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Monitoring of high-power laser welding using high-speed photographing and image processing

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ABSTRACT

In conjunction with the rapid development of high quality laser welding, industrial manufacturing has seen a growing demand for process monitoring and diagnostics. This paper proposes an effective method for monitoring the high-power laser welding. By combining a high-speed camera with an ultraviolet and visible band-pass filter, high contrast images of a laser-induced plume and spatters were obtained at three different welding conditions. After preprocessing the images, the quantification of the plume and spatter features was performed. Plume detection was conducted based on the mechanism of a laser-induced plume. Using static and dynamic feature of spatters, a time delay tracking algorithm was designed for spatter detection. The results revealed that the features of plume and spatters, including plume size, plume growing direction, spatter radius, spatter ejected direction, spatter gray value and spatter velocity, were related to the welding quality. The proposed method could be used to monitor the stability of the laser welding process.

1. Introduction

Laser welding has been widely used in various industries of automobile, shipbuilding, bridge construction, etc., due to its advantage in high production, automate processing and the formation of a high quality weld with small heat-affected zones [1,2]. However, high-power laser welding is a highly dynamic process and the heat transfer from a laser beam to a metal is extremely unstable. Consequently, effective and accurate methods of monitoring the laser welding process become more important in both quality inspection and adaptive control. Advanced monitoring techniques have been employed in condition evaluation [3–5]. One of the most effective methods of non-contact measurement is visual sensing. Recently visual sensing based on image processing technology has been applied to object detection [6,7], shape measurement [8], dynamic analysis [9,10], vibration measurement [11] and thermal inspection [12]. Especially in welding process, visual sensing has already been used in status monitoring of spot welding [13], system identification of laser welding [14], process control of arc welding robotic [15] and seam tracking of high-power fiber laser welding [16].

During high-power disk laser welding (power bigger than 10 kW), the laser-induced plume, mostly a metallic plasma, is generated above the keyhole because of the high energy density ranging from 100 kW/mm^2 to 1000 kW/mm^2. Plenty of spatters would be ejected by the high evaporation pressure in the keyhole. It is well known that the performance of

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laser-induced plume and spatter is critical to the welding quality [17,18]. Coaxial monitoring is one of the most effective methods for a molten pool and keyhole behavior detection [19], while lateral monitoring provides the most effective way for the plume and spatter detection during laser welding [20]. Based on coaxial monitoring system and high-speed photography, a Kalman filter with a linear-system model could be used for spatter tracking during laser welding [21]. Also, quality inspection and monitoring of welded beam have been reported [22,23].

This paper presents a new method for lateral monitoring of laser welding process, and introduces a new image processing algorithm for feature extraction of a plume and spatters. An ultraviolet and visible (UV/visible) sensing high-speed photography system has been applied to capture the plume and spatter images during high-power disk laser welding. A time delay recognition system based on static and dynamic feature has been employed to spatter tracking. The features of plume and spatter, including plume size, plume flowing direction, plume brightness, spatter radius, spatter ejecting velocity, spatter ejecting direction and spatter gray value (brightness), have been extracted from continuous image sequence. The relationship between the welding quality and those features was investigated.

This paper is organized as follows. Section 2 shows the experimental setup of high-power disk laser welding system and introduces the fundamental mechanism of a laser-induced plume and spatters. Section 3 presents the image preprocessing of UV/visible image and the plume feature extraction. Section 4 presents the spatter tracking algorithm and feature extraction. Section 5 investigates the relationship between the welding quality and the monitoring results. Section 6 draws conclusions.

2. Monitoring system and mechanism of laser-induced plume and spatters

The experiment was performed by using a high-power disk laser welding system which is shown in Fig. 1. The ServoRobot laser head was setup on a Motorman 6-axis robot. A high-speed camera was setup at the position perpendicular to the welding direction. A spectral band-pass filter, which is sensitive to the wavelength from 320 nm to 750 nm, was put in front of the high-speed camera in order to suppress light disturbance and to obtain high contrast images. The response curve of UV/visible sensing filter is shown in Fig. 2. The UV/visible images captured from the data box were transferred to the monitoring computer, where the image processing and feature extraction were performed. The disk laser wavelength was 1030 nm and the beam diameter of laser focus was 480 μm, while the laser power was 10 kW (Trumpf TruDisk 10003). The shielding gas (argon) flow was 40 L/min and the nozzle angle was 45°. The workpiece (stainless steel Type 304) was driven by a precise servo motor. Three different welding speeds, including low-speed (1.5 m/min), medium-speed (3 m/min) and high-speed (6 m/min), have been taken into consideration. The camera frame rate was 2000 fps and image resolution was 512 pixel × 512 pixel. The UV/visible image sequence and weld seam surface are shown in Fig. 3, which contains the information of a plume and spatters induced by high-power density laser beam.

By reviewing the UV/visible images, the basic mechanism of a laser-induced plume and spatters can be described as follows. First, the plume generated by high density laser beam grew upward out of the keyhole. Second, the spatters were ejected from the keyhole in different directions. It is true that some of the spatters ejected in the same direction of camera monitoring would be covered by plume. However, as have been tested before, most of the spatters are ejected either in the same or opposite direction of welding because of the shielding gas flow and the inertial characteristics. Only a few numbers of spatters, which appeared to be small sizes, are ejected in exactly the same direction of monitoring and covered by the

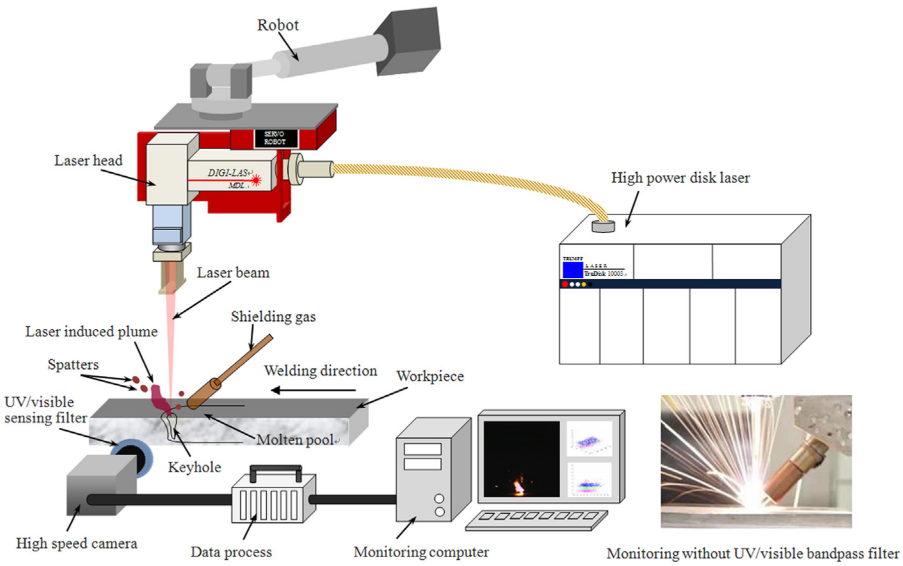

Fig. 1. Monitoring system of high-power disk laser welding.