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Effect of Line-Heating on the Microstructural and Mechanical Characteristics of 320-MPa-Grade High-Strength Hull Plates

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Abstract

This study examined the effect of the line-heating process on the microstructure and mechanical properties of 320-MPa-grade high-strength steel designed for low-temperature applications. The samples were heated thrice to the maximum temperature condition of 900 ℃ prior to air cooling or water quenching. Tensile strength and Charpy impact toughness tests were performed to understand the variation in the mechanical characteristics across the thermal histories. The decrease in the tensile strength of the air-cooled specimen was attributed to grain growth and phase transformation caused by slow cooling, while the water quenched specimen exhibited grain refinement. The experimental results indicated that the line-heating process was suitable because all the specimens with various thermal histories satisfied the international classification standard.

Key Words: High-strength steel, Line-heating test, Tensile strength, Impact toughness.

1. Introduction

Since global environmental regulations have become stricter in recent decades, the shipping industry has steadily increased its focus on alternative fuels for sustainable development, in order to reduce the significant amounts of pollutants and greenhouse gases emitted by traditional marine fuels[1-4]. Several studies have been carried out to develop new energy sources for maritime shipping. For instance, ammonia is a possible alternative fuel which has zero carbon and sulfur content with high hydrogen content[5]. However, several issues, such as high ignition resistance, high toxicity, and the possibility of ammonia slip must be addressed[6]. Hydrogen, which has remarkable environmental benefits as an alternative maritime fuel, also faces a critical challenge in terms of storage techniques for both liquid and compressed hydrogen blocks[7]. Under these circumstances, scientists have started to focus on liquefied petroleum gas (LPG), which has been successfully employed in the automotive industry as an eco-friendly energy source, as an alternative to petroleum[8-10]. Yeo et al. confirmed the feasibility of LPG because of its noticeable combination of advantages in terms of cost savings and eco-friendliness[11]. The explosion characteristics have also been studied to consider the safety of LPG fuel under various physical and chemical conditions[12]. Based on the literature, LPG is believed to have great potential in the shipping industry as an alternative fuel.

Welding, an essential and inevitable process for manufacturing structures, causes microstructural transitions and distortion due to drastic heating and cooling thermal cycles. Major shipyards adopt various kinds of processes for the purpose of correcting distortion[13-15]. Among them, the line-heating method, which utilizes thermal stress in the reverse direction for correcting distortion, has been primarily used because of its effectiveness[16]. The line-heating process can be performed flexibly according to the structural conditions and degree of distortion. However, it is notable that the effect of the line-heating process on the microstructure and mechanical properties is similar to that of post-weld heat treatment (PWHT). As the influence of PWHT on the microstructure and mechanical properties has been observed in high-strength steel plates, detailed analyses and process optimization for the line-heating must be conducted to ensure the structural safety of LPG storage and transportation systems[17].

Since we strongly believe that understanding the influence of the line-heating process is important for increasing the productivity of the shipping industry, this study focused on the effect of process variables in the line-heating process for 320-MPa-grade high-strength steel. The experiment was designed for diverse cooling methods, and the mechanical properties were measured in accordance with international standards. Microstructural analysis was conducted to understand the effect of the line-heating process in detail.

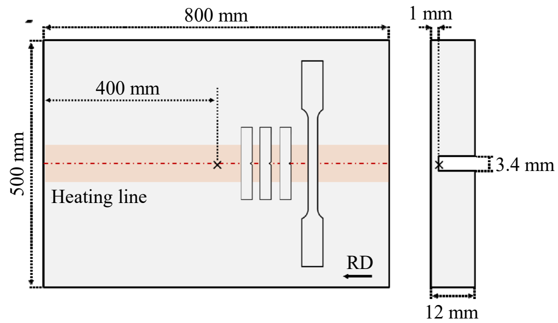
2. Experimental Procedure

To perform the experiments, a carbon steel plates with a thickness of 12 mm were fabricated in line with the international classification standards and IGC code for target service temperatures below -55°C. The chemical composition of the 320-MPa-grade steel used in this study is listed in Table 1.

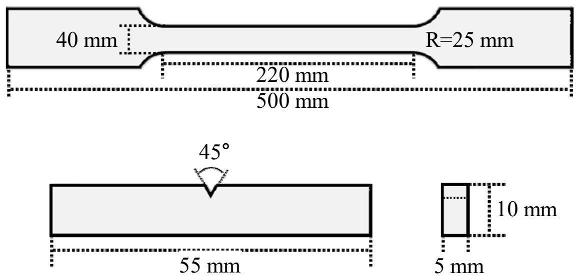
A schematic diagram showing the samples employed for the line-heating experiment is shown in Fig. 1, and the detailed conditions for line-heating process were presented in Table 2. As shown in the figure and the table, the plates were heated thrice using an LPG torch oriented parallel to the rolling direction at the maximum targeted temperature of 900°C prior to air cooling or water quenching.

The actual thermal histories were measured using a temperature recorder (MV1000, Yokogawa, Japan) through a thermocouple installed at the center of the plate 1 mm below the surface, as indicated by the X-marks. The blind hole was machined with a diameter of 3.4 mm.

To analyze the mechanical characteristics, tensile and low temperature Charpy impact toughness tests were adopted. The tensile tests were performed using a commercial tensile stress-strain machine (Z200, Zwick Roell Group, Germany) at room temperature. The Charpy impact tests were carried out at -60°C in line with the ASTM A370 standard using sub-sized V-notched Charpy impact test samples, manufactured from 1 mm below the heating line. The impact direction of the samples was perpendicular to the direction of rolling, and the impact tests were conducted in triplicate for each case after immersing the samples for 20 min in a liquid ethanol bath maintained at -60°C.



(a)



(b)

Fig. 1 (a) A schematic illustration of the steel plate and (b) samples utilized for line-heating experiment

For microstructure analysis, the samples were mechanically polished with SiC paper and a diamond suspension prior to be etched with 2% nitric acid etchant. A commercial optical microscope (DSX510, Olympus, Japan) was used to obtain representative microstructural images.

Table 1 Chemical composition o f the 320-MPa-grade steel plates

Fe	C	Si	Mn	P	S	etc.
Bal.	0.02 ~ 0.12	0.1 ~ 0.5	0.9 ~ 1.6	~0.02	~0.02	Al, Nb, Ti, N

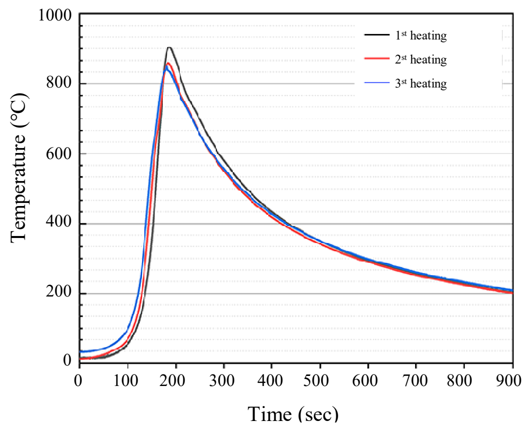
Table 2 Gas and torch conditions for line-heating process

Cooling method	LPG flow rate (l/min)	LPG pressure (kg/cm^2)	O_2 flow rate (l/min)	O_2 pressure (kg/cm^2)	Speed (mm/sec)	Stick-out (mm)
Air	7.3	0.12	24.0	0.9	0.8	20
Water	8.0	0.12	28.0	0.9	0.8	23

3. Results and Discussion

Fig. 2 shows the recorded thermal histories of the line-heating experiments in different cooling methods. As shown in the figure, the samples in both experiments were heated to 900℃ with the same heating rate prior to the cooling thermal cycles. The decrease in peak temperature with the increase in the number of line-heating processes increased was considered negligible because a constant flame condition was used for every heating process. On the other hand, in the cooling thermal cycles, the average cooling rate from the peak temperature to 500℃ was 2.4 and 10.1℃/s for the air-cooled and water-quenched specimens, respectively.

Fig. 3 shows the sub-sized Charpy impact toughness test results for the base metal and samples after the line-heating experiment. The sub-sized testing was employed in this study to obtain the specific toughness value of the heated zone with minimized microstructural inhomogeneity, caused by the plate thickness. According to the international association of classification societies (IACS), the impact toughness of



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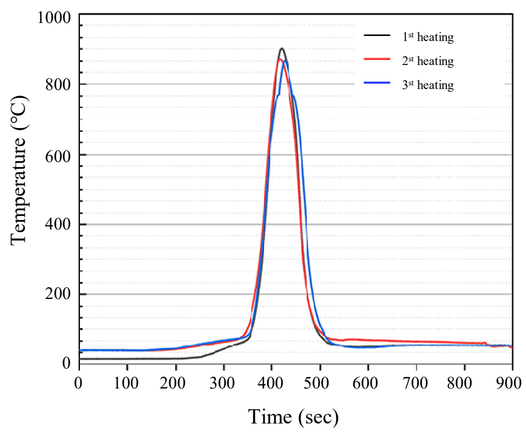

(b)

Fig. 2 Thermal histories of the line-heating experiments under the cooling conditions of (a) air cooling and (b) water quenching

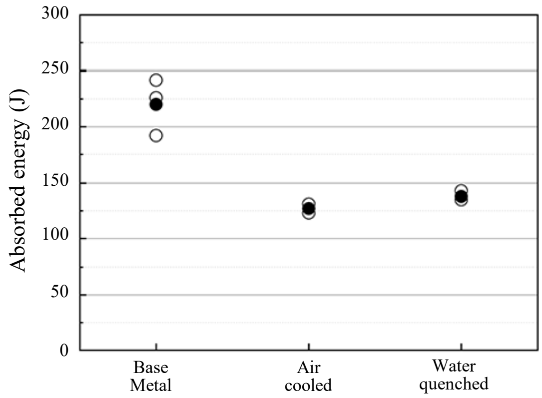

Fig. 3 Impact toughness profiles in base metal and specimens after line-heating at -60℃

320-MPa-grade high-strength steel should exceed 24 J at -60℃ for the full-sized Charpy impact toughness test. Therefore, it is plausible to say that all the toughness standards were satisfied, as shown in the figure, because all the values exceeded the toughness criteria even with the sub-size specimen, while the classification society usually defines the correlation between full- and sub-sized impact toughness values as follows[18-22].

$$E_{full} = 1.5 \times E$$

Table 3 lists the tensile testing results of the specimens. As shown in the table, after the line-heating process, all the tensile properties satisfied the international classification certification standards for 320-MPa-grade high-strength steel, which requires a yield strength of over 315 MPa and a tensile strength between 440 and 590 MPa. Notably, the tensile testing results were quite different depending on the cooling method. The water-quenched specimen had the same tensile properties as the original plate, including the strength and fracturing area. However, relatively low yield and tensile strength values were obtained in the air-cooled specimen compared to the others, and fracturing occurred in the heated zone.

To understand the influence of the line-heating experiment on the mechanical characteristics in detail, a microstructural investigation was carried out. Fig. 4 shows a representative optical micrograph of each specimen,

Table 3 Tensile properties and fracturing area of samples

	Yield strength (MPa)	Tensile strength (MPa)	Fracture area
Original plate	403	496	Base metal
Air cooled	376	485	Heated zone
Water quenched	404	495	Base metal

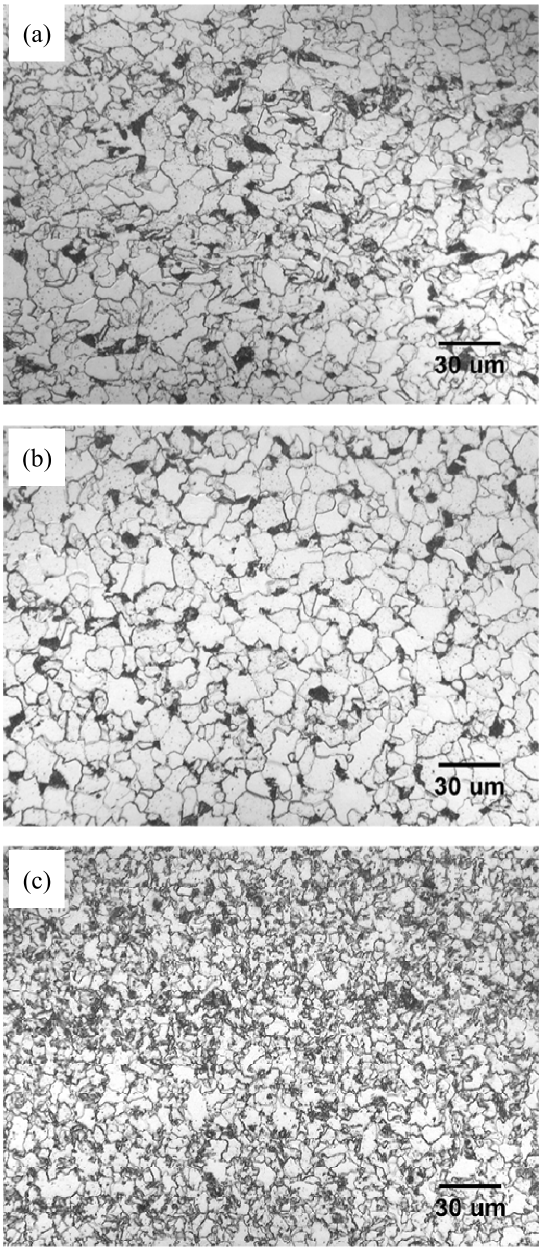

Fig. 4 Representative micrographs in (a) base metal and the samples subjected to line-heating with (b) air cooling and (c) water quenching

obtained at the heating line 1 mm below the plate surface. As shown in the figure, it was obvious that the original steel plate was composed of ferrite and pearlite, and the average grain size was measured as 13.9 μm. A comparison of the microstructures makes it apparent that the cooling methods had manifest influence on the microstructural transitions after the line-heating experiment. In the specimens subjected to air cooling, enlarged polygonal ferrite grains were observed, with an average grain size of 21.8 μm. In contrast, grain size decrement was observed in the specimens subjected to water quenching, with an average grain size of 9.0 μm. Considering the different cooling rates between air cooling and water quenching during the line-heating experiments, the microstructural transition behavior was in agreement with both the results of the mechanical properties and the difference in fracture location. It can be inferred that recrystallization and grain growth occurred during the thermal heating cycle in all cases since the maximum targeted temperature exceeded the minimum temperature for austenite transformation[23]. The pearlite structure must have transformed into austenite during heating and then changed back to pearlite. The final microstructure of the specimen was significantly affected by the cooling rate during the cooling thermal cycles. The slow cooling rate enhanced the grain growth and increased the inter-lamellar spacing of pearlite in the air-cooled specimen, which decreased the strength of the heated zone, according to the Hall-Petch relation[24,25]. Hence, fracturing must be initiated in the heated area during tensile testing. On the other hand, in the water-quenched specimen, drastic grain refinement occurred in the heated zone owing to accelerated cooling rate. It is quite obvious that grain refinement strengthened the heated zone and caused fracturing behavior at the base metal rather than heated zone.

Combining the aforementioned experimental results, we found that the mechanical properties of 320-MPa-grade high-strength steel have a direct relationship with the microstructural transition in the line-heating experiment. While contrasting tensile testing and fracturing results were obtained depending on the cooling method, all specimens satisfied the requirements regardless of the experimental conditions. Therefore, it was conceivable to say that the line line-heating process can be widely employed to design and manufacture in shipping industry using the examined alloy.

4. Summary

In this study, the applicability of the line-heating process was estimated in the 320-MPa-grade high-strength steel. Three thermal heating cycles were performed prior to air cooling or water quenching, and the effect of the cooling method on the microstructure and mechanical characteristics was investigated. In the air-cooled specimen, strength decrement occurred owing to recrystallization and grain growth. In contrast, dramatic grain refinement in the heated zone was observed in the water-quenched specimen. Although the air- and water-cooled specimens had different microstructural transition behavior, it was confirmed that both cases satisfied the international classification standards for shipping industry without severely deteriorating tensile or toughness properties.

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