Influence of meshing on thermal effect simulation of laser irradiation

Qiudong Qian¹,⁎, Qingtao Wang²,⁎ and Chongxu Wang¹, b

¹College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China
²College of Basic Education, National University of Defense Technology, Changsha 410072, China

⁎Corresponding author e-mail: 35016567@qq.com, a2415046862@qq.com, b297141508@qq.com

Abstract. When using the finite element software ANSYS to numerically simulate the thermal effect of laser irradiation, the calculation results will show some differences with the different ways of meshing. The thermal effect of finite element model under different meshing modes when loaded in the form of heat flux is studied, which is based on the process of laser irradiation of metal circular plates. The effects of element size ratio and mesh density on the simulation result are analysed. By comparing the theoretical analytical solutions with the calculation results under different element size ratio conditions, the overall scheme of meshing is determined first, and then the influence of mesh density is further explored. The calculation results show that when the element size ratio is 1 and the overall element size is 0.25mm, the finite element simulation solution gets high precision, which is consistent with the actual.

1. Introduction

As the basis of the laser processing industry, the importance of related research in the field of laser irradiation is self-evident. Modern laser technology research shows that materials are subjected to various energy forms such as thermal energy, mechanical energy, electromagnetic energy and light energy during the laser irradiation process. In general, the thermal effect on the material during this process has a greater impact. Therefore, research on laser irradiated materials has focused on the issue of thermal effects during laser irradiation. The emergence of finite element simulation software has broken through the limitations of many factors such as calculation volume, space, and cost. It is possible to carry out the numerical simulation under the consideration of various complicated conditions in the actual situation. An instantaneous accurate solution can be obtained at any position in the simulation process at any time and the requirements of geometrical nonlinearity, material nonlinearity, and contact nonlinearity of thermal analysis can be fulfilled, which shows that finite element simulation is very suitable for the study of laser irradiation.

The research on the thermal effects under laser irradiation mainly focuses on the calculation of temperature field distribution and temperature rise process inside and on the surface of material, which corresponds to the thermal analysis in the finite element analysis of ANSYS software. Guo [1] performed transient thermal analysis on the spot welding process of low-carbon steel sheet by
establishing an electro thermal coupled finite element model and obtained the temperature rise process of joints and other parts. Li [2] calculated the temperature field distribution of the pressurized cylindrical shell under laser irradiation for the two energy distributions of uniform distribution and Gaussian distribution. In order to obtain accurate results, the influence of various factors needs to be considered in the simulation calculation process. Among them, as the key of the pre-processing stage and the basis of the post-processing stage, the influence of meshing on the simulation calculation is very direct. The quality of the mesh division directly affects the calculation speed and the accuracy of the calculation results.

2. Influence of Meshing on Simulation Results

After the finite element model is established, it is necessary to operate the division of the element to generate the mesh model required for subsequent numerical simulations. Different meshing methods can be used for the same solid model to obtain different finite element mesh models and the analysis results are naturally different. Deng [3] studied the influence of grid generation on the calculation of catamaran flow field and proposed some improvement measures. The calculation results of improved meshing method and experimental data showed good consistency. Deng [4] analyzed the influence of factors such as the mesh density on the calculation results of the finite element stress by using a cylindrical shell-shaped open-hole pressure vessel as an example. The results show that meshing has certain influence on the related analysis of the plate and shell structure. Among them, the control of the mesh density in the thickness direction of the shell is particularly critical.

In theory, the meshing of the finite element model will affect the accuracy of the calculation results. Taking the mesh density as an example, under the premise that the boundary conditions are set correctly, the larger the mesh density is, the more accurate the calculation result is but the longer the calculation time is. When the mesh density is increased to a certain degree, the calculation accuracy is improved slightly but the calculation scale is significantly increased, which may even cause the computer to be unable to perform calculations due to the low configuration [5]. Therefore, the influence of various factors should be considered comprehensively. A suitable meshing method should be adopted under the premise of computer configuration conditions so as to make ANSYS software generate high-quality mesh models that meet the requirements of calculation accuracy. The efficiency of calculation is improved.

3. The Finite Element Calculation Example

An incident laser beam is irradiated perpendicularly on the surface of a metal circular plate. The metal material absorbs the laser energy and converts it into thermal energy, which causes a temperature rise, as shown in Figure 1. Based on ANSYS software finite element thermal analysis, the temperature field distribution and temperature rise process of metal circular plates can be simulated. Due to the symmetry of the metal circular plate and the laser beam, a quarter model was taken for research, as shown in Figure 2. The material of the metal circular plate is 45# steel and the relevant parameters for calculation are shown in Table 1 [6].
Figure 1. Laser irradiation geometric model

Figure 2. Quarter finite element model

Table 1. Relevant parameters used in the calculation process

| Density (kg/m³) | Specific heat capacity (J/kg·°C) | Thermal conductivity (W/m·°C) | Absorption rate | Circular plate radius (m) | Circular plate thickness (m) | Laser power density \( I_0 \) (W/m²) | Spot radius \( a \) (m) |
|----------------|---------------------------------|-----------------------------|----------------|--------------------------|----------------------------|---------------------------------|-------------------|
| 7810           | 468.9                           | 48.15                       | 0.37           | 0.05                     | 0.005                      | 1.0E7                           | 0.005             |

In this paper, the loading method of laser energy uses heat flux density load (HFLUX). HFLUX is a kind of surface load that can be applied when the heat flow rate through the surface is known. A positive HFLUX value indicates the heat flow input model. The boundary where no load is applied is regarded as a complete adiabatic heat treatment. The laser irradiation time is set to 5 seconds.

For the above laser irradiation calculation model, the analytical formula for the temperature field calculation can be derived from the thermal theory without considering the convective and radiative heat transfer on the surface of the metal circular plate as follows [7]

\[
T(x, y, z, t) = \frac{A I_0 a^2}{k} \sqrt{\frac{D}{\pi}} \int_0^t \exp \left( \frac{-z^2}{4D t_i} - \frac{x^2 + y^2}{4D t_i + a^2} \right) \frac{d t_i}{\sqrt{t_i \left( 4D t_i + a^2 \right)}} + T_f
\]

Where \( T(x, y, z, t) \) defines the temperature field distribution of the metal plate; \( I_0(r, t) \) defines the power density of laser when reaching the plate surface; \( A \) defines the energy absorption rate of the plate surface to the laser; \( a \) defines the spot radius of the incident laser; \( D = k/\rho c \) defines the thermal diffusion coefficient of the metal plate; \( \rho, c, k \) define the density, specific heat capacity and thermal conductivity of the metal target material, respectively; \( T_f \) defines the ambient temperature and \( T_f = 25°C \). Substituting \( x, y, z = 0, t = 5s \) into the above formula, the temperature value \( T = 300°C \) of the center point of the front side of the laser irradiation of the metal circular plate at the end of the irradiation can be obtained.

4. Influence of Element Size Ratio
Firstly, the influence of meshing on the calculation results is studied from the perspective of element shape, that is, element size ratio. GAO [8] pointed out that the ideal side length ratio of the element is 1
and the accuracy of the solution can be close to the actual value when the structural elements are all composed of regular hexahedral elements. Three-dimensional eight-node solid element solid70 was used for analysis. Three right-angled edges of a quarter flat cylindrical metal plate were equally divided and the obtained elements were all hexahedrons. Since the circular plates are symmetrical in the x and y directions, the mesh division is the same. The thickness of the plate is 5mm. In order to avoid the inconsistency of the length/width and height of elements, the ratio of the length/width and height is defined as the size ratio R. The size ratios were set to 2 mm, 1 mm, and 0.5 mm for analysis. The calculation results are shown in Table 2.

Table 2. Temperature of the front center point of laser irradiation at 5 seconds

| Element size(xy*z)(mm) | Size ratio R | Number of nodes / number of elements | Center temperature(℃) | Theoretical solution error(%) | Calculation time(min) |
|------------------------|--------------|---------------------------------------|------------------------|-------------------------------|----------------------|
| 1*0.5                  | 2:1          | 21461/18750                           | 149                    | 50.3                          | 2.0                  |
| 0.5*0.5                | 1:1          | 84161/75000                           | 304                    | 1.3                           | 6.1                  |
| 0.25*0.5               | 1:2          | 333311/300000                         | 617                    | 105.7                         | 12.7                 |

As can be seen from Table 2, under the premise of keeping element size of the vertical direction (z direction) unchanged, the calculation results obtained are very different by changing element size of the horizontal direction (x/y direction), that is, changing the element size ratio. With the decrease of element size ratio, the temperature at the center point shows a clear tendency to increase in multiples. Compared with the theoretical analytical solution above, it is found that the element shape is ideal and the simulation result is closest to the actual one when the size ratio R = 1:1. This phenomenon can be understood as follows: the principle of using the finite element software ANSYS to solve the temperature field problem is to use a model of finite freedom degree to approximate the substance of infinite freedom degree. Therefore, the larger the element size ratio, the smaller the total number of elements, the less the degree of freedom, the weaker the target's ability to conduct thermal energy, and the lower the temperature rise during the same time, and vice versa. When the element size ratio is R = 1:1, the meshing of the finite element model is uniform in three directions and the shape of element is similar to a cube so that distortion is not easy to occur and the heat energy spreads more smoothly inside the target, which is consistent with the actual situation.

In summary, the element size ratio should be controlled when meshing and the calculation result is more accurate and more close to the actual situation when taking R = 1:1.

5. Influence of Mesh Density
The mesh density still has a very important influence on the accuracy of the calculation results under the premise of determining the element size ratio. It is worth further exploration. The overall element size were set to 1 mm, 0.5 mm, and 0.25 mm to conduct analysis by taking R = 1:1 as the basic condition. The calculation results are shown in Figure 3.
It can be seen from Figure 3 that when the mesh density is different, the temperature rise of central point of the front and back of irradiation face is basically the same. The temperature of central point of the front of the irradiation shows an increasing trend with the increase of the mesh density and the temperature rise gradually decreases. This phenomenon does not exist on the back. The temperature rise curves of each mesh density are in good agreement.

The above phenomena can be analyzed. The final result of the finite element simulation is the average value of the temperature of each node. When the mesh is sparse, the element size and the temperature difference between nodes are both large. The low temperature node will pull down the temperature value of the entire element, resulting in lower calculation accuracy. To solve this problem, the mesh is encrypted and the element size is reduced so that the temperature difference between nodes becomes smaller. The temperature value of front center point of laser irradiation surface gradually increases and approaches the real value. For the back surface, the temperature of each node has basically reached a stable state which is close to the true value because of the thorough internal heat transfer. The difference of temperature between nodes is so small that the effect of mesh density is not large.

Table 3. Temperature of the center point of the metal plate at different mesh densities at 5 seconds

| Overall element size(mm) | Number of nodes / number of elements | Center point of the front side(℃) | Center point of the reverse side(℃) | Calculation time(min) |
|--------------------------|--------------------------------------|----------------------------------|------------------------------------|-----------------------|
| 1                        | 11706/9375                           | 270                              | 195                                | 0.8                   |
| 0.5                      | 84161/75000                          | 304                              | 198                                | 6.1                   |
| 0.25                     | 636321/600000                        | 326                              | 200                                | 32.3                  |
| 0.125                    | 4944641/4800000                      | -                                | -                                  | Unable to calculate   |

In this example, the element size is reduced from 1mm to 0.5mm and then to 0.25mm and the number of elements increases significantly by enlarging the mesh continuously. Correspondingly, the increase in the calculation result of the temperature value of the front center point of laser irradiation surface has gradually decreased, from 11.2% to 6.7%, and the back side has decreased from 1.5% to 1%, which indicates that the calculation results are gradually approaching the actual true value and the mesh density basically meets the accuracy requirements. From the perspective of calculation cost, the calculation time has reached 32.3min when the element size is 0.25mm (the total number of elements is 600,000). At 0.125mm, the number of elements is an astonishing 4.8 million, which causes the resource allocation of
computer platform used unable to meet the calculation requirements so that the calculation process cannot be performed. Therefore, 0.25mm can be determined as the most accurate element size in this example with a comprehensive consideration of calculation accuracy and calculation cost. A calculation result close to the actual value can be obtained by taking the overall element size as 0.25mm for mesh division.

6. Conclusion

In the finite element simulation of the laser irradiation, the HFLUX form should be used for energy loading. In the finite element simulation of laser irradiation thermal effects, the meshing method has a significant effect on the calculation results. Only by comprehensively considering various factors such as calculation configuration, calculation time, and calculation accuracy, can a high-quality meshing method suitable for the actual situation be determined. By analyzing the laser irradiation temperature field of metal circular plates under different element size ratios and mesh densities, the following conclusions can be obtained:

1. When the heat flux density load is used for the finite element thermal analysis, the element size ratio will have a very critical impact on the calculation results. When \( R = 1:1 \) is set as the size ratio, the calculation results are in line with the reality.

2. The mesh density is closely related to the calculation accuracy. Encrypting the mesh within a certain range can significantly improve the calculation accuracy, but it is not as dense as possible. An overly dense mesh will greatly increase the calculation time and even lead to calculation failure, which does not meet the requirements of cost-effectiveness calculation.

3. In this example, a high-precision finite element simulation solution can be obtained when the calculation mesh model is divided by a 1:1 element size ratio and the overall element size is 0.25mm.

References

[1] Z. Guo, J. X. Zhang. Finite element analysis of transient temperature field of thin plate spot welding, J. Modern Manufacturing Technology and Equipment, 02 (2008) 68 - 69.

[2] Y. Z. Li, G.C. Zhang, H. Wang, B.J. Nan. Numerical Simulation of Temperature Field and Stress Field of Cylindrical Shell Filled with Laser Irradiation, J. Solid Rocket Technology, 01 (2006) 19 - 21 + 55.

[3] R. Deng, D. B. Huang, J. Li, X.K. Cheng, L. Yu. Discussion of grid generation for catamaran resistance calculation, J. Journal of Marine Science and Application, 02 (2010) 187 - 191.

[4] J. S. Deng. Influence of element and grid density on the results of finite element analysis, J. Petrochemical Equipment Technology, 01 (2017) 12-15 + 20 + 5.

[5] P. A. Du. Basic principles of finite element meshing, J. Machinery Design and Manufacturing, 01 (2000) 34 - 36.

[6] Engineering Materials Practical Handbook Committee. Practical handbook of engineering materials, Volume 1, structural steel stainless steel (2nd Edition), China Standard Press, Beijing, 1988: 38 - 40.

[7] C. W. Sun, Q.S. Lu, Z. X. Fan. Laser irradiation effect, National Defense Industry Press, Beijing, 2002.

[8] S. H. Gao. Research on Mesh Density and Finite Element Solving Precision, J. Heavy Industry Technology, 01 (2006) 12 - 15.