Thermal stress analysis for laser cutting corner with a fluctuant cutting speed in steel plate

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Abstract. The temperature and thermal stress field are important factors for controlling laser cutting quality. In the present study, thermal stress field analysis for laser cutting corner with a fluctuant cutting speed is carried out. Firstly, a three-dimensional (3-D) finite element model is established to simulate the temperature and thermal stress field. Then the factors of influencing the cutting speed fluctuation such as corner angle and cutting speed are studied in laser cutting corner. It is found that the constrained cutting speed at the corner introduces the phenomenon of corner burning and uneven residual stress distribution. The predicted temperature, thermal stress results agree well with the experiment data through the laser cutting corner experiment of 3 mm steel plate.

1. Introduction
Laser cutting is a kind of non-contact thermal cutting process and has many advantages such as good cutting quality, high cutting speed, small heat-affected zone, little pollution and so on. And it has been widely used in the industrial production. However, there is a certain decrease of cutting speed in order to avoiding cutting machine shock at the cutting corner [1, 2]. And this results in bad cutting quality such as corner burning, heat concentration and uneven residual stress distribution. So it is in dire need of solving this problem to improve laser cutting efficiency and extend application.

The heat transfer during laser cutting has been analysed by many scholars. Sheng and Joshi [3] analysed the heat affected zone formation for laser cutting of stainless steel. The energy balance at the cutting front was used to derive the steady-state kerf shape, and the extent of the heat affected zone (HAZ) can be determined from the area where properties of the workpiece material were significantly affected by the resulting temperature field. Prusa, Venkitachalam [4] presented a mathematical model to estimate the heat conduction losses during laser cutting. They predicted the thermal field in the heat affected zone (HAZ). The influence of gas jet velocity in laser heating with a moving workpiece was studied by Shuja and Yilbas [5]. They found that the effect of assisting gas jet velocity was more pronounced in the cooling cycle than in the heating cycle of the laser heating process. The temperature field during laser forming of plate metal was analysed by Ji and Wu [6]. An increase in the maximum values of temperature was found with an increase in laser output power, while increasing the cutting speed and workpiece thickness has an inverse impact on the temperature. Thermal stress of the workpiece in laser cutting is always the result of the thermal load which is determined by the coupled temperature field. Yilbas, Arif [7] established a three-dimensional finite model to predict thermal...
stress field for different materials. The thermal stress formation during cutting in different shapes such as circle, sharp edges has been studied [8-11]. In their studies, a constant temperature heat source at the melting temperature of material for the laser beam was introduced in the simulation. Comparatively, Nyon, Nyeoh [12] used the same method to simulate kerf width formation and thermal stress during the laser cutting process. And a Guassian-distributed laser heat source was adopted to model the heat input during the laser irradiation.

However, in above studies few research studies have been conducted on the factor of cutting speed fluctuation at corner. So in this paper, the influence of cutting speed fluctuation for thermal stress field is carefully analysed, and a Guassian-distributed heat source is also adopted as laser heat source in the 3-D finite simulation model. Meanwhile, the process of material melting is simulated by the method of element death and birth in ANSYS that the temperature of finite element over the melt temperature will be deactivated. A deactivated element remains in the model but contributes a near-zero conductivity value to the overall matrix.

2. Model of cutting speed fluctuation at corner

According to reference [13], the corner size and maximum speed for the machine tool and the distance of acceleration and deceleration must be considered to calculate the cutting speed at corner. The workpiece size and B, C, D locations are shown in Fig.1.

Considering the corner size, then

$$ v_f \leq \frac{T a_{\text{max}}}{2 \sin \frac{\alpha}{2}} $$

(7)

where $T$ is interpolation period, $a_{\text{max}}$ is maximum acceleration, $\alpha$ is corner size.

Considering the maximum speed $v_{\text{max}}$ of the cutting machine, then

$$ v_f \leq v_{\text{max}} $$

(8)

Considering the distance of acceleration and deceleration, then

$$ v_i^2 \leq v_{i-1}^2 + a_m L_i $$

(9)

$$ v_i^2 \leq v_{i+1}^2 + 2 a_m L_{i+1} $$

(10)

where $v_i$ is the initial velocity at acceleration distance $L_i$ to the corner, $v_{i+1}$ is the end velocity at deceleration distance $L_{i+1}$ away from the corner. $a_m$ is the maximum acceleration of cutting machine.

Combining Eqs.(7)-(10), the cutting speed at corner can be calculated as

$$ v_f \leq \frac{T a_{\text{max}}}{2 \sin \frac{\alpha}{2}} $$

(11)
In this study, specified cutting speed $v_0$ is 50mm/s, and maximum acceleration $a_{\text{max}}$ is 8000mm/s$^2$, and the interpolation period is 5ms. The cutting speed at location B, C, D can be calculated by speed fluctuation model as: $v_B = 36.8\text{mm/s}$, $v_C = 21.92\text{mm/s}$, $v_D = 36.8\text{mm/s}$. It is obvious that the speed at location C decreases most. The cutting speed variation along the laser scanning path for location B, C, D is shown in Fig.2.

![Cutting speed variation](image)

Fig.2 The curve of cutting speed variation

3. Finite element simulation

The cutting parameters used in the simulation are listed in Table 1 which are the same with that in the experiment for comparison. The process of laser beam moving along the corner is realized by program as shown in Fig.3, and only half part of the cutting kerf is modeled due to its symmetry. The temperature distribution and the resulted thermal stress in the workpiece are performed by the FEM software ANSYS using ANSYS parametric Language (APDL). The mesh in finite element analysis is shown as Fig.3. The mesh is more intensive near the cutting edge. The mesh comprises about 70000 elements.

![Model and meshing](image)

Fig.3 Model and meshing

The moving distance of laser source in each time step is the length of an element. The cutting parameters and material mechanical properties in simulation model are shown in Table 1. Temperature dependent thermal properties of plate are shown in Table 2.

| Cutting Speed (mm/s) | Laser power (W) | Plate thickness (mm) | thermal expansion coefficient $\alpha (1/K)$ | Poisson ratio $\nu$ | elasticity modulus E(GPa) | $\rho$ (kg/m$^3$) |
|----------------------|-----------------|----------------------|---------------------------------------------|-------------------|--------------------------|-----------------|
| 50                   | 3000            | 3                    | 63 x10^{-6}                                 | 0.29              | 210                      | 7854            |
4. Results and discussion

4.1. Effects of corner size

Firstly, the corner size declines from 48.3° to 38.5°. The acceleration is 5000mm/s², and the cutting speeds for location B, C, D are calculated as: B=34.45mm/s, C=21.16mm/s, D=34.45mm/s. It can be found that the cutting speed for location C declines because of the smaller corner size. Temperature distribution contrast along Y-axis at location C for two kinds of corner size is separately shown in Fig.4 (a) and (b). The temperature distribution along Y-axis for two kinds of corner size is almost the same when the laser beam is at location C in Fig.4 (a). However, the temperature for smaller corner size at cut edge is higher when laser cutting finishes, as shown in Fig.4 (b). The reason for this is that smaller corner size leads to smaller heat diffusion area. Meanwhile, smaller corner size results in bigger decline of cutting speed and the corner attains more energy. Consequently, the corner burning is more serious.

Fig.4 Temperature distribution contrast along Y-axis at location C

\[ \alpha_i = 48.3^\circ (C_0), \quad \alpha_i = 38.5^\circ (C_1) \] (a)

Laser beam at location C (b) after cutting

Von Mises stress distribution along Y-axis contrast with different corner size for location C is shown in Fig.5. Time T2 is when the laser beam is located at point C, and time T4 is when the workpiece is completely cool. The Von Mises stress has always rose from distance 0 to 0.056m at time T2 for different corner size. But the von mises stress has declined from distance 0.056m to cutting edge because of modulus of elasticity declining obviously near the melting temperature. It also should be noted that the Von Mises stress is smaller for smaller corner size because of more serious heat concentrationand smaller temperature gradient. The residual stress has the same variation trend as Von Mises stress at time T4. The reason for this is that residual stress results from the Von Mises stress. Meanwhile, the corner with smaller size also has smaller residual stress. The maximum residual stress of different corner size at different locations is shown in Table 3. It can be found that the residual stress reach the maximum at location B, D. Meanwhile, residual stress has increased when the corner size declines.

| Table 3 residual stress at locations B, C, D |
|--------------------------------------------|
|    | B    | C    | D    |
| C=48.3rad | 275MPa | 130MPa | 270MPa |
| C=38.05rad | 290MPa | 120MPa | 280MPa |
4.2. Effects of cutting speed

The cutting speed declines from 50mm/s to 30mm/s. The acceleration is 5000mm/s². Then the cutting speed for location B, C, D is changed to 30mm/s, 21.92mm/s, 30mm/s. Temperature distribution contrast along Y-axis at location C for two kinds of cutting speeds is shown in Fig.6. The temperature distribution along Y-axis for two cutting speeds near cutting edge is almost the same when the laser beam is at location C in Fig.6 (a). It should be noted that the temperature is higher for smaller cutting speed at distance from 0.036mm to 0.055mm. The reason for this is that smaller cutting speed leads to the material attaining more energy. The temperature for two kinds of cutting speed at cut edge is the same when laser cutting finished in Fig.6 (b). The reason for this is that the cutting speed at corner declines almost to the same value. And this corner burnt phenomenon is the same for two cutting speeds. However, the temperature is higher for smaller cutting speed at distance 0.02mm to 0.051mm for the same reason that smaller cutting speed leads to more absorbed energy.

Fig.6 Temperature distribution along Y-axis contrast at location C, 50mm/s(C0), (a) Laser beam at location C, (b) after cutting

The Von Mises stress distribution along Y-axis contrast with different cutting speed for location C is shown in Fig.7. Time T2 is when the laser beam is at location C, and time T4 is when the workpiece is completely cool. It can be found that the Von Mises stress is smaller for smaller cutting speed because of more serious heat concentration. Meanwhile, the corner with smaller cutting speed also has a smaller residual stress. The maximum residual stress of different cutting speed at different locations is shown in Table 4. Residual stress has declined when the cutting speed declined.

| Table 4 residual stress at locations B, C, D |
| --- | --- | --- |
| V=50mm/s | 275MPa | 130MPa | 270MPa |
| V=30mm/s | 265MPa | 120MPa | 265MPa |
5. Experiment

The laser used in the experiment is continuous CO2 laser and cutting parameters are the same with that used in the simulation. The temperature data is measured by thermocouple. And the residual stress is obtained by XRD. Then the surface quality of corner can be gained by optical microscope.

Fig. 8 shows the temperature variation curve of location A for simulation and experiment. It can be found that the simulation has good agreement with the experiment. The residual stress at different locations for simulation and experiment is shown in Table 5. It also can be found that the simulation has good agreement with the experiment. Fig. 9 shows the surface quality of corner. The surface has a poor quality in Fig. 9. At the same time, it can be found that there exist serious corner burning and large adhering slag at bottom.

|                | B       | C       | D       |
|----------------|---------|---------|---------|
| Experiment(X-axis) | 83.32 ± 8.39 | 74.31 ± 6.4 | 59.87 ± 8.19 |
| Model predict(X-axis) | 72      | 81      | 70      |
| Experiment(Y-axis)  | 127.20 ± 7.13 | -21.06 ± 8.89 | 115.13 ± 14.35 |
| Model predict(Y-axis) | 123      | -35     | 130     |

Fig. 7 Von Mises stress distribution contrast along the y-axis at location C
6. Conclusion
A 3D model of laser cutting corner with a fluctuant cutting speed is established, and the cutting process of laser heat source moving along the corner trajectory is simulated. Then the temperature and thermal stress field are analysed, and also the effects of changing cutting parameters such as corner size and cutting speed are studied.

1) Based on heat transfer, thermodynamics theory and speed fluctuation model, the modeling approach for laser cutting corner with a fluctuant speed is analyzed. The phenomenon of slower heat diffusion at the corner and corner burnt are been found in the 3D simulation model. At the same time, the influence of fluctuant speed on laser cutting quality is confirmed.

2) The influence of laser cutting parameters in the 3D simulation model is carried out. It is found that the temperature changes more slowly at the corner and the phenomenon of corner burning happens. Smaller thermal stress is obtained when the corner size decreases. And if the cutting speed decreases, the same phenomenon can also been found.

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8. References
[1] Farin, G.E., J. Hoschek, and M.-S. Kim 2002 Handbook of computer aided geometric design (North Holland)
[2] Tsai, M.-S., H.-W. Nien, and H.-T. Yau 2008 Comput.-Aided Des. 40 554-566.
[3] Sheng, P.S. and V.S. Joshi 1995 Journal of materials processing technology 53 879-892.
[4] Prusa, J.M., G. Venkitachalam, and P.A. Molian 1999 International Journal of Machine Tools and Manufacture 39 431-458.
[5] Shuja, S. and B. Yilbas 2000 Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 214 1059-1078.
[6] Ji, Z. and S. Wu 1998 Journal of Materials Processing Technology 74 89-95.
[7] Yilbas, B., A. Arif, and B. Aleem 2009 Optics and Lasers in Engineering 47 909-916.
[8] Yilbas, B. and S. Akhtar 2012 Optics and Lasers in Engineering 50 204-209.
[9] Yilbas, B., S. Akhtar, and C. Karatas 2011 Journal of Materials Processing Technology 211 1296-1304.
[10] Yilbas, B., A. Arif, and B. Abdul Aleem 2010 Optics and Lasers in Engineering 48 10-19.
[11] Yilbas, B., A. Arif, and B.A. Aleem 2010 Journal of materials engineering and performance 19 177-184.
[12] Nyon, K., et al. 2012 The International Journal of Advanced Manufacturing Technology 60 995-1007.
[13] Hu, J., et al. 2006 The International Journal of Advanced Manufacturing Technology 28 930-935.