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The Effects of Tempering and Cooling Media on The Strength of Hadfield Steel

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Abstract: Hadfield steel is a steel known for its good toughness, but it often experiences damage due to excessive loads. In this study, an analysis of the heat treatment process was conducted on Hadfield steel to enhance its strength through homogenization at a temperature of 850°C and tempering at 600°C with a holding time of 30 minutes, followed by a rolling process with a 20% reduction. The data analysis results indicate that the sample cooled using water as the cooling media produced the most optimum strength. This is evident from its tensile strength value, which reached 941 MPa, with a grain size of 3.51 μm. Although its hardness value 351.98 BHN is slightly lower compared to the sample cooled with air, the difference is not significant. The metallographic observations show that there is a phase change in the sample. Initially, the sample only had an austenite phase during the homogenization process. However, after undergoing tempering, there is a phase change to austenite, ferrite, martensite, and carbide phases. This change will result in an increase in the strength of Hadfield steel.

Keywords: Hadfield Steel, Homogenization, Tempering, Cooling Media
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INTRODUCTION

Steel Hadfield, also known as austenitic manganese steel, has a high content of carbon and manganese, reaching 0.9-1.2% C and 11-14% Mn [1]. The high carbon and manganese content make this material predominantly austenitic at room temperature. The advantages of Hadfield steel are its good toughness, high wear resistance and hardness, and resistance to corrosion [2],[3]. In its applications, this type of steel is widely used in industrial components that require good toughness [4]. However, a common problem is the premature failure of Hadfield steel due to excessive loading, resulting in a significant decrease in its strength.

Several studies have been conducted to improve the strength of Hadfield steel, such as the research by Ilham Azmy et al., which studied the effect of tempering process on the microstructure and post-annealing hardness of austenitic manganese steel. The study showed that tempering process caused a decrease in hardness due to the formation of martensite phase and coarse-grained carbide phase ($FeMn_3C$) within the austenite matrix [5]. Another study conducted by Permana et al, [6] showed that variations in holding time and cooling media during the solution treatment process of $Fe_{12}Mn_{1.5}Mo$ steel result in a microstructure consisting of a dominant austenite phase as the matrix, with the presence of undissolved carbides at grain boundaries and within grains [6]. The manganese content and austenitization temperature also influence the microstructure and mechanical properties of manganese steel, where manganese steel with medium (9-10% Mn) and high (15-16% Mn) manganese content results in a stable austenite structure. Increasing the austenitization temperature in manganese steel leads to the emergence of a dominant austenite phase, which cause the hardness of manganese steel to decrease in the as quenched condition [2].

In this research, a heat treatment process will be conducted on Hadfield steel through 2 stages, namely homogenization and tempering. The homogenization stage is carried out to make the structure of Hadfield steel more homogeneous, with the formation of a fully austenitic phase, while tempering is done to improve the strength of the steel. In addition, variations in cooling media are also conducted in this study to obtain optimal strength, so that the premature failure of Hadfield steel can be avoided before its service life is over.

MATERIALS AND METHODS

A. MATERIALS

The equipment used in this study includes a furnace for heat treatment (Nabertherm LH-15/14"/C440 type), Hypertherm Plasma Cutting Machine, Hardness Brinell Test AFFRI/206 RTD, Tinius Olsen 300SL Testing Machine, and an Olympus BX 53M optical microscope. The materials used in this research are Hadfield steel samples with dimensions of 9.9 cm x 5.56 cm x 1.62 mm, sandpaper (80 to 1500 mesh), polishing cloth (5 m and 1 m), alumina, hardener, resin, ethanol, and 2% nital etchant. The chemical composition of the Hadfield steel sample was analyzed using SpectroLab OES (Optical Emission Spectroscopy), as shown in Table 1 [7].

Table 1. Chemical Composition of Hadfield Steel

Element	Mn	Si	S	C	Ni	P	Mo	Cr	Fe
Wt%	13	0.40	0.03	1.15	10.86	0.045	0.90	0.462	Bal.

B. METHODS

The process begins with cutting the Hadfield steel test sample using a Hypertherm Plasma Cutting Machine with dimensions of 9.9 cm x 5.56 cm x 1.62 mm. Furthermore, 2 stages of heat treatment homogenization and tempering, as well as two cooling variations using air and water as the cooling media. The homogenization process involves heating the test sample to a temperature of 850 ^{0}C with a holding time of 30 minutes, followed by rolling with a 20% reduction percentage. This is followed by the tempering process, which involves reheating the test sample to a temperature of 600 ^{0}C with a holding time of 30 minutes and rolling with a 20% reduction. Variations are also made in the cooling process, using air and water as the cooling media. Please refer to Figure 1 for the stages of heat treatment for Hadfield steel.

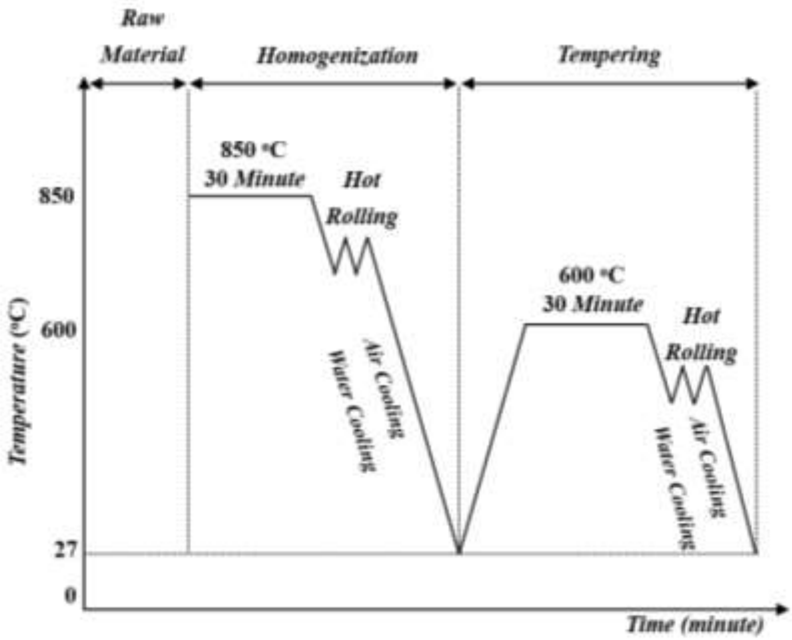


Figure 1. Heat Treatment Process of Hadfield Steel

RESULTS AND DISCUSSION

A. HARDNESS TEST RESULT

The hardness testing in this study was conducted using the Brinell method, which involves applying pressure to the surface of the sample using a steel ball indenter at 5 different points [8]. The results of the hardness testing for Hadfield steel can be seen in Figure 2.

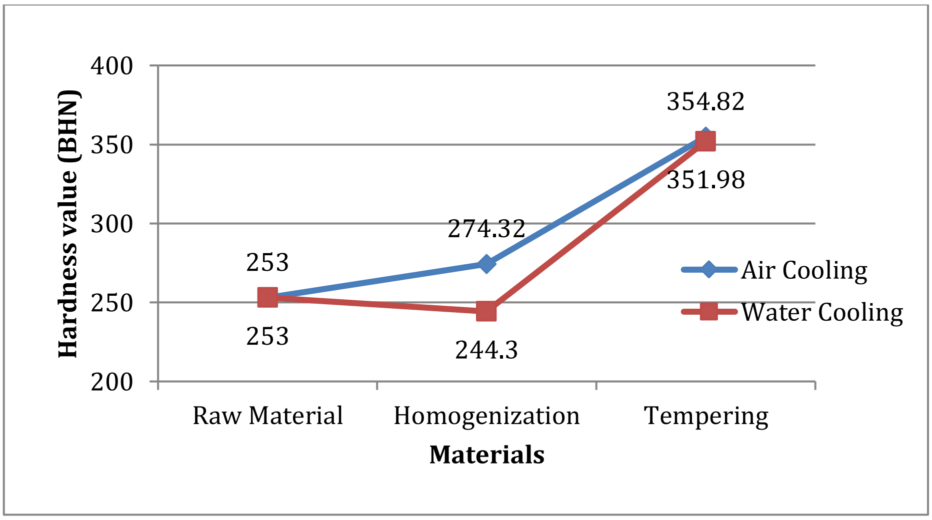


Figure 2. Brinell Hardness of Hadfield Steel

Based on Figure 2, it can be seen that after the tempering process, the hardness value of Hadfield steel increases, whether it is cooled with air or water. This increase in hardness value reaches more than 38% from the previous value, from 253 BHN to 354.82 BHN for air cooling and 351.98 BHN for water cooling. Looking at the given treatment process, this increase in hardness value can be attributed to the hot rolling process [9], as stated in the study by Paristiawan et al., 2020 [10] which indicates that the hot rolling process can increase the hardness value of materials. The difference in cooling processes is also observed in this sample, where cooling with air actually results in a higher hardness value compared to water [11], although the difference is not significant. The slow cooling rate during air cooling will lead to the formation of a stronger structure [12],[13].

B. TENSILE STRENGTH RESULT

Tensile strength testing is a method of testing that involves applying opposing forces to a material in a direction away from the center point. Tensile testing is performed to determine the mechanical properties of a material[14].

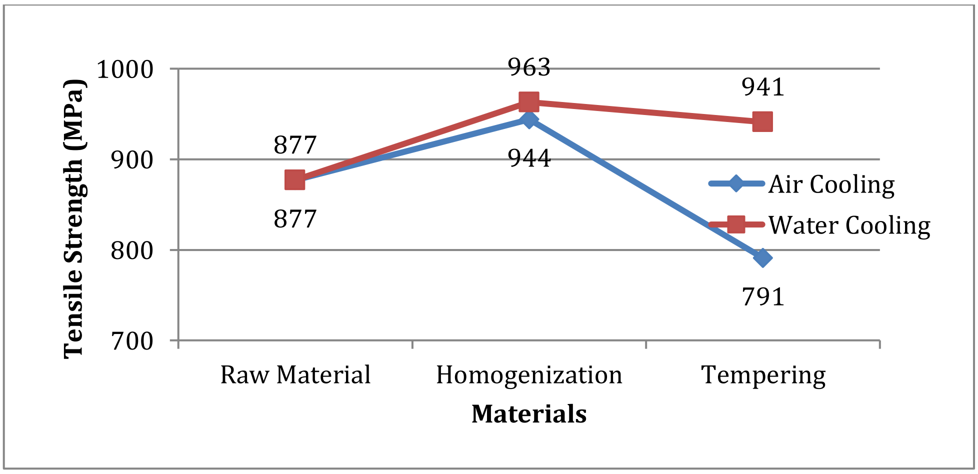
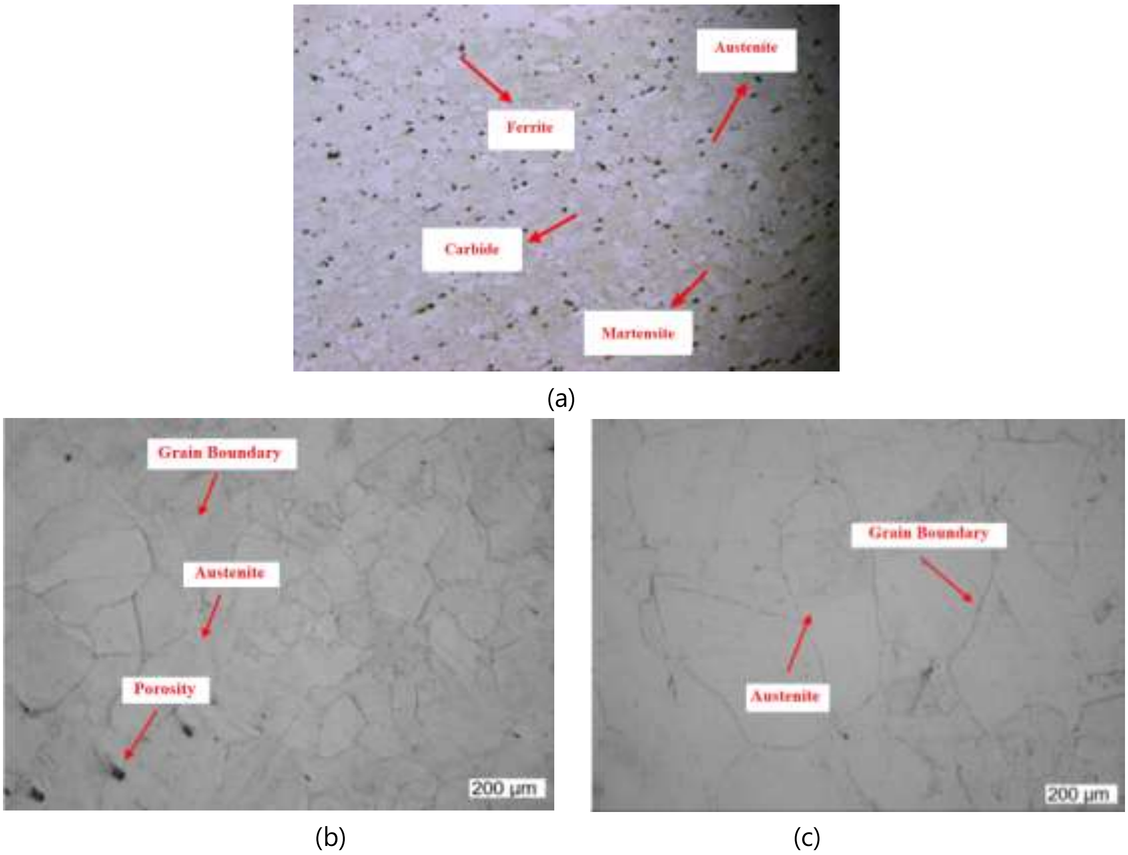


Figure 3. Tensile Strength of Hadfield Steel

Based on the data from the tensile strength test as shown in Figure 3, it can be observed that the tensile strength values of the samples increase after the homogenization process. This indicates the success of the homogenization process, which makes the samples more homogeneous and results in the formation of fully austenite phase and the dissolution of carbides within the grain boundaries [15]. The heating process at 850°C also disperses the carbides more evenly within the grain boundaries, as seen from the metallographic results, leading to an improvement in the sample's toughness. However, after undergoing the tempering process, the tensile strength values decrease again, although they are still higher than the raw material. This occurs because repeated heating processes can cause carbide re-precipitation at the grain boundaries which can reduce the toughness value [16], [17]. Overall, the tensile strength values of the test samples tend to increase, especially for samples cooled using water, from an initial value of 877 MPa to 941 MPa. Although there is a decrease in samples cooled with air compared to before, it is due to the increase in hardness value, which impacts the decrease in tensile strength values of samples cooled with air.

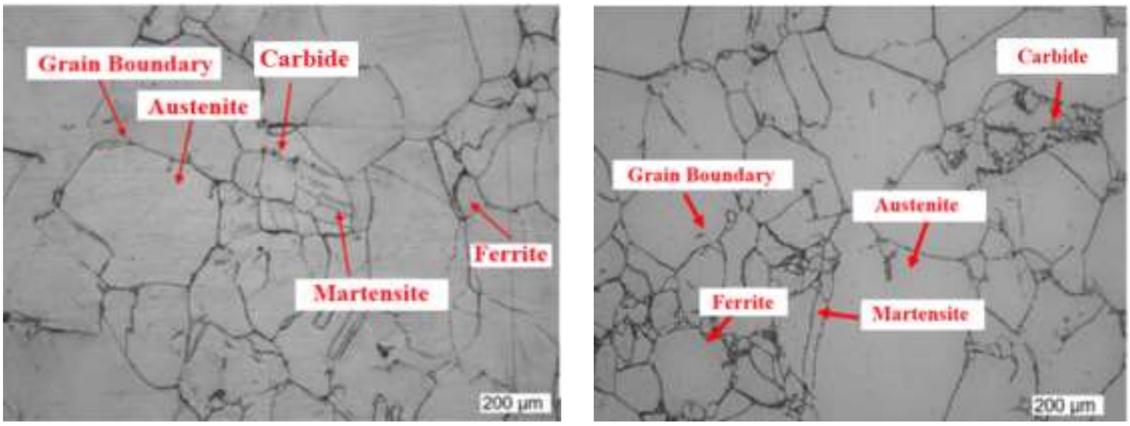
C. METALOGRAPHY

The microstructure of Hadfield steel samples was observed using metallographic techniques with an Olympus optical microscope at a total magnification of 20x. The results of the microstructure observation are presented in Figure 4.



(a)

(b) (c)



(d) (e)

Figure 4. Optical Microscope Observation Results: Raw Material (a), Homogenization With Air Cooling (b), Homogenization With Water Cooling (c), Tempering With Air Cooling (d), Tempering With Water Cooling (e)

In Figure 4, it can be observed that there is a difference in the phases formed between the raw material and the sample that has undergone the homogenization process at a temperature of 850°C. In both samples cooled with air and water, no carbides were found at the grain boundaries, and carbon atoms in the carbides have fully diffused into the austenite phase. The homogenization process successfully creates a homogeneous sample with a fully austenite phase. The formation of this phase can enhance the toughness of the sample as it is soft and ductile [18], as proven by the increased tensile strength test results. After undergoing the tempering process, in addition to the austenite phase, other phases such as ferrite, martensite, and carbides are also formed at the grain boundaries. All of these phases are detected in the samples that have undergone the tempering process, whether cooled with air or water. The formation of carbide phases is a result of the repeated heating process conducted on the test samples, while the formation of martensite phase is a result of the austenite phase transformation during rapid cooling [19].

D. GRAIN SIZE

The size and shape of grain structures in the microstructure of a material affect its properties, especially its strength, hardness, and toughness.

Table 2. Grain Size of Hadfield Steel

Sample	**Grain Size (μm)**
Raw Material	5.33
Homogenization Air Cooling	3.81
Homogenization Water Cooling	3.07
Tempering Air Cooling	4.54
Tempering Water Cooling	3.51

In Table 2, it can be seen that the homogenization and tempering processes result in a reduction in the grain size of the samples, from the initial size of 5.33 µm to 4.54 µm for samples cooled with air, and 3.51 µm for samples cooled with water. This is because the high-temperature heating process has a high energy input, resulting in faster cooling rates and smaller grain growth [20]. Based on Table 2, it is also known that smaller grain sizes lead to better sample strength, as found in the research by Arif et al., 2023 [7]. This is further supported by the tensile strength test results, where samples with a grain size of 3.51 μm exhibit higher tensile strength of 941 MPa compared to samples with a grain size of 4.54 μm, which have a lower tensile strength of 791 MPa.

CONCLUSIONS

Based on the test results, it is known that Hadfield steel can be strengthened through a heat treatment process, which includes homogenization at a temperature of 850 ^{0}C and tempering at 600 ^{0}C with a holding time of 30 minutes, followed by hot rolling with a 20% reduction. The data analysis results indicate that the sample that underwent the cooling process using water as a medium produced the most optimum strength, as seen from its tensile strength value reaching 941 MPa with a grain size of 3.51 μm. Although its hardness value of 351.98 BHN is slightly lower compared to the sample cooled with air, the difference is not significant. The metallographic observation results show that there is a phase change in the test sample. Initially, it only had an austenite phase during homogenization, but after undergoing the tempering process, it transformed into austenite, ferrite, martensite, and carbide phases.

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