A study on the influence of ultrasonic processing on microstructure during laser welding phases

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Abstract. This paper proposes new welding technology that combines ultrasonic processing across different phases based on laser welding (UPPLW) and laser processing technology. The welding experiment used a 1.5 mm thick titanium alloy. The specimen was made metallographically prepared and the microstructural grain size of the welded joint was rated by metallurgical processing software, verifying that this new process can refine grains and improve joint properties.

1. Introduction

Aircrafts on aircraft carriers are susceptible to collision damage as wells as corrosion fatigue cracks while occur readily under marine condition. Consequently, it is often necessary to perform aircraft maintenance on-ship where conditions are less than ideal. This can lead to residual stress from welding, leading to deformities in the aircraft and reduced stability. In fact, repeated repair can create new cracks at the weld toe, thereby making the repair process more harmful than productive. As a result, it is important to find alternative repair technology for aircraft [1].

Titanium alloys continue to play an increasingly important strategic role in the field of modern aerospace and defence. It has high specific strength and good corrosion resistance[2-5]. The alloy has excellent comprehensive performance, so it can be welded, machined, and worked at temperatures of 400\degree C for long periods of time. The alloy is often used as important bearing components of aircrafts, including the strengthening frame, beam, joint bolts, and wall board[6-10].

Laser welding has been widely used in manufacturing aircrafts, automobiles, and ships because it has a small heat affected zone, it is stable, it produces small welding deformations, it can be easily automated, and it can be used to weld difficult welding material [11]. However, high power heating causes high local temperature gradients in the material. This leads to rapid stratified solidification of the molten pool; restriction of the base material will lead to welding deformations and residual stress. In addition, a very short laser molten pool solidification time does not promote the molten pool flowing during solidification, which leads to uneven weld solidification microstructure and to micro cracks. Due to these factors, we studied welding with power ultrasonic trailing vibration, which proved to be suitable for shipboard maintenance and airfield emergency maintenance.

2. Experimental equipment

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Fig. 1 shows a system schematic. The process was mainly composed of an ultrasonic vibration system, laser welding system, and specimen constraint system; the main parts were the ultrasonic vibration system, pressure measuring modules, a digital ultrasonic generator that automatically tracks frequency, an ultrasonic transducer, and an ultrasonic amplitude transformer. The specifications of the main working mechanism are as follows: a 20 kHz ultrasonic vibration frequency was subsidiarily exerted in the nearby scan location on the same side of the area when laser welding was used to repair damaged metal. The ultrasonic vibration was imported by the tool head and lead to the specimen forming a resonance effect with the ultrasonic generator frequency tracing, thus affecting several key transition stages including the formation, flow, and solidification of the welding pool and the high temperature superplastic solid-state phase transformation of the welding area. Ultimately, the technology can improve weld solidification microstructures, control welding deformation, slow-release residual joint stress, improve joint mechanical properties, and reduce defect occurrences.

3. Experimental material and methods
TC4 titanium alloy is close-packed hexagonal structure martensite alloy, which has good comprehensive properties. It has characteristics that promote high limit and ultimate strength, exceptional deformation resistance, a large ratio of yield limit and ultimate strength, and low plastic deformation at room temperature. Thus which belongs to the difficult deformation material, so it was difficult for welded titanium alloy thin-walled structure to be achieved plastic extension.

Slip plane of close-packed hexagonal structure will substantially increase when TC4 alloy was being at high temperature, so plasticity significantly improved and deformation resistance decreased sharply. On the other hand, we can analyze from the aspect of the high temperature dynamic behavior of titanium alloy: the main influence factors of the thermal deformation including deformation temperature, strain rate and deformation amount, the influence of the deformation temperature and strain rate for the thermal deformation process were more significant than deformation amount, the influence relation among deformation temperature, strain rate and the deformation resistance was shown in equation (1) [12],

$$
\sigma = \sigma_0 e^{(b_1 T/b_2) + b_3} \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^{b_4 \frac{T}{T_0}} \left( \frac{\varepsilon}{\varepsilon_0} \right)^{b_5 \frac{T}{T_0}}
$$

In the equation, $\sigma$ denotes the deformation resistance, $\sigma_0$ denotes the deformation resistance reference value, $T$ denotes the deformation temperature, $\dot{\varepsilon}$ denotes the deformation rate, $\varepsilon$ denotes the deformation degree, and $b_1$ to $b_5$ denote the regression coefficient. Through the previous equation,
we know that when the component deformation reached a certain amount, deformation resistance dropped along as the temperature increased under the same strain rate. TD4 titanium alloy thermal deformation tests showed that the peak stress fell sharply and temperature increased when the strain rate was maintained at 1 s\(^{-1}\); the peak stress of 890°C was 200 MPa, and the peak stress of 950°C was only about 90 MPa. These peak stresses differed more than 2 times at 60°C temperature intervals. Table 1 shows the material composition, which was detected by third-party professional testing institutions. The specimen size was processed for 50 mm\(\times\)30 mm\(\times\)1.5 mm by wire-cutting.

**Table 1.** TC4 chemical compositions (mass fraction %).

| Element | Al | V  | Fe | O  | H  |
|---------|----|----|----|----|----|
| Mass fraction % | 6.15 | 4.13 | 0.08 | 0.009 | 0.002 |

**Table 2.** TC4 laser welding parameters.

| Parameter | Current (A) | Impulse width (ms) | Frequency (Hz) | Welding speed (mm\(\cdot\)s\(^{-1}\)) | Spot diameter (mm) |
|-----------|-------------|--------------------|----------------|-------------------------------------|-------------------|
| Value     | 175         | 9                  | 6              | 2                                   | 0.3              |

The welding equipment was a pulsed laser repair machine with independent intellectual property rights. A Japan ERCR HP3 - AA00 robot was used as an actuator. Table 2 presents the welding parameters. Before welding, the sample was smoothed with metallographic sand paper and then cleaned with acetone; specimens were welded within 24 hours of this preparation. Metallographic specimens were prepared after welding was completed; a corrosion liquid with a composition of 3 ml HF + 30 ml HNO\(_3\) + 67 ml H\(_2\)O was used to etch metallographic specimens about 8~10 min at room temperature. Then, the specimens were cleaned with alcohol. The metallographic microscope (OM) was used to observe the specimens’ microstructures, and the three circles cutoff point method was used to measure the microstructural grain sizes of conventional laser welding versus this process [13].

As shown in Fig 2, the stepped tool head was used to oscillate the welded specimen, the vibration position was 100 mm from the molten pool, the downward pressure was the vibrator weight, the vibration frequency was 20 kHz, and the ultrasonic generator power was 1200 W.

### 4. Results and discussion

Table 3 presents the grain size measurement data, which was observed by a metallographic microscope with 100 magnification. Team A and B respectively present samples of our process and conventional welding joints. SRMAS metallographic analysis software was used to evaluate the level of microstructural grain sizes via the three circles cutoff point method. The experiment shows that reliable accuracy can be obtained when the cut point count of each sample was 500.

The measure grid of 500 mm was used to cutoff points statistics in 8 field, the measuring data was tested by \(X^2\) (Kai). The results showed that the cutoff point count was a normal distribution; thus, the measure value can be processed according to the statistical methods of the normal distribution. According to the relevant calculation methods of the grain size, the grain sizes of A and B contrast test group and can be calculated.
Figure 2. The ultrasonic laser welding system.

Table 3. Specimen statistics.

| Team   | Sample number | Level of grain size G |
|--------|---------------|-----------------------|
| Team A | 1             | 8.21                  |
|        | 2             | 8.19                  |
|        | 3             | 8.15                  |
|        | 4             | 8.23                  |
|        | 5             | 8.20                  |
| Team B | 1             | 7.30                  |
|        | 2             | 7.22                  |
|        | 3             | 7.36                  |
|        | 4             | 7.39                  |
|        | 5             | 7.28                  |

Table 4. Specimen logarithm statistic.

| Team   | A   | Team   | B      | \( x_{ai} - x_{bi} \) | \( (x_{ai} - x_{bi})^2 \) |
|--------|-----|--------|--------|------------------------|-----------------------------|
| Team A | \( x_{ai} = \lg G_{ai} \) | \( x_{bi} = \lg G_{bi} \) | \( x_{ai} - x_{bi} \) | \( (x_{ai} - x_{bi})^2 \) |
|        | 0.9143 | 0.8633 | 0.0510 | 0.0026                |
|        | 0.9133 | 0.8585 | 0.0548 | 0.0030                |
|        | 0.9112 | 0.8669 | 0.0443 | 0.0020                |
|        | 0.9154 | 0.8686 | 0.0468 | 0.0022                |
|        | 0.9138 | 0.8621 | 0.0517 | 0.0027                |
|        | \( \Sigma \) | | 0.2486 | 0.0125                |

The grain size value was taken the logarithm, and the two experimental datasets were contrastively
analyzed in accordance with the group comparison test of the fatigue reliability theory, as shown in Table 4.

The average value $\overline{a-b}$ and standard deviation $s_{a-b}$ can be obtained from Table 4; they were respectively 0.0497 and 0.0059. Then, $t$ can be calculated as 18.8360. The significant level was identified as $\alpha = 1\%$, degrees of freedom was known as $\nu = 4$, $t_a = 4.604$ can be obtained with the consulting related schedule [14] because $t > t_a$. Consequently, there were obvious differences between the two, namely, because the two experimental samples came from different normal population samples, and ultrasonic laser processing significantly influences grain size refinement. Therefore our process proved to be an effective and feasible technology in improving welding joint properties.

5. Conclusions
The study provides support the utility of combined ultrasonic and laser processing combined with conventional laser welding, and we reach the following conclusions:

- The combined process was efficient in refining welding joint microstructures and in increasing welding joint grain size by about 1 grade.

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