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# The influences of welding parameters on the metal vapor plume in fiber laser welding based on 3D reconstruction

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ABSTRACT

Fiber laser has significant advantages in the welding of moderately thick stainless steel plates. However, the influences of welding parameters on interaction behavior are still not fully understood. The metal vapor, as process product of fiber laser welding, carries abundant information of interaction behavior. A novel three-dimensional reconstruction technique was used to establish spatial structure of metal vapor during fiber laser welding. The spatial field of temperature and electron density were computed based on the 3D distribution of radiation intensity, as well as the relative spectral intensity method. Experimental results showed that the temperature of the metal vapor was generally at about 4000–5500 K. Defocusing amount had a significant influence on metal vapor and its energy interaction process in fiber laser welding.

## 1. Introduction

In recent years, fiber laser has developed rapidly. High power fiber laser has the advantages of good beam quality and high flexibility. It has been widely used in the industrial field of automobile and shipbuilding [1]. In laser deep penetration welding, the local evaporation of base material was induced by high energy density of incident laser. The keyhole provides a channel for laser beam to go inside material and transmit heat to material. With the energy interaction, metal vapor erupts from keyhole and plays an important role in the energy interaction process [2]. In $CO_2$ laser welding, the density of metal vapor has a close relationship with the interaction between the laser beam and the material [3]. Different from $CO_2$ laser welding, the effect of metal vapor in high power fiber laser welding was not clear.

Kawahito et al. proved that the ionization degree of metal vapor was very low and its effects on incident laser was negligible [4]. GAO and his colleagues pointed out that the shielding effect of metal vapor could not be neglected [5]. The radiation spectrum of metal vapor was collected and analyzed by Sibillano and his colleagues in $CO_2$ laser welding, YAG laser welding and fiber laser welding, respectively. Experimental results showed that the quantitative relationship between the electron temperature of metal vapor and the penetration depth existed no matter the laser source, and it could be used for real-time control of weld penetration depth [6]. In order to understand the interaction process, the internal structure and dynamic behavior of metal vapor provided information in spatial domain and time domain. Li et al. used high-speed camera to observe metal vapor in fiber laser welding. They pointed out that the particle density of metal vapor kept in high level although it stayed in weak ionization state [7]. Liu Guiqian and so on used high-speed photography and image processing technology to calculate the two-dimensional image area of the high power fiber laser welding metal vapor, and analyzed the periodic fluctuation of the metal vapor. The area of metal vapor was computed based on high speed photograph and image processing technology. The periodic fluctuation of metal vapor in fiber laser welding was analyzed [8]. Because the metal vapor is asymmetric and changes rapidly during welding process, the spectrometer provides information of one point, while traditional camera obtain only two-dimensional information.

In order to fully understand the metal vapor and its effects on fiber laser welding, the three-dimensional information of metal vapor is an important prerequisite. Recently, the research on three-dimensional distribution of temperature or particle density was carried out for plasma plume in $CO_2$ laser welding [9]. However, fiber laser welding put forward higher requirements because the metal vapor of fiber laser welding was smaller and lower ionized. Related studies have rarely been reported.

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In this paper, a novel method was proposed to reconstruct the spatial distribution of metal vapor in fiber laser welding. Three identical imaging devices were established to shoot the metal vapor simultaneously from different angles. Based on the central projection model, the spatial distribution of radiation intensity is reconstructed by algebraic iteration. It was found that the core of metal vapor was uneven. The morphology and position of metal vapor changed with the fluctuation of molten pool and keyhole. Experimental results showed that the reconstruction method provided a new way to understand the energy interaction during fiber laser welding.

## 2. Experimental setup

A series of bead-on-plate laser welding was carried out on stainless steel with fiber laser source, YLS-10000. The wavelength is 1.07 μm. The focal length is 300 mm, and the diameter of the minimum focal spot is 0.4 mm. The Rayleigh length is 10 mm. During welding experiments, the metal vapor was shot by three lenses established from different angles. The metal vapor fluctuates violently in size, morphology and brightness, which puts forward high synchronization requirements for 3D reconstruction imaging system. For fast changing objects, the accuracy of 3D reconstruction is affected by the synchronization degree. The serious time differences among the cameras can even result in the failure of 3D reconstruction. The imaging system was presented in Fig. 1. The spatial coordinates (X, Y, Z) were established by taking the incident point of laser on the surface of the workpiece as the origin. The lens A and the lens B were respectively arranged in the direction of the X axis and the Y axis, and the lens 3 was positioned above the work piece. The distance between lenses and the coordination origin was 1 m. The light radiation of metal vapor was collected by three lens, and then transmitted through image bundles to the integrated bundle. After the convergence, a camera is used to complete the shooting, thus effectively avoiding the error of the multiple triggering system. It provides an effective method to obtain the images strictly synchronously. At the end of image bundles, a spectroscope was used to split image into two directions. In the range of visible light, 50% intensity of light is emitted by a spectroscope, and the other light passes through the spectroscope, thus forming two identical beams of light. In each direction, there were a CCD with a filter and micro lens. The central wavelength of two filters were 532 nm and 537 nm, respectively. The bandwidth of two filters were 3 nm and 5 nm. The two CCDs were controlled by a synchronous external trigger to capture images at same time strictly. In the welding process, the frame frequency of the camera was 40fps, and the exposure time was 0.1 ms.

The size of welding sample was 150 mm × 100 mm × 8 mm. Before welding, the surface of the test plate was polished, cleaned and cleaned. The laser power was 6 kW. The welding speed was 1 m/min. The defocusing amount was -6mm. Argon was used as shielding gas. The gas flow rate was 20 l/min. The gas pipe was arranged in front of laser, and the angle between pipe and workpiece was 45°.

## 3. Reconstruction theory and image processing

For 3D reconstruction of metal vapor in laser welding, a central projection model was presented based on the improved dimensionality reduction algorithm. The three-dimensional spectral distribution of metal vapor was calculated by synchronous images of three projective angles. Projection is a line integral process. Projective 3D reconstruction is to reconstruct the spatial distribution of the physical properties of the object through projection images from different angles. The basic idea is the inverse transformation of Radon [10], presented in Fig. 2.

Suppose the spectral radiation distribution of the object to be reconstructed in the XOY plane is $f(x, y)$. It was expressed as $f(\rho, \phi)$ in polar coordinate. $P(l, \theta)$ was the projection of $f(x, y)$ along an arbitrary straight line$l$with angle$\theta$. According to the Radon inverse transformation, the distribution function of spectral radiation inside the object can be obtained [11]:

$$f(x, y) = f(P, \phi) = \frac{1}{2\pi^2} \int_0^{\pi} \int_{-E}^{E} \frac{\partial P(l, \theta)/\partial l}{P\cos(\theta - \phi) - l} dl d\theta \qquad (1)$$

where $E$ was the boundary of the object to be reconstructed.

3D reconstructed by Radon inverse transformation is the most commonly used algorithm in CT technology. The reconstruction are divided into analytic method and iterative method. The analytical method has a high accuracy and a small amount of calculation, but requires the continuous projection data of the object. The iteration method can be carried out based on a few sets of projection data, but its calculation process is complex and the amount of calculation is huge. In the process of laser welding, it is impossible to place a large number of sensors because of space and cost constraints. Therefore, an iterative reconstruction method, referred to ART (algebraic reconstruction technology) [12], was chosen to carry out the reconstruction of metal vapor.

Suppose: (1) the reconstructed area was divided into many cubes with very short sides; (2) the optical radiation function$f(i, j, k)$of each cube was even. As far as the 2D image of metal vapor, the brightness of each pixel was the accumulation of a series of radiation from cubes inside the metal vapor [12].

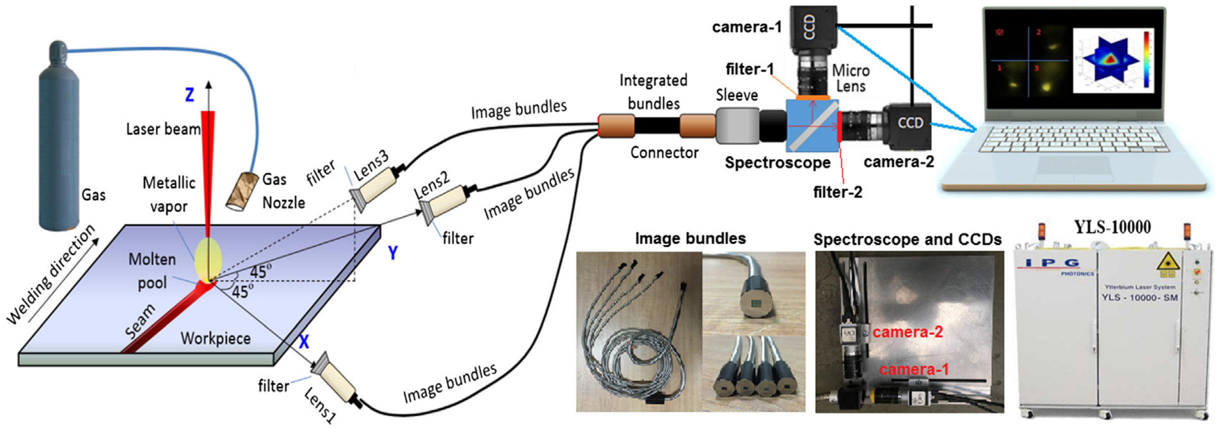

Fig. 1. The Synchronous imaging system based on image bundles for metal vapor.