Analysis of the residual stress in additive manufacturing of Ti-6Al-4V

Junjun Liu1, Hao Jiang2, Zhenkun Lei1*a, Ruixiang Bai1b* and Shen Yu1

1State Key Laboratory of Structural Analysis for Industrial Equipment Department of Engineering Mechanics, Dalian University of Technology, Dalian 116024, China
2 School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, China
*a*leizk@dlut.edu.cn, b*bairx@dlut.edu.cn

Abstract. Minimizing the residual stress build-up in metal-based additive manufacturing plays a pivotal role in selecting a particular material and technique for making an industrial part. However, there are still some limitations for this application, especially the unfavourable final shape and undesired macroscopic properties of metallic parts built in additive manufacturing systems. The distortion or crack due to the residual stress of these parts leads usually to severe problems for some kinds of metal additive manufacturing technology. Therefore, it is necessary to study the distribution of residual stress in the process, which can provide an important reference for the process control of laser cladding. Taking Ti-6Al-4V (TC4) alloy as the research object, a nonlinear sequential thermal mechanical coupling model is established by combining the finite element numerical simulation and experimental deformation measurement. A least squared cost function between the Finite Element Cladding model and the experimental deformation measurement is proposed, and the finite element model updating method is constructed to retrieve the heat source parameters of TC4 Alloy in laser cladding. By comparing the numerical results with the experiment, the rationality of the inversion results of heat source parameters is verified. After that, the stress near the cladding layer is analyzed, and the influence of temperature field on the mechanical field distribution is further studied through the affects of stress distribution.

1. Introduction

As a rapid manufacturing and surface modification technology of metal parts that can easily realize automation, laser cladding technology has been more and more widely used in the field of modern mechanical manufacturing [1]. Compared with traditional surface modification technologies such as thermal spraying or welding, laser cladding provides many advantages, mainly including: cooling rate is as high as 106 ℃/s, large temperature gradient and fine grain structure can be formed, resulting in fine microstructure. The energy density is concentrated, the dilution ratio and heat affected zone are small. The thickness and width of cladding layer are controllable, which is easy to realize automation [2-4]. The bonding between cladding layer and substrate is metallurgical bonding, so the bonding strength is high.

Titanium alloy materials have low density, corrosion resistance and excellent thermophysical properties. Laser cladding technology based on titanium alloy is widely used in aerospace, medical, petrochemical, nuclear energy and power generation industries [5]. Because the limit temperature of aluminum alloy in engineering application is only 130℃ [6], titanium alloy is often used to replace
aluminum materials in high-temperature service. According to the research, titanium alloy is widely used in the aerospace industry. The consumption of titanium alloy on aircraft is 70% of its total output. It is mainly used for Aeroengine components, such as shell, engine blade and rotor, as well as aircraft cabin and structural parts [7]. In addition, titanium alloy is non-magnetic, non-toxic, has strong biological affinity and low corrosion rate in blood immersion environment [8], so it is also commonly used in medical industry, such as heart stent, artificial bone, etc.

Laser cladding is a rapid melting and solidification process, and it is difficult to monitor the changes of various physical quantities in real time through experiments. Therefore, numerical simulation has become an effective means to determine the temperature and stress evolution law of laser cladding and fully understand the microstructure degradation and residual stress formation mechanism of cladding. Khamidullin [9] established a two-dimensional laser cladding model to simulate the macro morphology change, crystallization process and temperature field evolution of the cladding layer. Wirth [10] established a finite element model to simulate the laser cladding process based on the experimental parameters such as powder flow, heat transfer and surface tension, and well predicted the effective power of the laser. Jiang [11] improved the traditional contour method based on Levenberg Marquardt (LM) algorithm, and corrected the residual stress distribution of thin plate by comparing the displacement results of contour method and numerical simulation.

Firstly, this paper introduces the basic theory of cladding heat source model, including TC4 material parameters, heat source model and heat source parameter inversion process. Then, according to the preparation process of the specimen, the measurement method of the experimental data and the simulation process of the Thermo-elastic-plastic finite element method are given. Finally, aiming at the inversion problem of cladding heat source parameters, a method for inversion of single-layer cladding heat source parameters is proposed based on the finite element model updating strategy. Using the experimentally measured bending deformation of the plate after cladding as the reference data, the shape parameters of the double ellipsoid heat source are iteratively corrected, which can avoid the complex parameter measurement in the cladding process, The temperature and stress distribution of the specimen are analyzed.

2. Experimental details
All the materials used in the experiment are TC4 (including substrate and powder), and its size is shown in Figure 1. Before cladding, firstly, wipe the surface of the substrate with a cotton ball moistened with alcohol and fix it on the experimental platform. Then, turn on the nitrogen switch connecting the powder blower, adjust the nitrogen pressure between 0.3~0.4MPa, and use the water cooler to ensure that the working temperature of the laser is within the safe range. Finally, set the cladding path and laser control parameters. In the cladding experiment, ZKSX3008 YAG laser is used to cladding the powder on the substrate surface. After the cladding is completed, the test piece is allowed to stand for 3000s to ensure cooling before measurement and observation.
The deformation of specimens should be measured when the specimen is ready. Considering of the large temperature gradient between the cladding layer and the substrate, whose expansion coefficient is different, the strain at the interface is large after the completion of the cladding experiment [12]. Among all deformation amounts, the warping deformation amount of the substrate can directly reflect the strain of the cladding layer. Figure 2 is the schematic diagram of substrate deformation. Because the heat distribution at both ends of the substrate at the beginning and end of cladding is very complex, this study only takes the middle section as the research object, and it is considered that the substrate deformation of the middle section is the same.

3. Construction and Geometrical Dimensions of Specimens
According to the size of the test piece (160mm) × 160mm × 10mm), the finite element model is established on abaqus2020 software. The eight-node hexahedron thermal analysis element is adopted in the finite element model, and the mesh model is shown in Figure 3(a). In order to accurately calculate the thermal cycle process of the cladding layer and reduce the calculation speed, the fine grid is used in the cladding layer and heat affected zone, and the gradual grid increases with the increase of the distance from the cladding layer is used for the division of other areas. Since there is only the support boundary of the ground in the experiment, it is necessary to apply the boundary conditions to prevent the rotation of the substrate on the model, as shown in Figure 3(b). The thermophysical material properties of TC4 used in the simulation refer to references [13, 14].
4. Inversion of heat source parameters

In the process of laser cladding, the cladding layer is a strip area with small thickness width ratio and the size of molten pool is small, the moving double ellipsoid heat source model proposed by Goldak [15] is adopted, as shown in Figure 4.

In this study, the plate cladding deformation is used as the experimental data, and the heat source parameters of the double ellipsoid model are inversed by means of finite element model updating, and then the heat source parameters are used in the mechanical analysis of cladding components. This method simplifies the complex coupling problem in cladding by modifying the parameters of double ellipsoid heat source. In order to accurately evaluate the consistency between numerical simulation and experiment, the following evaluation function is used, as follows:

\[ F_{RMSE} = \sum_{i=1}^{n} w^i [f_{FEM}^i(p) - f_{REF}^i]^2 \]  

Where \( w^i \) is the weight, \( f_{FEM}^i \) is the result of numerical simulation, and \( f_{REF}^i \) is the result of experimental measurement, \( p=[a, b, c, c_f, c_r] \).

5. Results and discussion

Using the double ellipsoid heat source parameter inversion method proposed in Section 4 of this paper, the variation of the calculated error evaluation function RSME with the iteration step is shown in
Finally, a set of reasonable heat source parameters are obtained: \( a = 2.483 \text{ mm} \), \( b = 1.706 \text{ mm} \), \( c_{f} = 4.067 \text{ mm} \), \( c_{r} = 5.485 \text{ mm} \). At this time, the comparison between the deformation curve of the corresponding simulation results and the deformation curve of the actual specimen is shown in Figure 5(b), which shows that the experimental results are in good agreement with the finite element results, and the deformation contour is roughly the same.

Figure 5(a). Figure 6 shows the stress nephogram results of TC4 thick plate after cooling for 3000s. It can be seen from the figure that the longitudinal stress value is large, and the residual stress of laser cladding is mainly concentrated in and around the cladding layer, and its stress value is stable at about 1200Mpa, which exceeds the yield strength of TC4 alloy at room temperature by 1098Mpa.

Figure 6. Calculation results of residual stress

6. Conclusion
In this paper, the transient thermal mechanical coupling finite element method is applied to optimize the heat source parameters of TC4 Alloy during cladding by LM iterative method. The optimized deformation is consistent with the experimental results. This method has strong practicability and can avoid the complex thermal metallographic stress analysis in the cladding process. Then, through this method, the influence of the temperature field of single pass cladding on the distribution of residual stress is analyzed, and the main conclusions are as follows:

- From the simulation results of the optimized sample, the deformation of the sample is highly consistent with the experimental results, and the accurate shape parameters of the heat source
can be obtained. The method proposed in this paper is not limited to the size and shape of specimens, so this method is also applicable to other complex structures.

- The high stress area is mainly concentrated in and around the cladding layer. Through the stress analysis of the representative path of the cladding layer, it is found that the von Mises stress has the same distribution trend as the longitudinal residual stress, and the peak value of the longitudinal residual stress is 4mm away from the cladding layer.
- In the width direction of the cladding plate, the longitudinal residual stress presents a 'tension compression' distribution. There is a negative stress zone at 10mm, about 100MPa. This stress distribution leads to the warpage of the substrate.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (Nos. 12002078, 11772081, 11972106).

References
[1] Toyserhani E., Corbin S., Khajepour A. Laser Cladding. (2005) The Chemical Rubber Company Press, London.
[2] Vollertsen, F., Partes, K., Meijer, J. (2005) State of The Art of Laser Hardening and Cladding. International Journal of Human Resources Development and Management, 70(4): 116-116
[3] Wang W., Pinkerton A.J., Wee L.M., Li L. (2008) Component Repair Using Laser Direct Metal Deposition. In: Hinduja S., Fan KC. (eds) Proceedings of the 35th International MATADOR Conference. London. Vol.222
[4] Kattire P., Paul S., Singh R. (2015) Experimental Characterization of Laser Cladding of CPM9V on H13 Tool Steel for Die Repair Applications. Journal of Manufacturing Processes, 2015, 20(3): 492-499
[5] Casalino G., Curcio F., Minutolo F. (2005) Investigation on TiAl4V Laser Welding Using Statistical and Taguchi Approaches. Journal of Materials Processing Technology, 167(2-3): 422-428
[6] Lima M. (2005) Laser Beam Welding of Titanium Nitride Coated Titanium Using Pulse-Shaping. Materials Research, 8(3): 323-328
[7] Moiseyev V. N., Titanium Alloys. (2005) Russian Aircraft and Aerospace Applications, Taylor and Francis, Russian
[8] Choubey A., Basu B., Balasubramaniam R. (2004) Electrochemical Behavior of Intermetallic Ti-based alloys in Simulated Human Body Fluid Environment. Intermetallics, 12(6): 679-682
[9] Khamidullin B. A., Tsivilskiy I. V., Gorunov A. I. (2019) Modeling of The Effect of Powder Parameters on Laser Cladding Using Coaxial Nozzle. Surface and Coatings Technology, 364: 430-443
[10] Wirth F., Wegener K. (2018) A Physical Modeling and Predictive Simulation of The Laser Cladding Process. Additive Manufacturing, 22: 307-319
[11] Jiang H., Liu J., Lei Z. (2021) Noise-insensitive contour method for residual stress measurement in laser butt welding. Thin-Walled Structures, 165
[12] Zhao H., Zhang H., Xu C. (2009) Temperature and Stress Fields of Multi-Track Laser Cladding. Transactions of Nonferrous Metals Society of China. 19: S495-S501
[13] Mills K. C. (2002) Recommended Values of Thermophysical Properties for Selected Comm. Aircraft Engineering and Aerospace Technology, Woodhead Publishing, Abingto.
[14] Sha W., Malinov S. (2009) Titanium Alloys: Modelling of Microstructure, Properties and Applications. Aircraft Engineering and Aerospace Technology, 81(3): 95-202
[15] Goldak J., Chakravarti A., Bibby M. (1984) A New Finite Element Model for Welding Heat Sources. Metallurgical Transactions B, 15(2): 299-305