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Finite Element Analysis and Experimental Research on Micro-treatment of Coniferous Wood Surface

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The micro-crack on surface of coniferous wood direct influence its surface integrity, that results in destruction of appearance or component failure during usage could have impact on service life and safety. It's found one of main cause of such micro-crack is result from thermal stress. This paper demonstrate laser ablation effect on the microcosmic surface by numerical simulation which set up model of coniferous wood's surface by applying ABAQUS, to analyze the heat flux temperature field distribution of surface which was ablated by laser, acquire the ablation state of wood surface by means of the unique model, which define attribution, create analysis step, define interaction and load. Furthermore study on ablation effect in microcosmic surface by adjusting laser power and size of beam. Finally, verify the simulation results by means of existing lab working equipment.

1. Introduction

With the development of laser processing machine and maturity of laser processing technology, especially, the increasingly demands of micro precision machining in modern industry led the laser processing technique to be widely used (Marletta and Evola, 2013). Laser micro-machining has been a processing technology developed under this background. Compared with traditional processing method, pulsed laser processing have such advantages as less deformation, less pollution and optional of processing areas (Hang et al, 2009). Consequently, the research of laser micro-machining is of great significance and extensive prospect. Wood products are widely used and processing is important industrial activities in China (Qiang et al, 2003). From processing to finish product, wood have to be deburred. Nevertheless, the continuity and the intensity of wood fiber will be destroyed by milling cutter while proceeding of wood surface milling, such as being torn, split, rubbed, collapse, etc., in addition. The hollow wood cell will lead to a large number of micro burrs generated surface of wood products. Burrs are very much impact on beauty and quality of wood. Because of multitudinous advantages, applying the laser processing technology to have wood surface deburred after milling is entirely possible to achieve, such technology can greatly improve the efficiency of wood processing, reduce processing costs (Singh and Narayan, 1989). In this paper, write corresponding subroutines in line with analyzing of laser heat source, that applying "ABAQUS" to set up model of coniferous wood surface and relevant database. Defining its thermal properties parameter, create analysis step, define interactions and loading, divide grid reasonably and optimize model. Finally submit jobs and view analysis results to get the temperature field and heat flux of ablation crater and surrounding. In the actual experiment, Finland wood to be used by laser ablation and then gold-plating. After that, observe ablation areas for actual ablation morphology by scanning electron microscope, verify the simulated conditions.

2. The theory of wood laser processing

During the course of wood laser processing, because of the feature of nanosecond laser, monochromatic, directional, coherent and high intensity of nanosecond laser, focus energy on a small area and a certain direction to ablate wood to what pattern needed (Sivakumar et al, 2015). Setting the laser beam diameter is D,

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the divergence semi-angle of the beam is θ, the focal length of the lens is *f*, and the spot radius of the focal plane is *r*, then there are the following approximate relationships between *r*, *f*and θ:

$$\theta \approx tg\theta = r / f \tag{1}$$

Spot diameter *d*:

$$d = 2f\theta \tag{2}$$

For different laser sources, the form of laser beam transmission is different, and the calculation method of d-value is also different. The smallest diameter of focal spot:

$$d_{\min} = \frac{4\lambda f}{\pi D} \tag{3}$$

In formula (3), *f* is focal length, *D* is the laser beam diameter, and λ is the wavelength of the laser. The main principle of laser processing is to gather a great energy in a short time. Therefore, the laser irradiance reflects its irradiation power (power density) on unit area. The power density of the focusing surface which diameter is of*d*:

$$q = \frac{dN}{dA} \tag{4}$$

In formula (4), *dA* is unit area of focusing surface, *dN* is radiant flux.

3. Microscopic mechanism of laser heating

For laser, in the process of heating, because of the energy momentary change, the molecules, atoms, electrons, photons and so on are being changed inside the material; however, it is not the same microscopic mechanism of heat conduction for different materials (Heltzel et al, 2015). For wood, it is a composite of organic matter which mainly composed of cellulose, hemicelluloses and lignin, together with casein viscous liquid and water form the whole wood ware. After being heated, momentary high temperature dissolve the water and the mucus firstly, make the heat conduct alone with wood cell tube to increase the temperature of the xylem (Ping et al, 2007). They will start to burn while the temperature over the ignition point of lignin and cellulose, however, the process of wood burning is extremely short due to monetary gasified since laser irradiate with huge energy. When the laser is launched from the surface into the wood, compared to the laser beam, the wood infinite, so the power density can be wrote as the following formula:

$$q = -\mu \frac{\partial T}{\partial n} \tag{5}$$

$$\mu = \mu_1 + \mu_2 \tag{6}$$

In formula (5): μ_1 is the thermal conductivity of water and liquid saccharines, μ_2 is the thermal conductivity of wood, *T* is temperature gradient, *n* is the number of electrons per unit volume. This is process of the microscopic mechanism of wood processing by nanosecond laser, the formula (5) and (6) inferred respectively reflect the macro and micro changes of energy in the course of wood processing. The heat conduction processes of wood are different in each direction because of anisotropic material. At this time it is a tensor, can describe internal changes in the combustion process of wood more accurately. If it is assumed macro-isotropy material, then:

$$[\mu] = \begin{bmatrix} \mu_{xx} & \mu_{xy} & 0 \\ \mu_{yx} & \mu_{yy} & 0 \\ 0 & 0 & \mu_{zz} \end{bmatrix} \tag{7}$$

4. Equipment and results of the experiment

4.1 Equipment and wood

The equipment used in this experiment includes ablation equipment, spray plating equipment and observation equipment (For figure 1, 2, 3). Ablation equipment includes: power supply, cooling system, control system, laser, gas injection device, focusing system, observation and alignment system, and worktable. At the same time, the equipment is YAG laser, the laser power supply is JDW3-250 type, the laser cooling-water chiller is PH-LW06-BLP type, and the focusing system consist of optics. Observing the ablation morphology in surface when coniferous wood was processed by laser. Since the wood is non-conducting, observe the ablation area before spray a layer of metal in it. On the basis of it, the spraying equipment is SCD 005 Ion sputtering table in this experiment. After finished spraying of coniferous wood surface, use observation equipment scanning electron microscope to observe it.

Figure 1: Ablation equipment

Figure 2: Spraying equipment

Figure 3: Observation equipment

A Finnish pine was selected (moisture content 16.8%), same was cut alone the grain and tangent milled. By using the laser equipment as shown in figure 1, apply the laser ablation on the wood surface and get the plates is shown in figure 4. Cutting down the parts that were laser fired, get smaller parts as shown in fig. 5, then, overgild the parts after cutting down and get as shown in fig. 6.

Figure 4: Finnish pine

Figure 5: Part of wood

Figure 6: After gold sprayed

4.2 Experimental results

The wood was observed by scanning electron microscope as shown in Figure 3. More detailed observation and analysis can be obtained under different magnification. The image information of before and after laser irradiation by the scanning electron microscope are as shown in Fig. 7~10.

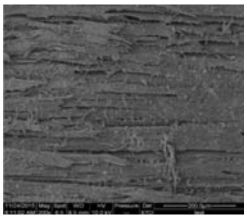

Figure 7: 200 times magnified before treatment

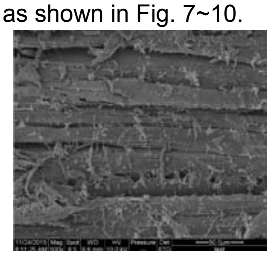

Figure 8: 500 times magnified before treatment

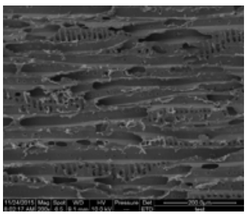

Figure 9: 200 times magnified after treatment

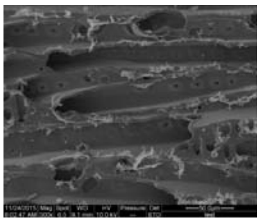

Figure 10: 500 times magnified after treatment

Figure 7 and Figure 8 are the surface condition of wood that cut alone the grain in radial section, magnify 200 and 500 times respectively. Figure 9 and Figure 10 are effect pictures of wood surface that laser fired under the same cutting condition, the parts of laser fired were magnify 200 and 500 times respectively. Show the surface of wood laser fired more meticulously. Clearly see the poriform structure of wood, as well as part of the area into a white. It is shown that the comparison before and after laser fire aim at above four pictures. Burrs are wiped off, to see the tubes of wood. Relatively, the surface of the wood will be much smooth, mussy burrs have been ablated by laser. But under high-magnification, shown that some parts of wood turn white. It states that this area has been carbonized. So in the practical application, the laser power is chose reasonably, radius and other technical parameters, in order to avoid damage to the wood surface in the application.

5. Simulation analysis

5.1 Dividing mesh

The pulse laser ablation for wood, the two-dimensional model is shown in Figure 11. Because the energy density of the pulse laser is very high and the effective heating area is very small (Fu et al, 2006). When divide mesh, using a very small grid size in the inner and nearby area of laser spot, and using a biggish size in the area far away from the spot (Lin et al, 2007). Because of the very large number of grid units, for reducing computation, the whole of wood divided roughly and the middle part divided meticulously. Making the dividing meticulous part is focused only near the spot heat source. Figure 12 is mesh model.

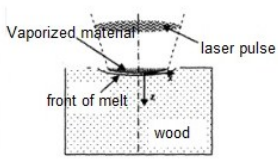

Figure 11: Model of laser fired wood

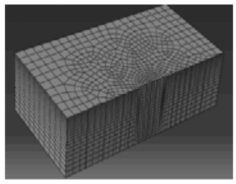

Figure 12: Mesh model

5.2 Treatment of parameters of material thermal characteristics

The heat conduction in the process of pulsed laser ablation is a complicated nonlinear problem. The parameters of thermal characteristics such as thermal conductivity, specific heat capacity and so on change with the change of temperature (Stefanizzi et al, 2013). Therefore, it is necessary to establish a material database, which provides material data of the physical characteristics, the heat transfer, parameters of the mass transfer process and so on.

5.3 Analysis and loading of laser heat source

The profile of light intensity distribution *I*(*x*,*y*,*t*) is the Gauss distribution of time and space. Considering Gauss distribution of pulse with time, *I*(*x*,*y*,*t*) is expressed as:

$$I(t) = I_0 \exp\left(-\frac{(t-t_p)^2}{t_p^{\,2}}\right) \tag{8}$$

In this formula, I_0 means average power density, t_p is pulse width, tis time. Considering Gauss distribution of pulse with space, $I(x,y,t)$ is expressed as:

$$I(x,y) = \begin{cases} 0 \\ I_{max} \exp\left[-\frac{x^2}{a^2} - \frac{y^2}{b^2}\right] dxdy \end{cases} \tag{9}$$

$$Q(x,y,z,t) = C(1-R)\, I(x,y,t) \exp(-\alpha_0 z) \tag{10}$$

In this formula, *C* means correction factor of plasma, *1-R* is surface absorption, *R* is reflectivity, α_0 is absorption coefficient of laser in material, *I*(*x*,*y*,*t*) is the laser power density with time and space variation.
Usually laser absorption occurs on the surface of the wood in one to five micron range, therefore, the thermal action of laser in wood is seen that occurs in the surface of an infinitely thin area. So regard the laser heat source as the surface heat source. Using heat flux to loading heat source in the software. Heat source function using Function in software for loading.

5.4 Initial condition treatment

The initial conditions of simulation are: while *t*=0, wood material has a uniform temperature distribution *T*o (293k)

$$T(x,y,z,0) = T_0 \tag{11}$$

Set the initial temperature of the wood to ambient temperature（293k）by order. This is room temperature, the most commonly used in laboratory. And in the boundary between wood and environment, the energy is heat exchanged by convection radiation. According to the heat transfer, the heat flux of convection heat transfer through the boundary can be obtained:

$$q1 = -h\left(T_s - T_0\right) \tag{12}$$

In this formula, *h* is coefficient of convective heat transfer, T_s is temperature of solid surface, T_0 is ambient temperature.

5.5 Analysis of result

Through the Abaqus calculation, the analysis results are obtained. The following are the distribution maps of heat flux density at different analysis time.

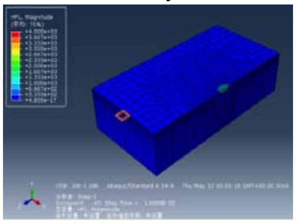

Figure 13: 0.01s

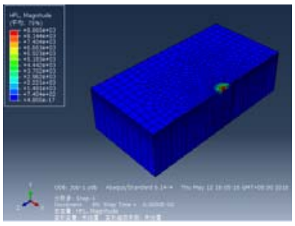

Figure 14: 0.06s

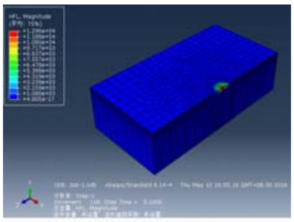

Figure 15: 0.1s

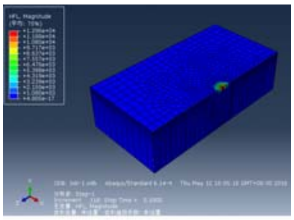

Figure 16: 0.5s

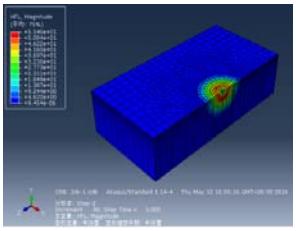

Figure 17: 5s

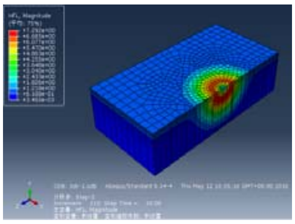

Figure 18: 10s

For Figure 13 to 18, showing respectively the heat flux distribution in the laser action area of 0.01s, 0.06s, 0.1s, 0.5s, 5S, 10s. Total action time of laser is 0.5s. Starting from 0.01s, with the increase of the laser action time, the heat flux density of the laser action area increases gradually. The heat flux density in middle area is the highest, from the regional center of action, showing a decreasing trend, but the overall density of heat flux increases with time. At the time of laser irradiating and after it, the heat flux density in irradiation area has a great change. When the laser irradiation is not in the wood, the maximum heat flux density in irradiation sharply almost reduced to the original 1/10. It is shown that laser has a great impact in irradiation area of wood. Laser transfer high heat to increase the heat flux density. With the increase of time, the heat flux density of the laser action area decreases gradually. In the process of heat transfer to the nearby area, there is a certain impact for heat flux density in the surrounding area, and the impact gradually becomes smaller with the increase of time and distance. Assuming that the wood will not be ablated by laser. According to the above results we can know, when the wood is irradiated by the laser, the heat will gradually spread to the surrounding and lead to the increase of heat flux density of the surrounding wood, affect the wood surround irradiation.

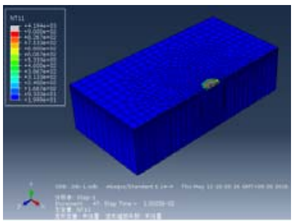

Figure 19: 0.01s

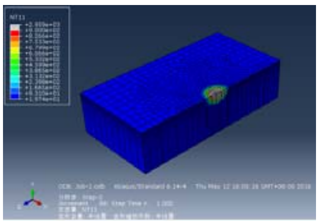

Figure 20: 1s

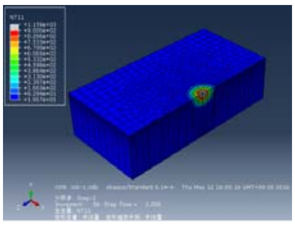

Figure 21: 10s

For Figure 19 to 21, we set the temperature of wood gasification (when temperature over this temperature wood will disappear) to 900 degrees centigrade. Because of laser irradiation, the temperature of wood increase. As known that, by setting wood gasification temperature, when the temperature of wood over this limit, it will be grayed out. The temperature around the ablation area gradually decreases, the heat slowly spread to the surrounding area and result in an elevated temperature. As the thermal diffusing, the overall temperature is gradually decreased until the entire block return to room temperature. The irradiated area is gasification instantaneously at the moment of laser irradiation, ablated craters. And due to the effect of heat transfer, the crater area is larger than the laser irradiation area. According to above experiment, we can know that, in the moment of laser irradiation, temperature of irradiation spot instantly reached more than four thousand degrees. For huge temperature difference, the surrounding wood is also affected by the heat. And then temperature is increased, the affected area becomes larger with the increase of time.

6. Conclusions

In this paper, the specific laser ablation experiments were carried out to verify the results. Use ABAQUS to set up the model surface microstructure of coniferous woods and apply subroutine loading Gauss heat source model to simulate ablation of wood, to obtain the distribution of temperature field in the wood with nanosecond pulse laser ablation and crater morphology satisfying ablation requirements. It is proved that the ablation crater can be also adjusted by the parameters, and in the controllable range. This theoretical analysis provides the corresponding basic theory for the setting of laser parameters and the selection of wood, and optimized ablation effect can be achieved by changing the laser parameters.

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