Numerical simulation of two-track laser hardening process of 42CrMo steel

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ABSTRACT
In this study, a thermal–phase–mechanical coupled numerical model was presented for the prediction of the distribution of temperature, phase and residual stress of 42CrMo steel during two-track laser hardening process. Austenite and tempering transformation were simulated based on the isocconversional method. K-M equation was used to calculate the fraction of martensite. Residual stress was calculated considering the thermal strain, transformation strain and transformation plasticity. The accuracy of the numerical model was verified according to the comparison with experimental results. The stress distribution of two-track laser hardening process was studied according to numerical simulation results. And the effect of the second track on the residual stress produced by the first track in two-track laser hardening was also analyzed by using this numerical model.

KEYWORDS
Laser hardening; numerical simulation; overlapping; residual stress

Introduction
As a surface strengthening technology, laser hardening is widely used in the treatment of mechanical parts, such as bearing, gear, guide and die, which may easily fail due to fatigue and wear. During laser hardening process, the surface of part is heated rapidly by laser irradiation, then the heat spreads to the entire part through heat conduction, resulting in rapid cooling. A hardened layer can be formed by laser hardening, of which the depth depends on the laser power, scanning speed and laser spot size [1]. The hardened layer consists of martensite and carbide, which can improve the hardness, strength and wear resistance of the part [2]. In addition, the stress state of laser-hardened layer is compressive, which is beneficial to slow down the propagation of the short crack and improve fatigue life [3]. Compared with other surface strengthening technologies, the advantages of laser hardening include high heating and cooling speed, and accurate hardening region without additional quenching medium [4].

Many studies are implemented focusing on the investigation of the strengthening mechanism and residual stress distribution of laser hardening. Zhang et al. [5] investigated the hardness distribution and the depth of 9CrMo steel after laser hardening, and found that the hardness of the surface was lower than that of the subsurface because the austenite grains of surface grew up due to overheating. Sun et al. [6] investigated the microstructure of different layers of 42CrMo steel after laser hardening. According to the results, the microstructure of surface layer is butterfly martensite, and in laser transformation hardened zone, the microstructure mainly includes the mixture of needle, lath martensite and retained austenite. A. Solina et al. [7] measured the residual stress distribution after the laser hardening of several steels, and analyzed the evolution of stress during laser hardening theoretically. Kostov et al. [8] studied the time-dependent stress evolution during laser hardening by using in-situ stress analysis method. Liverani et al. [9] established a numerical model for the prediction of the distribution of axial stress and circumferential stress of an AISI 9810 steel after laser hardening.

However, the utilization of laser hardening for large parts is limited by laser spot size and laser power. One solution to this problem is multi-track laser hardening in which the martensite at the edge of overlapped area will be tempered during the last laser track, causing the deterioration of mechanical properties [10]. Most of the researches focused on the simulation of hardness distribution of multi-track laser hardening based on the thermal–transformation numerical mode. The effect of the process parameters on hardness distribution was analyzed for technology optimization [10–12]. And yet, few works have dealt with the
coupling of microstructure transformation and residual stress of the multi-track laser hardening due to its complexity.

The material experienced heating, cooling and tempering stages during the multi-track laser hardening process. The residual stress produced by different laser tracks interacts with each other by thermal and transformation strain of multiple thermal cycling. Therefore, it is necessary to study the multi-physical model of multi-track laser hardening for the prediction of the temperature, microstructure and residual stress. For this purpose, a two-track laser hardening process of 42CrMo steel was investigated based on a thermal-transformation–mechanical coupled numerical model in this work. Three types of phase transformation, austenitizing, quenched and tempered martensite transformation, were taken into consideration in the simulation of the laser hardening process. The corresponding experiment was conducted to verify the proposed numerical model. The temperature, microstructure and residual stress at the hardened layer and heat-affected zone were analyzed to study the influence of the overlapped hardening. The research of this paper provides a feasible method for the modeling of multi-track laser hardening.

**Numerical model**

Multi-track laser hardening is divided into three phase-transform steps:

(a) Base material transforms to austenite during heating.
(b) The austenite decomposes during rapid cooling.
(c) The martensite at the edge of overlapped zone decomposes because of tempering.

In this study, the numerical simulation of two-track laser hardening process includes the coupling of thermal, phase transformation and stress fields. A 3-D moving heat source model was utilized for the simulation of the thermal effect of laser and heat conduction was calculated by using the Fourier conduction equation. In addition, austenite transformation and tempering process were simulated by using the isoconversional method, and K-M equation was used for the calculation of the fraction of martensite. The thermal strain, transformation strain and transformation plasticity were considered in stress model.

**Thermal field model**

Fourier conduction equation is used for the analysis of heat conduction, which can be expressed as:

\[
\lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q' = \rho c_p \frac{\partial T}{\partial t}
\]  

where \(\lambda\) refers to the thermal conductivity, \(\rho\) represents the density, \(c_p\) stands for the specific heat and \(q'\) denotes the internal heat source. The second boundary condition is used to describe the thermal effect of laser spot, which is expressed as:

\[
-\lambda \frac{\partial T}{\partial n} = q_w(x, r, t)
\]  

where \(\frac{\partial T}{\partial n}\) refers to the temperature gradient on the surface of part, and \(q_w(x, r, t)\) represents the energy distribution function of laser spot. In this study, the energy distribution in laser spot is uniform, which can be expressed as:

\[
q_w(x, y, t) = \begin{cases} 
\frac{\alpha Q}{ab} & \text{if } vt - \frac{a}{2} \leq x \leq vt + \frac{a}{2} \text{ and } nd - \frac{b}{2} \leq y \leq nd + \frac{b}{2} \\
0 & \text{else}
\end{cases}
\]

where \(\alpha\) refers to the absorptivity of 42CrMo steel. In this study, \(\alpha = 0.4\). \(Q\) denotes the laser power, \(a\) and \(b\) represent the length and width of laser spot, respectively, and \(v, n\) and \(d\) stand for the scanning speed, track number and the distance between tracks, respectively.

The heat transfer between surface and surroundings can be described by the third boundary condition, expressed as follows:

\[
-\lambda \frac{\partial T}{\partial n} = H_k(T - T_c)
\]

where \(H_k\) refers to the total temperature-dependent heat transfer coefficient, and \(T_c\) stands for the surrounding temperature. In this study, \(H_k\) can be expressed as [13]:

\[
H_k = \begin{cases} 
0.0668T & \text{if } T < T_c < 500^\circ \text{C} \\
0.231T - 82.1 & \text{if } T > 500^\circ \text{C}
\end{cases}
\]

**Phase transformation model**

**Austenitizing model**

At the heating stage of laser hardening, the base material was heated to above austenitizing temperature, and transformed into austenite. The austenite transformation rate can be expressed based on the isoconversional theory [14], expressed as follows:

\[
\frac{df_a}{dt} = k' \exp \left( -\frac{Q}{RT} \right)
\]

where \(f_a\) refers to the volume fraction of austenite, \(t\) represents the heating time, \(R\) stands for the gas constant, \(T\) denotes the temperature, \(k'\) is the preexponential factor, and \(Q\) refers to the activation energy. The relationship among \(k', Q\) and \(f_a\) can be fitted using the transformation-temperature curves at different heating rates.
Martensitic transformation model

The austenite transforms to martensite at the cooling stage through non-diffusive transformation. Assuming that the martensite fraction is a function of the temperature, Koistinen and Marburger [15] put forward an empirical equation to describe this relationship (K-M equation) as:

\[ f_M = 1 - \exp[-k_s(M_s - T)] \]

where \( f_M \) refers to the volume fraction of martensite, \( M_s \) represents the starting temperature of martensitic transformation and \( k_s \) stands for a material constant. In this paper, \( k \) and \( M_s \) of 42CrMo steel were measured by thermal dilatation tests.

Tempering model

Multi-track laser hardening is necessary if the region to be treated is larger than laser spot, and the martensite at the edge of overlapped zone will be tempered in the laser track. It is generally accepted that the tempering process of 42CrMo steel can be divided into four stages [16]:

(a) Stage 1(<200°C): segregation of C-atoms and precipitation of metastable \( \varepsilon \)-carbide.
(b) Stage 2(200–300°C): decomposition of retained austenite.
(c) Stage 3(300–400°C): metastable \( \varepsilon \)-carbide and segregated C-atoms transform into \( \varepsilon \)-carbide (cementite).
(d) Stage 4(>400°C): coarsening of cementite and precipitation of metastable cementite.

According to the thermal dilatation test, the volume change is obvious in Stage 3 of tempering. While Stage 1, 2 and 4 can be ignored in stress calculation due to the absence of transformation strain. The isoversional model is also adopted to describe the transformation kinetics of tempering.

Mechanical model

In the process of laser hardening, the total strain \( \{\varepsilon\} \) is the linear superposition of elastic strain \( \{\varepsilon_e\} \), plastic strain \( \{\varepsilon_p\} \), thermal strain \( \{\varepsilon_t\} \), transformation strain \( \{\varepsilon_{tr}\} \) and transformation plasticity \( \{\varepsilon_{tp}\} \), which can be described as follows:

\[ \{\varepsilon\} = \{\varepsilon_e\} + \{\varepsilon_p\} + \{\varepsilon_t\} + \{\varepsilon_{tr}\} + \{\varepsilon_{tp}\} \]

Von Mises yield criterion is used to determine whether the material is in plastic state. According to the thermoelastic theory, Hooke’s law can be written as:

\[ \{\sigma\} = [D_e]\{\varepsilon\} \]

where \( \{\sigma\} \), \( [D_e] \) and \( \{\varepsilon\} \) refer to stress tensor, elastic matrix and elastic strain tensor, respectively. The total differential form of Equation (9) is:

\[ d\{\sigma\} = [D_e](d\{\varepsilon\} - d\{\varepsilon_0\}) \]

where \( d\{\varepsilon_0\} \) represents the additional strain due to the consideration of the effect of temperature on elastic modulus, which can be expressed as:

\[ d\{\varepsilon_0\} = \frac{\partial[D_e]}{\partial T}(\{\sigma\}dT) \]

Substituting Equation (8) into Equation (10), Equation (12) can be obtained as:

\[ d\{\sigma\} = [D_e](d\{\varepsilon\} - d\{\varepsilon_t\} - d\{\varepsilon_{tr}\} - d\{\varepsilon_{tp}\} - d\{\varepsilon_0\}) \]

For plastic state, considering the effect of temperature on yield, Von Mises yield criterion is described by using Equation (13):

\[ \sigma - \sigma_t(d\varepsilon_p, T) = 0 \]

where \( d\varepsilon_p \) stands for the increment of equivalent plastic strain. According to Prandtl–Reuss flow rule, the relationship among \( d\varepsilon_p \), incremental plastic strain and stress state can be expressed as:

\[ d\{\varepsilon\} = d\varepsilon_p \frac{\partial\sigma}{\partial\sigma_t} \]

The total differential form of Equation (12) is:

\[ d\varepsilon_p = \left( \frac{\partial\sigma}{\partial\sigma_t} \right)^T [D_e](d\varepsilon - d\varepsilon_t - d\varepsilon_{tr} - d\varepsilon_{tp} - d\varepsilon_0) - \frac{\partial\sigma_t}{\partial T}(\{\sigma\}dT) \]

Substituting Equations (14) and (15) into Equation (8), the incremental constitutive equation of thermal elastoplastic can be written as:

\[ d\{\sigma\} = [D_{ep}](d\{\varepsilon\} - d\{\varepsilon_t\} - d\{\varepsilon_{tr}\} - d\{\varepsilon_{tp}\} - d\{\varepsilon_0\} + d\{\sigma_0\}) \]

where \( [D_{ep}] \) refers to the elastoplastic matrix and \( d\{\sigma_0\} \) represents the additional strain based on the consideration of the effect of temperature on plastic modulus:

\[ [D_{ep}] = [D_e] - \left( \frac{\partial\sigma}{\partial\sigma_t} \right)^T [D_e] \left( \frac{\partial\sigma_t}{\partial\sigma_t} \right) + \left( \frac{\partial\sigma}{\partial\sigma_t} \right)^T [D_e] \frac{\partial\sigma_t}{\partial T} \]

\[ d\{\sigma_0\} = \left( \frac{\partial\sigma}{\partial\sigma_t} \right)^T [D_e] \frac{\partial\sigma_t}{\partial T}dT \]
The increment of thermal strain can be calculated by:

\[ \Delta e_{\text{th}} = \sum_{i=0}^{3} f_i \xi_i dT \]  \hspace{1cm} (20)

where \( f_i \) refers to the volume fraction of the \( i \)th phase, and \( \xi_i \) represents the thermal expansion coefficient of the \( i \)th phase.

Transformation strain is generated due to volume change in phase transformation, which is expressed as follows:

\[ \Delta e_{\text{tr}} = \sum_{i=0}^{3} \beta_i(T) df_i \]  \hspace{1cm} (21)

\[ \beta_i(T) = \beta_i(T_0) + (\xi_i - \xi_{i-1})T \quad i \geq 1 \]  \hspace{1cm} (22)

where the subscript \( i \) and \( i-1 \) represent the new and parent phase, respectively, and \( \beta_i(T_0) \) refers to the volume difference between parent and new phase at temperature \( T_0 \).

The strain produced by martensite transformation plasticity is calculated by using Desalos model, which can be expressed as:

\[ e_{\text{tp}} = K \sigma m(2 - m) \]  \hspace{1cm} (23)

According to the flow rule, the increment form of Equation (23) in multiaxial stress state can be expressed as:

\[ \Delta e_{\text{tp}} = 3K\sigma_i(1 - m)\Delta m \]  \hspace{1cm} (24)

where \( K \) refers to Desalos parameter of martensite phase transformation, \( m \) represents the volume fraction of martensite, and \( \sigma_i \) stands for the deviatoric stress tensor.

**Material parameters**

The material parameters used in numerical simulation include thermophysical properties and mechanical properties. In this paper, the specific heat of 42CrMo was measured by using SETARAM 96-Line high-temperature calorimetry, and the conductivity was measured by using TA DLF-1600 laser thermal diffusivity instrument. The specific heat and conductivity of 42CrMo steel as a function of temperature are shown in Figure 1.

The mechanical properties of different microstructures of 42CrMo steel were measured by tensile tests at various temperatures. Figure 2 shows the strain–stress curves of austenite, martensite and tempered martensite at different temperatures. The elastic modulus and the yield stress were measured by using strain–stress curves, as shown in Figure 3. The Poisson ratio of 42CrMo steel is 0.3.

A cylindrical sample (φ1 × 10 mm) made of 42CrMo steel was used in the thermal dilatation test with DIL 805A/D/T quenching dilatometer, which was heated to 900°C and kept for 5 s, then cooled to room temperature. The thermal cycling was repeated after 5 s at the heating and cooling rate of 100°C/s. The axial dilatation of the sample was measured. Figure 4 shows the process of thermal dilatation test, and Figure 5 illustrates the thermal dilatometric curve.

For different microstructures, the thermal expansion coefficient, critical temperature and parameters of transformation strain can be fitted by using the thermal dilatometric curve. In addition, thermal dilatometric curves of 42CrMo steel were tested at 1100°C at the heating rate of 0.2, 2, 10, 20, 50 and 100°C/s, respectively, as shown in Figure 6. The parameters of phase transformation kinetics were fitted by using these thermal dilatometric curves, as listed in Table 1.

The lever rule was applied to convert thermal dilatometric curves into temperature-volume fraction curves at different heating rates, as shown in Figure 7.

Taking the logarithm of Equation (6):

\[ \ln \left( \frac{dy}{dt} \right) = \ln k' - \frac{Q}{RT} \]  \hspace{1cm} (25)

It is clear that there is a linear relationship between logarithmic transformation rate and the reciprocal of temperature. The intercept and slope are \(-Q/R\) and \( \ln k' \), respectively. The parameters of isocconversional theory for austenite transformation is shown in Figure 8a,b shows the parameters for tempering by previous work. The parameter \( k \) of Equation (7) is...
also calculated by thermal dilatometric curve, and \( k = 0.035 \). Desalos parameter of martensite phase transformation is \( 4.53 \times 10^{-10} \text{ Pa}^{-1} \) \([17]\).

**Experimental and simulation procedure**

In this paper, a 2 kW fiber laser (IPG YLS-2000, wavelength 1070 nm) was used to irradiate the surface of sample through a laser head mounted on a 5-axis machine tool. The size of laser spot is \( 1 \times 10 \text{ mm} \). Two kinds of laser hardening processes were conducted in experiments. Specifically, the first sample was hardened by one-track laser hardening process to explore the morphology of hardened layer and the distribution of residual stress after the first laser track of the two-track laser hardening. The second sample was hardened by two-track laser hardening process to describe the effect of the second track on the residual stress produced by the first track. A 600 s air cooling was conducted between two tracks to decrease the residual temperature of the first track. The sample is a blank in the dimension of \( 80 \times 40 \times 10 \text{ mm} \) for treatment with one-track laser hardening process, and \( 50 \times 40 \times 10 \text{ mm} \) to be used in two-track laser hardening process, respectively. All samples were tempered at 600°C for 4 h to eliminate the internal stress of material before laser hardening.

The laser power of both processes was 1300 W, and the scanning speed was 4 mm/s. The track length of the two processes were 60 and 40 mm, respectively. For two-track laser hardening process, the width of overlapped zone is 3 mm, as shown in Figure 9. The

**Figure 2.** Stress–strain curves of (a) austenite, (b) martensite and (c) tempering martensite at different temperatures.

**Figure 3.** (a). Elastic modulus and (b) yield stress of different microstructures at different temperature.
residual stress were measured using X-ray diffraction method which is capable of determining the elastic strain in the irradiated area by measuring the lattice spacing. The stresses can be evaluated using the expression of Hooke’s law [18]:

$$\sigma = E(\Delta d/d_0)$$  \hspace{1cm} (26)

where $E$, $\Delta d$ and $d_0$ refers to elastic modulus, lattice spacing without stress and lattice spacing with stress to be determined, respectively. In our work, an X stress 3000 G3 X-ray diffractometer is used to determine the residual stress on the surface because X-ray penetration is of the order of 0.025 mm.

**Figure 10** shows the finite element mesh models of the sample used in both processes. The geometric models have been meshed with 246,518 and 383,873 tetrahedron elements using finer elements in the laser irradiation regions. Only half of the sample was modeled to improve the efficiency of simulation based on the symmetric feature of the model. The simulation was performed using MSC.MARC with user defined subroutines written.

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**Figure 4.** Schematic of the thermal dilatation test.

**Figure 5.** Thermal dilatometric curve of the sample.
Results

The first laser track laser hardening process

Figure 11 illustrates the temperature distributions on the surface and the middle cross section during the first laser track process at different times (5 s, 10 s and 15 s). The maximum temperatures of the sample at 5 s, 10 s and 15 s are 1342.6°C, 1353.6°C and 1353.5°C, respectively. In addition, the maximum temperature of sample increases due to heat accumulation at the initial stage of laser hardening process, and then remains unchanged because of the balance between laser heat and convective heat transfer. Figure 12 shows the temperature distributions of laser track in X/Y/Z directions at 10 s. XY plane and XZ plane refer to the surface and the middle cross section, respectively. The surface temperature is higher than the internal temperature. In the direction of laser scanning (X direction), the temperature gradient decreases with the increase of the distance to the...
front of laser spot. While in the vertical direction of laser scanning (Y direction), the temperature gradient decreases with the increase of the distance to the center of laser spot. In the depth direction (Z direction), the temperature gradient decreases with the increase of depth. Besides, the maximum heating depth is at the rear of laser spot.

Figure 13 shows the temperature evolutions on the surface during the first laser track at selected depths (0, 0.25, 0.5, and 1 mm). The maximum temperature decrease with the increase of depth. The average heating rate on the surface of sample is 179.9°C/s. The surface temperature decreases to 200°C after being cooled for 2.6 s with the average cooling rate of 442.1°C/s which is higher than the critical cooling rate for martensite formation.

Figure 14 illustrates the comparison of laser hardened layer morphology between experimental and simulated results, verifying the validity of the numerical model. The morphology of middle cross section is crescent. The maximum depth and width are 875.0 µm and 5 mm, respectively.

Figure 15 shows the residual stress distribution of laser track after the first laser hardening process. According to the result, the residual stress along X and Y direction are compressive in the laser hardened layer due to the volume expansion of martensite transformation. Figure 16 illustrates the residual stress distribution along Path1 and Path2. To verify the simulation result, the residual stress at different points in hardening area was measured by using X-ray diffraction method. The residual stress in hardening area is evenly distributed. The average values are −272 MPa and −445 MPa on X and Y direction, respectively. However, the residual stress at the edge

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**Table 1. Transformation parameters of 42CrMo.**

| Type of the transformation | Parent phase | New phase | $\xi_i$ (10^-5 / °C) | $\xi_j$ (10^-5 / °C) | $\beta_i(T_0)$ (10^-3) | Critical temperature (°C) |
|---------------------------|-------------|-----------|----------------------|----------------------|------------------------|---------------------------|
| Austenitizing             | Sorbite     | Austenite | 1.45                 | 2.24                 | −7.546                 | 806                       |
| Second Austenitizing      | Tempered martensite | Second Austenite | 1.45 | 2.35 | −8.736 | 768 |
| Martensitic               | Austenite   | Martensite| 2.24                 | 0.727                | 9.6                    | 320                       |
| Tempering                 | Martensite  | Tempered martensite | 1.35 | 1.45 | −0.9381 | 385 |

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**Figure 8.** The parameters of isoconversional theory for (a) austenite transformation and (b) tempering.

**Figure 9.** Schematic of overlapped zone in two-track laser hardening process.

**Figure 10.** Finite element mesh model of the sample used in (a) one-track and (b) two-track laser hardening process.
Figure 11. Simulated temperature distributions on (a) the surface and (b) the middle cross section.

Figure 12. Simulated temperature gradients of all directions in the laser spot at 10 s.

Figure 13. Simulated temperature evolutions on the surface during the first laser track process at selected depth.
Figure 14. Experimental and simulated laser hardened layer morphology.

Figure 15. Simulated distribution of (a) X direction and (b) Y direction residual stress after the first laser track process.

Figure 16. Experimental and simulated residual stress distribution curve of (a) Path1 X direction (b) Path1 Y direction (c) Path2 X direction (d) Path2 Y direction.
is significantly higher than that at the center of laser track. Both simulation and experimental results show that residual stress on X/Y direction is tensile and unevenly distributed in the heat-affected zone. The maximum residual stress on X and Y direction are 300 MPa and 1000 MPa, respectively. And high tensile stress will lead to high possibility of crack initiation at the edge of the hardened area. Multiple variables, such as heating rate and peak temperature can be optimized to achieve optimal residual stress distribution.

Figure 17 exhibits the stress evolution of the hardened layer, heat affected zone and substrate during the first laser track process. In the hardened layer, the residual stress is a summation of two factors, i.e. the thermal stresses caused by thermal gradient and that originated from the volume change of phase transformation [16]. The laser irradiation zone is subjected to the constraint of surrounding materials due to the volume expansion in the heating period. Thus, the stress state of this period is compressive. At cooling stage, the temperature decreases rapidly, which induces volume shrinkage. The compressive stress state changes to tensile stress which first increases and then decreases slightly. At the temperature below Ms point, the austenite of hardened layer transforms into martensite, which is accompanied by the volume expansion due to the decrease of specific volume. In the hardened layer, transformation stress is larger than thermal stress due to large phase transformation. On the contrary, there is less phase transformation, and thermal stress contributes more to the stress in the heat-affected zone. Therefore, the residual stress of hardened layer is compressive, while that in the heat-affected zone is tensile.

**The second track laser hardening process**

Figure 18 shows the optical microscopy image of hardened layer after the second laser track process. Zone A and C represent the hardened layer formed during the first and second scanning track. The microstructures of both A and C (Figure 18(b,d) are as-quenched lath martensite with the average hardness of 646.9 Hv. Zone B is hardened by first track and tempered by the second track. The width of zone B is 1.7 mm on the surface and 2.5 mm on the subsurface. The microstructure of zone B retains the lath martensite morphology. The growth time of precipitated tempered carbides is short due to the fast heating and cooling rate during the second thermal cycle. Therefore, plenty of tempered carbides with small dimensions can be observed in Figure 18(c). The average hardness of tempering zone is significantly lower than that of laser hardened layer, which is only 487.8 HV.

Figure 19 shows the temperature and phase fraction distribution curves at 5 s during the second laser track process. The blue and red curves represent martensite and tempered martensite fraction distribution of the path, respectively. The martensite generated by the first laser track is austenitized, and then transformed into martensite when the maximum temperature during the second track exceeds 768°C. When the maximum temperature is in the range from 385°C to 768°C, the quenched martensite transforms into tempered martensite. Figure 20 illustrates the simulated distribution of martensite and tempered martensite. The width of tempering zone is 1.65 mm, which is equal to the width of tempering temperature range, and close to the experiment results. It should be noted that the width of tempering zone is independent with the dimension of overlapped area, but depends on the temperature gradient on the edge of the laser track.

The distribution of residual stress on the surface after the second laser track process is illustrated in Figure 21. Figure 22 shows the comparison between experimental and simulated distribution of residual stress at the path. The result shows that the value of the residual stress in the tempering zone is much lower than the hardened zone. The X and Y direction residual stress on the center of the tempering zone are 156 MPa and 35 MPa, respectively. It should be
Figure 18. (a) The optical microscopy image of hardened layer. SEM images of (b) zone A, (c) zone B and (d) zone C. (e) Hardness distribution on the surface.

Figure 19. Simulated temperature and phase fraction distribution curves at 5 s during the second laser track process.
noted that there are two factors, creep and transformation volume change, that contribute to the decrease of stress during tempering [16]. The creep strain has little effect on the stress relive because of the short time during laser treatment. The volume shrink during tempered martensite transformation produces tensile stress which counteracts the hardened compressive stress during the first laser track.

Figure 20. Simulated distribution of (a) martensite and (b) tempered martensite.

Figure 21. Simulated distribution of (a) X direction and (b) Y direction residual stress after the second laser track process.

Figure 22. Experimental and simulated residual stress distribution curve of (a) X direction (b) Y direction.
The residual stress of the heat-affected zone of the second track remains compressive, with the average value of −400 MPa and −600 MPa on X and Y direction, respectively. The simulation result fits well with that obtained from experiment at the selected points. Compared with Figure 16(c,d), the residual stress of the first track decreases due to the temperature rise during the second track process. Therefore, the value of the residual stress in the second track is slightly higher.

Figure 23 shows the stress evolution of the first track without transformation, heat-affected zone and tempering zone during the second laser track hardening. The compressive residual stress of the first track and heat-affected zone decreases slightly due to stress relaxation based on tempering. In the tempering zone, quenched martensite transforms to tempered martensite, which leads to volume shrinkage. Both thermal and phase transformation will produce tensile stress. Consequently, the stress of the tempering zone changes to tensile stress.

Conclusions
A thermal–phase–mechanical coupled numerical FE model was established for the prediction of the distribution of temperature, microstructure and residual stress during two-track laser hardening process. The following conclusions are drawn:

1. The maximum temperature on the surface is 1353.6°C during laser heating. The tempered martensite can be obtained at the edge of overlapping area during the second laser track process. The width of the tempering zone is independent with the dimension of overlapped area, but depends on the temperature gradient on the edge of the laser spot.
2. After the first laser track process, the residual stress state is compressive on the hardened layer and tensile on the edge. The residual stress of the first track decreases slightly during the second laser track. The residual stress of the tempering zone is much lower than hardened layer after the second laser track process.
3. The simulation results fit well with the experimental ones in terms of the comparison of microstructure and residual stress. It can be concluded that the proposed model could be used for the prediction of temperature, transformation and residual stress of multi-track laser hardening process.

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