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Research on the microstructure and properties of laser-MIG hybrid welded joint of Invar alloy

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ABSTRACT

In order to solve the problem of large deformation, low production efficiency and high tendency of hot cracking in welding 19.05 mm thick plates of Fe36Ni Invar alloy, laser-MIG hybrid multi-layer welding technique (LMHMW) has been developed. To investigate the influence of different welding parameters on the joint properties, optical microscope observation, SEM, EDS and microhardness measurement were conducted. Experimental results illustrated that different matching of welding parameters significantly affected the depth-to-width ratio, formation of defects and HAZ width. Besides, weld zone were consisted of two regions according to the different grain shape. The region near center of weld seam (region 1) was columnar dendrite induced by laser, while the region far away from weld seam center (region 2) was cellular dendrite which was mainly caused by MIG arc. The peak value of microhardness appeared at the center of weld seam since the grains in region 1 were relatively fine, and the lowest hardness value was obtained in HAZ. In addition, results showed that the sheets can be welded at optimum process parameters, with few defects such as, surface oxidation, porosity, cracks and lack of penetration in the welding seam: laser power of backing weld P = 5500 W, welding current I = 240 A, welding speed v = 1 m/min. laser power of filling weld P = 2000 W, welding current I = 220 A, welding speed v = 0.35 m/min. laser power of cosmetic weld P = 2000 W, welding current I = 300 A, welding speed v = 0.35 m/min.

1. Introduction

With the properties of minimum thermal expansion coefficient, low cost, excellent structural stability and vacuum stability, Fe36Ni Invar alloy has been generally considered as a potential mold material with extensive applications in aerospace field [1–6]. However, welding thick plate over 15 mm is a key and difficult technology in Invar alloy mold manufacture industry [7]. Welding methods appeared in recent years such as narrow gap arc welding, vertical gas electric welding and electron-beam welding are difficult to be popularized and applied in welding thick plates, due to the poor material adaptability, difficult technology and high requirements for equipment [8–12]. Therefore, hybrid welding, which couples advanced laser beam and traditional arc source into one process, has shown great advantages and became more and more widely used in welding thick plate [13,14]. The combination of the two heat sources in a single welding process synergistically benefits the advantages and overcomes the drawbacks of each individual heat source [15,16]. Not only in the case on increasing penetration and welding speed has been the reason for experimenting and introducing this technology to applications [17,18]. For these advantages, laser-arc hybrid welding technology has received significant attention in recent years [19,20].

However, when two techniques are coupled, the number of process parameters is large and therefore it is difficult to optimize in order to achieve the desired weld quality and speed [21]. Many operating parameters have been studied extensively to better understand and gain more knowledge about their influences on the welding process. Kim et al. designed a coaxial weld monitoring system for hybrid welding to obtain reliable images. Experiments with varying laser power, welding speed, and arc current were carried out to identify the influence of the process variables on the bead width [22]. Hu et al. optimized the welding groove size of thick plate by studying the interaction between arc and plasma. Besides, 28 mm thick steel plates were welded with four layers by laser-double MIG (metal inter-gas welding) hybrid welding.

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The results showed that the proposed procedure could realize the jointing of thick section steels with high efficiency and good quality [10]. An innovative hybrid laser-arc welding technique was developed by Wahba et al. to one-pass weld 25 mm thick plates in I-butt joint configuration. A square groove butt joint was prepared with 2.5 mm air gap and cut-wire particles were inserted into the gap. Then, hybrid welding was performed. Results showed that the weld seam had good mechanical properties and few defects. This technique was then successfully applied to double-side weld 50 mm thick I-butt joints [23]. Zhen et al. summarized the outstanding advantages of laser–arc hybrid welding by comparing with welded joint of traditional MAG (metal active gas arc welding) welding, and realized the welding of 16 mm thick plates of weathering steel S355J2W+N in three-layer and three-pass. It was revealed that the transverse tensile strength, yield strength and elongation rate of the hybrid welded joint were almost the same as the base metals under rational parameters [24].

Besides, only a small amount of scholars and research institutions have carried out some relevant research on the Invar alloy under laser-MIG hybrid welding technology, which are mainly concentrated on single pass welding of thin plate. Li et al. did a comparative study on laser and laser-arc hybrid welding of 5 mm thick Fe36Ni Invar alloy and analyzed the microstructure, coefficient of thermal expansion, and mechanical properties of laser welding and hybrid welding. It was found that the hybrid welding was better than laser welding in mechanical property, thermal property, and microstructure [25]. Xu et al. studied the microstructure of welded joints after dissimilar welding of WC-30Co cemented carbide and Invar alloy. To obtain the full-penetrated welding components, the laser-TIG hybrid welding was adopted to join cylinder components with the thickness of 6 mm and the diameter of 48 mm. It revealed that the microstructure of welded joints consisted of columnar crystals, cellular crystals, eutectic structure, fir-tree crystal and dendritic crystals [26,27]. In subsequent researches, Xu et al. studied the effect of tungsten carbide dissolution on the cold crack susceptibility after laser-TIG welding of Invar alloy [28].

The research status indicates that a majority of existing literatures on the welding of thick plate is scanty which is mainly concentrated on carbon steel or aluminum alloy, and studies on the extension of current understanding of welding Invar alloy are limited. Meanwhile, the practical application of Invar alloy thick plate hybrid welding is rare due to the existing research of this technology still has some shortcomings, for instance, the process stability and adaptability is insufficient, the deformation after welding is large, and air tightness is insufficient since cracks and pores appear in solidification process [29]. Attempts should therefore be made to exploit the benefits of MLMHW to overcome problems associated with welding thick plate of Invar alloy.

In this paper, quantitative research on the microstructure and properties was performed in order to further promote the application of laser-MIG hybrid technology in Invar alloy thick plate welding. An orthogonal experiment was designed to explore the effect of different laser power, welding current and speed on the welding process of invar alloy. Furthermore, the microstructure and properties of each parameter's corresponding joint were detected and compared. This paper lays the foundation for the application of laser-arc hybrid welding in the mold manufacturing industry.

2. Experimental details

2.1. Experiment materials and apparatus

The schematic diagram of laser-MIG hybrid welding is shown in Fig 1.

The material used in the current study is 19.05 mm thick plate of Invar alloy, whose chemical compositions are given in Table 1 with dimensions of $100 \times 100 \times 19.05\ \text{mm}^3$, as shown in Fig 2(a). A solid filler wire of stainless steel with 1.2 mm diameter is used whose chemical compositions are also presented in Table 1. The diagram of groove is shown in Fig 2(b), where V groove of 30 degree, root face of 6 mm thick, space between two half plates of 0.8 mm are selected. These parameters are ascertained on the basis of preliminary simulation and optimization experiment on process parameter.

The welding device in the current study includes Fronius welding machine of TPS-5000, KUKA robot of KR30HA, fiber laser of IPG YLS-6000 and matching fixtures. The physical diagram of laser-MIG hybrid welding device is shown in Fig. 3. The pure Argon with 99.99% concentration is used as protective gas whose flow rate is 15 L/min, which is appropriate for this paper since some related research has been carried out in other documents [30]. The laser beam is transmitted by a 300 μm core-diameter fiber, collimated by a lens with 100 mm focal length, and focused by a lens with 250 mm focal length. The defocus distance of the laser beam is 0 mm during welding. The angle of the laser beam to the vertical direction is 0°, and the angle of MIG torch to work piece surface (β) is 45°, besides, the distance of the laser beam to the wire tip (D_{LM}) is 3 mm. D_{LM} and the angle between laser beam and MIG torch are extremely important parameters, which can seriously affect the coupling of laser and arc, as well as the final forming results of weld seam. In order to minimize the number of parameters that need to be controlled in this paper, preliminary experiments have been conducted, and the most appropriate combination of angle and distance has been ascertained. The basic welding parameters are given in Table 2.

2.2. Design of experiment

The laser-MIG hybrid heat source is adopted in backing weld, filling weld and cosmetic weld, which is shown in Fig. 4. It is informed from preliminary tests that backing weld is mainly affected by laser power, while the filling weld and cosmetic weld are mainly affected by welding current [31]. Therefore, the best matching parameters of laser power, welding current and welding speed are discussed independently while other parameters are fixed. Besides, the wire feed rate matches the welding current. Since there are three layers in the whole weld seam, one of the parameters is adjusted in welding of each layer, which are laser power in backing weld, welding current in filling weld and cosmetic weld. The detail parameters for each specimen are given in Table 3.

2.3. Specimen preparation

Mechanical polishing of base metal is performed before welding, and the oil on groove surface is cleaned. When the interlayer temperature is cooled below 100° in the air, the welding of next weld seam is carried out. HF320M wire cutting machine is applied to cut the welded plate with dimensions of $100 \times 100 \times 19.05\ \text{mm}^3$ into small specimens of $20 \times 15 \times 19.05\ \text{mm}^3$ after welding. After grinding and polishing, 75% HCl + 25% HNO_3 solution (aqua regia) is used to etch the samples.

The morphologies are pictured by MR-5000 optical microscope. The microstructure is observed by scanning electron microscopy (SEM), and the element composition is analyzed by energy-dispersive spectrometer (EDS). HXS-1000AY microhardness testing machine is used to measure the hardness of specimens.