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Experimental Research and Numerical Simulation of Heat Transfer of Nanosecond Laser Ablation Wood

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By using nanosecond laser material ablation, which is widely used in mechanical micro machining fields. Based on this theory, in the northeast of red pine as the research object, establish the wood ablation heat transfer model, and derive the relationship between laser power density and the depth of ablation. Through simulate internal temperature distribution of wood in the ablation process and ablation depth, using the software, the experimental results are verified with simulation analysis approximation(Bo et al., 2010). After laser ablation wood interior presented regulation of temperature gradient, wood surface appear carbonation phenomenon(Chi et al., 2000). Through this process, with guidance function of the theory to control the actual design of laser parameters, and find reasonable laser ablation area through the ablation depth and laser power density relation, in order to provide theoretical basis for the relief of laser sand mill design.

1. Introduction

Laser has the characteristics of coherence, monochromaticity, directivity and high power density output, with the rapid development of laser processing technology, it’s widely used in surface processing, punching, cutting, welding, heat treatment and so on many domains(Jiang et al., 2006). With the improvement of factory automation requirements, the wood industry is considered as one of the areas which is most likely to use laser technology since the wood has a very good processability relative to the lase source(Marletta and Evola, 2013). When the laser is used in wood processing, there are a variety of different methods and processing conditions, such as using what kind of method and what kind of strength or trees can reduce the burning degree of ablation mouth, under what conditions can increase the ablation depth and make the fracture crack is relatively narrow, so as to achieve good processing conditions when laser ablation wood, it’s necessary to carry out research in this area. In this paper, in order to implement sanding for the surface of pine anaglyph, find the best way to eliminate surface roughness under the best action of sanding; established the thermodynamics model for the surface of pine anaglyph when laser ablation instantaneously, by considering the energy absorption and the mechanism of heat transfer, latent heat, thermal parameters of materials, simulated the distribute of temperature field and the parameters such as the shape and depth of the laser ablation analyzed and compared with experimental results at the same time, obtained referenced date after the laser ablation process, not only contributed to deeply understand the physical mechanism of action between laser and wooden materials, but also take a theoretical guiding function to the control parameters of actual design(Ming et al., 2001). In the meanwhile, find reasonable sanding area of the laser ablation from thermal stress distribution of pine embossment, on the basis of cell crack experiment image analysis, get the sintering process condition of pine anaglyph embossed shaped surface by laser ablation, find out formation mechanism of sanding and ablation, can provide a theoretical basis for the design of anaglyph laser sand mill.

2. The laser ablation mechanism of wooden material

There are two different mechanisms in the laser processing for wooden materials: the instantaneous evaporation and combustion. Laser processing depends on the power density and irradiation time, in irradiation instant, if the laser power density is big enough to cut point of materials to form a vaporization seam. In this process, the wood cutting speed is fast, heat can’t transfer to the base material uncut, carbon-

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free cutting surface is only slightly dark and glaze(Sivakumar et al., 2015). In irradiation instant, if the laser power density is insufficient, it can only reach wood burning, material formed molten slag when burnt and blowing away from the cutting seam under the influence of auxiliary gas(Stefanizzi et al., 2013).

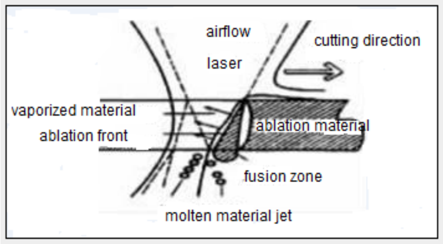


Figure 1: Laser machining process

An actual wood cutting process almost at the same time accompanied by the evaporation mechanism of the combustion process. The reason is that although the mechanism is evaporated with high efficiency, but requires a high laser power density, in the parts of the material irradiated site, beam power density is lower than needed by evaporation in the irradiated site of material. In addition, formed combustible and noncombustible gas in the evaporation process, produced water vapor and leaved some coke unevaporated. Laser machining process diagram as shown in figure 1.

3. Experimental equipment and analysis

3.1 Experimental equipment and materials

Ablation apparatus used in the experiment shown in figure 2, consists of the following parts: the cooling system, laser, power supply, control system, focusing system, observe the alignment system, gas injection device and operation platform. The type of loser power is JDW3-250, the type of laser is YAG, the cooling system is PH-LW06-BLP laser water chiller, focusing system consists of combination of optical lenses.

The pine anaglyph is experimental materials(moisture content 16.8%), the thickness of 20 mm, a template of typical furniture relief. First cut and polish the specimen and do simple dry processing, then use laser to do surface ablation treatment.

Figure 2 ablation equipment

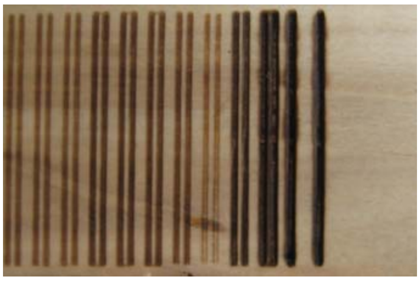


Figure 3: Ablation surface of target

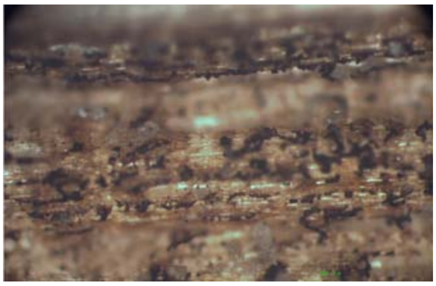


Figure 4: Part of target surface

Figure 5: The target material microstructure

3.2 Experimental results and analysis

As shown in figure 3 nanosecond pulse laser ablation topography in the same deal relief target material surface with the same laser parameters(wavelength, frequency, pulse width), but choosing different power intensity. Can be seen from the figure, laser ablation region showed obvious trench morphology erosion pit, there is a weak subsidence in the center of trench ablation region, little depth, there are some raised edges and a little fuzzy on both sides, surrounded by hot melt traces, leaving some residual coke at the same time, is the region influenced by thermal effects of laser largely.

As shown in figure 5 is the tissue microstructure of pine anaglyph after ablation under the microscope, under the action of high power laser intensity, organization vaporizing disappeared at the ablation center of the anaglyph surface, forming strip pit recessed, we can see the changes of laser power intensity parameter have a great impact on the ablation effect.

4. Numerical simulation analysis

Laser ablation process to wooden target is described as follows: when nanosecond pulsed laser act on the anaglyph surface, except part of the laser energy is reflected, the other most of the laser energy is absorbed by the anaglyph surface, causing the phenomenon such as temperature, melting, gasification. Laser beam irradiates on the surface of anaglyph, anaglyph surface absorb the laser energy, making the local surface temperature rise sharply, phase-change situation will occur when the melting point of wooden material and gasification temperature is reached, continue heating when laser energy absorbed by relief surface reach ablation latent heat, part of the material will be evaporated from the surface of the target.

The heat conduction in the process of nanosecond pulse laser heating wooden material, should constitute a three-dimensional heat flow problem, but because of the laser pulse duration is very short, in such a short time, the macro diffusion distance of heat conduction should be very small, which means that the ablation depth of target material should be very small. Therefore, the vertical depth to the surface of the target should be shorter several orders of magnitude than parallel radius to the surface of the target. As a good approximation, when dealing with problems of heat conduction, the relief surface can be seen as infinite plane, the related heat conduction problems can be seen as the problems of nanosecond pulse laser energy transmit along target material surface perpendicularly and flow to lengthways depth of target material along this direction.

4.1 Theoretical model

Heat conduction equation

Assuming that the laser beam shoot into body surface perpendicularly(Z=0), the heated material target is located on the upper half-space, the reflectivity of target material surface for laser is R(x,y,z), the power density of incident laser beam at Z=0 is I_0(x,y,z), the temperature field of the target material T can be described by the heat conduction equation:

$$\rho c \frac{\partial T}{\partial t} = \nabla \times (k \nabla T) + (1 - R)\alpha I_0 e^{\alpha z} + Q \quad (1)$$

In the formula, thermal physical constants(material density), c(material specific heat), k(material coefficient of thermal conductivity) related to the position and the temperature; $\nabla$is the gradient operator; Q is other solid heat source term and t is more than 0, z is more than 0.

Plane heat source equation

Target material for laser absorption occurs within the scope of the surface layer is thin, and concentrated in the vicinity of the laser spot, almost no absorption spot outside, therefore the laser source can be used as a plane heat source when considering the simulation of laser ablation. The second term on the right side is solid heat source, if far less than 1 or R is approximately equal to 1, using surface absorptivity A instead of 1-R, this solid heat source can be changed to plane heat source and expressed as:

$$Z=0: -k(\partial T/\partial n)=AI_0 \quad (2)$$

The equation of target material ablation depth

When the laser beam irradiates to the target, the target absorbs the energy of laser, when the laser energy absorbed by target is more than sublimation energy of material, the material is evaporated from the target, in the ablation process of laser, the position of ablation surface will reflect the ablation depth. Set the power density of the position s infiltrated by laser and within the target is I(s), this is:

$$\frac{dI(s)}{ds} = AI(sk) \quad (3)$$

Choose the origin of coordinates on the ablation surface of relief, when s=0, deduce:

$$I(s)=I_0e^{AS} \quad (4)$$

When the laser incident position, the power density of the laser is reduced to I_t, the laser will not be able to have enough energy to evaporate the target, this article marks the depth of the position as ablation depth d, deduced from (4):

$$s_t = \left(\frac{1}{A}\right) Ln\left(\frac{I_0}{I_t}\right) \tag{5}$$

Seen by the physical basics common sense, if the wooden target whose depth is d all evaporate, the laser energy required must be more than energy *E* for vaporization of material, there are:

$$\rho E \cdot s = \tau \int_0^s AI(s)ds = \tau I_0\left(1 - e^{-As}\right) \tag{6}$$

τ is the laser pulse duration

Use fourier series to expand e^{As} in s=0, omit high order term meanwhile:

$$e^{As} = 1 - As + \frac{1}{2}A^2 s^2 \tag{7}$$

Deduced from (6) and (7):

$$s = 2\left(\frac{1}{A} - \frac{\rho E}{\tau A^2 I_0}\right) \tag{8}$$

Ablation boundary conditions

Under the initial conditions, the temperature of anaglyph ablation surface is same as the surrounding environment temperature, setting To=297K. We can know by the basic principle of heat transfer, the energy exchanged by convection and radiation. There is such a process in the surrounding of target. So we can define the boundary condition of target:

$$-KT\frac{\partial T}{\partial n} = h\left(T - T_{gas}\right) + e^{\sigma}\left(T^4 - T_{gas}^4\right) \tag{9}$$

$\partial T/\partial n$ refers to the rate of change of temperature along the outer normal of target, T_{gas} is the adjacent temperature of target surface, if the laser is not heated by the laser beam, then $T_{gas}=T_0$, *e* is the surface emissivity of target, σ is Stefan-Boltzman.

On the upper surface of target, it can be divided into two specific regions, spot inside and spot outside, the power density of laser in spot inside is *P(x,y,0,t)*, the power density of laser in spot outside is zero, the upper surface boundary condition can be expressed as:

$$\frac{\partial T(x,y,t)}{\partial z}\Big|_{z=0} = \frac{\alpha\varepsilon}{KA}P(x,y,t) + \frac{h}{K}\left[T(x,y,0,t) \quad T_{gas}\right] + \frac{e^{\sigma}}{K}\left[T^4(x,y,0,t) \quad T_{gas}^4\right] \tag{10}$$

The energy exchange process between the surface of wooden anaglyph and lab environment include:

Heat flux density of convective heat transfer q_c:

$$q_c = h\left(T_{gas} - T_0\right) \tag{11}$$

Heat flux density of radiant heat transfer q_r :

$$q_r = a_r\left(T_{gas} - T_0\right)$$

(12)

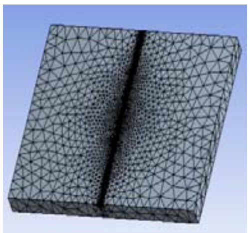
h is convective heat transfer coefficient, a_r is adiant heat transfer coefficient.

Comprehensively conclude that total heat flux density of the relief surface *q* is:

$$q = h\left(T_{gas} - T_0\right) + a_r\left(T_{gas} - T_0\right) \tag{13}$$

4.2 finite element model and parameter settings

Using the workbench software to imitate and calculate the situation of ablation wooden anaglyph surface under the condition of all kinds laser power density, its simulation is transforming laser energy into heat energy essentially, meanwhile representation of melting and gasification, the parameter of temperature field distribution and ablation depth under various conditions can be obtained, and obtain relation of laser power density and the relief surface ablation depth(Xia et al., 2009). The energy density of pulse is higher, so when dividing mesh, it demands to use small grid size near the processing area and use larger grid size far away from the processing area(Yang,1995). The laser ablation mode of target, the unit quantity is very large, in order to reduce the calculated amount, making subdivided mesh only concentrated near facula heat source, while the other parts far away from the facula can keep relatively sparse mesh on the premise of guarantee accuracy. The pyroconductivity, density and specific heat capacity of pine changes with the temperature changes, it need to establish a database for setting. While for the corresponding phase transformation of melting and gasification, define enthalpy under different temperature in software, to solve the influence of temperature field caused by latent heat of phase change(Yu et al.,2005). Establish the model of target and divide mesh in software, the model is shown in figure 6.



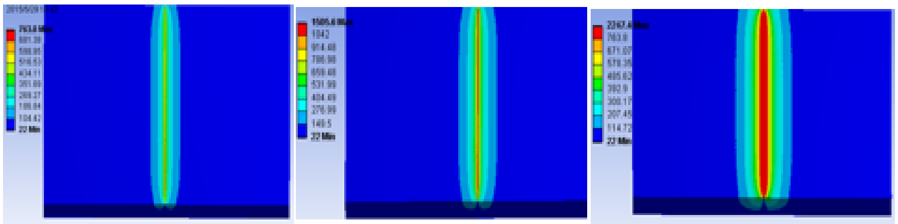


Figure 6: Mesh model Figure 7: The temperature field distribution of target under different laser power density

4.3 Solving process

Heating effects of laser on anaglyph surface can be seen happened in an infinite thin area, using heat flux to load laser heat source seen as surface source. Set a model and set material parameters (ignoring the impacts of radial and tangential parameter changes), choose the northeast Korea pine as target, the density is 0.46g/cm3, warm-transfer coefficient is 1.67kj/(kg'k), thermal conductivity is 0.11w/(m'k), moisture content is 9%, poisson's is 0.4, Calculate the surface temperature distribution of red pine, and then using the simulation software to solve the ablation depth parameter, and get morphology of ablation parts.

4.4 Result and analysis

There are a lot of power density value, this article takes three typical laser power density,$0.5X10^9$ kw/m^2, $1X10^9$ kw/m^2 and $1.5X10^9$ kw/m^2,simulate the ablation surface temperature field distribution of red pine target under three power density of laser. As shown in figure 7, corresponding to different power density, the center higher temperature of red pine after ablation is different, extreme temperature of the center are 763, 1505 and 2247. When the temperature is higher than the gasification point, some material will gasify. The simulated temperature distribution of target and the shape of ablation crater seam are same with situation in the process of experiment, it can be verified from the picture after the experiment.

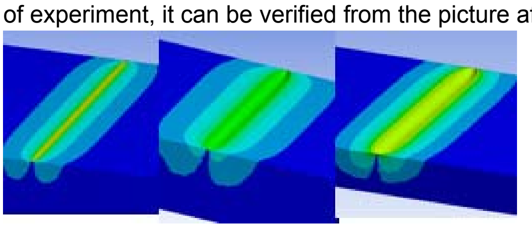


Figure 8: The ablation crater morphology of target under different power density

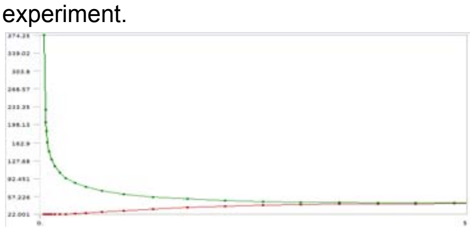


Figure 9: Temperature variation curve in $1X10\ ^2kw/m^2$

Using the lase whose power density is $1X10\ ^2kw/m^2$, the changing process of target surface between center maximum temperature and edge minimum temperature within the first five seconds. As shown in figure 8, the surface ablation pit morphology of target under the three typical power density, the variation trend of ablation pit morphology and depth is same with experiment, the area influenced by laser heat increased with power density.

As shown in figure 9, we can see, the center temperature rises gradually and the edge temperature changes little due to away from center, in accordance with actual situation.

Table 1 is the contradistinctive result of ablation depth simulation and experiment, it can be seen that the ablation depth is same with experiment, experiment result slightly less than simulation value, because there will be some carbide residue of target leaving inside the ablation pit, affect the accuracy of measurement.

Table 1: The ablation pit depth under different laser power density

Power density	simulated value	measured values
$0.5\times10^9 kw/m^2$	0.025	0.02
$0.6\times10^9 kw/m^2$	0.065	0.05
$0.7\times10^9 kw/m^2$	0.108	0.09
$0.8\times10^9 kw/m^2$	0.155	0.12
$0.9\times10^9 kw/m^2$	0.220	0.18
$1\times10^9 kw/m^2$	0.250	0.21
$1.1\times10^9 kw/m^2$	0.338	0.30
$1.2\times10^9 kw/m^2$	0.409	0.34
$1.3\times10^9 kw/m^2$	0.449	0.39
$1.4\times10^9 kw/m^2$	0.535	0.46
$1.5\times10^9 kw/m^2$	0.561	0.49

5. Conclusions

By laser ablation experiment and numerical simulation process, comparing the result of nanosecond pulse laser action to the surface of pine target, it can be concluded: the laser processing can quickly and effectively remove irregular burrs on the surface of wooden target, improve the surface quality, reduce the processing area minimally at the same time. It can obtain the pit morphology meeting the requirements of ablation by changing the laser power density. The ablation depth can be adjusted and in a controlled area.At the same time, setting up the relationship between laser power density, wood species and ablation depth, providing the related basic theory to solve involved the laser parameter setting and wood type selection.

Acknowledgments

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