Effects of Laser Welding Parameters on the Characteristics of Deposition Layer

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Abstract. Laser welding with filler wire makes welding more cost efficient due to its properties. However, fluctuation of welding parameters seriously affects the stability of welding process and the quality of deposition layer. Based on the high speed camera system and welding process test, this paper focuses on effects of welding parameters on the laser-wire coupling behavior, the transition behavior of molten metal and the characteristics of deposition layer. The results showed that the transition behaviors of liquid metal were decomposed into globular transition behavior, liquid-bridge transition behavior and spreading transition behavior, among which the liquid-bridge transition behavior was most stable relatively. Different dynamic welding processes in different circumstances were established to interpret the laser-wire coupling behaviors and the transition behaviors of liquid metal while the D was zero. It was found that the coupling behavior and the transition behavior of liquid metal belonged to different dynamic process with the variable welding parameters. The optimized welding parameters were obtained by analyzing the stability of welding process and the characteristics of deposition layer.

Keywords: Laser welding · High-speed camera · Coupling behavior · Transition behavior · Deposition layer

1 Introduction

Laser Additive Manufacturing with Metallic Materials is a research focus because of the urgency of decreasing manufacturing cycle and costs. Meanwhile, it also has broad application prospects in the aerospace, defense military and other fields owing to its good properties such as high flexibility, integration, and high degree of automation [1, 2]. Over the past 20 years, some researchers have mainly studied Laser Additive Manufacturing technology based on metallic powder and achieved some results. However, because of its high cost of raw materials and low utilization rate, the use of metallic powder is limited seriously [3]. Compared with metallic powder, Laser Additive Manufacturing with Filler Wire takes laser heat as a heat source, which has high density of heat input and the smaller heat affected area so as to improve the stability of the welding process. Moreover, by using the metallic wire, no dust pollution as well as material saving are expected with this technique. In this circumstance, laser welding with filler wire has gained worldwide popularity for its capacity of increasing economy [4, 5]. At

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present, to obtain the well-shaped deposition layer, previous researches of technology have performed. Many researchers have reported effects of welding parameters on characteristics. To our knowledge little has been focused on the laser-wire coupling behavior and the transition behavior of molten metal.

The research focus on the effects of welding parameters on the laser-wire coupling behavior, the transition behaviors of molten metal and the characteristics of deposition layer by means of high speed camera technology and process test.

For our purposes, the process test with variable welding parameters was carried out and the welding process was gathered with high speed camera accordingly. Then the dynamic welding processes were established to analyze the experimental results. Finally, the size of deposition layer was measured and analyzed.

2 Material and Method

A 180 × 70 × 4 mm Q235 carbon steel sheet is processed for the experiment, and E501T-1 low alloy steel filler wire is employed as the welding consumable, which diameter is 1.2 mm and its chemical composition is shown in Table 1.

Table 1. Chemical compositions of E501T-1

Elements	C	Mn	Si	P	S
Content (%)	0.036	1.40	0.52	0.013	0.011

The schematic diagram of experimental system can be seen in Fig. 1, the Dlight3 semiconductor lasers is used for providing the welding heat source, whose main parameters are as follows: maximum power 1.5 kW, wavelength 976 nm, spot size 3 mm × 1 mm, working distance 275 mm, and working mode CW. In order to reduce the damage of laser heat to the laser device and other components, the central axis of the laser is deflected against the welding direction at a small angle in welding process. The modified SB-10 wire feeder system is adopted and the wire feeding speed is adjusted to vary from 0 m/min to 5 m/min stably. To keep the high temperature welding pool and molten metal from being oxidated, Ar at a constant flow rate of 5 L/min is applied for shielding. The air supplying pipe locates at the rear end of welding direction; moreover, it is coplanar with laser beam and filler wire fed in. Four-axis linkage walking mechanism

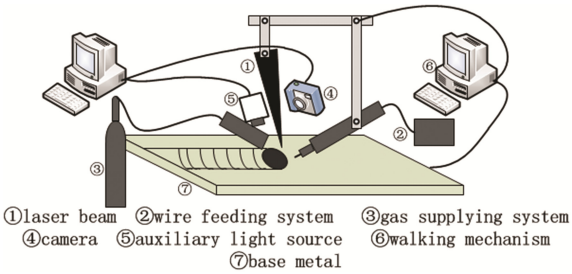

Fig. 1. Schematic diagram of experimental system

was designed for experiment. To gather the welding process real-timely, the high-speed camera system is applied at 1000 frame rate. The NBT's HSX-F300 xenon lamp is used as an auxiliary light source in order to improve the clarity of acquisition area.

3 Results and Discussion

3.1 Effect of the D on the Characteristics of Deposition Layer

As shown in Fig. 2, the *D* (distance between the laser and the filler wire) is the spacing between laser spot and the contact point of wire ends to workpiece [6], which affects the liquid metal transition, the stability of welding process and the characteristics of deposition layer indirectly by affecting the laser-wire coupling behavior directly.

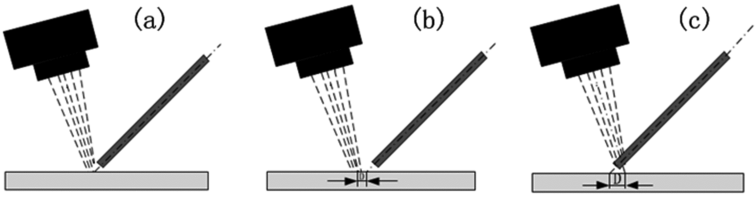

Fig. 2. Schematic diagram of the *D*: (a) $D = 0$; (b) $D > 0$; (c) $D < 0$

Based on the high-speed camera system, the effect of variable *D* on the laser-wire coupling behavior and stability of welding process was studied. The welding parameters were given in Table 2.

Table 2. Welding parameters

Parameters	*P*/W	*V*/(mm/min)	*V*(*f*)/(cm/min)	Angle/(°)	*S*/(mm)	Gass/(L/min)
Values	1500	120	120	45	8	5

The mechanism of the interaction between laser heat and filler wire is complicated. The transition behavior of liquid metal was liquid bridge transfer when the *D* varied from −1 mm to 0.5 mm. At the beginning of welding process, a portion of laser heat was used to melt filler wire and others melted base metal so as to form a welding pool, the reason for this was that laser beam was partially overlapped by the filler wire. With the progress of welding process, the absorption rate of laser heat increased accordingly because of the increased liquid metal in welding pool, filler wire was melted adequately by the interaction of laser heat and thermal conduction of liquid metal. Finally, molten metal was transferred into welding pool by way of liquid bridge transfer, which caused the stable welding process and the well-shaped deposition layer. The transition behavior of liquid metal was globular transfer when the *D* below or equal to −1 mm. Most of the laser heat was absorbed by filler wire since the filler wire happened to lie almost directly over laser beam, which resulted in the relatively small penetration owing to the lesser laser heat transferred to the surface of base metal. Furthermore, because of the larger

distance between the molten metal and the surface of base metal, the volume of liquid metal increased as filler wire fed in. Finally, liquid metal was transferred into welding pool by way of globular transfer when the gravity of droplet was greater than surface tension. As a result of impact effect of liquid metal to welding pool, the welding process was unstable and the deposition layer was discontinuous. The liquid metal transition behavior was spreading transfer while the *D* varied from 0.5 mm to 1 mm. The reason for this was that the most of laser heat was mainly used to melt the base metal, which resulted in the increase of the penetration and width of deposition layer. Meanwhile, the end of filler wire reached the edge of welding pool, which made filler wire bent and hindered the continuous wire feeding. Then the bent filler wire fed in welding pool was melted fully by the thermal conductivity of liquid metal and formed a deposition layer. The transition behaviors of liquid metal and the appearance of deposition layer with variable *D* are shown in Figs. 3 and 4.

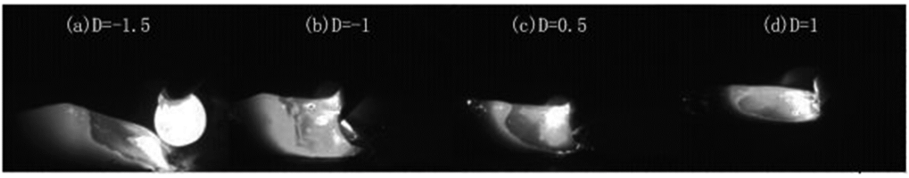

Fig. 3. The transition behavior of liquid metal with different *D*

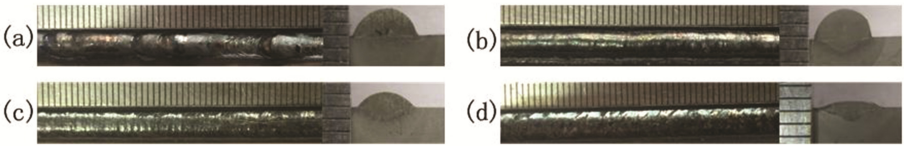

Fig. 4. Apprearance and cross-section of deposition layer with different *D*: (a) $D = -1.5$ mm; (b) $D = -1$ mm; (c) $D = 0.5$ mm; (d) $D = 1$ mm

3.2 Effects of Welding Parameters on the Characteristics of Deposition Layer

The welding parameters are of great significance for the stability of welding process and characteristics of deposition layer. While the *D* is zero, stable welding process and well-shaped deposition layer can be obtained under the optimized parameters. However, the fluctuation of welding parameters affects the stability of welding process and the characteristics of deposition layer by affecting the filler wire melting mechanism and the liquid metal transition behaviors. Combined with high-speed camera technology and process test, the effects of welding parameters on the laser-wire coupling behaviors, the transition behaviors of liquid metal and the characteristics of deposition layer were studied.

Different Dynamic Welding Processes

In one case, owing to the coincidence of the laser spot and the tip of filler wire, a portion of laser heat was used to melt filler wire and others melted base metal to form a welding pool while the D was zero. On the premise that welding heat-input is greater than the heat required for melting filler wire, the filler wire was melted completely by laser heat and formed a droplet at the beginning of welding process. But the droplet was attached to the end of filler wire instead of transferring into welding pool, the reason for this was that the surface tension between filler wire and liquid metal was larger than the gravity of droplet due to the smaller size of droplet. With the progress of welding process, the volume of molten metal and the size of droplet increased accordingly. And the lower surface of droplet contacted with the upper surface of molten metal at a moment, which formed a liquid bridge. Meanwhile, liquid metal was transferred into welding pool under the combined effects of gravity, surface tension and blow force of gas. The dynamic welding process shown in Fig. 5(I) is used to interpret the laser-wire coupling behavior and transition behavior of liquid metal in this case.

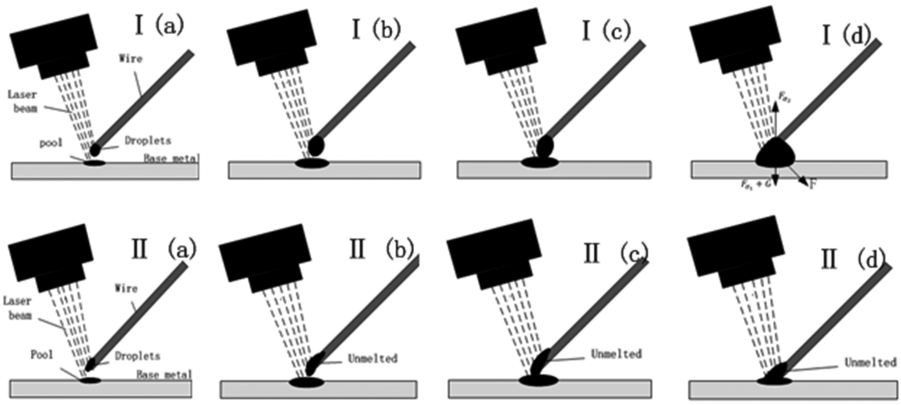

Fig. 5. Different dynamic welding processes: (a) wire melting process; (b) droplet growth process; (c) contact process; (d) liquid bridge transition

In another case, filler wire was melted partly while the heat-input was less than the heat required for melting filler wire, which was different from the case mentioned above. As the welding progressed and filler wire fed in, the volume of unmelted filler wire increased accordingly. Finally, molten metal formed by filler wire was transferred into welding pool similarly while the unmelted filler wire inserted into welding pool and formed a deposition layer under the thermal conductivity of molten metal. The dynamic welding process shown in Fig. 5(II) is used to interpret the coupling behavior and transition behavior of liquid metal in this case.

The condition of liquid bridge transition behavior can be discussed as follows:

$$F_{\sigma_1} + G + F\sin\alpha > F_{\sigma_2} \tag{1}$$

where F_{σ_1} is the surface tension between molten metal and upper surface of base metal; G is the gravity of molten metal, F_{σ_2} is the surface tension between molten metal and tip of filler wire while F is the blow force of gas.

Effect of Laser Power on the Characteristics of Deposition Layer

To verify the effect of laser power on the characteristics of deposition layer. In this experiment, laser power was set to vary from 900 W to 1500 W, welding speed and wire feeding speed were 120 mm/min and 100 cm/min respectively while other parameters were equal to Table 2.

As shown in Figs. 6(a) and 7(a), filler wire fed in was melted completely by laser heat and transferred to base metal while the laser power was 900 W. However, the laser heat that transferred to base metal was not enough to form a welding pool, which led to the solid-state heated physical process. Moreover, molten metal transferred to base metal by way of liquid bridge transition behavior and cooled quickly, which caused the weld defect of incomplete fusion. Figures 6(b)–(d) showed that the surface of base metal began to be melted gradually when laser power was larger than 900 W and the molten metal formed by filler wire transferred into welding pool, which could be described clearly in the dynamic welding process(I). As laser power increased, the size of welding pool and penetration increased accordingly, which resulted in the increased absorption rate of laser heat. The volume of molten metal also increased due to this reason. Owing to the sufficient interaction between molten metal and welding pool, stable welding process and well-shaped deposition layer were obtained, the appearance and size of deposition layer with variable laser power are shown in Figs. 7 and 9(a).

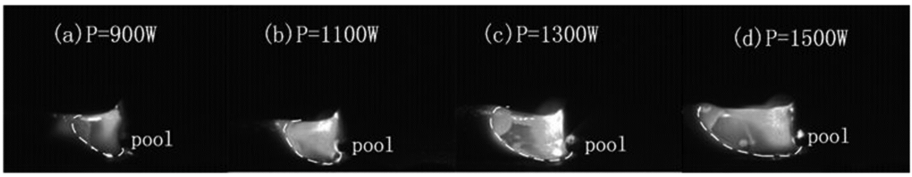

Fig. 6. Transition behavior of liquid metal with variable laser power

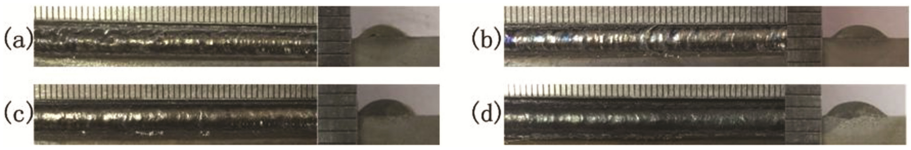

Fig. 7. Appearance and cross-section of deposition layer with variable laser power: (a) $P = 900$ W; (b) $P = 1100$ W; (c) $P = 1300$ W; (d) $P = 1500$ W

Effect of Welding Speed on the Characteristics of Deposition Layer

The welding speed mainly affects the width of liquid bridge and the solidification rate of liquid metal.

As seen clearly in Figs. 8(a)–(b), owing to the higher welding heat-input, filler wire fed in was melted adequately and transferred into welding pool through a relatively wide liquid bridge while welding speed was less than 150 mm/min, which could be interpreted by the dynamic welding process (I). Meanwhile, the welding pool existed relatively for a long time and freezed slowly because of the higher energy of welding pool, which made molten metal interact sufficiently with welding pool. Owing to this, the width of deposition layer increased while the height reduced relatively. With the increase of welding speed, the filler wire fed in was melted slowly by the interaction of molten metal and welding pool, the reason for this was that the welding heat-input transferred to base metal reduced relatively. It is shown in Figs. 8(c)–(d) that molten metal transferred into welding pool through a relatively narrow liquid bridge, which was interpreted by the dynamic welding process(II). Meanwhile, the welding pool existed relatively for a short time and freezed quickly, which made molten metal spread in a narrow area. As a consequence, the width of deposition layer reduced while the height increased with the increase of welding speed, the size of deposition layer with variable welding speed can be seen in Fig. 9(b).

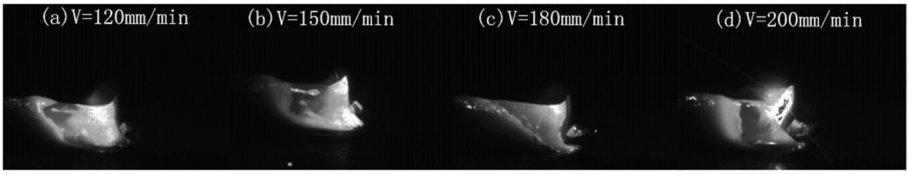

Fig. 8. Transition behavior of liquid metal with variable welding speed

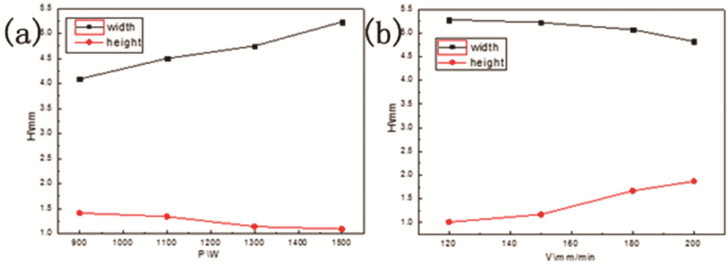

Fig. 9. Effects of welding parameters on the size of deposition layer: (a) effect of laser power on the size of deposition layer; (b) effect of welding speed on the size of deposition layer

Effects of Filler Wire Feeding Speed and Angle on the Characteristics of Deposition Layer

In order to obtain the stable welding process and a well-formed deposition layer, wire feeding speed must be matched well with laser power and welding speed.

On the premise that other things being equal, it is seen in Figs. 10(a)–(b) that the filler wire was fully melted by laser heat and transferred into welding pool while wire feeding speed was less than 150 cm/min, which could be interpreted by the dynamic welding process (I). As the wire feeding speed increased, the heat required to melt filler

wire increased accordingly due to the increased length of wire fed in per unit of time, which resulted in the decreased heat transferred to base metal. As a result, the height of deposition layer increased while the penetration reduced, the appearance and cross-section of deposition layer are shown in Figs. 11(a)–(b). In the condition that wire feeding speed was larger than 150 cm/min, laser heat is not enough to melt filler wire fed in so that unmelted wire inserted into the welding pool. On the one hand, as shown in Figs. 10(c)–(d), unmelted wire was melted fully and formed a deposition layer by the thermal conductivity of molten metal, which was the same as the dynamic welding process (II) discussed in Sect. 3.2. On the other hand, the actual wire feeding speed was smaller than the value set in experiment because of the resistance of welding pool. In consequence, it is seen in Figs. 11(c)–(d) that the height of deposition layer and penetration were almost unchanged.

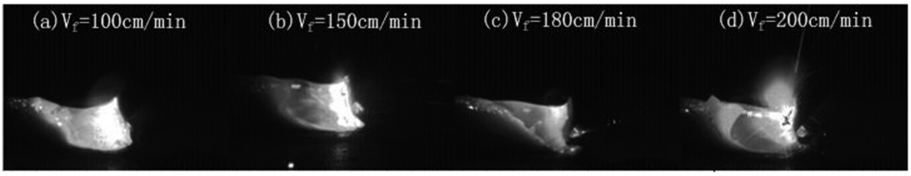

Fig. 10. Transition behavior of liquid metal with variable filler wire feeding rate

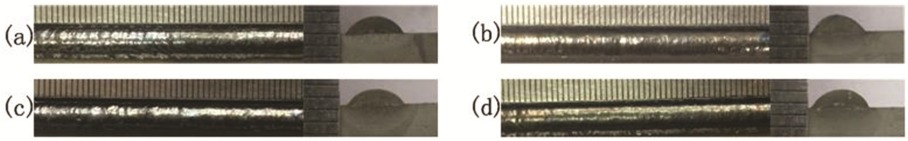

Fig. 11. Appearance and cross-section of deposition layer with variable filler wire feeding rate: (a) V_f = 100 cm/min, (b) V_f = 150 cm/min, (c) V_f = 200 cm/min, (d) V_f = 250 cm/min

As shown in Fig. 12, the wire-feeding angle α is the acute angle between the filler wire and the base metal, and the wire feeding speed V_f can be decomposed into the velocity component V_{f_x} that is perpendicular to the direction of laser beam and the velocity component V_{f_y} which is parallel to the direction of laser beam [6]. V_{f_x} affects the absorption rate of laser heat by changing the length of filler wire fed in per second while V_{f_y} decides the impact action of molten metal on welding pool. As shown in Fig. 13(a), filler wire was melted incompletely while the wire feeding angle was small ($\alpha = 30°$) relatively. The reason for this was that laser heat acted on the unit length of filler wire reduced relatively due to the smaller velocity component V_{f_x} in this case. Moreover, the wire extension was stretched, which caused the deteriorated wire directivity and unstable welding process. With the increase of wire feeding angle, it is showed in Figs. 13(b)–(c) that V_{f_x} decreased while V_{f_y} increased, and filler wire fed in was melted fully by the increased laser heat acted on the unit length of filler wire. Finally, molten metal was transferred into welding pool through the liquid bridge transfer behavior, which could

be described clearly by the dynamic welding process (I). The welding process was stable and the deposition layer was well shaped. Figure 13(d) shows that the filler wire was melted incompletely while the wire feeding angle increased continuously ($\alpha = 75°$). The reason for this was that the length of filler wire along the direction of laser beam increased accordingly. Moreover, the distance between the molten metal and welding pool increased due to the oversized wire feeding angle. As a result, the impact action of molten melt on welding pool became stronger accordingly. It is worth noting that stable welding process and well-shaped deposition layer can be obtained while the wire feeding angle varied from 40° to 70°.

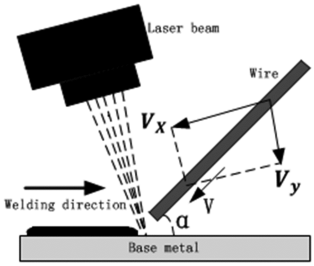

Fig. 12. Schematic diagram of filler wire feeding components

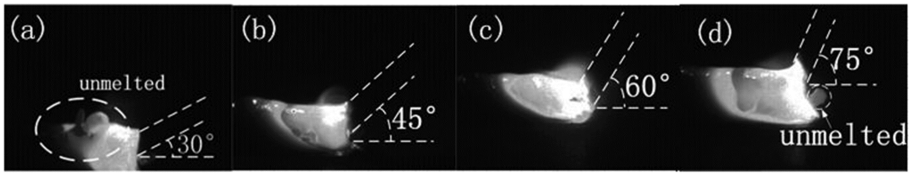

Fig. 13. Transition behavior of liquid metal with variable filler wire feeding angle

4 Conclusions

1. Owing to the different *D*, the transition behaviors of liquid metal were decomposed into three transition behaviors and the liquid-bridge transition behavior was most stable relatively. Two dynamic welding processes can be used to interpret the laser-wire coupling behavior and transition behavior of liquid metal while the *D* was zero.
2. The welding process was solid-state heating physical process while laser power was less than 900 W. With the increase of laser power, the size of welding pool and width of deposition layer increased while the height of deposition layer decreased.
3. The welding speed had a great influence on the width of liquid bridge and the solidification rate of molten metal. Molten metal interacted with welding pool sufficiently when welding speed was less than 150 cm/min. With the increase of welding speed, molten metal freezed quickly; the width of liquid bridge became narrower; the width of deposition layer and penetration decreased while the height increased.

4. The wire feeding rate could be decomposed into the velocity component V_{f_x} that affected the absorption rate of laser heat and the velocity component V_{f_y} that decided the impact action of molten metal on welding pool. With the increase of wire feeding angle, V_{f_x} decreased while V_{f_y} increased. The stable welding process and well-shaped deposition layer can be obtained while the wire feeding angle varied from 40° to 70°.

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