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The Effect of Cooling Rate on Microstructure and Mechanical Properties of GS20Mn5 Steel Used for Manufacturing of Cast Bogie

Mohammad Hasanpour[1], Amin Owhadi[2*], Seyed Mohammad Ali Boutorabi[1]

[1]School of Metallurgy and Materials Engineering, Iran University of Science and Technology, Narmak, Tehran 16846-13114, Iran

[2]School of Railway Engineering, Iran University of Science and Technology, Narmak, Tehran 16846-13114, Iran

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The GS20Mn5 steel is a low carbon manganese steel used for cast freight bogies manufacturing. The impact toughness of such steels for freight bogie solebars must be at least 17J/cm^2 at -60°C according to GOST32400 standard. In the present work, the effect of cooling rate after the austenitizing at two temperatures on the structure and mechanical properties of GS20Mn5 steel is investigated, including toughness at -60°C. The cooling rate varies from 1 to 5.4°C/Sec. The optimum toughness and strength are observed after two hour austenitizing at 930°C and quenching rate of 2.8°C/Sec where the impact energy mean values reached 32J/cm^2 at -60°C.

1. Introduction

Manganese low-carbon cast steel is one of the steels used to produce bogie frames of freight railway wagons [1, 2]. The use of these bogies at temperatures below 0°C indicates the role of toughness in the final properties of this steel. According to GOST32400-2013, the toughness of 20GL steel must be at least 17 J/cm^2 at -60°C [3].

Heat treatment, one of the essential steps in the production of casting bogies, helps improving the mechanical properties, (in particular toughness) [4]. In addition, factors such as chemical composition, non-metallic inclusion and casting defects, have significant effects on toughness [3, 5, 6].

Some researchers have studied the heat treatment of these steels including normalization, normalization with tempering, double normalization with tempering, double quenching with tempering, volume–surface quenching (VSQ) and controlled cooling in the air stream [7-10].

Normalization is an effective way to improve the microstructure and mechanical properties of low-alloy and low-carbon steel. The casting steel is usually normalized by heating within the range of 30 to 50°C above the A_{c3} line, holding it for a certain time and cooling by air. The final structure of normalizing on manganese low-carbon cast steel (20GL steel) is ferrite-perlite, which suffers from the segregation of alloying elements and non-uniform microstructure. In order to eliminate these defects for a better performance of bogie, tempering is usually employed after normalizing [11-13]. It is important to achieve high strength and toughness simultaneously at low temperatures which is

*Corresponding author, Assistant professor
Email: aohadi@iust.ac.ir

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extremely difficult through the conventional heat treatment methods such as normalization and tempering.

In double normalization with tempering treatment, the steel is cooled from both austenite and two-phase regions, followed by the tempering. This results in the formation of polygonal ferrite, spheroidised pearlite and tempering sorbite in the steel, which improves its impact properties [7].

Double quenching with tempering is another heat treatment method in which steel is first quenched from the austenite region and then from the two-phase region by water before the tempering. This treatment results in the formation of a disperse and fine structure consisting of quasi polygonal acicular ferrite and spheroidized cementite. Bagmet et al [7] showed that this three-stage heat treatment improves the impact strength at low temperatures, such that at –60°C the impact strength of the charpy samples is no less than 24.5 J/cm^2.

In volume–surface quenching, the casting is cooled with the water spray. As a result, a gradient structure is formed across the wall consisting of a hardened martensite-like surface layer and a ductile core with a lamellar perlite structure [14-18]. The main difference between the fracture surfaces of steel in the normalized state and the state after VSQ is the type of fracture facets. The fracture surfaces after VSQ are substantially more ductile and characterized by a mixed ductile-brittle fracture with predominant quasi-cleavage facets and a slightly higher fraction of a ductile component [3].

Vainshtein et al [10] investigated the effect of soaking temperature and air cooling rate on 20GFL steel. Slow cooling rate leads to the formation of structural inhomogeneity, carbide precipitation, and impoverishment of austenite with respect to carbon, which forms a pearlitic network over austenite grain boundaries reducing impact strength. Although increasing the cooling rate facilitates the conversion of the austenite into the lower bainite region. This increases in impact strength during the cooling.

In this study, the effect of cooling rate after the austenitizing on the structure and mechanical properties of the GS20Mn5 steel at two temperatures are investigated.

2. Materials and Experimental Methods

2.1. Casting

To make GS20Mn5 steel, melting is carried out in a 5-ton induction furnace using steel scrap, FeSi, medium carbon and low sulphur FeMn, and low carbon FeCr. Subsequently, aluminum was added to the ladle in order to deoxidize the steel. Finally, keel block castings were prepared in sand-clay molds. The chemical composition of the steel is given in Table 1.

2.2. Heat Treatment

2.2.1. Determination of Cooling Rate after Austenitizing Treatment

The cut-out specimens from the keel blocks (170×20×20 mm) were heated in a furnace at 880°C and 930°C for two hours and then cooled at different environments to reach the room temperature. The cooling conditions are shown in Table 2 and Figure 1. Figure 2 shows the cooling channel apparatus schematically.

To determine the cooling rates of the specimens from the austenitizing temperature to 650°C, a thermocouple was inserted into the hole at the end of the specimens. The temperature is recorded as a function of time through a data logger.

2.3. Evaluation

2.3.1. Metallography

The specimens are etched in 2% nital solution for 10 to 12 seconds. ImageJ software is used to determine the percentage of ferrite, pearlite structures, and their sizes.

VEGA//TESACAN Scanning electron microscope equipped with an EDAX analyzer is used to investigate metallographic specimens. The fracture surfaces resulting from the impact testing are analyzed by using this system.

2.3.2. Mechanical Properties

A. Impact test

V-notched impact test specimens with the dimension of 10 x 10 x 55 mm are prepared from keel block castings according to State Standard GOST 9454-78. For each case, three specimens are tested and the results are averaged. All impact tests are performed at–60°C. The temperature is adjusted by using Cryo Porter CS-80C apparatus.

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Table 1. Chemical composition of GS20Mn5 samples, wt %

C	Mn	Si	P	S	Cr	Mo	Ni	Al	Cu	Pb
0.18	1.0	0.56	0.026	0.016	0.14	0.027	0.03	0.063	0.065	0.04

Table 2. Heat treatment conditions

Austenitizing temp. (°C)		Time (hr)	Air velocity (m/s)	Humidity (%)
880	930			
A1	A2	2	-	-
B1	B2	2	9	50
C1	C2			70
D1	D2			90

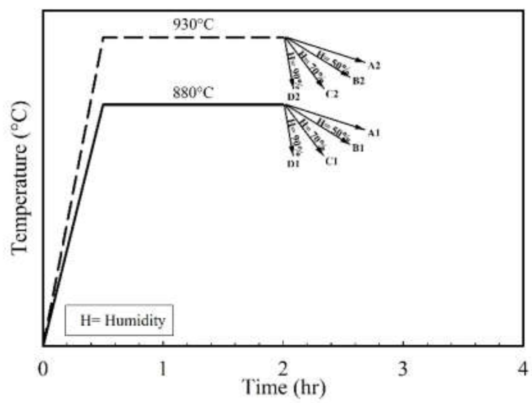

Figure 1. Heat treatment conditions applied to the steel specimens

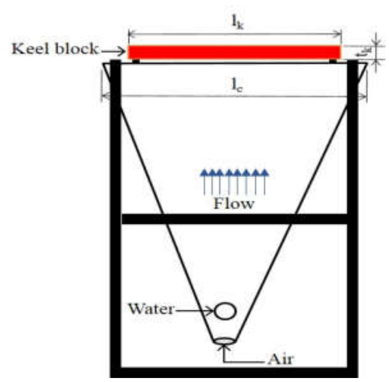

Figure 2. Schematic view of the cooling channel

B. Tensile test

Tensile specimens with a diameter of 5 mm and an initial length of 25 mm are prepared from keel block castings according to GOST 1497-84. For each case, three specimens are tested and averaged.

C. Hardness

Hardness testing is carried out according to the Vickers method with a 10-kg load on a Testor-2RC automatic system. For each case, three specimens are tested and averaged.

3. Results and Discussions

3.1. Cooling Rate from Austenitizing Temperature

The cooling rate of the specimens heated at temperatures of 880°C and 930°C for 2 hours until the temperature dropped to 650°C is shown in Figure 3. Initially, the cooling rate is very fast, but after a very short period of time, the difference in cooling rates that is resulted from different cooling environments become apparent.

Specimens cooled in normal air have a low cooling rate of about 1 °C/s. But the other specimens that are cooled in forced air with different humidity percentages have a higher cooling rate, varying in the range of 2.5–5.4°C/s. From the results that are presented in Figure 4 it can be observed that the cooling rate slightly increases with increasing austenitizing temperature from 880 to 930°C.

3.2. Mechanical Properties and Microstructures

The mean values of yield strength, ultimate tensile strength, and elongation and hardness of the steel are presented in Figures 5 to 7. It is observed that the strength of GS20Mn5 steel increases by increasing the humidity percentage (or cooling rate) with a slow slope, but the hardness increases with a steeper slope.

The increase in strength and hardness is primarily explained by the steel microstructure. The microstructure of GS20Mn5 steel has a non-uniform distribution of pearlite and ferrite regions. Colony of pearlite is located at the cell boundaries and single ferrite is located at the centers of cells, as carbon is rejected to the cell boundaries during the solidification [19].

Figures 6 and 7 also present the influence of cooling rate on the content and size of the pearlite and single ferrite. As the cooling rate increases, a few characteristics change in the

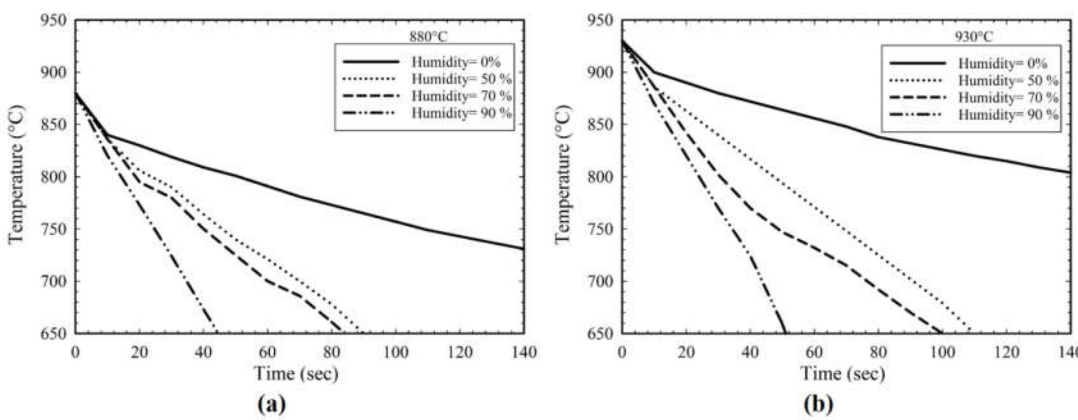

Figure 3. Influence of humidity and air blowing on the cooling rate of the specimens after the austenitizing at (a) 880°C; (b) 930°C

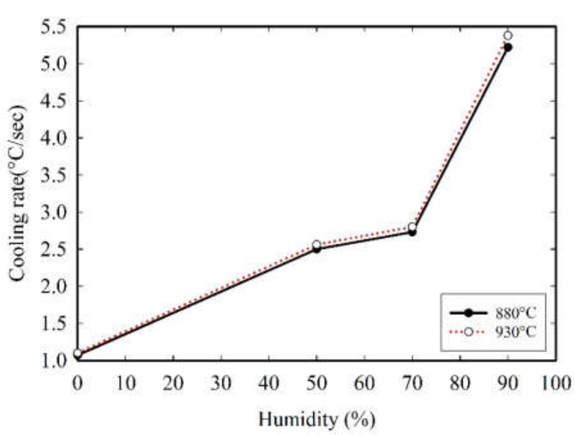

Figure 4. Relationship between the moisture content and cooling rate of specimens at two austenitizing temperatures (880 and 930°C)

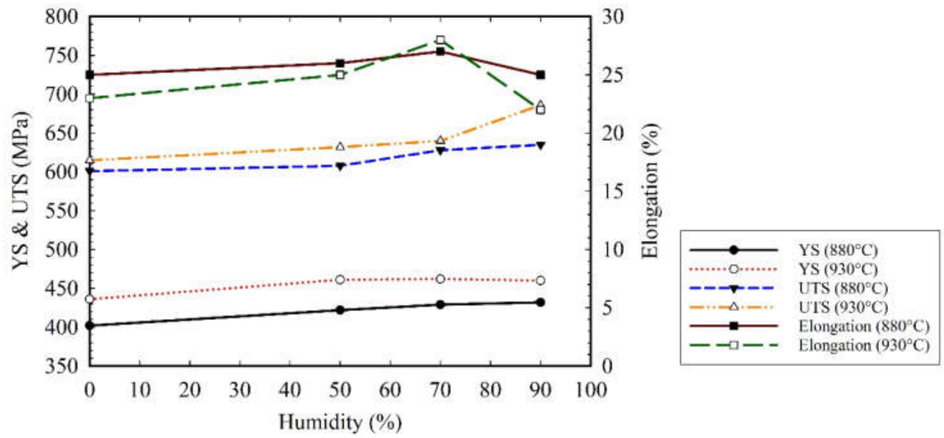

Figure 5. The effect of cooling rate on the tensile properties of GS20Mn5 steel at two austenitizing temperatures (880 and 930°C)

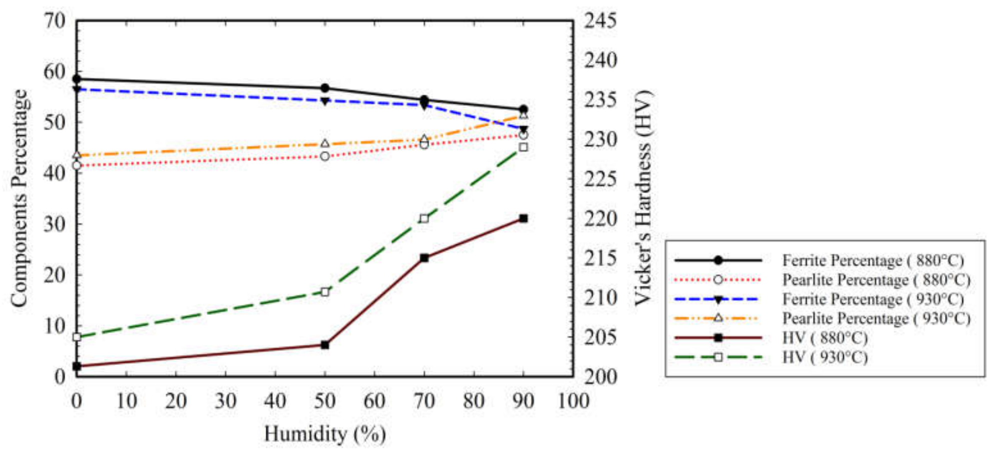

Figure 6. The effect of cooling rate on the amount of microstructural components and hardness of GS20Mn5 steel at two austenitizing temperatures (880 and 930°C)

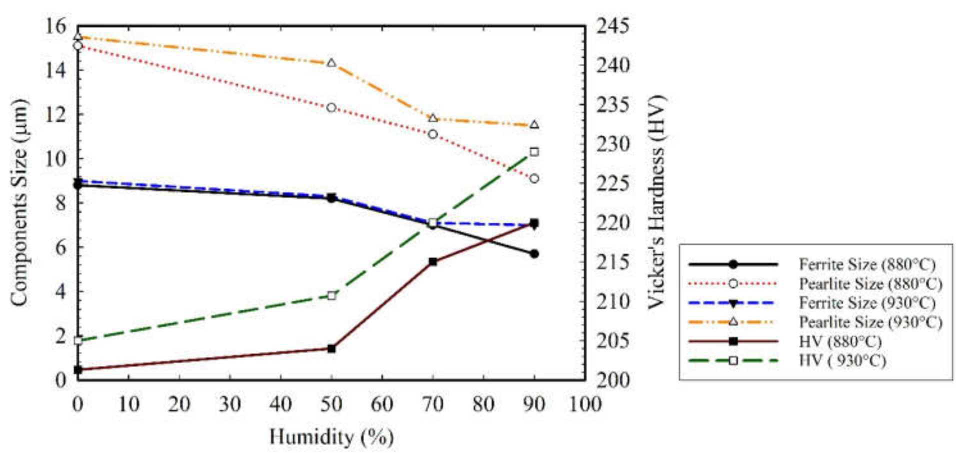

Figure 7. The effect of cooling rate on the size of microstructural components and hardness of GS20Mn5 steel at two austenitizing temperatures (880 and 930°C)

structure occur. These are the events that are capable of increasing the strength and hardness of the specimens, including increase in the volume of pearlite colonies and reduction in the volume of single ferrite, size of the pearlite colonies, and size of the single ferrites.

Figure 8 presents the microscopic structure of specimens that were austenitized at 880°C and cooled at different rates. It is observed that as the moisture content of the cooling medium increases, the size of the single ferrite and pearlite colonies becomes smaller, the pearlite content increases and the ferrite content decreases.

The morphology of pearlite also affects the mechanical properties. Calik has reported that when the steel is cooled at slower rates, carbon can diffuse relatively far and the spacing of the carbon rich phase Fe_3C is greater. The resulting pearlite is called coarse pearlite. When steel is cooled at a faster rate, carbon can diffuse only a short distance to result fine pearlite in carbon steels [20]. Figure 9 presents that as the cooling rate increases, the interlayer distance in the pearlite colonies decreases and the coarse pearlite gradually becomes fine perlite. This is also a factor that improves the strength and hardness of the steel. As an example, the structure of pearlite in GS20Mn5 steel after austenitizing at 880 C is presented in Figure 10. The structure of pearlite in a specimen cooled with the forced air at 70% humidity is finer than that of cooled with still air.

When the specimens are austenitized at 930°C, the strength and hardness of the steel are greater than austenization at 880°C (Figures 5 and 6) because the cooling rate is slightly higher at the higher temperature (Figure 4). Therefore, the higher cooling rates lead to the increase in the volume of the pearlite (Figure 6) in addition to reduction in the volume of the single ferrite (Figure 6), the size of the pearlite colonies (Figure 7), the size of the single ferrite (Figure 7), and the thickness of the layers of ferrite and cementite in pearlite colonies (Figure 9). These changes result in the strength and hardness enhancement.

The mean values of the impact energy of GS20Mn5 steel at -60°C is presented in Figure 11. Based on Figures 11 and 4, as the cooling rate increases from 1 to 2.8°C/Sec, the impact energy of the steel improves by approximately 47%, but as the cooling rate increases to 5.3°C/Sec, the impact energy decreases sharply. Similar to the impact energy of steel, the elongation increases with increase in cooling rate up to 2.8°C/Sec and then deteriorates.

One of the most important mechanical properties of cast bogie solebars is their impact toughness, determined according to GOST32400 which declares that the impact toughness of steel used to produce freight bogie solebars; must be at least $17 J/cm^2$ at -60°C. Therefore, if the cooling rate of GS20Mn5 steel is increased to 2.8 °C/Sec, the impact energy can drive 76% beyond the required minimum.

Several factors can explain the improvement in the impact energy (Figure11) due to the increasing cooling rate. The distribution of the pearlite and single ferrite becomes more uniform as shown in Figure 8. At the same time, the pearlite colonies become smaller (Figure 7) and lose their elongated morphology.

As the cooling rate increases, the thickness of the ferrite and cementite layers in the pearlite colonies decreases (Figure 9). Although reduction in the thickness of the ferrite layers in the pearlite structure degrades the impact toughness, simultaneous reduction in the thickness of the cementite layers improves it [19].

In principle, the high volume fraction of the pearlite decreases the ductility and impact toughness [19]. The increase in the pearlite due to increasing the cooling rate (Figure 6) reduces the impact energy. When factors increasing the impact energy are dominant, the toughness increases otherwise it decreases. Therefore, the changes in the impact energy (Figure 11) is due to the competition between these factors. The fracture surface of these specimens are presented in Figure 12. The fracture morphology can accurately reflect the fracture mode of the entire impact fracture. In the air-cooled specimens, the fracture mechanism is ductile with the predominant quasi-cleavage regions. The low fraction of a ductile component is mainly represented by small dimples surrounded by the quasi-cleavage regions (Figure 12(a)). When the humidity content reaches 50%, the fraction of the ductile component increases in the form of small dimples while the quasi-cleavage regions decrease (Figure 12(b)). As the humidity increases by up to 70%, small and large dimples in the fracture surface increase (Figure 12(c)).

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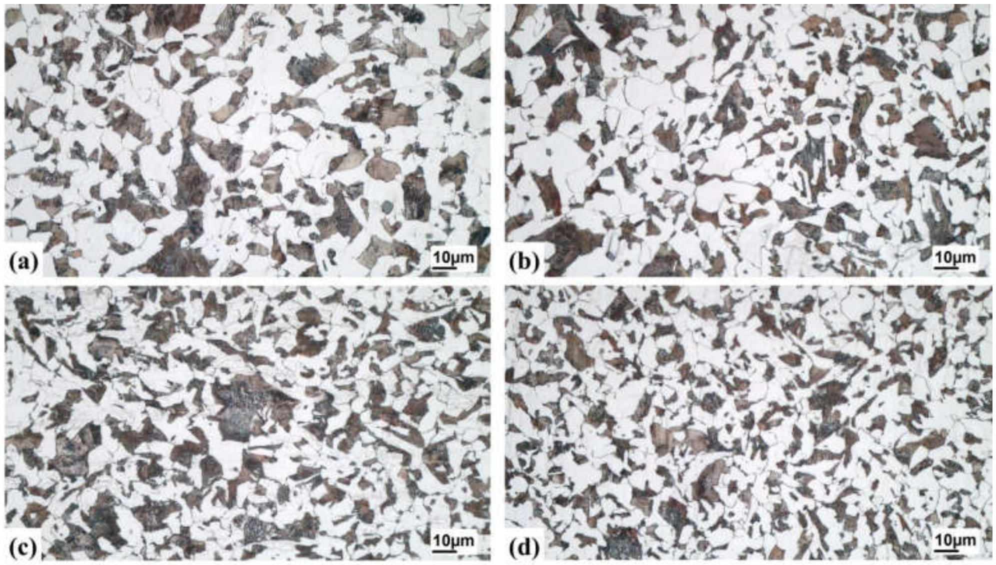

Figure 8. Microstructure of specimens (a) cooled by still air; (b) cooled by forced air with 50% humidity; (c) cooled by forced air with 70% humidity; (d) cooled by forced air with 90% humidity

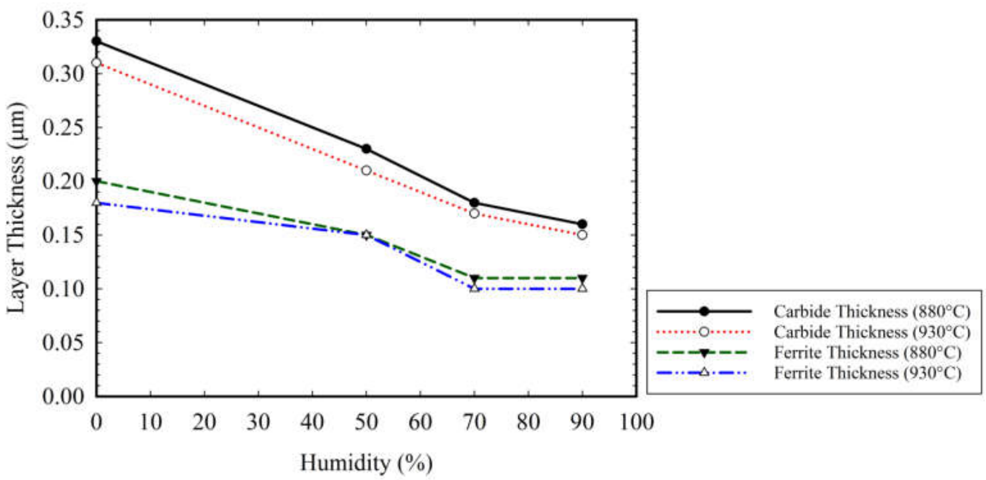

Figure 9. The effect of cooling rate on the thickness of ferrite and cementite layers in pearlite colonies

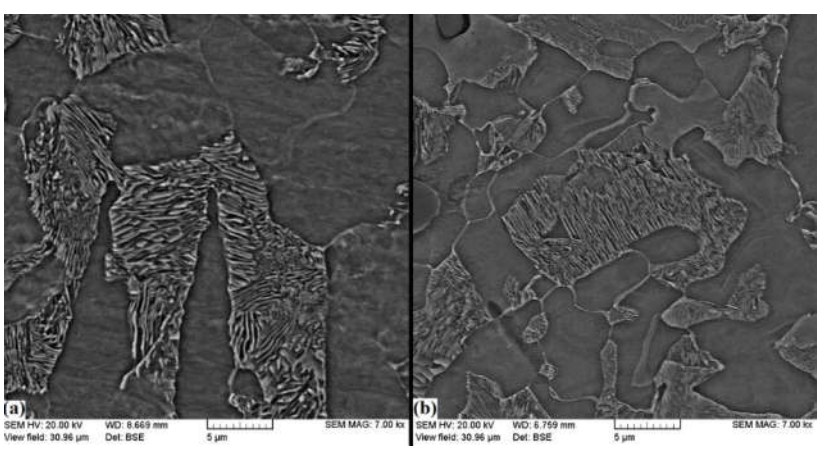

Figure 10. Pearlite structure of specimens austenitized at 880°C and (a) cooled with still air (b) cooled with forced air with 70% humidity

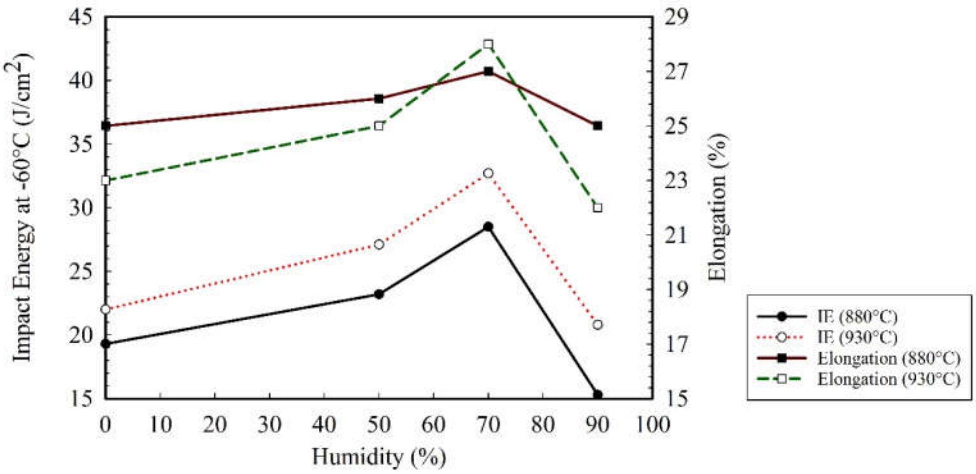

Figure 11. The effect of cooling rate on the impact energy (at -60°C) and elongation of GS20Mn5 steel at two austenitizing temperatures (880 and 930°C)

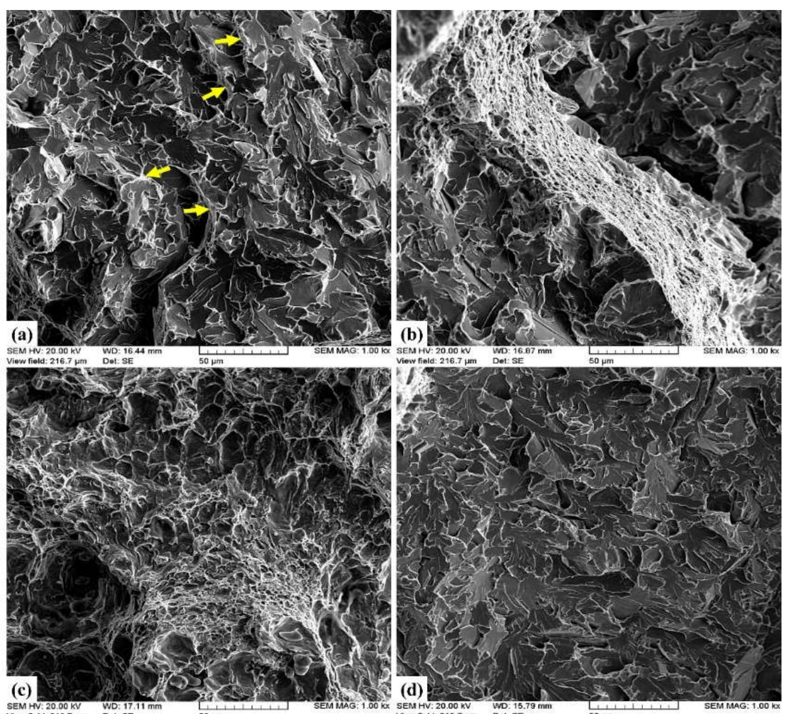

Figure 12. Fracture surfaces of a GS20Mn5 steel specimen austenitized at 930°C and cooled at different rates (a) cooled by still air; (b) cooled by forced air with 50% humidity; (c) cooled by forced air with 70% humidity; (d) cooled by forced air with 90% humidity (small dimples indicated by arrows)

Subsequently, as humidity is increased to 90%, the quasi-cleavage areas with smaller dimensions develop (Figure 12(d)).

As the austenitizing temperature increases, it is possible to grow austenite grains which leads to a more uniform carbon distribution in the grains contributing to the uniform distribution of the pearlite and ferrite in the structure [20, 21]. Therefore, austenitizing at 930°C changes the distribution of the ferrite and perlite in the structure and makes it more uniform relative to austenitizing at 880°C. Also, the thickness of the cementite layer in the pearlite colonies is lower at 930°C (Figure 9). Thus, the impact energy and

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ductility of GS20Mn5 steel austenitized at 930°C are higher (Figure 11).

4. Conclusions

In this study, the effect of cooling rate after the austenitizing on the structure and mechanical properties of GS20Mn5 steel that is used for the manufacturing of cast bogies at two temperatures was investigated. Here are the highlights of the findings:

- GS20Mn5 steel structure composes of pearlite colonies and single ferrite.
- As the cooling rate increases, the volume of the pearlite colonies increase while the volume of the single ferrite decrease.
- As the cooling rate increases, the size of the pearlite colonies and single ferrite decreases.
- As the cooling rate increases, the morphology of the pearlite changes from an elongated to a non-elongated shape with a uniform distribution.
- As the cooling rate increases, the pearlite structure becomes finer.
- Increasing the austenitizing temperature has almost the same effects as increasing the cooling rate on the steel structure.
- As the cooling rate increases, the hardness and tensile properties of GS20Mn5 steel increase.
- As the cooling rate increases, the toughness and ductility of the steel increase initially but start decreasing at a certain point.
- As the temperature of the austenitizing increases, the toughness and ductility of the steel increase.

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