Microstructure and Mechanical Properties of 0.63C-12.7Cr Martensitic Stainless Steel

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Abstract. Microstructure and mechanical properties of 0.63C-12.7Cr martensitic stainless steel during various tempering treatments were investigated in this study. Results demonstrate that finely distributed primary carbides were observed on 0.63C-12.7Cr martensitic stainless steel. It was also found that the hardness of 0.63C-12.7Cr martensitic stainless steel after 300°C tempered treatment for 60 minutes can still reach to 679Hv. The variation of measured hardness was found not significant during tempering treatments (200°C-500°C). The matrix phase of 0.63C-12.7Cr martensitic stainless steel tempered below 500°C was identified as martensite. However, the matrix structure of mixed ferrite and martensite can be observed when tempered at 500°C and 600°C. On the other hand, mixed of M\textsubscript{7}C\textsubscript{3} and M\textsubscript{23}C\textsubscript{6} carbide particles were observed on specimen when tempered at 200-600°C. The amount of M\textsubscript{7}C\textsubscript{3} carbides was found decreased as increase the tempering temperature.

Keywords: Martensitic stainless steel, Carbide, Tempering treatment, Hardness

I. Introduction
Martensitic stainless steel containing 13%Cr are common utilized in quench and tempered processes for bearing steel \cite{1}. It is well known that the properties obtained in these materials are significantly influenced by associated heat treatment processes. The amount and type of carbide particles exerts an important effect on hardness, resistance to corrosion, wear and etc. \cite{2}. For example, the hardness of SUS440C type martensitic stainless steel can be reached to 660-720 Hv owing to its high contents of C and Cr (0.95–1.20 wt% of carbon, 16–18 wt% of chromium). However, large size of carbide particles will precipitate during cooling processes because of high content of C and Cr. Large size of carbides particles can not only induce the stress concentration when this material was utilized but also decrease the hardness during tempering, especially when tempered at about 300°C. Besides, large size carbide particles may change the surface roughness of material locally which will cause the noise problem when this material is applied in bearing. Recently, modified 440 type martensitic stainless steel (containing 0.63C-12.7Cr) has been developed. By reducing the content of carbons, chromium and controlling the size and amount of carbide particles, the properties of the new-developed material can still maintain as that of SUS440C type martensitic stainless steel. Although the heat treatment conditions of 440C type martensitic stainless steel can be used for 0.63C-12.7Cr martensitic stainless steel (called as 440M martensitic stainless steel). The relation between mechanical properties and the heat treatment conditions should be reconstructed. Therefore, the purpose of this study will focus on the mechanical properties and microstructure change of 440M martensitic stainless steel during various tempering treatments.

II. Experimental Procedure
The samples of this study were supplied by Bo-Shum Co. The chemical composition of 440M martensitic stainless steel was confirmed by ICP-OES. Table 1. shows the composition of as-received specimen. The specimen was then carried out with solid-solution treatment at temperature range of 1010–1070°C and followed by air cooling. The specimen were then tempered treatment at 200°C, 300°C, 400°C, 500°C and 600°C for 60 minutes, respectively. After tempering treatment, hardness with various heat treatment conditions was then tested by micro-hardness testing machines. On the same time, microstructure of specimens after various heat treatment conditions was also investigated by FE-SEM. In this study, Vilella’ s reagent (1g picric acid, 15ml HCL and 100ml ethanol) was applied in microstructural investigation. TEM and associated diffraction technique were also utilized to verify the phases of carbide.

III. Results and Discussion
3.1. Primary carbide
Fig.1 (a) and (b) show the microstructure of both as-received SUS440C stainless steel and 440M stainless steel. It clearly exhibits that large size (about 3-10 \( \mu m \)) of primary carbide particles was observed on 440C stainless steel. On the other hand, finely distributed of primary carbide particles (about 0.5-1.5 \( \mu m \)) were observed on 440M stainless steel.

### 3.2 Microstructure analysis during various tempering heat treatment

Transformation from austenite to martensitic phase was usually observed on martensitic stainless steel when quench from high temperature to room temperature. The start martensitic transformation temperature Ms can be calculated by the formula [3]:

\[
Ms \left( ^\circ C \right) = 539 - 423(\%C) - 30.4(\%Mn) - 17.7(\%Ni) - 12.1(\%Cr) - 7.5(\%Mo) \quad \text{------------------------- (1)}
\]

The start martensitic transformation temperature (Ms) of SUS440C (17.4Cr-1.04C) stainless steel temperature is calculated to be -127.0\(^\circ\)C. It indicated that retained austenite will exist when austenite transformed to martensitic phase. In general, this should be carried out by additional sub-zero treatment. On the contrary, Ms temperature will be increased to 96.4\(^\circ\)C on 440M (12.7Cr-0.63C) stainless steel materials due to its lower carbon and chromium content indicating the sub-zero treatment can be eliminated. Fig. 2(a)-(e) shows the microstructure of as quenched, tempered at 200\(^\circ\)-600\(^\circ\)C of 440M specimens, respectively. It shows that small size of secondary carbides was found after tempering treatment. The amount of secondary carbides was found increased as increase the tempering temperature.

Fig.3 shows the TEM micrograph of 440M stainless steel at as quenched conditions. The matensitic structure was observed as the matrix structure. M\(_7\)C\(_3\) carbide particles with the size of about 0.8\(\mu m\) can also be found on this condition. Fig.4 reveals the TEM microstructure of specimen tempered at 300\(^\circ\)C. The matrix structure was identified as tempered martensitic phase. Mixed structures of M\(_7\)C\(_3\) and M\(_2\)C\(_6\) carbides particles can also be observed on specimen tempered at 300\(^\circ\)C. Similar result was also reported [4] that secondary carbide of M\(_2\)C\(_3\) can be observed on specimen when tempered at 300\(^\circ\)C. While, M\(_2\)C\(_6\) carbide was observed on specimen when tempered at 500\(^\circ\)C. However, it was observed that the amount of M\(_7\)C\(_3\) carbides was decreased as increase the tempering temperature.

Fig.5 reveals the TEM micrograph of 440M stainless steel when tempered at 500\(^\circ\)C. It was found that part of the matrix structure of martensite phase started to transform into ferrite structure. Ferrite structure can be clearly identified using diffraction technique (as shown in Fig.5 (a)). M\(_2\)C\(_6\) carbides particles (as shown in Fig.5 (b)) were found on specimen tempered at 500\(^\circ\)C. Fig.6 demonstrates the TEM micrograph of 440M stainless steel when tempered at 600\(^\circ\)C. In this tempering condition, the majority of the matrix phase has been transformed to ferrite structure. This phase change causes the tremendous decreasing on hardness.

### 3.3. Hardness during various tempering heat treatment

Fig.7 depicts the hardness of SUS440C and 440M stainless steel during various tempering conditions. The hardness value of 855Hv can be measured on SUS440C specimens after quench and it drops to 603Hv when tempered at 300\(^\circ\)C. The hardness was then increase to above 700Hv when tempered at 400\(^\circ\)-500\(^\circ\)C due to secondary carbides produced at this condition. While on 440M stainless steel, the average measured hardness was about 726Hv when tempered at 200\(^\circ\)C. Moreover, the average measured hardness was about 679Hv when tempered at 300\(^\circ\)C. It is important to note that the hardness value of 440M when tempered at 300\(^\circ\)C can still fulfill the hardness requirement in industry (higher than 655Hv). The average measured hardness was about 680Hv and 657Hv when tempered at 400\(^\circ\)C and 500\(^\circ\)C, respectively. The average measured hardness was dropped to 341Hv when tempered at 600\(^\circ\)C.

### IV. Conclusions

1. Finely distributed (about 0.5-1.5 \( \mu m \)) of primary carbide can be observed on 440M (0.63C-12.7Cr) stainless steel.
2. Hardness value of 440M stainless steel can still reach to 677Hv when tempered at 300\(^\circ\)C for 60 minutes.
3. Martensitic transformation temperature (Ms) of 440M stainless steel is calculated about 96.4\(^\circ\)C, representing that the percentage of austenite to martensitic transformation can be increased when quench to room temperature.
4. Mixed of M\(_2\)C\(_3\) and M\(_2\)C\(_6\) carbide particles were coexisted during tempering processes.
5. The matrix structure start to change from tempered martensite to ferrite structure when tempered at 500\(^\circ\)C.

### Acknowledgment

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References

Chart arrangement

Figure 1(a) microstructure of SUS440C stainless steel showing large size particles of primary carbide, (b) microstructure of 440M stainless steel demonstrating small and finely distributed primary carbides.

Figure 2. Microstructure of 440M stainless steel at various heat treatment conditions: (a) as quenched, (b) tempered at 200 °C, and (c) tempered at 300 °C.
Figure 2. (cond.) Microstructure of 440M stainless steel at various heat treatment conditions: (d) tempered at 400 °C, (e) tempered at 500 °C, and (f) tempered at 600 °C.

Figure 3. TEM micrograph of as quenched 440M stainless steel showing (a) plate-shaped martensitic matrix structure on [111] zone axis (inset) and (b) M7C3 carbide particle on [01T1] zone axis (inset).
Figure 4 TEM micrograph of 440M stainless steel tempered at 300 °C, showing (a) tempered martensitic matrix on [011] zone axis (inset), (b) secondary M$_7$C$_3$ carbide particles on [130] zone axis (inset) and (c) secondary M$_{23}$C$_6$ carbide particles on [011] zone axis (inset).

Figure 5 TEM micrograph of 440M stainless steel tempered at 500 °C, showing (a) ferrite matrix structure on [111] zone axis (inset) and (b) secondary M$_{23}$C$_6$ carbide particles on [013] zone axis (inset) and (c) secondary M$_{23}$C$_6$ carbide particles on [111] zone axis (inset).
Figure 6 TEM micrograph of 440M stainless steel tempered at 600 °C, showing ferrite matrix structure on [T11]zone axis (inset).

Figure 7. Hardness measurement of SUS440C and 440M specimens at various tempering conditions

Table 1 Chemical composition of 440M stainless steel

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<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
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