Analysis of Spreading of the Melt in Diode Laser-TIG Hybrid Cladding Process

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Abstract. A diode laser-TIG hybrid cladding process was proposed in this study to make further improvement on wettability and spreadability of cladding layer. Cladding layers fabricated with different heat sources were wire-cutted to observe their cross section so as to characterize the wettability. The role of TIG arc in this process is analyzed and illustrated in detail through the cladding process recorded by a high-speed camera. The functions of TIG arc in this process are elevating thermal input to reduce surface tension and exerting extra forces on the melt to help it spread out.

Keywords: Cladding · Wetting · Contact angle · TIG arc

1 Introduction

In order to obtain components with improved surface performance and extended service life, laser cladding has been applied to deposit high-performance material on the substrate for many years. However, many problems such as balling (the molten cladding material does not spread out and wet the substrate), pore and crack etc. may occur in the process of laser cladding. These unfavorable formations can severely limit the application of laser cladding, especially in the field such as petrochemical and machinery industries which require an excellent formation of cladding layers. Balling is the most undesirable formation among them all, since it will cause porosity and will be obstacle for the fabrication of subsequent tracks of cladding layer. The traditional method to solve this problem is optimizing process parameters or adding a trace of active elements to reduce the surface tension of molten cladding material. A. Simchi have studied the effects of laser sintering process parameters and reported that balling can be avoided by reducing scanning spacing [1]. J.P. Kruth et al. found that the element P can lower the surface tension of the melt, thus improving wetting, and balling can be suppressed by applying very high pulse energy [2]. But these methods bring up higher demands for powder manufacturing and laser devices, and improvements on wetting by these methods are limited. As the optimizing of powder components comes to meet its limitation, it is time to improve wetting in another way.

By the inspiration of laser-TIG hybrid welding, which has shown clear advantages such as increased welding speed and penetration [3], a diode laser-TIG hybrid cladding

S. Chen et al. (eds.), *Transactions on Intelligent Welding Manufacturing*,
Transactions on Intelligent Welding Manufacturing, DOI 10.1007/978-981-10-5355-9_13

process was proposed in this study. High power diode laser has been proved to be an ideal heat source for cladding because of its high absorption degree by metals and high efficiency [4], compared with the early adopted laser in cladding such as CO_2 laser or Nd:YAG laser. But with higher power comes more intensive thermal input and higher crack tendency [5]. A TIG arc was coupled with diode laser to reduce the required laser power. It can also change the heat distribution and forces exerted on the melt. The functions of the two heat sources in this process are going to be analyzed in this paper.

2 Experimental

A 1.5 kW Focus Light diode laser and a Panasonic TIG welding machine were used in this experiment to melt pre-placed Ni60 powder on Q235 steel. The cladding process was recorded by a high-speed camera manufactured by PointGrey from an angle perpendicular to the scanning direction. The experimental setup of this system is shown in Fig. 1.

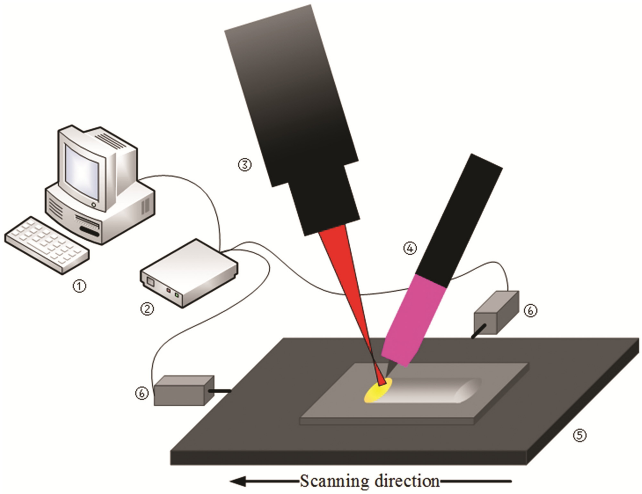

Fig. 1. Schematic of the experimental setup: ① computer for controlling the work table movement; ② stepper motor driver; ③ diode laser; ④ TIG torch; ⑤ worktable; ⑥ stepper motor

Ni60 powder was pre-placed on the Q235 plate with the thickness of 1 mm by a laying powder device. The composition of Ni60 powder used in this experiment is shown in Table 1. Q235 plates were polished to remove the oxide film before cladding. The cladding layers a, b, c and d were obtained by laser, TIG arc and laser-TIG hybrid heat source, respectively. The process parameters used in this experiment is shown in Table 2. After cladding, specimens with dimensions of 15 mm × 15 mm × 4 mm were wire-cutted from the cladded Q235 plates. And then specimens were polished and etched by nitric acid alcohol solution so as to observe the contact angle.

Table 1. Composition of Ni60 powder

Element content/wt.%	C	Cr	Si	W	Fe	B	Ni
Ni60	0.8	15.5	4.0	3.0	15.0	3.5	Bal.

Table 2. Process parameters

Sample number	Laser power (W)	Defocusing distance (mm)	TIG arc current (A)	Shielding gas flow rate (L/min)	Scanning speed (mm/s)
a	–	–	50	3	2
b	1000	+20	–	–	2
c	1500	+20	–	–	2
d	1000	+20	50	3	2

3 Results and Discussion

Wetting of liquids on surfaces is a complex phenomenon, due to its sensitivity to a great number of factors. Contact angle is a well-accepted measure to characterize the degree of wetting of a surface by a liquid. It is defined as the angle between tangent drawn at the triple point between the three phases and the substrate surface, as shown in Fig. 2. A generally accepted theory is that the smaller the contact angle, the better the wettability. Wettability in this study was characterized by the contact angle from the cross section and macroscopic appearance from above.

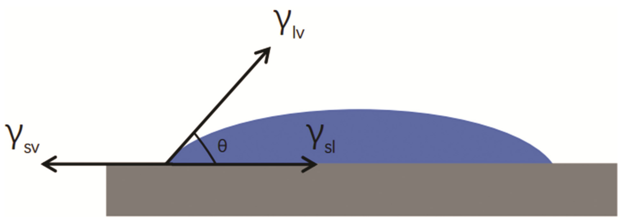

Fig. 2. Illustration of contact angle

The four single track cladding layers fabricated with TIG arc, laser and laser-TIG hybrid heat source and their cross sections are shown in Fig. 3. It can be seen in Fig. 3(a) that the cladding layer fabricated with a 50A TIG arc is discontinuous mainly due to the lack of thermal input. Besides, the arc force and shielding gas flow blew away a large amount of powder. In that case, only a small amount of powder was melted and then attached to the substrate. That is the main reason why TIG arc is not a suitable heat source for pre-placed powder cladding unless the pre-placed powder is mixed with special binder to be adhered to the substrate, which will make the process far more complex. Figure 3(b) shows the cladding layer obtained by a 1000 W diode laser, the melt did not spread out well, resulting in high contact angle and bad formation on the edge of cladding layer. This would present an obstacle to the subsequent deposition of material in multi-track cladding. It is a common observation that the surface tension of the liquid decrease with increase in temperature. Hence wettability should improve in any systems with increase in temperature [6]. This can explain why the formation of cladding layer fabricated with a 1500 W diode laser, as shown in Fig. 3(c), is better. However, cracks can be found on the cladding layer. The trapezoid temperature gradient of diode laser, as shown in Fig. 5, and comparatively high thermal input are the main reasons why cracks occurred. Besides, an obvious penetration into the substrate can be found from the cross section. This indicates dissolution of the substrate in the melt occurred, which can reduce the observed contact angle by decreasing the surface tension of the liquid and forming a crater under the melt [7]. Substrate melting is necessary for cladding, since it indicates a metallurgical bond is formed between cladding layer and substrate. However, with substrate melting comes the dilution of cladding layer by substrate, which will compromise the cladding layer performance. Hence keeping the dilution rate as low as possible is vital to the cladding layer performance. A perfect dilution rate was obtained by laser-TIG hybrid cladding process, as shown in Fig. 3(d). Moreover, the contact angle is far smaller than that in Fig. 3(b), even smaller than that in Fig. 3(c), which indicates an excellent wettability.

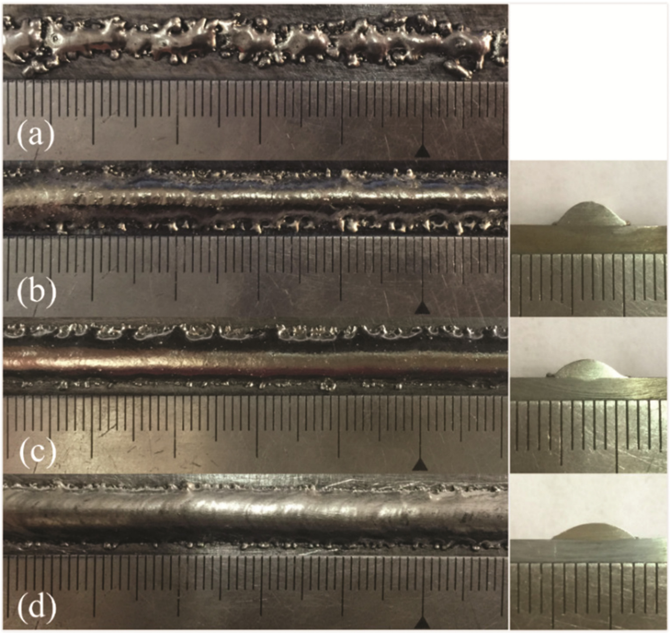

Fig. 3. The macroscopic appearance and cross section of cladding layer fabricated with different heat sources: (a) cladding layer obtained by a 50A TIG arc; (b) cladding layer obtained by a 1000 W diode laser; (c) cladding layer obtained by a 1500 W diode laser; (d) cladding layer obtained by a 50A TIG arc coupled with a 1000 W diode laser

The classic Young's equation gives the basic formulation of contact angle in terms of interfacial tensions:

$$\cos\theta = \left(\gamma_{sv} - \gamma_{sl}\right)/\gamma_{lv} \tag{1}$$

where γ_{sv}, γ_{sl} and γ_{lv} are the interfacial tension of the solid/vapor, solid/liquid and liquid/vapor interface, respectively, and θ is the equilibrium contact angle.

According to this formulation, a good wettability can be achieved when γ_{sv} is as large as possible while γ_{sl} and γ_{lv} are as small as possible. γ_{sv} in this equation is considered an invariant constant for given substrate and atmosphere. γ_{sl} and γ_{lv} need to be focused on, in order to improving wettability. The most important factors that affects the solid/liquid interfacial tension γ_{sl} is the formation of reaction products at solid/liquid interface. Most interfacial products can improve wetting and dramatically reduce the contact angle. As for the liquid/vapor interfacial tension γ_{lv}, the factor that influences it most is temperature. The influence of different heat sources on the heat distribution and forces exerted on the melt is going to be analyzed in terms of the two interfacial tensions, γ_{sl} and γ_{lv} in the following paragraphs.

From the cladding process recorded by a high-speed camera, as shown in Fig. 4, the different wetting and spreading process can be analyzed to illustrate why the introduction of TIG arc can greatly improve wetting while maintaining a smaller contact angle.

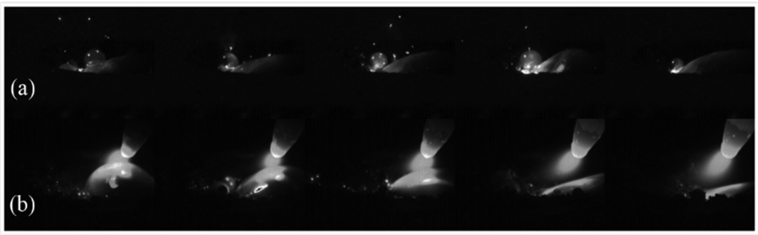

Fig. 4. Screenshots extracted from the video recorded by a high-speed camera: (a) a 1000 W diode laser cladding; (b) a 1000 W laser coupled with a 50A TIG hybrid cladding

In the 1000 W diode laser cladding process, as shown in Fig. 4(a), powder was melted into small balls by laser first. And then, these small balls gathered together and became a bigger ball. With the movement of the workpiece, the molten ball spread out and eventually became a single-track cladding layer.

Since diode laser irradiates a rectangular-shape spot, a trapezoid temperature gradient can be formed, as shown in Fig. 5 which led to a low surface tension in the middle while high surface tension on both sides of the melt. The presence of surface tension gradient, caused by temperature gradient, can naturally cause a flow from the low surface tension area to high surface tension area, as shown in Fig. 6, since a liquid with high surface tension pulls more strongly on the surrounding liquid than one with a low surface tension. That is what have been called Marangoni effect. Because of this effect, the melt tended to spread out. It need to be noted that, although the effect of gravity is normally not taken into account in wetting process according to the many investigation, gravity in this experiment cannot be neglected. Gravity helped the melt spread and formed a plane contact instead of a spot contact with the substrate, which accelerated the thermal conduction between the melt and substrate. With the high temperature gradient mentioned above and the accelerated thermal conduction, the temperature of the melt decreased rapidly and surface tension γ_{lv} increased. These are the main reasons why contact angle of the cladding layer obtained by laser cladding is relatively high.

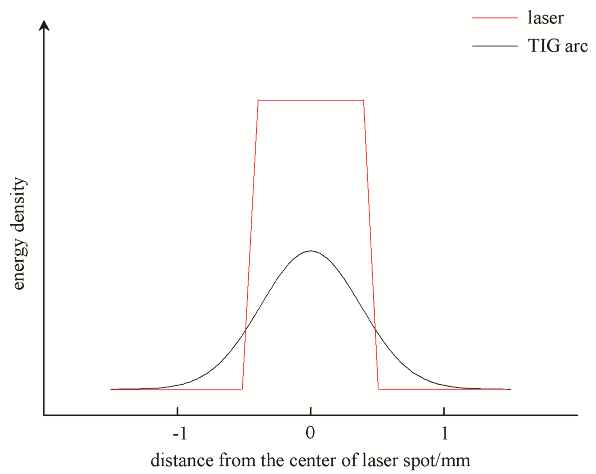

Fig. 5. Heat distribution of diode laser-TIG hybrid cladding process

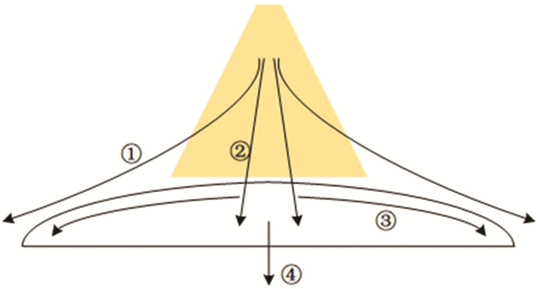

Fig. 6. Schematic of the forces exerted on the melt and the Marangoni flow in the melt: ① plasma flow force and shielding gas flow; ② axial component of electromagnetic pinch force; ③ Marangoni flow arising from surface tension gradient; ④ gravity

In the hybrid cladding process, as shown in Fig. 4(b), the TIG arc was ignited after a molten ball was formed and it quickly flattened the molten ball. In this process, laser melted powder ahead while the following TIG arc helped to spread out the liquid metal.

When TIG arc was introduced in this process, it can exert extra forces on the melt. According to the electromagnetic pinch effect due to the same direction electricity in arc column, there would be an electromagnetic pinch force on the arc, which would yield an axial component to flatten the melt. The plasma flow force and shielding gas flow force also had a positive effect on the spreading. The schematic of the three forces is illustrated in Fig. 6. These forces can also stir the weld pool to improve its wetting. Laser in this process can stabilize and compress the arc to make arc force more concentrated. This is the how TIG arc improves wetting and spreading in the force aspect.

While in the heat aspect, the most obvious one is that the introduction of TIG arc elevated the thermal input and reduced surface tension γ_{lv} of the melt. TIG arc also affected the heat distribution on the melt. Since TIG arc is a Gauss heat source, it altered the unfavorable heat distribution to a complex but mild distribution, as shown in Fig. 5. There was no steep gradient on both sides of the laser spot, which helped to slow down the heat conduction from processing area to nearby area. Hence the temperature of the melt was comparatively high and surface tension was low. With all the lowered surface tension mentioned above, smaller contact angle can be formed. Besides, the elevated thermal input also intensified interfacial reaction which yielded interfacial products to reduce γ_{sl} and improved wettability. The mild heat distribution also helped to reduce crack tendency.

4 Conclusions

Wetting of a solid by a liquid is of great application importance and affected by a large number of factors including liquid properties, substrate properties and system condition, and wettability is generally measured in terms of contact angle. High power laser must be applied in order to obtain cladding layers with a smaller contact angle since the surface tension gradient, or so called Marangoni stress, resulted from temperature gradient is the only driving force for spreading in laser cladding. However, the attendant high dilution rate and crack tendency are inevitable. A TIG arc can be coupled with laser to reduce required laser power and exert extra forces on the melt to help it spread out. The main function of TIG arc in laser-TIG hybrid cladding process can be explained in two aspects, which is force and heat. In force aspect, it is mainly about the forces that helped to flatten the spherical melt. While in heat aspect, the introduction of TIG arc increased thermal input and reduced liquid surface tension.

Acknowledgment. This work was supported by the National Natural Science Foundation of China (51675256).

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