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Progress In the Study of Beam Oscillation on The Organization and Morphology of Laser Welded Joints

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Abstract

Laser welding technology plays a very important role in joining homogeneous and heterogeneous metals, metals and non-metallic materials. However, after laser welding, the weld seam will have defects such as poor molding, high porosity, serious spatter, and macro segregation. A large number of researchers have found that adding a specific trajectory to the laser beam can reduce the defects in the weld after laser welding. This paper introduces the basic principle of oscillating laser and several common oscillating paths, as well as domestic and foreign scholars for the oscillating laser welding for the same metal, dissimilar metal weld appearance and mechanical properties of the progress of the research, hope to be able to provide appropriate reference for subsequent researchers.

Keywords

Laser welding; beam oscillation; weld shaping; macroscopic deviation.

1. INTRODUCTION

In recent years, with the advancement and development of science and technology, laser as a processing tool is active in major fields, such as cutting [1, 2], welding [3, 4], and additive manufacturing [5, 6]. High-energy laser beams are an ideal heat source for welding, and laser welding has the advantages of high energy density, small spot size, narrow heat-affected zone, high weld quality, and easy to realize fully automated welding [7, 8]. The quality and efficiency of welding is much higher than that of conventional melt welding. However, with the improvement of product precision and the popularization of new materials, the conventional laser welding process can no longer meet the current production requirements due to the defects of poor weld formation, high porosity, serious spattering, and macroscopic segregation.

Beam oscillation technology as an important parameter in the laser welding process, in the study of weld metal organization and performance has attracted wide attention. With the development of modern manufacturing industry, the requirements for welding quality and performance are getting higher and higher. As a technical means to improve the welding process, beam oscillation has the ability to control the morphology of the welded joint and the dynamic behavior of the molten pool, which plays an important role in improving the welding quality and optimizing the properties of the metal organization. Through a large number of studies found that beam oscillation can be very effective in reducing the porosity of the weld greatly improve the quality of the weld [9-12]. Wang [13] and others have studied the use of linear, circular and infinity three laser oscillation welding to reduce the weld porosity defects. The results show that the weld porosity of oscillatory laser welding is lower than that of

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conventional laser welding, and the infinite oscillation mode has the smallest weld porosity. Jiang et al [14] found that the use of oscillatory laser can improve the inhomogeneity of the organization of the fusion zone of the dissimilar metal weld and reduce the generation of macroscopic segregation.

Oscillating laser welding is to make the heat source under the premise of maintaining a constant welding speed, along a specific trajectory for repetitive movement of the welding technology, commonly used oscillation route is mainly transverse oscillation, longitudinal oscillation, circular oscillation and infinite oscillation and other ways. In contrast to conventional pulsed laser welding, where the effect of the laser energy is altered in the temporal dimension to achieve better welding results, oscillating laser welding is more effective in the spatial dimension. With the continuous development of modern optical technology, the defect suppression strategy by changing the oscillation form of the laser beam has received more and more attention. This paper will be from the formation of the principle of laser beam oscillation, as well as beam oscillation on the weld tissue morphology and the impact of beam oscillation control and optimization to carry out a comprehensive overview, and hope that the future development of laser welding to play a role in promoting.

2. PRINCIPLE OF LASER WELDING AND FORMATION MECHANISM OF BEAM OSCILLATIONS

Laser welding is a welding method that utilizes a laser to emit a beam of light into an extremely high energy density heat source that melts the material at the joint, followed by rapid cooling of the liquid metal to form a high-quality weld. The physical process is that the laser beam passes through a polarizer and enters the focusing device, the spot diameter becomes small and the energy density is high, when irradiated on the material surface, the light energy absorbed by the material is converted into very high temperature heat energy, so that the material melts, and the weld is formed by the rapid solidification of the melted material after the laser beam leaves the weld.

Laser Oscillatory Welding (LBOW) is a new, relatively simple but effective welding process. Oscillating laser welding is to make the heat source under the premise of maintaining the welding speed is unchanged, along a specific trajectory for repetitive movement of the welding technology, laser oscillation welding experimental system is mainly composed of lasers, oscillating weld head, mobile platform and other equipment. When the laser beam passes through the vibrating mirror installed in the laser head, the original trajectory of the beam is changed by deflecting the vibrating mirror to produce a variety of oscillating trajectories [15]. At present, the oscillation of the spot is mainly realized in two forms: (1) the oscillation of the spot is realized by a vibrating mirror that can withstand high power laser, as shown in Figure 1. (2) The use of wedge-shaped lens, the use of wedge-shaped lens rotation to realize the spot movement.

Beam oscillation has a variety of forms, our common beam oscillation form of sinusoidal oscillation, circular oscillation, “8” shaped oscillation, “∞” shaped oscillation, zig-zag oscillation is also known as sawtooth oscillation and so on.

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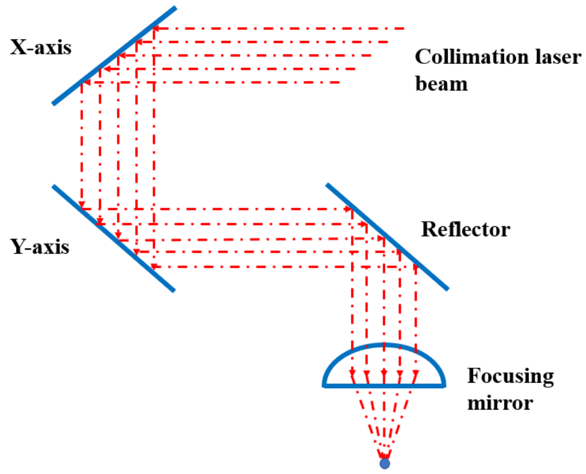

Figure 1. Schematic diagram of oscillating laser beam

3. EFFECT OF BEAM OSCILLATION ON WELD ORGANIZATION AND PROPERTIES

Conventional laser welding has obvious defects such as poor weld shaping, high porosity, and severe spatter, etc. Huang et al. [16] found that through a combination of experimental and simulation studies, beam oscillation laser welding can produce welds with ideal chemical composition, microstructure, and properties by proper adjustment of all process parameters.

3.1 Effect of beam oscillation on weld morphology

Common defects in laser welded metals include spatter, porosity, macro-segregation and other defects. Spattering is a frequent defect in hole-locked mode laser welding, especially in ultra-high laser power welding [17], high-speed laser welding [18], and the welding of highly reflective materials such as aluminum, copper, and magnesium [19, 20]. It has been found that beam oscillation laser welding technology can effectively reduce the spatter generated during the laser welding process and reduce the porosity [11, 12]. The use of sawtooth oscillation path can effectively improve the aesthetics of the weld and can be beneficial to reduce the magnitude of the variation of the locking hole opening to prevent spattering [21, 22]. Xu et al. [23] further confirmed experimentally that the number of spatters can be easily reduced with the increase of the frequency and found that, in a single cycle, the fusion state of the newly generated melt and the existing molten pool determines the morphology of the molten pool boundary, which presents a “W-U-W” shape change. Meng et al. [24] used annular oscillation method and compared it with the traditional 250 Hz annular oscillation method, and the results showed that the energy uniformity was increased by 1.9 times and the stirring intensity in the small holes was increased by 25% in the annular oscillation method, which solved the defects of weld due to the uneven distribution of energy under the action of annular oscillating beams. Ai et al. [15] used a machine learning approach to the 6061 aluminum alloy metallography and found that BP neural network (BPNN) can better determine the optimum welding conditions; in addition, Hao et al. [21] studied the lock holes and the molten pool under the annular vibration path, and found that under the annular vibration path, the size of the keyhole changes a lot under the annular vibration path, and a bulge is formed on the surface of the molten pool, which causes more spattering; whereas, under the Z-shaped vibration path In the case of the Z-shaped vibration path, the keyhole and the melt pool observed by high-speed photography are more stable, and there is little spattering. Cheng et al. [25] also confirmed that beam oscillation can significantly reduce weld spatter.

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In response to the problem of severe segregation which is very easy to occur during laser welding, Wang et al. [26] utilized ring laser vibration technology to add Ni to Al-Si clad compression steels, and it was shown that the laser vibration can significantly improve the width of the molten pool, and effectively inhibit the segregation. Wang et al. [27] introduced the oscillation into the laser-arc combination welding, and also proved that under high frequency vibration, by stirring, eddy current, etc., can improve the turbulence and convection velocity in the molten pool and realize the homogenization of the alloy composition, thus significantly suppressing the macroscopic segregation.

With regard to the T-joint weld there is a long-term porosity problem, in order to overcome this problem researchers have made a lot of research, Xia et al. in order to solve this problem proposed dual laser beam welding (DLBW) and oscillation process, and analyzed and considered the impact of the laser incidence angle on the porosity, and set up a numerical model for verification found that the DLBOW significantly reduces the porosity, and the laser incidence angle on the porosity, as well as the laser incidence angle on the porosity. porosity, and the smaller the laser incidence angle, the lower the porosity. Xia et al [28] found that beam oscillation and smaller beam incidence angle can effectively inhibit the emergence of weld porosity, so that the circumferential tensile strength and tensile strength of T-joints were increased by 89.5% and 71.6% compared to the base metal by the incidence angle of 20°~30° for 2219Al-Cu alloy. Not only T-joints, but also ordinary metal can produce high porosity when welding.

In summary, the addition of beam oscillation in laser welding can make the laser energy distribution uniform, increase the stirring of the molten pool, greatly reduce the spatter, macro segregation, porosity and other phenomena, so that the appearance of the weld is more beautiful.

3.2 The effect of beam oscillation on the microstructure and mechanical properties of welds

Grain refinement can improve the mechanical properties of the weld, the periodic motion of the laser beam makes the leading edge of the molten pool to form eddy currents and a certain degree of turbulence, which accelerates the solidification speed of the molten pool and reduces the size of the molten pool. Increasing the oscillation frequency of the light interferes more with the solidification of the molten pool, and grain refinement is more pronounced [29].

The mechanical properties of the weld are a key factor in determining the quality of the weld, some researchers have added beam oscillation during laser welding and studied the weld to find that the mechanical properties are improved accordingly. Zhang et al [30], in their study of X2CrTiNb18 ferritic stainless-steel plates, found that annular beam vibration has no significant effect on its unidirectional tensile properties, but its plastic toughness has been greatly improved; at the same time, the beam oscillations caused changes in the microstructure of the weld. As shown in Figure 2, at a depth of 290μ m, an equiaxed grain area appears at the top of the weld, and the columnar crystals grow in a certain direction along the weld centerline, and there is a certain angle along the weld centerline, and the direction of the weld centerline gradually decreases, and with the movement of the spot, the direction of the columnar crystals grows gradually. The area at the beam vibration weld is significantly higher than that at the straight weld zone, indicating that beam oscillation can effectively increase the area of the heat affected zone, thus significantly improving the fracture toughness of the material. Yan et al [31] found that the ring seam structure changed from lumpy and columnar crystals to granular and spherical during the ring beam oscillation laser welding process, and the toughness of the joints was increased by 110.41% and 153.14% respectively compared to the strong and tough joints of the no-beam vibration laser welded joints .Zhang et al. [32] found that annular beam vibration could obtain a good weld of 192 MPa during the improvement of SiCp/2 xxAl alloy welding, Hu et al. [33] showed that the strength and elongation of the fusion zone of GH909 at 300 Hz were 859.5 MPa and 38.6%, which were significantly higher than those of the laser welded joints (731.1 MPa, 17.9%), while the average hardness of the fusion zone (melting zone) of light oscillation welding (LOW) was about 16 HV higher. Through the study of its microstructure, two strengthening mechanisms of solid solution and precipitation phase enhancement were revealed, which provided a theoretical basis for the welding of LLDPE. Kang et al [34] showed through the study of the performance of welded joints of AA5052 aluminum alloy (AA5052), that the modulated Beam Welding (MBW) requires a much lower maximum wave speed for complete penetration than High Speed Beam Welding (GBW), but it better forms a better molten pool morphology. Jiang et al. [14] studied the welds of two heterogeneous materials, Ni-Cr-Mo and CuCr-Zr, by using the Zig-Zag beam oscillation technique. The results showed that the mixing zone and the locally melted reinforcement layer in the alloys were significantly reduced, and the distribution of the main constituents was more homogeneous; Yang et al. [35] carried out the Zig-Zag beam oscillation laser welding of 6061 Al/AlSl304 lap weld, and the results showed that the Zig-Zag beam oscillated in the welds of the two heterogeneous materials. The results show that beam oscillation has obvious inhibition effect on IMCs, and the tensile and shear properties of the weld are improved under appropriate laser power; at the same time, by increasing the interfacial bonding region and restraining the intermetallic compounds, the maximum fracture load is increased from 80-120 N/m to 120 N/m.

The addition of beam oscillation to laser arc composite welding also plays a positive role in the molding of the weld as well as the improvement of the mechanical properties. Hao et al [36] also confirmed that the width of the heat-affected zone of beam oscillation is increased and the elongation is increased by a comparative study between beam oscillation laser welding and laser arc composite welding of Q235 steel. In order to verify the difference between beam modulation and ordinary Gaussian beam welding, Hao et al [37] realized laser-arc composite welding of AZ318 magnesium alloy using CNTs with CNTs, and showed that electron beam vibration can effectively inhibit the agglomeration of CNTs in FSW, which in turn refines the weld organization and improves the weld plasticity. The applicant found in the previous study that in the annular laser vibration- Tig composite welding, the residual stresses in the weld were reduced and homogenized due to the beam oscillations that could make the microstructure more uniform, and at the same time, the beam oscillations did not significantly affect the tensile strength of the weld, which greatly improved the plasticity of the weld. He et al.[39] Through the laser welding experiments on the two metals, it was It was found that under suitable welding parameters, the tensile strength of the welded joint could reach up to 2.2 KN, which was 69.23% higher than that of the welded strength without vibration, due to the following reasons: during the welding process, the introduction of the electron beam changed the heat flow in the molten pool, which improved the uniformity of the welding energy; at the same time, it was found that by comparing the line vibration, the trajectory of the motion was much smaller, which could avoid the remelting several times, thus further refinement of the grain size of the material was further improved, thus further improving the mechanical properties of the material. Zhou et al. [40] compared three different types of 2060 aluminum-lithium alloys occurring during the laser welding process ("line" type, "∞" type, "8" type), the results show that the '8' shape laser vibration can accelerate the liquid flow and produce fine grains and large angular grain boundaries, and its cellular dendritic zone (CDZ) decreases from 105.27 μm to 89.67 μm. Meng et al. [42] achieved two different forms of laser energy uniformity by using an "8" beam oscillation method with a titanium intermediate layer, which enhanced the weld width from 0.6 mm to 2.4 mm and increased the shear stress by a factor of 3.8 compared to circular oscillation.

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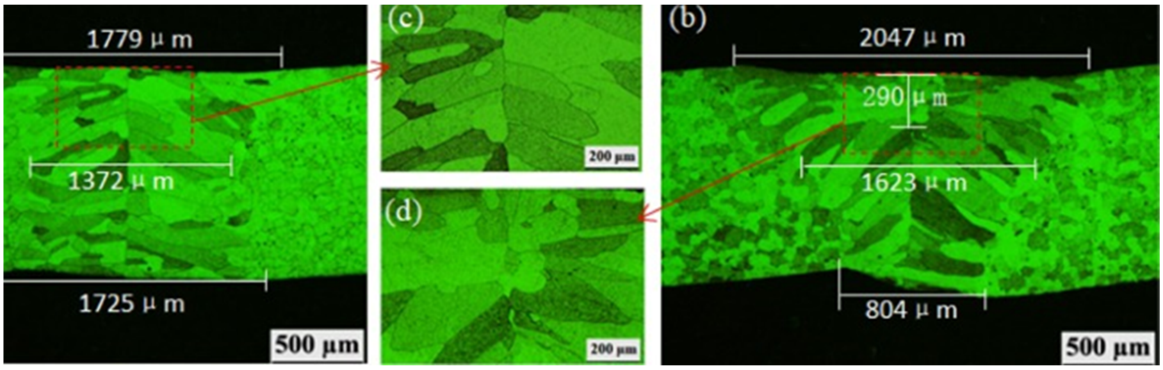

Figure 2. Microstructure of welded joint section
(a) Fiber laser welding, (b) Oscillating fiber laser welding, (c) Partial magnification of fiber laser welding, (d) Partial magnification of oscillating fiber laser welding

How the change of the external environment affects the beam oscillation laser welding is also the direction that the current researchers focus on. Bi et al [43] proposed a new method of ultrasonic vibration-assisted laser beam oscillation welding (UV-LBOW), due to the ultrasonic vibration and the laser beam oscillation on the molten pool has a common effect. Comparing the elemental distribution under different welding methods, it can be clearly seen that the UV-LBOW method formed a uniform elemental distribution between the weld boundary and the fusion region, which increased the tensile strength and elongation of magnesium-aluminum alloy weld by 347 MPa and 19.0%, respectively, which also proved that the uniformity of elemental distribution often plays a key role in the mechanical properties of the weld. Yang et al [44]. By changing the external experimental environment to sub-atmospheric pressure and using circular beam oscillation laser welding on AA2219-T87 (aluminum alloy), it was found that there was a significant improvement in microstructure and mechanical properties at low atmospheric pressure, according to Fig. 3, it can be seen that at 102Pa pressure, the laser beam oscillation frequency of 80Hz when the pores are suppressed, the weld morphology is better, after measurement of the tensile strength of the weld reaches 388.62Mpa, the mechanical properties have been improved.

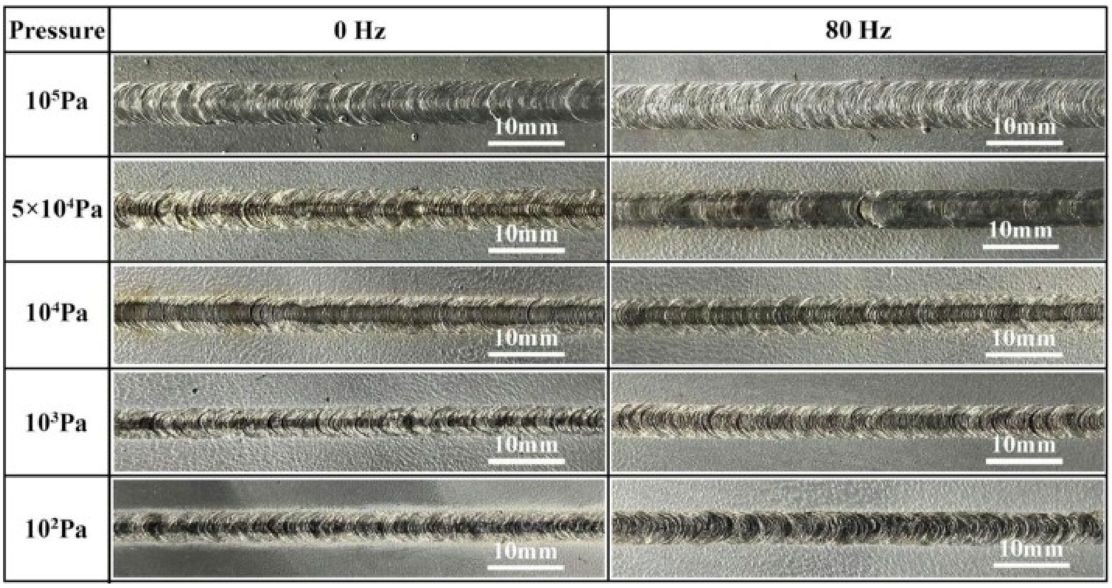

Figure 3. Welding topography of circular oscillation paths at different atmospheric pressures

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In summary, researchers have discussed the effects of circular beam oscillation, sawtooth beam oscillation, “8” beam oscillation laser welding on the mechanical properties of welded joints and microstructure, and found that the different paths will form a better impact on the weld seam molding, and to a large extent will be able to make grain refinement to improve the mechanical properties of welded joints, and some researchers have even compared two or more of our common forms of beam oscillation to find the optimal method and parameters for different metals to achieve when welding. Mechanical properties, some researchers will even be our common forms of beam oscillation of two or more kinds of comparative study to find out the optimal method and parameters of different metal welding.

4. EFFECT OF OPTIMIZED WELDING PARAMETERS ON LASER WELDING PERFORMANCE

Beam oscillation parameters (oscillation frequency, oscillation amplitude, welding speed, etc.) also have a significant effect on the tissue morphology and mechanical properties of laser welded joints. Xu et al [45] through the aluminum-silicon coating under the 22MnB5 laser oscillatory welding carried out a detailed analysis found that the laser power for the tensile strength of the welded joints is the most significant effect, followed by the oscillation frequency, welding speed and oscillation amplitude. As for the porosity of welded joints, Zhang et al [46] found that the effect of oscillation amplitude and oscillation frequency on porosity is huge, while the effect of changing the laser power on the porosity of welded joints is limited by Figure 4.

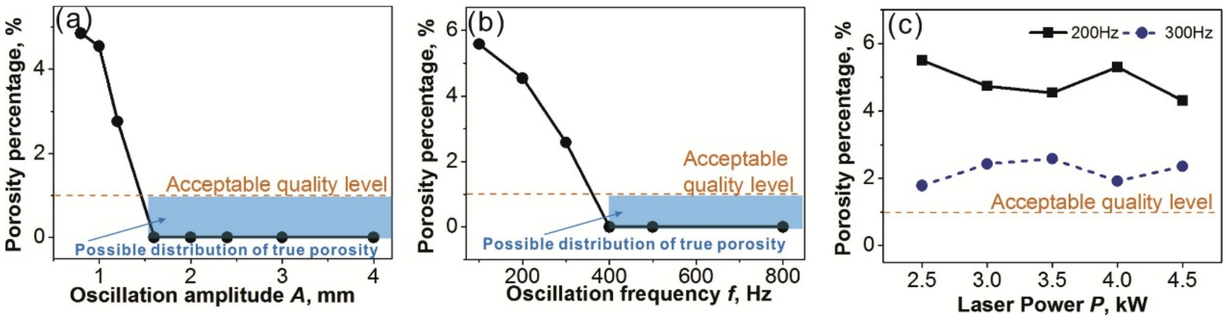

Figure 4. Relationship between porosity percentage and different processing parameters; (a) Effect of different oscillation amplitude on porosity (b) Effect of different oscillation frequency on porosity (c) Effect of different laser power on porosity

4.1 Effect of varying laser power on beam oscillation laser welding performance

Laser power as the most important parameter in laser welding plays a very big role in weld quality. H R et al [47] found that the oscillating beam can make the weld surface smoother under the condition of increasing laser power through the optimization of 5052-H32 aluminum alloy laser welding process by the sinusoidal light oscillation path. Han et al [48] modulated the beam oscillating laser welding power for aluminum alloy laser welding found that the weld using gradient power mode is larger than the constant power mode of the weld depth to width ratio; due to the strong stirring effect to promote the escape of porosity. Tan et al [49] studied the effect of S-curve power on the sinusoidal beam oscillating laser welding of 5A06 aluminum alloy. It was found that better joints can be obtained by using S-curve power laser oscillatory welding compared with constant power laser oscillatory welding. The results of the tensile experiments in Fig. 5(a) show that the average tensile strength under the S-curve power reaches 377 MPa, which exceeds the constant power by 88 MPa, whereas the BM is the average tensile strength of the base material The tensile strength of the welded specimens under the S-curve power is about the base material (340 MPa) of 99.1%, Figure 5(b) shows that the elongation of S1 is about 20% much higher than the elongation under constant power.

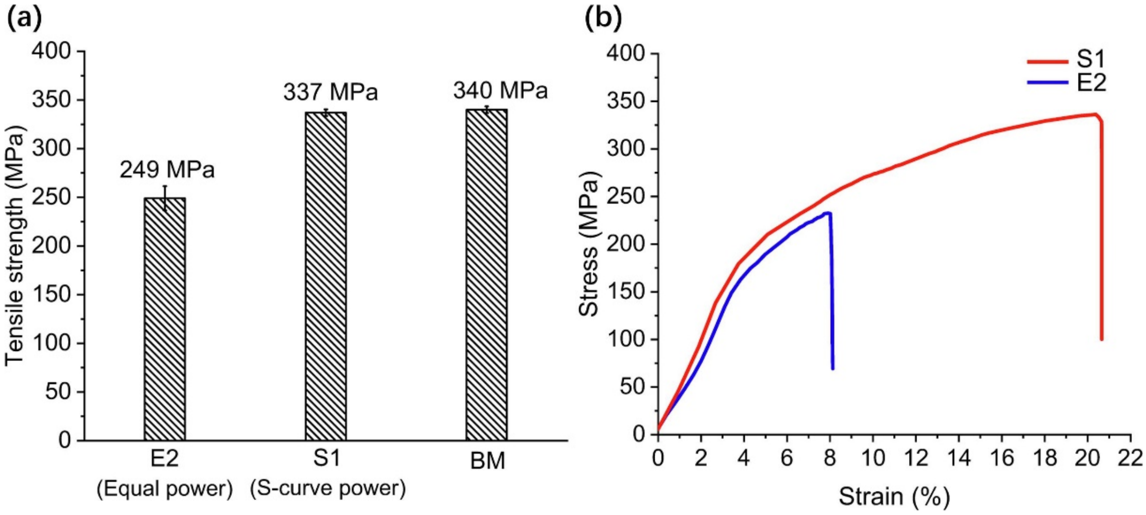

Figure 5. Tensile test results in different power modes: (a) average tensile strength of laser oscillatory welded 5A06 samples and base material; (b) tensile stress-strain curves of S1 and E2 welds.

4.2 Effect of vibration frequency on beam oscillation laser welding performance

Oscillation frequency is the number of spot movements per unit area. The increase of the laser frequency in the same unit area also means that the energy distribution is more uniform, which makes the weld shape more beautiful, spatter reduction, mechanical properties have been improved. Xu et al. [50] for different oscillation frequency on the mechanical properties of 22MnB5 weld and failure behavior of the oscillation frequency and amplitude of the static laser beam welding of zero as a comparison of the laser oscillation frequency from 0 to 320 Hz increase, the weld shape from “X” shape to “Y” shape, the tensile strength and elongation of the welded joint. The shape of the weld changes from “X” to “Y”, and the tensile strength and elongation of the welded joints first increase and then decrease from the minimum value (426.45 HV, 1159.92 MPa, 1.14%) to the maximum value (476.98 HV, 1521.39 MPa, 1.14%), and then decrease to the maximum value (476.98 HV, 1521.39 MPa, 1.14%). HV, 1521.39 MPa, 2.76%). In order to further verify the effect of oscillation frequency on laser welding welds. Zhao et al. [51] studied Incar alloys at different frequencies, the results showed that at high frequencies, the laser beam had a great influence on the microstructure near the fusion line, but it did not always improve the microstructure in the center of the weld, the grains became very small at 50 Hz, and the grain refinement effect was not obvious after 100 Hz. Meng et al. found in the vibration welding of magnesium-aluminum alloys that 90 Hz vibration can make the maximum shear stress in the joint as high as 3.3 KN. Liu et al. [11] achieved grain refinement by using ring laser oscillation in the range of 300 Hz, and at 300 Hz, the grain refinement was up to 41%. Hu et al. et al. investigated the effect of oscillation frequency on welded joints of heterogeneous aluminum alloys, and the results showed that higher vibration frequency can improve the mechanical properties of the joints. Wan et al [22] investigated the effect of beam oscillation locking eye penetration of thin galvanized steel remote laser pin welding sputtering using a sawtooth oscillation path. It was found that the sawtooth oscillation of 5 cycles/mm can significantly improve the weld aesthetics and reduce the quality loss caused by spatter compared with the baseline condition of conventional linear welding. In addition, the weld quality changes with the change of vibration frequency. Zhou et al. in order to study the TC4 and 7075 aluminum alloys in the welding, for the energy saving, found that in the 1663 N ~ 1672 N range of laser power every decrease of 100 W, the corresponding frequency increased by 50 Hz, the performance of the TC4/7075 dissimilar joints will not have a significant fluctuation of energy-saving rate with the decrease of the laser power and the increase of vibration frequency increases, which provides a basis for the evaluation of the energy saving rate of the new Ti/Al process green manufacturing. Zhou et al [52] in order to be able to solve the effects and constraints on the mechanical properties of the brittle and cracked joints of Ti-Al intermetallic compounds, obtained an effective connection between TC4 titanium alloy and 7075 aluminum alloy, which fully verified and solved the defects such as pores, cracks and other defects in the laser welded joints. And according to Fig. 6, it can be found that changing the vibration parameters can change the quality of the weld, with the increase of the vibration frequency, the maximum load of the joint increases and then decreases, and reaches a maximum value of 1852 N when the vibration frequency is 150 Hz, which is 76.38% higher than that without vibration. Accordingly, when the vibration frequency exceeds the critical value, the interface layer is too thin to form an effective connection, and the performance of the joint deteriorates.

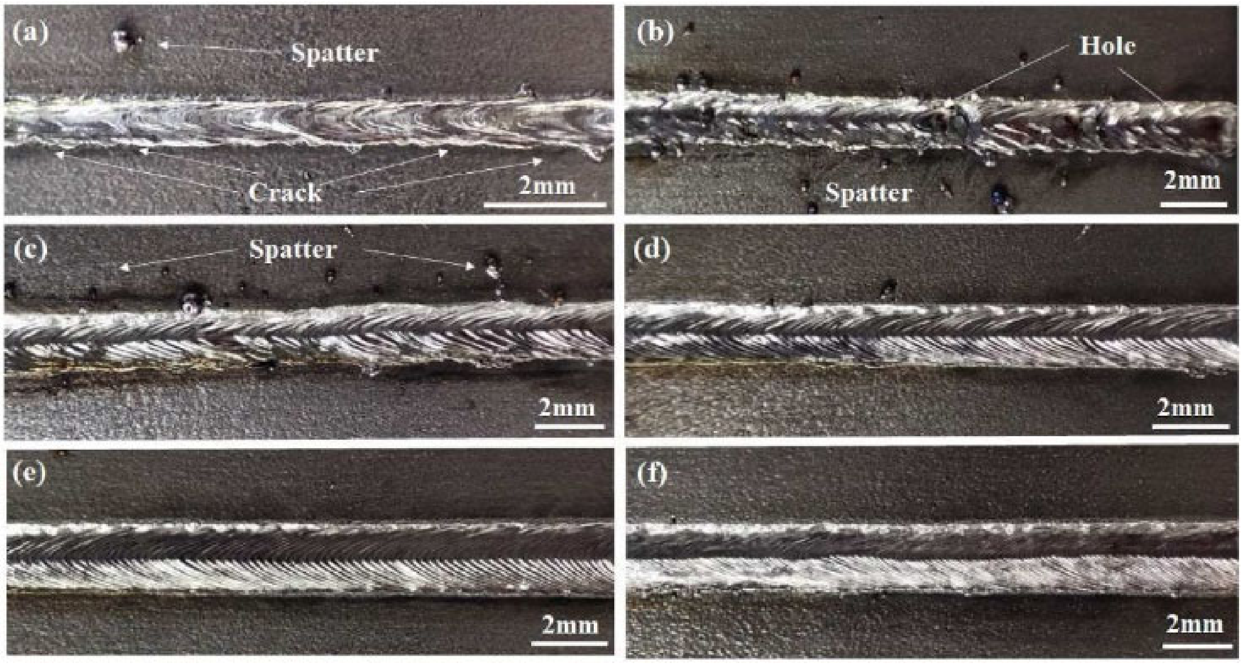

Figure 6. Effect of vibration frequency on the surface appearance of welds: (a) f ¼ 0 Hz; (B) f ¼ 50 Hz; (c) f ¼ 100 Hz; (d) f ¼ 150 Hz; (e) f ¼ 200 Hz; (f) f ¼ 300 Hz.

In summary, increase the spot vibration frequency can affect the organization around the fusion line, refine the organization of the grain, reduce spatter to reduce porosity has a significant impact on improving the quality of welding, but the increase in vibration frequency should be adjusted in the appropriate range rather than the higher the better, the higher the vibration frequency of the quality of the weld may not have an impact on the weld, or even make the weld mechanical properties of the weld to reduce.

4.3 Effect of vibration amplitude on laser welding performance

The change of vibration amplitude affects the increase of the spot motion trajectory, and the morphology of the weld becomes smooth with the increase of vibration amplitude, which is due to the increase of vibration amplitude and the increase of the stirring intensity of the molten pool [53].Chen et al [9] investigated the effect of different vibration amplitudes on the microstructure and mechanical properties of 6061/2A12 heterogeneous aluminum alloy, and the results showed that increasing laser amplitude is beneficial to improve the fusion zone The results show that increasing the laser amplitude is conducive to increasing the proportion of equiaxial crystals in the fusion zone and decreasing the average diameter of equiaxial crystals. Yi-Cin Ciou et al [54] investigated the effect of vibration amplitude and vibration frequency on the tensile strength of welds in different oscillation modes, and an appropriate increase in the

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vibration amplitude can effectively improve the tensile strength of the weld, and when the vibration amplitude of 1 mm, the tensile strength of the sawtooth oscillation and the circular oscillation modes have reached the maximum value.

5. CONCLUSION

With people's in-depth study of the laser path, the use of beam oscillation on the laser welding organizational properties of the research has achieved certain results, the conclusions are mainly as follows:

(1) Firstly, beam oscillation has a significant effect on the morphology and molten pool behaviors of welded joints. It was found that under the circular oscillation path, the keyhole length of the welded joint varied greatly and the molten pool appeared to be convex, resulting in more spatter. Under the sawtooth oscillation path, the keyhole and the melt pool are relatively stable, and the spattering phenomenon is reduced.

(2) Secondly, beam oscillation also affects the grain size, grain boundary orientation, phase composition and other properties of the weld metal. Researchers have found that appropriate beam oscillation can achieve finer grain size, better grain boundary orientation, and more uniform phase composition distribution through optical microscopy, scanning electron microscopy, and X-ray diffraction characterization. These characteristics of improved metal organization are important for improving the mechanical properties, corrosion resistance and fatigue life of welded joints.

(3) In addition, beam oscillation also has an effect on the weld area of the welded joint. It has been found that appropriate beam oscillation can increase the weld area and improve the strength and sealing performance of welded joints. This is important for special applications such as aerospace and automotive manufacturing.

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