Effect of collapse and hump on thermomechanical behavior in high-power laser welding of 16-mm marine steel EH40

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Abstract
This paper concerns high-power laser welding of thick plates for the ship industry. Thermomechanical behavior during laser welding of 16-mm marine steel EH40 using 25-kW laser power was investigated by a 3D finite element model. The objective is to analyze the effects of weld collapse and hump on the residual stress-induced thermal cycle. A double-cylindrical source model was proposed to simulate the transient distribution of temperature field. Heat flow distribution area is a cylinder, radial heat flow presents a Gaussian distribution, while heat flow peak in the direction of thickness is decaying then increasing exponentially. The predicted weld geometry had good agreement with the actual results. When collapse and hump were considered, simulation error of temperature distribution was only 1.54%. In addition, cooling curves obtained from the thermal simulation were incorporated into the continuous cooling transformation diagram of EH40 to explain the evolution mechanism of microstructure. It was shown that collapse and hump affected the values and distribution trend of residual stress in different thickness, especially in the high gradient stress zone near the weld center. The collapse mainly affects the residual stress distribution on the top surface, while the hump affects that on the bottom surface. Both of them have little influence on the residual stress in the middle thickness area. The cold contraction of weld metal and the stress concentration caused by weld shape during the cooling process are the fundamental reasons that collapse and hump affect the distribution of welding residual stress.

Keywords Laser welding · Marine steel · Collapse · Hump · Residual stress

1 Introduction
Laser welding has become an important method of marine steel plate joining because of the advantages of high-power density, low thermal distortion, rapid welding speed, and so on. Unt et al. [1] investigated laser welding of single-sided T-joint on shipbuilding steel. It was reported that T-joint single-sided full penetration welding of AH36 with a thickness of 8 mm was realized; possible cracks in fillet welds were avoided successfully. Guo et al. [2] reported that narrow gap laser welding required less filler material and could reduce the cumulative heat input to material, which is helpful to control the buckling distortion, referred to as out-of-plane warping.

However, distribution of residual stress of laser-welded joints is complex, which may harm the mechanical properties of the joint. Ibrahim et al. [3] investigated the effectiveness of welding procedures for steel plates with thickness larger than 50 mm. Results showed that development of welding residual stress is exacerbated, and distribution of that becomes more complicated due to the increase of constraint to material’s expansion and contraction, especially for the middle and thick plate. Irvine et al. [4] studied the residual stress distribution in SA508 steel with a thickness of 30 mm, and found that tensile residual stresses of joint were high throughout the entire weld thickness due to particularly steep temperature gradients during welding. Xu et al. [5] analyzed in homogeneous thermal–mechanical distributions in laser welding of austenite stainless steel 316L, and discussed the effect of shear behavior caused by residual stress on tensile strength. It was concluded that shear behavior would be caused by inhomogeneous residual
stress distribution, which could reduce the tensile strength. Meanwhile, Ferro and Berto [6] quantified the influence of residual stress on fatigue strength of welded joints. In high-power laser welding, residual stress of a high gradient is formed near the weld bead because of high cooling rate, thus reducing the fatigue performance of the joint. Therefore, a detailed investigation of the residual stress distribution of high-power laser welding thick plate is required. It is widely known that numerical simulation is an important research method to reduce experiment and time cost, and to facilitate the optimization of processing parameters. Farrokhi et al. [7] studied the thermal and residual stress field of full and partial penetration of thick-section steels, and found that residual stress distribution of full penetration joint is more uniform than that of partial penetration. Rong et al. [8] proposed a finite element model of residual stress integrated with a thermodynamics-based solid phase transformation to accurately predict residual stress in laser welding of EH36 steel. Results showed that the peak value of residual stress was observed at the heat-affected zone rather than at the center of the fusion zone, which reached measurements well.

In addition, there are many factors affecting the residual stress distribution, such as properties of base material, groove type, welding parameters, and constraints. Lee [9] found that the maximum longitudinal residual stresses in similar steel welds increased with increasing yield stress of the steel. Ye et al. [10] confirmed that groove type not only affected the distribution of residual stress, but also angular distortion and sensitization region width. Elmesalamy et al. [11] studied the effect of welding parameters on residual stress distribution, and found the higher laser power, the stronger peak residual stress, while width of the region sustaining tensile residual stresses was mainly affected by welding speed. Serizawa et al. [12] investigated the influence of mechanical restraint on weldability, and further found that effect of external constraints on residual stress distribution and possibility of weld cracking can be effectively reduced by increasing plate size. Yang et al. [13] found that adjusting the path sequence can reduce 17% transverse residual stress in 52-mm-thick plate multi-pass welding.

Generally, collapse and hump are easy to form in thicker section laser welding with a single pass, which must lead to stress concentration affecting residual stress distribution. There have been many research achievements in the residual stress distribution of laser welding. However, investigations about the influence of collapse and hump on residual stress are few in high-power laser welding. In this study, combined experiment and simulation influence of collapse and hump on residual stress was investigated, working with 15-mm-thick marine steel EH40.

2 Experiment

The base metal was marine steel EH40 with a size of 100×100×16 mm, and its chemical components are given in Table 1. The laser welding system is shown in Fig. 1a. The fiber laser, IPG YLS 30000, is a continuous-wave fiber laser. The laser header was equipped with a coaxial-air-blow-protection device and attached to a KUKA robot. Bead-on-plate welding was performed. Laser power was 25 kW, welding speed was 1.5 m/min, defocus length was 0 mm, and shielding gas was argon with a flow of 2.1 m³/h. Before welding, the sample surface was cut to remove the oxide layer and cleaned with acetone to avoid the negative influence of dust and oil contamination.

After welding, the residual stress along line 1 was measured by an X-ray stress analyzer. Eight points were measured, and the distance between each measurement point was 20 mm. The cross section sample of the weld was extracted by wire electrical discharge machining and eroded using a solution of HNO₃:alcohol = 4:96 to obtain the weld geometry. The microstructure of the weld was observed by an optical

![Fig. 1 Laser welding EH40 steel (a) experimental system; (b) laser; (c) butt joint](image-url)
microscope and a scanning electron microscopy (SEM). Hardness was measured with a Vickers micro-hardness tester, using a load of 300 g and a dwell period of 15 s.

3 Numerical analysis process

Thermal elastic plastic finite element method (TEP-FEM) was used to investigate inhomogeneous stress distribution in the weld joint. The temperature field and mechanical field were simulated by the sequential coupling method. Based on Fourier’s thermal conduction law, a 3D transient heat source model was used to compute the distribution of temperature. Then, the results of temperature field analysis were applied as input load for mechanical field analysis. Simulated results were verified by weld geometry, microstructure, hardness, and experimental residual stress. Meanwhile, four cases were considered in this study: nothing was considered in case 1; collapse was considered in case 2; hump was considered in case 3; collapse and hump were both considered in case 4. To simplify the calculation, the shape of collapse and hump were approximated into rectangle and arc, as shown in Fig. 2.

3.1 Thermal analysis

In thermal analysis, the transient temperature field was computed by Fourier’s thermal conduction law, as shown in Eq. (1).

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

(1)

where \( \rho(T) \) is the density, \( c_p(T) \) is the specific heat capacity, \( \lambda(T) \) is the thermal conductivity, and \( q(x, y, z) \) represents the input thermal flux.

Considering actual hourglass-shaped weld geometry, a double-cylindrical heat source model was proposed, as shown in Fig. 3. This heat source was derived by shifting and flipping the peak exponential decay cylindrical heat source. Radial heat flow presents a Gaussian distribution; heat flow peak in the direction of thickness is exponentially decaying then increasing.

Exponential decay cylindrical heat source is described by the following equation:

\[
q(x, y, z) = \frac{9Q}{\pi h r_0^2 (1 - e^{-3})} \exp \left( -\frac{3x^2 + y^2}{r_0^2} \right) \exp \left( \frac{3z}{h} \right)
\]  

(2)

where \( r_0 \) is the radial distribution parameters of heat source, \( h \) is the heat source height, and both of these parameters need to be determined artificially.

The double-cylindrical heat source model is composed of two cylindrical heat sources. Then, expressions of \( q_1 \) and \( q_2 \) are obtained through a three-dimensional coordinate transformation of Eq. (2), as shown in Eqs. (4) and (5).

\[
q_1(x, y, z) = q_1(x, y, z) + q_2(x, y, z)
\]  

(3)

\[
q_1(x, y, z) = \frac{9\lambda Q_1}{\pi f_1 f_2 h_1 r_0^2 (1 - \exp(-3))} \exp \left( -\frac{3x^2 + y^2}{(f_1 r_0)^2} \right) \exp \left( \frac{3z}{h} \right)
\]  

(4)

\[
q_2(x, y, z) = \frac{9\lambda Q_2}{\pi f_1 f_2 h_1 r_0^2 (1 - \exp(-3))} \exp \left( -\frac{3x^2 + y^2}{(f_2 r_0)^2} \right) \exp \left( \frac{3z + h}{f_2 h_2} \right)
\]  

(5)

where \( \lambda \) is the welding efficiency, \( Q_1 \) and \( Q_2 \) are the upper and lower power respectively, \( f_1 \) is the radius adjustment

Fig. 2 Schematic of four cases in this study: (a) weld section; (b–e) case 1, case 2, case 3, and case 4

Fig. 3 (a) Schematic diagram of heat source model; (b) curve of peak value with thickness; (c) weld section geometry
coefficient, $f_2$ is the height adjustment coefficient, $h_1$ is the height of the upper part, $h_2$ is the height of the lower part, and $r_0$ is the radius of the heat source model. The sum of $Q_1$ and $Q_2$ is laser power. And their ratio equals the ratio of the distance between the top and bottom surface to the thinnest position of the weld section. So are $h_1$ and $h_2$, $r_0$ equals to the laser beam diameter. Values of the heat source model are listed in Table 2. Meanwhile, four cases adopt the same heat source parameters.

The initial temperature of the sample is 25 °C. Considering heat radiation losses and heat convection losses, equivalent heat transfer is adopted as the boundary condition [14].

$$h_r(x, y, z) = \begin{cases} 0.0668 \cdot T & W/(m^2 \cdot °C) T < 500°C \\ 0.231 \cdot T - 82.1 W/(m^2 \cdot °C) T \geq 500°C \end{cases}$$

(6)
3.2 Mechanical analysis

Inhomogeneous heating and cooling caused local contraction and expansion, thereby resulting in stress and deformation. When stress exceeds the yield strength of the material, the joint will deform plastically. Thereby, the total strain increment can be described by Eq. (7).
where \( \varepsilon_{\text{total}} \) is the total strain increment, \( \varepsilon_{\text{e}} \) is the elastic strain increment, \( \varepsilon_{\text{p}} \) is the plastic strain increment, and \( \varepsilon_{\text{T}} \) is the temperature strain increment. Computations of these strain increments are all related to material properties under different temperatures, as shown in Fig. 4.

### 3.3 Computation implementation

The whole TEP-FEM procedure was completed by ANSYS Parametric Design Language. Considering a high non-linear characteristic of the thermal–mechanical behavior in laser welding, the no-uniform mesh method was adopted to improve computation efficiency and accuracy. Mesh near fusion zone was refined, while that far away fusion zone was sparse. To reduce the influence of meshing accuracy on simulation results, the same meshing method was adopted in four cases except for collapse and hump. The numbers of four cases are 51,774, 50,574, 54,574, and 53,974 respectively. Take case 3 as an example, where the minimum element size is 1 mm \( \times \) 1 mm \( \times \) 0.486 mm, as shown in Fig. 5. SOLID 70 and SOLID 185 were used in thermal analysis and mechanical analysis respectively. In mechanical analysis, three points (A, B, and C) were constrained to prevent rigid body motion of the sample to improve the convergence.

### 4 Results and discussion

#### 4.1 Microstructure and hardness

Figure 6 shows the weld geometry to analyze the phase transformation of the weld joint. Based on differences in microstructure, the weld is divided into fusion zone (FZ), coarse-grained heat-affected zone (CGHAZ), fine-grained heat-affected zone (FGHAZ), intercritical heat-affected zone (ICHAZ), and base metal (BM).

The microstructure of FZ is martensite, while that of BM is ferrite and pearlite. With distance from the fusion line increasing, martensite decreases while pearlite and ferrite increase. As can be seen, the single-phase microstructure of martensite was formed in CGHAZ, which is the same as FZ. The microstructure of FGHAZ was almost all martensite with little ferrite. At the same time, it is obvious that the austenite boundary shrinks, as shown at points B and C in Fig. 6, which is related to the peak temperature in welding. In the ICHAZ, martensite content decreased rapidly, and ferrite increased; that means only partial austenitizing occurred.

The hardness distribution of the weld joint also confirms that martensite is the main phase in FZ and HAZ, as shown in Fig. 7. Hardness is high in FZ, CGHAZ, and FGHAZ, and decreases rapidly in ICHAZ, which is well consistent with microstructure distribution. Furthermore, the hardness of different positions in the thickness direction has similar distribution law, which confirms the validity of the microstructural analysis.

#### 4.2 Validity of temperature distribution

As mentioned in Sect. 3, thermal analysis results were applied as input load for mechanical analysis. Thus, the accuracy of
temperature is key to simulate mechanical field by being verified by weld geometry.

Figure 8 shows the temperature field of four cases compared with weld geometry. It is obvious that collapse has a significant effect on weld upper temperature distribution. Taking collapse into account in the modelling process, the arc contour of the fusion zone at the upper part of the weld can be accurately simulated. Moreover, the weld lower temperature distribution is influenced by hump. When hump is considered in the model, simulated weld geometry is relatively wide, which is more consistent with the actual weld geometry. Moreover, taking the area of fusion zone of weld section as the evaluation standard and using image-processing technology, simulation results of four cases and actual fusion zone area were compared, and error between them is shown in Table 3. It is obvious that case 4 is also the closest to the actual value, with the smallest error of −1.54%.

4.3 Microstructure evolution mechanism based on thermal analysis

Many investigations show that peak temperature [15] and temperature change rate [16] of the thermal cycle affected microstructure. Thereby, the produced microstructure throughout the fusion zone and heat-affected zone and hardness of weld joint could be explained by numerically predicted temperature distribution.

As mentioned above, case 4 has the highest temperature simulation accuracy. Take case 4 for example, Fig. 9 shows the thermal cycles at five locations depicted in Fig. 6. It is obvious that, in high-power laser welding, temperature changes rapidly, rising to the highest temperature almost instantaneously. The maximum temperature change rate at point A in the FZ even reached 16,283.09 °C/s. Moreover, the heating rate is much higher than the cooling rate, as shown in Fig. 9, which is a typical feature of high-power laser welding. In addition, there are significant differences in the thermal cycle at different locations of the weld section, not only peak temperature but also temperature change rate. Unsurprisingly, only point A underwent the melting and solidification process, consistent with the basic facts. Although the other four points did not melt, they were affected by the heat transfer effect to varying degrees.

Furthermore, the produced microstructure throughout the FZ and HAZ could be explained by a study of numerically predicted cooling curves that were generated by thermal analysis. Based on the material properties of EH40, the continuous cooling transformation (CCT) diagram was obtained, as shown in Fig. 10. Cooling curves of points A,
B, and E were incorporated in the CCT diagram of EH40. In particular, points C and D were not selected, because the temperature distribution in HAZ changes violently and requires a very dense grid to achieve high prediction accuracy. To reduce calculation time, the grid in HAZ was not refined in this study. So compared with other points, points C and D have a little bit bigger computation error. It can be seen that the anticipated phase of points A and B should be the full martensite microstructure, which is well consistent with the microstructural evolution that occurred in the weld. In addition, it can be inferred that the transformation in HAZ should be composed of martensite transformation as the predominant transformation from cooling curves of points B and E.

In summary, peak temperature and cooling rate are the main factors that determine the process of microstructure evolution and final phase composition. For EH40 steel, only the peak temperature is higher than $A_{c1}$; there may be phase transformation. Since the base metal of EH40 is composed of pearlite and ferrite without martensite, martensite tempering is not considered. In addition, it is easy to form martensite under a high cooling rate, and even form a fully martensitic microstructure.

### 4.4 Residual stress analysis

Longitudinal residual stress distribution was studied, which is depicted in Fig. 11 and Table 4. The longitudinal residual stress distribution at different positions on the mid-plane section is compared and analyzed. Need of special note is residual stress at the collapse was not measured for protecting the measuring head of equipment. Moreover, numerical residual stress distribution on the top surface of case 2 and case 4 is not discontinuous, due to considering the collapse.

As can be seen, for longitudinal residual stress distribution on the top surface (along line 1), numerical and experimental results of case 2 and case 4 have a relatively more similar trend. On the one hand, their error between simulated values and experimental values is smaller. The average error of simulation with the collapse is $-52.4$ MPa, while that

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**Fig. 11** Comparison of experimental and numerical longitudinal residual stress on the mid-plane section (a) schematic diagram of contrast position; (b) along the line 1; (c) along line 2; (d) along line 3
without the collapse is $-84.4$ MPa. On the other hand, their peak positions are more consistent with experimental peak positions. The error of peak distance is $-0.86$ mm when collapse is considered, and increases to 2 mm when collapse is not considered. It is indicated that collapse has a significant effect on the top surface residual stress distribution, and considering collapse in the simulation calculation will improve the simulation accuracy, especially in the zone near the weld bead. In addition, this also indicates that the influence of hump on the top surface’s residual stress distribution is little, since there is little difference between cases considering hump and cases not considering hump, as shown in Fig. 11b.

The error of residual stress distribution simulation on the top surface is acceptable, so the simulation results of four cases are used to analyze the distribution of longitudinal residual stress along line 2. Figure 11c shows that, for residual stress distribution on the middle thickness (along line 2), differences of four cases are mainly around the weld bead, and the fluctuation trend is similar with differences in values. Surprisingly, the residual stress distribution of case 1 and case 4 is similar, in which collapse and hump are all considered, and in which none is considered. In other words, for residual stress distribution on the middle thickness, collapse and hump have opposite effects. When only one of that is considered, the accuracy of numerical simulation will be reduced. Residual stress distribution along line 3 is shown in Fig. 11d. It is observed that case 1 and case 2 have almost the same residual stress distribution, as well as case 3 and case 4. Obviously, the hump plays a more important role than collapse in longitudinal residual stress distribution on the bottom surface. Residual stress trends of the four cases basically coincide with each other. However, there are two peaks near the fusion line in the cases without hump, while there is none in the cases with hump. It is probably that the presence of hump offsets the fluctuation near the fusion line. Furthermore, cases considering hump have a bigger fluctuation range in FZ, which is 2.8 times that of the case without the hump. Peak value increases from 390 to 455 MPa, and trough value decreases from 331 to 288 MPa. Obviously, when hump is not considered, residual stress value is underestimated, which is not conducive to the accurate prediction.

In the welding, the expansion and contraction of the metal in the weld will exert a tension and compression effect on the base metal, thus forming welding residual stress. After collapse and hump formation, the formation of welding residual stress is affected by them. Residual stress on the top surface of the weld is significantly increased by collapse. On the one hand, the cooling contraction effect is weakened by the missing metal on the top of the weld, and the tensile stress of the base metal is reduced. Therefore, the reaction force in the base metal also decreases correspondingly, the residual stress near collapse increases. On the other hand, the shape of the weld bead protrudes, and the cooling contraction effect increases, thus forming greater tensile stress in the weld. On the other hand, the shape of

| Distance from the weld center | Experimental results | Simulation results | Error |
|-----------------------------|---------------------|--------------------|-------|
|                             | $322.26 \pm 27.18$ MPa | 146.72 MPa         | $-175.54$ MPa $-0.54472$ |
| $-6$ mm                     | $469.62 \pm 27.61$ MPa | 421.19 MPa         | $-48.43$ MPa $-0.10313$ |
| $-4$ mm                     | $561.43 \pm 27.61$ MPa | 448.95 MPa         | $-112.48$ MPa $-0.20035$ |
| $-3$ mm                     | $484.50 \pm 26.99$ MPa | 449.06 MPa         | $-35.44$ MPa $-0.07315$ |
| $3$ mm                      | $429.15 \pm 24.46$ MPa | 447.09 MPa         | 17.94 MPa $0.041804$    |
| $4$ mm                      | $536.43 \pm 24.90$ MPa | 446.43 MPa         | $-90$ MPa $-0.16778$    |
| $6$ mm                      | $411.88 \pm 26.41$ MPa | 423.20 MPa         | 11.32 MPa $0.027484$    |
| $8$ mm                      | $297.95 \pm 27.39$ MPa | 129.19 MPa         | $-168.76$ MPa $-0.5664$ |
the joint between the hump and the plate causes stress concentration, resulting in significant fluctuations in the stress. In conclusion, the cold contraction of weld metal and the stress concentration caused by weld shape during the cooling process are the fundamental reasons that collapse and hump affect the distribution of welding residual stress, as shown in Fig. 12.

Furthermore, take case 4 as an example to analyze the global inhomogeneity of residual stress in laser welding. After the sample was cooled to room temperature, the distribution of residual stress was given in Fig. 13. Equivalent stress is between 146.1 and 388.9 MPa, which is mainly concentrated along welding direction, and decreases in magnitude with increasing distance from the weld centerline, until they become compressive in the far-field. Zone with high residual stress is mainly concentrated in start and end welding positions, while peak residual stress is located at Point P. Figure 13 shows the transient residual stress fluctuation curve of Point P. When laser heat source passes through Point P, residual stress shows a sharp change then tends to be stable, which is consistent with the characteristics of high cooling rate in laser welding. Meanwhile, it can be seen that start and end welding positions are more prone to fracture failure than other zones, which is influenced by shape end effect and thermal end effect [17].

5 Conclusions

In this work, a three-dimensional thermomechanical finite element model was introduced to study the temperature distribution, thermal histories, and residual stress distribution of the joint made by the high-power laser welding process. The main outcomes are as follows:

1. A double-cylindrical source model was proposed to simulate the transient distribution of the temperature field. Four cases were considered in this study, case 1 with none, case 2 with collapse, case 3 with hump, and case 4 with collapse and hump. Simulation results showed a good agreement with the experiment results in weld geometry, and prediction errors of four cases are 10.85%, −8.44%, 21.05%, and −1.54%, respectively.
2. Based on differences in microstructure and hardness, the weld joint can be divided into FZ, CGHAZ, FGHAZ, ICHAZ, and BM. The microstructure of the weld joint was mainly composed of martensite and non-transformed ferrite and pearlite phase, which agreed with the microstructure predicted by the CCT diagram and cooling curves generated by thermal analysis.
3. The numerical and measurement results of residual stress on the top surface were relatively in the same trend. Comparing residual stress distribution of four cases, it can be found that collapse has a significant influence on residual stress distribution on the top of the weld joint, while that on the bottom is affected by hump. For that on the middle thickness, collapse and hump have little effect. The cold contraction of weld metal and the stress concentration caused by weld shape during the cooling process are the fundamental reasons that collapse and hump affect the distribution of welding residual stress.
4. Simulation results suggest that start and end welding positions have higher residual stress values, where cracking initiation and fracture behavior are easy to occur, especially for end welding position.
Nomenclature  $ρ(T)$: density; $c_p(T)$: specific heat capacity; $λ(T)$: thermal conductivity; $q(x, y, z)$: input thermal flux; $r_0$: radial distribution parameters of heat source; $h$: heat source height; $λ$: welding efficiency; $Q_1$: the upper power (part of the laser power); $Q_2$: the lower power (part of the laser power); $f_1$: radius adjustment coefficient; $f_2$: height adjustment coefficient; $h_1$: height of the upper part; $h_2$: height of the lower part; $T$: temperature; $h_e$: equivalent heat transfer coefficient; $dε_{total}$: total strain increment; $dε_r$: elastic strain increment; $dε_p$: plastic strain increment; $dε_T$: temperature strain increment; $A_{C1}$: initial temperature of austenite transition.

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Declarations

Ethics approval  Not applicable.

Consent to participate  My co-authors and I would like to opt into In Review.

Consent for publication  Not applicable.

Competing interests  The authors declare no competing interests.

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