The effect of solid solution treatment on the hardness and microstructure of 0.6%wt C-10.8%wt Mn-1.44%wt Cr austenitic manganese steel

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Abstract. Austenitic manganese steel is steel alloy that has high manganese content (10-14%wt Mn). The characteristics of austenitic manganese steel are good in toughness, ductility, and wear resistance. Effect of solid solution treatment on the hardness and microstructure of austenitic manganese steel was studied in this experiment. The solid solution treatment process of austenitic manganese steel, 0.6%wt C-10.8%wt Mn-1.44%wt Cr, was conducted by heating the material at varied temperatures (950°C, 1000°C, 1050°C) for an hour and then quenching it in two different quenching media, i.e. oil and water. Further, the samples were tempered at three different temperatures (300°C, 400°C, and 500°C) for 2 hours. The treated materials were analyzed by Rockwell Hardness Tester to obtain the information of materials hardness and by an optical microscope and XRD to investigate the microstructure phase of the treated materials. Heating the austenitic manganese steel at 950°C for an hour followed by water quenching dissolved all carbide in as-cast condition and resulted the fully austenitic on its microstructure. Carbide precipitation occurred due to the prolongation of soaking time in solid solution treatment and tempering process. The optimum hardness of sample was 53.3 HRC, which was resulted by heating this material until 1000°C for an hour, followed by water quenching and tempering at 400°C for 2 hours.

1. Introduction
Austenitic Manganese Steel, also known as Hadfield Steel was found by Robert A. Hadfield in 1882. It has chemical composition 1.0-1.4%wt C and 11-14%wt Mn or the C/Mn ratio is 1:10 [1]. Manganese steel is a wear resistant material with very good toughness and hardness after it was heat-treated and work-hardened. As a wear resistant material, austenitic manganese steel is commonly used in crushing machine components, railways, and heavy equipment components [2]. Austenitic manganese steel has 379 MPa of yield strength, 965 MPa of ultimate tensile strength, 190 HBN of hardness, and 169 J of Charpy V-Notch impact [3]. The microstructure of this material after heat treated is fully austenitic with a crystal lattice face centered cubic where the structure of this lattice consists of interstitials of carbon atoms and substitution of manganese atoms. Although it has the same structure as stainless steel, this material has very low corrosion resistance [4]. In as-cast condition, this austenitic manganese steel is brittle (having low toughness and elongation) [5]. It is caused by the formation of carbide (\(\text{Mn}_3\text{C}\)) along with the grain boundaries on its microstructure due to the slow cooling in solidification process. The experiment to improve its mechanical properties had been done
by addition of alloying elements, such as Nb and Ti for obtaining fine austenitic structure and a lot of hard dispersed carbide [6]. Heat treatment is another method to improve the mechanical properties of the austenitic manganese steel. Solid solution treatment is one kind of heat treatment process that is commonly applied in austenitic manganese steel to obtain homogeneous austenitic phase on its microstructure. This heat treatment process includes heating this material at 1000-1100°C and then it is quenched rapidly. This fully austenitic structure will transform into martensite after work-hardening and the hardness will increase. It is called strain induced martensite [7]. The other heat treatment process to improve the hardness of austenitic manganese steel is by precipitation hardening. It was reported by Aribo, S. et al, that the artificial aging at 700°C for 2 hours increased the hardness of austenitic manganese steel which is caused by carbides particles finely dispersed in the austenite matrix [8].

However, there is still less information about the evolution of austenitic manganese steel microstructure after being heat treated at various solid solution and tempering temperature. The objective of this work is to obtain the optimum hardness of the austenitic manganese steel by solid solution treatment and tempering process. In this experiment, the effect of solid solution and tempering temperature, also two different kinds of quenching media on the hardness and microstructure of the austenitic manganese steel was clearly investigated.

2. Material and Method

The solid solution treatment was applied to the austenitic manganese steel. The chemical composition of the sample is presented in table 1. Austenitic manganese steel was heated at various austenitization temperature, i.e. 950°C, 1000°C, 1050°C for an hour and then it was quenched rapidly by using two different quenching media, i.e. oil and water. The effects of the austenitization temperature and quenching media on the hardness and microstructure of austenitic manganese steel were studied. The measurement of hardness was conducted by using Rockwell hardness testing machine, while the microstructure was analyzed by an optical microscope (Nikon Eclipse MA 100, Japan) and X-Ray Diffraction (XRD). The sample with the optimum hardness resulted from this austenitization and quenching process was obtained. The experiment was continued by investigating the soaking time in the austenitization process that the sample was heated at optimum austenitization temperature, soaked for 1, 2, and 3 hours, and quenched rapidly. The tempering temperature was also investigated by heating the sample at 300°C, 400°C, and 500°C for an hour.

| Element | C | Mn | Cr | Si | Ni |
|---------|---|----|----|----|----|
| % wt    | 0.59 | 10.81 | 1.44 | 0.37 | 0.04 |

3. Result and Discussion

3.1. Characterization of as-cast austenitic manganese steel

The microstructure of austenitic manganese steel 0.6%wt C - 10.8%wt Mn - 1.44%wt Cr in as-cast condition comprised austenite and some of the dendritic carbides (Fe,Mn),C, as shown in figure 1. The composition of carbides was analyzed by Energy Dispersive X-Ray Spectroscopy (EDS). The carbides were also found in XRD analysis, as shown in figure 2. The carbides were formed and precipitated along austenite grain boundaries due to the slow cooling in solidification process. This carbide network resulted a negative effect on toughness, therefore the solid solution treatment must be applied on this austenitic manganese steel to improve its mechanical properties. From figure 1 and 2, the matrix was austenite. The hardness of this austenitic manganese steel in as-cast condition was only 12 HRC due to the formation of soft austenite in matrix.
The influence of solid solution temperature, soaking time, quenching media, and tempering temperature on the hardness and microstructure of austenitic manganese steel 0.6%wt C-10.8%wt Mn-1.44%wt Cr is discussed briefly in this paper.

Figure 1. Microstructure of austenitic manganese steel in as-cast condition

Figure 2. XRD analysis of austenitic manganese steel in as-cast condition

3.2. The effect of austenitization temperature and quenching media

Solid solution treatment was conducted to dissolve all carbides that were found in as-cast condition. XRD pattern in figure 3(a) shows the microstructure of austenitic manganese steel after solid solution treatment at 950°C for an hour and quenched by oil. It was found that ferrite and carbide appeared on its structure. While from figure 3(b) when the water was used as quenching media, there was no-carbide structure and the austenite was replaced the ferrite structure. From figure 5, it can be seen that although the trend of hardness in quenching by oil and water was similar, the hardness of quenched material by water was higher than that of quenched material by oil. Water has higher cooling rate than oil, thus the matrix will be dominated by austenite and no-ferrite structure. The formation of ferrite occurred because of the slow cooling after solid solution treatment. This ferritic matrix resulted the low hardness of this austenitic manganese steel. Ferrite is softer than austenite, therefore the hardness resulted from oil quenching was lower than that resulted from water quenching. figure 3(c-d) show that there was no-carbide structure. All carbides were dissolved into the matrix by heating this material at 1000°C and 1050°C for an hour and quenching rapidly by water. Carbon will be dissolved in the austenitic matrix at a critical temperature of the austenitic formation. It was called a solid solution temperature. Generally, it was 1050°C for manganese steel which has 0.9-1.4%wt C and 1-15%wt Mn [7]. The solid solution treatment temperature in this experiment was lower i.e. 950°C, due to the lower carbon content in this 0.6%wt C-10.8%wt Mn-1.44%wt Cr austenitic manganese steel. The higher carbon content will be resulted in more stabilized carbide structure, consequently it takes a higher
temperature to dissolve carbon into the matrix. The hardness of this austenitic manganese steel increased by heating this material from 950°C until 1000°C, however it decreased after heating at 1050°C. The highest hardness was obtained at austenitization temperature of 1000°C due to the appearance of martensite phase, as shown by XRD pattern in the figure 3(c).

**Figure 3.** XRD patterns of austenitic manganese steel: (a) 950°C, oil quenched; (b) 950°C, water quenched; (c) 1000°C, water quenched; (d) 1050°C, water quenched

**Figure 4.** Solid solution treatment of austenitic manganese steel: (a) 1000°C, oil quenched; (b) 1000°C, water quenched; (c) 1050°C, oil quenched; (d) 1050°C, water quenched.

**Figure 5.** Hardness of manganese steel at different austenitization temperature and quenching media
The hardness of martensite is higher than that of austenite and ferrite, hence the hardness of this austenitic manganese steel increased significantly by heating at 1000°C. As reported by Schilke, et al., that the martensite formation in this manganese steel occurred because the carbon content in this material was not sufficient to stabilize the austenite structure [9]. Manganese and carbon play an important role to stabilize the austenite structure in the manganese steel. High carbon manganese steel commonly has fully austenite structure after being heated at 1050°C and quenched rapidly by water. However, in this current study, the martensite structure still existed although this medium manganese steel was heated at 1050°C, as shown by XRD pattern in figure 3(d).

The manganese steel heated at 1050ºC had lower hardness than that heated at 1000°C due to the growth and coarsening of grain size. Figure 4 shows that the grain size of manganese steel heated at 1050°C was larger than that heated at 1000°C, either quenched by oil or water.

3.3. The effect of soaking time at austenitization temperature

The manganese steel was heated at 1000°C for 1 to 3 hours and then water quenched to investigate the effect of soaking time on this solid solution treatment. Figure 6 shows that the hardness of manganese steel increased due to the prolongation of soaking time in solid solution treatment. It was also confirmed by microstructure analysis that there was no carbide structure after the solid solution treatment at 1000°C for an hour, as shown previously in figure 3(c). The carbide structure was formed on its grain boundaries after heating this material for 2 and 3 hours, as shown in figure 7(a-b). The composition of this carbide shows in figure 7(c). From figure 6 and 7, it can be found that the longer soaking time of solid solution treatment in this austenitic manganese steel promoted the reaction of carbon and manganese to form carbide. This condition also led the increase of hardness because the grain size of carbide on its microstructure will reduce at the longer soaking time. The higher hardness will be obtained at the smaller grain size.

![Figure 6. Hardness of manganese steel with water quenching after solid solution treatment with various holding time at 1000°C](image)

![Figure 7. Microstructure of solid solution treatment on manganese steel with various holding times; (a) 2 hours; (b) 3 hours, (c) EDS of carbide on grain boundaries](image)

3.4. The effect of tempering at austenitic manganese steel

The manganese steel was heated at 1000°C for 3 hours continued by water quenching and tempering in various temperatures to investigate the effect of tempering on the solid solution treatment process.
Figure 6(b) shows that the tempering process reduced the hardness of austenitic manganese steel after solid solution treatment. The carbide was dissolved after tempering at 300°C. There was no-carbide structure on its grain boundaries (figure 8(a)), but the small amount of secondary carbide was formed inside the matrix. After tempering at 400°C, there were more carbide dispersed on the matrix that caused the increase of its hardness (figure 8(b)). Further, the hardness decreased after tempering at 500°C because the grain size was too large as shown in figure 8(c). The grain growth will reduce the hardness of the austenitic manganese steel. It was in accordance with Aribo, et al, that the grain size will increase due to the increase of tempering or aging temperature [8]. The large grain size will promote more dislocation in grain boundaries, consequently the finely dispersed carbide will separate from the matrix and move to fill the dislocation along the grain boundaries, as shown in figure 8(c). Figure 9 shows that the hardness of this material increased after being heated into 400°C. However, the hardness was decreased after being heated at 500°C. This secondary carbide will give positive effect on its mechanical properties, such as both of toughness and hardness, while the large grain size growth will reduce the hardness.

![Figure 8](image-url)

**Figure 8.** Microstructure of austenitic manganese steel with solid solution treatment at 1000°C for 3 hours, water quenching, and tempering for 2 hours at: (a) 300°C, (b) 400°C, (c) 500°C, (d) EDS analysis of carbide on matrix

![Figure 9](image-url)

**Figure 9.** Hardness of manganese steel at various tempering temperature for 2 hours.

### 4. Conclusion

The microstructure of austenitic manganese steel with 0.6%wt C-10.8%wt Mn-1.44%wt Cr consisted of the austenitic matrix with carbide along its grain boundaries. Solid solution treatment of this austenitic manganese steel was only 950°C due to its low carbon content. Martensite was found at higher temperature solid solution treatment. Fine carbide dispersed within the matrix was obtained after tempering this manganese steel at 400°C, thus it resulted the optimum hardness. At higher tempering temperature, larger grain size and lower hardness were obtained.
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