Prediction of drilling micro-hole in CO\textsubscript{2} laser irradiated sticking plaster

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Abstract. This paper reports a simulation model of drilling micro-hole in sticking plaster heated with a 1064 nm continuous CO\textsubscript{2} laser beam. Laser spot sizes ranged from 0.1 to 0.2 mm diameter with axial irradiance power levels of 25-100 W. To apply software Ansys, the measured steady-state surface temperature is calculated to rise with both increasing beam power and incident laser irradiance. For temperatures above 450 \degree C, sticking plaster vaporized into ventilation hole, and the size of ventilation hole 0.15 mm diameter spent 1.7 ms heated with laser power lever of 100 W with the size of spot 0.15 mm diameter, in good accordance with reported in earlier experiments studies. Similarly, the size of ventilation holes changed with beam power and laser spot diameter. These results show that software Ansys can be used to predict drilling micro-hole in CO\textsubscript{2} laser irradiated sticking plaster and the result of simulation can guide to laser drilling experiments.

1. Introduction

With the rapid development of laser technology, laser applications in the field of pharmaceutical production more and more widely in recent years. Drilling micro-hole in sticking plaster heated with a laser beam is an important application of laser technology [1-5]. Laser drilling micro-hole technology improved production efficiency and quality of medicines due to its more high-speed and more precision characteristics than that of conventional drilling micro-hole technology in the pharmaceutical production fields.

FEA (finite element analysis) software Ansys is good to predict the time evolution of temperature material properties, and it can calculate the distribution of the temperature field after laser irradiation materials [6-7]. It can be applied to a birth-and-death-element technique of Ansys to remove the part of the material and the formation of small holes if the temperature of the material is beyond the melting value. Materials can be simulated the size of the hole after laser irradiation.

This paper studies a simulation model of drilling micro-hole in sticking plaster heated with a 1064 nm continuous CO\textsubscript{2} laser beam. To apply software ANSYS, the measured steady-state surface temperature is calculated to rise with both increasing beam power and incident laser irradiance.

2. Theoretical approaches
The dimension of sticking plaster is 1mm×1mm×0.3mm and the sample is irradiated by a continuous CO₂ laser beam, which is shown in Figure 1. In order to analyze the thermal behavior numerically, the FEA software Ansys was used in this study. Before the mathematical model is established, some assumptions should be made:

1. All the physical parameters of sticking plaster are temperature-independent.
2. The CO₂ laser energy is fully absorbed by sticking plaster.
3. The sticking plaster sample is treated as the black body.
4. In this study, the energy loss is negligible in the phase change.
5. Heat transfer is not affected by thermal expansion.
6. The CO₂ laser beam is regarded as a surface-heating source.

![Figure 1. The setup of model with laser beam.](image)

The grid structure of the sticking plaster is shown in Fig.2. A fine meshing was applied on the laser path to analyze the thermal behavior around the heated zone. Based on the above assumptions, the mathematical heat transfer model can be established as follows [8]

\[
k \nabla^2 T = \rho c \frac{\partial T}{\partial t}
\]  

(1)

Where, \(k\) is the thermal conductivity, \(c\) and \(\rho\) are the heat capacity and the density, respectively. A laser beam irradiated on the top of sticking plaster contains TEM₀₀ mode, the intensity can be expressed in Eq.2. The CO₂ laser is absorbed fully by the sticking plaster and the absorbing depth is less than 15μm, so the laser beam is treated as a surface energy and the impulse function \(\delta(z)\) is applied in Eq.2.

\[
I(x, y, z, t) = \frac{P}{\pi r^2} \exp \left( -\frac{x^2 + y^2}{r^2} \right) \delta(z)
\]

(2)

Where \(P\) and \(r\) are the power and the radius of the CO₂ laser beam, respectively. The initial temperature \(T_0 = 20\)°C, which is the same as the ambient temperature. The boundary conditions of the FEA model illustrated in Fig.2 were carried out as Eq.3 and Eq.4.

\[-k \frac{\partial T}{\partial z} + h(T_s - T_0) + B \varepsilon (T_s^4 - T_0^4) = \alpha I(x, y, z, t) \text{, at } z = 0 \]

(3)

\[-k \frac{\partial T}{\partial n} = h (T_s - T_0) \text{, at } z = H, x = \pm \frac{L}{2}, y = \pm \frac{W}{2} \]

(4)
Where, $T_h$ denotes the temperature of the heated zone and $T_n$ denotes the temperature of the area without laser heating, $h=10\text{Wm}^{-2}\text{K}^{-1}$ is the convection heat-transfer coefficient, $B=5.670\times10^{-8}\text{Wm}^{-2}\text{K}^{-4}$ is the Stefan-Boltzmann constant, $I(x, y, z, t)$ is the density of the laser power, and $n$ is the direction cosine of boundary. The surface emissivity is assumed as $=1$ and the absorption coefficient is assumed as $=1$. The sticking plaster material is chosen as the thermal conductivity $k = 0.21\text{Wm}^{-1}\text{K}^{-1}$, the heat capacity $c = 1890\text{Jkg}^{-1}\text{K}^{-1}$ and the density $\rho = 1200\text{kgm}^{-3}$. For temperatures above 450°C, sticking plaster will be vaporized. Based on the mathematical model of heat transfer, the process of drilling sticking plaster by laser beams can be simulated by Ansys. In this study, a birth-and-death-element technique was applied to simulating the process of drilling sticking plaster [9]. The principle of this technique is that the element will be killed and disappear in the model if the temperature of this element is beyond the melting value (450°C) of sticking plaster. The drilling hole is illustrated in Figure 3 which is simulated by Ansys.

3. Results and discussion
The continuous CO$_2$ laser is chosen as $P=100$ W, and the diameter is $D=0.15$mm, which calculated by Ansys. The time history of the depth of the hole is shown in Fig.4. It can be seen that the depth of the hole increases with the time of the laser irradiance. When sticking plaster heated with laser beam last time about 0.4ms, hole is produced. When $t=1.5$ms, the depth of the hole arrive at 0.3mm. When sticking plaster heated with laser bean spent on 1.7ms of time, the shape and size of the micro-hole is shown in Fig.5. As shown in Fig.5, the size of ventilation hole 0.15mm diameter spent 1.7ms heated with laser power lever of 100w with the size of spot 0.15mm diameter, in good accordance with reported in earlier experiments studies [2].
Fig. 6 shows the profile of the hole with different laser diameter but the same laser power (P=50 W, t=1.5ms). The depth of the hole increases with the decreasing laser diameter. On the other hand, the width of the hole is decreases with the decreasing laser diameter.

Fig. 7 shows the profile of the hole with different laser power but the same laser diameter (D=0.15mm, t=1.5ms). We can see that the depth and width of the hole increases with the increasing laser power.

Figure 4. The time history of the depth of the hole.

Figure 5. The depth and width of the hole.

Fig.6 shows the profile of the hole with different laser diameter but the same laser power (P=50 W, t=1.5ms). The depth of the hole increases with the decreasing laser diameter. On the other hand, the width of the hole is decreases with the decreasing laser diameter.

Fig.7 shows the profile of the hole with different laser power but the same laser diameter (D=0.15mm, t=1.5ms). We can see that the depth and width of the hole increases with the increasing laser power.
4. Conclusion

The mathematical model of micro-hole by continuous CO$_2$ laser was illustrated and the micro-hole was simulated by FEA software Ansys. For temperatures above 450°C, sticking plaster vaporized into ventilation hole, and the size of ventilation hole 0.15mm diameter spent 1.7ms heated with laser power lever of 100w with the size of spot 0.15mm diameter, in good accordance with reported in earlier experiments studies. Similarly, the size of ventilation holes changed with beam power and laser spot diameter. These results show that software Ansys can be used to predict drilling micro-hole in CO$_2$ laser irradiated sticking plaster and the result of simulation can guide to laser drilling experiments.

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