The 8th International Conference of the Slovenian Society for Non-Destructive Testing
»Application of Contemporary Non-Destructive Testing in Engineering«
***September 1-3, 2005, Portorož, Slovenia*, pp. 335-339**

REAL TIME SURFACE DEFORMATIONS MONITORING DURING LASER PROCESSING

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ABSTRACT

We present a novel approach to monitoring the surface deformations during various types of laser processing, e.g., engraving, marking, cutting, bending, and welding. The measuring system is based on a laser triangulation principle, where the laser projector generates multiple lines simultaneously. This enables us to measure the shape of the surface with a high sampling rate (80 Hz with our camera) and high accuracy (±7 μm). Full-field measurements of steel-plate deformations are presented for plates of different thickness and with different processing parameters.

***Keywords**:* Three-dimensional measurement, Laser triangulation, Noncontact, Laser material processing, Laser drilling, Laser engraving, Laser bending

1. Introduction

Laser surface-processing techniques have become increasingly common as industrial processes over the past few years [1]. A common feature of all these techniques is the need for them to operate as close as possible to the optimum working point. However, this situation usually involves a compromise between the operation time for the process and the quality of the finished product. For example, increasing the average power of the laser and the traveling speed of the laser beam usually decreases the operating time; however, at a certain point the quality of the processed surface is no longer acceptable as a result of unwanted permanent deformations, which are caused by various thermoplastic mechanisms, such as the temperature-gradient, the buckling or the upsetting mechanism [2,3]. On the other hand, during laser-forming processes the deformation should generate the required shape with the minimum of deviations [4-6].

So far, experimental measurements of the deformed surface have been limited to some characteristic values, such as the bending angle or the radii of curvature [2,7]. What is more, these measurements are normally performed after the process is complete, using a linear variable differential transformer (LVDT), a coordinate measuring machine (CMM), or techniques such as laser point or line triangulation. At the time of writing, only one group has published some preliminary experimental results from a full-field dynamic shape measurement during laser-based plate bending [6].

Here, we describe sets of experiments involving the full-field absolute-distance measurement during laser surface processing. The first set shows the behavior of a "simple" hole-drilling process, while the second set shows deformations during engraving of a "complex" pattern on steel plate. By using three-dimensional measuring apparatus we easily determined such processing parameters, providing the deformations were inside the acceptable limits.

2. Experimental set-up

The experimental set-up for the laser surface processing is shown in Fig. 1. The main components are the processing laser with its XY scanning head, the three-dimensional measuring apparatus and the personal computer. The specimen lies on the console table with the hole in the middle. The specimen’s top side is laser processed, while the measurements are made simultaneously on the bottom side. The problem of very intense scattered light from the processing laser, which disables the shape measurement near this point, is effectively solved by using such a configuration. The specimen's material, 0.2-mm-thick steel plates, has the designation Ck 101, in accordance with the DIN 17222 standard.

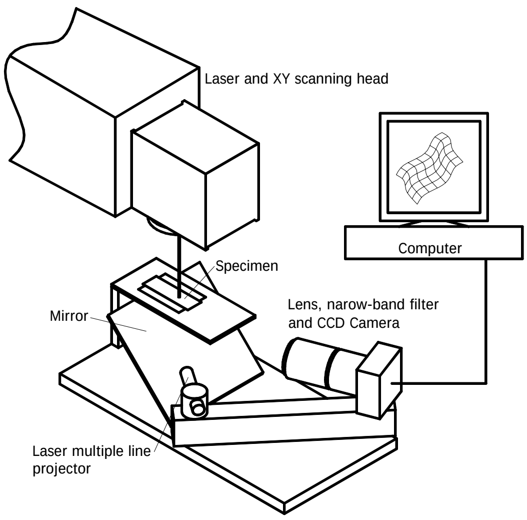

Fig. 1: Experimental set-up.

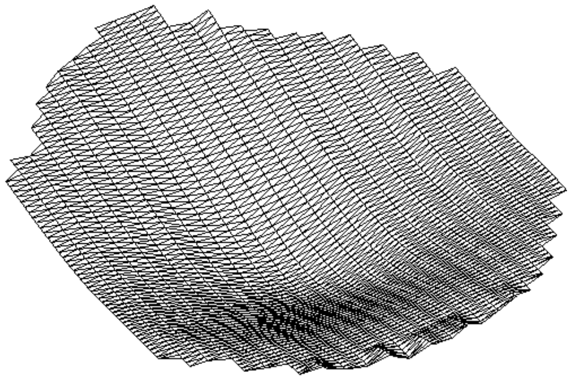

Fig. 2: Example of the measured surface, where deformation is magnified 10 times.

The processing laser is a diode-pumped Nd-YAG laser with a wavelength of 1064 nm and maximum average output power 8 W. It can operate in either pulsed or continuous modes. The pulse duration varies from 50 to 600 ns according the variation of pulse frequency in the range from 440 Hz to 50 kHz. The XY galvo-type scanning has an f-theta lens with a 160-mm focal length. It has a square scanning region with side lengths of 90 mm. The resolution along each axis is 1.5 μm, the maximum traveling speed of the beam is 90 m/sec, and the minimum traveling speed is 1.8 mm/sec. This laser system is primarily designed for marking or engraving applications, but the laser drilling of small-diameter holes and the cutting of thin plates can also be accommodated.

The shape-measuring apparatus is based on the multiple-line laser triangulation principle, similar to the one used in [8]. It consists of a laser projector and a camera. The diode-type laser projector (Lasiris SNF-533L, 20 mW, 670 nm) generates a light pattern of 33 equally inclined light planes that are directed toward the measured surface. The camera (Basler 301f, 656×494 pix., 8 bit, 80 frames/sec., FireWire) records the illuminated surface from a different viewpoint, and consequently, the light pattern is distorted by the shape of the surface. To improve the image contrast, by eliminating the ambient light, an interference filter (10 nm FWHM, centered at 670 nm) is placed between the lens and the camera’s CCD sensor. The measuring apparatus is designed to operate in two modes: high-speed and real-time. In the high-speed mode the image sequence is acquired first, and the processing is done later. The maximum acquisition speed is limited to 80 Hz by the camera. In the real-time measuring mode all the processing is done after each image is acquired. The maximum measuring speed is, therefore, lower. However, it is still fairly high, approximately 5 Hz, when using a 1-GHz Celeron processor.

The measuring range of the apparatus is approximately 40×30 mm in the horizontal plane and approximately 10 mm in the vertical direction. The calibration is made *in situ*, simply by replacing the specimen with a reference sample: a groove-shaped plate that can be measured at various heights. The parameters related to the optical geometry of the apparatus are then numerically optimized until the minimum deviation (the sum of the squared errors) between the measured points and the reference surface is found. The major advantage of this procedure is that all the transformation parameters can be determined in a single measuring step, i.e., the camera's internal parameters (focal length, central point and distortion), the projector's distortion and the projector's position relative to the camera (rotation and translation). The accuracy of the calibrated apparatus in vertical direction is ±7 μm, which is calculated as a standard deviation between points of a measured and nominal reference surface.

The measuring software enables us to view the three-dimensional shape of a measured object in a real time. We can choose between points-drawing, triangulated (Fig. 2) or shaded-surface rendering. Deformations can be magnified by a certain factor and/or compared with another, e.g., reference, surface.

3. Results and discussion

As the first set of experiments we have been chosen a small-diameter hole-drilling process, which was carried out on a 0.2-mm-thick steel plate. The plates were clamped circularly (with a radius of 12.5 mm) and illuminated at their center, i.e., near-cyclic-symmetrical loading conditions were achieved. The laser was operated in a pulsed mode and the frequency was varied from 50 kHz down to 440 Hz.. The pulse duration was also varied, depending on the variation in the frequency, which is related to the size of the heat-affected zone. As a consequence, the final deformation is closely related to the frequency. Table 1 shows the maximum deformations using different laser frequencies. The maximum deformations were found at 50 kHz, and the minimum were found at 442 Hz. The latter were very close to the detection limit of the apparatus during the process and below the limit after the specimen had cooled down.

Table 1: Maximum deformations of a plate after the hole drilling using various laser frequencies.

Freq. (kHz)	0.44	10.2	20.4	50.0
Max. def. during the process (μm)	7	370	540	590
Max. def. after the process (μm)	no detectable	6	23	54

In the second set of experiments we measured the plate deformations during the laser-engraving process. The specimen was clamped circularly, as in the first example. The engraved inscription (see Fig. 3) was the same size and shape in all cases. The laser was operated at maximum power and its frequency was varied from 1.3 kHz to 13.3 kHz. The maximum deformations during and after the laser engraving are shown in Table 2. We can see that the maximum deformations are closely related to the laser frequency. The deformations are minimal at the lowest frequency, where the pulse duration is also the smallest.

We found in both sets of experiments that the permanent deformations were much smaller (>20×) than the maximum deformation. This is mainly due to us using a high-strength steel plate.

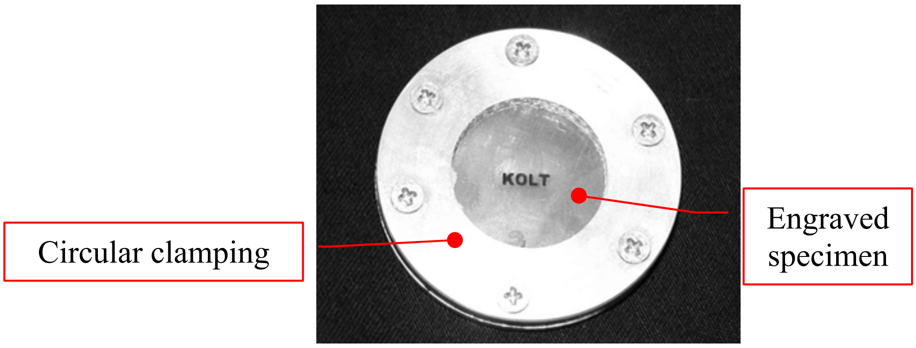

Fig. 3: Photograph of the clamped specimen with a laser-engraved inscription.

Table 2: Maximum deformations of a plate after the engraving process using various laser frequencies.

Freq. (kHz)	1.3	4.4	8.8	13.3
Max. def. during the process (µm)	200	420	530	510
Max. def. after the process (µm)	46	64	85	97

4. Conclusions

Our high-speed technique for full-field three-dimensional measurements of plate deformation presented above is opening up new possibilities for monitoring and controlling various laser-processing techniques, e.g., laser forming, drilling, cutting, and engraving. The measuring apparatus is based on a laser multiple-lines triangulation principle. It has a high measuring speed (80 Hz) and a high accuracy (±7 µm).
The full-field measurements of the steel-plate deformations during the laser drilling and engraving processes are presented for various laser-pulse frequencies. The presented measuring technique is a very useful tool that can help us to adjust the process parameters accurately and quickly in order to control the maximum allowable deformations.

5. References

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