Dual-beam laser welding and seam accurately tracking control for 3D T-joint

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Abstract. The processing methods and quality of T-joint directly affect the performance of stiffened panels. In this paper, firstly, a ten-six axis dual-beam laser welding system is constituted to research the T-joint welding process. Then, the ten-six axis controller in laser welding system is designed to achieve the accurate controlling for position and attitude of welding head during 3D welding of T-joint. In addition, the real-time measurement on both sides of T-joint is adopted to enable deformation compensation and precise tracking for welding seam. Finally, the T-joint welding tests are carried out and the results show that the welding seam errors are within allowable range. Consequently, the dual-beam laser welding and seam tracking control technology presented in this study can meet the processing requirements for T-joint.

1. Introduction

The earliest dual-beam laser welding equipment was developed in the 1990s by the Bremen Institute of Radiation, Helmholtz Association, Fraunhofer Institute for Materials and Radiology, Hannover Laser Institute, Aachen University of Technology and other scientific research institutes. After nearly ten years of research and development, it has been successfully applied to the welding of the lower panel of the Airbus A380 nose [1]. Domestically, the dual-beam laser welding of T-joints is often conducted by two welding robots [2], which is usually applied to the dual-beam welding test to verify the process feasibility. However, this method is not suitable for integral welding of large-sized ribbed structures, and cannot guarantee the production accuracy and efficiency, thus not meeting the welding practical application conditions. In order to meet the growing demand for large-scale ribbed structural parts in various industries, it is urgent to independently develop three-dimensional dual-beam laser welding technology.

The best way of T-joint laser welding is to use dual-beam laser to weld the on both sides of T-joint synchronously [3], [4]. The dual-beam can be obtained by optical spectrometry or by using two lasers to separate the light. Compared with traditional processing, laser welding can reduce the weight of workpiece, improve the stiffness of parts and improve production efficiency [5]. Generally, the technical difficulties of the 3D double-beam laser welding of T-joint are as follow [6]-[9]: the position and attitude of the welding head must meet the accuracy requirements in the 3D welding process; the welding speed, laser power, laser focus must meet the welding process requirements during the 3D welding process; the weld seam is prone to deformation during the laser welding, which will result in
poor quality of weldment or even welding failure, and thus real-time tracking and compensation is necessary in the laser welding process; in the dual-beam welding process, the adjustment of one side will affect the other side, which must be controlled and restrained. Therefore, it is necessary to independently research and develop dual-beam laser welding controller system for 3D T-joint. In addition to the 3D welding, this system also needs to complete the following control functions: dual-beam laser control; 3D welding trajectory teaching and motion planning; real-time online measurement, modeling and tracking of bilateral welding seam [10], [11]; the integration of six-axis motion control and device of welding seam measurement and tracking [12]; automatic adjustment of the laser focus position according to the welding process; the control system software is integrated with the CAD/CAM system.

2. Structure and coordinate system of ten-six axis welding system
In this section, a six-axis machine tool is built to control the position of solder joint through three translation axes and the incident direction of the laser beam through three rotation axes, meeting the requirements for the position and posture controlling of the welding head during 3D laser welding process. The structure of ten-six axis dual-beam laser welding system is shown in Fig. 1. The dual-beam laser welding platform is formed by integrating a three-degree-of-freedom dual-beam welding head on a three-coordinate machine tool. The rotating mechanism of the C-axis is installed inside the ram so that the working part can rotate around the Z-axis, and then through the rotating mechanism of the A-axis and B-axis, the 3D motion can be completed on arc plate. Moreover, since the simultaneous processing of the two laser beams is required to ensure during dual-beam welding process. As show in Fig. 2, the welding seam tracking device is arranged on both sides of the arc plate, and the four auxiliary axes \( U1, V1, U2 \) and \( V2 \) are divided into two parts to respectively constitute two sets of cross slides, which realize the deformation compensation and welding seam tracking. On the working surface of laser welding head, a two-dimensional coordinate system \( U1-V1 \) is established, where \( V1 \) is the incident direction of the laser beam, and \( U1 \) is the direction perpendicular to \( V1 \) direction at a point on the laser beam. Similarly, the two-dimensional coordinate system \( U2-V2 \) is established on the other side. In addition to ensuring that the position and normal vector of the laser welding head meet the requirements, it is also necessary to constrain the tangent vector of the solder joint. The dual-beam welding has two welding heads, and accordingly if the tangential direction is not limited, the one welding head will lose its machining direction when the other welding head changes tangentially. Therefore, a bilateral independent control method is used to adjust the welding seam deviation during the welding process, and in this method, two sets of cross slides are assembled, each of which independently works in \( U \) and \( V \) directions respectively.

3. Design of ten-six axis controller
The structure of six-axis motion controller is shown in Fig. 3. The host IPC mainly provides man-machine interface, parameter setting, system diagnostics and program background management. The six-axis motion controller achieves the precise control of three-dimensional welding motion trajectory.
Since the transmission mechanism in each axis is complex, in order to ensure the motion accuracy, the grating scale and circular grating are respectively adopted in the linear axis and rotary axis for position and angle feedback. As the execution component of each motion axis, AC servo motor and servo drive form a full-closed loop control with motion controller. The response performance of each motor can reach the required static and dynamic indicators through the adjustment of PID parameters. High-speed Ethernet is used between host IPC and six-axis motion controller to realize two-way data communication in real time.

In addition, a dual-axis tracking controllers are located on both sides of the T-joints to realize dual-way seam tracking and compensation control. In order to realize the adaptive control of welding seam tracking in the laser welding process, the welding seam deformation must be detected and compensated in real time. The welding seam measurement and tracking control system is shown in Fig. 4. In order to ensure the real-time performance of the welding seam measurement and tracking, both of the laser welding head and the visual measuring head are installed on the two sets of cross slides to measure and compensate the welding seam deviation in real time. In the laser welding process, the machine tool control system controls the welding head to move along with the seam trajectory, and the image of the seam partial surface is captured in real time by visual measuring head and then is transmitted to the host IPC for image processing. When there is a deviation between the position of seam and the position of laser welding head, the measurement system will calculate the speed and direction of the two axes on the cross slide according to the deviation. The calculated speed and direction are converted into signed analog signals by DA and then transmitted to the servo drive which works in speed mode. The servo drive controls the two motor movements in the two cross slides to compensate the deviation, namely a position closed loop is formed through visual measurement to achieve real-time detection and precise tracking of welding seam.
micro depth of field area and the local plane of joint is presented in the visible range of camera. At last, based on the captured image, the width, position, and normal vector of the welding seam are obtained.

4. Real-time and precise tracking control of welding seam

4.1. 3D welding trajectory generation

In this section, a 3D trajectory generation method is constructed. As described above, it is necessary to ensure the $U$ direction alignment of the dual-beam laser and the $V$ direction laser focus tracking. The focal length of the laser beam $V$ is not considered in this method, meaning that the laser beam is considered to be an infinitely long ray. Firstly, the welding head working plane is constructed with reference to the one side welding curve. Then, the laser beam process tilt angle on the working surface is set as a constraint to set the laser beam attitude. Finally, the virtual tool is constructed by taking the intermediate orientation of the two laser beams as the actual control tool. As long as the two laser beams are projected onto the welding curves on both sides respectively, the seam deviation compensation in the $V$ direction can be conducted by the welding and tracking system. After laser beam position planning on both sides is completed, a virtual tool is assumed in the center position, which uses the intersection point of the laser beam as the tool tip and the knife axis bisects the left and right laser beams. In conclusion, this method translates the two-beam trajectory planning problem into a single path planning problem for virtual tool. In this method, the position and posture planning of laser beam on the both sides is conducted firstly:

$$\begin{align*}
P_{ki} &= \text{disc}(S_k, i) \\
T_{ki} &= t_{ki}, \\
N_{ki} &= n_{ki} \cdot \text{Rot}(t_{ki}, \theta_k)
\end{align*}$$

(1)

where, $P_{ki}$ represents the $i$-th welding point on the welding curve $S_k$, which is obtained by dispersing $S_k$; $T_{ki}$ represents the tangent vector on the $i$-th welding point, and the direction is the tangential direction of the point on the welding curve $S_k$, while $N_{ki}$ represents the normal vector at the $i$-th welding point, and is obtained by rotating the inclination angle $\theta_k$ around the tangential direction of the welding point. The welding point $P_{ki}$, tangent vector $T_{ki}$ and normal vector $N_{ki}$ constitute the position data of $i$-th welding point, representing the main side laser beam position and posture. A plane $R_i$ is created as a welding head working surface crossing the point $P_{ki}$. The tangent vector $T_{ki}$ in the position data of $i$-th welding point is regarded as the normal vector of $P_{ki}$ on the plane $R_i$, and in this case, the welding head working surface $R_i$ is always perpendicular to the curved surface. $P_{2i}$ represents $i$-th welding point on the welding curve $S_2$, which is obtained by intersecting the plane $R_i$ with the welding curve $S_2$. $T_{2i}$ represents the tangent vector of the welding point $P_{2i}$, and it is the same as the corresponding tangent vector of weld points $P_{ki}$. $N_{2i}$ represents the normal vector at $i$-th welding point on welding curves $S_2$, which is numerically equal to the normal vector $N_{ki}$, and has been rotated the inclination angle $\theta_2$ around the tangential direction of the welding point. The welding point $P_{2i}$, tangent vector $T_{2i}$ and normal vector $N_{2i}$ constitute the position data of $i$-th welding point on the on welding curves $S_2$, representing the position and posture of secondary side laser beam. At last, the position and posture of virtual welding head is obtained, namely the point $P_{3i}$, $P_{3i}$ is the intersection point of the two laser beams, which is recorded as the $i$-th virtual welding joint. The tangential and normal vectors of the point $P_{3i}$ are respectively the average values of the above two tangential and normal vectors. Here in the welding point file, $P_{3i}$ is expressed as $X$, $Y$ and $Z$ in the three-dimensional space, and $N_{3i}$ are expressed as $I$, $J$ and $K$, while $T_{3i}$ are expressed as $L$, $M$ and $N$. The above data form the position data of $i$-th virtual welding point, and is regarded as the welding point data of virtual control, and is also the welding point data involved in the post calculation.

After trajectory generation, the control system records the information of each teaching points, such as the seam center position and the normal vector, and automatically saves them to data file. Then, the post-processing of the teaching data is processed in the computer aided design module. A 3D model of the T-joint is established firstly, and the NC code of the welding and measuring control is
output, so that the laser focus of the welding head is always at the center of the welding seam. The schematic diagram of 3D welding trajectory generation is shown in Fig. 5.

4.2. Adjustment of defocusing amount
Two welding heads are mounted on both sides of the circular disk respectively, which is fixed together and can be regarded as a rigid body. The virtual welding head of the double beam welding is attached to this rigid body. The trajectory planning of the welding head can be seen as the posture planning of the rigid body on the T-joint weldment. As shown in Fig. 6, point A is the rotation center of the arc plate at the end of the machine tool, namely is the rotation center of A-axis in Fig. 2, and points B and C are the locations of the laser welding head on the left and right sides, while the point D is the intersection point of the two laser beams. Obviously, the relative positional relationship of A, B, C, and D are fixed, and they can be considered as a rigid body. The trajectory planning is to set the posture of welding heads of both sides. The laser beams are projected to the points E and F on the welding curve. In other words, the rigid body ABCD is leaned on the two welding curves. In the subsequent welding points, if the length of the line segments BE and CF change, it is indicated that the actual welding points E and F are not fixed. In this case, the laser beam defocusing amount of both sides is varied during welding process. Therefore, the welding heads on both sides must be controlled in V1 and V2 direction to make the defocusing amount constant to ensure the welding quality.

4.3 Welding seam tracking and deviation compensation control
During the dual-beam welding process of T-joint, the position, width, depth and normal vector of the welding seam centre in the acquired image are obtained by real-time measurement, and then the measurement information is compared with the programmed path. If the deviation exceeds the given threshold, the position and posture of welding heads should be adjusted. The deviations of the welding points in measurement coordinate system are calculated firstly, and then the compensation for the deviation is completed by the compensation controller. Since the welding platform built in this paper respectively uses independent controllers for tracking and compensation, the six-axis linkage controller completes the precise tracking of the three-dimensional trajectory, and the compensation controller is responsible for seam deviation compensation control. The flow chart of welding seam tracking and deviation compensation control is shown in Fig. 7.
5. Experiment
Firstly, the independently researched and developed dual-beam laser welding machine has been tested in this section. The maximum strokes and maximum speeds of each axis can meet the requirement of processing of T-joint in stiffened panels of large structures. Moreover, the positioning accuracy and repeat positioning accuracy of welding platform and welding head can meet the requirements of accurately tracking of welding seam. Then, a section of a 3D T-joint is selected to conduct the welding test. The welding 3D trajectory code is obtained through the weldment modeling. A 3D T-joint of 200mm is welded with the deviation compensation and tracking control under the welding speed of 8 m/min. The experimental results are shown in Fig. 8. It is obvious that the weldment is qualified and the maximum deviation of the welding seam is 0.2mm, which is within the allowable range, meeting the processing requirements of 3D T-joint in large structural parts.

6. Conclusion
This paper researches and develops a ten-six axis dual-beam laser welding and seam tracking control system. This system is organized as the structure of “host IPC (industrial personal computer) + six-axis motion controller + dual-channel two-axis tracking controller”. On the basis of the realization of the 3D trajectory teaching and planning, the six-axis linkage control unit realizes the accurate control
for the position and posture of laser welding heads on the both sides. The real-time measurement and tracking unit performs real-time welding seam measurement on both sides of the T-joint, which realizes deviation compensation and precise tracking of welding seam. Through the welding test, it is verified that the ten-six axis dual-beam laser welding and tracking control system meets the processing requirements of 3D T-joint in large structural parts.

Acknowledgments
This research is supported in part by DongGuan Innovative Research Team Program (No.201536000100031), and in part by Science and Technology Planning Project of Guangdong Province (2017B090913001).

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