Simulating the Heat Treatment Process of the Shell Liner of Cr-Mo Steel

H. Rastegari *[1], M. Lakhi [2], M. Farazi [3], M. R. Haghighi [4]

[1, 2, 3] *Department of Mechanical and Materials Engineering, Birjand University of Technology, South Khorasan, 97198-66981, Iran*
[4] *Division of Research and Development, Isfahan Casting Industries Co. (ICI), Isfahan 83551-1111, Iran*

Abstract

The aim of the present research is to simulate the heat treatment process of the autogenous grinding (AG) shell liner of Cr-Mo steel in different quenching media (still air, air blowing, oil and water) using ABAQUS software, in order to calculate the cooling curves. In this regard, the microstructure and hardness for each arbitrary point within the mill liner's bulk could be predicted based on using the CCT diagram of Cr-Mo steel and superimposing the cooling curves. Moreover, the results of the simulations and the industrial data were compared to prove the validity of the simulation. The findings showed that the microstructure of pearlite, duplex pearlite+bainite and martensite were achieved by quenching, using air fan, oil and water, respectively. The simulated cooling curves were consistent with the measured cooling curves, and simulation could be a promising method for designing the heat treatment process for mill liners.

Keywords: Cr-Mo steel; Simulation; Heat treatment; Cooling curve; Microstructure.

1. Introduction

The main roles of mill liners are to transmit energy to the mill charge for the occurrence of the grinding process also, to protect the shell of the mill from wear. During the service life, the liners heavily encounter impact and wear. Therefore, controlling the heat treatment parameters and the resulting microstructure can have a significant effect on the performance of the mill liners. The shell liner of Cr-Mo steels (commercially named as Wood Steel or WS140) is one of the most important part in the SAG/AG mills; it is, in fact, considered to be a replaceable wear resistant layer within the grinding mills. Indeed, Cr-Mo steels with the typical chemical composition of (in wt.%) 0.65-0.75 C, 0.4-0.6 Si, 0.6-0.8 Mn, 2-2.3 Cr, 0.3-0.4 Mo and 0.1-0.3 Ni provide a good combination of wear resistance and impact energy, as well as a low production cost. Obviously, heat treatment process has much to do with the final microstructure and, hence, the performance of mill liner. Industrially, The heat treatment process of mill liner includes homogenizing at the elevated temperature of 1200 °C, austenitizing at the temperature range of 900-1000 °C, holding for about 5-7 hr and finally, continuous cooling by a specific quenching medium. The non-occurrence of cracking and achieving the desired mechanical properties were the deciding factors in selecting the quenching medium. In this regard, a relatively high cooling rate could result in cracking; on the other hand, slow cooling could be followed by a considerable reduction in hardness and wear resistance.

** Corresponding author*
Tel.: +98 56 32391239; Fax: +98 56 32252098
E-mail: rastegary@birjandut.ac.ir
Address: Department of Mechanical and Materials Engineering, Birjand University of Technology, South Khorasan, 97198-66981, Iran
1. Assistant Professor
2. B.Sc.
3. B.Sc.
4. B.Sc.

Hence, the type of quenching medium could have a significant effect on the lifetime and efficiency of the mill liner [1-5].

However, due to the expensive industrial testing for such a mill liner, it is reasonable for identifying the best heat treating condition by the use of simulation method. Although some earlier investigations have considered the thermal simulation of work-pieces [6, 7], no work has been performed on simulation the heat treatment process of the shell liners and also predicting the microstructural evolution and mechanical properties in order to reduce the industrial testing and achieving the optimum performance. Therefore, the purpose of the present research was to simulate the heat treatment process of the shell liner (for AG mills used at Chadormalu iron ore mine) in different quenching media including still air, air blowing, oil and water. A finite element method based on ABAQUS software was used for calculating the temperature (T) and the heat flux (q). In addition, the industrial tests were carried out to validate the results of the simulations. It is worth mentioning that the tempered martensite and bainitic microstructure could result in the appropriate mechanical properties. Thus, heat treatment process should be accurately controlled to achieve the appropriate microstructure [8, 9].

2. Experimental Procedure

The steel used for manufacturing the shell liner was WS140 steel. The chemical composition of steel is listed in Table 1. (in wt.%) 0.67 C, 0.48 Si, 0.72 Mn, 2.13 Cr, 0.32 Mo, and 0.25 Ni. Fig. 1 shows the photograph of the shell liner used at Chadormalu concentration plant mills with about 1100 kg weight. It should be noted that the thicker part of the shell liner, with the height of 285 mm, lifts the mill charge and faces most of the wear and impact. Austenitization temperature was chosen to be equal to 900 °C; while the reduction of temperature was the result of two main mechanisms including thermal radiation and convection through the adjacent fluid. In this regard, the temperature and heat flux variations for the assumed locations (Fig. 2, positioned with 20 mm distance from each other) were calculated in different quenching media including still air, high and low velocity air blowing, oil, and water. Cooling time was considered to be equal to 90, 30 and 10 minutes for air, oil and water, respectively. Moreover, temperature distribution was analyzed using the Runge–Kutta method. Considering the energy equation and heat transfer mechanisms (including convection and radiation), a non-linear differential equation was employed as follow:

$$\frac{dT}{dt} = -\frac{hA}{mC}\left(T - T_a\right) - \frac{A\sigma\varepsilon}{mC}\left(T^4 - T_a^4\right) \qquad \text{Eq. (1)}$$

, where, the first part of equation related to convection mechanism and the second part of the equation related to radiation mechanism. One should notice that the mill liners were industrially cooled using air fan from an austenitizing temperature.

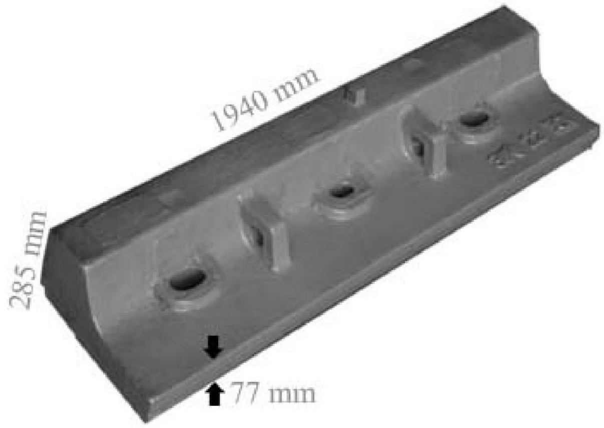

Fig. 1. Photograph of the shell liners used at the Chadormalu concentration plant mills.

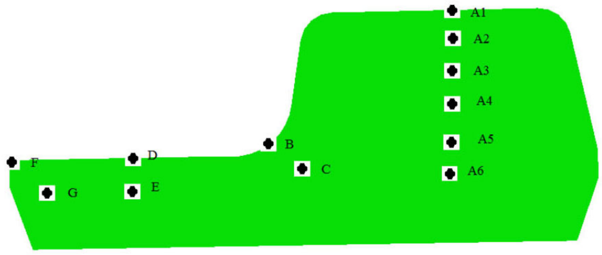

Fig. 2. Cross-section of the shell liner and assumed locations considered for calculating temperature and heat flux in this research.

Table 1. Chemical composition of WS140 steel (wt. %).

Composition	C	Si	Mn	Cr	Mo	Ni	S	P
	0.67	0.48	0.72	2.13	0.32	0.25	0.01	0.02

For this purpose, it was initially needed to find out the physical properties of the studied steel. As known, the physical properties of the steel are the functions of microstructure and temperature. In addition, during cooling with different quenching media for the studied steel, various microstructures such as austenite, pearlite, bainite and martensite could be formed. Thus, variation in the physical properties of the steel (density, specific heat, thermal conductivity and thermal expansion coefficient) with the temperature was taken into account based on the literature [10, 11]. Also, a constant value of 0.7 was considered to be the emissivity coefficient in the analyses. Furthermore, convection heat transfer coefficient ($\bar{h}$) is the most important factor determining the quenching severity. Therefore, $\bar{h}$ value was calculated for oil and water, according to Eqs. (2-4).

$$Ra_l = Gr\,Pr = \frac{g\beta(T_S - T_\infty)L^3}{\nu\alpha} \quad \text{Eq. (2)}$$

$$\overline{NU} = \frac{\bar{h}l}{k} = 0.27 Ra_l^{\frac{1}{4}} \quad \text{Eq. (3)}$$

$$\bar{h} = 0.27\frac{k}{l}\left(Ra_l\right)^{\frac{1}{4}} \quad \text{Eq. (4)}$$

, where *Ra*, *Gr*, *Pr* and Nu refer to the Rayleigh, Grashof, Prandtl and Nusselt numbers, respectively. Also, T_S , T_∞ , β , α , *k*, *g*, *v* and l are surface temperature, free stream temperature, volumetric thermal expansion coefficient, thermal diffusivity, thermal conductivity, gravitational acceleration, kinematic viscosity and length, respectively. In addition, the value of $\bar{h}$ for air with a specific velocity was calculated according to Eqs. (5), (6).

$$Re = \frac{\rho VL}{\mu} \quad \text{Eq. (5)}$$

$$\overline{NU} = \frac{\bar{h}l}{k} = 0.664 Re^{\frac{1}{2}} Pr^{\frac{1}{3}} \quad \text{Eq. (6)}$$

, where Re, ρ , V and μ are Reynolds number, mass density, fluid velocity and viscosity, respectively. Calculated convection coefficient values in different quenching media are listed in Table 2. It should be noted that the fluid temperature was assumed to be 300 K [12].

In order to validate the results of the simulations, industrial trial tests were carried out. Thus, a medium-frequency induction furnace (manufactured by Inductotherm Group) and the sand-mold casting technique were used for manufacturing the shell liners. Heat treatment process was conducted using a 10-ton heat treating furnace. After removing the shell liners from the furnace, temperature reduction was monitored by a calibrated pyrometer. For microstructural characterization, samples were polished and observed

Table. 2. Coefficients and constant values considered for calculating convection coefficient in different quenching media.

Quenching Medium	Kinematic viscosity (ν)	Thermal conductivity (k)	Thermal diffusivity (α)	expansion coefficient (β)	Prandtl number (Pr)	Fluid velocity (u)	Convection coefficient ($\bar{h}$)
Unit	$\left(\times 10^6 \frac{m^2}{s}\right)$	$\left(\times 10^3 \frac{W}{m.k}\right)$	$\left(\times 10^7 \frac{m^2}{s}\right)$	$\left(\frac{1}{K}\right)$	Non-dim	$\left(\frac{m}{s}\right)$	$\left(\frac{W}{m^2.k}\right)$
Still air	15.89	26.3	2.25	0.0034	-	0	4.3
Air fan	15.89	26.3	2.25	-	0.707	2500	30.1
						16444	77.3
Oil	550	143	0.859	0.0007	-	0	264.3
Water	μV = 587565	613	0.859	0.000214	0.707	0	2107.8

using an optical microscopy. The two-step etching technique was employed to reveal different phases in the microstructure. For this purpose, firstly, Picral reagent (a mixture of 4 mlpicric acid and 100 ml ethanol) and then, 2% Nital reagent (a mixture of 2 ml nitric acid and 98 ml ethanol) were used as etchants. Rockwell C hardness was measured on a Koopa hardness tester.

3. Results and Discussion

3. 1. Experimental validation

In order to validate the simulated results, temperature reduction was measured at the top surface and the corner edge of the shell liner. Fig. 3 exhibits the comparison between the predicted and the measured cooling curves in different quenching media and locations. It could be seen that the predicted cooling curves were consistent with the experimental results. It is worth mentioning that increasing temperature (at the temperature of about 550 °C) was due to the occurrence of phase transformation from austenite to pearlite and the consequent release of the latent heat.

3. 2. Simulation results

Firstly, the simulation results obtained for conventional cooling (i.e. low velocity air blowing) were evaluated. The predicted cooling curves at the surface (A1, Fig. 2) and depth (up to 10 cm, A2 to A6, Fig. 2) of the shell liner (thick part) are shown in Fig. 4a. As can be seen, the cooling curves were superimposed on the CCT diagram of the Cr-Mo steel to predict the microstructure evolution during cooling. By ignoring the first 30 seconds (rapid temperature drop due to radiation), the average cooling rate was about 8 °C/min. Based on the CCT diagram, this slow cooling rate resulted in the formation of a relatively coarse pearlitic microstructure throughout the thick part of the shell liner. Metallographic observations also confirmed the formation of such a microstructure (Fig. 4b). Moreover, a relatively low hardness value of about 35 HRC was obtained at the top surface of the shell liner; while the hardness value was decreased to about 31 HRC in the depth of 2 cm. Fig. 5 shows the difference between the ranges of cooling rates obtained for still air, high and

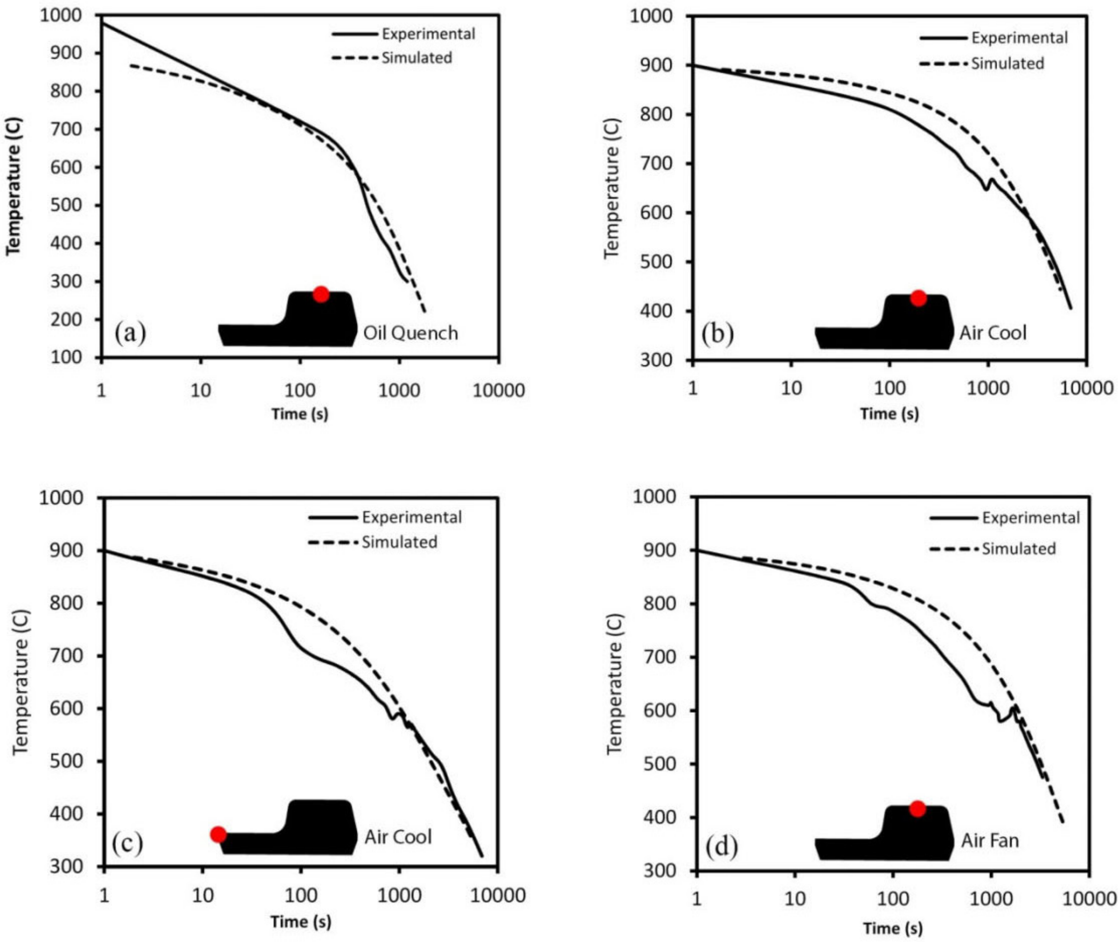

Fig. 3. Comparison between the predicted and the measured cooling curves (a) at the top surface for oil quenching (b) at the top surface for air cool, (c) at the corner edge for air cool and (d) at the top surface for air fan.

low velocity air blowing. It could be concluded that utilizing the air as a cooling medium only resulted in the formation of a fully pearlitic microstructure. Thus, the higher air velocity just leads to the finer pearlitic microstructure; while bainitic or martensitic microstructure cannot be formed.

Temperature distribution on the 3D solid model and across the liner cross-section is depicted in Fig. 4c. It is obvious that the center region and the corner edge of the shell liner showed the maximum (422 °C) and minimum (222 °C) temperature, respectively. In other words, the highest cooling rate (about 16 °C/min) was achieved for a narrow band in the edge of the shell liner. However, such a cooling rate could promote the formation of the duplex banitic-pearlitic microstructure through the narrow band highly prone to longitudinal cracking. The occurrence of such a longitudinal cracking has already been reported by Javaheri et al. [13] for the AG mill shell liners of Sarcheshmeh copper complex.

The predicted heat flux curves at different locations (A1 to A6) are illustrated in Fig. 4d. It is apparent that the amount of q at the surface of the shell liner (A1) increased quickly, reaching a maximum value of about 90 kJ/s.m^2 after 15 seconds; then it decreased continuously. The maximum q value with a significant difference, especially at the initial time, was achieved for the surface. For the rest points located in the depth (A2 to A6), the q value, after a delay, started to rise, reaching a maximum value followed by a gradual decrease. Moreover, the delayed time was extensively enhanced by moving toward the deeper points. Indeed, after 200 s from the beginning of cooling, the temperature of the center part of the shell liner showed no change and then started to cool down slowly. Therefore, a coarse pearlite microstructure or a partially spheroidized microstructure (based on the divorced eutectoid transformation mechanism [14]) could be established inside the shell liner's bulk. This phenomenon

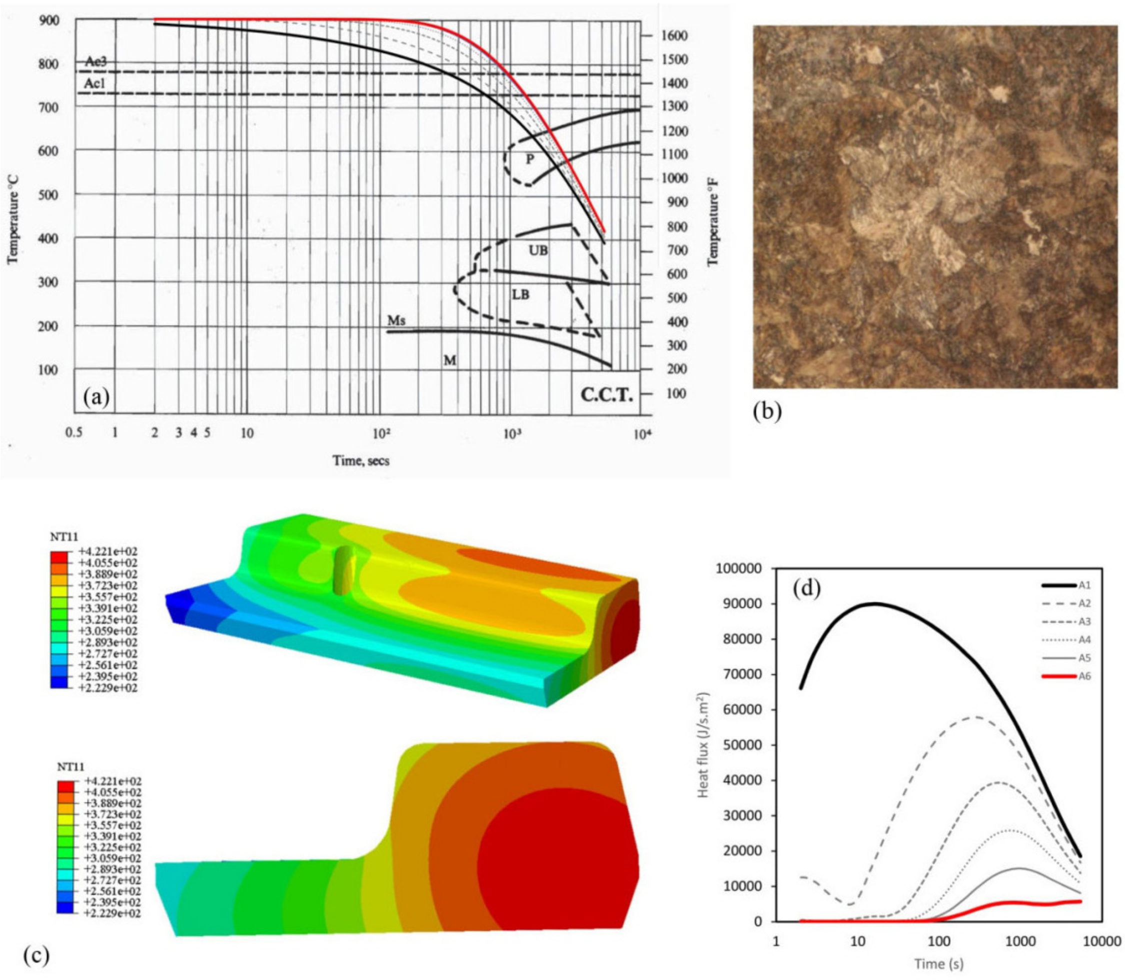

Fig. 4. Temperature and heat flux analysis for low velocity air blowing medium; (a) superimposition of predicted cooling curves and CCT diagram of the Cr-Mo steel, (b) fully pearlitic microstructure, (c) three-dimensional and cross-sectional temperature distribution and (d) simulated variation of heat flux with time in different locations as dedicated in Fig. 2.

directly affects the wear life by decreasing the hardness and wear resistance. The change of the lifter profile during the service clearly shows the increase in wear rate, as reported by banisi et al. [2)].

The superimposition of the predicted cooling curves on the CCT diagram of the Cr-Mo steel for oil quenching at different locations (A1 to A6) is exhibited in Fig. 6a. The average cooling rate was about 25 °C/min. Based on the CCT diagram, the time to begin the austenite to pearlite transformation at the nose temperature was less than 900 s. Therefore, the cooling curves did not cut the nose of CCT diagram, as a result of preventing the pearlitic transformation; instead, the microstructure should be a duplex bainite+martensite microstructure (Fig. 6b). As expected, the hardness measurement indicated that oil-quenched specimen had higher hardness (46 HRC), as compared to the air fan specimen (35 HRC). Moreover, the hardness value remained approximately constant up to 4 cm in depth. The results also showed that oil medium could be effectively used for obtaining the fully bainitic microstructures through the interrupted quenching technique. By the use of interrupted quenching, the austenitized shell liner could be immersed in an oil bath for sufficient time (based on the predicated cooling curves) and then removed from the bath to allow the temperature rise again. This action could be repeated until the temperature would be reduced to the bainite transformation region to ensure the formation of the bainitic microstructure. The 3D and cross-sectional temperature distribution are shown in Fig. 6c. As can be seen, after 30 minute, the maximum temperature of 290 °C and the minimum temperature of 48 °C were obtained for the center region and the corner edge of the shell liner, respectively. However, formation of the fully martensitic microstructure was promoted at the corner edge of the shell liner due to the high cooling rate of about 150 °C/min; while the presence of a considerable amount of heat flux (Fig. 6d) during the cooling process resulted in tempering, as a result of reducing the crack sensitivity. As shown in Fig. 6d, the same ascending and descending trends were observed for heat flux curves where the *q* value at the surface increased to a maximum value of about 257 kJ/s.m^2 after 10 seconds and then decreased gradually. The significant difference between the value of *q* for air and oil media could have an effect on the hardening depth. In addition, occurrence of tempering process during the cooling could be concluded due to a delay and the presence of a hot core inside the shell liner.

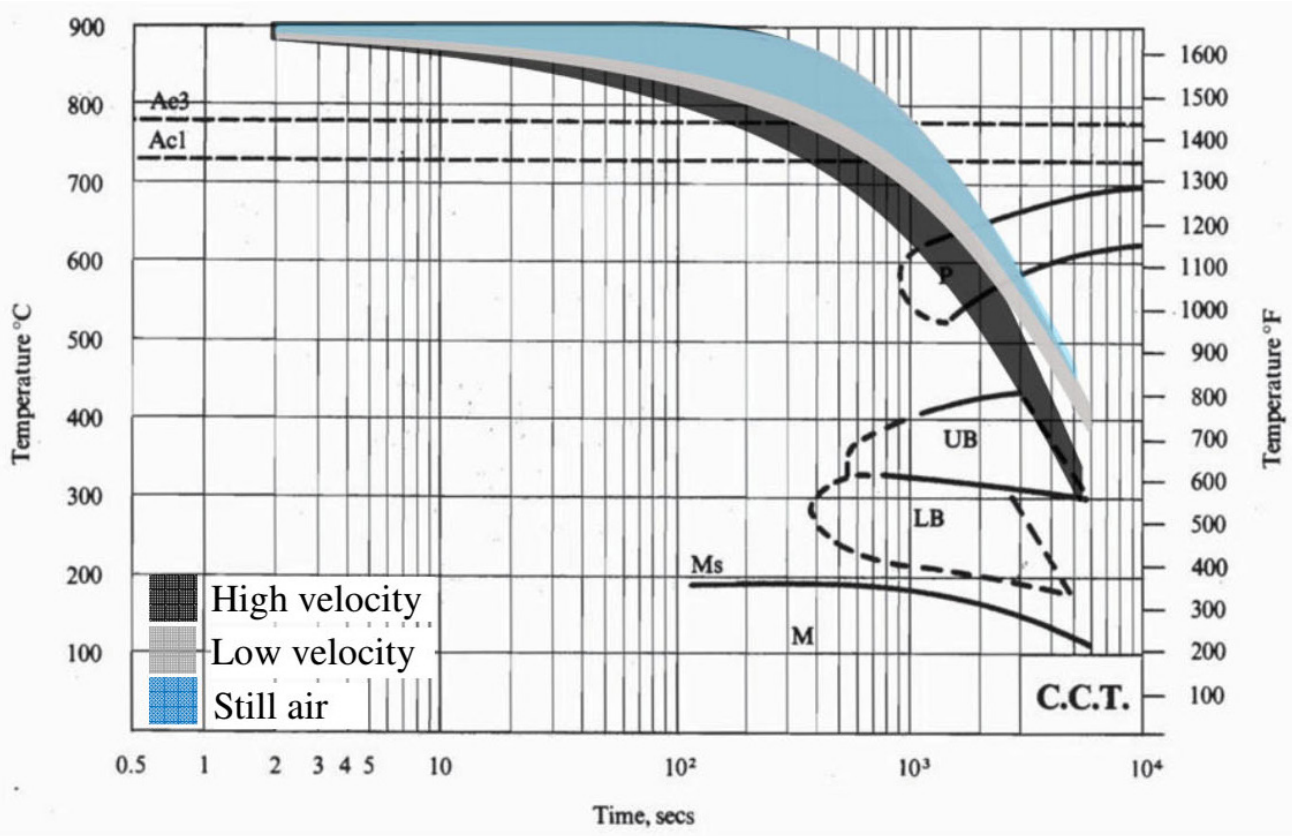

Fig. 5. Comparison the calculated range of cooling rate for still air, high and low velocity air blowing.

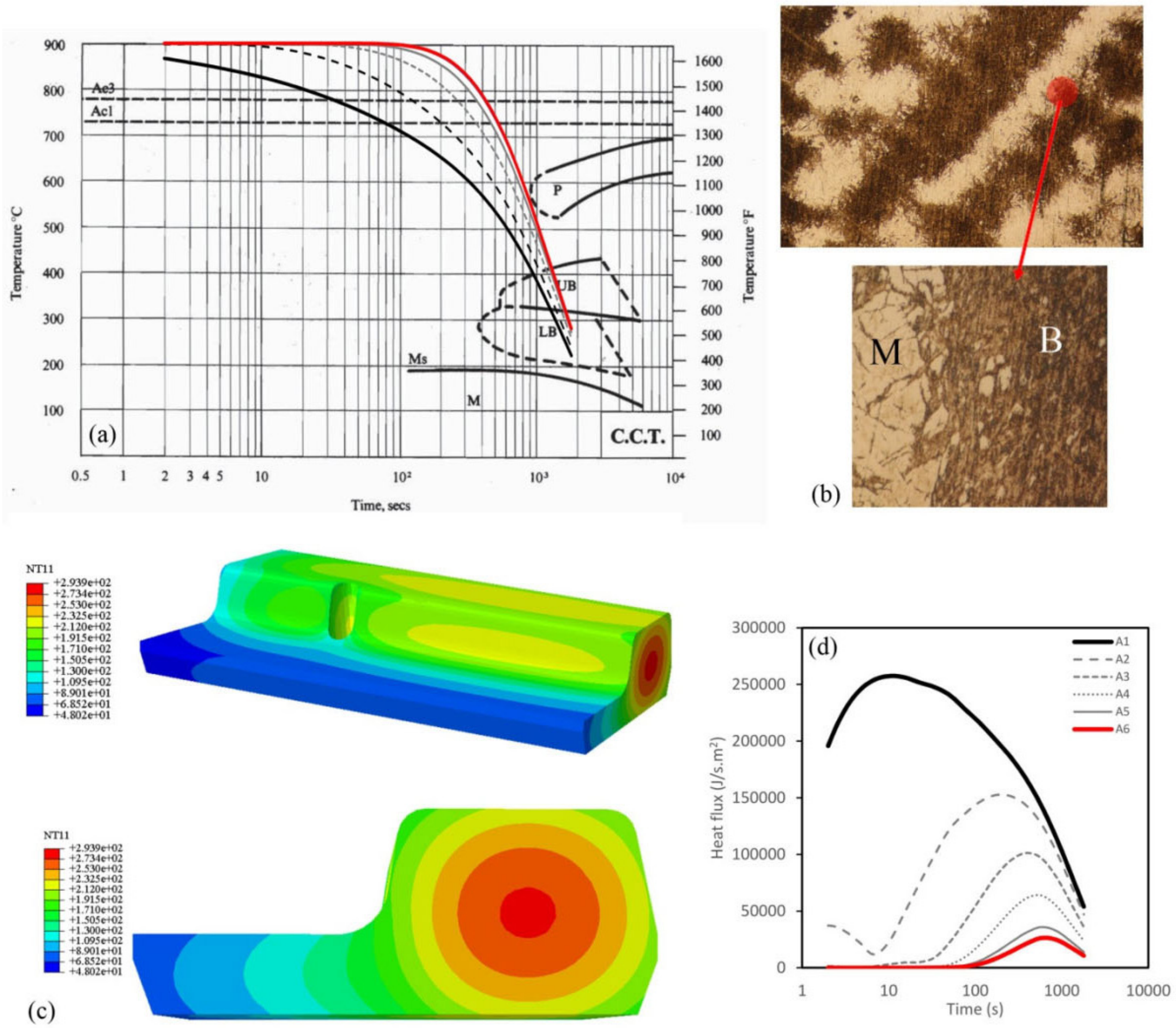

Fig. 6. Temperature and heat flux analysis for oil quenching medium; (a) superimposition of predicted cooling curves and CCT diagram of the Cr-Mo steel, (b) duplex martensitic+banitic microstructure, (c) three-dimensional and cross-sectional temperature distribution and (d) simulated variation of heat flux with time in different locations as dedicated in Fig. 2.

Fig. 7 shows the simulated results and the observed microstructure for water quenching. Due to the high amount of value (Table 2) and the high cooling severity of water, a severe drop in temperature was obtained (Fig. 7a and c). In other words, the surface of the shell liner was cooled rapidly, while the center region was cooled slowly. This non-uniform cooling behavior could cause the non-uniform phase transformation (i.e. on-uniform volume changes) along the cross section of the shell liner, resulting in the occurrence of distortion and formation of transgranular micro-cracks, as shown in Fig. 7b. It is obvious that a fully martensitic microstructure was formed at the surface, as demonstrated in Fig. 7b. Actually, a certain thickness from the surface was transformed to martensite at the early stage of cooling; while the center regions have not transformed yet, and they contained the metastable austenite phase. Hence, when the interior regions transformed, the martensitic outer shell restricted the expansion, leading to the severe residual stress and cracking. The maximum hardness value of 58 HRC was achieved for the water-quenched specimen. According to Fig. 7d, the amount of q at the surface of the shell liner (A1) increased very rapidly, reaching a maximum value of about 1300 kJ/s.m^2 after 7 seconds and then decreased. However, a similar behavior has been observed for heat flux curves; there was a substantial difference between the amount of heat flux at the surface and the center of the shell liner. Thus, the efficiency of tempering process during the cooling reduced, and crack formation could not prevent the cracking.

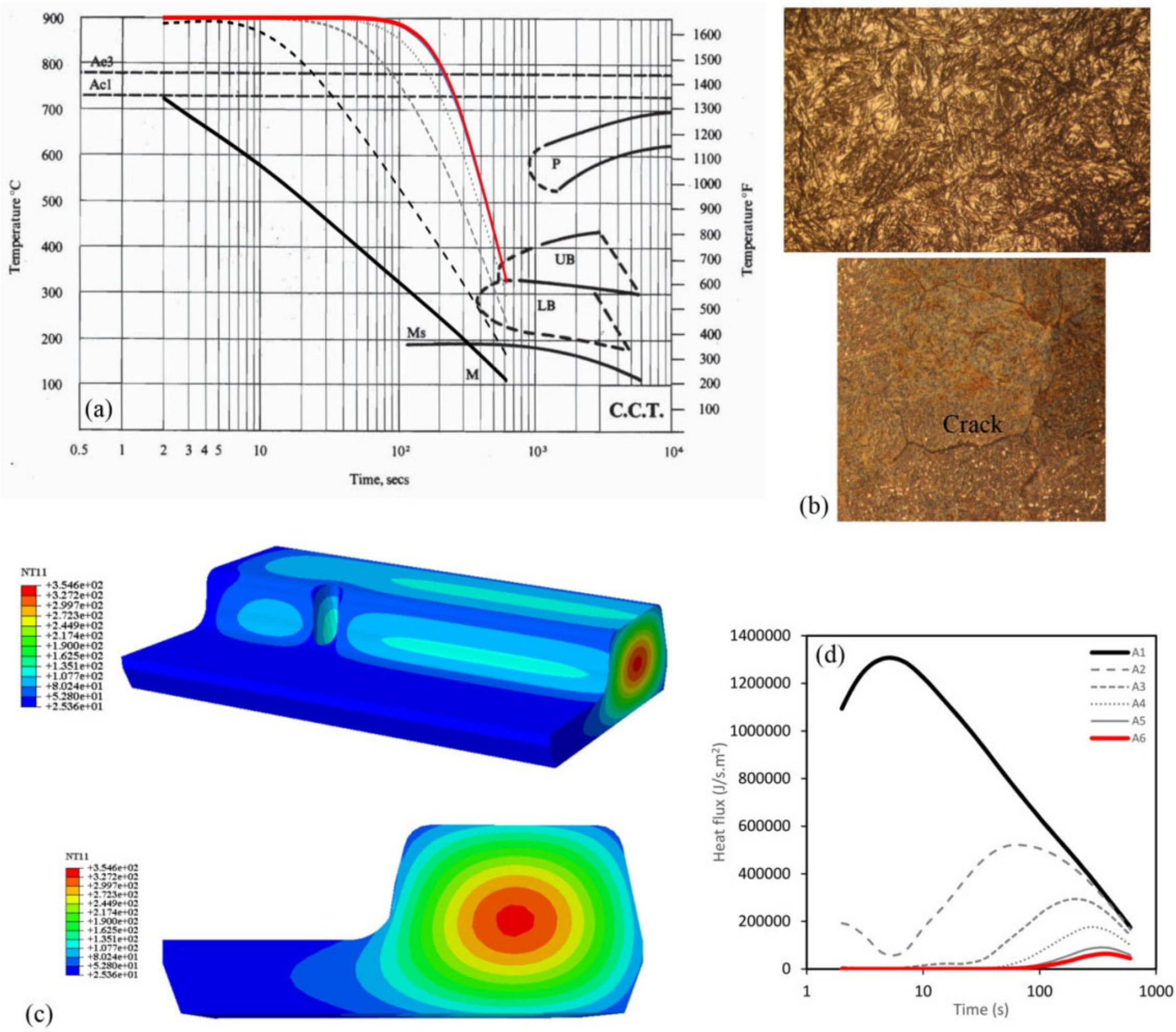

Fig. 7. Temperature and heat flux analysis for water quenching medium; (a) superimposition of predicted cooling curves and CCT diagram of the Cr-Mo steel, (b) martensitic microstructure and occurrence of transgranular cracking, (c) three-dimensional and cross-sectional temperature distributions and (d) simulated variation of heat flux with time in different locations as dedicated in Fig. 2.

4. Conclusions

In this study, the heat treatment process of an AG mill liner of Cr-Mo steel has been simulated in the different quenching media, using ABAQUS software. The cooling curves and heat flux curves have been predicted for the assumed locations delineating various kinds of microstructures. A novel heat treatment procedure has been proposed for the appropriate microstructure and mechanical properties. However, the following conclusions can be drawn from this research:

• The simulated results were consistent with the experimental data, and simulation could be a useful tool to optimize the heat treatment process of mill liners.

• Utilizing air fan, oil and water as quenching media resulted in formation of fully pearlite, duplex pearlite+bainite and martensite microstructures, respectively.

• Fully bainitic microstructure could be achieved by oil quenching through the interrupted quenching technique as an alternative to isothermal heat treatment.

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