Influence of Retained Austenite on the Mechanical Properties of Low Carbon Martensitic Stainless Steel Castings

Behnam AKHAVAN TABATABAEI,1) Fakhreddin ASHRAFIZADEH2) and Ali Morad HASSANLI3)

1) Department of Materials Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran. E-mail: Behnam.akhavan@gmail.com 2) Department of Materials Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran. E-mail: ashrafif@cc.iut.ac.ir 3) University of Shiraz and University of South Australia, School of Natural and Built Environments, Mawson Lakes, South Australia 5009 GPO Box 1471 Australia. E-mail: ali.hassanli@unisa.edu.au

(Received on May 24, 2010; accepted on November 4, 2010)

The amount of retained austenite formed during tempering process can moderately improve the structure and properties of martensitic stainless steels. In the present study, 25 heat treatment cycles were carried out on specimens cast in CA6NM in order to investigate the effect of tempering treatment on the structure and mechanical properties of this alloy. X-Ray diffraction, mechanical testing, optical and scanning electron microscopy were employed for evaluation of the specimens. SEM micrographs and X-ray diffraction patterns indicated that with enhancement of tempering temperature, the amount of retained austenite initially increased and then decreased. The changes in mechanical properties of specimens including hardness, impact toughness, elongation and tensile strength were found to depend mainly on the amount of retained austenite. Such variations are discussed in terms of amount of retained austenite and its stability during tempering process of martensite.

KEY WORDS: martensitic stainless steel; tempering treatment; retained austenite; tensile test; impact test.

1. Introduction

Martensitic stainless steel 13Cr–3.6Ni–0.6Mo, known as CA6NM, has less than 0.06% Carbon, 11.5 to 14% chromium and 3.5 to 4.5% nickel. Due to superior low temperature toughness, resistance to cavitation erosion and stress corrosion cracking, this steel has found wide applications in the structures where good mechanical properties in combination with satisfactory corrosion and erosion resistance are of prime importance.1) CA6NM is currently being used for fabrication of under water parts specially hydro turbine runners and ship blades.2) Austenite is the most important phase which can moderately improve the structure, mechanical and corrosion properties of this steel under the effect of an appropriate tempering treatment cycle. Austenite is formed in CA6NM after tempering treatment above austenite transformation temperature (A1) and is retained in the microstructure to ambient temperature.3,4) The retained austenite is remarkable stable and resists the transformation to martensite at temperatures as low as $-196^\circ C$.5,6)

The retained austenite in CA6NM has a direct influence on mechanical properties including hardness, impact toughness, yield and tensile strength. Increasing the retained austenite in steel causes the reduction of hardness, yield and tensile strength and an increase in the elongation and impact toughness.7) In recent years a number of research papers have been published on wrought martensitic stainless steels,8–10) but a review of literature shows that there is not sufficient published work on retained austenite, especially in cast martensitic stainless steels that have a different structure compared to wrought alloys.

In the present paper, the results of an investigation on the effect of temperature and time of tempering cycles on the amount of retained austenite are presented and their impact on the mechanical properties of cast CA6NM steel are discussed.

2. Experimental Procedure

2.1. Materials and Specimen Preparation

Initial melt of CA6NM was prepared using a medium frequency induction furnace with the charge of stainless steel scraps. The carbon content of the melt was reduced to 0.06% using an argon oxygen decarburization converter. Alloying elements were added in order to achieve chemical composition corresponding to AISI standard. The refined melt was poured into sodium silicate sand moulds of size $60 \times 20 \times 40$ mm and 27 cubic specimens of approximately 15 mm in size were cut. After preparing and degreasing in acetone, chemical composition was determined using optical spectrometry method (Table 1). Tensile and Charpy V-notch impact testing specimens were machined from cast blocks in agreement with ASTM A 370 and ASTM E 23 respectively (Fig. 1).

2.2. Heat Treatment

The heat treatment procedure used in this study is illustrated in Fig. 2. The process for each specimen involved
(1) To obtain a homogeneous structure, the specimens were austenitized in a muffle furnace for 3 h at 1100°C, followed by air cooling.

(2) The specimens were then tempered at various temperatures and time periods and then air cooled according to data in Table 2.

2.3. Metallography and X-ray Diffraction

Optical and scanning electron microscopes were used to examine the microstructural features of the specimens. To observe the structure with optical microscopy, a standard metallographical procedure was carried out; the specimens were polished and etched in Vilellas’s reagent (5 mL HCl, 1 g picric acid and 100 mL ethanol). X-Ray diffraction tests were performed by a Phillips X’pert-MPD system using copper tube (wavelength 1.5415 Å). A range of 30–80 deg was selected for parameter and preset on the diffractometer with the step size and time per step of 0.05 deg and 1 s, respectively. The volume fraction of retained austenite at ambient temperature was estimated using the following equations and by measuring the integrated intensities of (111) and (110) diffraction lines;

\[
\begin{align*}
V_\gamma + V_{\alpha'} &= 1 \\
V_\gamma &= \frac{1.4I_\gamma}{I_{\alpha'}+1.4I_\gamma}
\end{align*}
\]

Where \(V_\gamma\) and \(V_{\alpha'}\) are the volume fractions of \(\gamma\) austenite and \(\alpha'\) martensite and, \(I_\gamma\) and \(I_{\alpha'}\) are the integrated intensities of (111) \(\gamma\) and (110) \(\alpha'\) peaks, respectively, in the X-ray diffraction patterns.

2.4. Mechanical Testing

Hardness testing of cast and heat treated specimens was carried out using the Brinell method (load 187.5 kg). Five hardness readings were taken and averaged for each specimen. Room temperature tensile tests were carried out by a hydraulic testing machine, coupled with a stress–strain recorder. The tests were performed at a constant strain rate of \(\dot{\varepsilon}=10^{-3}\) s\(^{-1}\). The yield point was determined based on the 0.2% offset method. Tensile tests were repeated three times for each specimen and the results were averaged. Impact testing, \(\Delta\varepsilon_{IC} = 10^{-3}\) s\(^{-1}\), was carried out using a Charpy impact machine at 273 K. The impact energies reported are average values of three readings.

3. Results and Discussion

3.1. Structure and Phase Analysis

Optical and scanning electron micrographs of as-cast CA6NM specimens are shown in Fig. 3. As it can be seen, the structure is approximately 100% martensite due to its superior hardenability. The nickel- and chromium-equivalents of the experimental material calculated by using Shaeffler formula are 5.88 and 15.85, respectively. According to these values in Shaeffler diagram in Fig. 4, the microstructure of as cast CA6NM was expected to consist of a mixture of martensite and ferrite phases. However, it seems that when the cast block is given sufficient time, \(\delta\) phase would transform to austenite; the melt being completely austenitized during solidification and, after cooling, it has been transformed to martensite. At higher magnification of the scanning electron microscopy, martensite laths, formed by diffusionless shear mechanism from prior austenite grain boundaries, can be observed. Due to the low carbon content of this steel, the microstructure is a typical lath martensite. Figure 5 demonstrates the results of X-ray diffraction of as-cast and tempered specimens; the patterns of both as-cast and T550-4 specimens confirmed a single martensitic phase with no evidence of retained austenite. In the XRD patterns of other specimens, in addition to two peaks of martensite \((110)\) and \((111)\) \(\alpha'\) peaks, respectively, in the X-ray diffraction patterns.
martensitic stainless steels, metallic carbides form and grow with an increase in tempering temperature up to $A_1$. For this specimen, in addition to austenite and martensite phases in the XRD pattern, small amounts of chromium carbide phases, probably $\text{Cr}_2\text{C}_6$ and $\text{Cr}_7\text{C}_3$, were identified at angles $2\theta=48.64^\circ$ and $2\theta=47.76^\circ$, which were partially precipitated at 600°C by carbon and chromium diffusion towards prior austenite grain boundaries. In the optical micrographs of this specimen (Fig. 6), dark regions may reflect chromium carbides precipitated along prior austenite grain boundaries. Similar result has also been reported by Calliari.8)

Similar to specimen T600-4, austenite and martensite peaks can be observed in T700-4 specimen, but the intensity of the austenite peak in the latter is remarkably higher than T600-4. Figure 7 displays the scanning electron micrograph of T700-4. This specimen has about 9% austenite which appears as white regions, in the form of distributed islands, within the martensite microstructure. Since specimen T700-4 possessed the lowest hardness, tensile and yield strength along with the highest values of elongation and toughness among the tempered specimens, it was anticipated that this value must be the maximum amount of austenite that could be formed in one-stage tempering in this steel. The peaks belonging to carbide phases were not detected in this specimen in spite of specimen T600-4. This is due to the fact that chromium carbides precipitated dur-
ing lower temperatures of the tempering process are mainly dissolved in the alloy matrix at temperatures higher than 600°C. For specimen T750-4, despite the increase in reverted austenite due to higher tempering temperature, the amount of retained austenite has been reduced in comparison with previous specimens of lower tempering temperatures. This is due to the diffusion of dissolved nickel from austenite to martensite at higher temperatures and, accordingly, the rise in martensite transformation temperature (Mₐ). Moreover, retained austenite with the morphology of distributed islands (Fig. 7) has higher inclination to destabilization, leading to relatively easier transformation to martensite.¹⁴) Under such conditions, the austenite stability is reduced and, as a result, part of the retained austenite is transformed to martensite while cooling from tempering temperature.¹⁵) Calculations, based on Eq. (1), indicated that the amount of retained austenite in this specimen was only about 3% which means a decrease of approximately 60% compared to that in specimen T700-4. It is important to note that due to the low carbon content of this steel, the martensite and ferrite peaks are too close to be resolved as separate diffraction lines. Thus, in tempered specimens which are consisted of a mixture of martensite and ferrite phases, the observed peaks at angles 2θ=65° and 2θ=44.6° signify a combination of these two phases.

Variations in the percentage of retained austenite as a function of tempering temperature in CA6NM steel are presented in Fig. 8. The effects of these variations on the mechanical properties are further discussed in the following section.

### 3.2. Mechanical Properties

The hardness of the as-quenched specimen was found to be 345 BHN. Compared with conventional martensitic cast steel grades, this is a remarkable low hardness value in the nontempered condition. The extremely low percentage of carbon in this steel (0.061%) is the main reason for such a rather low hardness value of this cast martensitic structure. Figure 9 illustrates the relationship between the hardness of specimens and the tempering time at various temperatures. It can be seen that the time interval is not remarkably effective during the tempering process of cast CA6NM stainless steel. The effect of tempering temperature on hardness and impact energy of the specimens is shown in Fig. 10. It is evident that the hardness and impact toughness curves have opposite trends versus the tempering temperature. At the beginning of tempering, although the amount of retained austenite has not remarkably changed, the relaxation of martensite structure to ferrite and a decrease in the dislocation density are responsible for the increase in the impact energy, and the abrupt decrease in hardness. Increasing the tempering temperature of the specimens to 600°C, increased the hardness to a relative maximum and decreased the impact energy to a relative minimum. This is attributed
to chromium carbide precipitations confirmed according to micrographs and X-ray diffraction pattern of specimen T600-4 (Figs. 5 and 6). At the temperature range of 650–750°C, the hardness gradually decreases, exhibiting a minimum at 700°C and increases again, while toughness is maximum after tempering around 700°C. These relative minimum and maximum points are associated with the variations in the amount of retained austenite (Fig. 8).

**Figure 11** illustrates the relationship between the elongation, yield and tensile strength of the specimens as a function of tempering temperature. At the temperature range of 550–600°C, the increase in elongation and the drop in yield and tensile strength are attributed to the effect of martensite decomposition to ferrite. It appears that the formation of chromium carbides around 600°C did not have a remarkable effect on the tensile properties of the specimens. However, the effect of reversion and transformation of austenite on the amount of elongation, yield and tensile strength at tempering temperatures above 650°C is significant.

## 4. Conclusions

In this study, the effect of retained austenite phase on the structure and mechanical properties of CA6NM martensitic stainless steel casting was investigated. The conclusions derived from this study are summarized as follow.

1. By air cooling from $A_{C1}$ temperature, the structure of CA6NM entirely transforms to martensite due to high hardenability of the alloy.
2. At the beginning of tempering, in the range of 550°C, the relaxation of martensite structure of CA6NM to ferrite and a decrease in the dislocation density are responsible for the increase in the impact energy, and the abrupt decrease in hardness.
3. By tempering CA6NM in the range of 600°C, chromium carbides are precipitated at the prior austenite grain boundaries. This caused an increase in the hardness and a reduction in the toughness of the alloy.
4. By tempering of alloy CA6NM at temperatures above 600°C, the amount of retained austenite increased, exhibiting a maximum at about 700°C. The amount of retained austenite had inverse effect on hardness and strength but, direct relation with impact toughness and elongation.

## Acknowledgements

The authors acknowledge the contribution of Department of Materials Engineering of Isfahan University of Technology for provision of research facilities and Godaz Sanat Company for preparation of as-cast material.

## REFERENCES