Laser Micro Bending Process of Ti6Al4V Square Bar

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Abstract: Laser micro bending process of Ti6Al4V square bar are carried out using a 3D thermo-mechanical finite element analytical model (FEM). The transient temperature fields, displacement fields, stress fields and strain fields are obtained and analyzed. The results show that the bending angel during laser micro bending process is in good agreement with experimental measurements. The effects of process parameters on temperature and deformation are also investigated here. During the bending process the temperature increases with the increase of the laser power and the irradiation time. Radiation of the laser beam yields to a rapid temperature increase at the irradiated surface, which leads to the high temperature gradients between the irradiated surface and the unirradiated surface, which suggest that the mechanism of laser micro bending is the temperature gradient mechanism. The z displacement of forward direction and reverse direction increase when the laser power and irradiation time increase. Laser micro bending process can obtain the larger bending angles reverse to laser beam using higher laser power and shorter irradiation time.

Keywords: laser micro bending; square bar; bending mechanism; FEM

1. Introduction

As a new type of flexible manufacturing process for precise mechanical components, laser micro bending is the accumulative forming method under the thermal state condition. Furthermore, it can shape hard or brittle metals, such as Ti-alloys, etc. However, traditional methods proved to be inapplicable or highly consuming. Moreover, there is no springback in the cooling process because of
the forming process in the thermal state. In addition, laser micro bending can be used for compound process with forming, cutting and welding easily [1].


These researches above gave many helpful instructions for the plate or foil in laser micro bending. The attention on laser micro bending has been focused on linear and curve irradiation paths. However, few researches have been focused on the laser micro bending of square bar with spot irradiation. Micro square bar has the characteristics of good stability compared with plate or foil. The main application area for micro square bar is the electronic sector, MEMS and other fields, are playing an increasingly important role. The laser micro bending mechanisms of square bar and plate are different due to the size difference. This paper aims at a systematic understanding of the thermo-mechanical reaction of square bar during laser micro bending. The finite element analytical model including establishment of laser spot heat flux and boundary conditions is built. The temperature fields, displacement fields, stress fields and strain fields under provided conditions are analyzed. Effects of laser power and irradiation time on temperature and deformation are also investigated.

2. Finite Element Analytical Model

Figure 1 shows the schematic diagram of the laser micro bending process of square bar. The z-axis is defined as the direction of laser beam irradiation. The x- and y-axes are defined in the plane of the bar. The length of the bar is 25 mm, the width and the thickness is 0.5 mm. The end of the bar is constrained, and the other end is in a free state. The middle position of the bar surface is irradiated by laser beam. The material is Ti6Al4V, its thermo-physical property parameters taken from [10]. The distribution of laser intensity follows the Gaussian mode. During the laser bending process, the heat flux density obeys the normal distribution as Equation (1).

\[ I = \frac{2AP}{\pi R^2} \exp\left(-\frac{2r^2}{R^2}\right) \]  

(1)

where \( I \) is the thermal flux density of the laser beam, \( A \) is the absorption coefficient on the sheet metal surface, \( P \) is the output power of laser, \( R \) is the radius of the laser beam irradiated to the surface of the
sheet metal, and \( r \) is the distance from the laser beam center.

The other boundary condition is as follow:

\[
K \frac{\partial T}{\partial n} = h(T - T_0) + k_c(T - T_0)
\]  \hspace{1cm} (2)

where \( n \) expresses the direction of the surface, \( h \) is the natural convection exchange coefficient, and \( k_c = \varepsilon \sigma (T^2 + T_0^2)(T + T_0) \), where \( \varepsilon \) is the surface emissivity and \( \sigma \) is the Boltzmann constant.

3. Results and Discussion

3.1. Analysis of Temperature Fields

Figure 2 shows the temperature distribution at \( t = 1 \) s. It can be observed that obvious temperature gradient in the irradiation region can be found due to the heat exchange. As can be seen in Figure 3, irradiation of the laser beam yields to a rapid temperature increase at the irradiated surface, which leads to high temperature gradients between the upper and lower surfaces. So, the mechanism of laser micro bending is the temperature gradient mechanism.
3.2. Analysis of Displacement Fields

Figure 4 shows the bending angles along with irradiation time. It can be seen that the simulated results during the laser bending process and the experimental results demonstrate good correlation. A noticeable counter-bending occurs due to thermal expansion in the irradiation zone when the laser beam has just irradiated the square bar. After the laser beam irradiating the bar, the irradiation surface begins to show shrinkage and the lower surface begins to expand due to heat transfer, which causes the
deformation in the direction of the laser beam. The final displacement can be gained while cooling to room temperature, which can be seen as Figure 5.

**Figure 4.** Bending angles along with irradiation time.

**Figure 5.** Displacement distribution at $t = 1$ s: (a) $x$ direction; (b) $y$ direction; and (c) $z$ direction.
3.3. Analysis of Stress and Strain Fields

The simulation results shown that the temperature and displacement distributions referred above, the yield stress and plastic strain distributions displayed in Figures 6 and 7. It can be seen that
compressive stresses occur in the irradiation zone because the materials around the radiation zone are cold, and slight tensile stresses occur in the neighboring areas. The unirradiated surface keeps compressive strain during the irradiation process. Moreover, there exists a large strain difference between the irradiated surface and the unirradiated surface in the three directions in the irradiation zone, which leads to the bending deformations.

**Figure 6.** Stress distribution at $t = 1$ s: (a) $x$ direction; (b) $y$ direction; and (c) $z$ direction.
Figure 6. Cont.

Figure 7. Strain distribution at $t = 1$ s. (a) $x$ direction; (b) $y$ direction and (c) $z$ direction.
3.4. Effects of Laser Power and Irradiation Time on Temperature

In practical work, laser micro bending is a thermo-mechanical coupling process, but solving the coupling problem is too complicated. The main mechanism of the laser micro bending process is the
temperature gradient mechanism. Figure 2 shows a steep thermal gradient into the material that result in a differential thermal expansion through the thickness due to the laser beam rapid irradiation. For the spatial work piece, the temperature gradients are mainly concerned with the temperatures of laser beam irradiated surface. So, the temperature of irradiated surface can evaluate the variation mechanism of the laser micro bending process. Moreover, the effects of the laser power and the irradiation time on the temperature fields are investigated systemically using the finite element simulation.

Figure 8 shows variation of temperature with laser power. It can be seen that the temperature increase when the laser power increases. Figure 9 shows variation of temperature with irradiation time. The temperature increases with the increasing of the irradiation time. Effects of laser power and irradiation time on the temperature play the same role. However, the relationships between temperatures and processing parameters are non-linear.

**Figure 8.** Variation of temperature with laser power.

![Figure 8](image1)

**Figure 9.** Variation of temperature with irradiation time.

![Figure 9](image2)
3.5. Effects of Laser Power and Irradiation Time on Deformation

Figure 10 shows variation of displacement with laser power. It can be seen that $z$ displacement of forward direction and reverse direction increase when the laser power increases. However, $z$ displacement of the reverse direction is mainly. The ratio of reverse direction deformation and forward direction deformation is 4.2 when laser power is 700 W.

Figure 11 shows variation of displacement with radiation time. It can be observed that the bending deformation time increases when the radiation time increases. However, the effect of radiation time on the bending deformation of the square bar is lesser.

**Figure 10.** Variation of displacement with laser power.

**Figure 11.** Variation of displacement with irradiation time.
3.6. Surface Quality Analysis

Figure 12 shows surface morphology of laser radiation zone. The morphology in the laser irradiation region is circular due to the laser beam Gaussian profile. Morphology change is mainly oxidation of material under the action of laser radiation, which can be seen in Figure 13. The degree of oxidation of the material is very small, which does not affect the application requirements.

**Figure 12.** Surface morphology of laser radiation zone.

**Figure 13.** Element analysis of laser radiation zone.

4. Conclusions

A finite element model of heat flux based on laser micro bending was built. The proposed model can be used to make the thermo-physical process simulation of laser micro bending. Finite element
simulation of transient temperature fields, displacement fields, stress fields and strain fields produced by laser beam radiation on the forming square bar were carried out. The simulated results are in good agreement with experimental results. The temperatures of sheet increase with the increase of the laser power and the radiation time. The $z$ displacement of forward direction and reverse direction increase when the laser power increases. However, $z$ displacement of the reverse direction is mainly. The bending deformation time increases when the radiation time increases. However, the effect of radiation time on the bending deformation of the bar is lesser. The radiation of the laser beam yields to a rapid temperature increase at the irradiated surface, which leads to high temperature gradients between the upper surface and the lower surface. The mechanism of laser micro bending is the integrated effects of the temperature gradient mechanism.

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Author Contributions

Peng Zhang contributed on the process design. Gang Chen contributed on the process analysis. Gang Chen and Peng Zhang wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

References


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