

Research Article

Heat Treatment in High Chromium White Cast Iron Ti Alloy

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The influence of heat treatment on microstructure and mechanical properties of high chromium white cast iron alloyed with titanium was investigated. The austenitizing temperatures of 980°C and 1150°C for 1 hour each followed by tempering at 260°C for 2 hours have been performed and the effect of these treatments on wear resistance/impact toughness combination is reported. The microstructure of irons austenitized at 1150°C showed a fine precipitate of secondary carbides (M_6C_{23}) in a matrix of eutectic austenite and eutectic carbides (M_7C_3). At 980°C, the structure consisted of spheroidal martensite matrix, small amounts of fine secondary carbides, and eutectic carbides. Titanium carbides (TiC) particles with cuboidal morphology were uniformly distributed in both matrices. Irons austenitized at 980°C showed relatively higher tensile strength compared to those austenitized at 1150°C, while the latter showed higher impact toughness. For both cases, optimum tensile strength was reported for the irons alloyed with 1.31% Ti, whereas maximum impact toughness was obtained for the irons without Ti-addition. Higher wear resistance was obtained for the samples austenitized at 980°C compared to the irons treated at 1150°C. For both treatments, optimum wear resistance was obtained with 1.3% Ti.

1. Introduction

High chromium cast iron is one of the wear resistant materials used in a variety of applications where stability in an aggressive environment is a principal requirement. These applications include slurry pumps, brick dies, several pieces of mine drilling equipment, rock machining equipment, and similar areas [1, 2]. Its competitive position in the market is based on its low production costs and stability of its properties at high temperatures, compared to other wear resistant materials [3]. In the as-cast condition, the microstructure of high chromium molybdenum white iron consists essentially of dendrites of austenite in a matrix of eutectic mixture of austenite and $(Fe, Cr)_7C_3$ carbides [4, 5]. For many applications, castings are heat treated prior to service to increase the wear resistance as well as impact toughness. Hardening and tempering are commonly used. The reduction in carbon and chromium contents of the austenite results in substantial transformation of the austenite into martensite upon cooling to room temperature [6, 7]. The eutectic carbides are generally thought to be unaffected by the destabilization heat treatment [8, 9].

As shown in Figure 1, there is an optimum austenitizing temperature to achieve maximum hardness which is diverged for each composition. The austenitizing temperature determines the amount of carbon that remains in solution in the austenite matrix. Too high austenitizing temperature increases the stability of austenite, which in turn obtains higher retained austenite in the structure and consequently reduces hardness. Low austenitizing temperature results in low-C martensite, which in turn reduces both hardness and abrasion resistance. Therefore, the successful heat treatment produces austenite destabilization by precipitation of secondary carbides within the austenite matrix. It is also recommended to temper castings before putting them into the service to restore some toughness in the martensitic matrix and to further relieve residual stresses [10].

Another possible strategy for improving wear resistance and toughness of white iron is to add carbide forming elements such as vanadium, tungsten, niobium, and titanium [11]. In this study titanium is added, where titanium is a strong forming element, since TiC has a high formation temperature and would be the first phase to precipitate during solidification. Therefore, this paper aims at studying the

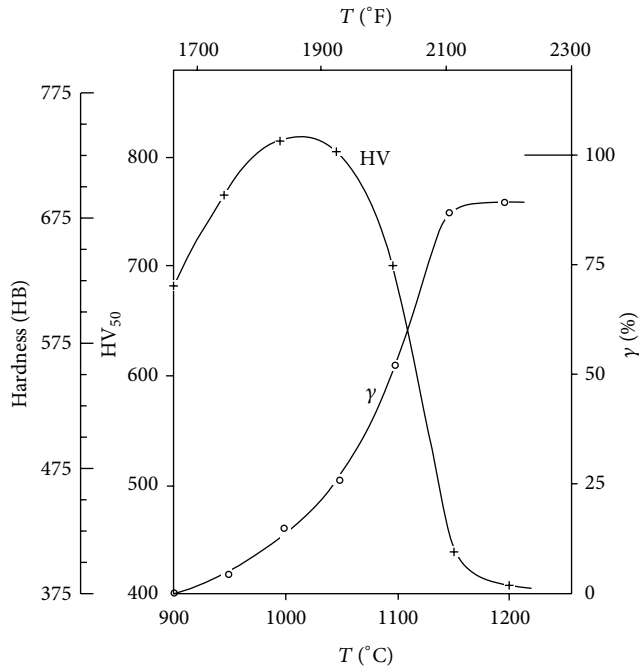


FIGURE 1: The correlation between the ratio of retained austenite and hardness of a typical high chromium abrasion resistant cast iron [10].

TABLE 1: Chemical composition of the investigated alloys.

C	Si	Mn	Cr	Mo	Ni
2.48/2.55	1.33/1.52	1.05/1.13	15.45/16.23	1.25/1.36	2.21/2.30

effects of both Ti-additions and heat treatment conditions on microstructure as well as abrasion resistance and impact toughness.

2. Experimental Work

The chemical composition of the studied high Cr-Mo white iron is given in Table 1. Sulphur and phosphorous contents were below 0.05%. The alloys were melted in a medium frequency induction furnace. Titanium was added as Fe-Ti (20% Ti) to give Ti-contents in the alloys of 0.471, 0.93, 1.31, and 1.78 wt.%. The liquid metal was poured at 1520°C into chemical bonded sand moulds in the form of tensile and impact specimens.

Two different heat treatment cycles were used; the first one was applied by austenitizing at 980°C for one hour and tempering at 260°C for 2 hrs. The second cycle was performed by austenitizing at 1150°C for one hour and tempering also at 260 for 2 hrs. Samples for metallographic investigation were polished to a 1 μm diamond finish and chemically etched in a freshly prepared solution that contained 1g of picric acid and 5 cm³ of hydrochloric acid in 100 cm³ of methanol. The samples were etched for a slightly longer time than would be expected for optical microscope observations. Microstructure investigation was undertaken by light and scanning electron microscopes. Samples measuring

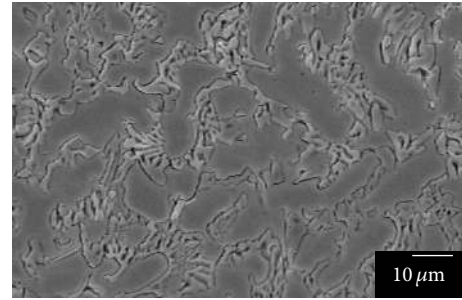


FIGURE 2: Typical microstructure of the as-cast condition with no Ti-addition.

15 mm × 15 mm × 2.5 mm were cut using water cooled cutting machine for XRD investigation. The respective 15 mm square faces were polished to a 1 μm diamond finish to remove relatively any mechanical deformed layer at the surface. X-ray crystallography was conducted using Cu K_α X-ray source. Hardness was measured on Vickers hardness scale with 30 kg load and a diamond pyramid indenter typical for this scale. Tensile test and Charpy impact test were carried out according to the American Standards ASTM E8 and ASTM E23, respectively. Wear test was carried out on a pin-on-ring type wear testing machine. The test was carried out against 70-mesh SiC abrasive disc at 65 rpm constant speed under different applied loads of 30, 60, 110, 140, and 180 N for 30 minutes each. The samples were weighted before and after the wear test using 0.1 mg precision digital scale to determine the weight loss. The weight loss was taken for two samples as an average for each condition.

3. Results and Discussion

3.1. Microstructure. The microstructure of as-cast high chromium white cast iron with no Ti-addition consists of M₇C₃ carbides that form during solidification as eutectic phase (a mixture of M₇C₃ and austenite) after the formation of proeutectic austenite dendrites (Figure 2). In an earlier study, Ibrahim and Nofal [12] discussed briefly the microstructure of these alloys, with different Ti-additions up to 1.78%, in the as-cast condition. Figure 3 shows SEM for the carbides feature existing in the investigated alloys. In Figure 3(a), the eutectic carbides (M₇C₃) are distributed in the matrix and TiC particles are spread either in matrix or over the eutectic chromium carbides [12]. Titanium carbides can also be found stacking close to the eutectic carbides M₇C₃ (Figure 3(b)).

The effect of Ti-addition (1.31% Ti) and austenitizing temperatures on microstructure of the studied irons is shown in Figures 4(a) and 4(b). As seen in Figure 4(a), the samples treated at 980°C obtained a microstructure consisting of M₇C₃ carbides embedded in martensitic matrix, TiC carbides, small amounts of retained austenite, and also small amount of secondary carbides. The samples austenitized at 1150°C showed a structure consisting of a netted eutectic carbides ((Cr,Fe)₇C₃, M₇C₃) embedded in an austenite matrix, secondary carbides, and TiC particles (Figure 4(b)). These

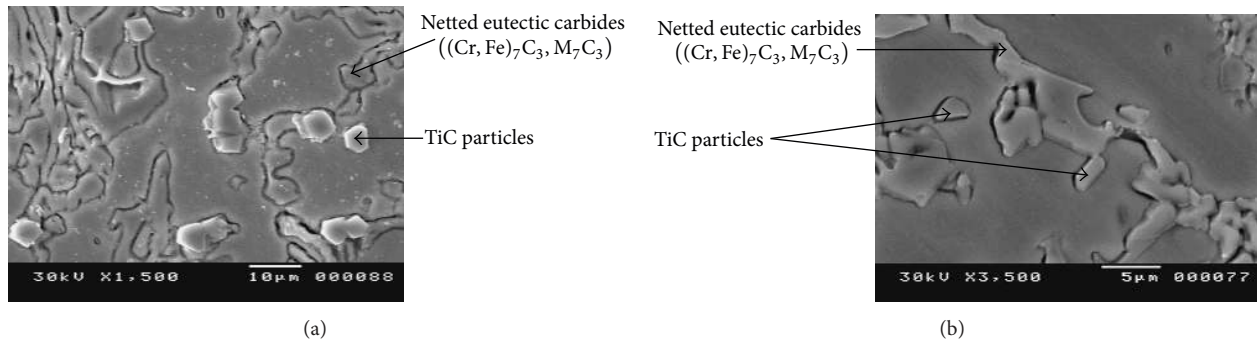


FIGURE 3: Carbides distribution feature in the investigated high chromium cast irons.

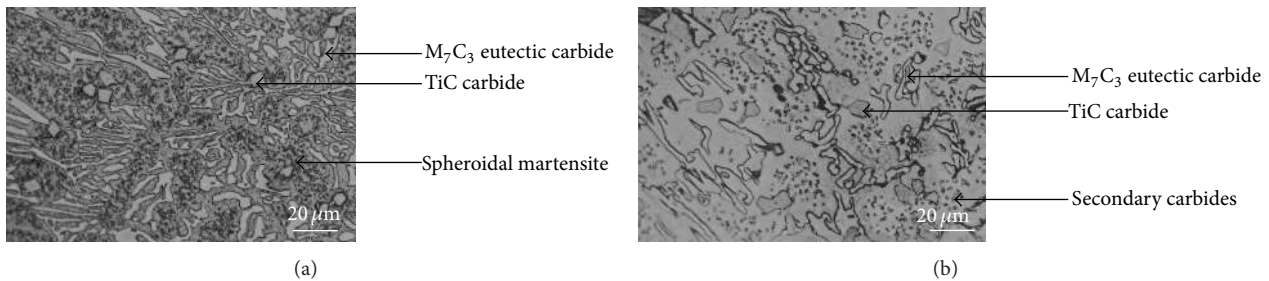


FIGURE 4: The microstructure constituents of the alloy contained 1.31% Ti and were treated at (a) 980°C and (b) 1150°C.

TiC particles have faceted cuboidal morphology with an average diameter of about 3-4 μm . The volume fraction of TiC particles increases with increasing Ti-content in the alloy. The TiC particles are uniformly dispersed throughout the matrix.

The microstructure of the samples treated at 980°C for 1 hr shows small amounts of copious fine precipitation of secondary carbides and spheroidal martensite which appears dark in the micrograph (Figure 5). These fine secondary carbides are uniform in size and homogeneously distributed in matrix. They are localized in the austenite grains, where the netted eutectic carbides are essentially unchanged after the heat treatment. The precipitation of secondary carbides from austenite results in decreasing Cr and C contents in the austenite. The depletion of both C and Cr in the austenite phase will consequently shift the martensite start temperature to a higher level of temperature. Thus, the martensite start temperature will be moved to above room temperature. Therefore during subsequent cooling to ambient temperature, the austenite transforms into martensite. Although a large amount of austenite transforms to martensite after heat treatment, still the iron contains some small amounts of retained austenite.

X-ray diffraction profiles of the investigated alloys after heat treatment comparing with the as-cast condition are shown in Figures 6(a)–6(c). The peaks associated with austenite phase and martensite phase are indicated by γ and M, respectively. For example, comparing the results after heat treatment to that for the as-cast, it is seen that the amount of martensite increases markedly while the amount of retained austenite is decreased significantly by applying the heat treatment. In the as-cast condition, the secondary carbides

TABLE 2: X-ray diffraction results for the investigated alloys.

d -spacing (Å)	Intensity (%)	$\sin^2\theta$	Phase
2.036	45.6	0.1431	Carbide
2.011	17.6	0.1431	Carbide
2.080	62.0	0.1372	Austenite
1.268	2.8	0.3687	Eutectic austenite
2.073	40.7	0.1379	Eutectic austenite
0.827	2.6	0.8677	Eutectic austenite
0.904	3.2	0.7278	Austenite

cannot be observed because the eutectic carbides M_7C_3 are the most formed carbides in the cast condition, while, after treatment, the secondary carbides are more obvious ($M_{23}C_6$). This observation is in agreement with microstructure feature that was obtained in this study (Figures 2 and 5) and also with other studies that were conducted by Carpenter et al. [13] and Vidyorthi et al. [14]. Some crystallographic data from the diffractometer is presented in Table 2. This table shows the $\sin^2\theta$ values obtained for the phase constitutes where θ is the Bragg angle. The table defines also the d -spacing of phase indices. The lattice parameters a and c for the eutectic chromium carbide $(\text{Fe, Cr})_7\text{C}_3$ were calculated from the data given in Table 2. This is because this type of carbide $(\text{Fe, Cr})_7\text{C}_3$ has a hexagonal crystal lattice structure and therefore they are indexed using Miller-Bravais system of coordinates. The values of a and c were 1.394 and 0.452 nm, respectively. In addition, the lattice parameter a of both primary and eutectic austenite was also estimated. It is found that a for primary

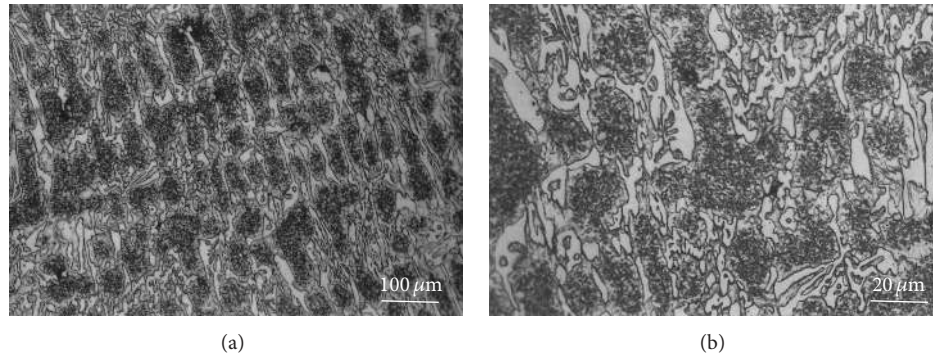


FIGURE 5: Microstructure of the martensitic heat treated samples.

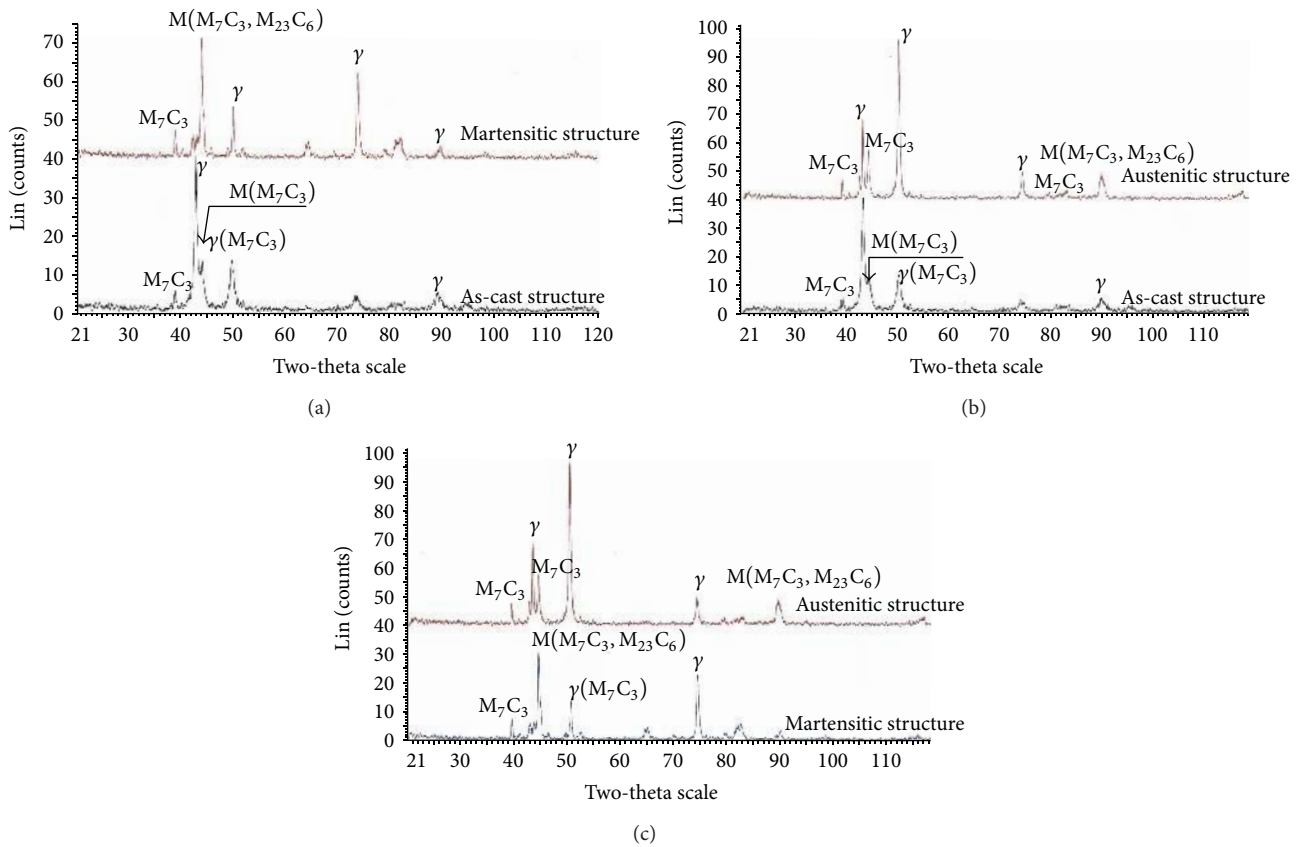


FIGURE 6: X-ray diffraction profiles of the investigated alloys. (a) Martensitic structure versus the as-cast structure. (b) Austenitic structure versus the as-cast structure. (c) Austenitic structure versus martensitic structure.

and eutectic austenite was found to be 0.361 and 0.359 nm, respectively.

The microstructure of the irons treated at 980°C (Figure 7) shows a feature of eutectic M_7C_3 carbides embedded in martensitic matrix, TiC carbides, small amounts of retained austenite, and also small amount of secondary carbides. On the other hand, Figure 8 shows the micrographs of heat treated samples at 1150°C for 1hr. It shows netted eutectic carbides ($(Cr,Fe)_7C_3$, M_7C_3) embedded in an austenite matrix. A very fine-scale precipitation of

secondary carbides has been formed and localized in the austenite grains as compared to the other samples treated at 980°C. Moreover, the micrographs show cuboidal particles of TiC by adding Ti from 0.47% to 1.78%. The higher volume fraction and larger size of TiC were obtained by adding 1.78% Ti to the iron. Titanium addition resulted also in decreasing the volume fraction of M_7C_3 carbides due to migration of a part of carbon to TiC, which indicates that titanium carbides were the first to solidify and may have then acted as nuclei for the proeutectic austenite dendrites, and thereby refining

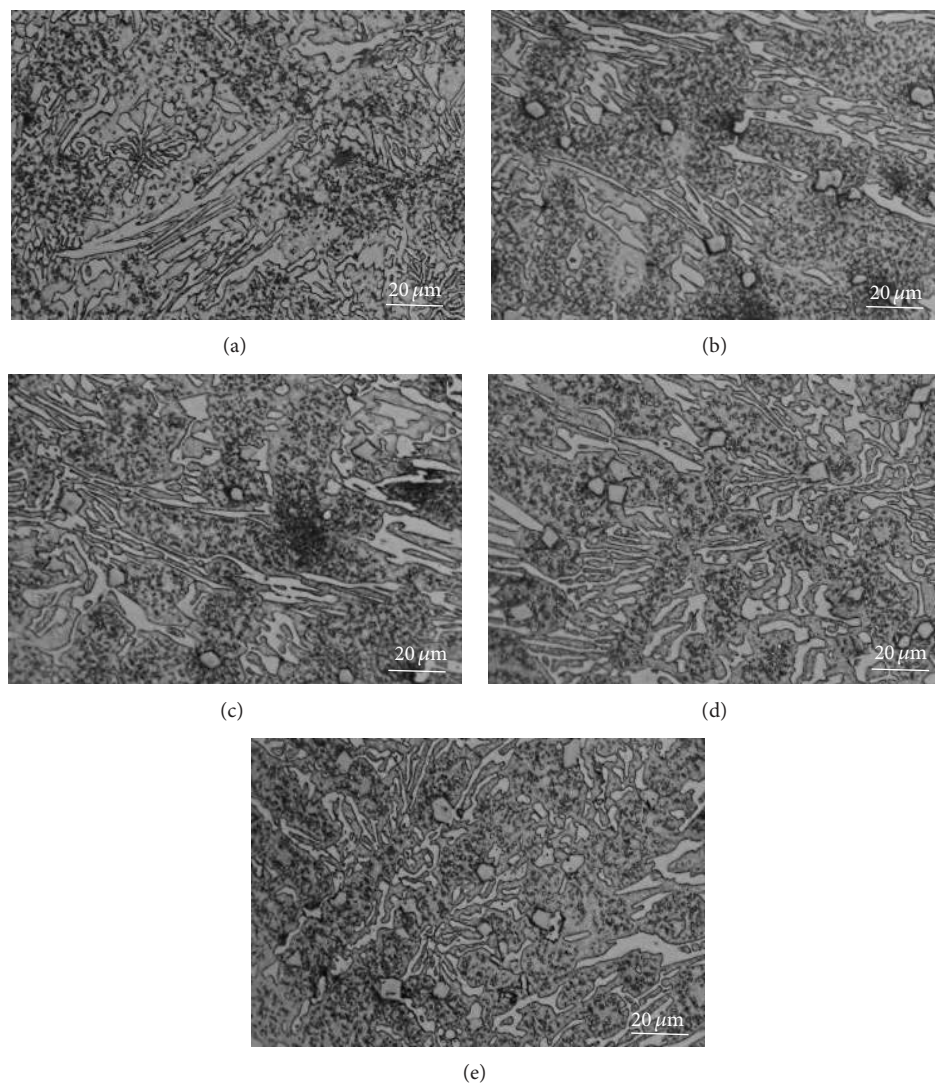


FIGURE 7: Effect of Ti-addition on microstructure of the heat treated martensitic irons with (a) 0% Ti, (b) 0.47% Ti, (c) 0.93% Ti, (d) 1.31% Ti, and (e) 1.78% Ti.

the structure. Similar studies related to the effect of boron addition on microstructure of white cast iron found that boron refines also the microstructure [15–18].

3.2. Mechanical Properties. Figure 9 shows the effect of both Ti-addition and austenitizing temperature on hardness of the studied white irons. It seems that hardness values are higher for the samples austenitized at 980°C compared to the others austenitized at 1150°C. This is considered a logical phenomenon due to forming of martensitic structure at 980°C which is considered a hard phase compared to the austenitic matrix containing secondary carbides that formed at 1150°C. Farah et al. [19] mentioned in his study for high Cr white cast iron alloyed with Nb that heat treated martensitic structure obtained higher hardness than the treated austenitic one due to improvement in carbon diffusion in the austenite phase which in turn will transform into higher carbon martensite. This high carbon martensite structure will be harder than

the austenitic one. In this study, both heat treated samples (martensitic and austenitic structures) show the same trend for hardness with increasing Ti-additions up to 1.78%. At 980°C, the increase in hardness was substantial, where it rises from 650 HV₃₀ for the base alloy with no Ti-addition to 776 HV₃₀ for the alloy with 1.78% Ti. On the other hand, at 1150°C, the samples showed the same trend as the sample treated at 980°C but with lower hardness values. At 1150°C, the base iron with no Ti-addition obtained a hardness value of 510 HV₃₀ and it rises to 650 HV₃₀ for the iron with 1.78% Ti.

As shown in Figure 10, the tensile strength of the heat treated samples at 980°C and 1150°C obtained also the same trend, where the tensile strength increases with increasing Ti-additions up to a maximum value corresponding to 1.31% Ti and then decreases with further higher Ti-additions (1.78% Ti). Such increase in tensile strength could be attributed to the strengthening effect of the heat treated martensitic or austenitic matrices by homogeneously distributed TiC in

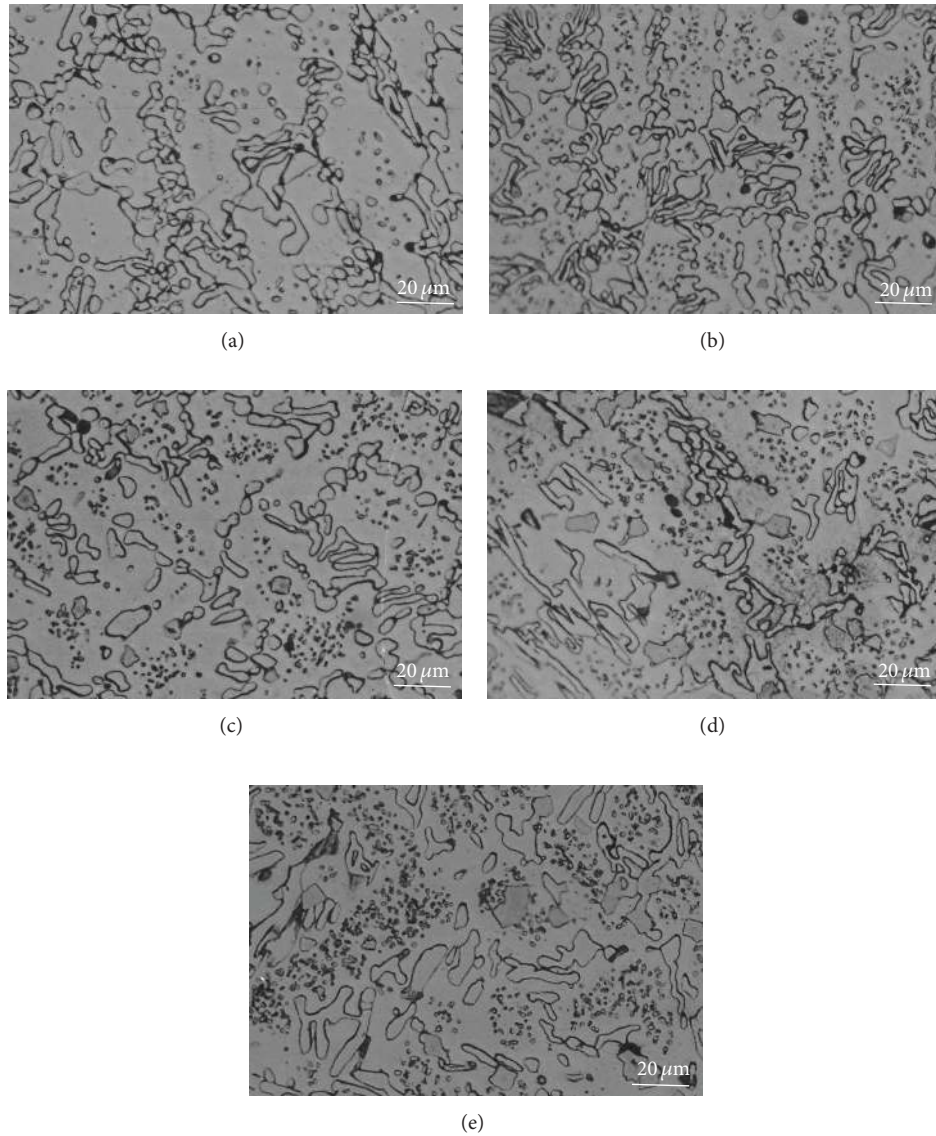


FIGURE 8: Effect of Ti-addition on microstructure of the heat treated austenitic irons with (a) 0% Ti, (b) 0.47% Ti, (c) 0.93% Ti, (d) 1.31% Ti, and (e) 1.78% Ti.

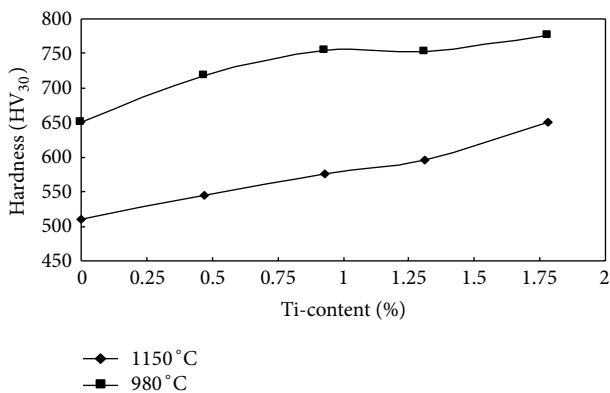


FIGURE 9: Effect of austenitizing temperature and Ti-addition on hardness of the investigated alloys.

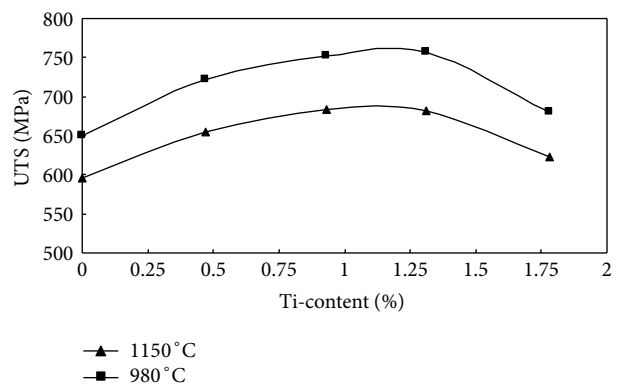


FIGURE 10: Effect of austenitizing temperature and Ti-addition on tensile strength of the investigated alloys.

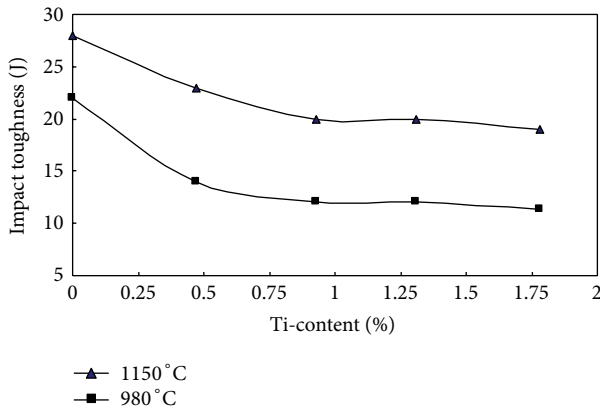
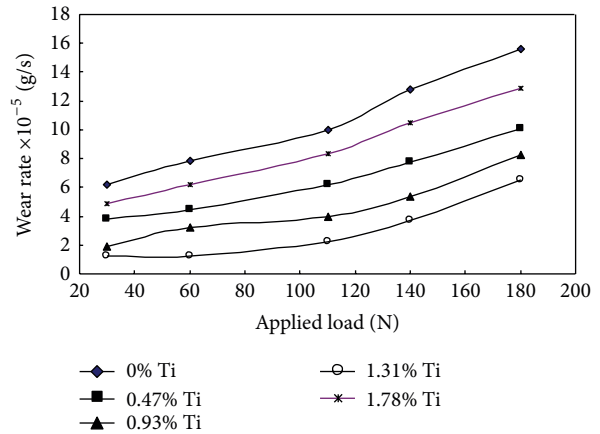


FIGURE 11: Effect of austenitizing temperature and Ti-addition on impact toughness of the investigated alloys.

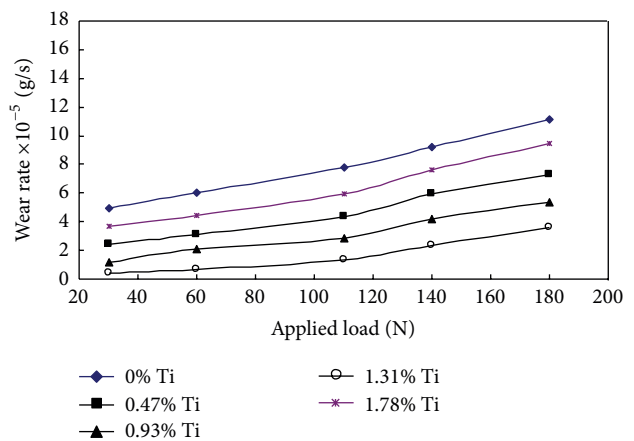
those matrices. However, a drop in the strength was obtained with further Ti-addition (1.78% Ti) due to the clustering effect of TiC particles in both matrices. In addition, the martensitic matrix showed higher tensile strength compared to the austenitic matrix reinforced with secondary carbides. This is of course related to the nature of the matrices, in which the martensitic matrix is considered harder and has higher strength than the austenitic one.

The results of impact toughness of the studied heat treated unnotched samples are shown in Figure 11. It is obvious that both austenitizing temperatures have the same behaviour with Ti-additions, where the samples without Ti-addition showed the highest impact value and started to decrease gradually to keep with approximately constant values with Ti-additions ranging from 0.93% to 1.78%. Normally for the metallic materials an increase in tensile strength associated with a decrease in impact toughness, but it is clear here in this study that the white iron alloyed with Ti in the range of 0.93% to 1.78% showed an increase in tensile strength without a decrease in impact toughness. It is suggested that the refinement in structure happened by Ti-addition and also strengthened the matrix by secondary carbides resulting in no loss in the impact toughness. This was obvious for the irons alloyed with 1.78% Ti, where the reinforcement of matrix with secondary carbides can compensate the deterioration in toughness that happened as a result of forming some locations of TiC agglomeration in matrix. Therefore, in this study the applied heat treatment by austenitizing either at 980°C or at 1150°C is very beneficial to keep the impact toughness constant specially with higher values of Ti-contents (>0.93% Ti). In a similar work done by Bedolla-Jacuinde et al. [11] for studying the effect of Ti-addition (in the range of 0–2.02% Ti) on wear resistance and fracture toughness of 16% Cr white cast iron in the as-cast condition, they noticed that fracture toughness kept almost constant with all ranges of Ti-addition due to the refinement effect of Ti-addition on the microstructure.

High chromium white iron is specially qualified for abrasion resistant applications. The predominant carbides in its structure provide it with a high hardness necessary for



(a)



(b)

FIGURE 12: Effect of austenitizing temperature, applied load, and Ti-addition on abrasion wear rate of the investigated alloys treated at (a) 1150°C and (b) 980°C.

crushing and grinding other materials without degradation. Therefore, high chromium white iron is considered a proper choice as a high wear resistant material. Moreover, it can be cast easily into net shapes required for crushing and grinding or handling abrasive materials.

In this investigation, the effects of applied load, austenitizing temperatures, and Ti-additions on abrasion wear of high chromium white iron have been studied, as shown in Figures 12(a) and 12(b). In both austenitizing temperatures (980°C and 1150°C) all samples show the same trend, where wear rate increases with increasing the applied load. This is logical due to the increase in applied shear stress over the worn surface by increasing the applied load. The effect of Ti-addition on wear behaviour of the investigated samples austenitized at 980°C and 1150°C shows also the same trend, where the wear rate of both structures decreased with increasing Ti-addition up to 1.31% Ti. This could be attributed to the structure refinement effect, which is corresponding to eutectic structure with mixed chromium carbides and titanium carbides particles achieved by adding Ti up to 1.31% Ti. This is in a general agreement with the results reported by Chung et al. [20],

where they studied the effect of Ti-addition up to 6% Ti on wear resistance of 25% Cr-4% C white cast iron. They noticed that wear rate decreased with increasing the amount of Ti-addition due to refining the microstructure by Ti-addition. In addition, chromium carbides were replaced by Ti carbides, which are harder than the former. In another study done by Arikian et al. [21] on the effect of Ti-addition up to 0.38% Ti on hardness and wear resistance of heat treated 15% Cr-3% Mo white iron, they observed that wear resistance can be increased by increasing the amount of Ti-addition due to the structure refinement effect. In this study the minimum wear rate was reported for the iron alloyed with 1.31% Ti and the maximum one for the iron with no Ti-addition. For the iron alloyed with 1.31% Ti, massive amount of TiC particles are homogeneously distributed in both martensitic and austenitic matrices. Therefore, it could be concluded here that the optimum Ti-addition should be kept 1.31% to avoid agglomeration of TiC in matrix which will weaken the matrix and increase its wear rate. In spite of the fact that the iron contains a high amount of Ti-addition (1.78%), it gave a high amount of wear rate. This behavior was clear in both heat treatment conditions (980°C and 1150°C). This can be explained by the agglomeration of TiC particles in certain locations in matrix, where it was easy to pull the carbides out from the matrix and leave cavities. These cavities are considered weak points in matrix and cause in turn higher wear rates. Moreover, these pulled-out particles will insert between the worn surface and the rotating disc causing a third body abrasion wear mechanism which is characterized by high wear rate.

4. Conclusions

- (1) The samples treated at 980°C showed a structure consisting of fine spheroidal martensite, fine precipitation of secondary carbides, small amount of retained austenite, TiC particles, and eutectic carbides (M_7C_3).
- (2) The samples treated at 1150°C showed a structure consisting of fine precipitation of secondary carbides embedded in an austenite matrix, TiC particles, and eutectic carbides (M_7C_3).
- (3) TiC particles were well distributed in both heat treated matrices for Ti-additions up to 1.31% and then started to agglomerate with higher Ti-addition of 1.78%.
- (4) Ti-addition caused an increase in hardness due to formation of hard TiC particles with the M_7C_3 carbides as well as the secondary carbides embedded in the heat treated matrices.
- (5) Tensile strength and abrasion resistance showed maximum values with 1.31% Ti and then these properties were deteriorated with further Ti-addition (1.78% Ti) due to TiC particles clustering.
- (6) Maximum impact toughness was reported for the iron without Ti-addition and started to deteriorate slightly with further increase in Ti-addition.

- (7) Minimum wear rate was reported for the martensitic structure obtained at 980°C as compared to the other one treated at 1150°C.
- (8) Optimum abrasion resistance and impact toughness of the investigated white iron (16% Cr, 1.3% Mo, and 2.3% Ni) can be achieved by austenitizing the samples at 980°C and adding 1.31% Ti.

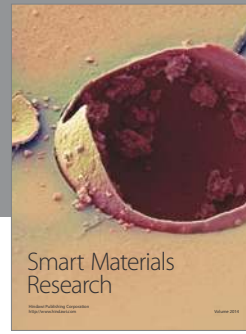
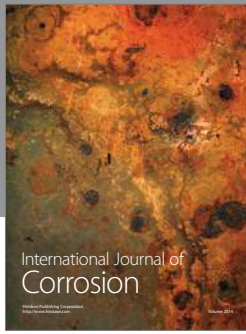
Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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