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A laser-based machine vision measurement system for laser forming

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ABSTRACT

Laser forming continues to be a promising technology in manufacturing due to its fast speed, flexibility, and low-cost. Measurement of deformation after laser forming is widely needed to verify its convergence to the intended shape in academic research. With the development of laser forming, high requirements on the measurement of the deformed work-piece have been sought such as a 3D profile of the deformed surface, a large measuring range, and measuring convenience. In this paper, a laser-based machine vision measurement system was developed to measure the 3D profile of deformed surface by a one-off scanning process. Based on the 3D profile data, the vertical displacement of the deformed plate was calculated for bending analysis. In addition, as one of the important feature parameters, transverse shrinkage was automatically determined through a novel image-based method during the scanning process. A measuring accuracy of 0.03 mm for vertical displacement measurement and 0.0125 mm for transverse shrinkage were achieved in the developed measurement system. This measurement performance is acceptable in most of the laser forming processes currently studied.

1. Introduction

Laser forming is a promising forming technology that plastically deforms the metal plate by thermal stresses induced through laser irradiation [1]. Due to its fast speed, flexibility, and low cost, it has been widely applied in different industries, such as shipbuilding, aerospace and automotive [2,3]. A large number of experimental studies, analytical simulations, and process controls [4–7] have been done on laser forming since its inception in 1980s. In these studies, the deformed surfaces were measured to verify their convergence to the intended shapes. Traditionally, experimental measurements of the deformed surface were limited to two characteristic values (see Fig. 1): the bending angle β and the transverse shrinkage Δl (it's defined as the change of distance between two parallel lines after laser heating). Several commercially available profilometry devices have been reported to measure the deformed surface, including the coordinate measuring machine (CMM) [8], laser displacement sensor [9], and Taylor CLI 2000 [7]. In addition, Hu et al. [6] developed an integrated machine vision measuring system based on the "pinhole" lens model, which measured the bending angle after each scanning pass. Mark et al. [4] achieved the shape measurement by projecting a coherent fringe pattern onto the object surface. Jezersek et al. [10] developed a shape measurement system based on the laser triangulation principle. Most measurement systems currently available for laser forming are stationary with respect to the measured object, leading to a limitation of measuring dimensional range. Measurements and studies were restricted to the local area, which was usually less than 200 mm by 200 mm. Nowadays, the heavy metal

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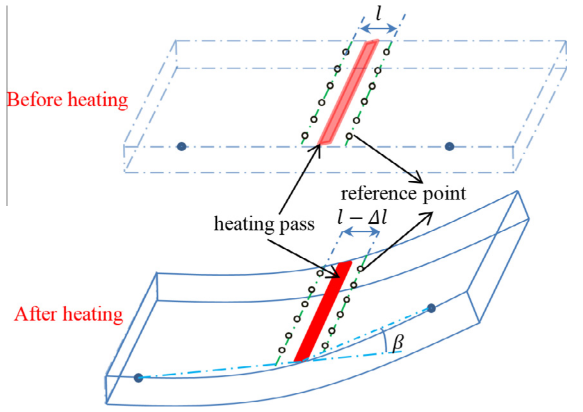

Fig. 1. Schematic of bending angle and transverse shrinkage during laser metal-forming process.

industry has been involved in forming large structures where the length of the heating line was over one meter long. The need exists for an automatic measurement system that does not limit the measuring dimensional range. In measuring the transverse shrinkage, the existing method measures the individual position and determines the transverse shrinkage through coordinate measuring machine (CMM), which generally has accuracy of 0.001 mm. It is time consuming and often not feasible especially in the case of large plates. Moreover, with the development of the laser forming process, many complex shapes have been formed with various heating patterns. The currently used geometrical parameters such as bending angle and transverse shrinkage would be insufficient to describe fully the geometry of the deformed plate. A fast measurement for 3D profile without a limitation to the measuring range is greatly needed.

In this study, a laser-based vision system was developed to measure the 3D profile of deformed surface after laser heating. The vertical displacement curve after heating was extracted from the 3D profile for bending analysis, and its accuracy was analyzed. To directly measure the transverse shrinkage, small holes were drilled as reference points at each side of the heating pass (see Fig. 1), and a highly efficient and easy-to-implement image processing algorithm was proposed to detect the reference points and calculate the transverse shrinkage.

2. Design of the measurement system

As shown in Fig. 2, the laser-based vision measurement system includes three major modules: a laser-based vision sensor module, an image-processing module, and a multi-axis motion control module. A laser stripe was projected perpendicularly at the measured surface. The height information of the stripe can be determined by processing the image of the laser stripe captured by the vision sensor module. The principle and design of the vision sensor is detailed in Section 2.1. The vision sensor was installed at the vertical axis of a multi-axis liner positioning system. The worktable moved along the *Y* direction (scanning direction) so that the vision sensor scanned the full length of the deformed surface. During the scanning process, the physical *Y* position of the stripes was recorded by the servomotor in *Y* direction. The 3D profile data of the entire surface was reconstructed by the image-processing module detailed in Section 2.2. The transverse shrinkage was determined by measuring the change of the distance of the reference points on each side of the heating pass. In this study, small 1 mm deep holes with radius of 0.7 mm along the lines were drilled as reference points. Since the laser stripe profile deformed when it reached a reference point during the scanning process, the detection and localization of the holes were conducted through the image-processing module. It is worth to mention that drilling small holes as reference points would destroy the surface of work-piece when applied in industry, but it is acceptable for research that studies the effect of processing parameter on the degree of deformation of the large scale plates. As a standard yet flexible off-the-shelf development platform, LabVIEW was used to develop the image-processing module, the multi-axis motion control module, and the end-user interface. A fire wire 1394 adapter was adopted to capture the frames. A National Instrument (NI) 4-axis motion controller PCI-7344 was used to control the three servomotors.

2.1. Design of the laser-based vision sensor

As shown in Fig. 3a, a typical laser triangulation vision sensor consists of a structured-light laser diode, a GigE CCD camera, a focus lens, and an optical filter. The structured-light laser diode projected a laser stripe with a wavelength of 658 nm on the surface of the target work-piece. The laser light was scattered by the target piece and reflected in a different direction. The CCD camera installed at an angle with respect to the laser diode could collect the reflected laser light with a band-pass optical filter (658 nm) installed in front of it. Based on the formed image of the laser stripe on the image plane, the distance between the vision sensor and the work-piece, the lateral position, and the geometrical features of the work-piece could be precisely determined based on the geometrical optical path involved between the laser diode, the GigE CCD camera, and the focus lens. To ensure that the image of the target work-piece always focused on the image plane, the principle of laser triangulation was used to determine the relative geometrical position of the laser diode, the GigE CCD camera, and the focus lens [11]. Fig. 3b shows the relationship between the physical world and the image pixel. The physical 3D spatial position of the laser stripe can be obtained through analysis in depth direction and along the laser stripe direction as follows:

(1) Depth direction: assume point "A" in Fig. 3b is the intersection point of the laser axis and the optical axis of the focus lens. Point "B" is the measured point on the laser axis. The images of point "A, B" are formed at point "a, b" on the image plane respectively. The distance between point "A" and "B" is *H*. The distance between point "a" and "b" is *h*. According to the principle of laser triangulation, the mapping relationship between *H* and *h* is established as: