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Comparison of processing window in full penetration laser welding of thick high-strength steel under atmosphere and sub-atmosphere

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HIGHLIGHTS

- Full penetration laser welding was performed under atmosphere and sub-atmosphere.
- There was a significant change of cross section with a decrease in ambient pressure.
- The processing window of laser welding under atmosphere was very narrow.
- Laser welding under vacuum showed excellent weld quality and wide processing window.

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ABSTRACT

In order to show the advantages of laser welding under vacuum or sub-atmosphere in fabrication of thick section structures, fiber laser welding of thick high-strength steel was performed under atmosphere and sub-atmosphere, respectively. The effect of ambient pressure on penetration depth and cross section was investigated, and the processing window in full penetration welding of 10 mm thick high-strength steel under atmosphere and sub-atmosphere was compared. The results showed that the processing window of full penetration laser welding under atmosphere (101 kPa) was very narrow because of the appearances of various weld defects. Full penetration sound welds could only be achieved in a small processing window near the parameter of 10 kW laser power and 1.5 m/min welding speed. It was found that there was a sharp increase in penetration depth and a significant change of cross section from "nail-head" shape to parallel shape with a decrease in ambient pressure. Full penetration welds joint under sub-atmosphere (0.1 kPa) displayed high weld quality with extreme smooth surface appearances. The processing window under sub-atmosphere with laser power ranging from 4 kW to 6 kW and welding speed ranging from 0.5 m/min to 1.5 m/min was much wider than that under atmosphere.

1. Introduction

Thick section structures have been widely applied in many industries, such as shipbuilding, high speed train, lifting equipment, wind power tower, oil transportation pipe line and nuclear [1–3]. Welding is an important production step in fabrication of thick section structures and components. Currently, the most prevalent thick section welding process includes shielded metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) and submerged arc welding (SAW) [4,5]. In general, these traditional arc welding processes can satisfy the basic requirements for weld quality. However, low efficiency, numerous time consuming and extensive bevel groove preparation are often associated with multi-pass arc welding of thick structures. Moreover, low welding speed, long welding time and high heat input lead to significant distortion and residual stress. In contrast, high energy beam welding (electron beam welding and laser beam welding) potentially offers a good option for welding thick structures. The high energy beam with the ability to penetrate deeper into materials makes it possible to weld thick structure in full penetration with a single pass and reduce the total heat input [6,7].

Alali et al. [8] developed full penetration electron beam welding of 20 mm thick AISI 316L stainless steel. Defect-free sound weld profile was obtained and the microstructure and mechanical properties were investigated. Vasileiou et al. [9] performed electron beam welding of 30 mm thick ferritic steel plates using a single pass. The welds were radiographed to demonstrate that they were free of significant defects according to the acceptance criteria in ASME IX:2013. The other previous studies [10–12] have also demonstrated that electron beam was able to weld materials over 50 mm thickness and obtain acceptable weld performance. Electron beam welding has obvious advantages in

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penetration depth and weld quality. However, the requirement of fine vacuum leads to high cost and consumption of time. In addition, it needs additional protection of X-rays induced by the decelerated high speed electron beam. As another kind of high energy beam welding, laser welding has already be widely used in industry due to the advantages of high production efficiency and high flexibility [13,14]. Recently with the development of modern laser systems (fiber laser or disk laser), high power laser welding attracts more and more attention and becomes a new and superb option for welding thick structures. Lots of trails have been done to weld thick structures with a single pass using a high power laser. Zhang et al. [15] developed a deep penetration laser welding process of thick stainless steel with a 10 kW fiber laser. They stated that the focal position strongly affected the high power fiber laser welding of thick plates and a sound full penetration joint was achieved only under the conditions of a critical region of welding speed, a proper focal position and a good gas protection. Kaplan et al. [16] also encountered the problem of narrow processing window while welding thick plate using a 15 kW fiber laser. They reported that although narrow sound welds could be achieved, heavy spatter ejection along with underfill could take place at the top and root side, particularly for high power density and low line energy. In order to obtain deeper penetration and higher weld quality, 2G position [17,18] and electromagnetic weld pool support [19,20] were also used in high power laser welding. The results showed that the improvement brought by 2G position and electromagnetic field was still limited. Although high power laser welding gets rid of the limitation of high vacuum, the narrow process window and various defects make it difficult to apply for welding of structures with more than 10 mm thickness.

Recently, laser welding under vacuum or sub-atmosphere was developed in order to unite the advantages or eliminate the disadvantages of electron beam welding and laser welding. Many studies [21–25] were conducted to present the effect of ambient pressure on penetration depth in laser welding. It has been proved that the penetration depth increased with a decrease of ambient pressure. Moreover, it was also found that the penetration improvement became independent of ambient pressure below some critical pressure. Based on the present reports about laser welding under vacuum, the critical pressure was in the range of 0.1–10 kPa. In addition, the weld bead achieved by laser welding under vacuum was high quality with deep penetration, which is similar to that obtained by electron beam welding, and the “vacuum” should be defined more broadly in this context. It means that a deep penetration sound weld joint close to electron beam weld joint could be achieved in a low vacuum using a high power laser. Compared with electron beam welding, the cost and time for pumping vacuum were minimized, and the equipment could also be simplified. Therefore, laser welding under vacuum or sub-atmosphere would be a promising technology for welding thick structures. The present studies about laser welding under vacuum mainly focused on the effect of ambient pressure on penetration depth and weld cross-section profiles in partial penetration. The study is scarce in full penetration laser welding under vacuum. Moreover, the comparative study of processing window in full-penetration laser welding under atmosphere and sub-atmosphere is more scarce. In this paper, full penetration laser welding of 10 mm thick high-strength steel was performed under atmosphere and sub-atmosphere. The processing window of sound welds obtained under atmosphere and sub-atmosphere was compared.

2. Materials and experimental procedure

2.1. Materials

High-strength steel with thickness of 10 mm and 20 mm was used in this study. Its chemical composition is listed in Table 1. And its yield strength and ultimate strength are about 780 MPa and 900 MPa, respectively. The sample size was 150 mm × 50 mm. Before laser welding experiment, the vicinity of weld track on the specimen surface was treated by mechanical wire brushing to eliminate the oxidation film. And then the acetone was used to clean surface contamination. After laser welding experiment, metallographic specimens were cut transverse to the welding direction from the stable part in the middle of the weld by wire electrical-discharge machining. And the metallographic samples were prepared according to standard procedures. They were ground, polished, etched with a solution of 5 ml nitric acid and 95 ml ethanol for 10 s, and then observed under an OLYMPLUS GX71 light microscope.

Table 1
The chemical compositions of high-strength steel (wt.%).

C	Si	Mn	P	S	Ni	Cr	Mo	Fe
0.11	0.25	0.57	0.010	0.008	4.47	0.60	0.040	Bal.

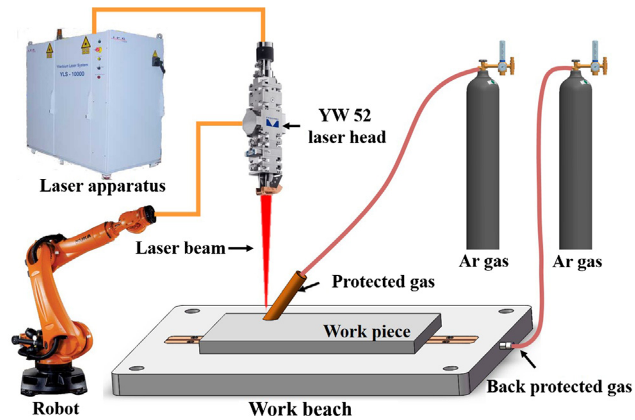

Fig. 1. Schematic illustration of conventional laser welding under atmosphere.

2.2. Conventional laser welding process under atmosphere

Schematic illustration of conventional laser welding under atmosphere is shown in Fig. 1. A continuous wave fiber laser apparatus (IPG Photonics: YLS-10000) with 1070 nm wavelength and 10 kW maximum output was used in this study. A laser welding head (Precitec Group: YW 52) with a collimation lens of 150 mm focal length and a focusing lens of 300 mm focal length was mounted on an industrial robot (KUKA Robot Group: KR 16). The laser beam was optically delivered to laser welding head with a fiber core diameter of 200 μm. The laser head magnification of 2 corresponds to a theoretical focal spot of 400 μm. Argon gas was used to protect both the top and back surface of weld pool. The top protection gas was blown out through a cooper tube with a flow rate of 20 L/min. The back protection gas was blown into a shield channel beneath the specimens with a flow rate of 15 L/min. According to previous trials and other published result [4], the focus position was fixed at -8 mm (below the work piece). Full penetration bead-on-plate laser welding of 10 mm thick high-strength steel was performed at various laser powers and welding speeds in this study.

2.3. Laser welding under vacuum or sub-atmosphere

Schematic illustration of laser welding under vacuum or sub-atmosphere is shown in Fig. 2. The laser apparatus, industrial robot and laser welding head were the same as those used under atmosphere. A simple vacuum chamber was built in order to carry out laser welding under vacuum. A workpiece handling with an axial motion with a maximum shift of 300 mm was fixed in the chamber to carry the workpiece. A quartz glass was installed on the vacuum chamber as a coupling-in window to couple laser into chamber. The vacuum chamber could achieve a minimum pressure of 0.1 kPa by a 2XZ-8D vacuum