Study on temperature- microstructure- stress fields of thick-walled plate welded by hybrid laser arc welding

Hongjie Zhang\textsuperscript{1}, Tao Han\textsuperscript{1,*}, Yong Wang\textsuperscript{1}, Bangyu Wang\textsuperscript{1} and Guangxue Chen\textsuperscript{1}

\textsuperscript{1}School of Materials Science and Engineering, China University of Petroleum, Qingdao, China

\textsuperscript{*}Corresponding author: hantao@upc.edu.cn

Abstract. The 25mm DH36 steel was welded by hybrid laser arc welding (HLAW), and a sequence coupled thermal-metallurgical-mechanical (TMM) model was developed based on SYSWELD. The temperature-microstructure-stress fields are predicted by simulation verified by experiment. The ratio between the arc and laser energy showed a significant effect on weld profile. The laser provided the main power and ensured deep penetration, and the arc power showed a dominant effect on the bead width of the hybrid weld during HLAW. For the hybrid welding of a thick-walled plate, the microstructure and thermal cycles varied along with the thickness. The weld profile and microstructure were experimentally characterized. The 3-pass welding procedure produced larger welding residual stress than the 9-pass welding procedure, and the process stability is poorer than the 3-pass welding process. Overall, numerical results matched well with experimental results.

Keywords: hybrid laser arc welding, TMM model, temperature- microstructure- stress fields.

1. Introduction
As an essential material joining method, welding technology is a critical technology in the shipbuilding and marine engineering industries. Time and economic costs of the welding technology usually take 30\%-50\% of the total construction cost. According to the development tendency, large and high-grade industrial products become highly favored. Currently, for the welding of large plate carbon steel, whose thickness is above 5mm, Flux-cored arc welding (FCAW), submerged-arc welding (SAW), and gas metal arc welding (GMAW) are still the dominant welding methods. With low arc energy density, these welding methods are getting hard to meet the quality and efficiency requirement. In contrast, deep penetration laser-arc hybrid welding can produce more negligible thermal distortion, narrower heat-affected zone (HAZ), better weld appearance, and higher productivity [1].

Since hybrid laser-arc welding (HLAW) was firstly reported in the 1970s [2], it has attracted extensive attention. HLAW coupled the arc and laser beam in the same weld pool, and the hybridization effect of them adopted the advantages and avoided the drawbacks of both processes. Compared to laser welding, the hybrid high-energy heat source improved the gap bridging ability and significantly enhanced the penetration and welding speed relative to arc welding [3,4]. Despite these advantages, HLAW produces a high-speed cooling rate and generates brittle microstructure, especially for thick-
walled plate welding [5]. Due to the deep weld pool, the process stability is usually hard to guarantee. The porosity and hot crack can often find in the hybrid welding joints. For thick-walled steel, another problem is that the filler material is tough to deliver to the root of the groove [6]. Therefore, it is tough to obtain the homogeneous microstructure and property through the thickness of the weld joint. As reported by Wahba et al. [7], the dilution and homogeneity of filler material in the groove can be improved by pre-placing the cutting filler material in the groove. However, the pre-placed cutting filler material might affect the stability of the weld pool and introduced more porosity. Also, pre-placing filler material is often hard to apply to industrial manufacture. Compared to thin plate welding, larger heat input should be applied to thick-walled steel plates. The resulting coarse-grained heat-affected zone (HAZ) can significantly lower the toughness of the weld joint [8]. Even though HLAW shows good application prospects and availability in industries, as reported by many research articles. There are still many problems about the temperature- microstructure- stress fields remaining to be solved. A massive scope of experimental and numerical investigation on the thick-walled plate of hybrid welding should be taken to help optimize the welding parameters and improve the hybrid welding joint’s quality. Compared to experimental investigation, the numerical research is relatively less.

Recently, introducing metallurgical phase transformation kinetics into welding finite element simulation gradually became popular [9]. The thermal-metallurgical-mechanical (TMM) model can be developed and helps improve the calculation accuracy by introducing phase transformation kinetics. Prediction of microstructure and clarifying the effect of phase transformation on welding residual stress promote the optimization of welding parameters and the improvement of welding quality. As reported by Ahn et al. [10], welding residual stress provides the driving force for crack propagation and enhances the rate of fatigue rupture. The more significant residual tensile stress usually produces in thick-walled welding joints, and the corresponding welding distortion is troublesome for the follow-up assembly process. Therefore, it makes sense to furtherly research the welding residual stress in the hybrid welded thick-walled joints. As reported by Zhang et al. [11], most of the numerical simulations of HLAW were based on the thermal-elastic-plastic (TEP) model, and few articles are based on the TMM model.

In this paper, the 25mm DH36 steel was welded by hybrid laser-arc welding, and a TMM model was developed based on SYSWELD. The temperature, microstructure, and welding residual stress distributions are predicted by simulation. The transverse cross-sectional of the hybrid welded joint profile was characterized and compared with simulation results. The microstructure in HAZ and weld zone are observed by optical microscope and verified by predicted results.

2. Experimental and numerical procedures

2.1. Experimental process

In this research, an IPG YLS-10000 fiber laser combing a Fronius metal active-gas (MAG) welding torch was employed to manufacture the welding joints of DH36 steel. The dimension of the weld joint is 300(length)*300(width)*25(thickness) mm, and the detailed dimension information of the welding groove and sequence can be found in Fig. 1. It should note that the groove in Fig. 1 (a) was filled with 3 passes and Fig.1 (b) filled with 9 passes. ER70S-6 with a diameter of 1.2 mm was selected as the filler material and the chemical composition was shown in Table 1. The shield gas with a mixture of 20%CO₂ and 80% Ar was used to protect the weld pool from air.

![Fig 1. Groove shape (mm).](image)
Table 1. Chemical composition (in wt%) of DH36.

| Material  | C   | Si   | Mn  | P   | S   | Cr  | Nb  | V   | Ti  | Mo  |
|-----------|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|
| DH36      | 0.13| 0.162| 1.46| 0.16| 0.053| 0.024| 0.04| 0.041| 0.015| 0.004|
| ER70S-6   | 0.073| 0.88 | 1.49| 0.01| 0.011|--  | --  | --  | --  | --  |

The welding parameters were listed in Table 2 and Table 3.

Table 2. 3-passes welded joint.

| Weld pass | Laser power (Kw) | Current (A) | Voltage/V | Welding speed (mm/s) |
|-----------|------------------|-------------|-----------|----------------------|
| 1         | 9.0              | 280         | 26        | 13.4                 |
| 2         | 6.0              | 280         | 26        | 13.4                 |
| 3         | 1.5              | 280         | 26        | 10                   |

Table 3. 9-passes welded joint.

| Welding Process | Welding pass | Laser power (kW) | Current/A | Voltage/V | Welding speed (mm/s) |
|-----------------|--------------|------------------|-----------|-----------|----------------------|
| HAW             | 1            | 5.5              | 200       | 20        | 10                   |
|                 | 2            | 5.5              | 200       | 20        | 10                   |
|                 | 3-4          | 2.0              | 325       | 30        | 10                   |
|                 | 5            | --               | 270       | 27.3      | 8.3                  |
| SAW             | 6            | --               | 410       | 30        | 8.63                 |
|                 | 7-9          | --               | 300       | 29        | 8.0                  |

2.2. Numerical procedures

A sequence coupled TMM model was developed based on SYSWELD. It means that the thermal and metallurgical processes were first calculated. Then thermal and metallurgical results were applied as the boundary conditions during the mechanical process. The finite element model was created entirely according to experimental weld joints, as given in Fig. 2. For balancing accuracy and efficiency, the finer meshes were used in the weld zone, and the heat-affected zone with the minimum size of 0.1*0.07*1.0mm, and the coarser meshes were used away from these areas. The constraint condition was shown in Fig. 3.

![Fig. 2. Finite element model (a) 3-passes model (b) 9 nine passes model](image-url)
In this research, a double ellipsoid heat source \([12]\) was adopted to describe the heat flux distribution of the gas metal arc welding (GMAW). The heat flux distribution equations of double ellipsoid heat source were shown below:

\[
q_f(x, y, z) = \frac{12\sqrt{5\eta UL}}{(a_f + a_b)c_a\pi} \left(-\frac{3x^2}{a_f^2} - \frac{3y^2}{b_f^2} - \frac{3z^2}{c_f^2}\right) x \geq 0
\]  

\[
q_r(x, y, z) = \frac{12\sqrt{5\eta UL}}{(a_f + a_b)c_a\pi} \left(-\frac{3x^2}{a_r^2} - \frac{3y^2}{b_r^2} - \frac{3z^2}{c_r^2}\right) x \leq 0
\]

Where \(q_f\) and \(q_r\) are the power density function, \(U\) and \(I\) is the welding voltage and current, respectively; \(\eta\) is the thermal efficiency; \(a_f, a_r, b_f, b_r, c_f\) and \(c_r\) are double ellipsoid heat source parameters.

We used the conical heat source to describe the heat flux distribution of the laser beam through the thickness of the weld joint. The power density of the conical heat source was exponentially enhanced along the central axis. The heat flux distribution equations were expressed below.

\[
q(r, z) = Q_0 \exp\left[\frac{\ln(\chi)}{z_i - z_r}(z - z_r)\right] \exp\left[-\frac{3r^2}{r_0^2(z)}\right]
\]

\[
Q_0 = \frac{3Q_1 \ln(\chi)}{(r_c^2 - r_e^2 - 2r_e^2 r_e - r_e^2 \ln(1 - \chi))} \times \frac{1}{\pi(1 - e^{-1})(z_i - z_r)}
\]

where \(z_r\) is the height of the top surface of the heat source, \(z_i\) is the bottom surface of the heat source, \(Q_0\) is the calculation coefficient, \(\chi\) is the proportion coefficient, \(r_e\) is the function of the heat source radius, \(r_e\) and \(r_r\) are the heat source radiiuses, \(Q_1\) is the power of the laser.

The JMAK (Johnson-Mehl-Avrami-Kolmogorov) equations were applied to describe the diffusion-controlled transformations. The K-M (Koistinen-Marburger) equation was used to describe martensite transformation. Isotropic hardening was adopted to describe the yield behavior. In SYSWELD, the total strain rate equation was shown below.

\[
\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_p + \dot{\varepsilon}_a + \dot{\varepsilon}_n
\]

3. Thermal-metallurgical analysis

3.1. Thermal analysis
As given in Fig. 4, the predicted cross-sectional temperature distribution of the weld joint was compared with the actual cross-sectional weld profile. The process stability of the 9-pass procedure is poorer than the 3-pass welding process. Overall, the numerical weld profiles matched well with the experimental results. From Fig. 4 (a), it can be found laser power showed a significant effect on weld penetration, and arc power showed a dominant effect on the bead width of the hybrid weld.

It can also be found that the energy ratio between the arc and laser (RQAL) had an important effect on weld profile. The RQAL can be defined as:

\[ RQAL = \frac{Q_{\text{arc}}}{Q_{\text{laser}}} \]  

where \(Q_{\text{arc}}\) the power of arc, \(Q_{\text{laser}}\) is the power of the laser.

For convenience, the typical “wine-glass” weld profile of HLAW can be divided into “arc dominate zone” and “laser dominate zone”. The “arc dominate zone” located at the top of the weld bead showing the typical profile of arc welding. The “laser dominate zone” laid beneath the “arc dominate zone” and showed the typical profile of laser welding. With the increase of the RQAL, the boundary between “laser dominate zone” and “arc dominate zone” turned to be smooth and the length of the “laser dominate zone” ratio to “arc dominate zone” became larger. From Fig. 4, it can be found that the HAZ of the 9-pass weld joint was much larger than that of the 3-pass weld joint.

The thermal cycles were also studied in detail. Four typical locations in the 3-pass procedure showing in Fig. 4 (a) were investigated in this paper. The thermal cycles of point a, point b, point c, and point d were drawn in Fig. 5 (a). It can be found that the thermal cycles located at “laser dominate zone” and “arc dominate zone” showed different cooling rates. The cooling rate of the “laser dominate zone” was much higher than that of the “arc dominate zone”. The laser power and arc power also showed an important effect on the cooling rate. It implied that the microstructures of weld metal and HAZ along
with the thickness were heterogeneous. The different cooling rates along with the thickness showed an important effect on the heterogeneity of microstructure. There is another reason contributing to the heterogeneity of microstructure is that the heterogeneous chemical composition of weld metal along with the thickness. With the increase of weld penetration, the filler material became harder to be delivered to the bottom of the groove. Thus, the dilution rate of weld metal varied from top to bottom. The different chemical compositions and microstructure along thickness can be harmful to the security of weld joints. In the 9-pass weld joint, the different cooling rates between different welding passes still existed.

![Fig 5. Thermal cycles.](image)

3.2. Metallurgical analysis

![Fig 6. Microstructure of 3-pass welding joint.](image)

As shown in Fig. 6, the weld metal was dominated by ferrite and bainite. From the top of the weld pass to the bottom, the dilution rate got smaller and the cooling rate got higher. Thus, the percentage of granular bainite in the “laser dominate zone” is much higher than that in the “arc dominate zone”. In contrast, the acicular ferrite in the “laser dominate zone” is lower than that in the “arc dominate zone”. In the HAZ of the 1st pass, lots of lath bainite and lath martensite were found, and more upper bainite in the HAZ of the 2nd pass was found. The cooling rate and the interaction of arc and laser showed a significant effect on the microstructure.
As shown in Fig. 7, the microstructures of the weld metal of the 1st and 2nd weld pass were mainly composed of acicular ferrite and granular bainite. The homogeneity of weld microstructure is relatively good because the weld penetration is decreased. Thus, the filler material can be delivered to the bottom of the groove. The microstructures in the weld metal of SAW mainly consisted of polygonal ferrite, granular ferrite, and a small number of granular bainite. The microstructure of HAZ mainly consisted of bainite and martensite. Due to the different cooling rates and dilution rates among the welding passes, the homogeneity of the microstructures got worse.

![Microstructure of 9-pass welding joint.](image)

Fig 7. Microstructure of 9-pass welding joint.

Based on the metallurgical phase transformation kinetics, the microstructure distributions in the 3-pass and 9-pass weld joint were predicted by SYSWELD. As given in Fig. 8 and Fig. 9, the microstructures in the weld joints matched well with the experimental results. It should be mentioned that the difference in dilution rate between different weld passes was not considered in our model, the microstructure inhomogeneity in the weld metal and HAZ mainly resulted from the cooling rate.

![Microstructure of 3-pass welding joint.](image)

Fig 8. Microstructure of 3-pass welding joint (a) ferrite (b) bainite (c) martensite.
4. Welding residual stress
As shown in Fig. 10 and Fig. 11, it can be found that the longitudinal stress in the 3-pass weld joint is larger than that of the longitudinal stress in the 9-pass weld joint. However, the magnitude of transverse stress in 3-pass and 9-pass weld joints showed little difference. The longitudinal residual stress distribution laws in 3-pass and 9-pass weld joints are generally different.

5. Conclusions
The 25mm DH36 steel was welded by hybrid laser arc welding (HLAW), and a sequence coupled thermal-metallurgical-mechanical (TMM) model was developed based on SYSWELD. The temperature-microstructure-stress fields are predicted by simulation verified by experiment.
(1) The numerical weld profiles matched well with the experimental results. The ratio between the arc and laser energy showed a significant effect on weld profile. The laser provided the main power and ensured deep penetration, and arc power showed a dominant effect on the bead width of the hybrid weld during HLAW.

(2) For the hybrid welding of a thick-walled plate, the microstructure and thermal cycles varied along with the thickness. The different cooling rates and dilution rates among the welding passes resulted in the heterogeneous microstructures along with the thickness.

(3) The 3-pass welding procedure produced larger welding residual stress than the 9-pass welding procedure.

Acknowledgments
This work was financially supported by the Fundamental Research Funds for the Central Universities of Shandong, China [Grant No. 18CX06054A]; the Natural Science Foundation of Shandong Province, China [Grant No. ZR2019MEE111].

References
[1] B. Acherjee, Hybrid laser arc welding: State-of-art review, Opt. Laser Technol. 99 (2018) 60-71.
[2] W. M. Steen, Arc augmented laser processing of materials, J. Appl. Phys. 51 (1980) 5636-5641.
[3] P.T. Swanson, C.J. Page, E. Read, H.Z. Wu, Plasma augmented laser welding of 6 mm steel plate, Sci. Technol. Weld. Joining. 12 (2007) 153-160.
[4] X. Gu, H. Li, L. Yang, Y. Gao, Coupling mechanism of laser and arcs of laser twin-arc hybrid welding and its effect on welding process, Opt. Laser Technol. 48 (2013) 246-253.
[5] I. Bunaziv, O. M Akselsen, J. Frostevarg, Alexander F. H. Kaplanc, Deep penetration fiber laser-arc hybrid welding of thick HSLA steel, J. Mater. Process. Technol. 256 (2018) 216-288.
[6] S. Gook, A. Gumenyuk, M. Rethmeier, Hybrid laser arc welding of X80 and X120 steel grade, Sci. Technol. Weld. Join. 19 (2014.) 15-24.
[7] M.Wahba, M.Mizutani, S. Katayama, Single pass hybrid laser-arc welding of 25 mm thick square groove butt joints, Mater. Des. 97(2016) 1-6.
[8] J. Yoo, K. Han, Y. k, C. Lee, Correlation between microstructure and mechanical properties of heat affected zones in Fe-8Mn-0.06C steel welds, Mater. Chem. Phys. 146(2014) 175-182.
[9] S. Neubert, A. Pittner, M. Rethmeier, Influence of non-uniform martensitic transformation on residual stresses and distortion of GMA-welding, J. Constr. Steel. Res. 128(2017) 193-200.
[10] J. Ahn, E. He, L. Chen, R.C. Wimpory, J.P. Dear, C.M. Davies, Prediction and measurement of residual stresses and distortions in fiber laser welded Ti-6Al-4V considering phase transformation, Mater. Des. 115(2017) 441–57.
[11] H. J. Zhang, Y. Wang, T. Han, L.L. Bao, W. Qian, S.W. Gu, Numerical and experimental investigation of the formation mechanism and the distribution of the welding residual stress induced by the hybrid laser arc welding of AH36 steel in a butt joint configuration, J. Manuf. Process. 51(2020) 95-108.
[12] J. Goldak, A. Chakravarti, M. Bibby, A new finite element model for welding heat sources, Metall. Trans. B. 15(1984) 299–305.