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Physical simulation on Joining of 700 MC steel: A HAZ and CCT curve study

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Keywords: gleeble, CCT, CGHAZ, microstructure, 700 MC steel

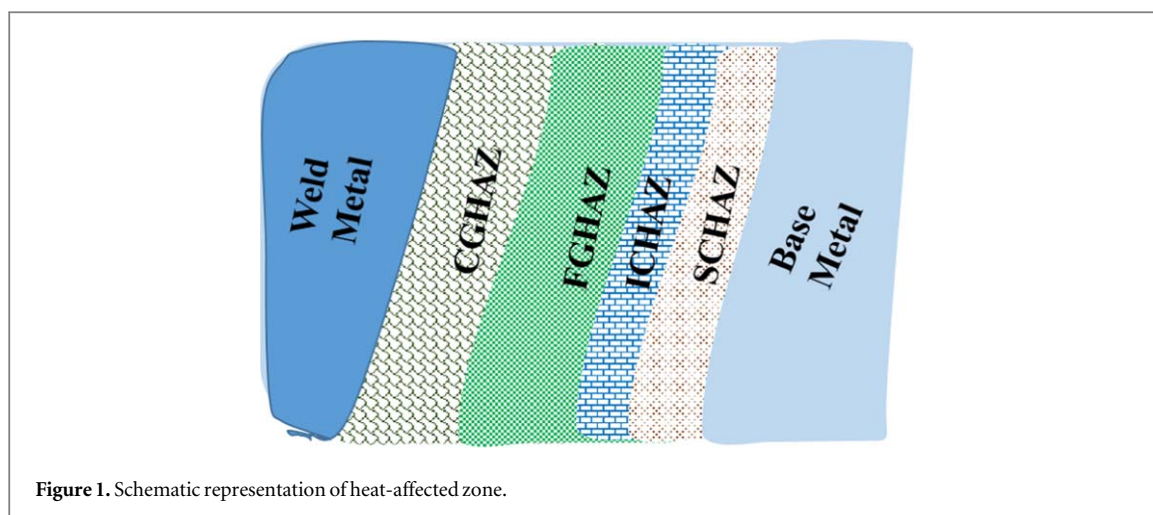
Abstract

In the present work, coarse grain heat-affected zone (CGHAZ) was simulated by Gleeble 3800 thermo-mechanical simulator. A continuous cooling transformation (CCT) diagram was generated from the results of the dilatometer, hardness, and microstructure analysis. The heating rate of $100\text{ }^{\circ}\text{C s}^{-1}$, the peak temperature of $1300\text{ }^{\circ}\text{C}$, the holding time of one second, and thirteen different cooling conditions representing the actual welding condition were chosen here for simulation where the cooling rate was controlled by $t_{8/3}$. At slow cooling rate ferrite, cementite, pearlite, and bainite were obtained. At a medium cooling rate, ferrite, bainite, and a small amount of martensite were observed. At a fast-cooling rate i.e., $100\text{ }^{\circ}\text{C s}^{-1}$ fully martensite was obtained. The obtained hardness values were 225 HV, 263 HV, and 342 HV for slower, medium, and fast cooling rates respectively. The increase in hardness value shows that the amount of non-diffusional phases increases with an increase in cooling rate. The CCT curve shows the range of cooling rate and phase transformation temperature of ferrite, bainite, and martensite.

1. Introduction

In the modern age, lightweight steels are in demand due unique features such as their eco-friendly and highly efficient nature. Due to these features, high-strength steel is generally used in building cranes, containers, ships, and steel plates [1]. In this experiment, 700 MC steel is used which is produced by the thermomechanical rolling process. The steel consists of good strength and toughness with a yield strength of 700 MPa. The presence of fine-grain pearlite and a few amounts of bainite provide adequate strength and formability. In addition, to increase the strength of steel precipitation hardening is done with the help of Nb carbonitrides and a small amount of Ti carbides [2].

The original microstructure obtained from thermomechanical controlled processing changes within the heat-affected zone (HAZ) due to the thermal cycle of welding [3]. The heat-affected zone contains four major subzones, such as coarse-grained heat-affected zone (CGHAZ), fine grain heat-affected zone (FGHAZ), intercritical heat-affected zone (ICHAZ), and subcritical heat affected zone (SCHAZ) [4–6]. The CGHAZ forms near the fusion line where the temperature goes above $1250\text{ }^{\circ}\text{C}$. FGHAZ is formed after CGHAZ where the peak temperature goes above $1050\text{ }^{\circ}\text{C}$. The region after FGHAZ which is partially recrystallized is called ICHAZ. It generally experiences a peak temperature greater than $750\text{ }^{\circ}\text{C}$ [7]. The last region after ICHAZ is called SCHAZ [8]. The mechanical property of steel is highly dependent on cooling rate and peak temperature. Because, in slow cooling conditions austenite transforms to ferrite and pearlite, but in the fast-cooling condition it transforms into bainite and martensite. In the arc welding process, within the CGHAZ, austenite transforms into various product phases depending on the heat input [9]. The transformation of austenite into different phases at different cooling rates has its own importance in practical application. In actual HAZ, it is a tricky task to



distinguish between different subzones to analyze their behaviour on different cooling rates due to inclined nature and non-homogeneous microstructure distribution [10]. Hence, in earlier works, many researchers have performed HAZ simulation by Gleeble thermomechanical simulator to obtain homogeneous microstructure and found that it is an efficient and reliable technique to generate the CCT diagram [11]. Figure 1 shows a schematic representation of different heat-affected zone of arc welding.

Out of the above zones, CGHAZ is nearest to the weld pool and experiences the highest temperature and dissolution of precipitates [4]. Hence, the amount of prior austenite grain boundary decreases, grains become coarsen, which makes the nucleation of diffusional phases like ferrite and pearlite difficult and enhances the generation of detrimental non-diffusional phases like bainite and martensite [12, 13]. This facilitates grain coarsening, reduces toughness, and increases the hardness value. Due to the above-mentioned reasons, CGHAZ is the most critical, highly sensitive, and weak portion of an arc-welded joint [14]. CCT diagram of CGHAZ provides information about phase transformation over a wide range of cooling rates, which helps to optimize the welding heat input to obtain the desired microstructure for a particular application [15]. Kumar *et al* performed a thermal physical simulation of reheated coarse grain heat-affected zone and concluded that multi mass welding helps to improve the mechanical properties of the welded joint [16].

Welding is a suitable joining process in structural application. Previous literatures already reported the degradation of tailored properties and microstructure due to the welding thermal cycle in the joining of 700 MC steel [17, 18]. Hence, understanding the phase transformation behaviour and optimization of heat inputs is essential to obtain adequate strength and toughness of the weld. Since the thermal cycle generated in weld CGHAZ differs from the thermal cycle generated during heat treatment, the CCT curve drawn for the heat treatment process is not applicable in welding. Therefore, this study aims to understand the transformation behaviour in CGHAZ of 700 MC steel under different cooling rates and to generate a CCT diagram based on the result of dilation, hardness, and microstructure.

2. Materials and methods

Cylindrical samples of 6 mm in diameter and 71 mm in length (perpendicular to the rolling direction) were used here for dilatometry experiments (figure 2). The samples were prepared by wire EDM from a 10 mm thick 700 MC steel plate. Table 1 shows the chemical composition of 700 MC Steel, determined by optical emission spectroscopy.

A K-type thermocouple was welded at the mid-length of the cylindrical sample to measure the instantaneous temperature. Then the sample is placed inside the sample holder of Gleeble 3800. A LVTD (Linear Variable Displacement Transducer) dilatometer was attached at the midsection to record dilatation change during simulation. Vacuum pressure of approximately 10^{-3} torr was maintained during HAZ simulation. Input parameters (heating rate, 800 °C to 300 °C cooling time($t_{8/3}$), peak temperature, and peak temperature holding time) were inserted into the Gleeble software. The experiment started after reaching the required vacuum level. A similar procedure was followed for every sample.

The test specimens were heated linearly at 100 K s^{-1} up to 1573 K (peak temperature) and held there for 1 s. During actual welding, the temperature of CGHAZ goes above 1300 °C. Therefore, 1573 K was selected here as peak temperature which represents the temperature distribution in CGHAZ during actual welding. The cooling rate is decided based on the value of $t_{8/3}$. In this investigation, thirteen cooling rates (100, 62.50, 50, 33.33, 25,

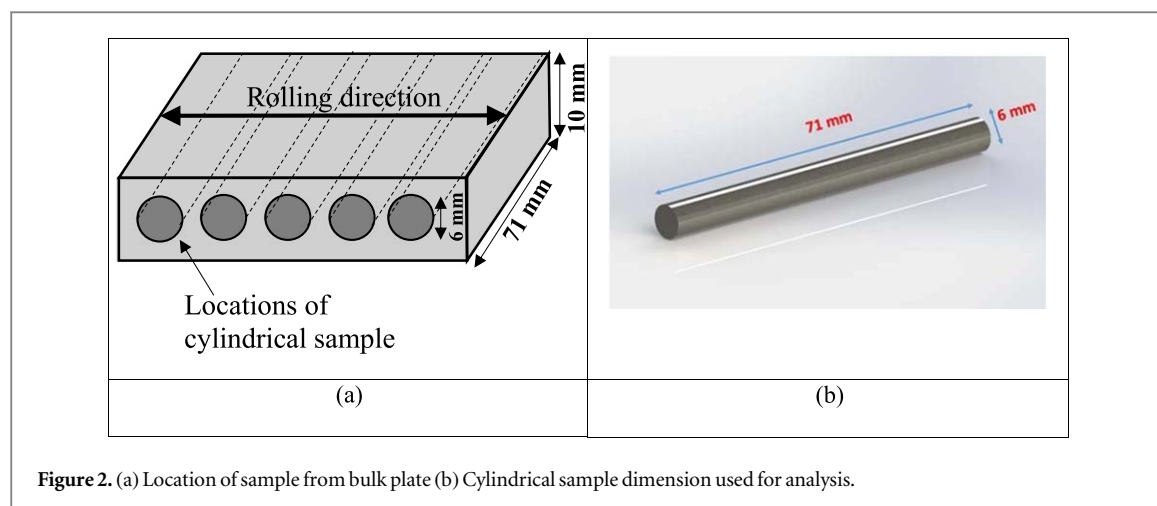


Table 1. Chemical composition of 700 MC steel.

Sample details	C	Mn	P	Si	Al	Cu	Cr	Ni	V	Nb	Ti	Fe
700 MC	0.065	1.82	0.012	0.015	0.025	0.0115	0.025	0.037	0.014	0.053	0.102	Balance

16.67, 10, 8.33, 6.67, 5.00, 3.33, 2.50, and $1.25\text{ }^{\circ}\text{C s}^{-1}$) were employed and the Ryklin-3D heat-transfer model suitable for thicker section was used [19].

3. Results

3.1. Dilatometry curve

Dilatometry graphs were created by the instantaneous data of temperature and strain (dL/L_0) obtained by thermocouple and LVTD type dilatometer respectively during HAZ simulation. Temperature and dilation data were plotted along the X and Y-axis respectively. The tangent method was used to find the austenite start (A_{c1})-finish (A_{c3}) temperature and phase transformation start (A_{r3}) and finish (A_{r1}) temperatures during the heating and cooling thermal cycle respectively [4]. Figure 3(b) shows the tangent method of phase transformation temperature determination. During the heating process, the contraction occurs due to the transformation of BCC ferrite (atomic packing factor = 0.68) to FCC austenite (atomic packing factor = 0.74). Similarly, during cooling expansion occurs due to ferrite to various products (ferrite, bainite, martensite) phase transformation. The gradual expansion (before A_{c1} & after A_{c3}) during heating and gradual contraction (before A_{r3} & after A_{r1}) during cooling occur due to thermal expansion and contraction receptively [13]. Since the conversion of austenite into product phases is cooling rate dependent, the first derivative analysis of the cooling curve is performed to get this information [20–22]. But, the removal of noise is essential to get a smooth derivative curve. So, a low pass filter was used here to smoothen the dilatometry curve. The peak of the first derivative curve represents the phase transformation and its corresponding temperature.

As the cooling rate lowered, A_{r3} shifted towards a high temperature. It is well known that the formation of diffusional phases like ferrite and pearlite occurs at a higher temperature during slow cooling conditions. Whereas formation of diffusion-less phases like Bainite and Martensite occur at lowered temperatures during the fast cooling condition. When the cooling rate increases, the tendency for diffusion-less transformation increases and the transformation temperature of such phases is much lowered than diffusional phases. Therefore, both the transformation starts and transformation completion temperature shift towards lower temperature at a high cooling rate. The cooling curves and their first derivative curve as shown in figure 3 clearly shows the shifting of A_{r3} towards high temperature with decreasing of the cooling rate. The average value of A_{c1} and A_{c3} temperatures are $729\text{ }^{\circ}\text{C} \pm 10\text{ }^{\circ}\text{C}$ and $943\text{ }^{\circ}\text{C} \pm 9\text{ }^{\circ}\text{C}$ respectively.

3.2. Microstructure

Figure 4 shows the SEM microstructure of the base material of 700 MC steel. The microstructure contains fully polygonal ferrite and a small amount of carbide.

Figure 5 shows the optical micrographs of the coarse-grained heat-affected zone obtained after simulation of the test sample at different cooling rates. At a slow cooling rate ($1.25\text{ }^{\circ}\text{C}-5\text{ }^{\circ}\text{C s}^{-1}$), the different diffusional

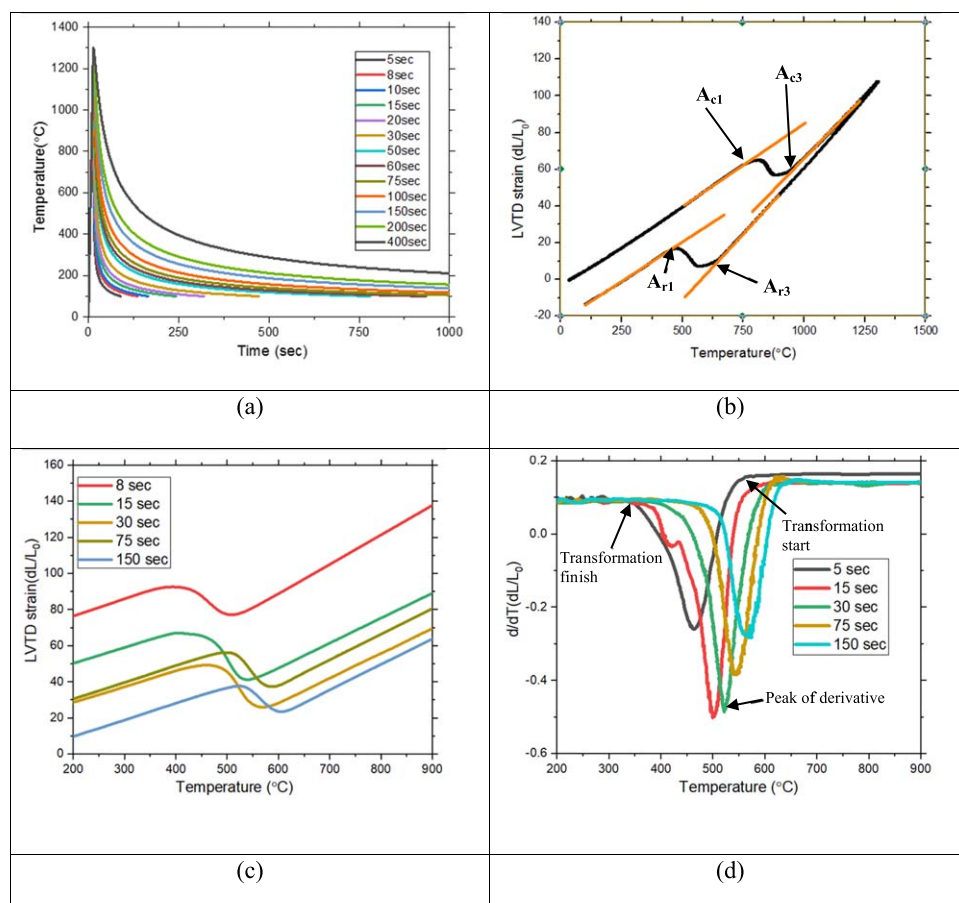


Figure 3. (a) Programmed cycle (b) tangent method (c) cooling curve (d) first derivative curve.

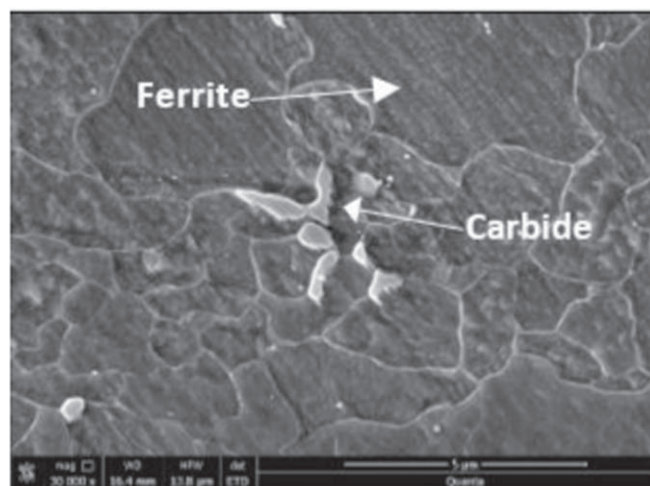


Figure 4. SEM image of the base material.

phases present are ferrite, bainite, and pearlite. The presence of the above microstructure was visible in SEM images of $1.25\text{ }^{\circ}\text{C s}^{-1}$ as shown in figure 6(e). Evidence of ferrite, cementite, and pearlite was found at the slowest cooling rate, but the fraction of pearlite is small as compared to ferrite and cementite. At a slower cooling rate, a longer incubation time is required for the nucleation of product phases as compared to faster cooling rate. It helps in nucleation of ferrite and pearlite at slow cooling condition [4].

At a medium cooling rate ($5\text{ }^{\circ}\text{C} - 25\text{ }^{\circ}\text{C s}^{-1}$), ferrite, bainite, and martensite were obtained as the final product after transformation. Which is a combination of both diffusional and diffusionless phases. At $8.33\text{ }^{\circ}\text{C s}^{-1}$, a

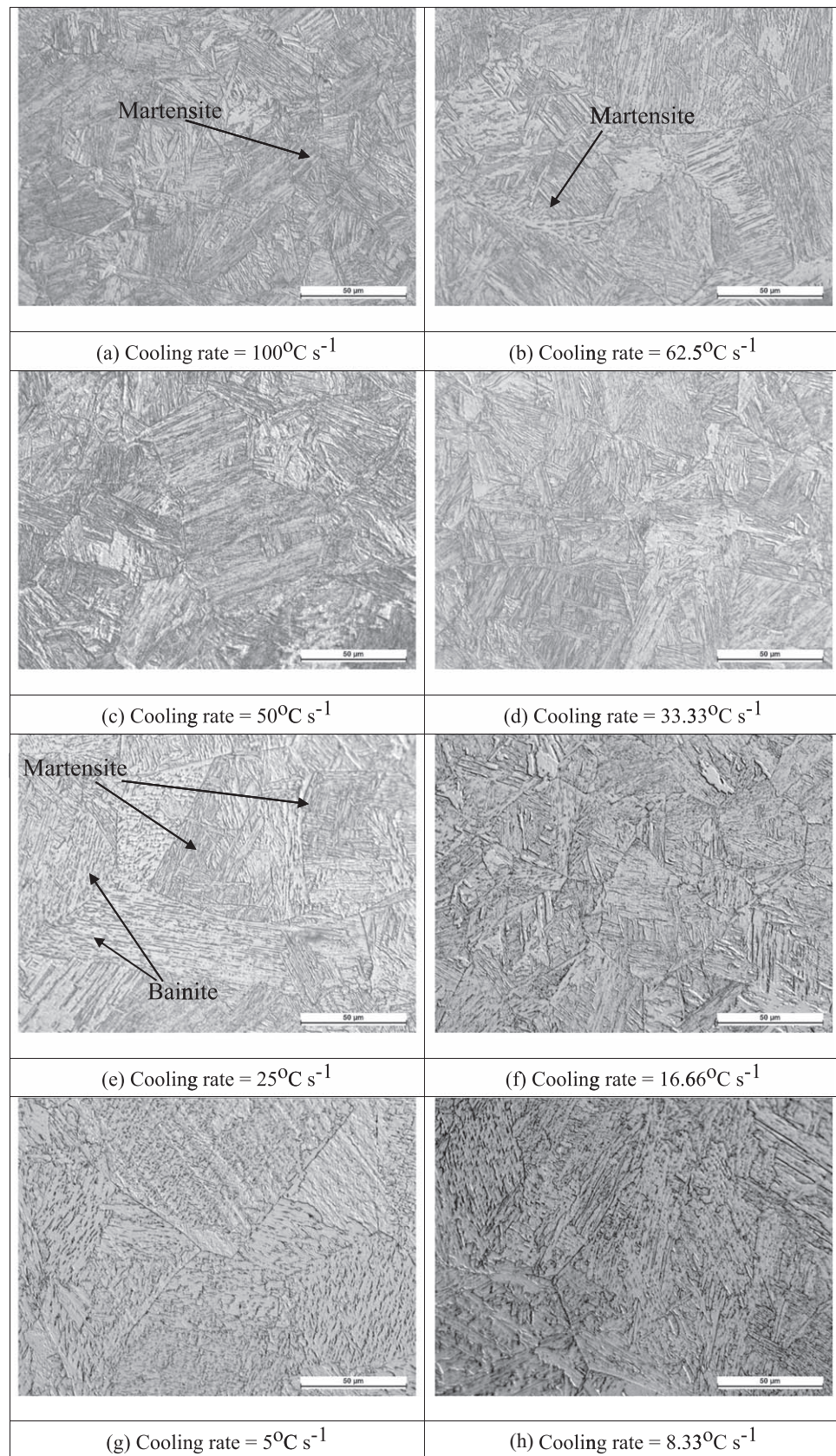


Figure 5. Optical micrographs of 700 MC steel at different cooling rates.

mixed microstructure of ferrite and bainite was observed, but the major portion was bainite. Hence, we can conclude that it is the ideal cooling rate for bainite formation. SEM image of $25^{\circ}\text{C s}^{-1}$ shows carbide precipitates inside ferrite grains which may be lower bainite.

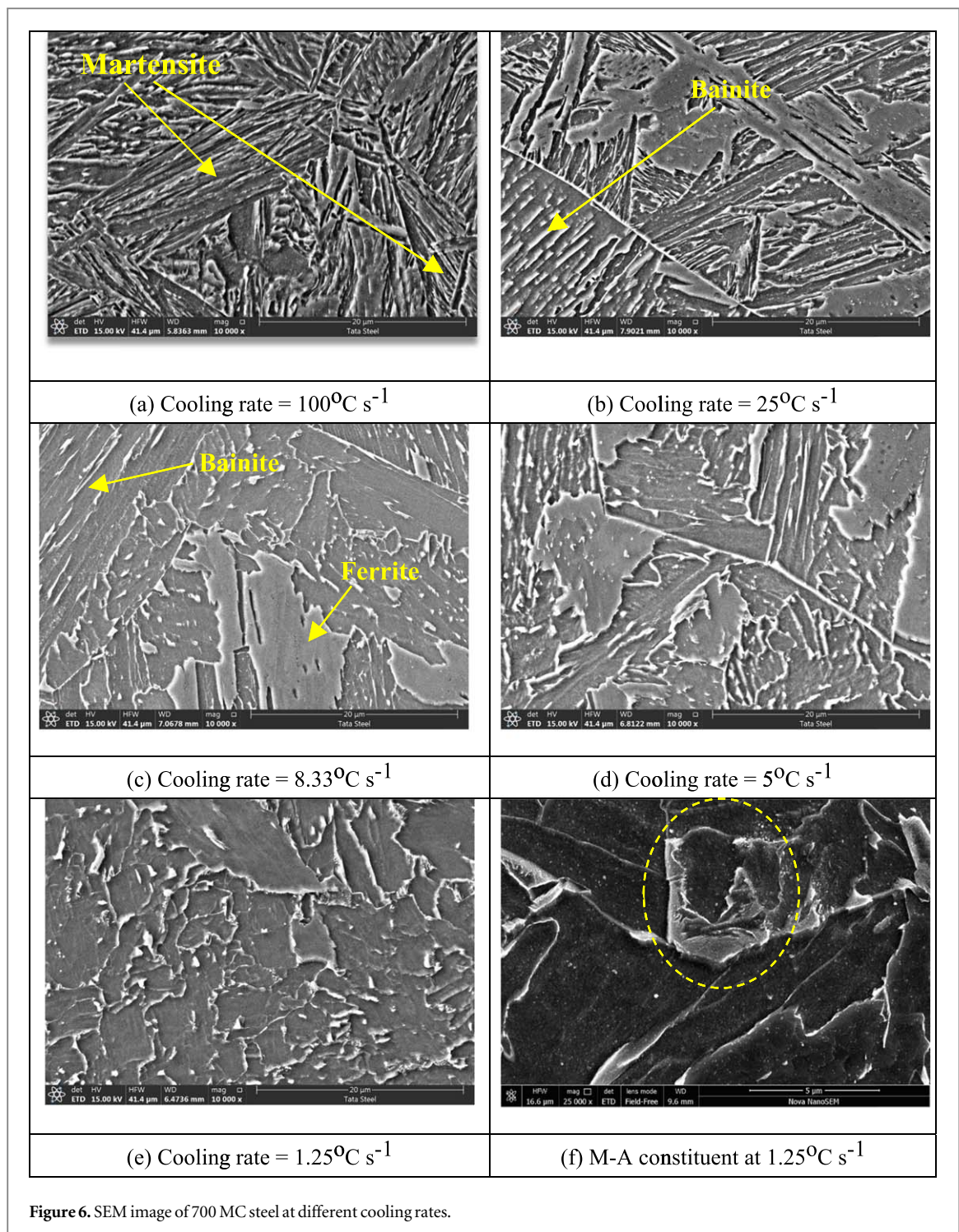


Figure 6. SEM image of 700 MC steel at different cooling rates.

At faster cooling conditions (25°C – $100^{\circ}\text{C s}^{-1}$), bainite and martensite were obtained as a product after transformation. At $100^{\circ}\text{C s}^{-1}$ a fully martensitic structure was formed which can be easily observed in SEM and optical images. In addition, minute M-A constituent found at $1.25^{\circ}\text{C s}^{-1}$. According to the recently published literature, it comes under blocky M-A constituent [23]. The M/A constituent is a mixture of untempered martensite embedded in carbon-enriched retained austenite. When transformations of bainitic ferrite occur above the martensite start temperature, the residual austenite is enriched in carbon and its martensite-start temperature (M_s) is further reduced (M_{s_r}). If M_{s_r} is greater than ambient temperature, some of the carbon-rich retained austenite will transform into martensite. This small quantity of martensite and carbon-enriched austenite is the M/A constituent [24]. Even if some previous literatures have reported the morphology change of M/A constituent with cooling rate, in the present work minute amount of M/A constituent is found at the slowest cooling rate. The evolution of microstructures at different cooling rates is similar to previously published literatures [10, 15, 25].

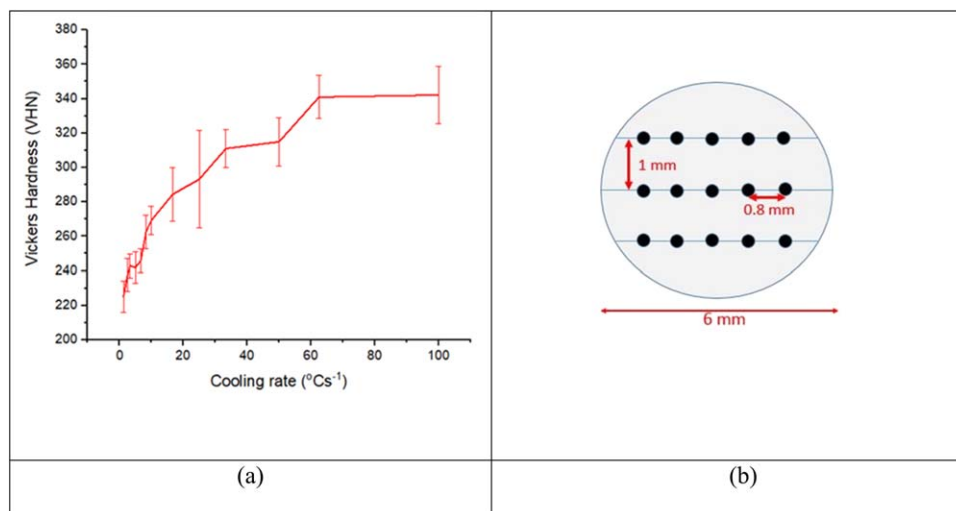


Figure 7. (a) Hardness profile of CGHAZ at different cooling rates, (b) Indent locations of Vickers hardness test.

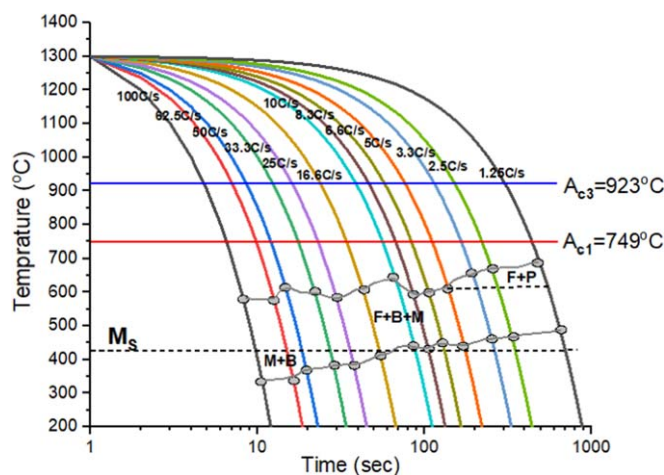


Figure 8. CCT diagram for CGHAZ in 700 MC steel (F: Ferrite, P: Pearlite, B: Bainite, M: Martensite).

3.3. Hardness analysis

Vickers microhardness tests (LECO-LM 247) were performed at room temperature on the samples at a load of 300 gm and a dwell time of 13 s by taking 15 readings in each sample. The hardness profile of CGHAZ at different cooling rates and locations of indentation were shown in figure 7. It shows that hardness increased continuously with an increase in cooling rate. At the starting stage, hardness increased drastically up to $10\text{ }^{\circ}\text{C s}^{-1}$. Then it increases gradually up to $33\text{ }^{\circ}\text{C s}^{-1}$ and finally increases slowly up to $100\text{ }^{\circ}\text{C s}^{-1}$. The maximum hardness value is 342 VHN which was obtained at $100\text{ }^{\circ}\text{C s}^{-1}$ and the minimum hardness value is 225 VHN which was obtained at $1.25\text{ }^{\circ}\text{C s}^{-1}$. A similar trend of hardness was also obtained by Wang *et al* [25] and Kumar *et al* [26]. At maximum hardness, the microstructure is fully martensitic and at minimum hardness, the microstructure is a combination of ferrite, cementite, and pearlite. The optical microstructure shows that almost complete martensitic transformation happens at $62.5\text{ }^{\circ}\text{C s}^{-1}$. Therefore, a minute improvement of hardness was observed after $62.5\text{ }^{\circ}\text{C s}^{-1}$.

3.4. CCT curve analysis

Figure 8 shows the CCT curve generated from dilation, hardness, and microstructure analysis. It clearly shows the starting temperature for the formation of different phases at different welding conditions. JMatPro software and chemical composition were used to determine the isothermal transformation start temperatures of ferrite ($840\text{ }^{\circ}\text{C}$) and pearlite ($665\text{ }^{\circ}\text{C}$) [11]. The following equations were used to calculate the bainite ($592\text{ }^{\circ}\text{C}$) and martensite ($421\text{ }^{\circ}\text{C}$) start temperature [20].

$$T_{Bs} = 634.8 - 193.1C + 102.3C^2 - 31.2Mn - 4.6Si - 32.4Cr - 15.6Mo + 10.36 \ln(d_\gamma)$$

$$T_{Ms} = 475.9 - 335.1C - 34.5Mn - 1.3Si - 13.1Cr - 10.7Mo + 11.67 \ln(d_\gamma)$$

Phase transformation start and finish temperature were determined by the tangent method. The transformations occurred in the range of 329 °C to 684 °C. In slow cooling conditions, the transformation occurred within the ferrite and pearlite zone. In a medium cooling condition, the transformation occurred in the bainitic region. In fast cooling condition transformation occurred in the bainitic and martensitic regions. Hence, the transformation was shifted from diffusional to non-diffusional with an increase in cooling rate.

4. Conclusion

In this research work, we studied the effect of different cooling rates on coarse grain heat-affected zone by the characterization of microstructure, hardness, and continuous cooling transformation curve. The following results were concluded from this study.

- At the highest cooling rate, the microstructure was fully martensitic. A combined microstructure of bainite and martensite was obtained in the cooling range of 25 °C–100 °C s⁻¹.
- In the medium cooling condition (5 °C–25 °C s⁻¹), the mixed microstructure of ferrite, bainite, and martensite was observed.
- At a slow cooling rate (1.25 °C–5 °C s⁻¹), different diffusional phases present are ferrite, cementite, and pearlite.
- Hardness increased from 225 HV to 342 HV with increasing the cooling rate from 25 °C s⁻¹–100 °C s⁻¹. Which denotes the shifting of transformation from diffusional to diffusionless with an increase in cooling rate.
- The continuous cooling transformation curve was generated from the results of the dilation curve, microstructure, and hardness analysis of gleeble simulated samples of 700 MC steel. The generated curve further helps for optimization of welding parameters before welding.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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