Optimization of Laser Deep Penetration TIG Hybrid Welding Technology for Stainless Steel

Jialei Zhu, Wei Li, Zhibo Li, Xiangdong Jiao, Cong Feng, and Kai Wang

Abstract The experiment is carried out on the stainless steel with a thickness of 4 mm. A laser deep penetration TIG hybrid welding machine is used in hybrid welding. The influence of main process parameters on weld forming is analyzed, and high-quality weld joint is obtained. The results show that to ensure that other welding parameters remain unchanged. At the space 0–2 mm, the defocus −1.5–0 mm, weld is good. At the laser power 3 Kw, the arc current 270 A, the velocity 1.2 m/min, the tensile strength of the joint reached up to 99.44%, and hardness is higher than base metal.

Keywords Laser-arc hybrid welding · Welding speed · Stainless steel

1 Introduction

Stainless steel has a decisive position in the industrial field [1]. Among them, austenitic stainless steel, as the main steel, has good corrosion resistance, good mechanical properties, and strong moldability. As a typical austenitic stainless steel, 304 stainless steel has a wide range of applications in engineering structures such as nuclear power, underwater oil production platforms, and subsea oil pipelines [2]. Scholars at home and abroad have made a detailed study on the welding methods and welding characteristics of 304 stainless steel. Li et al.'s finds of Harbin Institute of Technology [3] carried out an underwater wet welding test on 304 stainless steel using self-protected nickel strip flux-cored wire and analyzed the microstructure and

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mechanical properties of the welded joint; Han et al. find [4] the thickness of 304 stainless steel plate with 5 mm thickness was welded by laser-MIG hybrid welding. The effect of laser-wire distance on weld formation and mechanical properties was studied, and the mechanism of arc on microstructure and microhardness of weld was analyzed. The results show that the laser-wire distance affects the synergistic effect between the laser heat source and the arc heat source and the stability of the droplet transfer. When the laser-wire distance is 1 mm, the droplet transfer is stable and the weld is well formed. Su et al. finds of Tianjin University [5] used pulse melt inert-gas welding (MIG) to weld 304 stainless steel. The signal acquisition system and high-speed camera perform synchronous acquisition to study the droplet transition. The results show that the addition of laser improves the welding quality and welding efficiency; Zhang et al. finds of Tsinghua University [6] adopted laser-MIG arc hybrid welding method, and the research object was SUS444 ferrite with gap of 0.5 mm and thickness of 1 mm. The butt joint has a good welding seam forming quality, and the limit welding speed of penetration can reach 12 m/min, while the limit welding speed of the lap joint is 5 m/min. In 1997, the Commonwealth Scientific and Technological Research Organization of Australia improved TIG welding and invented the keyhole TIG (K-TIG) welding method [7]. K-TIG welding has a tungsten current-carrying capacity of 300 A or higher [8]. It can realize single-sided welding and double-sided forming on 3–6 mm stainless steel plates without gaskets. The welding process is stable [9, 10]. K-TIG welding is a small hole welding similar to plasma welding, but K-TIG welding equipment is less expensive than plasma arc welding equipment, welding costs are low, and welding automation is easier to achieve [11]. Laser deep penetration TIG hybrid welding is similar to laser plasma hybrid welding, and its main advantage is high-speed welding of thin plates. With regard to this type of hybrid welding, domestic scholars have also made related research. Li et al. finds of Hunan University of Science and Technology [12] aimed at high-power laser deep penetration welding of 304 austenitic stainless steel, the quality of the weld is poor, and a “nail head” is easily formed. At the same time, the welding speed, defocus amount, and side blow protection were studied. The influence of the air nozzle diameter on the weld morphology was also studied. The effect of adding active sulfur powder on the weld pool and the effect on the formation of the weld seam were also studied. The results show that the optimization of welding process parameters and the addition of active powder are the effective method of welding to controlling “nail heads”. This paper mainly studies the process optimization of laser deep-melting TIG arc hybrid high-speed welding of stainless steel.

Table 1 Chemical composition of 304 stainless steel

Grade	C	Si	Mn	P	S	Cr	Ni
0Cr18Ni9	0.0436	0.5020	1.1274	0.0301	0.0021	17.245	8.0520

Table 2 Mechanical properties of 304 stainless steel

Project	Stretching test			Hardness test
Property	Yield strength 0.2	Tensile strength	Elongation	HV
Value	274	642	58%	164

2 Experimental Program

2.1 Experimental Materials

The experimental material used a 4 mm-thick 304 stainless steel plate with a plate size of 150 mm × 130 mm and a thickness of (4 ± 0.1) mm. The chemical composition and mechanical properties of 304 stainless steel are shown in Tables 1 and 2.

2.2 Experimental Equipment and Methods

The laser deep-melting TIG hybrid welding experimental system is mainly divided into four parts: laser-integrated equipment, deep-melting TIG welding equipment, motion table, and high-speed camera acquisition equipment, as shown in Fig. 1. Among them, the laser equipment is the YSL-4000 laser produced by the United States IPG company, the largest fiber laser manufacturer. Panasonic YC-500WX welding machine is used for deep-melting TIG welding machine, and the rated current

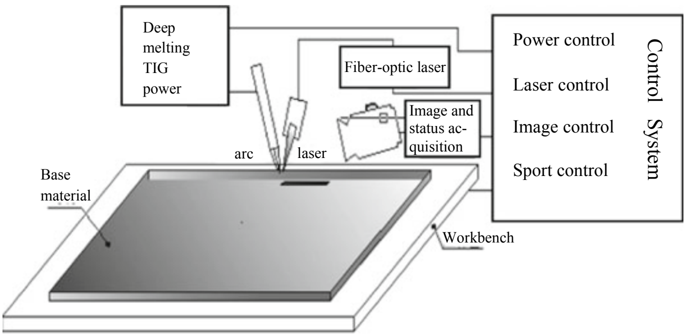


Fig. 1 Experiment system of laser deep TIG hybrid welding

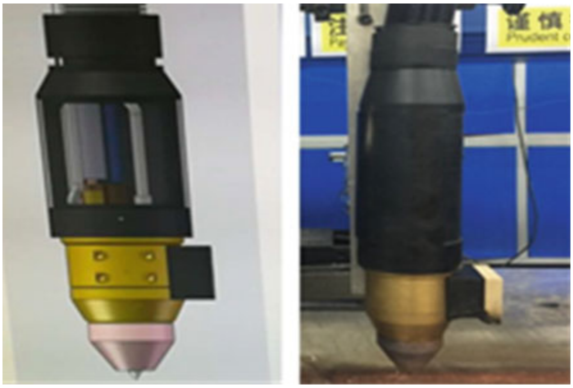


Fig. 2 Three-dimensional map and physical map of deep TIG welding torch

is 500 A. The welding torch is a deep-melting TIG welding torch independently developed by Tangshan Kaiyuan, as shown in Fig. 2.

2.3 Experimental Process

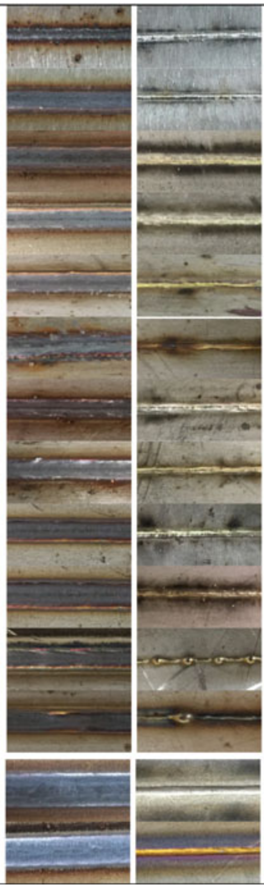
A schematic diagram of the welding process is shown in Fig. 1. The welding torch and laser are compound with a range axis, each inclined at 15°. The energy output of the two is always on a straight line. The laser is in the front, and the arc is behind. The different welding parameters are grouped in Table 3. The variables in the hybrid process are laser power, welding current, welding speed, defocus amount, and heat source distance.

3 Experimental Results and Analysis

3.1 Influence of Process Parameters on Weld Formation

For 4 mm stainless steel laser deep-melting TIG single-sided welding and double-sided forming process, the matching value of laser power and arc current is very important. For example, Chen et al. of Huazhong University of Science and Technology [13] studied the welding penetration of MAG and YAG laser hybrid welding at different currents with laser power. Experiments have concluded that when the laser power exceeds 1.5 Kw and the arc current is 157 A, the maximum penetration depth is obtained. However, when the current is 200 A, the obtained penetration is equivalent to that obtained by laser welding. In addition, the laser-arc hybrid welding with a large welding current does not have a tendency to reduce welding spatter and a tendency to increase penetration during the welding process. It can be

Table 3 Experimental parameters

Number	Laser power P_L *Kw*	Welding current I *A*	Welding speed V *m/min*	Defocus amount Δf *mm*	Heat source distance D_{LA} *mm*	Heat Input *KJ/mm²*	Welding surface forming
1	4	0	2	0	0	0.12	
2	4	150	1.8	0	0	0.20	
3	4	180	2	0	0	0.18	
4	4	180	2	0	1	0.18	
5	4	180	2	0	2	0.18	
6	4	180	2	0	3	0.18	
7	4	180	2	0	4	0.18	
8	4	180	2	0	5	0.18	
9	4	180	2	-1.5	0	0.18	
10	4	180	2	-5	0	0.18	
11	4	180	2	1.5	0	0.18	
12	4	180	2	5	0	0.18	
13	3	270	1.2	0	0	0.40	
14	2.5	250	1	0	0	0.34	

seen that there is a large difference in parameter adjustment between laser-arc hybrid welding and conventional welding methods, which requires a detailed exploration. In addition, the two heat sources of laser and deep penetration TIG belong to deep penetration welding of small holes, and the recombination process of the two is more complicated.

As can be seen in Table 3, the experiment obtained a total of four sets of valid data, and the weld surface was free of any defects: $P_L = 4$ Kw, $I = 150$ A, $V =$

Table 4 Results of tensile testes

Sample No	Morphology after breaking test	Tensile strength /*MPa*	Achieving base material performance percentage /%	Fracture location
2		614.688	95.75%	Heat affected zone
3		635.42	99.12%	Base material
13		638.333	99.44%	Base material
14		630.56	98.22%	Base material

1.8 m/min; $P_L = 4$ Kw, $I = 180$ A, $V = 2$ m/min; $P_L = 3$ Kw, $I = 270$ A, $V = 1.2$ m/min and $P_L = 2.5$ Kw, $I = 250$ A, $V = 1$ m/min.

On this basis, the influence of the distance between the heat source and the amount of defocus on the formation of the weld seam is explored. The experimental data are 5–13 groups. When other welding parameters are kept constant, the welding seam is well formed when the heat source distance is 0–2 mm; when the heat source distance is 3 mm, the spatter is large, but the formation is good; when the heat source distance is 4–5 mm, the concave of the front side of the weld is increased. There are spatters during welding, but the back penetration is good; when the spacing gradually increases, the back penetration starts to be uneven. When other welding parameters are not changed, when the defocus amount is −1.5–0 mm, the weld seam is well formed.

3.2 *Tensile Properties of Welded Joints*

Table 4 shows the test results of the tensile properties of the welded joints of the above four sets of valid data. It can be known from the table that three groups of the four effective parameters of the welded joint are subjected to the tensile test fracture position of the base metal, and the tensile strength can reach a maximum of 99.44% of the performance of the base metal.

3.3 *Hardness Analysis*

The hardness of a material refers to the ability of a metal to resist elastic deformation, plastic deformation, or cracking within a small surface or volume. It can reflect a

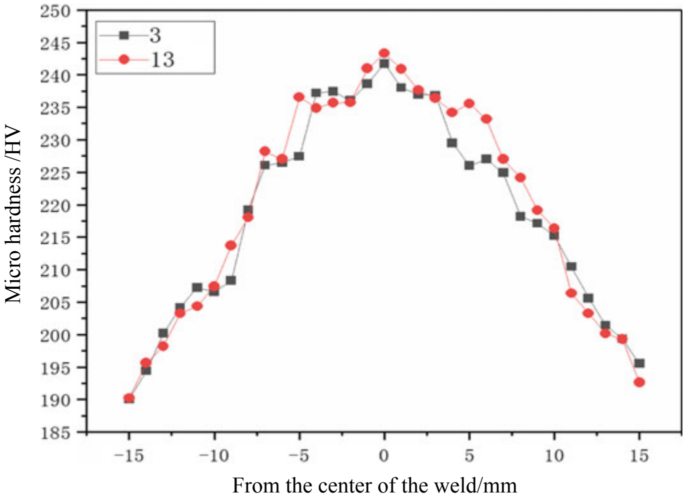


Fig. 3 Hardness graph of welded joint

series of different mechanical performance indicators such as elasticity, strength, plasticity, and toughness. In addition to the above mechanical properties, the hardness of welded joints can also characterize the uniformity of the weld structure distribution after welding and the distribution of some special phases [14]. Figure 3 shows the hardness distribution of 304 stainless steel welded joints in groups 3 and 13.

It can be seen from Fig. 3 that the hardness of the portion near the center of the weld in the laser deep-melting TIG welding joint is the highest, the hardness away from the center of the weld gradually decreases, and the heat-affected zone 3 reflected by the image is wider, more than about 1 cm. Corresponding to the morphology of composite welded joint. The weld seam has a higher hardness than the base metal.

4 Conclusion

1. For laser deep penetration TIG hybrid welding of 4 mm stainless steel, the matching value of laser power and arc current is very important. In this experiment, a total of four effective parameters were obtained.
2. Under the condition that other welding parameters are unchanged, the welding seam is well formed when the heat source distance is 0–2 mm and the defocus amount is −1.5 – 0 mm.
3. The hybrid welding parameters are obtained when the laser power is 3 Kw, the arc current is 280 A, the welding speed is 1.2 m/min, or the laser power is 4 Kw, the arc current is 180 A, and the welding speed is 2 m/min. The welded joint has a tensile strength of more than 99% of the base metal and a higher hardness than the base metal.

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