Research on Optimization of Key Parts of Nuclear Reactor Based on Finite Element Simulation

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Abstract. In view of the higher technical requirements of the third generation PWR for the control rod drive mechanism (CRDM), China's third generation nuclear reactor CRDM hook parts are designed to multi-tooth hook with wear-resistant surfacing. The surfacing welding process is simulated and optimized based on finite element simulation, and reasonable welding process and parameters are determined by simulation results in this paper. According to the optimized welding process, the parts are trial-produced, and the parts of the hook are subjected to metallographic inspection, hardness test and thermal life test. The results show that the optimized hook parts have high hardness and wear resistance, and meet the requirements of the third generation PWR nuclear power plant.

Keywords: Nuclear reactor, CRDM, Surfacing Process, Finite Element Simulation

1. Introduction
The hook is the key part of the CRDM, and all kinds of actions of the CRDM are finally realized by the hook. When the driving mechanism moves, keep the hook and the moving hook alternately meshing with the ring groove on the driving rod, thus driving the control rod assembly to rise or fall in step way. The third generation nuclear reactor require the CRDM to complete the action of tens of millions of steps in the whole life period, which puts higher requirements for the life of the hook.

2. Structural Design Optimization
At present, hook mostly is single tooth structure, its wear surface is small, and the operation life is short. Therefore, it can not meet the requirements of the third generation PWR. The wear area can be increased and the wear resistance of driving mechanism can be improved by using double-tooth hook [1] [2].

Double-tooth hook with surfacing cobalt-based alloy on wear surface is designed the third generation PWR. The base material of hook is austenitic stainless steel (00Cr18Ni10N), and the welding filling material is cobalt-based alloy welding wire (Stelle-6). The improved design of the hook is shown in Figure 1.
3. Optimization of surfacing technology

The welding process of hook surfacing is the key technology of hook manufacturing. Cobalt-based wear-resistant alloy surfacing layer has high hardness, poor toughness and brittle cracks. The main reason of brittle crack in weld seam is welding residual stress, so the residual stress in surfacing process is reduced [3]. This section uses ANSYS finite element analysis software to explore the influence of welding sequence and other factors on the temperature field and stress field of the workpiece, and finds out the best process combination through the analysis results to provide theoretical basis and scientific support for the solidification and improvement of the surfacing technology of the product.

3.1. Calculation model

A full-size physical model is established in this ANSYS. The temperature distribution of the workpiece is calculated by indirect coupling analysis. Then the calculation results are applied to the stress calculation process in the form of load. [4].

3.1.1. Finite Element Model of Claw. The temperature field analysis uses high-precision hexahedron Solid 70 element, and the thermal stress deformation analysis uses the corresponding high-precision hexahedron Solid 45 element. In addition, to ensure the accuracy of the analysis and facilitate the application of welding heat source, the whole hexahedron element is used to divide the model grid. After grid division, 31160 units, 35511 nodes, a total of 106533 degrees of freedom.

3.1.2. Heat source model. The process of surfacing welding adopts oxyacetylene flame welding as heat source. In order to ensure the accuracy and reliability of thermal stress solution, the energy distribution of oxyacetylene flame is simulated by superposition of two double ellipsoidal heat sources.

\[
q_t(x, y, z) = \frac{6\sqrt{3}Q}{a_t b_d \pi \sqrt{\pi}} \exp \left( -\frac{3x^2}{a_t^2} \right) \exp \left( -\frac{3y^2}{b^2} \right) \exp \left( -\frac{3z^2}{d^2} \right)
\]

\[
q_r(x, y, z) = \frac{6\sqrt{3}Q}{a_t b_d \pi \sqrt{\pi}} \exp \left( -\frac{3x^2}{a_t^2} \right) \exp \left( -\frac{3y^2}{b^2} \right) \exp \left( -\frac{3z^2}{d^2} \right)
\]  

The Q is oxyacetylene flame heat, \(a,fa,rb\) and \(d\) are ellipsoid shape parameters. Since the \(x\) coordinates are always unchanged, the surfacing speed \(v\) and time \(t\) introduced into the transformation formula by the changes of \(y\) and \(z\).
3.1.3. Temperature Field Simulation of Pin Hole Stack Welding. The surfacing process adopts the surfacing welding of the pin hole first and then the tooth surface surfacing welding. For pin hole surfacing, according to the different layer temperature, welding sequence and the number of surfacing layers, the schemes A, B, C and D are designed for pin hole surfacing welding. The initial temperature is 260 °C, surfacing layer number is two. Figure 2- Figure 4 shows the simulation results of temperature field.

![Figure 2. Scheme A](image1)

![Figure 3. Scheme B](image2)

![Figure 4. Scheme C](image3)

![Figure 5. Scheme D](image4)

According to the calculation results of the temperature field, the summary table 1 is as follows.

| Scheme   | Maximum temperature (°C) | Maximum gradient (°C/mm) |
|----------|---------------------------|--------------------------|
| A        | 1390                      | 358104                   |
| B        | 1360                      | 337224                   |
| C        | 1426                      | 330108                   |
| D        | 1368                      | 361928                   |

From the calculation results, it can be seen that the peak temperature of the system is the lowest in scheme B, and the maximum peak gradient is also at a lower level. As a result, it is relatively appropriate to get the scheme B from the above analysis.
For the further investigation of 3 layer surfacing, the simulation of 3 layer welding scheme is carried out. The calculation summary is shown in Table 2.

**Table 2. Temperature field results of 3 layer surfacing welding**

| Scheme  | Maximum temperature (℃) | Maximum gradient (℃/mm) |
|---------|--------------------------|-------------------------|
| A       | 1768                     | 262508                  |
| B       | 1722                     | 132532                  |
| C       | 1747                     | 161230                  |
| D       | 1790                     | 134332                  |

From the calculation results, it can be seen that the peak temperature and temperature gradient are the lowest in scheme B. At the same time, this scheme also has strong maneuverability for field surfacing welding. As a result, the pin-hole surfacing scheme is defined as the two-layer pin-hole surfacing scheme B.

3.1.4. Temperature Field Simulation of Stack Welding. According to the engineering experience, four scheme of tooth surface surfacing are formulated. The calculation summary is shown in Table 3.

**Table 3. Temperature field results of surfacing welding**

| Programme | Maximum temperature (℃) | Maximum gradient (℃/mm) |
|-----------|--------------------------|-------------------------|
| 1         | 1990                     | 145236                  |
| 2         | 2203                     | 130060                  |
| 3         | 2311                     | 185237                  |
| 4         | 2171                     | 230785                  |

3.1.5. Residual stress analysis. The lower the peak temperature during surfacing, the more favorable it is to control the interlayer temperature, improve the cooling rate of the system, and improve the structure and performance of surfacing layer and joint [5].

The temperature gradient of Scheme 2 is lower, but the temperature is slightly higher than that of Scheme 1, so it is necessary to further compare the residual stress and distribution. The following figures 6 and 7 show the residual stress field of scheme 1 and scheme 2.

**Figures 6. Scheme 1 Residual stress field**

**Figures 7. Scheme 2 Residual stress field**

From the calculation results, the peak stress of scheme 2 is slightly lower than that of scheme 1, but the stress field distribution of the two is basically the same, and the maximum stress is located at the junction of the surfacing layer and the matrix. Combined with temperature field analysis, it can be determined that scheme 2 is the optimal scheme. Furthermore, the Von Mises elastic strain of schemes 1 and 2 is 0.023591 and 0.023268, which also shows that scheme 2 is the optimal scheme for surfacing welding.
4. Testing of surfacing products
According to the optimized surfacing sequence obtained by the above exploration, the actual hook surfacing welding is made. Metallographic examination, hardness test and thermal life test were carried out.

4.1. Metallographic examination
From the metallographic photos, it can be seen that there are no visible defects on the surfacing layer, and the surfacing layer combines well with the base metal, without virtual welding, leakage welding and so on. Carbides are mainly formed at grain boundaries. As the number of carbides increases, the eutectic region on grain boundaries becomes thicker and the resistance to matrix deformation is stronger [6].

![Metallographic examination](image)

**Figure 8.** Metallographic examination

4.2. Hardness tests
Ten hardness measuring points are selected on the tooth surface and hole surfacing layer respectively. The distribution of specific measurement results is shown in Figure 9. The results show that the hardness is between the HRC41–HRC45, and the difference between the maximum and minimum values is not more than HRC5, meet the design requirements, and the uniformity is very good.

![Hardness measurement](image)

**Figure 9.** Hardness value HRC each surfacing part of test piece
4.3. Thermal life test
In order to verify the product quality, the limit life test of the hook after surfacing welding is carried out 15 million steps. There was no obvious change in the hardness of the surfacing layer before and after the test, the wear amount of tooth surface height was 1.3 mm, the wear amount of tooth surface thickness was 1.7 mm; and the wear amount of pin hole was 0.1 mm. According to the size analysis of the hook, the hook parts after 15 million step life test can continue to operate normally.

5. Conclusions
In this paper, the welding process of double-tooth hook is optimized by finite element simulation, and then the surfacing welding piece is carried out. The results show that the hardness of the surfacing layer is in the range of HRC41~HRC45; the test piece after 15 million steps life test wear amount is very small, still can engage with the drive rod normally. The test results show that the process has superior wear resistance, and it is also proved that the service life of the CRDM can be greatly improved by the double-tooth structure.

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