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Simulation on deforming progress and stress evolution during laser shock forming with finite element method

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ABSTRACT

Laser shock forming (LSF) employs laser shock wave to form metal sheet, which is similar to explosive forming. Finite element method (FEM) is an effective method to better understand mechanism of LSF and select appropriate parameters to shape metal sheet accurately with LSF. In this paper, FEM analysis model is developed to simulate LSF, which includes how to determine the pressure loading, material constitutive model, and solution time. The commercial code LS-DYNA is applied to simulation. A sequence of dynamic deformation behaviors of metal sheet at the end of different periods are presented and discussed in detail, and the peculiar phenomena in dynamic deformation processing are discovered, which do not appear in the traditional forming processing. The final static deformation and residual stress are also predicted. The predicted results are accordance with the experimental data.

1. Introduction

Laser shock processing (LSP) is being served as a competitive surface treatment technique to strengthen metal material. LSP can refine material structure (Lu et al., 2010), and squeeze the beneficial compressive stress into material to a deeper depth than that achieved by shot peening (Hammersley et al., 2000), so the treated workpiece has better resistance to stress corrosion (Lim et al., 2012), and has a longer fatigue life (Lavender et al., 2008).

Laser shock can also induce plastic deformation, even fracture. Guo and Caslaru (2011) have fabricated micro dents on surface of titanium Ti–6Al–4V plate with pulse laser, which possesses average power ranged from 1 W to 4 W. The experiments show that the surface plastic dent depth increases with laser power increasing, and the deepest depth can be achieved 1 μm. O'Keefe et al. (1973) have studied the stainless steel irradiated by the laser with a flux of 1.4 GW/cm^2. The results exhibit that one-sided laser shock can lead to permanent deformation in cross section of metal sheet with thickness 0.063 cm. Zheng et al. (2013) have conducted experiment with $Fe_{78}Si_9B_{13}$ metallic glass shocked by laser. The experiment results show that strong pulse laser can lead to thin metallic glass failure. These investigations indicate that laser shock can shape metal sheet if its parameters are selected appropriately. In recent years, laser shock has been proposed as a tool to form metal sheet, which is similar to explosive forming. It is called laser shock forming (LSF). Compared with explosive forming, LSF is a safe and precise forming technique, because the location to be processed and the intensity of shock wave can be controlled accurately. So it seems to be very promising in practical application.

There have been lots of attempts in experiments and simulations to probe LSF basic peculiarities. Zhou et al. (2002) have employed experimental approach to deform a stainless-steel sheet with laser, and they discover some non-linear plastic deformation characteristics in LSF. Niehoff and Vollertsen (2005) have investigated the 50 μm thick Al99.5 foils impacted by laser, and gained some uniform domes. They point out particularly that LSF is a non thermal stretch-forming technology. Cheng et al. (2007) have employed laser to deform a copper foil with thickness 15 μm. Their investigations reveal that material grain has been refined and tensile stresses are distributed on both side surfaces of component after LSF. Fan et al. (2005) and Wang et al. (2005, 2007) have studied the copper stripes peened by laser. They report that the stripes bend upward and the compressive residual stresses are distributed on its both-sided surfaces after laser treatment. Sagisaka et al. (2010) have bended pure aluminum *A1*100-H18 (in JIS) with femtosecond laser. They claim that it is helpful to improve bending efficiency by means of elastic pre-bending and large laser spot during LSF. Nagarajan et al. (2013) have explored micro-dents array on copper thin film using LSF without mold. The experimental results demonstrate that it is feasible to implement fabricate

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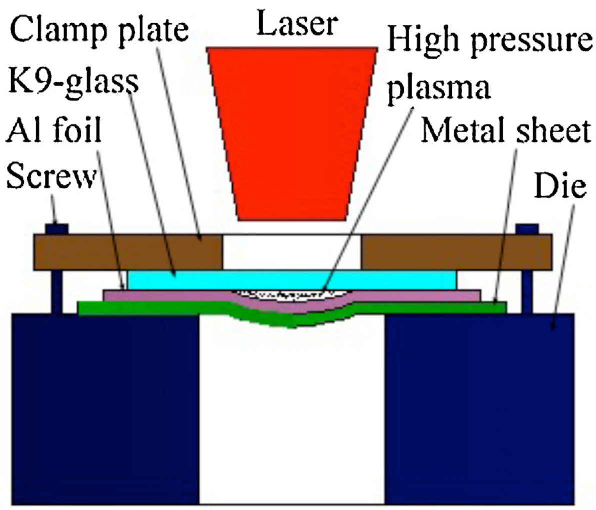

Fig. 1. Schematic of the setup for LSF.

near-spherical microcraters on thin metallic surface with LSF. All these researches are very useful to understand the characteristics of LSF. However, these investigations mainly focus on the influence of parameters on the deformed workpiece quality, and scarcely refer to dynamic behaviors of metal sheet. Up to present, there have been rare researches touched on the dynamic behaviors during LSF, because the dynamic deformation behaviors of metal sheet under ultrahigh strain rate are very complicate, and extremely difficult to be measured in situ experimentally. Wielage and Vollertsen (2011) have bended metals foil, Al and Cu, with laser shock wave. They conclude that, under the action of shock wave pressure 2.3 MPa, the temporal deformation velocity can be reached 40 m/s, and its strain rate attains 2×10^3 s^{-1}. Gao et al. (2009) have used finite element method (FEM) to simulate LSF process and its failure, in which copper foils (3 –15 μm thickness) were subjected to lasers with different intensities (0.5–1.2 GW/cm^2). They have investigated the effects of the critical parameters on its deformation behaviors, and obtained some important findings. However, their researches are confined to μLSF. Due to the effect of size, some dynamic behaviors in micro LSF are different from those in thicker plate LSF. Some dynamic forming characteristics are still unknown. Therefore, the dynamic deforming process of LSF is still worth research.

The aim of current work is first to introduce FEM to simulate metal sheet ultrafast dynamic response to laser shock, and then to achieve a better understanding of transient behaviors during LSF and gain an insight into the mechanism of LSF. The FEM model based on the commercial code LS-DYNA (2010) is described in detail. Dynamic behaviors of metal sheet have been analyzed. The final deformation and residual stress obtained from FEM are compared with the experimental results.

2. Mechanism of LSF and experimental setup

LSF employs mechanical force, a high pressure shock wave pulse, to deform metal sheet, while metal sheet is not affected thermally. It is different from laser forming, which uses laser to deform metal sheet by high temperature gradient between the irradiated surface and the neighboring material. The setup for LSF is shown in Fig. 1.

Prior to laser irradiating, a candidate metal sheet is laid on the top of die, and some coverings are deposited onto it top surface in advance. First, an aluminum foil (or black paint), served as laser ablating layer, covers metal sheet top surface to protect it from thermal damage. Subsequently, an **o**ptical glass, K9-glass with thickness 4.5 mm to act as overlay, is set on the top surface of an aluminum foil to increase the peak pressure of shock wave and prolong its action time. Finally, a blank holder, a thick plate with an axial hole at the center, is placed on K9-glass surface, which clamps tightly the above mentioned materials to die. These coverings are in place, and laser shock can be carried out. A high-power, Q-switched, pulsed neodymium-glass laser is used to produce a short-duration high-power pulse, which passes through k9-glass and illuminates vertically aluminum foil surface with a desired spot. The aluminum foil is partly vaporized immediately and generates plasma. The vapor and plasma proceed to absorbing the follow-up incident laser energy, and then expand and explode violently, which result in a strong pulse pressure on surfaces of K9-glass and metal sheet. The instant shock loading induces stress wave propagating into material and pushes metal sheet into die cavity. If metal sheet acquires sufficient momentum from shock wave, it deforms in line with the die, and the desired shape of metal sheet is obtained.

Table 1
Mechanical properties of LY12CZ.

Property	Value
Yield strength $\sigma_{0.2}$ (MPa)	275
Tensile strength σ_b (MPa)	435
Elongation δ (%)	11
Elastic modulus E (GPa)	68.9

In experiment, the material was a quenching and artificial aging of LY12CZ aluminum alloy, which was super hard and widely used in aircraft structure components for example, plane beam and frame rib. Its chemical composition (wt.%) was: 1.54 Mg, 0.58 Mn, 4.61 Cu, 0.29 Fe, 0.26 Si, 0.1 Zn, 0.024 Ni, and its mechanical properties were shown in Table 1. The specimen was 40 mm in diameter and 0.4 mm in thickness. It was irradiated by laser pulse with a full width at half maximum (FHWM) 23 ns, a wavelength 1.064 μm, energy 34 J per pulse, a repetition rate 2 Hz and a spot size 8 mm in diameter. The axial hole in blank holder was 16 mm in diameter, and the size of hole in die was 14 mm in diameter. After laser shock, the profile of the cross section of the deformed metal sheet was measured with a contour meter PGI400 (Taylor Hobson, England), and the residual stress was measured by X-ray diffraction tester XTress3000 (Stresstech Oy, Finland). In order to allow direct comparison, some data of the experimental conditions were imported into FEM model to simulate metal sheet dynamic responses to laser shock. The experimental results were used as references to validate FEM results.

3. FEM

3.1. Calculation code choosing

Numerical simulations of the material response to LSP with the commercial codes have been extensively reported. Braisted and Brockman (1999) first established 2-D FEM model to predict residual stresses. Ding and Ye (2003) also developed similar model to simulate metal material dynamic responses to different LSP treatment conditions and its final residual stresses. Yang et al. (2008) further utilized FEM to analyze effect of geometrical size on residual stresses induced by LSP. In these simulations, the commercial codes ABAQUS/Explicit and ABAQUS/Implicit were employed jointly. Hu and Yao (2008) utilized 3-D FEM with software LS-DYNA and ANSYS, instead of ABAQUS package explicit and implicit, to predict residual stresses of metal alloy subjected to LSP. These simulation processes all include explicit analysis step and subsequent implicit analysis step. The explicit analysis step is used to solve the dynamic response to LSP, and the following implicit analysis step is applied to making material become stable without long time. Peyre et al. (2007) applied ABAQUS to simulate LSP for 12% Cr martensitic