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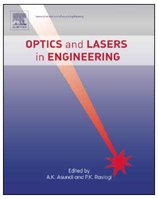

An experimental investigation of underwater pulsed laser forming

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ABSTRACT

Laser forming is a new forming technology, which deforms a metal sheet using laser-induced thermal stresses. This paper presents an experimental investigation of pulsed laser forming of stainless steel in water and air. The effects of cooling conditions on bending angle and morphology of the heat affected zone (HAZ) are studied. It is shown that the case of the top surface in air and the bottom surface immersed in water has the greatest bending angle based on the forming mechanism of TGM. The water layer above the sample decreases the coupling energy, leading to a small bending angle. For a thin water thickness (1 mm), the water effects on the HAZ are limited. As water layer thickness increases (5 mm), the concave shape of the HAZ is more remarkable and irregular because the shock waves by high laser energy heating water are fully developed. However, the area and the depth of the HAZ become less significant when water thickness is 10 mm due to the long pathway that laser undergoes.

1. Introduction

Laser forming is a new forming technology, which deforms a metal sheet by using the thermal stresses induced under a controllable laser beam heat source where external forces are not required. A review on the early work of experimental, numerical and theoretical studies of the process mechanism on laser forming is provided by Shen and Vollertsen in 2009 [1].

Geiger and Vollertsen [2] identified three key mechanisms to explain the thermo-mechanical behaviors in laser forming, namely temperature gradient mechanism (TGM), buckling mechanism (BM) and upsetting mechanism (UM). Some analytical models for determining the bending angle induced by the straight line scan in laser forming [3–5] have been developed. Numerical simulations have also been performed using various commercial codes [6–8] for evaluating the performance of laser forming. However, most of these studies focus on the forming process under the laser mode of continuous wave.

At present, there is a little work related to pulsed laser forming. An earlier experimental work for pulsed laser forming was described by Widlaszewski [9] in 1997. Experimental and numerical studies on micro-scale bending of stainless steel plates with pulsed laser were presented by Chen et al. [10], who compared the predicted deformations with experimental results. Lin et al. [11–13] investigated the vibration phenomenon and transient deformation during pulsed laser forming of thin metal plates using both numerical and experimental methods. Recently, Yang et al. [14] investigated the microstructure, micro-hardness and anticorrosion of the heat affected zone (HAZ) generated by pulsed laser forming. Parametric studies on the effects of material properties, laser power, beam diameter, scan velocity, sheet thickness, pass number and pulse duration on the bending angle of plates were studied by using finite element methods and/or experiments [15].

Since the deformation generated in the laser forming process is caused by thermal stresses, the overheating phenomenon in the heated area may exist. On the other hand, the small bending angle can be produced at each laser scan and a long waiting time is required between consecutive scans in order to reestablish initial conditions and avoid excessive surface oxidation or even melting. The effect of forced cooling on bending angle in multi-scan laser forming is investigated by Cheng and Yao [16]. In addition, the authors performed a comparison of material microstructure and mechanical properties in calm air and forced air. Different cooling schemes were carried out, including cooling on either top or bottom surface or both, varying the cooling air pressure, etc. Hennige and Geiger [17] conducted an experimental study on the influence of forced air and active water cooling in laser forming. It was highlighted that the employment of water as cooling medium can dramatically decrease the entire processing time and also increase the bending angle per scan. More recently, the effect of passive water cooling on non-irradiated surface in laser forming of thin sheets was experimentally investigated [18].

It is well known that heat accumulation around HAZ in laser bending is a noteworthy problem. In order to evaluate the effects

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of the cooling medium applied to the irradiated surface on the bending angle and surface quality, the experiment of pulsed laser forming of stainless steel 304 in water and air was carried out. The experimental set-up of laser forming was illustrated, and the bending angle as well as the morphologies of HAZ was presented in this paper.

2. Experimental set-up

Pulsed laser forming experiments were performed using an IPG fiber laser system operating at 1070 nm. AISI 304 stainless steel was used in the experiments because of its poor oxidation which reduces the change of absorption of the sheet surface during the forming process. The test samples were cut with a CO_2 laser to prevent them from residual stress and deformation. The size of the sheet samples is 100 mm × 50 mm and the thickness is 1 mm. No coating was used for samples in this experiment in order to better reproduce real industrial conditions. The clamped sheet sample was mounted onto a numerically controlled table and the laser scanning was executed along the direction of the sample's shorter side.

Angle deformations (orthogonal to the laser beam scanning direction) were determined by using the displacements in the *z*-direction, which were measured by a laser optical scanning system. In order to evaluate the repeatability of measurements, three measurements of the bending angle were performed on each sample. HAZ produced by the laser pulse was observed by a microscope and its profile was characterized utilizing a Keyence KS-1100 3D optical surface profilometer. In addition, in order to evaluate the treatment variability, two replications were performed for each processing condition.

The laser pulse parameters include the peak laser power, pulse duration and pulse frequency. As shown in Fig. 1, the laser energy E for a rectangular pulse can be expressed in terms of the peak power P_P and pulse duration τ as follows:

$$E = P_P \times \tau \quad (1)$$

The average laser power P_a can be defined as follows:

$$P_a = E/T \quad (2)$$

where $T=1/f$ and f is the pulse frequency.

Thus, the average laser power P_a can be rewritten as follows:

$$P_a = P_P \times \tau/T = P_P \times \tau \times f = P_P \times dc \quad (3)$$

where τ/T is the duty cycle dc. In this study, the laser peak power $P_p = 1580$ W and the duty cycle $dc = 10\%$ were chosen for different experiment conditions. This means that the relationship between the pulse duration τ and the frequency f can be solely determined by Eq. (3). According to the capacity of the laser system, six levels of the pulse duration and frequency were involved, the pulse duration from 0.2 ms to 10 ms and the frequency from 500 Hz to 10 Hz, respectively, as summarized in Table 1. Five different cooling conditions used in pulsed laser forming are listed in Table 2, including the irradiated surface with/without water layers. For the cooling condition of water 0, a portion of the sample (about 60% of the sheet thickness) is mounted under distilled water of 20 °C, which means that the area of the bottom surface beneath the laser scan line of the sample is immersed in water during the laser forming process, as shown in Fig. 2(a). The sample with water was placed in a plastic container. The underwater of laser forming is shown in Fig. 2(b), where h denotes the water thickness above the sample surface and varies from 1 to 10 mm. As a benchmark, the laser forming in air is also investigated. The distance between the lens and the sample was kept constant during all experiments.

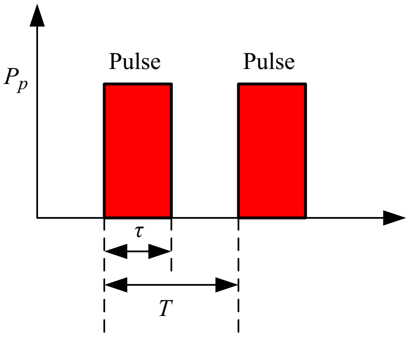

Fig. 1. Schematic diagram of laser pulse.

Table 1
Processing parameters used in experiments.

Case no.	Pulse duration τ (ms)	Energy per pulse E (J)	Frequency f (Hz)	Duty cycle dc (%)	Cooling condition
1	10	15.8	10	10%	1–5
2	5	7.9	20	10%	1–5
3	2	3.16	50	10%	1–5
4	1	1.58	100	10%	1–5
5	0.5	0.79	200	10%	1–5
6	0.2	0.316	500	10%	1–5

Table 2
Cooling condition.

Cooling condition	Cooling medium
1	Air
2	Water 0
3	Water 1 (h=1 mm)
4	Water 5 (h=5 mm)
5	Water 10 (h=10 mm)

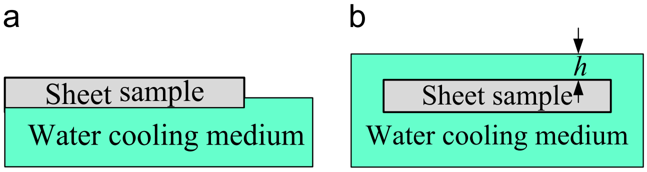

Fig. 2. Water cooling conditions employed in the laser forming process.

A series of preliminary tests were performed in order to obtain a proper scanning velocity in a given laser beam diameter, which makes the samples have enough deformations to measure for the process window listed in Table 1. Hence, the scanning velocity (V) of 20 mm/s and the laser beam diameter on the irradiated surface of 1.5 mm were selected. All experiments have also involved a single pass. The experimental set-up of pulsed laser forming in air and underwater is shown in Fig. 3.

3. Results and discussion

3.1. Bending angle

Fig. 4 shows that the bending angle decreases with the increase of the laser pulse frequency. Although the line energy (P_a/V) is constant under different processing conditions, the peak temperature on the top surface is lower with the higher frequency because of less heat accumulated. The more absorbed pulse energy of the sheet generates a greater temperature gradient between top and bottom surfaces, which makes the bending angle larger under