Numerical simulation and experimental verification of laser multi-section welding

Jia Liu (✉ liujia@cust.edu.cn)

Changchun University of Science and Technology

Tao Jiang

Changchun University of Science and Technology

Yan Shi

Changchun University of Science and Technology

Hongyin Zhu

Changchun University of Science and Technology

Yuchi Dai

Changchun University of Science and Technology

Original Article

Keywords: Laser multi-section welding, SYSWELD, Finite element analysis, Mechanical properties.

Posted Date: December 1st, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-116060/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Abstract

Aiming at the problems of large welding deformation and spatter in resistance spot welding of traditional lube oil cooler plate, a new welding method: laser multi-section welding is proposed. The major processes here involved were a finite element model of pulsed laser lap welding established using SYSWELD simulation software, and the laser welding process of different welding methods. Study the influence of different welding methods on welding quality, Optimize the parameters of average power and duty cycle according to the comparative analysis of experimental results and numerical simulation Experimental results indicate: When the new 6-sections welding method is adopted, the resulting welded joint has the most uniform heat input, the largest welding fusion area, the tensile properties of the welded joints were significantly improved, however, there are still pores. By changing the duty cycle, air holes can be effectively eliminated to further improve the quality of the joint.

1. Introduction

A lubricating-oil cooler is a widely used heat exchanger that plays an important role in nuclear power, chemical industry, and other related fields, with a certain effect on reducing energy loss [1], Figure 1 is a structural diagram of a lubricating-oil cooler. Austenitic stainless steel is broadly applied in railway vehicles and the heat exchanger/chemical industry owing to their good corrosion resistance, high strength, and efficient stamping performance[2-4]. In the current stage, the lube oil cooler plate mainly uses resistance spot welding to connect, but there are serious spatter issues in the process, As shown in Figure 2. At the same time, resistance spot welding also has the following shortcomings. First of all, when welding one of the points, a part of the current tends to flow through the welded solder joints, affecting the quality of the welding itself. Also, the resistance of the electrode and the workpiece can be easily affected by many factors such as temperature, electrode pressure, and other material properties, making it extremely vulnerable to outside conditions. Moreover, regarding cleanliness, the requirements are high. If there are impurities on the surface, the resistance between the weldments will increase significantly, affecting directly its conductivity features. Hence, considering such issues, laser welding technology is proposed to replace the original resistance spot welding process.

Laser welding is an efficient and precise welding method that has a high energy density laser beam as the heat source. It is advantageous not only because of its high energy density, but also due to its precise focus, strong penetrating ability, high welding efficiency, and applicability since its suitable for a myriad of materials. It is now mostly used in aerospace, automotive, microelectronics, and nuclear industries with high precision and high-quality welding area [5-7]. Compared with resistance spot welding, laser spot welding has many advantages, such as high welding accuracy, accurate energy control, and good penetration. Due to the use of non-contact welding, welding quality can be guaranteed for welding of complex structures, and the application is more flexible. However, as a cutting-edge spot welding method, laser spot welding still has many technical problems that have not been solved. The laser spot welding process will cause stress concentration and uneven heat input. At the same time, due to the extremely fast heating and cooling speed, extreme Defects such as pores and cracks are easy to produce, which seriously affects the quality of weld formation and weld strength[8,9].

Finite element simulation can be used in the initial stage of design since it is a powerful tool for experimentation and optimization in a virtual environment. This technique can also help to reduce the number of experiments and provides a theoretical basis for strength analysis [10,11].

Yan et al. [12] studied the structure and mechanical properties of 304 stainless steel joints welded by tungsten inert gas (TIG) welding, laser welding, and laser-TIG hybrid welding. The results of his experimentations show that the laser-welded joint has the highest tensile strength and the smallest dendrite size among all, while the TIG welded joint has the lowest tensile strength and the largest dendrite size. MP Chakravarthy et al. [13] also studied the effect of laser welding process parameters and welding speed on the welding performance of 70/30 Cu-Ni alloy welded joints. His processes proved that, when the laser uses a welding speed of 1.5 m/min, the joints produced fine, equiaxed, and uniformly distributed grains that have better mechanical properties than other joints in the fusion zone. Going further, Bowen Liu et al. [14] studied the dual laser beam welding of 316L austenitic stainless steel, using an artificial neural network (ANN) and genetic algorithm (GA) to obtain the best welding parameters of them. Some other studies have shown that porosity features are significantly reduced compared to the original weld. Derakhshan, E. D et al. [15] examined the effects of heat input on mechanical properties obtained by four different welding processes: Autogenous Laser Welding, Cold Wire Assisted Laser Welding, Hybrid Laser Arc Welding, and traditional Submerged Arc Welding. SYSWELD software was used to predict the temperature field, residual stress, and deformation and the experimental results had a satisfactory correlation with the calculated results. The process proved that, by increasing the cooling rate of the welding process, it is possible to effectively improve the microhardness of the weld center. Adding to that, S. Saravanan et al. [16] compared the macrostructures of Hastelloy C-276 joints obtained by Nd: YAG laser butt-welding through numerical simulation and experimental methods. The results show that SYSWELD is suitable for simulating the weld profile and temperature distribution of laser-welded Hastelloy C-276 joints. In this case, the profile obtained by the numerical simulation was also very consistent with the experimental results. Last but not least, Ganesh et al. [17] performed the thermo-mechanic analysis using SYSWELD and both residual stress and distortion predicted by FEM simulation were in acceptable agreement with the experimental measurements.

Since the lubricating-oil cooler has higher requirements for heat exchange efficiency, it is desirable to have the greatest strength under the same welding area to avoid excessive welding area from affecting the flow of fluid media and affecting heat transfer. On this basis, this article proposes a new type of laser welding method for plate heat exchanger welding: multi-section welding, this welding method is used instead of laser spot welding. The effect of different welding methods on the weld pool morphology, fracture morphology, and mechanical properties of the weld joint was studied by a combination of numerical simulation and experiment, and the parameters were further optimized. It is hoped that the study of this laser welding method can provide researchers and industrial engineers with more insights.

2. Materials And Methods

First, 304 austenitic stainless steel plates with the dimensions 100mm×15mm×2mm were used as the welding base metal. The length of the lap joint area is 35mm and the diameter of the circular weld is 4mm, as shown in Figure 3. The detailed composition of base metal is listed in Table.1. Before welding, it was necessary to clean the impurities on the surface of the workpiece with acetone reagent.

The laser welding system is composed of TruDisk 8002 laser and KUKA robot. After welding, the sample was cut for a tensile test. There are three samples for each experimental parameter. Take the average value to get the final average tensile shear force. Further on, a stereomicroscope photographed the fracture morphology of the stretched sample and was used to observe the morphology and fusion state of the combined surface of the welded joint. Moreover, prepare a metallographic sample and use a metallographic microscope to Observe weld morphology with a metallographic microscope and measure the depth of fusion, and width of fusion at the same time. The observation method is shown in Figure 4. Use this observation direction when using different laser welding methods

To ensure the weld strength, it is required that the overall penetration depth of laser welding is controlled within the range of 3 ± 0.2 mm. The different power parameters for segmental welding are listed in Table.2. The welding sequence from the center of the circle to the end of it and four welding methods (including 1-section, 4-sections, 5-sections, and 6-sections) are adopted. The detailed schematic diagram of welding is shown in Figure 5.

3. Finite Element Analysis

3.1 Establishment of heat source modes

It is noteworthy that the heat source should be checked

Table 1 Chemical composition of 304 stainless steel (mass ratio, %).

C	Si	Mn	P	Ni	Cr	N	Fe
≤0.08	≤0.75	≤2.0	≤0.045	8.0-10.5	18.0-20.0	≤0.1	Bal.

Table 2 Process parameters of different welding methods

Welding type	Average power (W)	Defocus (mm)	Duty cycle (%)	Welding speed (m/min)	Impulse frequency (Hz)	Shielding gas flow (L/min)
1-section	2100	+4	50	1.5	40	25
4-sections	2500/2400/1700 /800	+4	50	1.5	40	25
5-sections	2500/2375/2200 /1650/750	+4	50	1.5	40	25
6-sections	2500/2350/2350 /1975/1600/725	+4	50	1.5	40	25

In Figure 6, is the maximum input energy density; and are Gaussian parameters, where represents the maximum characteristic radius on the plane $z=$, represents the maximum characteristic radius on the plane

z_e ; and z_i are the 3D Gaussian heat sources. The position makes a parameter with the surface of the piece to be welded, where z_e is the relative height difference between the upper surface of the 3D Gauss heat source and the surface of the workpiece, and z_i is the relative height difference between the lower surface of the 3D Gauss and the surface, positive above the outward. There is also the possibility of this being negative. So, the parameter relation can be expressed as[18-20]:

$$r_0(z) = r_e - (r_e - r_i) \frac{z_e - z}{z_e - z_i} \quad (1)$$

Regarding the numerical simulation of laser welding, the total energy of the 3D Gaussian heat source is:

$$Q = \eta P \quad (2)$$

Therefore, when using a 3D Gaussian heat source to simulate laser welding, the energy distribution is represented as:

$$q(r, z) = \frac{9\eta P e^3}{\pi H(e^3 - 1)(r_e^2 + r_e r_i + r_i^2)} \exp\left(-\frac{3r^2}{r_0^2}\right) \quad (3)$$

In formula 1, is the maximum radius of action on the plane of height z . Formula 2 can be used to calculate the total energy of the heat source when using a 3D Gaussian heat source to simulate laser welding. In this case, Q is the total energy of the heat source; η is the absorption rate of the metal to the laser and P stands for the laser power. Last, Formula 3 addresses the energy distribution of 3D Gaussian heat source simulating laser welding where q represents the energy density from the center r on the plane of height z and H is the total height of the heat source.

In SYSWELD, the heat source parameters can be calculated from the actual weld profile. Here, the welded joint profile parameters of the single-pass weld optimized by previous experiments are used as the basis for calculating the heat source parameters, which can effectively reduce the optimization of the heat source parameters. The morphology of the single-pass weld pool obtained with a laser power of 2500 W, a pulse frequency of 40 Hz, and a welding speed of 1.5m/min is shown in Figure 7. The weld width is 2.35 mm, the penetration depth is 2.94 mm, and the joint surface width is 1.2mm. Input data to SYSWELD Among them, the heat source parameters obtained by the feedback are as follows: $Re=1.175$, $Ri=0.6$, $Ze=0$, $Zi=-2.94$. Apply this heat source parameter to laser multi-sections welding. Using the 1-section welding method, the laser parameters are as follows: laser power is 1800 W, defocus is +4 mm, welding speed is 1.5 m/min. As shown in Figure 8, through comparison, it is found that the morphology of the molten pool in the numerical simulation is the same as the morphology of the actual welded joint, The accuracy of the selected heat source model and heat source parameters can be proved.

3.2 The establishment of the finite element model

The energy density generated by laser welding is extremely high, and the heating speed is fast. When the weld is locally heated, the temperature difference between the weld and the surrounding area is very large, while in the area far away from the weld, the temperature distribution is basically not obvious. Based on the characteristics of the temperature distribution of laser welding, when meshing, a finer mesh is required in the weld area and its vicinity. The meshing result of the welded specimen is shown in Figure 9. To improve the calculation accuracy, the grid division has to be relatively fine in and fit around the weld zone. Here, the minimum grid size is 0.2 mm during the grid division, so that the result of the temperature field is more accurate. In the area far from the weld, the maximum mesh size reaches 4 mm, leading to a reduced number of grids and calculation time, while the small and big mesh are connected by the transition mesh.

4. Results And Discussion

4.1 Numerical simulation and experimental comparison

Welding experiments were carried out according to the welding parameters shown in Table 2. Further on, it was necessary to compare the simulated molten pool morphology with the actual joint morphology when the welding experiment is completed. The diameter of the circular weld is 4mm, so take a cylinder with a diameter of 4mm for temperature field observation and the change depth of fusion can be observed directly. The temperature field cloud diagram obtained when the welding method is 1-section is shown in Figure 10. As can be seen, the depth of fusion was gradually increasing, with a change range of 3-3.38 mm. The alterations are a result of the different temperatures on the workpiece, brought with the action of the moving heat source during the welding process. The moving heat source has a significant performance on each position of the weld due to the circular welding path and the small diameter of the circumference. Therefore, the secondary heating has a superimposed effect on the weld, resulting in a greater change in the depth of fusion.

The joint morphology with the welding mode of 1-section shown in Figure 11 helped to closely observe the differences in depth of fusion. As shown, the molten pool morphology of numerical simulation is the same as the morphology of the actual welded joint, but the range of weld penetration is way too large to meet the experimental requirements, There will be no further discussion.

Considering the 4, 5, and 6-sections of welding, the temperature field distribution cloud diagrams obtained are shown in Figure 12, Figure 13, and Figure 14 respectively. As it can be observed, the welding process is the most stable one, and the variation range (3-3.12 mm) of the depth of fusion is the smallest when the 6-sections welding method is adopted. In addition, the morphology of the welded joint is shown in Figure 15, Figure 16, and Figure 17, proving that the depth of fusion is maintained at about 3 mm. It achieved the best welding effect also when the 6-sections welding method was adopted.

Figure 18 shows the temperature field of the welded combined surface and in the area enclosed by the welding path, the overall fusion is better. However, there is still a small part of the unfused areas. It was also observed that the incomplete fused positions at the combined surface of the welding joint are all around the welding starting point. The welding method of the 6-sections changed to a new welding path as shown in Figure 19, that is, the length of the initial welding section is increased from 2 mm to 3 mm (new 6-sections), while the other paths remained the same. The corresponding average power of each segment also changed -

to 2500/2350/2150/1975/1600/725 W—while other process parameters had no alterations. The final welding joint morphology obtained is shown in Figure 20, and it was achieved after a numerical simulation calculation of the temperature field and laser welding experiment. In this stage, the morphological properties are consistent with those of the actual welding joint, and the depth of fusion of the molten pool is about 3 mm. Figure 21 is the combined surface temperature field of the welded joint obtained by the new 6-sections welding method, the welded combined surface is completely fused. properly meeting all the experimental requirements.

4.2 Mechanical properties

To study the influence of different welding methods on the mechanical properties of weld joints, tensile experiments were carried out on welded joints obtained under the conditions of sections 4, 5, 6, and new 6-sections. It can be seen from Figure 22, The tensile shear force obtained by the 6-sections welding method is significantly improved compared with the 4-sections and 5-sections welding method, reaching over 10256N. Under the conditions of the new 6-sections welding method, the tensile shear force performance of the welded joint is further improved, that the average tensile shear force of the welded joint is 10454 N, and the maximum tensile force is increased by 2% compared with the one obtained by 6-sections welding. This indicates that the mechanical properties of this process are up to the mark.

To explore the reasons for the different tensile properties caused by different welding methods, it was necessary to conduct a numerical simulation analysis and experimental verification of the temperature field at the joint surfaces. The way of tensile fracture is shown in Figure 23, fracture positions are all at the combined surface. Figure 24 shows the tensile fracture morphology of the welded joint, and the existence of the area without fusion on the combined surface of the weld is consistent with the results of the temperature field simulation in Figure. 18 and 21. Also, The area of the fusion zone obtained in the 4, 5, 6, and new 6-sections methods are 15.95 mm², 15.88 mm², 17.50 mm², and 17.97 mm² respectively as shown in Figure. 25. Ergo, It can be concluded that the fusion area of combined surface and mechanical properties of welded joints has been greatly improved under the welding method based on new 6-sections.

4.3 Process parameter optimization

After observation and analysis of the welded joint obtained by the new six-sections welding method, a small number of pores could still be found. In pulse laser welding, laser transmission behavior has significant differences with the variation of the duty cycle, and this greatly affects the weld appearance and detects formation [21]. The porosity was reduced by changing the duty cycle, thereby further improving the quality of the welded joint. The detailed welding process parameters are shown in Table 3.

Figure 26 shows the weld morphology of welded joints under different duty cycles. Figure 27 and Figure 28 respectively represent the fusion area and tensile shear force of the welded joint also in different duty cycles. As shown, when the duty cycle is increased from 35% to 46%, the fusion area of the welded joint remains basically the same - maintained at about 18.5 mm². However, when the duty cycle is 35%, the tensile shear of the welded joint is significantly reduced. When the duty cycle is small, a high-power density laser beam acts on the workpiece to instantly vaporize the metal to form a keyhole, but at the same time, a large amount of plasma is generated to shield the absorption of laser energy by the molten pool. As the duty cycle increases.

Although the power density of the laser is weakened, the plasma generated is also reduced, but the absorption rate of the laser energy by the molten pool is increased. Finally, the heat obtained at the combined surface is not so divergent, make the change of the fusion area at the combined surface not obvious. When the duty cycle is 35%, the power density of the laser spot is extremely high, and a large amount of metal vapor is generated. Due to the small pulse width, the laser acts on the workpiece only for a short time, and the weld pool rapidly cools and solidifies. At this stage, it is too late for the metal vapor to escape, making it easier to form porosity defects. Combined with the tensile fracture morphology of the welded joint shown in Figure 29, it can be said that there are larger porosity defects at the tensile fracture with a duty cycle of 35%, therefore, the tensile properties of the welded joint are reduced

During the duty cycle from 46% to 75%, as it increases, the tensile shear force of the welded joint is gradually reduced. An increased duty cycle causes the laser power density to continue to downgrade, resulting in a reduction in the fusion area of the combined surface. When the duty cycle is between 54% and 58%, the fusion area is nearly equal, but the tensile shear force of the welded joint differs

by about 220 N. This is because, in this scenario, the power density of the pulsed laser is lower, so the generated energy is not enough to maintain the stable existence of the keyhole. Consequently, the keyhole collapse is easy to occur, causing the gas to stay in the weld, thus forming the pore defect. This phenomenon happens precisely due to the pores at the tensile fracture that the welded joint is pulled, causing the reduction of tensile shear force. When the duty cycle is increased to 75%, the laser power density is extremely low. It can be seen from the topography that there are large unfused areas and multiple pore defects at the joint surface, thereby weakening the tensile properties of welded joints. Based on the above analysis it is possible to state that, when the selected duty cycle is 42% to 46%, the best quality welded joint is obtained with a maximum tensile shear force of about 10632 N. As shown in Figure. 30, the new 6-sections welding method and the 45% duty cycle were used to conduct welding experiments on the trial plate pairs of the lubricating oil cooler. The welding seam quality is good, and there is no splash in the welding cavity, which fully meets the experiment.

Table 3 Process parameters under different duty cycles.

Welding type	Duty cycle (%)	Average power (W)	Welding speed (m/min)	Impulse frequency (Hz)	Defocus (mm)	Shielding gas flow (L/min)
New 6-sections	35	2500/2350/2150/1975/1600/725	1.5	40	+4	25
New 6-sections	42	2500/2350/2150/1975/1600/725	1.5	40	+4	25
New 6-sections	46	2500/2350/2150/1975/1600/725	1.5	40	+4	25
New 6-sections	50	2500/2350/2150/1975/1600/725	1.5	40	+4	25
New 6-sections	54	2500/2350/2150/1975/1600/725	1.5	40	+4	25
New 6-sections	58	2500/2350/2150/1975/1600/725	1.5	40	+4	25
New 6-sections	75	2500/2350/2150/1975/1600/725	1.5	40	+4	25

5. Conclusions

Considering the major outcomes of the experimentations here conducted, some main conclusions could be obtained after finishing all the processes:

1. By comparing the simulation results of different welding methods, it is concluded that the best welding process is the new 6-segment welding method, the new 6-sections welding method has the smallest fluctuation range of depth of fusion. The experimental results are in good agreement with the simulation results.
2. Through the tensile test, the mechanical properties of the welded joints under different methods are obtained. When conducted with the new 6-sections method, the tensile shear force is the largest. Simultaneously the temperature field of the combined surface of the welded joint and the macroscopic morphology of the actual tensile fracture is analyzed. When the welding method is the new 6-sections, there is no unmelted area on the combined surface of the welded joint, which is also consistent with the temperature field results of the numerical simulation.
3. The change in the duty cycle affects the pulse width of the laser. When the duty cycle is between 42%-46%, the laser power density is high, the fusion area of the combined surface is large, and The formed keyhole is stable, so it is not conducive to the formation of porosity. In this case, the resulting welded joints have the highest quality.

Declarations

Acknowledgments

Not applicable.

Funding

Supported by Jilin Province Department of Science and Technology, China (20180201063GX).

Authors' contributions

LL was in charge of the whole trial; TJ wrote the manuscript; HYZ and YCD assisted with sampling and laboratory analyses. YS supervised the study All authors read and approved the final manuscript.

Competing interests

The authors declare no competing financial interests.

Authors Details

²Engineering Research Center of Laser Processing for Universities of Jilin Province, No.7089 Weixing road, Changchun 130022, Jilin, China

³National Base of International Science and Technology Cooperation in Optics, No.7089 Weixing road, Changchun 130022, Jilin, China

Biographical notes

Jia Liu, born in 1983, is currently an associate professor at *Changchun University of Science and Technology, China*. He received his Ph.D. degree from *Changchun University of Science and Technology, China*, in 2012. His research interests include laser welding, laser composite processing, and its finite element simulation technology.

Tel: +86-431-85582207. E-mail address: liujia@cust.edu.cn

Tao Jiang, born in 1992, is currently a master candidate at the Engineering Research Center of Laser Processing, *Changchun University of Science and Technology, China*.

E-mail: 815793095@qq.com

Yan Shi, born in 1972, is currently a professor at *Changchun University of Science and Technology, China*. He received his Ph.D. degree from *Changchun University of Science and Technology, China*, in 2007.

E-mail: shiyan@cust.edu.cn

Hong-Yin Zhu, born in 1994, is currently a master candidate at Engineering Research Center of Laser Processing, *Changchun University of Science and Technology, China*.

E-mail: 407484332@qq.com

Yu-Chi Dai, born in 1994, is currently a Ph.D. candidate at Engineering Research Center of Laser Processing, *Changchun University of Science and Technology, China*.

E-mail: 1377416376@qq.com

References

1. Shirzad, M., Delavar, M. A., Ajarostaghi, S. S. M., & Sedighi, K. (2019). Evaluation the Effects of Geometrical Parameters on the Performance of Pillow Plate Heat Exchanger. *Chemical Engineering Research and Design*. R C Goertz, R C Thompson. Electronically controlled manipulators. *Nucleonics*, 1954, 12(11): 46–47.
2. Hemant kumar, N.K. Singh. Performance of activated TIG welding in austenitic stainless steel 304 welds. *Materials Today: Proceedings*, Volume 4, Issue 9, 2017, Pages 9914-9918.
3. Shashi Kumar, N. Murugan, K.K. Ramachandran. Microstructure and mechanical properties of friction stir welded AISI 316 austenitic stainless steel joints. *Journal of Materials Processing Technology*. Volume 254, April 2018, Pages 79-90.
4. Sukhdeep Singh, Kjell Hurtig, Joel Andersson. Investigation on effect of welding parameters on solidification cracking of austenitic stainless steel 314. *Procedia Manufacturing*. Volume 25, 2018, Pages 351-357.
5. Wu, J. Gong, G. Chen, L. Xu, Research on laser welding of vehicle body, *Opt Laser Technol.* 40 (2) (2008) 420–426.
6. Gao, Y. Kawahito, S. Kajii, Observation and understanding in laser welding of pure titanium at subatmospheric pressure, *Opt. Exp.* 25 (12) (2017) 13539–13548.
7. Miyamoto, Y. Okamoto, A. Hansen, J. Vihinen, T. Amberla, J. Kangastupa, High speed, high strength microwelding of Si/glass using ps-laser pulses, *Opt. Exp.* 23 (3) (2015) 3427–3439.
8. Masoumi, M., Marashi, S. P. H., & Pouranvari, M. (2010). Metallurgical and Mechanical Characterization of Laser Spot Welded Low Carbon Steel Sheets. *Steel Research International*, 81(12), 1144–1150. doi:10.1002/srin.201000064.
9. Yang, Y. S., & Lee, S. H. (1999). A study on the joining strength of laser spot welding for automotive applications. *Journal of Materials Processing Technology*, 94(2-3), 151–156. doi:10.1016/s0924-0136(99)00094-1.
10. Dal, M., & Fabbro, R. (2016). [INVITED] An overview of the state of art in laser welding simulation. *Optics & Laser Technology*, 78, 2–
11. Balasubramanian, K. R., Suthakar, T., Sankaranarayanan, K., & Buvanashakaran, G. (2011). Laser Welding Simulations of Stainless Steel Joints Using Finite Element Analysis. *Advanced Materials Research*, 383-390, 6225–6230.
12. Yan, J., Gao, M., & Zeng, X. (2010). Study on microstructure and mechanical properties of 304 stainless steel joints by TIG, laser and laser-TIG hybrid welding. *Optics and Lasers in Engineering*, 48(4), 512–517.
13. Chakravarthy, M., Ramanaiah, N., & Sundara Siva Rao, B. (2014). Effect of laser welding on mechanical properties of 70/30 Cu-Ni alloy welds. *Proceedings of the Institution of Mechanical Engineers, Part B:*

- Journal of Engineering Manufacture, 228(9), 1153–1161.
14. Liu, B., Jin, W., Lu, A., Liu, K., Wang, C., & Mi, G. (2020). Optimal design for dual laser beam butt welding process parameter using artificial neural networks and genetic algorithm for SUS316L austenitic stainless steel. *Optics & Laser Technology*, 125, 106027.
 15. Derakhshan ED, Yazdian N, Craft B, et al. Numerical simulation and experimental validation of residual stress and welding distortion induced by laser-based welding processes of thin structural steel plates in butt joint configuration. *Opt Laser Technol*. 2018; 104:170–182.
 16. Saravanan, S., Raghukandan, K., & Kumar, G. S. (2018). Comparison of numerical and experimental macrostructure in Nd: YAG laser welding of Hastelloy C-276. *Optik*. doi:10.1016/j.ijleo.2018.11.139.
 17. C. Ganesh, M. Vasudevan, K.R. Balasubramanian, N. Chandrasekhar, S. Mahadevan, P. Vasantharaja, T. Jayakumar, Modeling, prediction and validation of thermal cycles, residual stress and distortion in type 316 LN stainless steel weld joint made by TIG welding process, *Procedia Eng*. 86 (2014) 767–774.
 18. Welding simulation user guide, Sysweld manual ESI Group, Available online: https://www.esigmbh.de/downloads/ESI/Dokumente/Welding/The_Welding_Simulation_Solution_210408 (access on February 2016).
 19. Kik, T.; Górka, J. Numerical simulations of laser and hybrid S700MC T-joint welding. *Materials* 2019, 12, 516.
 20. Wu, C.S., Wang, H.G., Zhang, Y.M. A new heat source model for keyhole plasma arc welding in FEM analysis of the temperature profile. *Weld. J*. 2006, 85, 284–
 21. Meng, W., Xu, Z., Ma, Q., Yin, X., & Fang, J. (2019). Pulse fiber laser welding of AISI 321-AISI 405 stainless steel thick plates butt joints. *Journal of Materials Processing Technology*.

Figures

Figure 1

Lubricating-oil cooler.

Figure 1

Lubricating-oil cooler.

Figure 2

Resistance spot welding process and internal section photos of the sealed cavity: (a) Spatter during welding; (b) The deposition of splashes in the cavity.

Figure 2

Resistance spot welding process and internal section photos of the sealed cavity: (a) Spatter during welding; (b) The deposition of splashes in the cavity.

Figure 3

Geometric model

Figure 3

Geometric model

Figure 4

Schematic diagram of the observation direction of the metallographic sample

Figure 4

Schematic diagram of the observation direction of the metallographic sample

Figure 5

Schematic diagram of laser overlap welding method: (a) 1-section; (b) 2-sections; (c) 3-sections; (d) 4-sections

Figure 5

Schematic diagram of laser overlap welding method: (a) 1-section; (b) 2-sections; (c) 3-sections; (d) 4-sections

Figure 6

3D Gaussian heat source

Figure 6

3D Gaussian heat source

Figure 7

The shape of the welded joint of single-pass weld

Figure 7

The shape of the welded joint of single-pass weld

Figure 8

Comparison of weld morphology of welded joints: (a) Numerical simulation of molten pool morphology; (b) Actual weld joint morphology.

Figure 8

Comparison of weld morphology of welded joints: (a) Numerical simulation of molten pool morphology; (b) Actual weld joint morphology.

Figure 9

The meshing result of the welded specimen: (a) Grid within the weld; (b) Overall grid

Figure 9

The meshing result of the welded specimen: (a) Grid within the weld; (b) Overall grid

Figure 10

The temperature field distribution cloud map under the welding condition of 1-section.

Figure 10

The temperature field distribution cloud map under the welding condition of 1-section.

Figure 11

The welding method is a 1-section of joint morphology: (a) Numerical simulation of molten pool morphology; (b) Actual welded joint morphology.

Figure 11

The welding method is a 1-section of joint morphology: (a) Numerical simulation of molten pool morphology; (b) Actual welded joint morphology.

Figure 12

The temperature field distribution cloud map under the welding condition of 4-sections

Figure 12

The temperature field distribution cloud map under the welding condition of 4-sections

Figure 13

The temperature field distribution cloud map under the welding condition of 5-sections

Figure 13

The temperature field distribution cloud map under the welding condition of 5-sections

Figure 14

The temperature field distribution cloud map under the welding condition of 6-sections

Figure 14

The temperature field distribution cloud map under the welding condition of 6-sections

Figure 15

The welding method is 4-sections of joint morphology: (a) Numerical simulation of molten pool morphology; (b) Actual welded joint morphology.

Figure 15

The welding method is 4-sections of joint morphology: (a) Numerical simulation of molten pool morphology; (b) Actual welded joint morphology.

Figure 16

The welding method is 5-sections of joint morphology: (a) Numerical simulation of molten pool morphology; (b) Actual welded joint morphology.

Figure 16

The welding method is 5-sections of joint morphology: (a) Numerical simulation of molten pool morphology; (b) Actual welded joint morphology.

Figure 17

The welding method is 6-sections of joint morphology: (a) Numerical simulation of molten pool morphology; (b) Actual welded joint morphology.

Figure 17

The welding method is 6-sections of joint morphology: (a) Numerical simulation of molten pool morphology; (b) Actual welded joint morphology.

Figure 18

Temperature field of combined surface under different welding methods: (a) 4-sections; (b) 5-sections; (c) 6-sections.

Figure 18

Temperature field of combined surface under different welding methods: (a) 4-sections; (b) 5-sections; (c) 6-sections.

Figure 19

The welding method is the new 6-sections welding path.

Figure 19

The welding method is the new 6-sections welding path.

Figure 20

Weld joint morphology of new 6-sections.

Figure 20

Weld joint morphology of new 6-sections.

Figure 21

The welding method is the combined surface temperature field of the new 6-sections welding joint.

Figure 21

The welding method is the combined surface temperature field of the new 6-sections welding joint.

Figure 22

The maximum tensile force of welded joints under different welding methods

Figure 22

The maximum tensile force of welded joints under different welding methods

Figure 23

Schematic diagram of tensile specimen fracture

Figure 23

Schematic diagram of tensile specimen fracture

Figure 24

Tensile fracture morphology of welded joint under different welding methods: (a) 4-sections; (b) 5-sections; (c) 6-sections; (d) new 6-sections.

Figure 24

Tensile fracture morphology of welded joint under different welding methods: (a) 4-sections; (b) 5-sections; (c) 6-sections; (d) new 6-sections.

Figure 25

Fusion area of the combined surface of the welded joint under different welding methods.

Figure 25

Fusion area of the combined surface of the welded joint under different welding methods.

Figure 26

Weld morphology of welded joints under different duty cycles: (a) 35%; (b) 42%; (c) 46%; (d) 50%; (e) 54%; (f) 58%; (g) 75%.

Figure 26

Weld morphology of welded joints under different duty cycles: (a) 35%; (b) 42%; (c) 46%; (d) 50%; (e) 54%; (f) 58%; (g) 75%.

Figure 27

The tensile shear force of welded joints under different duty cycles.

Figure 27

The tensile shear force of welded joints under different duty cycles.

Figure 28

The fusion area of the combined surface of the welded joint under different duty cycles.

Figure 28

The fusion area of the combined surface of the welded joint under different duty cycles.

Figure 29

Tensile fracture morphology of welded joints under different duty cycles: (a) 35%; (b) 42%; (c) 46%; (d) 50%; (e) 54%; (f) 58%; (g) 75%.

Figure 29

Tensile fracture morphology of welded joints under different duty cycles: (a) 35%; (b) 42%; (c) 46%; (d) 50%; (e) 54%; (f) 58%; (g) 75%.

Figure 30

The welding seam morphology of the plate-pair laser welding of the lubricating oil cooler: (a) The front side of the weld; (b) The back of the weld.

Figure 30

The welding seam morphology of the plate-pair laser welding of the lubricating oil cooler: (a) The front side of the weld;(b) The back of the weld.