in disagreement with Tu et al., who report that bainite exhibited better performance relative to toughness and ductility at the same tensile strength [15]. Liu and Kao [16] and Sanvik and Nevalainen [17] have also shown that bainite exhibits extensive toughness.

The main goal of the work reported here is to compare Charpy impact properties using VND steel (SAE O1 tool steel) subjected to austempering and also quenching and tempering. This class of steel is very important and is considered a

TABLE 1

Chemical composition (%).

C	Si	Mn	P	S	Cr	V	W
0.970	0.260	1.120	0.028	0.009	0.52	0.070	0.420

cold-work tool steel. They are used to cut or form materials at low temperatures. Its high carbon composition produces high hardenability, wear resistance, average toughness, and heat-softening resistance.

Experimental

Table 1 shows the chemical composition of SAE O1 (VND steel from Villares Metals in Brazil) used for the work reported here.

Charpy samples were cut from a rolled bar (diameter of 15.87 mm) and 3 m long, as shown in **Fig. 1**. Test specimens were prepared according to ASTM E23-12c [18].

The test specimens were austenitized at 820°C for 60 min. Austempering was performed in a molten salt bath at 350°C with holding times: 20, 40, and 60 min. At 350°C, according to **Fig. 2**, is possible to obtain lower bainite. Quenching was performed based on the CCT curve shown in **Fig. 3**.

To avoid the embrittlement during tempering, the Charpy absorbed energy as a function of tempering temperature was obtained from tests performed before austempering and the quenching and tempering process for comparison between the two structures formed at the same hardness level. Results are shown in **Fig. 4**.

By analysis of these results, it was possible to determine that embrittlement is located between 290°C and 365°C. Therefore, the tempering temperature of 450°C (1 h) was selected, which is out of the danger range and produces the same hardness, 41 HRC as that obtained in the austempering process.

Fig. 5 shows the heat-treatment scheme used for this experimental work Charpy tests were performed according ASTM E23-12c [18–20] recommendations using an INSTRON WOLPERT PW30 machine. Hardness tests were performed using a

FIG. 1

Charpy sample obtained from round bar.

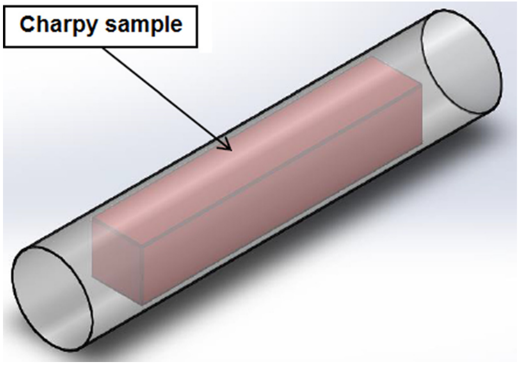


FIG. 2

TTT diagram for O1 steel [19].

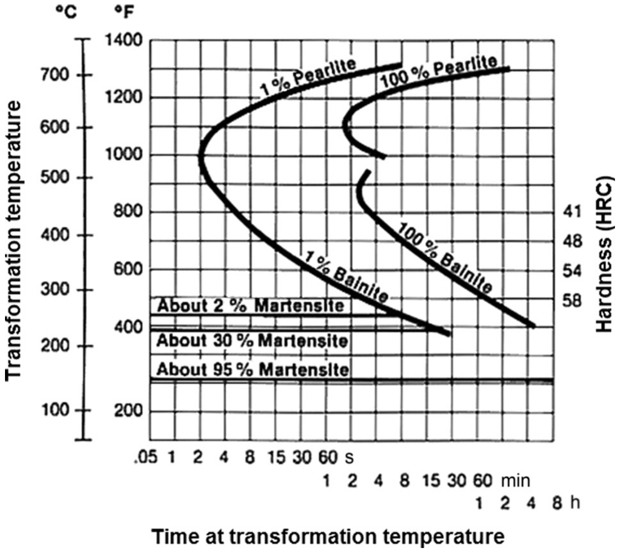


FIG. 3

CCT curve for SAE O1 for quenching and tempering, the austenitizing temperature was 820°C for 60 min and then quenched into oil at 60°C under agitated conditions [20].

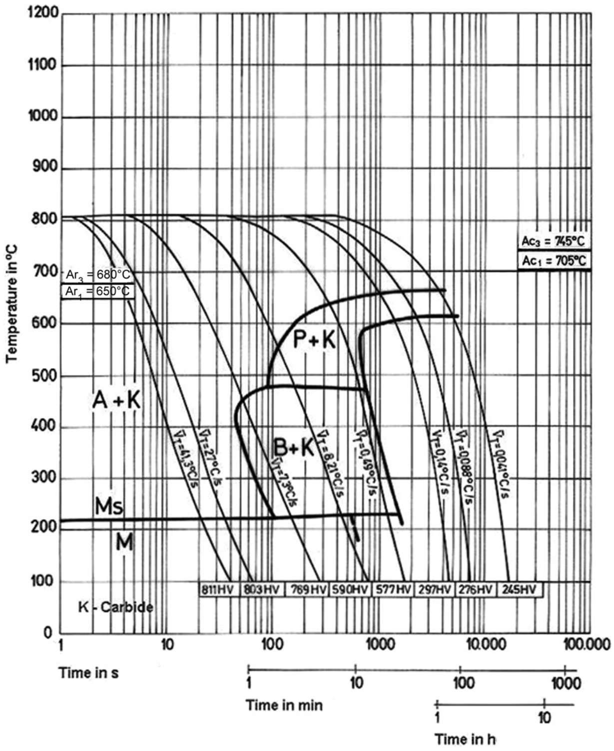
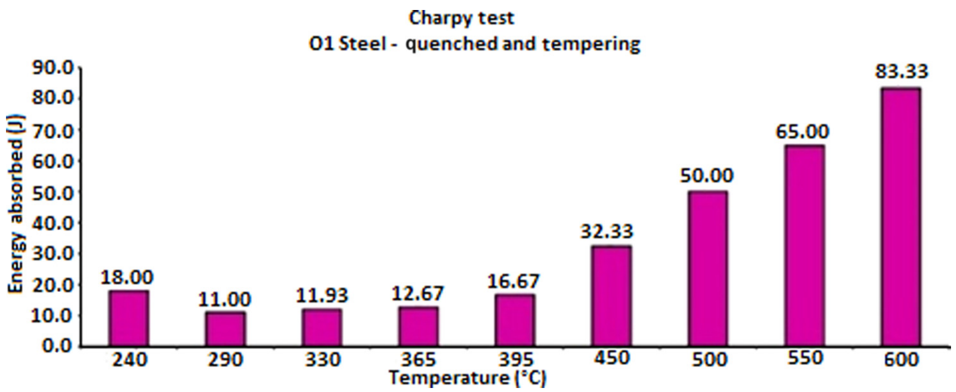


FIG. 4 Charpy absorbed energy as function of tempering temperature.



LECO machine, Model RT240a (eight measurements for each sample). Optical microscopy was also included in the analysis with etching.

Results and Discussion

Figs. 6 and **7** show micrographic aspects of the samples under different heat-treatment conditions.

Fig. 7 is representative of those microstructures obtained for the austempering processes. Bainite is the predominant microstructure and white spherical carbides can be observed. The microstructures were independent of the soaking time.

Results from hardness and Charpy absorbed energy results are shown in **Table 2**.

It is clear that quenching and tempering produces microstructures with better performance than the austempering process.

Macroscopic analysis results of the fractured Charpy samples confirm that different behaviors for absorbed energy were obtained (see **Fig. 8**).

A large shear lip at the surface boundary in the quenched and tempered sample indicated plastic fracture. The presence of shear lips is related to toughness and has a direct connection with the crack tip plastic zone size. On the other hand, in the austempered sample, an irregular topography of the fracture with an absence of shear lips characteristic of brittle fracture is observed. In this case, once cracks are

FIG. 5 Scheme of the heat treatments: (a) austempering and (b) quenching and tempering.

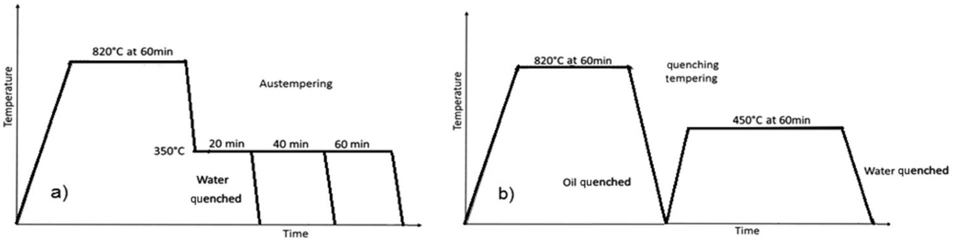
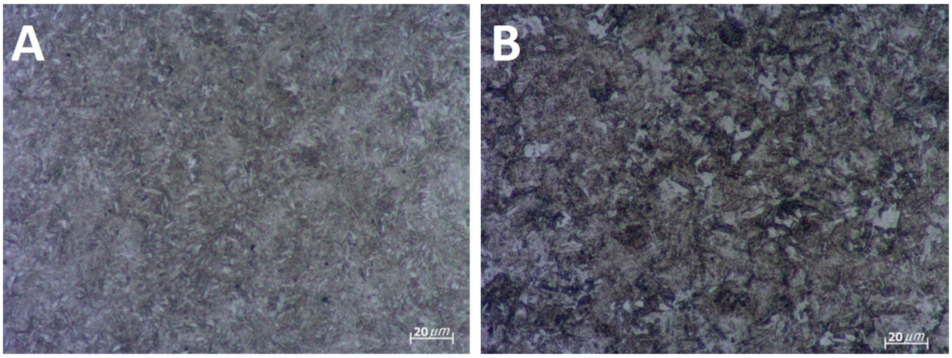


FIG. 6 O1 steel quenched and tempered (a), and austempered (40 min) (b); 2 % nital etching.



formed, there is no expenditure of energy for crack propagation. Energy is spent for crack nucleation. Observing **Fig.** 8a and 8b (black arrows), it can be seen that the martensitic fracture surface is flat and the bainitic surfaces exhibit some waviness. One possible explanation for the wavy fracture surface is that a high cracking speed is related to the bending stresses rearrangement during crack propagation, as shown in **Fig.** 9.

In the martensitic structure, because of the plastic crack-tip contribution, the crack propagates at a lower speed and the bending stresses can be rearranged during crack propagation. Similar conclusions can be made observing fractographic analysis results obtained by SEM of the fractured surface as shown in **Fig.** 10 comparing bainitic and martensitic matrixes.

Observing the images from **Fig.** 10, obtained from secondary electrons with high magnification, it is possible to conclude that both surfaces exhibit predominant transgranular fracture. However for quenching and tempering (**Fig.** 10a), the facets are more misaligned and the quasi cleavage mechanism is associated with many dimples, which represents a plastic contribution to the fracture mechanism, thus improving the material toughness.

FIG. 7 Microstructure representative for the three austempering conditions; 2 % nital etching.

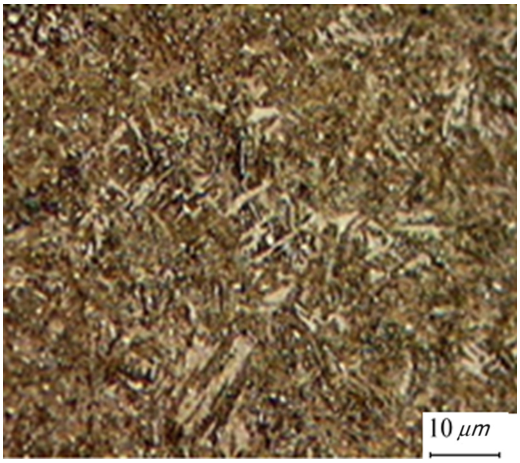


TABLE 2

Comparative results of hardness and Charpy absorbed energy for different heat-treatment cycles.

Heat Treatment/Isothermal	Hardness Average[a] (HRC) [21]	Absorbed Energy Average (J)
Austempering 20 min	38.9 ± 1.7	7.6 ± 0.9
Austempering 40 min	39.1 ± 1.8	12.8 ± 3.1
Austempering 60 min	40.4 ± 1.2	7.2 ± 1.1
Quenching and tempering	41.0 ± 1.2	33.0 ± 1.0

[a] Hardness values obtained from surface.

In the case of the austempered samples, the quasi cleavage facets are more misaligned and there are no dimples and/or microdimples. This would explain why austempered samples require low energy to propagate the crack, promoting a dynamic cracking with lower energy absorption as related to the quenched and tempered structure.

Fig. 11a–11h show fractographic images from different regions of the fractured bainitic Charpy samples. **Fig.** 11a and 11b are close to the mechanical notch, **Fig.** 11c and 11d are related to the region located 2 mm below the mechanical notch, **Fig.** 11e and 11f are 4 mm below the mechanical notch, whereas **Fig.** 11g and 11h are located on the opposite side of the mechanical notch. Analyses were made for 20 min and 60 min of holding time in the austempering temperature.

The scanning electron microscopy fracture surface shows a quasi-cleavage mechanism covering the entire fracture surface. The two austempering conditions (20 and 60 min of austempering) produced the same fracture mechanism topography. These results indicate that austempering exhibits lower toughness than tempered martensite obtained by conventional quenching and tempering. Although Santos et al. [12] found similar results showing martempering with better toughness behavior than austempering, most research results do not show this. In the industry, the comparison between bainite and tempered martensite in terms of toughness frequently does not take in account the hardness level. Kong et al. [4] indicate austempering as better process than quenching and tempering or even martempering for

FIG. 8

Macroscopic analysis of the fractured Charpy samples. (a) Quenched and tempered: presence of shear lips. (b) Austempered (40 min of soaking time): surface characteristic of brittle fracture without lateral deformed zone.

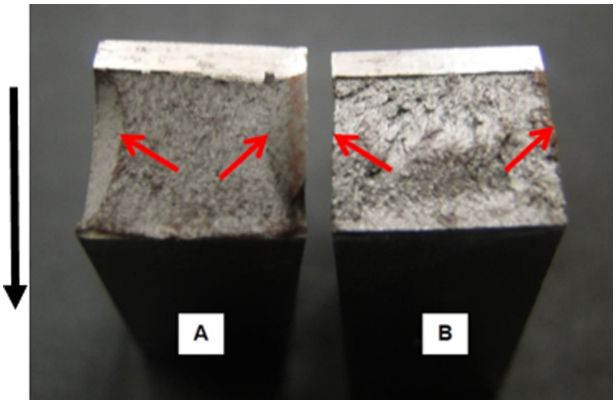
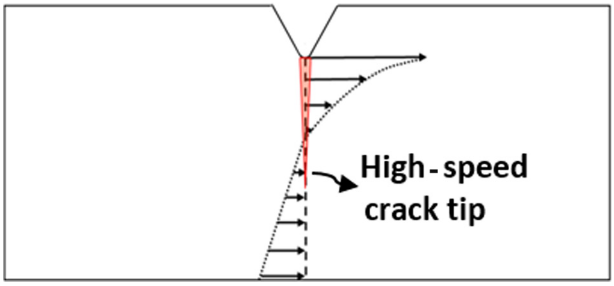


FIG. 9
Crack entering compression bending stresses lowering its speed and changing locally the trajectory.



toughness. On the other hand for fatigue resistance, Zepter [21,22] shows better results for the austempered structures. For the bainite microstructure, carbides are distributed along the ferrite slats and this situation cannot anchor microcavities nucleation. Carbides function like grain boundaries acting as deflectors of crack propagation during cyclic processes.

It is important to address the concern about the tempering temperature range used in the quenched and tempered samples used for the comparative tests. This is one question that must be investigated in more detail as it was not reported in the previous literature cited here.

FIG. 10
SAE O1 steel SEM fractography: (a) quenching and tempering, and (b) austempered.

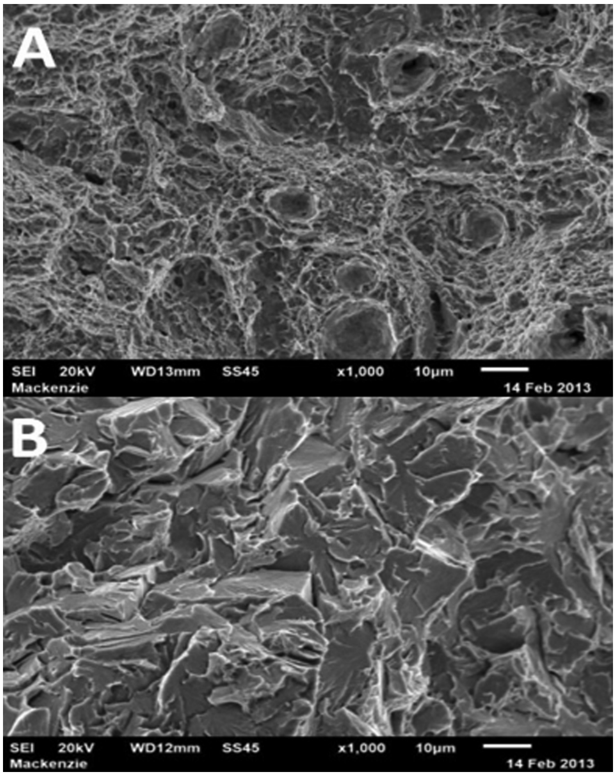
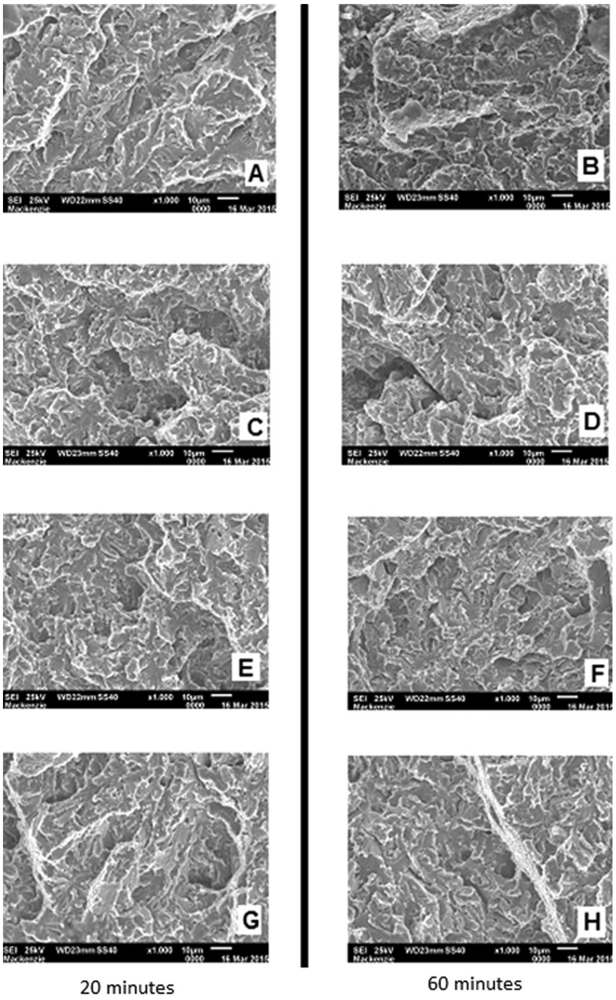


FIG. 11 Scanning electron images in different regions of the fractured Charpy samples from 20 and 60 min of soaking time. Quasi-cleavage mechanism: (a), (c), (e), and (g), 20 min; (b), (d), (f), and (h), 60 min.



One might question whether the austempering parameters selected in the present work were adequate to produce microstructures with high toughness characteristics. As indicated above, mechanical properties of austempered components exhibit a strong dependence on temperature and soaking time [5–10]. In this work, only one temperature with three soaking times was studied. Is it clear that independent of the soaking time, absorbed energy was lower for the austempered samples. This work is continuing using other austempering parameters to examine an expanded temperature range. It is noteworthy that higher martensitic energy absorption relative to bainite microstructure was obtained, even with a higher hardness level (about 52 HRC). Longer treatment times were not studied.

Conclusions

The conclusion of this work is that the austempering parameters selected promoted poorer toughness performance compared with conventional quenching and tempering for the same hardness level.

Even with at much higher hardness, around 52 HRC, the Charpy energy absorption of the martensitic structure was higher than the value obtained with bainitic samples around 40 HRC.

Other austempering parameters must to be evaluated to verify which set of parameters will produce greater toughness than conventional quenching and tempering.

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