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Relationship between spatter formation and dynamic molten pool during high-power deep-penetration laser welding

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ABSTRACT

The spatter and the molten pool behavior, which were the important phenomena concerned with the welding quality, were observed and studied by using the high-speed camera and the X-ray transmission imaging system during laser welding under different welding parameters. The formation mechanism of spatter and the corresponding relationships between the spatter and molten pool behavior were investigated. The increase of laser power could cause more intense evaporation and lead to more spatter. When the focal position of laser beam was changed, different forms of spatter were generated, as well as the flow trends of molten metal on the front keyhole wall and at the rear molten pool were changed. The results revealed that the behavior of molten pool, which could be affected by the absorbed energy distribution in the keyhole, was the key factor to determine the spatter formation during laser welding. The relatively sound weld seam could be obtained during laser welding with the focal position located inside the metal.

1. Introduction

The welding process with 10 kW-level high-power laser is very intense due to the huge amount of laser energy has been inputted which causes the intense evaporation of substrate metal. The high recoil pressure of evaporation extrudes the molten metal to form a deep keyhole. When the vapor plume is extruded out from the keyhole, the spatter is generated concomitantly. The generated spatter is the mainly factor to cause the mass loss of metal, which results in the weld defects, such as underfilling and undercutting at the top and bottom of weld pool [1,2]. To improve the weld seam quality during high-power deep-penetration laser welding, the spatter should be avoided. And the mechanism of spatter formation needs to be investigated firstly.

Kaplan et al. [3,4] observed four types of spatter under different welding parameters, which were: only little drops ejected ahead of the keyhole, a high vertical liquid column created behind the keyhole, an inclined liquid column created behind the keyhole, and the small drops ejected beside the keyhole. They concluded that the periodical fluctuating evaporation recoil pressure accelerated the upward-moving melt. For spatter to be created, the momentum of ejecting melt must be sufficient to overcome surface tension. But the different formation mechanisms for the four types of spatter were not discussed completely. Kawahito et al. [5] observed the large spatter formation which resulted in the underfilling. The strong shear force of ejective plume extruded the melt to form the large spatter. When the incident angle of laser beam was inclined 20° back to the weld pool, the spatter was greatly reduced. Because, the direction of out-blowing plume was changed, and the extruded melt could flow back to the molten pool. Fabbro et al. [6–8] studied the dynamical coupling between the vapor plume and the melt pool, and compared the results under different welding speeds. The friction stresses of expanding metallic vapor accelerated the melt pool. During high speed welding process, the vapor generated on the front keyhole wall could impinge on the rear molten pool to generate the droplets.

In summary, the spatter was generated due to the melt pool was extruded by the laser-induced metallic vapor inside and at the outlet of the keyhole. Zhang et al. [9] have observed the spatter generating process during partial and full penetration laser welding. The viscous friction drag was the important factor to accelerate the melt pool and cause spatter. At the bottom of keyhole, the spatter was generated due to the quickly downward-moving melt on the front keyhole wall. In the previous research work [10], a butt-joint configuration assembled from transparent glass and stainless steel was introduced to observe the dynamic keyhole profile and melt flow on the keyhole wall during deep-penetration laser welding.

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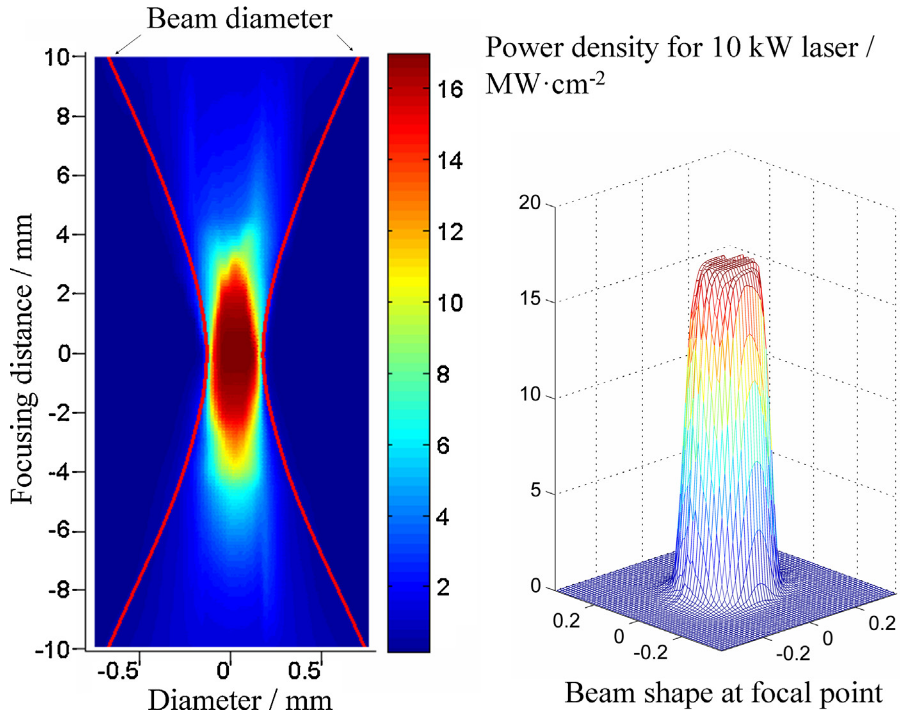

Fig. 1. Intensity distribution and laser beam profile.

The results revealed that the fluctuating vapor flow and pressure could cause the fluctuating keyhole wall and result in a vapor-generated wave of molten pool on the rear keyhole wall. When the vapor-generated wave broke at the keyhole outlet, it was accompanied by swellings, spatter, columns, a decrease of the diameter of keyhole inlet, and a change in the direction of plume.

However, all the previous investigations have not discussed the relationship between the generated spatter and the molten pool behavior clearly. During high-power laser welding, the experimental results showed that the spatter was easy generated under special conditions [3,6,11–13], such as high power, high speed, high ambient pressure. At the same time, the movement of molten pool was observed by using the X-ray machine, which was changing under different welding conditions [13,14], during high-power laser welding. These imply that the generated spatter has a closed relationship with the movement of molten pool. In the present work, a further work was implemented to study the behaviors of spatter and molten pool during high-power deep-penetration laser welding. Both the phenomena in the partial and full penetration welding processes were observed. The effects of welding parameters to the spatter formation and molten pool were investigated. And the appearance and cross section of weld seam were studied when the spatter was generated.

2. Experimental details

The experiments were carried out by using a high-power laser system (Trumpf TurDisk 16,002; wavelength: 1030 nm; beam parameter product: 8 mm mrad; maximum power: 16 kW). The laser beam was transmitted through an optical fiber and focused by a lens with 280 mm focal distance. The focus diameter is 0.28 mm. The Rayleigh length of laser beam is 2.4 mm. The intensity distribution and laser beam profile are shown in Fig. 1. During the experiments, the laser power was changed from 5 kW to 12 kW. The defocused distance was changed from −7 mm and +4 mm. The welding speed was set to 1.5 m/min and 2 m/min. In order to study the effect of welding parameter to the spatter formation independently, no shielding gas was used.

Fig. 2 shows the schematic diagrams of the experiments. The X-ray imaging system was used in the experiments to observe the behavior of molten pool. The X-ray imaging system consists of: a micro-focused X-ray tube generating the X-ray, an image intensifier converting the X-ray transmitted specimen to the visible image, and the high-speed camera capturing the image. The X-ray transmitted specimen was finally taken by the camera at a frame rate of 250 f/s. Another high-speed camera (frame rate: 5000 f/s) was set above the welding specimen to observe the dynamic molten pool and the ejecting spatter. A filter and an illuminating laser (wavelength: 980 nm) were introduced, accompanying the high-speed camera.

The welding material was SUS 304 stainless steel. During the experiments, the partial and full penetration welding processes were investigated. There were two types of specimen size, as shown in Fig. 3. In partial penetration welding, the height of steel plate was 25 mm. In full penetration welding, the height of steel plate was

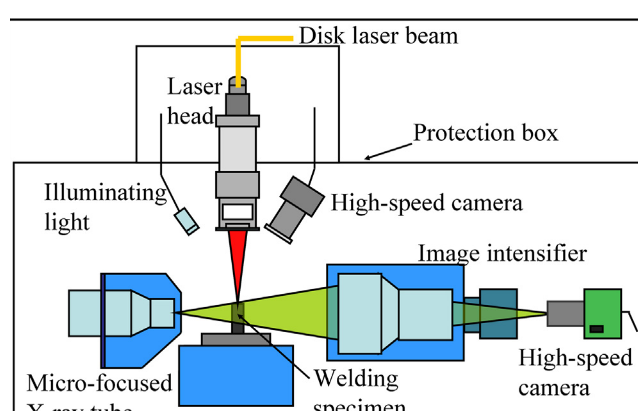

Fig. 2. Schematic for experiment.