Study on Laser Welding Technology and Properties of Ti75 Titanium Alloy

Shouqi Cao¹, Xin He¹,a, Wanrong Liu¹ and Jiecai Feng²,b
¹College of Engineering Science and Technology, Shanghai Ocean University, Shanghai, China
²Shanghai Ruirong Laser Welding Technology Co. Ltd, Shanghai, China
Email: a) xheshou@163.com, b) 978757782@qq.com

Abstract. For Ti75 titanium alloy with a thickness of 3mm, 10kW continuous fiber laser was used to conduct lap test on the material. By adjusting the reserved gap between two plates, laser power, welding speed and defocusing amount, the macroscopic morphology and microstructure characteristics of the welded joint were analyzed, and the tensile properties and micro-hardness of the welded joint were tested. The results show that, under the appropriate process parameters, the weld of the specimens is beautiful and the degree of oxidation is low, the tensile strength of the welded joint can reach the level of the base material, and the hardness value is higher than the base material. By adjusting laser welding parameters such as laser power, welding speed and defocusing amount, welding joint quality can be effectively controlled.

1. Introduction

With the implementation of the maritime power strategy, China's requirements for the performance of ship materials are constantly improving. As structural materials in Marine environment, Marine materials must have good strength, toughness and corrosion resistance [1-2]. Ti75 titanium alloy is a new type of titanium alloy, with medium strength, corrosion resistance, high toughness, elasticity and other characteristics, can be widely used in ship structure and power plant, so Ti75 titanium alloy has a good application prospect in ship materials. In the process of ship construction, there are many complex processing technologies, especially welding technology. Titanium alloy is easy to be oxidized in the welding process, resulting in pores and cold cracks, and the phenomenon of stress concentration and uneven structure of welded joints, which requires a high welding process [3-10]. The TIG welding process of Ti75 titanium alloy was studied by Li et al [11]. Li et al [12] studied the effect of welding parameters on laser welding of TC4 titanium alloy. Janasekaran et al [13] studied the effect of welding parameters of low power fiber laser on the performance of titanium alloy lap joints. However, there are few researches on Ti75 laser welding process and properties. Therefore, it is of great significance to study the influence of laser welding parameters on the welding joint forming to improve the welding quality of titanium alloy [14-17].

In general, it is difficult to obtain good welded joint in titanium alloy laser welding, and different technological parameters have great influence on the welded joint. For Ti75 titanium alloy, the optical fiber laser was used as welding heat source, and the flat plate lap experiment was carried out on the welded joint. Different technological parameters were studied to analyze the macroscopic morphology and microstructure characteristics of the welded joint, and the tensile properties and micro-hardness of the welded joint were tested. The microstructure characteristics and forming reasons of different parts
of the welded joint were analyzed. In this way, the matching range of process parameters is obtained, which provides certain guidance for industrial production [18-19].

2. Experimental Methods and Equipment
The experimental material is Ti75 titanium alloy, its size is 200.0mm×100.0mm×3.0mm. Its chemical composition is shown in table 1, and its mechanical properties are shown in table 2. As shown in figure 1, 10kW continuous fiber laser is used for laser butt welding of 3mm thick Ti75 titanium alloy plate. Before the experiment, use the grinder to smooth the welding surface, and then wipe the welding surface and specimen surface with alcohol to avoid other impurities affecting the welding. In the process of fixing the specimen with the fixture, it is ensured that the two plates are aligned horizontally, no up and down deviation occurs, and no gap error occurs during welding.

Table 1. Chemical composition of Ti75 titanium alloy

| Element | Mass fraction / % |
|---------|------------------|
| Al      | 2.9              |
| Mo      | 1.9              |
| Zr      | 2.1              |
| Fe      | 0.04             |
| O       | 0.09             |
| H       | 0.007            |
| Ti      | Bal.             |

Table 2. Mechanical properties of Ti75 titanium alloy

| Property                  | Value     |
|---------------------------|-----------|
| Yield strength / MPa      | 640       |
| Tensile strength / MPa    | 720       |
| Elongation / %            | 13.       |

KUKA robot laser welding system was used in the test, as shown in figure 1. Among them, KUKA robot is composed of fiber laser, water cooling system, robot and other systems. The laser is produced by IPG Company and has a focal length of 382mm. In the welding process, the workpiece is stationary, and the welding laser head is driven by the six-axis manipulator to complete the welding process.

![Figure 1. Laser welding system.](image)

In order to avoid the change of lap gap during the welding process, the two ends of the specimen were fixed by spot welding with 800W laser power, followed by continuous laser welding. Since oxidation is easy to occur in the welding process of titanium alloy, double-sided argon gas is adopted to protect the welding process, and the protection gas flow rate is 20min/L.

At the end of the test, the welded joint samples were mechanically polished and chemically etched with a volume fraction of 4.0% nitric acid ethanol solution. Then the metallographic samples were selected to observe the joint structure. The tensile specimens were intercepted and processed into standard tensile specimens as shown in figure 2 for tensile performance test. The specimens with good welding joints were selected and the micro-hardness test was conducted at 1/3 of the upper surface of the joints.
3. Experimental Results and Analysis

3.1. Effect of Process Parameters on Weld Forming

Laser welding experiment was conducted on 3mm thick Ti75 titanium alloy plate, and the shape and accommodation of the weld were obtained by adjusting different lap gap, laser power, welding speed and defocusing amount. The effects of different process parameters on weld forming and quality were analyzed.

3.1.1 Effect of reserved clearance on the amount of collapse under weld.

In the experiment, slices of 0mm, 0.1mm, 0.15mm, 0.2mm, 0.25mm and 0.3mm were placed between the two plates to produce different reserved gaps. Then use the clamp to fix the position between the two plates. The appearance of both sides of the weld with reserved clearance of 0mm, 0.15mm, 0.2mm and 0.25mm is shown in figure 3.
After welding, it was found that when the lap gap was 0mm, severe spatter occurred on the front side during the welding process, the weld was continuous and the weld appeared yellow, with serious oxidation, while the reverse weld was continuous and non-oxidation, and the weld appeared white. For the welded joint with a gap of 0.1mm and 0.15mm, the specimen is evenly welded through, with a small amount of spatter on the front side of the welding, no defects in the welded joint, and the weld is white, while the reverse weld is uniform and silver-white. The gap between 0.2mm and 0.25mm leads to a discontinuous weld line with an uninterrupted non-penetration area, which has a serious defect. In the process of 0.3mm gap welding, spatter occurs, the joint is completely welded, and the weld is discontinuous. Therefore, the reserved clearance of 0.1~0.15mm is good for forming, and the resulting seam collapse is shown in figure 4.

![Image](d) 0.25mm

**Figure 3.** The joint morphologies of 0mm, 0.15mm, 0.2mm and 0.25mm gaps

According to figure 3, when the lap gap is 0, a large amount of titanium vapor escapes from the outside of the plate, and the steam flies out with the melted liquid, causing splash. With the gradual increase of the reserved clearance, the accommodation of the weld gradually increased. When the overlap gap is 0.1~0.15mm, the weld line is continuous and beautiful, without porosity defects. If the reserved clearance exceeds 0.2mm, the weld accommodation will be large and the result is not ideal. According to the analysis, it is better to reserve the gap of 0.1~0.15mm for forming, so the overlap gap used in the following experiments is 0.1mm.

**Figure 4.** Effect of reserved clearance on the amount of collapse under weld

3.1.2 Effect of laser power on the amount of collapse of the weld.
Laser power is a key factor in the welding process, and the power determines the heat input to the titanium plate, thus affecting the quality of the welded joint. In the test, the control welding speed was
0.04m/s, the defocus was set to 0mm, the reserved gap was set to 0.1mm, and the laser power was 2700~3300W. The test of the sag of the welded joint is shown in figure 5.

![Graph showing the effect of laser power on the amount of collapse of the weld](image)

**Figure 5.** Effect of laser power on the amount of collapse of the weld

The results show that when the power is from 2700W to 3100W, the weld shape is gradually improved, spatter and porosity are gradually reduced. When the welding power is 2700W, the specimens cannot be continuously welded through due to the low output energy. At 2900~3100W, the weld shape is the best, the specimen is uniformly welded through and has few porosity defects. When the power is up to 3300W, the weld appears incomplete, the flow volume increases, the forming is poor, and the weld appears blue.

According to the analysis, the reason for this phenomenon is that when other welding parameters remain unchanged, with the increase of laser power, the heat input in the welding process increases, leading to the increase of temperature around the molten pool, increasing the tendency of the molten pool to absorb hydrogen, oxygen and nitrogen, and increasing the degree of oxidation of the molten pool.

### 3.1.3 Effect of welding speed on the amount of collapse under weld

The welding speed also determines the heat input to the titanium plate, which affects the quality of the welding joint. In the test, the laser power was set as 3100W, the defocusing amount was 0mm, the reserved gap was 0.1mm, and the welding speed was set as 0.03, 0.04, 0.045, 0.05, 0.06, 0.07, and 0.08m/s. The weld accommodation is shown in figure 6. After welding, it was found that when the welding speed was 0.03m/s, the welding front was yellow, and the welding seam gradually became silver white as the welding speed increased. According to the analysis, too slow welding speed will lead to too long contact time between the welding site and the air, resulting in serious oxidation. When the speed reaches 0.06m/s, the weld becomes narrower and the back of the weld is not fully welded. As the speed increases and the welding speed increases to 0.08m/s, the volume of accommodation on the front of the weld increases. Therefore, when the welding speed is between 0.04 and 0.045m/s, the weld line is formed beautifully, there is no weld penetration area, and the weld surface appears silver white.
3.1.4 Effect of defocusing amount on the amount of collapse of the weld.

In the test, the laser power is set to 3100W, the welding speed is 0.04m/s, and the reserved gap is 0.1mm. The influence of different defocusing on weld forming can be observed by changing the defocusing amount. Defocus is set to -2, -1, 0, 1 and 2mm respectively. It can be seen from the observation of the joint that when the defocusing amount is -2mm, the weld joint is incomplete, the weld front has a large splash and the back is not fully welded, and the weld stays are large. When the defocusing amount is between -1~1mm, the welded joint is beautiful and silver-white, spatter on the front of the weld is reduced, and the back of the weld is continuous without defects. When the defocusing amount is 2mm, the front of the weld appears light yellow and the weld is irregular, while the back of the weld appears unwelded. The collapse is shown in figure 7.

To sum up, the welding power is 3000~3100W, the welding speed is between 0.04~0.05m/s, the defocus is between -1~1mm, the reserved clearance is about 0.1mm, the external spatter is less, the oxidation is lower, the welding joint is relatively intact.
3.2 Morphology and Structure of Weld Joint

The reserved clearance was 0.1mm, the welding speed was 0.04m/s, the defocusing amount was 1mm, and the laser power was 2.9, 3.0, 3.1 and 3.3kW.

3.2.1 Macroscopical morphology of joint.

According to figure 8, under different laser power, the macroscopic morphology of the joint cross section shows obvious zoning characteristics, which is divided into three parts: weld (WS), fusion line (FL) and heat affected zone (HAZ). Among them, the weld zone is the solidification zone of the base metal after it is completely melted by heat, and the zone where the base metal is not completely melted under the welding heat input but has a solid phase transition is called the heat-affected zone.

In the process of welding, a small amount of metal on the surface of titanium alloy gasifies away from the surface of titanium alloy due to the action of heat input. As the heat input gradually increases, the phenomenon of metal gasification intensifies. The steam pressure generated will overcome the surface tension and gravity of the molten metal liquid and push the molten metal liquid to move around, resulting in a small number of dents on the surface of the joint. When the energy from the laser is enough to form penetrating holes, the metal vapor erupts up and down at the same time, creating dents on both sides. As the heat input is further increased to 3.1kW and 3.3kW, the heat input is excessive, so that most of the laser energy can penetrate the entire material to the bottom of the welded sample, resulting in more obvious occupancy of the joint.

With the gradual increase of heat input, the weld width also increases gradually. The weld width measured under the four types of heat input is 1.90mm, 2.32mm, 2.51mm and 2.85mm respectively.

![Figure 8](image.png)

**Figure 8.** Macro morphology of welded joints obtained at different heat inputs

3.2.2 Microstructure of welded joints.

The microstructure of welding zone under different heat input is shown in figure 8. Compared with the base material, the structure of the welded zone changed greatly. The equiaxed alpha phase and original beta phase are formed. This transformation is due to the fact that in the process of laser welding, under
the high power density of the laser beam, the grains of the original thick parent material melt and deform under the heat, and produce dynamic recrystallization, so as to precipitate out the phase and form the equiaxial grain structure.

After laser welding of Ti75 titanium alloy, there is a large amount of martensite structure in the welding seam. Figure 9 shows the typical structure of the weld. The residual black structure between the martensite and martensite bars, slices or needles is the residual. A large number of thick strips of martensite are interlaced with each other. The martensite in the weld stops growing at the grain boundary, and the martensite formed during rapid cooling has the same structure as the phase formed during slow cooling. The main difference between them is that the martensite stops growing at the original grain boundary.

![Figure 9. Microstructure of welded joint under different heat input](image)

3.3 Performance Testing and Analysis

3.3.1 Tensile properties.
The welded titanium alloy plate was sampled and the tensile test under room temperature and static load was conducted. The mechanical properties and fracture types of the welded joints obtained are shown in table 3.
Table 3. Mechanical properties of welded joints

| Laser power (P/W) | Speed (v/m·s⁻¹) | Defocusing amount (f/mm) | Tensile strength (Rm/MPa) | Fracture position |
|-------------------|-----------------|--------------------------|---------------------------|-------------------|
| 3100              | 0.4             | -1                       | 721                       | base metal        |
| 3100              | 0.4             | 0                        | 734                       | base metal        |
| 3100              | 0.4             | 1                        | 725                       | base metal        |
| 3000              | 0.4             | 0                        | 728                       | base metal        |
| 2900              | 0.4             | 0                        | 711                       | base metal        |
| 3100              | 0.4             | 0                        | 716                       | base metal        |
| 3100              | 0.45            | 0                        | 715                       | base metal        |
| 3100              | 0.5             | 0                        | 712                       | base metal        |

As can be seen from the experimental data, the fracture positions of the specimens all appeared on the base metal far from the weld, and the tensile strength remained at about 720MPa, with some ups and downs, but generally stable. Since the fracture location of the specimen is not on the weld, the tensile strength of the specimen cannot reflect the actual situation of the welding tensile strength, which only indicates that the tensile strength of the weld after Ti75 titanium alloy laser welding is higher than that of the base material. Based on the test results of the above mechanical properties, it can be concluded that the welding seam of Ti75 titanium alloy laser welding is well formed and the tensile strength of the joint can meet the performance requirements.

Therefore, Ti75 titanium alloy laser welding in a reasonable heat input, the joint tensile strength can reach the level of the base material, good tensile performance, meet the performance requirements.

3.3.2 Microhardness.

A hardness test was conducted on the welded joint with a reserved clearance of 0.1mm, a welding speed of 0.04m/s, a defocus of 1mm and a laser power of 3100W. Test one data every 0.1mm, and the obtained transverse joint hardness distribution is shown in figure 10. The hardness of the joint is the lowest in the base material, the highest in the affected area of heat, and the hardness of the welded area is lower than that of the affected area. The average hardness of Ti75 titanium alloy base material is 265HV, and the hardness value near the fusion line is about 315HV. The hardness value of the weld zone fluctuates from 340HV to 380HV, and there is no obvious softening.

![Figure 10. Microhardness distributions of full - penetration weld joints obtained](image)

It can be seen from the analysis of the reasons that the structure of the welding seam changes continuously from the base material to the welding seam in the process of laser welding. The material
underwent severe deformation under the heat input, and the martensite content of the material increased, resulting in an increase in hardness. As dynamic recrystallization occurred in the welded area, the effect of varying strength decreased. Therefore, the hardness value from the base metal to the heat-affected area showed an upward trend, and then showed a certain downward trend to the weld.

4. Conclusion
The effects of reserved clearance, laser power, welding speed and defocusing on welded joints were analyzed by single factor process analysis. It is concluded that the laser power is in the range of 3000–3100W, the welding speed is in the range of 0.04–0.045m/s, the defocus is in the range of -1~1mm, the lap gap is in the range of 0.1mm, the oxidation degree of weld is low, and the welded joint is relatively intact.

It is summarized and analyzed that the welded joint in the best welding process is beautiful in shape, with no big splash and few pores. At this time, the tensile strength is kept above 720MPa to meet the performance requirements.

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