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# Investigation of the humping formation in the high power and high speed laser welding

Yuewei Ai[a], Ping Jiang[a,*], Chunming Wang[b], Gaoyang Mi[b], Shaoning Geng[a], Wei Liu[a], Chu Han[a]

[a] The State Key Laboratory of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science & Technology, Wuhan 430074, PR China
[b] School of Materials Science and Engineering, Huazhong University of Science & Technology, Wuhan 430074, PR China

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ABSTRACT

High power and high speed laser welding is as an attractive way to achieve the higher productivity in practical production. The weld periodical appearance defect, humping, is frequently generated in the high speed welding process. The weld quality is sequentially deteriorated severely due to the formed humping defect, which greatly limits the improvement of welding efficiency. In this paper, the keyhole and weld pool dynamic behaviors in the normal welding and high power high speed welding are investigated in the welding process of 304 stainless steel using 3–9 kW fiber laser at different welding speeds. The complex keyhole evolution, metal flow and metallic vapor are recorded by the high speed video camera and described in schematic illustration. The weld pool behaviors in normal welding and high power welding are compared and their effects on the humping formation are discussed in details. The results show that the tilted angle of keyhole, narrow and long molten pool, collision of fluid flow are the main factors for humping formation. Moreover, both of the microstructure characteristics of pre-humping and humping welds induced by molten pool behaviors are further analyzed and compared based on the SEM images, which is essential for reducing welding defects and achieving high quality welding with high efficiency.



## 1. Introduction

Due to the advantages of high efficiency, high power and high beam quality, the fiber laser is regarded as one of the most desirable heat sources [1,2] and light source for optical switching [3–5], which has been widely utilized in the manufacturing industry. During the welding, higher welding efficiency and quality is growing required and attracted by the modern industry. In the high power and high speed laser welding, the welding defects, undercut [6], spattering [7,8], humping [9,10], are typically associated and existed in the welds since affected by the complex heat and mass transfer phenomena involved in the welding process. Improving the welding efficiency without sacrificing weld quality is severely limited by the weld formation defects. Therefore, understanding the formation process of humping in the high power welding is of great significance for improving the productivity and guaranteeing the weld appearance quality.

Welding humping as a periodical defect in the weld formation is found in most of fusion welding processes including the gas metal arc welding (GMAW) [11], laser beam welding (LBW) [12] and electron beam welding (EBW) [13], even the ferrous alloys and nonferrous alloys welding [14]. During the investigation of humping, diverse methods have been presented based on the experimental observation. Nguyen et al. [15] obtained the video images of the humping phenomenon during high speed GMAW using a laser strobe video imaging system. They identified the strong backward flow of molten metal induced by various forces in the weld pool of high speed welding as the major factor which is responsible for the humping formation. Alfaro et al. [16] discussed the characterization of humping weld based on the temperature gradient observed by the thermographic camera. Wang et al. [17] extracted the features of the backward flowing molten metal from the captured images of the weld pool. In their study, it was found that external magnetic field could be applied to suppress the humping defect. Additionally, some theoretical models were utilized to consider the complexity of heat and mass transfer to investigate the mechanism of humping formation in numerical simulation. Gratzke et al. [18] proposed the Rayleigh's theory model of the instability of a free liquid cylinder induced by the surface tension to explain the humping phenomenon. The threshold value of welding speed for humping emerging was predicted theoretically. Cho et al. [19] developed the numerical simulation model to analyze the humping formation process quantitatively. The thin liquid channel induced by surface tension pinching force and its premature solidification

* Corresponding author.
*E-mail address:* jiangping@hust.edu.cn (P. Jiang).

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were identified as the two conditions which were responsible for humping formation. Meng et al. [14] proposed the double-ellipse arc shear stress model and self-adaptive heat flux and arc pressure distribution model to study the periodical humping formation in high speed gas tungsten arc welding (GTAW). They obtained that the surface deformation of molten pool and gouging region elongation are two initial requirements for humping formation. Wu et al. [20] established the three-dimensional numerical model to investigate the convection in normal and high speed GMAW processes. The high momentum of the backward fluid flow, large variation of capillary pressure of the liquid channel and capillary instability were regarded as the three main factors resulting in the humping formation. Most of these researches were focused on the humping formation in the arc welding. The high energy beam and high speed welding induced humping defect are out of consideration.

The welding speed of laser welding which is as a typical high-energy beam welding is much larger than the conventional arc welding. The laser absorption and its mechanism are much more complex and completely different due to the fact that the deep keyhole is easily to be formed in the molten pool [21,22]. Only a few investigations about the humping phenomenon of laser welding have been reported in the literatures. Albright et al. [23] investigated the welding discontinuities and found that the humping was encountered at high laser power and high travel speeds. Kawahito et al. [1,7] performed the effects of the laser power, power density and welding speed on the formation of sound welds in bead-on-plate welding of 304 stainless steel plates with 6 kW and 10 kW high power fiber laser. The welding phenomena recorded by high-speed video camera and x-ray transmission real-time imaging system were clarified and they recognized that the humping formation was dependent upon the melt volume above the surface, strong melt flow and other dynamic or static factors. Fabbro [24] defined the characteristic regimes of laser welding by the penetration curve from the 0 to 50 m/min welding speed range. The humping weld seam with strong undercuts was observed at above 20 m/min high speed welding in their study. With the rapid development of numerical techniques, the theoretical models are started to be proposed and solved by simulation to explain the mechanism of humping defect in laser welding. Zhou et al. [25] reported that the humping was formed by the combined effects of recoil pressure induced strong metal back-flowing and rapid solidification rate in the numerical simulation. Amara et al. [26] developed a 3-D transient model for deep-penetration laser welding at high welding speed regime and observed the elongated keyhole shape and hump formation by simulating deformation under the laser beam effect and considering the local drilling velocity. The previous researches are mainly focused on the macro analysis of humping formation process based on the experimental and simulation results. However, the humping formation and associated welding phenomenon are not fully understood. Especially, the real characteristics difference of comprehensive transport phenomena between the normal welding and high speed welding is not being studied, which is greatly significant for understanding the fundamental mechanisms of humping formation and achieving the high quality weld in high power and high welding speed.

In the present study, the keyhole and weld pool dynamic behaviors in the normal welding and high power high speed welding are investigated on the welding of type 304 stainless steel using 3–9 kW fiber laser at different welding speeds. The keyhole, metal flowing and meltic vapor complex behaviors and the interaction involved in the welding process are observed using the high speed video camera and described in schematic illustration. To understand the humping formation process, the comparison of the normal welding and high speed welding has been conducted and the main causes which results in the generation of humping are identified. Moreover, the microstructure of the weld with pre-humping and humping defect are described and analyzed based on the SEM images. The typical molten pool behaviors in the humping formation have been further revealed, which is essential for reducing the welding defects and obtaining the sound weld.

The rest of the paper is summarized as follows: The introduction of the experimental details including the materials, experimental design, laser system, a high-speed camera and scanning electron microscopy is provided in Section 2. In Section 3, the weld appearance evaluation, the dynamic behaviors of keyhole, weld pool formation, humping formation, and microstructure characteristics are described. Finally, the conclusions of the current study are offered.

## 2. Experimental details

### 2.1. Materials and experimental design

Since the achieved penetration in the high power laser welding is much larger than that formed in the normal laser welding processing, two types of SUS304 austenitic stainless steel plates with 8 mm and 3 mm thickness are prepared for the laser welding experiments, as shown in Fig. 1. The dimensions of the welding specimens are 200 mm × 100 mm × 8 mm and 200 mm × 100 mm × 3 mm, respectively. The chemical composition of the base metal is tabulated in Table 1.

To compare the difference of the laser welding process in high and low laser power, the type 304 austenitic stainless steel sheets in 3 mm thickness is welded by the low power laser and the high power laser is used for 8 mm thickness plate. To compare the dynamic behaviors of lower and high power laser welding, the laser power is selected as from 3–9 kW. According to the previous researches [7,24], the humping defect is highly related to the welding speed. In the welding experiments, the welding speed is conducted from 2.5–24.0 m/min. The focal position is kept as 0 mm. According to the above experimental requirement, the corresponding welding parameters used in the experiments are listed in Table 2. The investigation of the humping formation in the laser welding process is conducted as the designed experiments.

### 2.2. Experimental process

The welding process is conducted by the continuous wave fiber laser (IPG YLS-10,000), as shown in Fig. 2(a). The maximum output power is 10 kW and the beam parameter product (BPP) is 7.5 mm•mrad. The spot radius is focused into 200 um by the lens of 300 mm focal length. During the welding experiment, the welding head is equipped on the robot to achieve the welding path, welding speed and focal position. The fiber laser beam is output from the laser and transmitted to the welding head. The laser power is controlled by the laser control system. To avoid the oil pollution and oxide film, all of the specimens were brushed with fresh wire brush and cleaned by acetone swabbing carefully before the welding experiment. The Argon is used as the shielding gas and supplied laterally at a flow rate of 30 L/min.

To observe the dynamic behaviors of the keyhole and molten pool, a high-speed camera is used with the 5000 fps (frames per second) rate. The diode laser with 808 nm wavelength in 10 W is employed to illuminate the molten pool zone and a filter with band-pass 810 ± 2 nm is installed in front of the camera lens to improve the contrast between the molten pool and other region, as shown in Fig. 2(b).

After welding experiments, the welding samples are cut from the cross-section of weld and the corresponding morphologies are observed by optical microscopy. To further compare the microstructure of the joint areas, scanning electron microscopy (SEM) images are obtained in JEOL (Japan) JSM-7001F thermal field emission SEM. Before taking the SEM images, the sample surface is sputter-coated with a thin Au layer to avoid charging effects.