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INVESTIGATION OF MICROSTRUCTURES AND PROPERTIES OF 440C MARTENSITIC STAINLESS STEEL

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ABSTRACT

440C steel is a high-carbon martensitic stainless steel with excellent mechanical properties. This paper describes the effect of heat treatments on microstructures and mechanical properties of 440C steel. Solution treatment was carried out at 1150°C and 60 minutes holding, followed by tempering process at 660°C with various holding time. In the as-quenched sample, SEM and EDX revealed existence of M_7C_3 carbides within the martensitic structures. While after tempering, $M_{23}C_6$ carbides were identified along with M_7C_3 carbides. Hardness tests found out that tempering at 30 minutes resulted in maximum hardness value of 49HRC. However, the hardness of the as-quenched sample was 43HRC. Tensile tests at this tempering time showed YS of 368MPa and UTS of 1044MPa. As comparison, the as-quenched sample showed YS of 124MPa and UTS of 517MPa. It is believed that secondary hardening phenomenon occurred while tempering and influenced the value of hardness and tensile strength of the 440C steel.

Keywords: Tempering, Microstructures, Hardness, Secondary hardening.

INTRODUCTION

440C steel is a high carbon martensitic stainless steel containing 12 to 17 percent Cr with sufficient carbon (0.15 to 1.0 percent C). As their properties can be changed by the heat treatment, this steel is suitable for a wide range of applications such as ball bearings, races, gage blocks, valve parts and many other manufacturing essential parts (Kwok *et al.*, 2003; Girodin *et al*., 2002; Subramonian *et al.*, 2005; Lo *et al.,* 2003). These alloys are called martensitic because they are capable of developing a martensitic structure after quenching from high temperature condition. There may also some retained austenite and carbides in the microstructure, since carbon and chromium lowered the martensite transformation temperature thus retaining austenite at room temperature (Caballero *et al.*, 2005).

After tempering, the microstructure of this steel generally consists of tempered martensite and carbides such as M_7C_3, $M_{23}C_6$ and M_2C, where the M represents Cr, Fe, Mo, V or other carbide-forming elements. Generally, tempering process usually leads to decrease in strength due to the precipitation of iron carbides from carbon that was originally in solid solution in the martensite. However when the steel contains strong carbide forming elements such as molybdenum, vanadium and chromium, it becomes possible to recover the strength. The recovery of strength occurs due to those carbides which precipitate in extremely fine, but dense, dispersions during tempering at elevated temperatures and time. This phenomenon known as secondary hardening and it depends on the alloy composition and heat treatment conditions (Fei et al., 2007; Honeycombe and Bhadfeshi, 1995; Bhadfeshi, 2001).

Equilibrium diagram of martensitic stainless steel, which gives α-ferrite and carbides at room temperature, is an attempt to identify the phase transformation and its behavior with temperature. Different microstructures along various temperatures were obtained. The aim of this paper is to investigate the microstructures and mechanical properties of 440C martensitic stainless steel in various conditions of heat treatment.

EXPERIMENTAL PROCEDURE

The steel studied in this work is 440C martensitic stainless steel. The chemical composition of the as-received state is given in Table 1. The material was subjected to rolling and annealing at 1040°C for 60 minutes before being supplied for this work. Then, solution treatment is performed at 1150°C for 60 minutes and followed by oil quenching. Figure 1 shows the equilibrium phase diagram of Fe-18wt%Cr-0.75wt%Mo-1.0wt%C alloy which was calculated by Thermo_calc software. It is a software package based upon a Gibbs Energy Minimizer and developed for performing various kinds of thermodynamic and phase diagram calculations.

Table 1: The Chemical Composition of 440C Steel (all in wt.%)

C	Si	Mn	Cr	Mo
1.0	1.0	1.0	17.0	0.75

The as-quenched samples were heat treated again at 1100°C for 30 minutes, in order to allow the second phase formation, followed by tempering (660^{o}C) at various tempering time (10-360 minutes). The purpose of this procedure is to investigate the influence of tempering time on the microstructures and their influence to the mechanical properties of these samples.

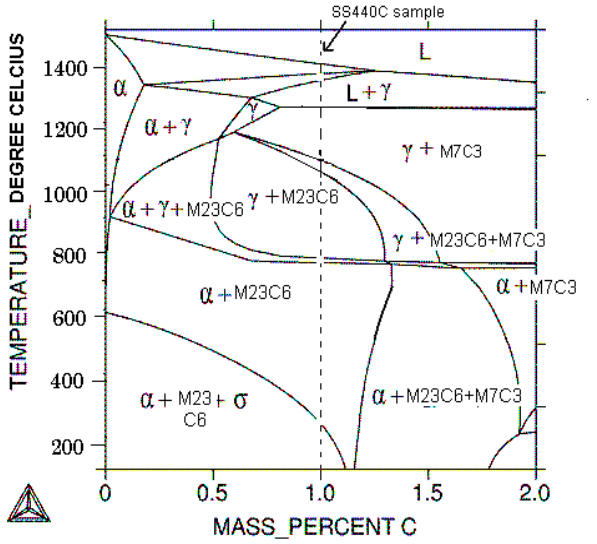

Figure 1. The Equilibrium Phase Diagram of 440C Steel

The samples were ground, polished and etched with Vilella's reagent. Microstructures were examined using the optical microscope (OM) and scanning electron microscope (SEM). As verification, energy dispersive x-ray (EDX) was conducted to confirm types of carbides that precipitate in the microstructures. Furthermore, the hardness and tensile properties were investigated by using Rockwell Hardness Tester and Instron Universal Testing Machine respectively.

RESULT AND DISCUSSION

Microstructural Investigation

Figure 2 are the scanning electron micrographs (SEM) of (a) as-quenched and (b) as-tempered 440C sample under back-scattered electron imaging mode. Figure 2 (a) shows the spheroidal carbides precipitate within the martensitic structures. Energy dispersive x-ray (EDX) spot analysis confirmed that these spheroidal carbides are M_7C_3 carbides. Figure 2 (b) shows two different types of carbides present in as-tempered 440C, the spheroidal and elliptical carbides. EDX spot analysis showed that the elliptical carbides are $M_{23}C_6$ carbides [6]. As shown in phase diagram, these $M_{23}C_6$ chromium rich carbides are dissolved at the austenization temperature (~1150^{o}C).

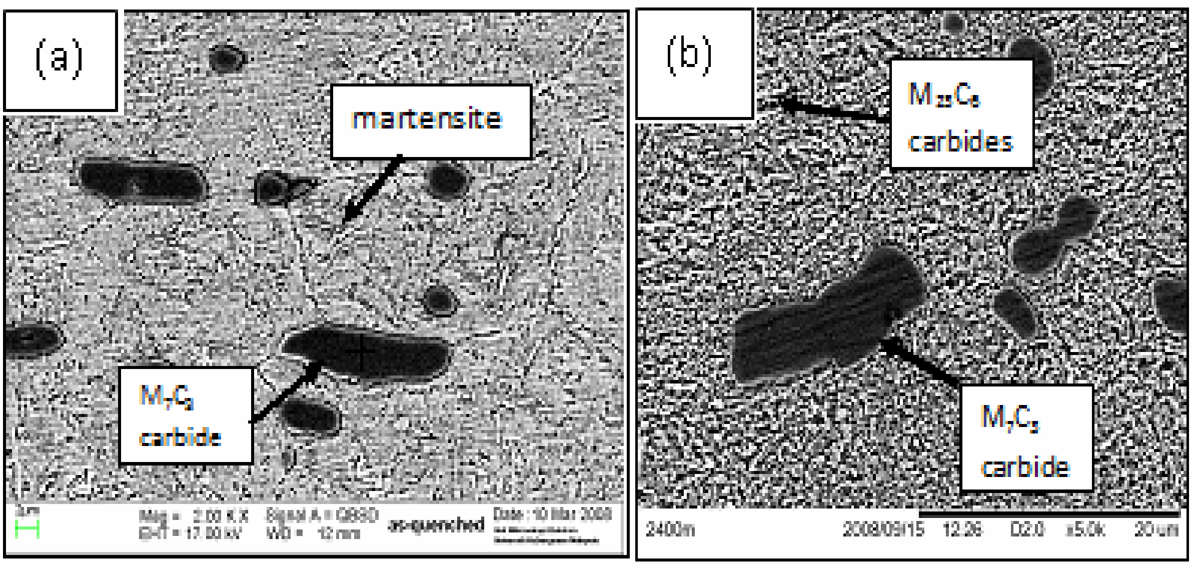

Figure 2. The Scanning Electron Micrograph of (a) As-quenched and (b) As-tempered Sample.

Mechanical Properties

Hardness

Figure 3 shows the influence of hardness at various tempering time on the average values of Rockwell hardness. The hardness value of as-quenched sample was 43HRC. For the as-tempered samples, it can be seen that average hardness gradually decreases with increasing tempering time. The change in hardness suggests the process of precipitation and growth of carbides, as well as the recovery and recrystallization of the matrix (Fei *et al.,* 2007). However, the secondary hardening phenomenon may have possibly occurred at 30 minutes tempering process, where the hardness value is highest. As have been mentioned before, the existence of some strong carbide forming elements such as Cr, Mo, and V may assist the strength recovery of 440C steel.

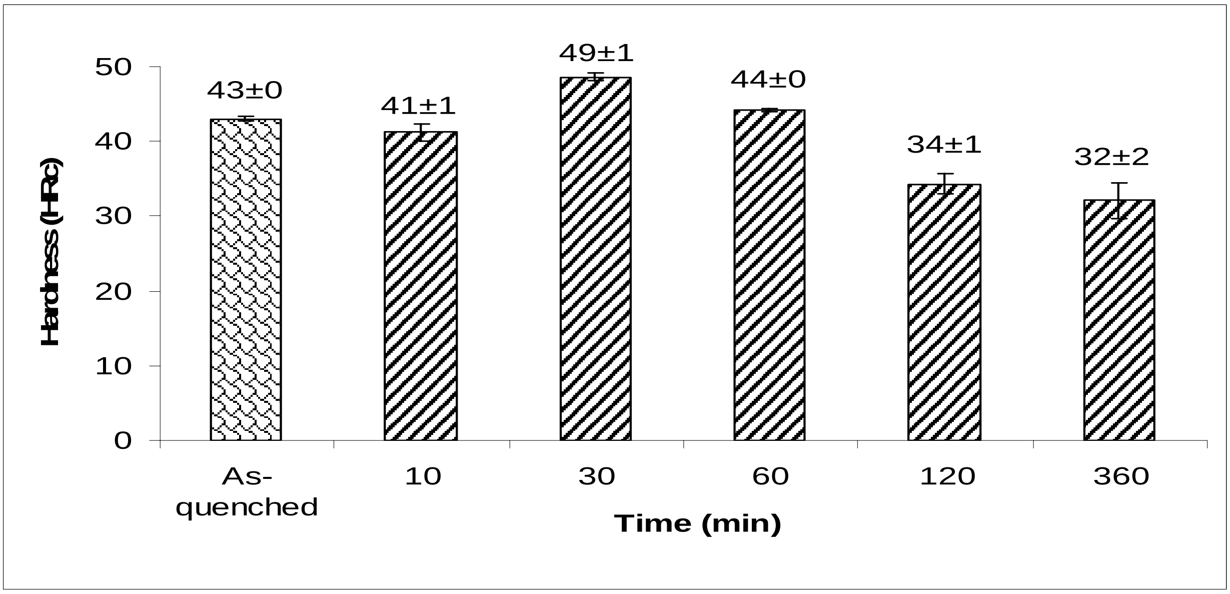

Figure 3. Hardness (HRC) Values of As-quenched and As-tempered Samples

Tensile Test

The tensile test was carried out for the as-quenched and 30 minutes-tempered samples. Figure 4 shows the tensile properties of as-quenched and 30 minutes-tempered sample of 440C martensitic stainless steel. It can be clearly seen that the UTS of the as-quenched sample was 517MPa and YS of 124Mpa. However, the UTS and YS of the as-tempered sample are 1044MPa and 368MPa, respectively. This might due to the high brittleness of the martensite structures in as-quenched sample. As a result, the 30 minutes-tempered sample had the best combination in both microstructural and mechanical properties. Furthermore, it can be concluded that the tempering process has not only increased the toughness of the steel; but also gives the higher tensile properties to the steel.

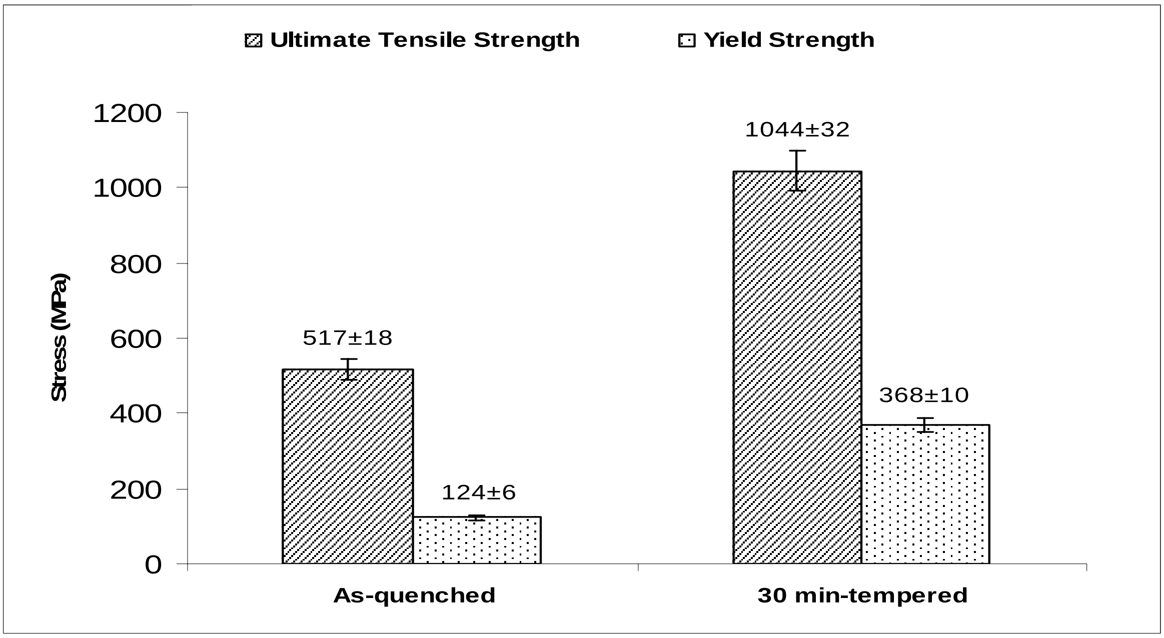

Figure 4. Tensile Properties of Heat-treated Samples.

CONCLUSION

The investigation on the microstructures and mechanical properties of the as-quenched and tempered 440C steel has led to the following conclusion:

1. $M_{23}C_6$ carbides precipitate only after the tempering process.

2. Hardness test showed highest value at 30 minutes tempering time. It is thought to have

occurred due to secondary hardening phenomenon.

3. Tempering process has not only increased the toughness of the steel; but also gives higher tensile properties to the steel.

4. The 30 minutes-tempered sample had the best combination of both microstructural and mechanical properties.

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