Effect of beam oscillating pattern on laser welding of steel to PMMA

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Abstract—Laser welding of 1 mm-thick steel and PMMA was employed via beam oscillating. Three modes of beam oscillation, transverse, longitudinal and circular were explored. Due to the stirring effect, the beam oscillation improves the weld formation and promotes the flow of bubbles in the molten layer. The circular oscillation gives the strongest weld homogeneous without overheating discoloration defect. The bonding strength was 38% more than the weldment without beam oscillation. The weld strength improvement was attributed to the variation of the oscillating speed varies the time-frequency distribution of the beam energy. This technology reduces the morphological defects and increases the uniformity of the weld. The improvement mechanism of beam oscillation on bubble behavior and melt flow behavior is also discussed.

1. INTRODUCTION

Recent developments of the connection of dissimilar materials, especially in the aerospace, automotive, and medical industries have attracted much attention. Only a single material cannot combine all the exceptional properties needed, such as high strength, high corrosion resistance, high conductivity, high toughness and light weight. It is exciting to combine materials with different properties to get all the benefits of their combined properties. Plastics have many desirable properties, including high corrosion resistance, high formability, and light weight [1]. Polymeric composites like amorphous thermoplastic polymer (PMMA) have additional highly tailored properties, such as brittleness, high stiffness, high surface hardness. Metals like 304 stainless steel possess good formability, a combination of low yield strength with high elongation, excellent corrosion resistance, good wettability and working well at high temperatures [2]. Joining these dissimilar materials to produce strong, robust and uniform joints requires using advanced joining techniques. However, the melting point of engineering plastics is generally lower than 400 °C, much lower than the melting point of metal materials, and the physical properties such as the plastic transformation interval and thermal expansion coefficient are very different, and it is difficult to form a sound joint [3]. Since the mechanical joining are limited materials
and structures, generally poor sealing, and not a large area to form a reliable connection. Adhesive bonding is greatly affected by environmental factors, especially temperature, requires long processing time for effectively joining, and easily makes environmental pollution [4]. The traditional welding method is limited by the process and the joint form, which is prone to large defects and the connection strength is generally low. For example, resistance spot welding needs to overcome the problem of material conductivity, and the connection interface is not continuous, which makes it difficult to complete large-area connections [5]. There are many inclusions in the brazing interface, and at the same time, it is necessary to overcome the problem of solder wettability to plastics [6]. Ultrasonic welding will destroy the internal fiber structure of the composite material and reduce the joint connection strength [7]. Friction stir welding needs to rely on a more rigid stirring head, which will produce defects such as holes [8]. Compared to other connection processes, laser welding can achieve high-quality connection of dissimilar materials. It has fewer welding defects, high efficiency, and can be applied to a variety of joint forms.

Previous research work used laser lap welding of PMMA plate and stainless steel plate, the welding quality is improved with the increase of laser energy [9]. However, increase laser power result in PMMA degradation, and thus produces holes, poor fusion and thermolysis. The strength, quality and aesthetics of the joint will be affected. CFRTP and 6061 aluminum alloy were connected by a laser with a swing length of 2mm. The application of laser swing mode is beneficial to obtain more uniform temperature field and larger bonding area [10]. The energy of the laser changes, so that the heat is evenly distributed, thus control the joint width and the bubbles distribution, he laser beam oscillation mode is helpful to promote the gaseous products from plastic pyrolysis, which can be controlled by adjusting the laser power, oscillation amplitude and frequency [11].

The above results show that laser oscillation welding can broaden the welding process window, realize the precise control of laser energy, and help to improve the welding morphology and quality of plastic/metal composite structure. However, most of studies about PMMA-stainless are carried out under optimize process parameters. Therefore, the laser oscillating welding of the PMMA-steel was carried out the effects of beam oscillating patterns on weld characterization of PMMA-steel including the macroscopic morphologies and tensile properties were investigated. The purpose of this paper is to explore the effects of three beam oscillation modes on the welding properties of laser welded PMMA-steel.

2. MATERIALS AND METHODS
The material is made of 304 stainless steel and PMMA plastic, the size is the same, 80mm × 30 mm × 1 mm. Before welding, the stainless steel plates were cleaned with alcohol and all weldments were placed in a dryer.

Welding experiments were carried out using an RFL-C 1500/B/15/W fiber laser. The fiber laser is in continuous beam mode with a wavelength of 1 064 nm and a beam parameter product (BPP) of 2.5 mm Mrad. The welding joint consists of a collimating unit with a focal length of 200 mm, a vibrator scanning unit and an F-Theta focusing unit with a focal length of 250 mm. The collimating unit has a length of 100 mm. The laser focal spot radius is about 0.1mm. In addition, the swing motion is provided by the swing head. The beam oscillation is controlled by a galvanometer scanner. The weld surface is protected by 20L/min argon gas. To restrict and prevent any movement during welding, workpieces were fixed onto the table by clamps as shown in Figure 1.

The oscillating patterns used are three types that were transversal, longitudinal and circular. In the welding process, the laser beam acts on the surface of 304 stainless steel and the workpiece moves at the same time. Therefore, the composite trajectory of the laser beam oscillation is spiral. The spiral trajectories of the three oscillation modes are shown in Figure 2. Several experiments were carried out for each vibration mode to optimize the parameters and obtain a sound welding effect. The purpose of this study was to investigate the real relationship between the macroscopic morphology and weld strength. The welding process parameters are shown in Table 1. The laser joining experiments with
different oscillating speed are implemented. The laser power was applied at 200 W with a beam defocused distance of 0 mm and a welding speed of 10 mm/s.

![Diagram of experimental device for laser oscillation welding.](image_url)

**Figure. 1.** Diagram of experimental device for laser oscillation welding.

![Schematic of beam oscillation modes and the actual path of laser beam.](image_url)

**Figure. 2.** Schematic of beam oscillation modes and the actual path of laser beam.

**TABLE 1 WELDING PROCESS PARAMETERS OF PMMA AND 304 STAINLESS STEEL**

| Weld no. | Oscillation pattern | Oscillating diameter, mm | Oscillating speed, mm/s |
|----------|---------------------|--------------------------|-------------------------|
| 0        | /                   | /                        | /                       |
| 1        | Transverse oscillation | 2                       | 10                      |
| 2        | Transverse oscillation | 2                       | 30                      |
| 3        | Transverse oscillation | 2                       | 50                      |
| 4        | Transverse oscillation | 2                       | 300                     |
| 5        | Transverse oscillation | 2                       | 10                      |
| 6        | Longitudinal oscillation | 2                       | 20                      |
| 7        | Longitudinal oscillation | 2                       | 30                      |
| 8        | Longitudinal oscillation | 2                       | 40                      |
| 9        | Longitudinal oscillation | 2                       | 50                      |
| 10       | Circular oscillation   | 2                       | 50                      |
| 11       | Circular oscillation   | 2                       | 100                     |
| 12       | Circular oscillation   | 2                       | 150                     |
| 13       | Circular oscillation   | 2                       | 200                     |
By using BYES 3020 lap shear test method and UTM 50000 computer controlled test machine, the fracture load of the mixed joint was obtained. The principle of tensile test is shown in Figure. 3.

3. RESULTS AND DISCUSSION

3.1 Weld macroscopic morphologies
Defects such as holes, poor fusion and thermolysis were ordinary in dissimilar welding of plastic/metal hybrid joint. As shown in Figure. 4(1), the defect of thermolysis was obvious without laser beam oscillation. Through the listed in beam oscillation with oscillating speed of three pattern, the weld appearance was then improved. Under given laser power of 200 W, welding speed of 10 mm/s and beam defocused distance of 0 mm, the oscillating speed of range 10 mm/s to 300 mm/s with transverse oscillation and the oscillating speed of range 10 mm/s to 40 mm/s with longitudinal oscillation, the thermal degradation was disappeared, but the defect of thermolysis and a pore channel occurred with the oscillating speed increases to 50 mm/s by longitudinal oscillation. Similarly, these defects have been found in the circular oscillation pattern. It is worth noting that these weldments were homogeneous without obvious thermolysis with a combination of process parameters in one of the three oscillation patterns, as shown in Figure. 4 listed in purple dashed areas.

3.2 Weld formation mechanism
During laser joining progress, PMMA plate is pressed under 304 stainless steel plate. The PMMA at the interface is melted by the heat transferred by the steel side after the laser is directly irradiated on the steel surface. In some cases, uneven energy distribution and thermal degradation defects are easy to occur. For the laser process Figure. 5(a), the bubbles easily appear in the molten pool because the thermal degradation of PMMA. The bubbles cannot escape into the air by the melt flow, but stay in the melting layer to form the high porosity. The melted PMMA herefore flows into the grooves created under the clamping pressure, eventually make a hybrid joint of steel to PMMA. For the oscillation laser process Figure. 5(b), on one hand, the energy accumulation peak of oscillating laser welding is less than that of non-oscillating laser welding, so the oscillating laser beam reduces the temperature gradient of the molten pool. On the other hand, The formation of bubbles in the laser process, the oscillating laser is scattered into the air. Moreover, the bubble volume is reduced is also beneficial for interface bonding.
Figure 4. Weld macroscopic morphologies, (0)-(13) corresponds to the process parameter table 1.

Figure 5. Schematic diagram of melt flow formation mechanism.
3.3 Tensile properties
The sample without beam oscillation for bead width and tensile properties is 7.1mm and 539N, respectively. Effects of welding parameters and oscillating pattern on bead width and weld strength with the three patterns oscillation, as shown in Figure 6. The energy input of the oscillating beam depends on the laser power, and the variation of the oscillating speed only changes the spatial distribution of the given laser energy, so the width of the weld is almost not affected by the oscillating beam. The optimum welding process parameters were determined through the comprehensive study of the weld forming and weld strength as circular oscillation beam, oscillating diameter of 2 mm and oscillating speed of 150mm/s, under given laser power of 200W welding speed of 10 mm/s and beam defocused distance of 0 mm. Laser oscillation welding can eliminate thermal degradation and reduce bubble volume. The weld strength achieved 72% of the PMMA matrix, and added was 38% comparing with the weldment without beam oscillation.

Figure 6. Effects of welding parameters and oscillating pattern on bead width and weld strength, (a) transverse oscillation, (b) longitudinal oscillation, (c) circular oscillation.

4. CONCLUSIONS
A novel method of laser beam oscillation was used to welding steel-PMMA. The effect of laser beam oscillation patterns on the surface morphology and shear stress of weldment were researched, the conclusions including following:

1) Compared with the pure laser welding seam, the transverse, longitudinal and circular beam oscillation modes can all improve the weld surface morphology.

2) The oscillation beam laser reduced the temperature gradient of melt pool and reduced bubbles generated due to thermal degradation of PMMA plastics.
(3) The optimized parameters were confirmed as circular oscillation beam, oscillating diameter of 2 mm and oscillating speed of 150mm/s, under given laser power of 200W welding speed of 10 mm/s and beam defocused distance of 0 mm.

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