Materials Research Express

PAPER

Modeling research on laser quenching process of GCr15 bearing steel basing on material properties obtained with experimental methods

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Keywords: Laser quenching, bearing steel, numerical simulation, microstructure evolution, technological parameter optimization

Abstract

A combination of temperature and microstructure prediction models for the laser quenching process of GCr15 bearing steel was established. The thermo-physical parameters and austenitization kinetics of GCr15 bearing steel were obtained with the laser flash and dilatometer experiments, respectively, to improve the prediction accuracy of the model. The dilatometric experiment results for the austenitization kinetics for high heating rates were fitted with the isochronal JMA relationship. Basing on the experimental results, the temperature and microstructure evolutions of GCr15 bearing steel during the laser quenching processes were simulated. According to the simulation results, optimized technological parameters for the laser quenching process were proposed.

1. Introduction

GCr15 bearing steel is the most widely used bearing steel, for its high hardness, wear resistance, elasticity, toughness, and low prices [1, 2]. As this material has been always worked under cyclic loads and high frictions, the excellent surface mechanical properties are needed [3]. Some surface modification technologies, such as carburizing [4], nitriding [5] and laser quenching [6], have been used to improve the surface mechanical properties. Laser quenching process has been widely used for its technical and economical advantages [7]. In the laser quenching process, the material is quickly heated to be austenitized by a laser beam, and then cooled to martensite to obtain high wear resistant surface without aid of any quenching medium [8]. The high cooling rate of the workpiece is attributed to transferring heat energy into bulk of the material matrix for its high thermal conductivity coefficient [9]. The laser quenching process is very fast and can get hardened workpiece surface with minimal deformation [10–12]. According to the previous research, GCr15 bearing steel could be laser quenched to produce a surface hardness in excess of 1000 HV [13–15]. Research has also found that the laser quenching process increased the corrosion resistance of the hardened surface [16, 17].

The key process parameters influencing the laser quenching process are laser power and scanning speed. When the laser power is low, or the scanning speed is fast, the energy input into the workpiece is small, thus the quenched layer should be shallow. Some researchers showed that low laser powers of the order of 100 W could also get the required properties of the materials [18, 19]. However, when the laser power is high, or the scanning speed is slow, the corresponding large energy input will lead to high temperature to melt the surface of workpiece. When the surface melting occurs, the bearing steel solidifies to a structure consisting of ledeburite eutectic, retained austenite and martensite. The mixtures of these microstructures are not beneficial to the rolling contact fatigue [13]. Even if the melted or partial melted surface obtain the similar hardness with the normal quenched workpiece, the oxidation and shrinkage porosities of the solidification process will also lead to...
the increasing of the roughness or altering of the geometry [20–22]. Therefore, the influences of the process parameters, such as laser power and scanning speed, on the surface mechanical properties of GCr15 bearing steel are very important. To optimize the laser quenching process of GCr15 bearing steel, the relationships between temperature and microstructure of the workpiece and the process parameters are needed.

To obtain these relationships with numerical calculation methods, accurate thermo-physical parameters and phase transformation kinetics of GCr15 bearing steel are needed. As the thermo-physical parameters are highly related to the temperature and composition of materials [23], the thermo-physical parameters of GCr15 should be measured accurately to improve the reliability of the temperature calculation model. According to the previous research, the austenitization kinetics of GCr15 bearing steel is highly related to the heating rate [24]. The heating rate for the laser quenching process is about 100 °C s\(^{-1}\), thus the austenitization kinetics near this heating rate is needed.

In the present research, temperature prediction models and combined austenitic and martensitic transformation models have been established to obtain the temperature and microstructure evolutions during the laser quenching processes of GCr15 bearing steel. To obtain reliable prediction results, the thermo-physical parameters and austenitization kinetics for high heating rate were obtained with experimental researches. The laser quenching processes of GCr15 bearing steel were finally optimized basing on the simulation results.

2. Methods

2.1. Experimental

A commercial-type GCr15 bearing steel (the alternative corresponding designations are AISI/SAE 52100 and DIN 100Cr6) with continuous casting was utilized. The chemical compositions of GCr15 bearing steel are 1.0 wt% C–1.42 wt% Cr–0.35 wt% Mn–0.25 wt% Si–0.025 wt% P–0.025 wt% S–0.3 wt% Ni–0.25 wt% Cu–0.10 wt% Mo. To obtain uniform microstructure, the material was homogenized at 1150 °C for 2 h and then air cooled to room temperature. The experimental samples were cut from the columnar grain zone of the billet.

Laser flash method was used to measure the thermo-physical parameters of the material. LFA 427 type laser flash heat conduction instrument was used in these experiments. The samples were cut to 10 mm in diameter and 4 mm in thickness. In the laser flash method, the thermal diffusivity of the material could be obtained by analyzing the temperature curves of the samples. The specific heat capacity of the material was obtained by comparing the heat absorption of sample to a standard specimen. Then the thermal conductivity of the material was calculated from the thermal diffusivity and specific heat capacity.

A DIL 805-type dilatometer was used to research the austenitizing kinetics of the steel. The samples for dilatometric experiments were cut to 4 mm in diameter and 10 mm in length. The samples were heated to 1200 °C with heating rates of 3, 30, 60 and 120 °C s\(^{-1}\) to be austenitized, then cooled to 50 °C with a rate of −100 °C s\(^{-1}\). As shown in figure 1, the temperatures of the samples were measured with B-Type thermo-couples and quickly recorded. The length changes of the samples were also quickly recorded by the dilatometer. According to the length change data the austenitized fractions of the samples could be calculated.
2.2. Models

2.2.1. Heat transfer
The temperature evolutions of laser quenching processes were simulated with finite element method basing on the ANSYS software. Gaussian laser spot beam was used in these simulations, thus the distribution of the heat input into the workpiece could be described as follows:

\[ q = Q \cdot \exp \left(-\frac{3 \times (x - x_0)^2 + (y - y_0)^2}{r^2}\right) \]  

(1)

Where \( x \) and \( y \) are the coordinates of points on the surface of the workpiece, have units of m; \( q \) and \( Q \) are heat flux and the peak heat flux on the workpiece surface, respectively, which have units of W \( \cdot \) m\(^{-2}\); \( v \) and \( t \) are the scanning speed and the moving time of the laser beam, have units of m \( \cdot \) s\(^{-1}\) and s, respectively; \( r \) is the radius of the laser spot, have units of m. As shown in figure 2, during the laser quenching process, the laser spot scanned along the line of \( x = x_0 \).

The heat transfer process inside the workpiece was described with the three-dimensional unsteady heat conduction model as follows,

\[ \frac{\partial}{\partial x} \left( \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{\partial T}{\partial z} \right) + Q = \frac{\rho c_p}{\lambda} \frac{\partial T}{\partial t} \]  

(2)

Where \( T \) is temperature, has units of K; \( \rho \), \( c_p \), and \( \lambda \) are the density, specific heat capacity and thermal conductivity of the material, which have units of kg \( \cdot \) m\(^{-3}\), J \( \cdot \) kg\(^{-1}\) \cdot K\(^{-1}\) and W \( \cdot \) m\(^{-1}\) \cdot K\(^{-1}\), respectively. The density of GCr15 bearing steel is 7817 kg \( \cdot \) m\(^{-3}\), \( Q \) is the inner heat source and equals to 0 for the laser quenching process.

As shown in figure 2, the sizes of the workpiece were 0.1 \( \times \) 0.2 \( \times \) 0.01 m. The boundary conditions of the upper and lower surfaces of the workpiece were set the third kind boundary condition. The heat transfer coefficient on the upper and lower surfaces was set 180 W \( \cdot \) m\(^{-2}\) \cdot °C\(^{-1}\) [25]. The boundary conditions of the side surfaces of the workpiece were set the thermal insulating boundary condition.

2.2.2. Phase transformations
The phase transformations during laser quenching process contain austenitic transformation in the heating stage and the martensitic transformation in the cooling stage. The austenitic transformation kinetics can be described by the JMA relationship [26, 27]:

\[ f_a = 1 - \exp(-\beta^n) \]  

(3)

Where \( f_a \) is the volume fraction of austenite; \( n \) denotes the JMA exponent. For isothermal process,

\[ \beta = k_0 \cdot \exp \left( -\frac{E_a}{RT} \right) t \]  

(4)

Where \( k_0 \) is a pre-exponential factor, has units of s\(^{-1}\); \( E_a \) is the activation energy of austenitic transformation, has units of J \( \cdot \) mol\(^{-1}\); \( R \) is the universal gas constant, equals to 8.314 J \( \cdot \) mol\(^{-1}\) \cdot K\(^{-1}\). For non-isothermal process,

\[ \beta = \int_0^t k_0 \cdot \exp \left( -\frac{E_a}{RT} \right) dt \]  

(5)

For the isochronal process, Kempen obtained the following expression by substituting equation (5) with its Taylor expansion [28]:

![Figure 2. Schematic diagram of thermal process model for laser quenching.](image-url)
Where \( j \) is the heating rate, has units of °C·s\(^{-1}\).

During the cooling stage, the martensitic transformation kinetics is described by the following equation derived from the Koistinen-Marburger empirical equation \([29]\):

\[
f_k = \frac{1}{\exp \left( \frac{k_0 R T^2}{E_a \phi} \exp \left( -\frac{E_a}{R T} \right) \right) + 1}
\]

(6)

Where \( \phi \) is the heating rate, has units of °C·s\(^{-1}\).

During the cooling stage, the martensitic transformation kinetics is described by the following equation derived from the Koistinen-Marburger empirical equation \([29]\):

\[
f_m = f_a \left( 1 - \exp[-0.011(M_s - M_q)] \right), \quad \phi \geq 50 \text{ °C} \cdot \text{s}^{-1}
\]

(7)

Where \( f_m \) is the volume fraction of martensite; \( M_s \) is the martensite start temperature; \( M_q \) stands for the temperature to which the specimen is quenched. \( M_s \) and \( M_q \) both have the units of °C. \( \phi \) is the minimum cooling rate for the martensitic transformation of GCr15 bearing steel. According to the previous research, the martensite starting temperature \( M_s \) of GCr15 bearing steel is about 200 °C \([30]\). As the cooling rates of laser quenching were close to oil quenching, the commercial \( T_q \) of 65 °C for oil quenching has been used in the present simulations \([31, 32]\).

To predict the phase transformations during the laser quenching process, the temperature evolution should be combined with phase transformation models. As shown in figure 3, the temperature distribution evolutions calculated with the thermal process model were used to calculate the phase transformations. During the heating stage, the temperature and heating rate data were put into the austenitic transformation model to calculate the austenite volume fraction; during the cooling stage, the temperature, cooling rate and the austenitic fraction.
fraction calculated by the austenitic transformation model were all put into the martensitic transformation model to calculate the martensite volume fraction. Calculating according to the above processes for every point in the workpiece, the microstructure distributions were obtained.

3. Result and discussion

3.1. Experimental

3.1.1. Thermo-physical parameters

Figure 4 shows the relationships between thermo-physical parameters and temperature. As shown in the figure, thermal conductivity of GCr15 bearing steel almost keeps unchanged from 25 to 300 °C, then decreases with the increasing of temperature from 300 to 700 °C. After 700 °C, the thermal conductivity increases a little and then tends to remain unchanged. Figure 4 also shows that the specific heat capacity of GCr15 bearing steel first increases with temperature and then decreases after reached the peak value at the temperature of about 700 °C. As shown in the figure, almost linear relationship between the specific heat capacity and temperature before the austenitic transformation starts can be seen. When the temperature reaches the austenitic transformation temperature, the specific heat capacity is mostly influenced by the latent heat. As the latent heat is proportional to the austenitic transformation rate, the specific heat capacity increases with temperature before the peak austenitic transformation rate is reached and then decreases after the peak rate. At temperature higher than 1000 °C, the specific heat capacity will remain nearly constant.
3.1.2. Austenitic transformation kinetics

Figure 5 (a) shows the relationships between dilatometric value and temperature. Linear relationships between dilatometric value and temperature are shown in the figure before and after the transformation of pearlite to austenite. During the austenitic transformation processes, the dilatometric values decrease with temperature for the volume shrinkage induced by the phase transformation. The curves also show that the start and finish temperatures of transformation obviously increase with the heating rate. This should be related to the incubation time needed for the nucleation of austenite. As shown in figure 5(b), the volume fraction of austenite transformed from pearlite was calculated with the following relationship:

$$f_a = \frac{\Delta d}{\delta_{a \rightarrow b}(T)}$$  \hspace{1cm} (8)

Where $f_a$ is the volume fraction of austenite, $\Delta d$ is the decrease of the dilatometric value induced by the austenitic transformation, has units of $m$; $\delta_{a \rightarrow b}(T)$ is the total decrease of the dilatometric value if all the pearlite is transformed to austenite at temperature $T$, has units of $m$. Figure 6 shows the volume fraction of austenite calculated with the dilatometric data.

According to equation (6), three parameters: activation energy $E_a$, JMA exponent $n$ and pre-exponential factor $k_0$ are needed to quantitatively describe the austenitic transformation kinetics. The activation energy $E_a$ for uniform heating process is always obtained with the following Kissinger-like relationship [27]:

$$\ln \left( \frac{\varphi}{T_p^2} \right) = \frac{E_a}{RT_p} + C$$  \hspace{1cm} (9)

Where $T_p$ is the temperature at which the peak austenitic transformation rate achieves, has units of $K$; $C$ is a fitting parameter. Figure 7(a) shows the relationships between the austenitization rate and temperature for
different heating rates. The austenitic transformation rate increases with the heating rate for the increasing of transformation temperature. Figure 7(b) shows the linear fitting results for the relationship between \( \frac{\ln \varphi}{T_p^2} \) and \( \frac{1}{T_p} \). According to equation (9), the activity energy \( E_a \) was calculated with the linear fitting slope to be \( 540551.3 \text{ J mol}^{-1} \).

Taking logarithms on both sides of the JMA equation, the following linear relationship was obtained:

\[
\ln \left( \ln \frac{1}{1-f} \right) = n \ln \left( \frac{\beta}{k_0} \right) + n \ln k_0
\]  

(10)

Where the expression \( \beta/k_0 \) can be evaluated with the following formula:

\[
\frac{\beta}{k_0} = \exp \left( -\frac{E_a}{RT} \right) \cdot \frac{T^2}{\phi} \cdot \frac{R}{E_a} \cdot \left( 1 - \frac{2RT}{E_a} \right)
\]  

(11)

According to equation (10), the parameters \( n \) and \( k_0 \) can be obtained by linear fitting the relationship between \( \ln \left( \ln \frac{1}{1-f} \right) \) and \( \ln \left( \frac{\beta}{k_0} \right) \). Figure 8 shows the linear fitting results for equation (10). The fitted values of \( n \) and \( k_0 \) are shown in Table 1. The JMA exponent \( n \) takes the average value for different heating rates to be 1.47. To parameterize the values of \( k_0 \), the following exponential formula describing \( k_0 \) with \( \varphi \) was used:

\[
\frac{k_0}{\varphi} = A \exp(B\varphi)
\]  

(12)

Where \( A \) and \( B \) are fitting parameters. Figure 8(b) shows the non-linear fitting results for equation (12). The values of \( A \) and \( B \) were fitted to be \( 2.15 \times 10^3 \) and 0.92, with the adjusted R-square larger than 0.99.

Using the parameters obtained by fitting the experimental data, the volume fractions of austenite during the austenitic transformations for different heating rates can be calculated with equation (6). Figure 9 compares the calculated values to the experimental data. As shown in the figure, the JMA model can describe the austenitic transformation kinetics with a reasonable precision.

| \( \varphi \) (°Cs \(^{-1} \)) | \( n \)  | \( k_0 \)  |
|-----------------|-------|----------|
| 3               | 1.31  | 5.05 × 10^15 |
| 30              | 1.50  | 5.56 × 10^15 |
| 60              | 1.85  | 6.33 × 10^14 |
| 120             | 1.23  | 2.16 × 10^14 |
3.2. Simulation

3.2.1. Temperature evolution

Figure 10 shows the simulated temperature distribution for $Q = 5 \times 10^7 \text{ W m}^{-2}$ and $v = 0.013 \text{ m s}^{-1}$. The laser spot moves in the positive direction of the $y$-axis. Asymmetric distributions of the temperature can be seen in front and behind the laser spot. The temperature gradient in front of the laser spot is much larger than the behind.

Figure 11 shows the influences of peak heat flux and scanning speed on the temperature distributions.

Figure 10. Simulation results of temperature distribution for $Q = 5 \times 10^7 \text{ W m}^{-2}$ and $v = 0.013 \text{ m s}^{-1}$.

Figure 11. Influences of peak heat flux and scanning speed on the temperature distributions.
shown in the figure, the temperature increases from the side to the center of the workpieces and shows a very large gradient near the center points. Though the peak temperature obviously increases with the peak heat flux, the temperature at the edge of the workpieces changes little. Figure 11(b) shows the temperature distribution along the line (y = 0.05 m, z = 0.01 m) at the time when the laser focus located at the line for the peak heat flux \( Q = 4 \times 10^7 \text{ W m}^{-2} \) for different scanning speeds. The temperature decreases with the increasing of scanning speed. When the scanning speed decreases from 0.005 to 0.003 m s\(^{-1}\), the peak temperature increases about 100 °C and the temperature at the edge increases little. However, when the scanning speed decreases from 0.003 m s\(^{-1}\) to 0.001 m s\(^{-1}\), the peak temperature increases about 350 °C and the temperature at the edge also increases about 100 °C. As the scanning speed is inversely proportional to heating time, the nonlinear influence of the scanning speed on the temperature means that the heating time should be a more sensitive factor than power. Figure 11(c) shows the temperature distribution along the line (x = 0.05 m, y = 0.05 m) at the time when the laser focus located at the line for the scanning speed \( v = 0.001 \text{ m s}^{-1} \) and different peak heat fluxes. Figure 11(d) shows the temperature distribution along the line (x = 0.05 m, y = 0.05 m) at the time when the laser focus located at the line for the peak heat flux \( Q = 4 \times 10^7 \text{ W m}^{-2} \) for different scanning speeds. As shown in the two figures, the linear influences of the peak heat flux on the temperature and the nonlinear influences of the scanning speed on the temperature further show that the heating time is a more sensitive factor than power.

Figure 12 shows the temporal evolution of temperature at point (x, y, z) = (0.05 m, 0.05 m, 0.01 m). Figure 12(a) shows the simulation results for \( v = 0.001 \text{ m s}^{-1} \) and different peak heat fluxes. As the laser moves to the point, the point on the workpiece is first heated then cooled rapidly. The peak temperature increases with the peak heat flux. The heating and cooling rates of the point are about 120 °C s\(^{-1}\) and −100 °C s\(^{-1}\), respectively. The figure also shows that the peak heating and cooling rates change little with the increasing of peak heat flux. It means that peak heating rate is mainly decided by the thermal diffusion process and influenced little by the laser power. Figure 12(b) shows the simulation results for \( Q = 4 \times 10^7 \text{ W m}^{-2} \) and different scanning speeds. The peak temperature decreases with the scanning speed, but the heating and cooling rates increase with the scanning speed. Comparing figures 12(a) and (b), it can be concluded that the peak heating and cooling rates are mainly decided by the scanning speed rather than the laser power.
3.2.2. Microstructure evolution

Figure 13 shows the simulation results of microstructure for different scanning speeds and peak heat fluxes. The figures show parabolic quenched zones distributed around the laser focus. As the heating rate of the workpiece decreases from the center to the edge of heat affected zone, the martensite fraction also decreases from the center to the edge. When the heating rate is low, the temperature will not reach the austenitization finishing temperature, thus the microstructure will be partially austenitized and then partially transformed to martensite. Figure 13(a) shows the simulation results of the martensitic volume fraction distribution at the cross section of $y = 0.05$ m after 200 s (when the laser focus left the right boundary of the workpiece) for $v = 0.001$ m s$^{-1}$ and different peak heat fluxes. The areas of the quenched zones increase with the peak heating flux for the increasing of heat input. Figure 13(b) shows the simulation results of the martensitic volume fraction distribution at the cross section of $y = 0.05$ m when the laser focus left the right boundary of the workpiece for $Q = 4 \times 10^7$ W m$^{-2}$ and different scanning speeds. As the scanning speed increases, the heat input into the workpiece decreases, thus the quenched zone decreases accordingly. The simulation results show that, increasing the heat flux or decreasing the scanning speed, which increase the heat input, both can deepen the quenched layer.

3.2.3. Technological parameters designing

Though the increasing of heat input will always deepen the quenched layer, it also increases the temperature of the surface. If the surface temperature is sufficiently high to melt the steel, the microstructure of the surface will
be changed and lead to the reducing of rolling contact fatigue life of the bearing steel. The surface temperature of the workpiece is always limited under 1300 °C to avoid overheating of the bearing steel during the laser quenching processes. As shown in figure 14(a), to obtain the critical technological parameters for avoiding overheating, the Newton iteration method was used to get the critical scanning speed for different peak heat fluxes. Figure 14(b) shows the relationship between the peak heat flux and the critical scanning speed. As shown in the figure, the critical scanning speed increases with the peak heat flux. If the technological parameters located under the critical parameter curve, the workpiece will be overheated. The parameters locate at the curve will lead to the deepest quenched layer and suitable microstructure.

Figure 15 shows the simulation results of the martensitic volume fraction distributions at the cross section of \( y = 0.05 \) m when the laser focus left the right boundary of the workpiece for the technological parameters located at the critical parameter curve as shown in figure 14(b). As shown in the figure, the depth of the quenched layer increases with the decreasing of the peak heat flux and the critical scanning speed. When the heat flux and scanning speed are low, more heat will be input into the workpiece before the temperature reach the limiting temperature, thus lead to deeper quenched layer. It should be mentioned that the quenched layers shown in figures 13(a) and (b) are deeper than the present predicted deepest quenched layer of \( Q = 3 \times 10^7 \) W m\(^{-2}\) and \( v = 0.0011 \) m s\(^{-1}\). As the quenched layers shown in figures 13(a) and (b) were simulated without considering the influences of the surface melting, the simulation parameters of the deeper quenched layers in figures 13(a) and (b) should locate in the overheated zone as shown in figures 14(b).

It should be emphasized that the parameter \( Q \) used in the present research is the peak heat flux at the surface of workpiece, not the usually used technological parameter laser power. As the surface absorptivity is always related to material property, surface condition and temperature, there should be nonlinear relationships between the surface heat flux and the laser power. Thus, when using the results of the present research, the relationships between the practical laser power and surface heat flux should be carefully considered.

4. Conclusion

The laser quenching process of GCr15 bearing steel was simulated with a combination of temperature and microstructure evolution models. Basing on the experimentally measured thermo-physical parameters and austenitic transformation kinetics, the temperature and microstructure evolutions for different technological parameters of laser quenching process was simulated with the models. According to the experimental and numerical simulation results, the austenitization kinetics of GCr15 bearing steel for high heating rates can be described by the isochronal JMA relationship, and the material parameters for the relationship have been obtained. The microstructure evolution of GCr15 bearing steel during the laser quenching processes were predicted. The relationships between the two parameters (peak heat flux at workpiece surface and laser scanning speed) and quenched layer depth were established. Thus, optimized technological parameters to deepen the quenched layer will be obtained basing on clarified relationships between the laser power and peak heat flux at workpiece surface.

Acknowledgments

This work was supported by the China Postdoctoral Science Foundation (No. 2018M631362).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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