

The Culation Method of Laser Quenching Temperature Field Simulation of Stainless Steel Knife

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Abstract: Stainless steel table knife is widely used because of its superior cutting performance and easy cleanliness. In this paper, the method of the stainless steel knife and the feasibility of the finite element method for the process of the heating and quenching. The study shows that the finite element method based on ANSYS-workbench is feasible during laser heating and quenching, and the results agree well.

Keywords: Laser Heating, Finite Element, Quenching, Stainless Steel.

1. Introduction

In addition to corrosion resistance, food grade tools also require high hardness, wear resistance, sharpness and durability. Stainless steel materials are widely used in the production of all kinds of tableware and knife because of its high quality corrosion resistance and beautiful brightness, and the stainless steel knife production materials on the market have 430,304,316 and other brands. In order to meet the requirements of wear resistance and hardness of high quality tools, domestic tool manufacturers generally adopt quenching and tempering process. At present, the heat treatment equipment is still mainly network belt furnace (see Figure 1 for the equipment). The mesh belt furnace is a continuous production, which is to send the tool to the furnace to preheat and heat, and then be cooled by the salt bath outside the furnace. The traditional heat treatment process of application network belt furnace equipment has problems such as poor tool performance, insufficient energy saving and environmental pollution.



Figure 1. Traditional Heat Treatment Equipment

Laser quenching is a heat treatment technique with the laser as a heat source, controlling the part of the laser scanning heat treatment to bringing the scanned area to 104~106W. With the heating and cooling speed of °C / s, the solid phase transition is completed within 1 second to obtain the desired quenching effect.^[1] Compared with traditional quenching, laser

quenching has the advantages of obvious strengthening effect, local quenching, green and clean process, reduced manufacturing cost, strong process controllability and so on.^[2] However, there is still no exact formula between the main process parameters and the reinforcement effect, and the lack of process specifications affects the popularization and application of laser quenching in food grade tool surface reinforcement to some extent.

In the study of laser quenching process, temperature field analysis in laser processing is crucial and has high theoretical and practical value.^[3-5] In this paper, a 304 stainless steel dining knife is studied, and a large general finite element software ANSYS-workbench is used to study the temperature field simulation of laser heating and quenching process. The calculation results were also discussed and analyzed.

2. Mathematical Model

(1) Knife Geometry Model

This article chooses a western food steak knife. According to the structure and size of the knives commonly used in the market, establish the geometric model of the knives, as shown in Figure 2.

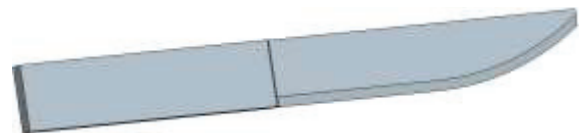


Figure 2. Food Knife Geometric Model

(2) Laser Heat Source Model

The laser heat source model adopts the Gaussian surface heat source, and the heat source function is described as:^[6]

$$q(x, y) = q_m \cdot e^{-3 \times \frac{x^2 + y^2}{R_0^2}}$$

In the above equation, $q(x,y)$ is the heat source power in W; The q_m is the heat flow density in W / m², and its given value of the laser heat source is 4e7 W/m²; R_0 is the spot radius of the heat source in m, and the heat source value is 0.0024m, namely 2.4mm; x and y is the axis coordinates on the heat source movement path respectively, in m.

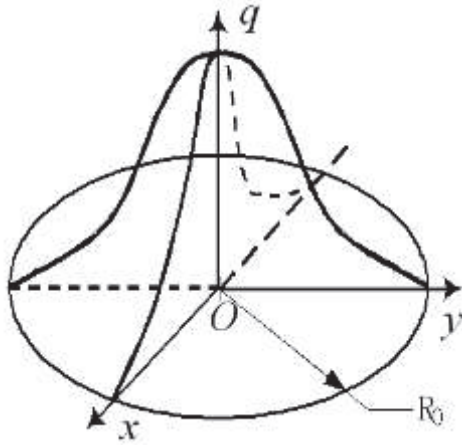


Figure 3. Schematic Diagram of the Heat Source on the Gaussian Surface

For mobile heat sources, its function is described as:

$$q(x, y) = q_m \cdot e^{-\frac{(x-v_x t)^2 + (y-v_y t)^2}{R_0^2}}$$

In the above equation, v_x and v_y are the speed of the heat source in the x and y axis, respectively, in m/s; v is the total speed of the heat source, $v = \sqrt{v_x^2 + v_y^2} = 0.015\text{m/s}$; t is the action time of the heat source, in s.

(3) Heat Conduction

Steak table knife is a continuous material structure. The thermal energy exchange caused by the temperature gradient in different parts of the continuum follows the Fourier's law:

$$q_m = K_{mn} \frac{\partial T}{\partial n}$$

In the above equation, K_{mn} is a thermal conductivity in $\text{W}/(\text{m} \cdot ^\circ\text{C})$ and the value of 304 stainless steel is $21.5\text{W}/(\text{m} \cdot ^\circ\text{C})$; $\frac{\partial T}{\partial n}$ is a temperature gradient along the direction of material distribution.

The conduction of calories in the knife eventually uniform the overall temperature distribution.

(4) Thermal Convection

Thermal convection is a thermal energy exchange phenomenon caused by the temperature difference between the solid surface and its surrounding fluid, which is described by the Newtonian cooling equation:

$$q_m = h_f (T_s - T_B)$$

In the above equation, h_f is the convective heat transfer coefficient; T_s is the surface temperature of the solid; T_B is the temperature of the surrounding fluid.

Heat convection heat exchange of meal knife exists in two processes: Firstly, the knife undergoes convective heat exchange with the air.; Secondly, during the quenching process of the dining knife, there is convective heat exchange between the knife and water. Usually, the convective heat transfer coefficient of stainless steel and air is $h = 5\text{W}/\text{m}^2 \cdot ^\circ\text{C}$, and that of water is $h = 1500\text{W}/\text{m}^2 \cdot ^\circ\text{C}$.

3. Simulation Calculation

(1) Control Differential Equation and Finite-element Integration Algorithm of Heat Conduction

The differential equation for controlling the heat conduction:^[7]

$$\frac{\partial}{\partial x} (k_{xx} \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k_{yy} \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k_{zz} \frac{\partial T}{\partial z}) + \ddot{q} = \rho c \frac{dT}{dt}$$

$$\frac{dT}{dt} = \frac{\partial T}{\partial t} + V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} + V_z \frac{\partial T}{\partial z}$$

In the above equation, k_{xx} , k_{yy} and k_{zz} are the thermal conductivity in three directions, respectively; \ddot{q} is the heat generation coefficient per unit volume; ρ is the material density; c is the specific heat capacity; V_x , V_y , V_z is the medium conduction rate.

Change the control differential equation into the finite element equivalent integral form:

$$\int_{vol} (\rho c \delta T (\frac{\partial T}{\partial t} + \{v\}^T \{L\}^T) + \{L\}^T \delta T ([D] \{L\}^T)) d(vol) =$$

$$\int_{S_2} \delta T q_m d(S_2) + \int_{S_3} \delta T h_f (T_B - T) d(S_3) + \int_{vol} \delta T \ddot{q} d(vol)$$

In the above equation, vol is the cell volume, and its calculation method as:

$$\{L\}^T = \begin{bmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \end{bmatrix}$$

δT is the temperature imaginary variable; S_3 is the area for the heat flux; and the area for convection.

(2) Mobile Path Planning of Laser Heat Source based on ANSYS-workbench

The blade laser heating of the dining knife adopts two stroke heating, that is, one heat source spot from the inside out, and then one heat source spot back from the outside to the inside, to ensure the full heating of the blade. The movement path planning of the two heat source spots is specified as follows:

The first heating path is shown in Figure 4. The heat source spot starts from the internal blade of the knife and passes through the paths L1, L2 and L3 respectively according to the arrow direction to reach the outermost blade of the knife.



Figure 4. Lane stroke heating path

As shown in the second heating path in Figure 5, the heat source spot starts from the outermost blade of the knife, passes through paths L3, L2 and L1 respectively according to the direction indicated by the arrow, and reaches the end of the heating.

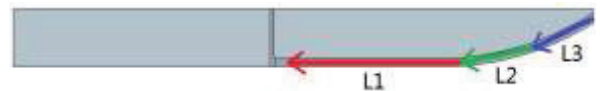


Figure 5. Lane stroke heating path

(3) The Calculation of Heating and Quenching of ANSYS-workbench

1) Finite Element Model

The model of the knife is divided with 10-node 4-faceted solid units, and the finite element model obtained after dividing the grid is shown in Figure 6.

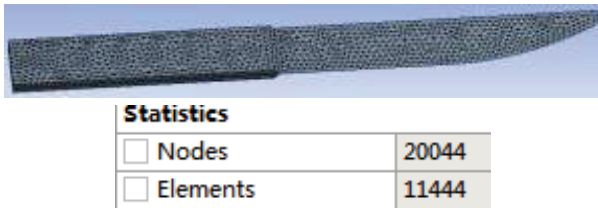


Figure 6. Finite element model, number of cells and nodes

Table 1. Performance Parameter of 304 Stainless Steel

the name of a shop	304	tensile strength (MPa)	≥ 515
density kg/m^3	7930	yield strength (MPa)	≥ 205
modulus of elasticity (GPa)	193	specific heat ($\text{J/kg}\cdot^\circ\text{C}$)	500
melting point ($^\circ\text{C}$)	1398~1454	thermal conductivity ($\text{W/m}\cdot^\circ\text{C}$)	21.5
hardness (HBW)	≤ 201	coefficient of linear expansion ($10^{-6} \text{ m}/^\circ\text{C}$)	18.4

2) Boundary Conditions

The mathematical model of the knife described in the anterior section is applied as a boundary condition to the finite element model of the knife.

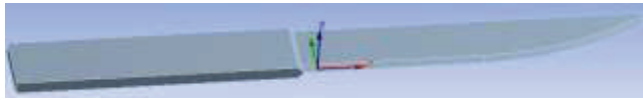


Figure 7. Location of coordinate system No.0 point

The laser moves the heat source and loads with a function. According to the path planning of the laser heat source movement, both 1 and 2 heating paths are composed of paths L1, L2 and L3, respectively.

The 1 heating path adopts the 0 coordinate series segment function, and the heat source moving segment function is described as:^[8]

$$L_1 : q(x, y) = 4e7 \times e^{-\frac{(-3 \times (x-0.015 \times t)^2 + y^2)}{0.0024^2}}$$

The action time was set to be 0-4s.

$$L_2 : q(x, y) = 4e7 \times e^{-\frac{(-3 \times (x-0.06-0.015 \times \cos(12.5) \times (t-4))^2 + (y-0.015 \times \sin(12.5) \times (t-4))^2)}{0.0024^2}}$$

Set the action time to be at 4-5.67s.

$$L_3 : q(x, y) = 4e7 \times e^{-\frac{(-3 \times (x-0.06-0.0244-0.015 \times \cos(25) \times (t-5.67))^2 + (y-0.0054-0.015 \times \sin(25) \times (t-5.67))^2)}{0.0024^2}}$$

Set the action time to be at 5.67-7.18s.



Figure 8. Location of the coordinate system No.12 point

The 2 heating paths adopt the 12 coordinate series segment function, and the heat source moving segment function is described as:

$$L_3 : q(x, y) = e^{-\frac{(-3 \times (x-0.015 \times \cos(25) \times (t-7.18))^2 + (y-0.015 \times \sin(25) \times (t-7.18))^2)}{0.0024^2}}$$

Set the action time to be at 7.18-8.69s.

$$L_2 : q(x, y) = 4e7 \times e^{-\frac{(-3 \times (x-0.0206-0.015 \times \cos(12.5) \times (t-8.69))^2 + (y-0.0096-0.015 \times \sin(12.5) \times (t-8.69))^2)}{0.0024^2}}$$

Set the action time to be at 8.69-10.36s.

$$L_1 : q(x, y) = 4e7 \times e^{-\frac{(-3 \times (x-0.045-0.015 \times (t-10.36))^2 + (y-0.01501)^2)}{0.0024^2}}$$

Set the action time to be at 10.36-14.5s.

Time 14.5-15.5, the natural heat conduction time between the knife and air;

Time 15.5-18, the knife is quenched in water, and severe convection heat exchange process with water.

The specific implementation of the above mobile laser heat source function equation in ANSYS adopts the command flow loading mode.

3) Setting of the Convection Heat Transfer Coefficient

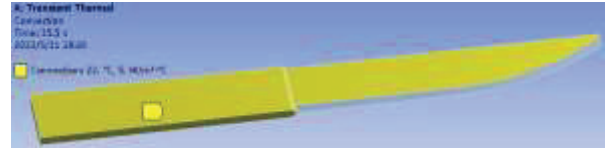


Figure 9. Convective Heat Exchange Boundary Conditions Setting of Meal Knife and Air

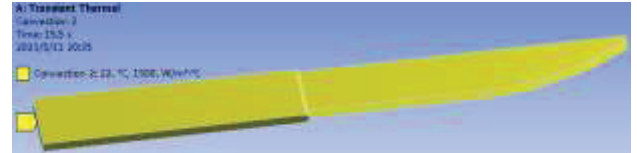


Figure 10. Setting of Convective Heat Exchange Boundary Conditions between Meal knife and Water

Table 2. Original Temperature Setting

Initial Temperature	Uniform Temperature
Initial Temperature Value	22 $^\circ\text{C}$

Table 3. Sets the search time and solution steps

No.1 Step Controls		No.2 Step Controls	
Number Of Steps	2	Number Of Steps	2
Current Step Number	1	Current Step Number	2
Step End Time	15.5s	Step End Time	18
Auto Time Stepping	On	Auto Time Stepping	On
Define By	Substeps	Define By	Substeps
Initial Substeps	1500	Carry Over Time Step	Off
Minimum Substeps	150	Initial Substeps	250
Maximum Substeps	15000	Minimum Substeps	25
Time Integration	On	Maximum Substeps	2500
		Time Integration	On

4. Finite Element Calculation

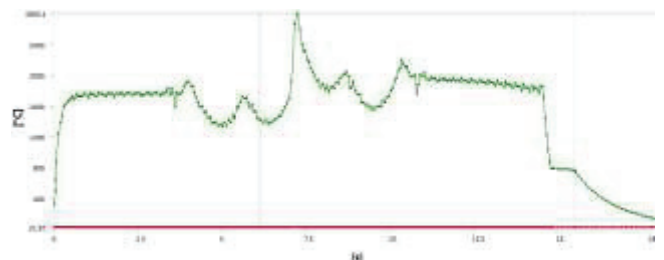
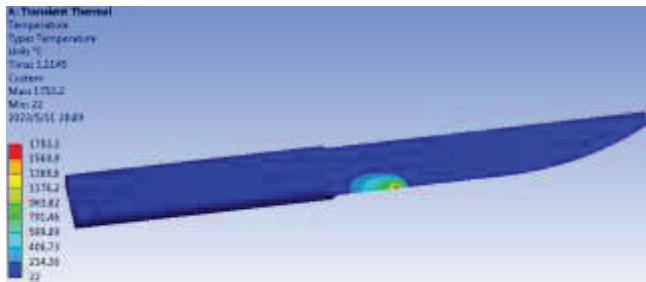
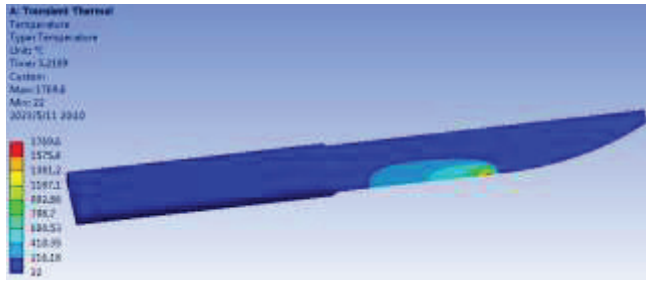


Figure 11. Change Curve of the Maximum Meal Knife Temperature in the Whole Process of Laser Quenching

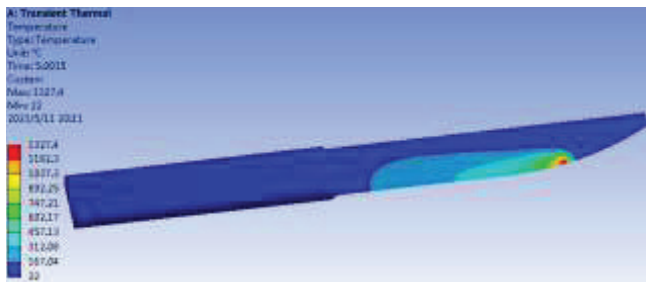
The instantaneous temperature distribution of the knife body during laser quenching is shown in Figure 12.



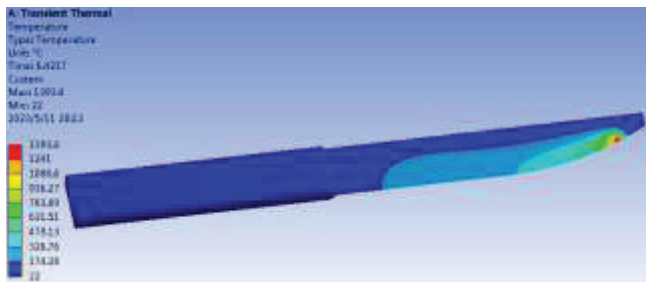
(a) Temperature Distribution for 1.1 seconds



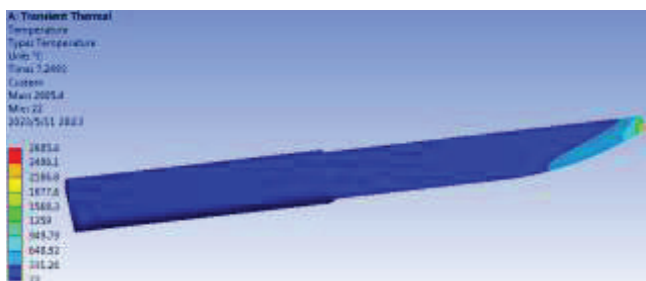
(b) the temperature Distribution for 3.2 seconds



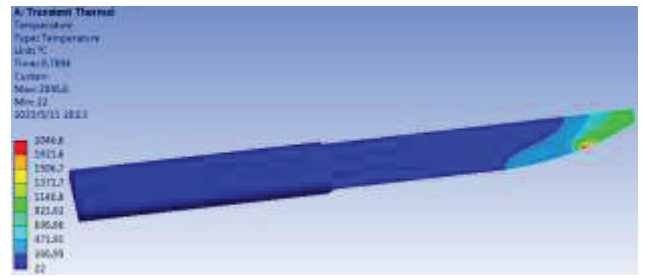
(c) Temperature Distribution for 5 seconds



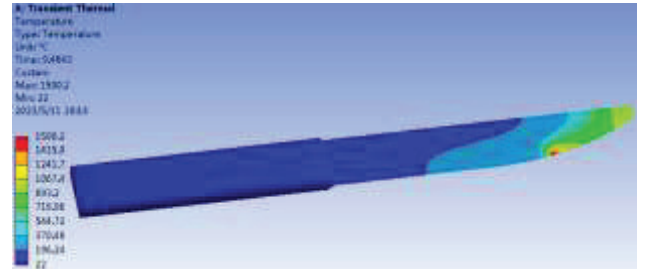
(d) the temperature Distribution for 6.4 seconds



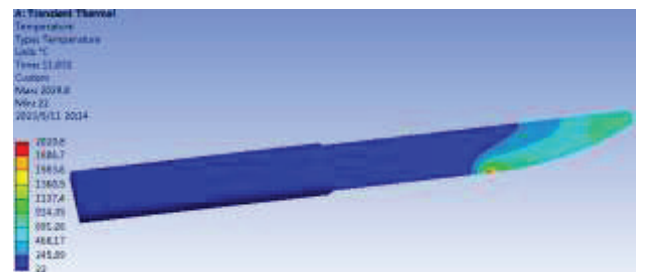
(e) Temperature Distribution for 7.2 seconds



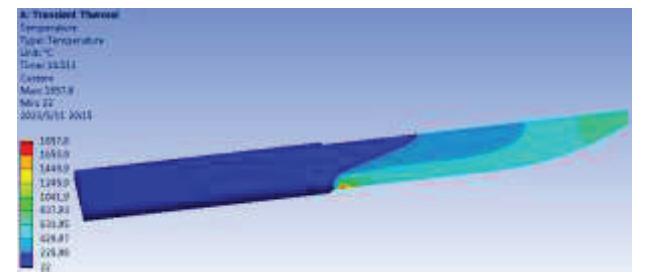
(f) Temperature Distribution for 8.7 seconds



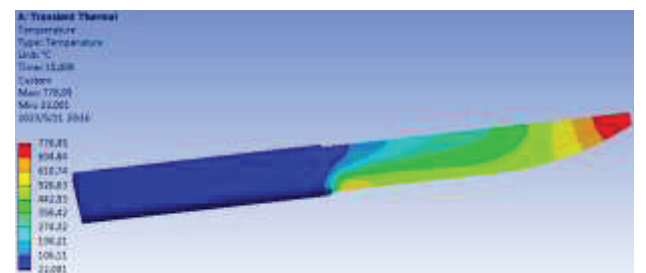
(g) Temperature Distribution for 9.5 seconds



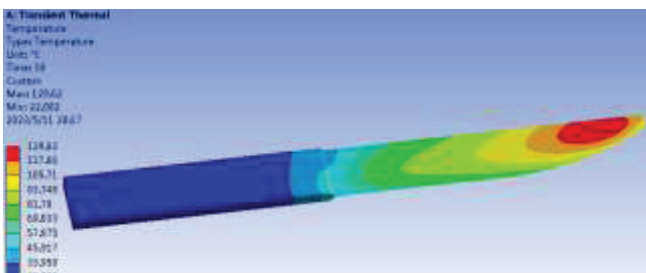
(h) Temperature Distribution for 11 seconds



(i) Temperature Distribution for 14.5 seconds



(j) Temperature Distribution for 15 seconds



(k) Temperature Distribution for 18s

Figure 12. Instantaneous temperature distribution

The temperature conversion curve of the specific points of each part of the blade is shown in Figure 13.

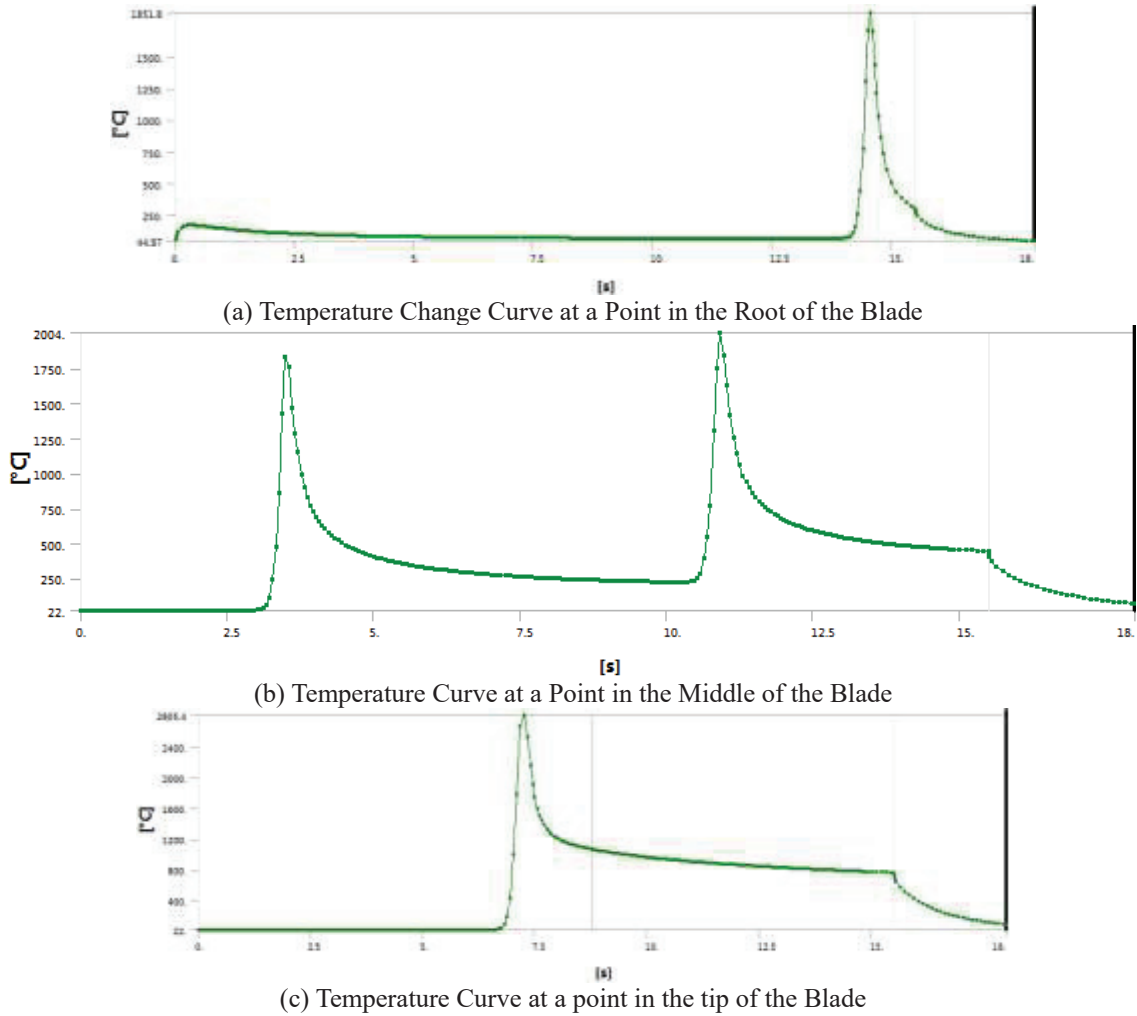


Figure 13. Temperature Conversion Curve Diagram of Specific Points in Each Part of the Blade

The steady state temperature distribution of the blade is shown in Figure 14, and the steady state temperature distribution on the path is shown in Figure 15.

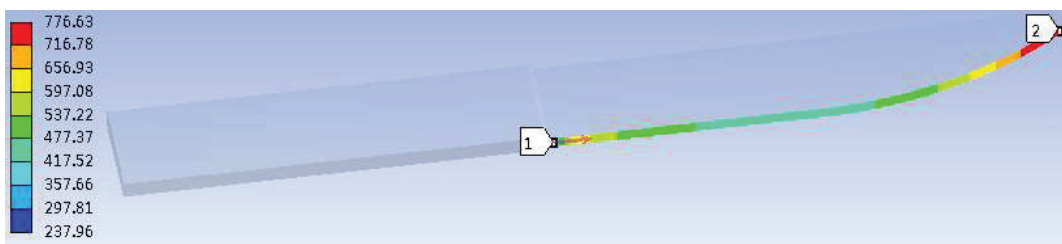


Figure 14. Steady-state Temperature Distribution of the Blade for 15s

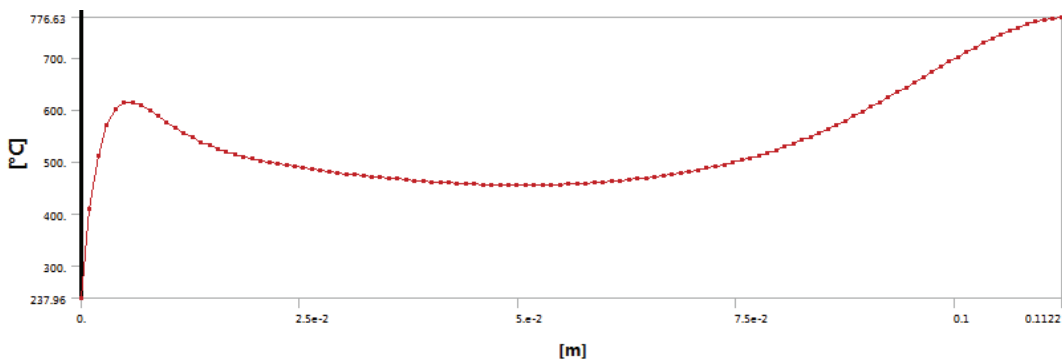


Figure 15. Steady-state Temperature Distribution on the Blade Path at 15s

The steady-state temperature distribution of the blade for 18 seconds is shown in Figure 16, and the steady-state

temperature distribution on the path is shown in Figure 17.

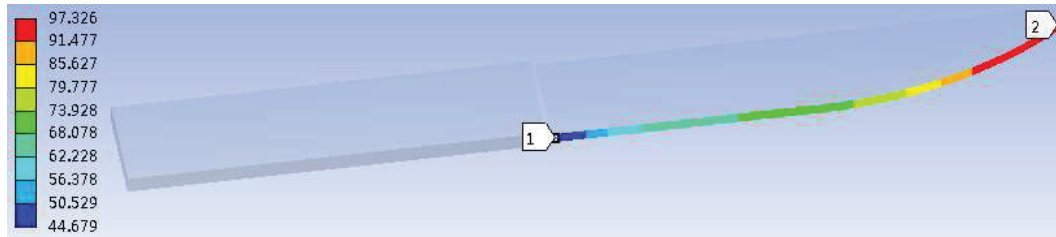


Figure 16. Steady-state Temperature Distribution of the Blade at 18s

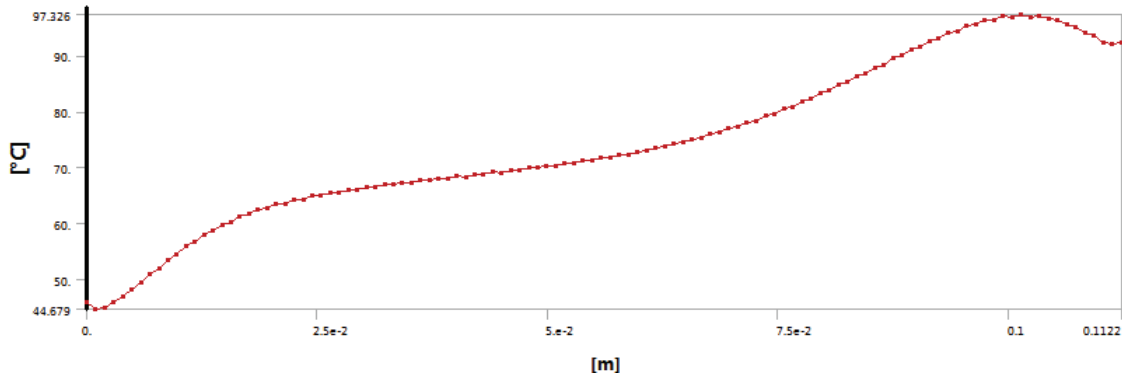


Figure 17. Steady-state Temperature Distribution on the Blade Path at 18s

Comparing the instantaneous states between 18 seconds and 15 seconds, the distribution of the quenching temperature

difference in the blade path is shown in Figure 18.

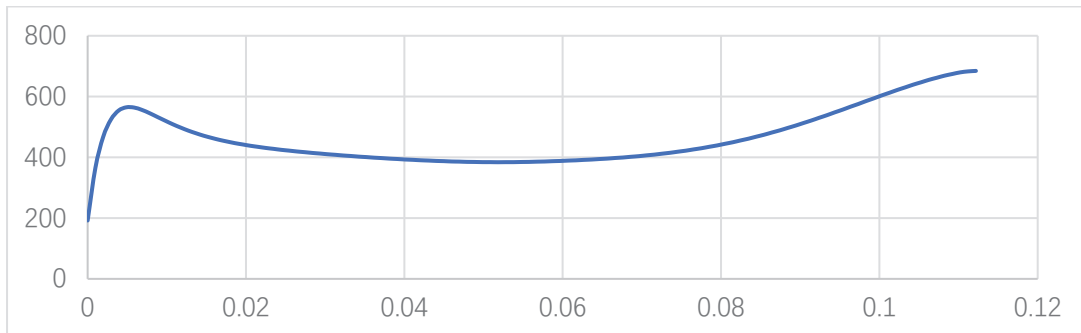


Figure 18. Distribution of Quenching Temperature Difference on the Blade Path (18s versus 15s)

5. Conclusion

Based on ANSYS-workbench software, the laser mobile heat source heating and quenching process of 304 stainless steel knife, and the following conclusions:

(1) The finite element method to calculate the heating and quenching process can be realized and the algorithm is feasible.

(2) The finite element method calculates the heating and quenching process of the meal knife, and the calculation results are in line with the actual process change trend. From the calculation data, the change trend of the results is well consistent with the actual situation.

(3) In the two heating processes of the mobile laser heat source, the highest temperature appears at the tip of the knife, and the knife tip is the end point of one heating, which is also the starting point of the two heating, so the temperature superposition is the most dense. In addition, the contact area between the knife tip and the air is the smallest, resulting in the highest temperature of the knife tip.

(4) The calculation results confirm the characteristics of laser heat source heating energy concentration and fast temperature rise, and fast heat dissipation. The energy of the

laser heat source is concentrated, and the highest temperature in the heating process often exceeds the melting point of the material, but due to the small diameter of the light spot, the melting of the material is not obvious, and the heat dissipation after the moving heat source sweep is fast, resulting in no obvious melting phenomenon and re-curing. After the end of the whole mobile heating process, the blade temperature of the meal knife is maintained at 450-800°C.

(5) In the process of laser heating and quenching, the temperature change of the tip and the nearby area is the most drastic, that is, the quenching effect of the tip area is the most obvious, followed by the root area of the blade.

Acknowledgment

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