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Surface characteristic of stainless steel sheet after pulsed laser forming

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ABSTRACT

Laser forming is a non-contact and die-less forming technique of producing bending, spatial forming, modifying and adjusting the curvature of the metallic sheet by using the controlled laser beam energy. One of the problems in laser forming is controlling the characteristic of laser scanned surface. The aim of the investigation is to explore the relation between the surface behaviors of heat affected zone (HAZ) scanned by pulse laser and the pulse parameters of the laser. This paper illustrated the fundamental theory of pulsed laser affected material, and pays attention to the microstructure, micro-hardness and the anticorrosion in the HAZ generated by the laser scanning. Metallographic microscope, scanning electron microscope (SEM), micro-hardness testing system are used to examine the surface characteristics. The work presented in this paper is beneficial to understand the mechanism of pulse laser affect to materials and improve controlling the surface behaviors scanned by pulsed laser.

1. Introduction

Laser forming is a process that has been investigated over the last twenty years or so as a novel material processing technique. The process is achieved by introducing thermal stresses into a work-piece by irradiation with a laser beam, thereby inducing rapid localized heating followed by cooling as the laser energy is either switched off or moved on to an adjacent area. One of the main advantages of the process is that it allows die-less and therefore contact-less forming procedure. As a consequence of the thermal induced forming process no spring-back occurs in the cooling phase after the laser is switched off [1]. And the high potential of laser forming for rapid prototyping demands and small series production was realized soon. In addition, the process is suitable for complex alignment tasks of extrusions and sheet metal parts. Presently, it is also considered as a forming technique for shaping hard and brittle materials that are problematic for conventional methods. Aerospace, shipbuilding, microelectronics and automotive industries have shown interests in this forming technique.

The early years of experimental and theoretical studies of process mechanisms, models and potential applications on laser forming were the subject of a comprehensive review by Magee in 1998 [2]. Geiger and Vollertsen [3] identified three key mechanisms to explain the thermo-mechanical behaviors in laser forming, these comprise the Temperature Gradient Mechanism (TGM), the Buckling Mechanism (BM) and the Shortening or planar Upsetting Mechanism (UM). Some analytical models for bending angle induced by the straight line scan in laser forming [4–8] have been presented, and numerical simulations have also been performed using various commercial codes [9,10] for laser forming. In order to increase the plastic deformation, the method that of adding external forces or bending moments during the laser forming process has been applied [11]. For a multi-scans study, numerical investigations have been carried out to examine the difference in temperature fields and plastic deformations between the two simultaneous laser scans and the sequential scans [12].

The laser forming process has been investigated in applications of many materials, such as mild steel [13], stainless steels [14], aluminum and aluminum alloys [15], titanium and its alloys [16], silicon [17,18]. For laser forming different types of lasers, such as Nd:YAG laser [19], CO_2 laser [10–13], diode laser [20,21] and others can be used. The influences of applied laser type on the experimental results can be put down to the fact that the specific wavelength of laser influences the interaction attributed to the material and selected laser parameters. There are many results of research activities about the influence on geometrical and energetic parameters. Decisive conditions for laser forming are a high temperature limited by surface melting and a high temperature gradient. Both demands are fulfilled by the high energy density of most kinds of lasers. The pulse parameters are the important influencing factors in the pulsed laser forming. The vibration phenomenon and transient deformation during pulsed laser forming of thin metal plates were investigated numerically and experimentally [22–24].

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Cheng et al. [25] presented an integrated fracture toughness model to study the fracture toughness of sheet metal after laser forming and illustrated a fatigue life model for the laser forming process of low carbon steel [26]. McGrath and Hughes [27] found an enhancement in fatigue life after laser forming based on fatigue life tests. Shen et al. presented the low carbon steel fatigue life based on the distribution of residual stresses under different laser processing parameters using low-cycle fatigue tests [28]. This observation can be attributed to the laser-hardening mechanism and the compressive residual stresses induced in the component after the laser forming application, both of which would result in a longer fatigue life. However, this study focused on the design of the fatigue life test, and the influence of the laser processing parameters on the microstructure was of little concern.

In this paper, the experiment of pulsed Nd:YAG laser forming of austenitic stainless steel 1Cr18Ni9 was carried out. And the fundamental theory of pulsed laser affected material was illustrated, and the relation between the surface behaviors of heat affected zone (HAZ) and the laser pulse parameters was presented. The microstructure, micro-hardness and the anticorrosion in the HAZ generated by the laser scan were tested with the metallographic microscope, scanning electron microscope (SEM) and micro-hardness testing system.

2. Mathematical theory of pulsed laser scanning

The pulse parameters of laser energy include the pulse height, pulse width (the pulse duration) and pulse frequency. The laser energy E in a rectangular pulse with a peak power P_P and a pulse width τ is given by:

$$E = P_P \cdot \tau \tag{1}$$

The mean outer power is equal to the number of the pulse energy issued by the laser in 1 s. So, in output pulses of energy E are issued at the rate of f pulses per second, then the mean outer power P_0 is given by:

$$P_0 = E \cdot f \tag{2}$$

Moreover, since pulse peak power is roughly proportional to the square of pulse height H, for the purposes of this discussion we can replace P_P by cH^2 (c is constant) in the expression for E to give

$$E = cH^2 \cdot \tau \tag{3}$$

And this can be substituted in the expression for P_0 to give

$$P_0 = cH^2 \cdot \tau \cdot f \tag{4}$$

A set of pulsed laser parameters is now defined that will help to clarify the approach used in this work: average peak power $P_P = E/\tau$, average peak power density $P_D = P_P/S$, where S is the area of the laser spot, if T is the pulse-to-pulse time, so the duty cycle $C_D = \tau/T$.

The pulsed laser forming process is actually a series of overlapping spot or discrete spot formed [29], as shown schematically in Fig. 1. To express the mathematical relationship of the overlap theory, relevant equations are formulated as follows. If v is the travel speed, d_{min} the minor diameter of the spot formed (laser spot diameter), d_{max} the major diameter of spot formed from a laser spot plus movement during a pulse ($d_{max} = d_{min} + v \times \tau$), and d' is the length in a single spot not overlapped by successive forming spots ($d' = v \times T$), and assuming one-dimensional overlapping, the rate of overlap, P_{PER}, in the X-axis direction is

$$P_{PER} = \frac{[d_{max} - d']}{d_{max}} \times 100\% = \left[1 - \frac{d'}{d_{max}}\right] \times 100\% = \left(1 - \frac{v \times T}{d_{min} + v \times \tau}\right) \times 100\% \tag{5}$$

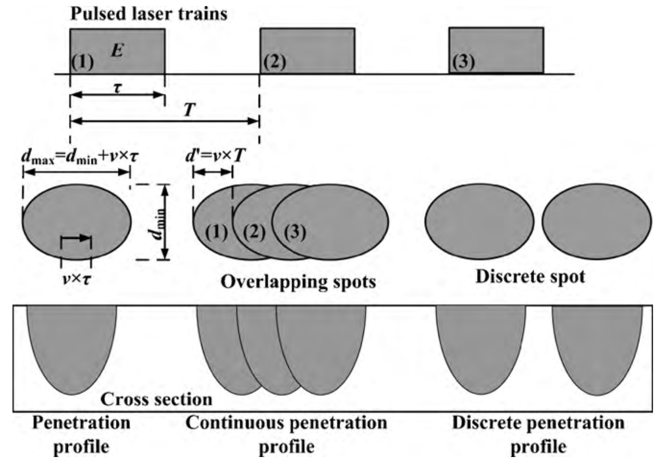

Fig. 1. Schematic diagram of laser power pulse trains and their corresponding partially overlapping spot.

For pulsed laser forming applications, the constraint $0 < P_{PER} \leq 1$ exists, the traverse speed for pulsed laser seam forming applications is subject to the following mathematical relationship:

$$0 < v \leq \frac{d_{min}}{T - \tau} \tag{6}$$

The interaction time (t_{in}) for pulsed laser forming in the one pulse:

$$t_{in} = \frac{d_{min}}{v} \times C_D = \frac{d_{min} \times \tau}{v \times T} \tag{7}$$

The overlapping rate:

$$P_{PER} = \left(1 - \frac{v \times T}{d_{min} + v \times \tau}\right) = \left(1 - \frac{d_{min} \times \tau}{d_{min} \times t_{in} + d_{min} \times \tau \times C_D}\right) \tag{8}$$

Fig. 2. Experimental set-up of laser forming.