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Effects of Different Annealing Heat Treatments on the Microstructure and Mechanical Properties of a Cr-rich High Manganese Hadfield Steel

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Abstract

Hadfield steel exhibits high wear resistance, combined with good toughness, leading to its widespread use in excavators, mineral crushing equipment and other severe mechanical environments. In this study, the mechanical properties of a Cr-rich high manganese Hadfield steel were investigated under different solutionizing heat treatment conditions. The heat treatment consisted of heating to temperatures of 1050, 1100, and 1150 °C with two holding periods of 1.5 and 3 h, followed by the quenching in water or brine. The metallographic examination was performed on all samples and the grain size and the volume percent of carbides were determined. Mechanical properties including the yield strength, UTS, hardness, impact energy, and fracture toughness were also evaluated. It was observed that the quenching in water produced finer grains than the quenching in brine. Increasing the temperature and the holding time caused a decrease in the volume percentage of carbides, as well as the quenching in brine. Indeed, cooling in brine generally produced carbides promoted on the triple junctions of the grains. Meanwhile, blurred dendritic/cellular structures could be observed in interior grains, especially at higher temperatures. It appears that the development of this cellular structure together with the nearly uniform distribution of finely dispersed carbides, has enhanced the mechanical properties. The best hardness was obtained at an annealing temperature of 1150 °C, a holding time of 1.5 h and quenching in water. However, the best fracture toughness and impact value were also obtained at an annealing temperature of 1100 °C, a holding time of 1.5 h, and quenching in brine.

Keywords: Hadfield steel, Heat treatment, High-manganese steel, Mechanical properties, Microstructure

1. Introduction

Cast high-manganese steel containing 1.0-1.4 % C and 10-14 % Mn, also called Hadfield steels (ASTM A128), have attractive properties such as high toughness, ductility, high work hardening and extreme wear resistance to abrasion and are widely used in the power industry and processing of various materials for components of crushers, mills, and construction machinery parts (lining plates, hammers, jaws, cones). However, modern variants may contain up to 1.7 % C and 16 % Mn and may also contain chromium. Almost all crushing equipment employed in the mineral processing industry depends on the wear and impact performance of their liners. Pebble crushers involve very hard materials and compression crushing forces, whereas aggregate crushers deal more with impact crushing conditions. This steel in the as-cast condition is characterized by an austenitic microstructure with precipitates of alloy carbides $(Fe,Mn)_xC_y$ and the triple phosphorus eutectic of a $Fe-(Fe,Mn)_3C-(Fe,Mn)_3P$ type. This appears when the phosphorus content exceeds 0.04 % [1]. It also contains non-metallic inclusions such as oxides, sulfides, and nitrides. This type of microstructure is undesirable due to the presence of the carbides dispersed along the grain boundaries [2]. According to Z. Stradomski [3], the precipitation of carbides at the grain boundaries causes the impact strength of high-manganese cast steel to decrease even ten times. For this reason, the aim of heat treatment is to produce a pure austenitic microstructure, i.e. free of carbide precipitates. Carbon contents of approximately 1.4% are less used in thicknesses greater than 100 mm (e.g. cone crusher liners) because carbon tends to segregate to the grain boundaries as carbides. Santos et al. [4] have provided evidence that this segregation or carbide re-precipitation leads to microstructure embrittlement, which can cause a significant reduction in toughness. On the other hand, hammers for crushers have higher carbon and manganese content with chromium addition (1.7% C, 16% Mn, and 1.4% Cr). Tecza and Sobula [5] have shown in this alloy that prolongation of the solution treatment time at 1150 ºC up to 240 min was also ineffective in terms of the formation of a purely austenitic structure and carbides still present at the grain boundaries. The addition of alloying elements such as Cr, V, and Mo causes the precipitation of complex carbides at the grain boundaries in the as-cast steel [6]. The presence of these carbides improves the strength and hardness of the Hadfield steel, but it creates stresses and increases brittle fracture [7,8]. Falodun et al. [9] investigated the effect of different amounts of manganese and chromium contents on the microstructure, hardness, wear and electrochemical behavior of manganese steels. They found that the hardness and wear resistance increased but corrosion resistance decreased with increasing chromium and manganese content [10]. Hosseini et al [11] considered the heat treatment of 1.3% C, 13.3 % Mn steel through austenizing temperature, time and quenching rate. They concluded that the hardness and carbide volume percentage decreased with increasing temperature and quench rate. Like conventional hypereutectic carbon steels, manganese Hadfield steels have a microstructure consisting of the separately inter-dendritic carbides and complex carbide network at grain boundaries as well as colonies of pearlites (or α-ferrite+carbide). Pearlite transforms to austenite when heated above the critical temperature A1 (about 600-700°C). Heating above the critical temperature A_{cm} causes the carbides to begin to dissolve thermodynamically, however, its kinetics is slow, especially when the alloying elements Cr, Mo, V, and Ti are present. Upon rapid cooling in water or brine, a metastable austenite matrix is formed with/without grain boundary carbides, and during service. Wear and impact loads cause the strain-induced transformation of austenite to α or ε-martensite [12]. Due to the above illustration, Mishra and Dalai [13] proposed a double-step heat treatment with a holding time of 3 h at 650 °C to ensure complete transformation of ferrite to austenite, while in traditional treatment this holding time is about 0.5-1 h. Owing to extensive research on the optimal heat treatment process of Hadfield steels, there are some misleading results in various compositions and correlations of microstructure with mechanical properties. Therefore, in this study, an attempt has been made to correlate microstructural evidence with various mechanical properties of a Cr-rich high manganese Hadfield steel under different solutionizing heat treatment conditions.

2. Materials and Methods

Plate samples with dimensions of 200×180×t (t=10 and 20 mm) were cast with the chemical composition listed in Table 1. The cast samples heat-treated after separating the gating and feeding system are shown in Fig. 1. The heat treatment method as shown in Fig. 2 was inspired by the literature [13]. The parts were placed in a furnace at a temperature of 150~200 °C and held for 1 h, then heated at a rate of 100 °C/h to a temperature of about 650 °C and held at this temperature for 1 h to thermally homogenize the parts during the eutectoid reaction. They were reheated to annealing temperatures (1050, 1100, and 1150 °C) at a rate of 150 °C/h and held at these temperatures for 1.5 and 3 h. Finally, the parts were removed from the furnace and immediately quenched in water or brine (water+5% salt by weight). The annealing heat treatment schemes are presented in Table 2. Tensile, hardness, impact, and fracture toughness test samples were extracted from the parts by the wire cut and machining method. Samples preparation and testings were carried out in accordance with relevant standards. ASTM A216 WCB with a gauge length of 50 mm was used for the tension testing, ASTM E10-15 for the Brinell hardness testing, ASTM E23-16b for Charpy impact testing, and ASTM E561 for fracture toughness. Also, ASTM E647 was employed for the fracture toughness measurements using the compliance method. Fig. 3a shows the apparatus used for developing fatigue crack at the groove tip of the CT specimen using a cam and follower system applied for fracture toughness testing. It can be observed in Fig. 3b. The tests were performed on both 10 and 20 mm thicknesses and the average results were reported.

Table 1.
Chemical composition of cast parts (wt. %)

C	Si	Mn	Cr	Mo	Ni	Al	P	S
1.32	0.40	13.3	1.93	0.2	0.33	0.07	0.07	0.03

Fig. 1. Hadfield cast samples with the gating and feeding system

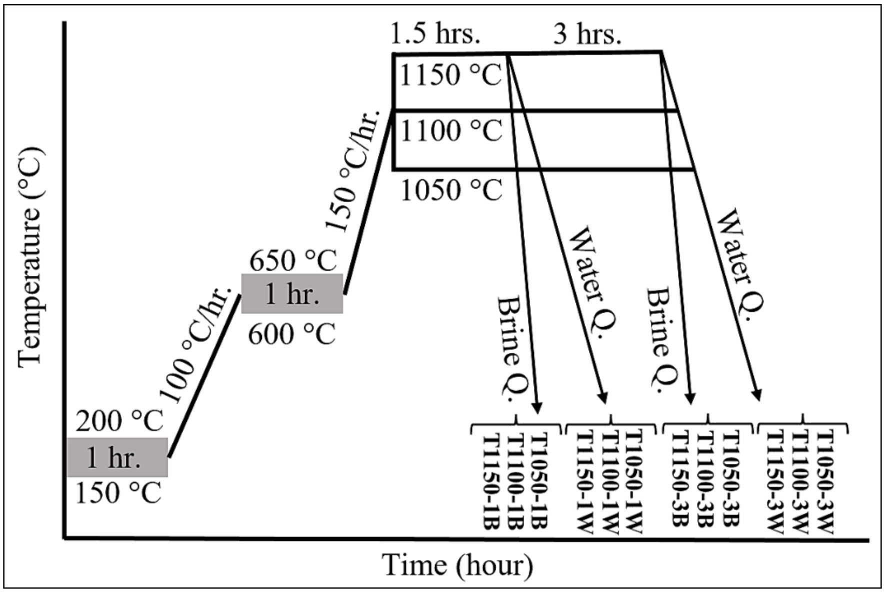

Fig. 2. Heat treatment cycles used in this study

Table 2.
Different annealing heat treatments were used in this study

Test No.	Test code	Annealing temperature (°C)	Holding time (h)	Quenching media
1	T1050-1W	1050	1.5	Water
2	T1050-1B	1050	1.5	Brine
3	T1050-3W	1050	3	Water
4	T1050-3B	1050	3	Brine
5	T1100-1W	1100	1.5	Water
6	T1100-1B	1100	1.5	Brine
7	T1100-3W	1100	3	Water
8	T1100-3B	1100	3	Brine
9	T1150-1W	1150	1.5	Water
10	T1150-1B	1150	1.5	Brine
11	T1150-3W	1150	3	Water
12	T1150-3B	1150	3	Brine

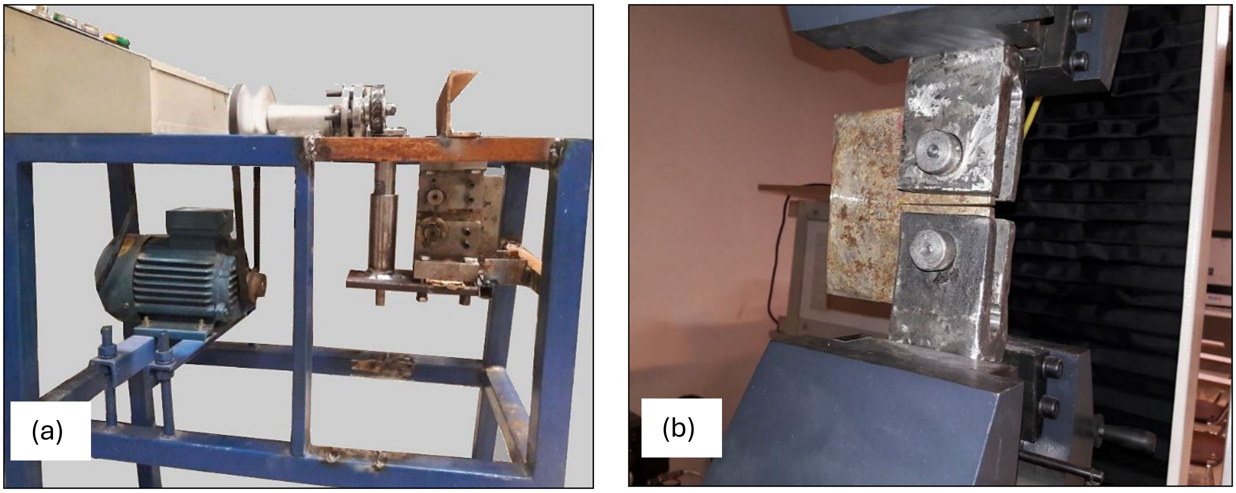

Fig. 3. (a) The apparatus used for developing of fatigue crack at the groove tip of the CT specimen (ASTM E647) using a cam and follower system, (b) Performing the fracture toughness test

3. Results and Discussions

Fig. 4 shows the microstructures of the heat-treated samples under different conditions. The grain size was obtained based on the Heyn interception method, ASTM E112. The carbide volume percentage was also calculated by image processing analysis. The results are presented in Fig. 5. As can be seen, increasing the temperature and time caused the grain size to become larger. Quenching in water resulted in a smaller grain size than that in salt water. Such a result has also been reported in the study of Hosseini et al. [11]. The carbide volume fraction decreased with increasing annealing temperature and time, which is due to the greater dissolution of carbides in the austenite matrix. However, cooling in water and salt water showed a dual behavior in terms of the effect on carbide percentage. At 1050 °C, quenching in salt water increased the volume fraction of carbides relative to water, but it had an opposite manner at 1100 and 1150 °C. Furthermore, quenching in water produced discrete and separate carbides, while the carbides produced during quenching in brine were more continuous.

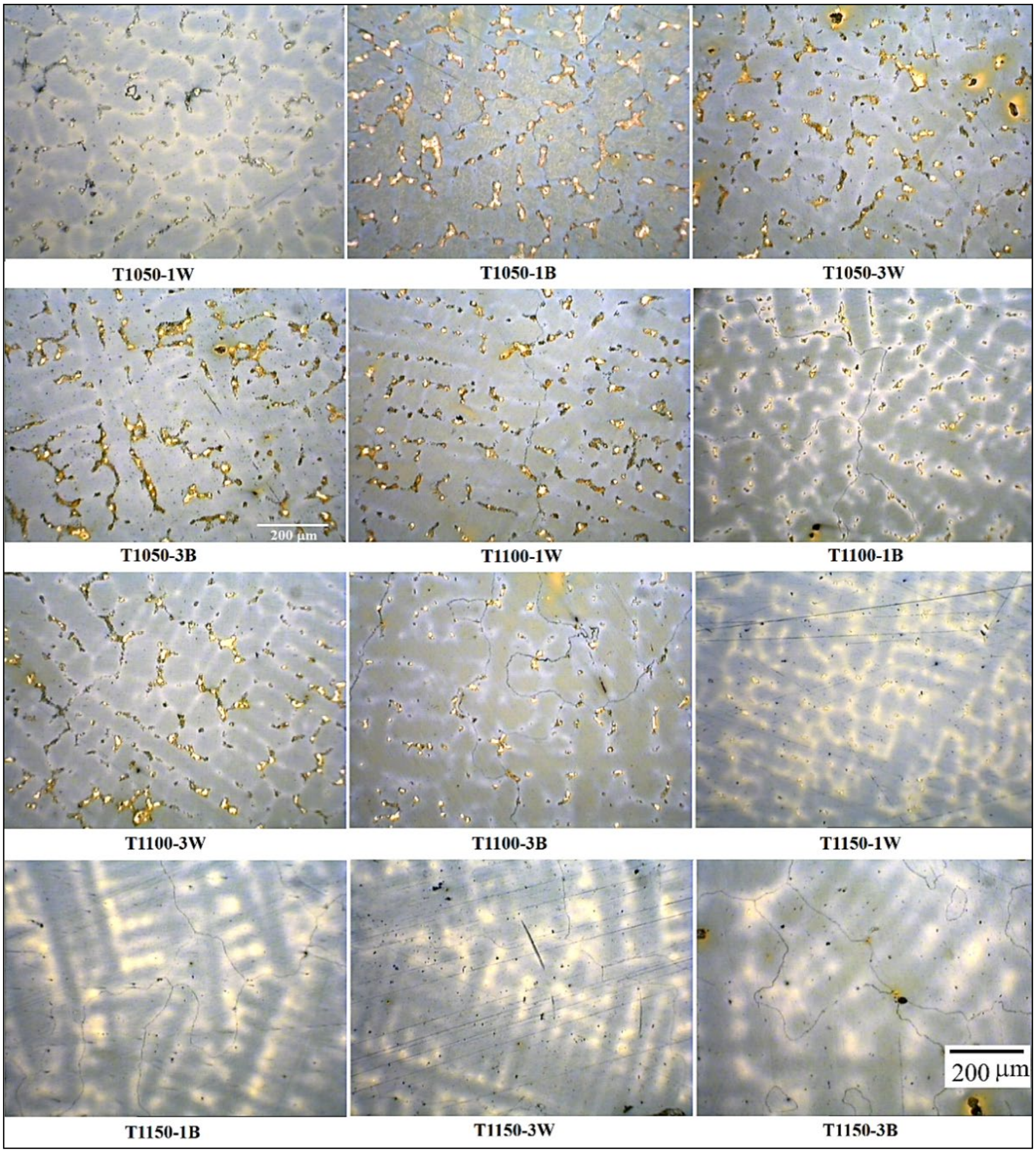
T1050-1W, T1050-1B, T1050-3W, T1050-3B, T1100-1W, T1100-1B, T1100-3W, T1100-3B, T1150-1W, T1150-1B, T1150-3W, T1150-3B

Fig. 4. Microstructures evolved under different heat treatment conditions

Another notable evidence in the microstructure is the presence of a ghost-shaped cellular or dendritic structure, which is mainly due to quenching in brine. It can be caused by the segregation of alloying elements such as C, Mn, and Cr to the inter-dendritic arms spaces of the primary austenite phase. This structure has been previously presented by Falodun et al. [9].

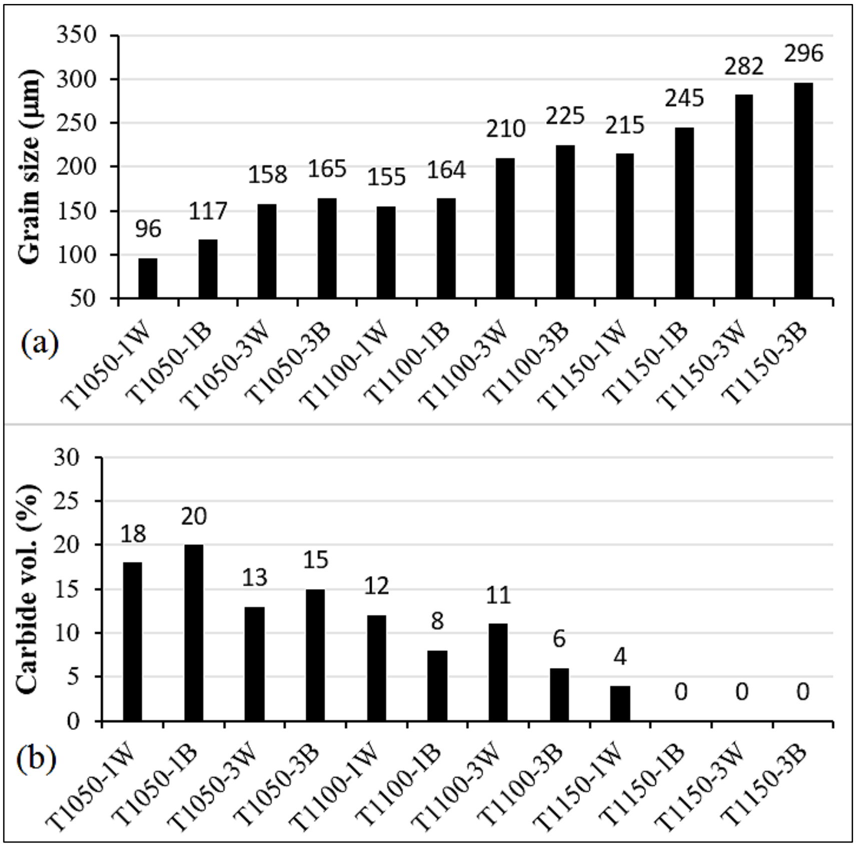

Fig. 5. (a) The grain size and (b) the carbide volume percentage at different annealing heat treatments

These phenomena can be explained as follows: During solution annealing, the concentration gradient of C and Mn is from the carbide interface towards the austenite interior. Meanwhile, there are a large number of vacancies in the austenite phase. During quenching, vacancies rapidly migrate towards the grain boundaries or carbide/austenite interface, and C and Mn also move with them. Since this migration occurs over a limited distance, the presence of higher energy paths (i.e. grain boundaries) and a low mean distance of carbides becomes important, so that if there are finer grains and a larger volume of carbides in structure, more C and Mn may be added to the carbides, thereby increasing the volume of the carbides. By increasing the cooling rate (quench in brine), vacancies migrate in greater numbers and over a greater distance to the grain boundaries or carbide/austenite interface. Thus, at 1050 °C, cooling in salt water increased the carbide volume compared to cooling in water. At higher temperatures, with increasing grain size and decreasing carbide volume (the greater the mean-distance of carbides), quenching in brine transferred C and Mn to the cell structure interior grains in the space between the dendritic arms. This causes the intra-granular cell structure be highlighted in the microstructure. Therefore, when the grains are smaller and the carbides have a higher volume percentage, a higher cooling rate will increase the carbides. When the grains grow and the carbides are dissolved and have a lower volume percentage, a higher cooling rate will strengthen the intragranular cellular structure. This can increase the work hardening of the matrix during servicing. Fig. 6 shows the stress-strain curves at different heat treatments. At 1150 °C, all the samples except T1150-1W fractured at low strain. This was due to the presence of some voids in the microstructure, which were probably formed by the local melting at this temperature.

Fig. 6 shows that samples quenched in brine have higher UTS than ones quenched in water. The yield strength also increased with quenching in brine at a holding time of 1.5 h, but contrarily, at a holding time of 3 h, quenching in brine reduced this value a few. Meanwhile, the work hardening rate increased significantly. This behavior is due to the dependence of yield strength on grain size and the substructure or cellular structure of the internal grains. Reducing of grain size or strengthening the cellular structure within the grains both lead to an increase in yield strength. The UTS mainly depends on the work hardening rate, which in turn is related to the segregation of alloying elements or the distribution of fine carbides within the dendritic arms or grain boundaries. Fig. 7 illustrates the method of determination of fracture toughness.

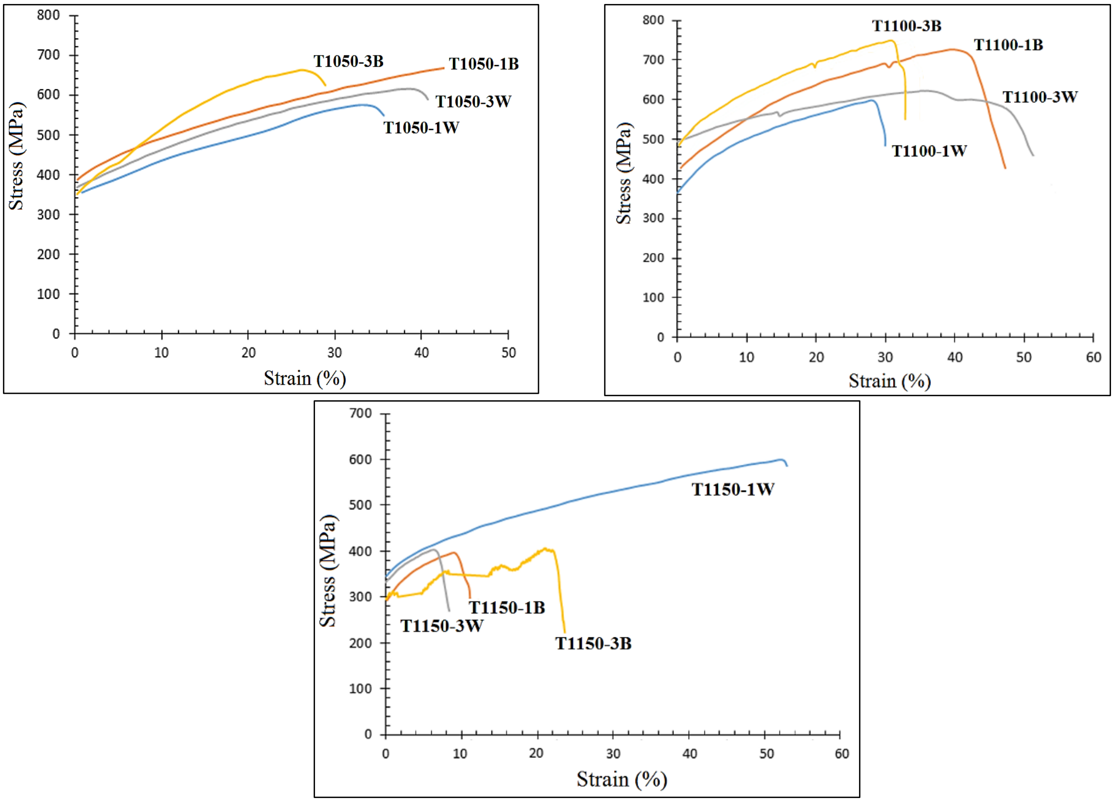

Fig. 6. The stress-strain curves at different annealing heat treatments

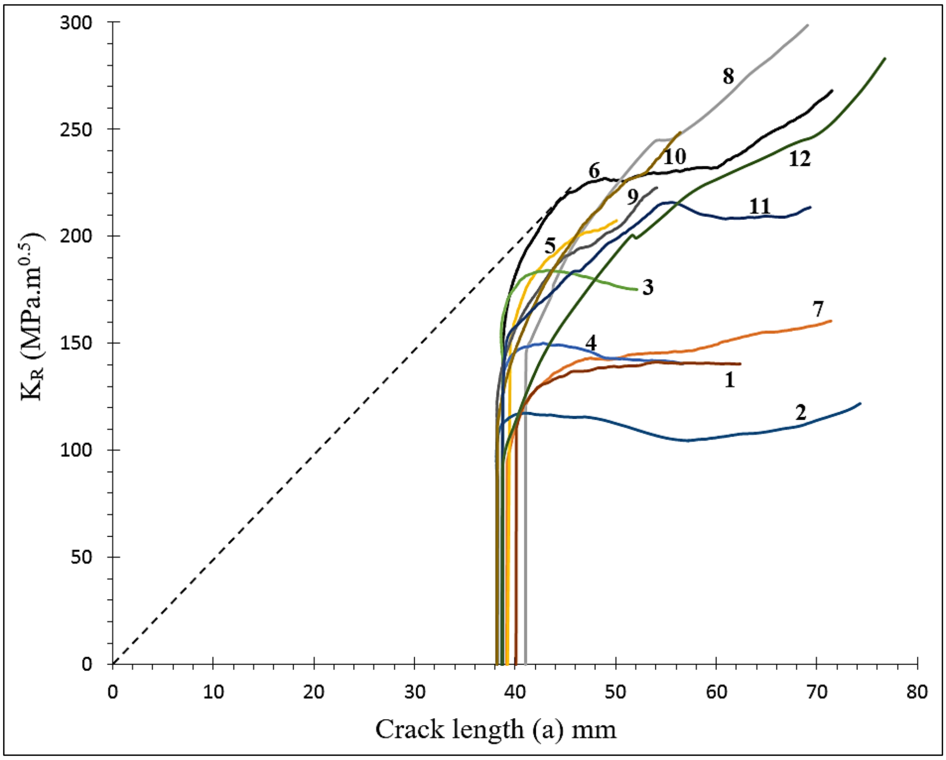

Fig. 7. Determination of fracture toughness according to ASTM E647

Fig. 8 shows the results of Brinell hardness numbers (BHN), impact energy values, and fracture toughness measurements of samples under different heat treatment conditions. It could be found from Fig. 8 that the quenching in brine leads to lower hardness and higher impact energy compared to quenching in the water. The decrease in hardness due to quenching in brine has been also reported by Hosseini et al. [11]. This is due to the higher dispersion of discrete carbides due to cooling in water. The highest hardness was obtained at an annealing temperature of 1150 °C, holding time of 1.5 h, and quenching in water (T1150-1W). This is due to the presence of fine carbides dispersed in the austenite matrix and the presence of a strengthened cellular structure interior grains due to segregation of alloying elements where the same as sub boundaries would increase the work hardening of the matrix. Interestingly, under these conditions, the sample showed good toughness and impact resistance.

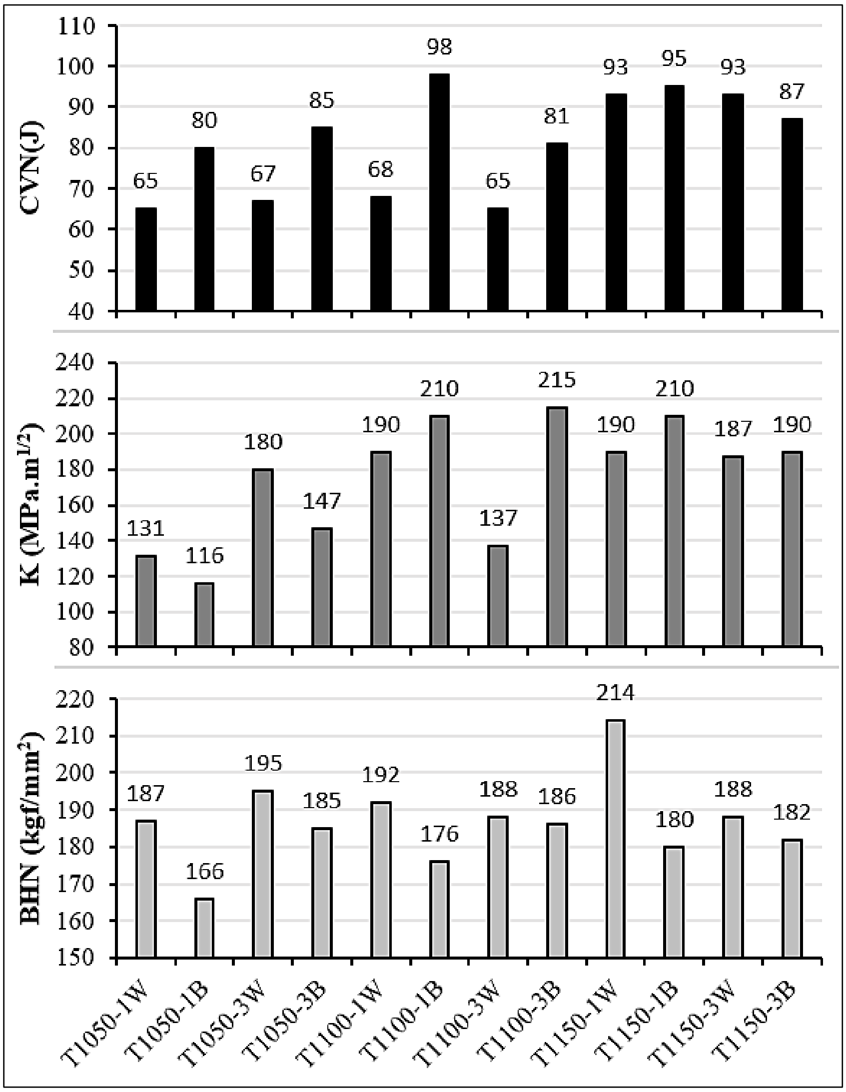

Fig. 8. Hardness, fracture toughness, and impact energy of samples at different heat treatment conditions

Impact test results are only valid when confirmed by microscopic fractography results or at least compared with fracture toughness tests. Since the impact test specimen is relatively small and the crack path is different under the same conditions, so the data dispersion can be high. Comparison of the impact and fracture toughness test results shows that the best conditions for toughness and impact are obtained under the same conditions (T1100-1B). The microstructure in this case is very similar to the T1150-1W condition, i.e. the fine carbides are distributed over the intragranular cell structure. However, the microstructure in the T1100-1B situation has finer grains and a relatively softer austenite matrix (low hardness). As a general result, it seems that to achieve suitable mechanical properties in Hadfield steels, the annealing heat treatment should be carried out in such a way that the result is a structure with fine carbides dispersed in the matrix together with an intragranular strengthened cellular structure due to the segregation of alloying elements. The grain boundaries or eutectic carbides on the triple junctions must also be completely eliminated.

4. Conclusions

In this work, the mechanical properties of a Cr-rich Hadfield steel were investigated under different annealing heat treatment conditions. The chosen annealing temperatures were 1050, 1100, and 1150 °C with holding times of 1.5 and 3 h followed by quenching in water or brine. After heat treatment, the microstructure of the samples was characterized, the grain size and volume percentage of carbides were measured and correlated with the mechanical properties. The following results can be extracted from the present study:

- (i) Mechanical properties are mainly controlled by grain size, volume percentage of carbides, and development of intragranular cellular structure.
- (ii) Increasing annealing temperature and time resulted in more dissolution of carbides, but cooling in water produced more discrete carbides than quenching in brine. An intragranular cellular or dendritic structure resulting from segregation of alloying elements could be observed in the structure, which is more evident when the samples are quenched in brine.
- (iii) Quenching in water leads to higher hardness and finer grains.
- (iv) Samples quenched in brine had higher tensile strength due to higher work hardening rate.
- (v) The best hardness was obtained at an annealing temperature of 1150 °C, a holding time of 1.5 h, and quenching in water, which was enhanced by the presence of fine carbides dispersed in the austenite matrix and the presence of a strengthened cellular structure interior grains.
- (vi) The highest toughness and impact properties were obtained at an annealing temperature of 1100 °C, a holding time of 1.5 h, and quenching in brine, in which fine carbides are distributed over the intragranular cell structure.

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