Specialized equipment for efficient cutting of door rings based on multi-robot collaboration

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This study is about the multi-robot collaborative cutting equipment for high efficiency of door rings to respond to the market demand and technological development trend. The high efficiency and high precision of door ring cutting are achieved through innovative solutions, such as multi-robot laser cutting technology, high-precision robot ontology and optimized control algorithms. Key technologies include motion path optimization and small hole cutting accuracy optimization. The self-developed software and customized cutting head improve the response speed and operation convenience of the system. The application of the real-time exchange system of robot control signals further improves the stability and processing efficiency of the system.

Keywords: Laser cutting; Multi-robot cooperative work; High-tensile steel: Hot stamping; Real-time data exchange.

1. Introduction

The generation and development history of 3D five-axis laser cutting machine can be traced back to the end of the 20th century. With the continuous progress of science and technology and the change of market demand, 3D five-axis laser cutting machine has gradually become an important equipment in the cutting industry.

At the beginning of the 21st century, with the continuous development of computer technology, numerical control technology and laser technology, three-dimensional five-axis laser cutting machine is gradually moving towards maturity. Its advantages of flexibility, easy operation, high precision and high speed make it more and more popular in the field of industrial manufacturing. At the same time, a number of domestic and foreign enterprises began to research and production of three-dimensional five-axis laser cutting machine, the market competition is gradually fierce. With the continuous improvement of 3D 5-axis laser cutting machine's performance and the gradual reduction of its price, it began to be widely used in a number of fields, such as automobile manufacturing, aerospace, mold manufacturing, advertising production and so on. More and more enterprises realize the advantages of 3D 5-axis laser cutting machine in improving production efficiency, reducing costs and improving product quality, and have purchased equipment for technological upgrading.

Beginning in 2010, three-dimensional five-axis laser cutting machine market competition is increasing, laser equipment manufacturing enterprises began to focus on the research and development of core technologies, such as high speed, high precision, automation and other functions. With the application of body lightweighting and hot

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stamping and forming of high-strength steel body parts, the demand for three-dimensional laser cutting has grown dramatically [1]. Three-dimensional laser cutting has become the main direction to gain great application, whether it is the parts of the body structure or the subsequent processing of the one-piece hot stamped parts with laser splicing plate [2].

Traditional five-axis machine tools cut large one-piece thermoformed structural parts such as door rings in as long as 3-5 minutes, encountering efficiency bottlenecks. Through the multi-machine collaboration of the robot workstation, the cutting time can be controlled in 1-2 minutes, exponentially increasing the work efficiency.

2. Innovative solutions for efficient cutting of door rings

2.1. *The technical path of multi-robot laser cutting and the challenges it faces*

(1) Single-robot cutting efficiency can be infinitely close to the technical advantages of five-axis machine tools.

With the continuous progress of robot technology, the performance and speed of robotic cutting equipment has been significantly improved, and robotic cutting processing has become ubiquitous. This makes the robot cutting technology with the improvement of machine control accuracy, in terms of speed and accuracy can gradually approach the five-axis machine tool. Robotic cutting equipment has a high degree of flexibility, and can realize multi-dimensional high-speed precision cutting processing. Compared with five-axis machine tools, robot cutting equipment in the processing of complex parts, can be better adapted to different processing needs, improve cutting efficiency.

(2) The efficiency advantage of robot multi-machine collaboration

Multiple robots can work together to complete complex tasks and realize collaborative operations. In the cutting process, the robots can cooperate with each other to ensure the accuracy and consistency of cutting. Multi-machine collaboration can improve cutting accuracy and ensure product quality. Through real-time data sharing and precise control, robots can realize high-precision cutting results. Multi-machine collaboration of the robot system has a high degree of flexibility, can quickly respond to market demand and task changes. According to the different cutting tasks, the robot can flexibly adjust the work mode and collaboration strategy to achieve efficient cutting.

(3) Cost advantages of using fiber lasers

Robotic cutting equipment adopts fiber-optic transmission technology with external light guide, and realizes modular integration, which will greatly reduce the acquisition cost. Secondly, in terms of operation and maintenance, the robotic cutting equipment performs equally well, with low maintenance costs and high operating efficiency, which can save a lot of operating costs for enterprises. In addition, the type and wavelength of the laser, as well as the absorption rate of the metal to be cut (as shown in Figure 1), are also important factors affecting cost. Its wide wavelength absorption range makes it adaptable to a wide range of metal cutting needs and improves the efficiency of equipment utilization.

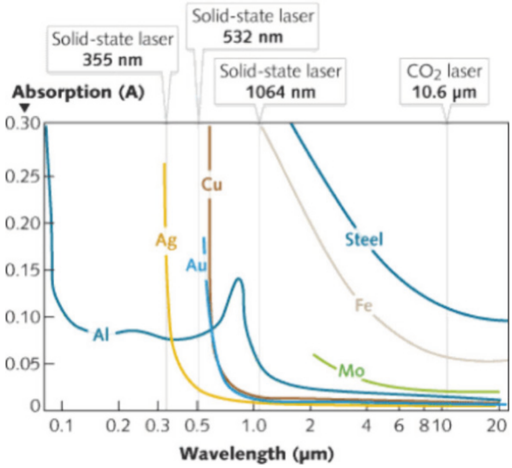

Fig. 1 Laser type and laser wavelength vs. absorption rate of the material to be cut [3].

3. Key technologies of multi-robot cutting technology

3.1. *Large Load Robot + Round Cutting Device*

This solution can easily realize the roundness requirement of ±0.1mm or even ±0.05mm. However, the disadvantage is the high maintenance and utilization cost of the cutting head with the round-cutting device. The volume and weight of the rounding device is large, which increases the chance of interference when cutting complex workpieces with multiple machines, and also increases the difficulty of adjusting the parts. There is little room for iterative optimization of cutting efficiency.

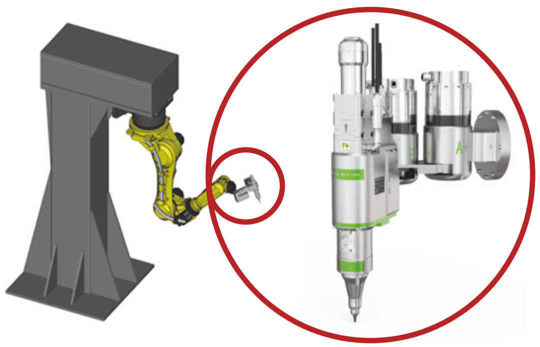

Fig. 2 Cutting head with round-cutting mechanism

Fig.3 High-precision robot body and conventional cutting head

3.2. *High-precision robot hardware and software supporting system*

The use of Stäubli robot TX2-160-HDP ontology, research three-dimensional laser cutting process, optimize the robot motion control algorithms, can directly cut small circles, high precision and speed, custom-developed one-piece cutting head is small and concise, interference with the smaller adjustable parts is simple, maintenance is simple and inexpensive. Its biggest advantage: cutting efficiency and subsequent optimization of the iterative space, a single robot cutting efficiency is expected to be comparable to the domestic five-axis, up to 0.75 times the imported five-axis.

3.3. *Small hole cutting accuracy optimization*

Robot and machine tool compared to the lower rigidity, and small hole high-speed cutting, the robot needs to be multi-joint reciprocating motion, it is easier to accumulate joint position deviation caused by the hole accuracy deterioration. How to improve the accuracy and efficiency of small hole cutting is the main focus of robotic laser cutting.

(1) Friction coefficient detection compensation

The robot joint friction coefficient detection compensation method is a proposed solution to the problem of robot joint friction. Due to factors such as the lubrication of each joint in motion and the variation of the difference in motion speed, the friction force on the robot joints will be different, which in turn will affect the accuracy of the robot's motion trajectory. In order to solve this problem, the robot joint friction can be compensated by the following methods:

- Collecting joint motion data: motion tests are performed on the robot joints at specific locations to collect friction data during motion. This data can help us understand the friction characteristics of different joints in different motion states.
- Analyzing friction characteristics: The collected joint motion data are statistically and analytically analyzed to extract the relationship between friction and motion speed, lubrication state and other factors. This can provide us with detailed information about the friction force and provide a basis for subsequent compensation.
- Establishment of friction model: based on the analyzed friction characteristics, the friction model of the robot joints is established. This model can describe the relationship between the friction force and the motion state of the joints, which helps us to better understand the effect of friction force on the robot's motion trajectory.
- Design compensation algorithm: design the corresponding compensation algorithm for the established friction force model. During the robot movement, the motion state of the joints is measured in real time, and the actual friction force is compensated according to the compensation algorithm, so as to improve the trajectory accuracy of the robot.
- Implementation of compensation: the designed compensation algorithm is applied to the actual robot control system to compensate the joint friction in real time. This can effectively minimize the effect of friction on the robot trajectory and improve the robot's motion performance.
- Monitoring and Adjustment: In the actual application, continuously monitor the robot's motion trajectory and friction compensation effect, and adjust and optimize the compensation algorithm according to the actual situation. This can ensure the

continuous effectiveness of the compensation effect, so that the robot can maintain high motion accuracy in different environments.

- Through the above methods, the robot joint friction problem can be effectively detected and compensated to improve the accuracy of the robot's motion trajectory, thus improving its performance in various application scenarios, and the effect before and after compensation is shown in Figure 4.

(2) Optimization of motion interpolation

The optimized motion interpolation of the robot laser cutting path is mainly reflected in the following aspects:

- Circular arc interpolation: circular arc interpolation is a kind of interpolation method for complex shaped workpieces. In this type of interpolation, the robot cuts along a circular path. Compared to linear interpolation, circular interpolation can better accommodate complex shapes and improve cutting results.
- Spline interpolation: Spline interpolation is a mathematical curve-based interpolation method. In this interpolation method, the robot will cut according to the pre-set mathematical curve. Spline interpolation is suitable for cutting workpieces with non-linear paths and allows for smoother cuts.
- Polynomial interpolation: Polynomial interpolation is a type of interpolation based on polynomial functions. By writing a polynomial function, it is possible to control the degree of curvature and speed variation of the robot's cutting path. This type of interpolation is suitable for cutting complex workpieces that require a large number of curves and slopes.
- Optimization Algorithm Interpolation: In terms of path optimization, a variety of algorithms can be used to optimize the cutting path, such as genetic algorithms, particle swarm optimization algorithms, and so on.

These algorithms can automatically search for the optimal cutting path, so that the movement time and cutting time in the laser cutting process can be minimized and the cutting efficiency can be improved. In practical applications, a suitable interpolation method can be selected for laser cutting according to the shape and characteristics of the workpiece. At the same time, the cutting path can also be adjusted in real time through the path optimization algorithm to achieve a more efficient and precise cutting effect. In addition, in order to ensure the cutting quality and efficiency, the robot's motion speed, laser power and other parameters need to be set reasonably.

(3) Motion speed smoothing processing

Robotic laser cutting technology is widely used in metal processing, manufacturing and other fields, and its motion speed smoothing is a key factor to ensure cutting quality and efficiency. In order to realize the motion speed smoothing processing of robot laser cutting, the following aspects need to be considered:

- Kinematic modeling and planning: kinematic modeling of the robot is carried out in order to facilitate the analysis of its motion trajectory in the cutting process. On this basis, motion planning is carried out to reasonably allocate the motion speed of each joint in order to realize smooth cutting.
- Laser Cutting Head Control: The positional accuracy and smooth movement of the laser cutting head are critical to cut quality. Through high-precision position sensors and servo systems, the position of the cutting head is monitored and adjusted in real time to ensure its stability during movement.
- Path Planning and Optimization: In the cutting process, path planning is of great significance to improve cutting speed and stability. By optimizing the cutting path and reducing redundant actions in the movement process, the cutting head can achieve higher movement speed while ensuring the cutting quality.
- Real-time monitoring and adjustment: During the cutting process, the status of the robot and cutting head is monitored in real time, and the motion speed is adjusted according to the actual situation. This helps to ensure a smooth cutting process and improve cutting quality.
- Cutting parameter optimization: Reasonable cutting parameter settings help improve cutting speed and smoothness. Through experiments and data analysis, laser power, cutting speed, cutting head inclination angle and other parameters are optimized to achieve better cutting results.

In conclusion, to achieve the smooth processing of the motion speed of robotic laser cutting requires comprehensive consideration from the control system, kinematic modeling, cutting head control, path planning, real-time monitoring, cutting parameter optimization and other aspects. Through these measures, the smoothness of the robot laser cutting process can be ensured and the cutting quality and efficiency can be improved, as shown in Figure 5.

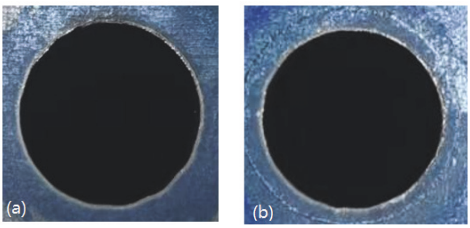

Fig. 4 Comparison before and after friction compensation: a) After friction compensation; b) Before friction compensation

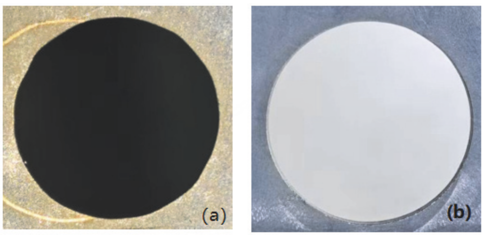

Fig.5 Motion speed smoothing process: a) Normal mode 60mm/S; b) Speed flat mode 100mm/S

3.4. *Path Optimization*

For the six-axis industrial robot to complete the three-dimensional spatial movement, any point for the robot has countless gestures to reach, because of workpiece interference and so on will affect the accessibility of some gestures of the machine, the development of path optimization function, in order to intelligently and quickly select the optimal trajectory of the movement mode, so as to make the operation of the trajectory of the path is more smooth and fluent. Figure 6 shows that after completing a program for demonstration teaching, the robot can automatically optimize the demonstration path through the path optimization function to make the robot movement path smoother and more fluent.

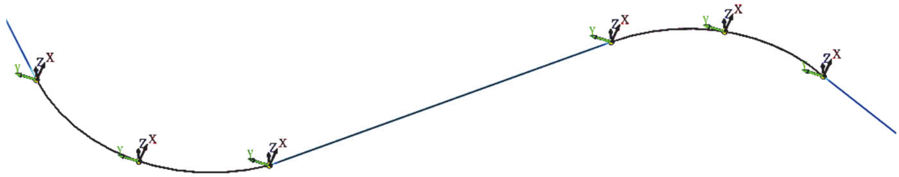

Fig. 6 Optimization of the path obtained by demonstration teaching to make the robot movement path smoother.

3.5. *Self-developed RapidCAM online mapping software*

The self-developed RapidCAM software can graphically display the robot cutting trajectory, and can quickly adjust the trajectory position and parameters, which helps to reduce the debugging time for the first piece and production changeover, the main functions are as follows:

- Simultaneous display of multiple robot trajectories
- Direct point-and-click selection of trajectories
- Multiple trajectory offset modes, support dual-machine program panning and rotating at the same time.
- Batch modification of speed and process parameters
- Standard graphic parameterization modification
- Text synchronized display

3.6. *Customized internal follower self-focusing cutting head*

Custom-developed cutting head, including built-in follower, auto focus, anti-collision and other functions. After lightweight design, the response speed of the system is greatly improved. The optimized performance data of the cutting head is as follows:

- Rated power: ≤4KW
- Follow stroke 30mm, speed 250mm/s
- Focusing stroke 20mm, accuracy 0.05mm
- Drawer type protective mirror can be changed quickly
- With anti-collision mechanism, it can be quickly stopped after collision, while the magnetic elastic mechanism can effectively reduce the collision damage and can be quickly recovered
- Dustproof design for motion mechanism and anti-collision mechanism.

3.7. *Robot control signal real-time exchange system*

The robot control signal real-time exchange system is a key part of the robot control system, which can realize the real-time transmission and processing of robot control signals. In this system, the accurate matching of laser power and robot movement speed is an important function. By monitoring and adjusting the laser power and robot motion speed in real time, the precision and efficiency of the robot processing can be ensured. In order to achieve this goal, the robot control system adopts high-speed data transmission, and the real-time exchange system needs to have high-speed data transmission capability to ensure the real-time and accuracy of the control signals. For example, it takes 50ms to exchange data with Modbus TCP, while it takes only 4ms to exchange data with EterCAT bus, as shown in Figure 7. With a cutting speed of 10 meters per minute, there is a positional lag of 8.3MM and 0.6MM, which is related to the rate and response time of data exchange.

Secondly, the control system needs to have precise algorithms in order to make real-time adjustments based on real-time data of laser power and robot motion speed. By using advanced control theories and algorithms, such as model predictive control and fuzzy control, precise control of robot motion speed and laser power can be realized.

In addition, the data exchange system requires high real-time performance, which can respond to various changes in the robot control process in real time, thus ensuring that the robot can quickly and accurately adjust the laser power and motion speed. Through real-time monitoring and processing of the data collected by the sensor, as well as real-time adjustment of the control parameters, real-time optimization of the robot control process can be achieved.

In conclusion, the real-time exchange system of robot control signals is of great significance in the accurate matching of laser power and robot motion speed. By realizing high-speed data transmission, precise control algorithms, real-time, flexibility and easy maintenance, it can provide stable and efficient control signals for the robot machining process.

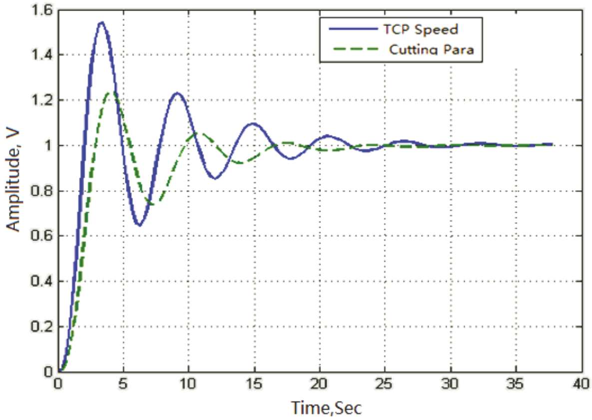

Fig. 7 Cutting control command and TCP execution speed

4. Results and Applications

According to the actual development and user requirements, three sizes of equipment were designed and developed as shown in Figure 8. The models are 1.5T, 3.0T and 4.0T specifications, which are adapted to the application requirements from 2100X1600MM to 3300X1600mm flat space respectively. A cutting system for hot stamped door rings for bodywork using 4 Stäubli robots TX2-160-HDP is shown in Fig. 9. The hole and edge cutting classification data and total cutting time of this model for the actual cutting of 2 types of door rings, as well as the data comparison with the conventional 5-axis cutting machine, are shown in Table 1.

In terms of machining accuracy, the roundness error of its positioning holes ≦ 0.1mm, the roundness error of other holes ≦ 0.2mm, the positional error of holes ≦ ±0.1mm, and the contour positional error ≦ ± 0.2mm, which can satisfy the machining progress of the hot stamped parts.

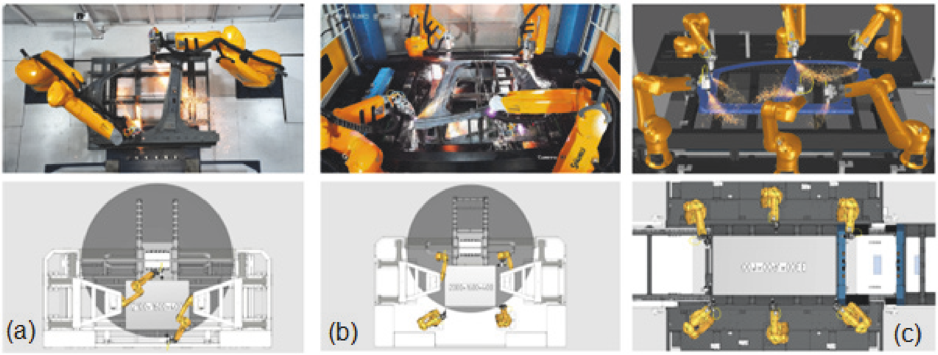

Fig. 8 Equipment solutions with different coverage: (a) 1.5T dual-robot model with maximum coverage of 2750*1600MM below single or double gates; (b) 3.0T quad-robot model with maximum coverage of 3100*1600MM below single or double gates; (c) 4.0T six-robot model with maximum coverage of 4000*1600MM below single or double gates.

Table 1 Comparison of efficiency between multi-robot cutting and conventional 3D 5-axis cutting machine

	Door Ring A.	Door Ring B
Number of large and small holes (number)	70	114
Cutting time for large and small holes (s)	70X2.85/4=50	114X2.5/4=72
Edge length (m)	13	15
Edge cutting time (s)	21	22
Robot cutting time (S)	71	94
Five axis cutting time (S)	172	230

Fig. 9 Four robots working together for body door ring cutting

5. Conclusion

By investigating a specialized equipment for efficient door ring cutting based on multi-robot collaboration, this study has made significant progress in the field of 3D five-axis laser cutting machines. Innovative technology paths and solutions provide high-efficiency and high-precision solutions for door ring cutting, which meet the market demand and technology development trend. The application and optimization of key technologies further improve the cutting efficiency and quality, making robotic laser cutting have a wider application prospect in industrial manufacturing. The self-developed software and customized cutting head facilitate the operation and maintenance of the equipment, while the application of the real-time exchange system of robot control signals improves the stability and efficiency of the system, which provides strong support for future intelligent manufacturing and robotized production.

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