Optimization of Manufacturing Process and Experimental Verification of Vulnerable Part in Reactor

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Abstract: The technical requirements of the control rod driving mechanism of the third generation PWR nuclear power plant are higher. The latch parts are designed with double tooth structure and welded on the wear-resistant surface by cobalt-based alloy surfacing. According to the structural characteristics and manufacturing process difficulties, a special welding device is developed. According to the test and finite element simulation, the related process parameters are optimized. The trial production of the parts was completed, and the parts were tested by metallography, liquid permeation test, hardness test and thermal life test. The results show that the latch parts have high hardness and wear resistance, and meet the requirements of the driving mechanism operation life of the third generation PWR nuclear power plant.

1. Introduction
The control rod drive mechanism (CRDM) is the equipment in the reactor to control the power of the reactor. The key moving parts of the latch part control rod drive mechanism. The function of the latch part is to mesh with the drive rod slot through the tooth surface of the latch, then to drive the drive rod up and down, and the drive rod to drive the control rod up and down, in order to adjust the power of the reactor and stop the reactor in emergency. Therefore, the performance of the latch directly determines the overall performance of the control rod driving mechanism.

2. Structure
The base metal of the latch is austenitic stainless steel, and the cobalt base alloy is surfacing on the pin hole and tooth surface to increase the hardness and wear resistance of the wear surface. The base metal is 00 Cr18Ni10N nitrogen-controlled austenitic stainless steel, and the welding filling material is AWS A5.21ERCoCr-A cobalt-based alloy wire. This material selection can effectively improve the hardness, wear resistance, corrosion resistance and high temperature stability of the wear surface of the parts, so that the latch has good comprehensive mechanical properties.
3. Manufacturing difficulties
Latch surface surfacing welding using oxygen acetylene surfacing welding. Due to the special structure, the following difficulties need to be solved in welding[1]:

1) The operation space of surfacing welding is narrow and the operation is difficult, which can easily lead to defects such as slag inclusion and porosity;
2) Welding stress difference is large, easy to produce cracks;
3) Tempering is easy to occur, which affects the continuity and stability of welding.

4. Development of specialized equipment

4.1. latch surfacing device
In order to ensure the stability of welding process and effectively control the carbon content of deposited metal, a special welding device is designed. Facilitate the operation of the operator, reduce the difficulty of welding, ensure the continuous of the welding process, this special device is installed on the positioner, the positioner driving device can rotate 360°, and the workpiece is always in the right position[2].

4.2. Anti-tempering device
Because of the limited welding operation space, most of the flame is rebounded to heat the torch, forcing the temperature of the mixed gas in the torch to rise rapidly, which can quickly reach the burning point of acetylene (305°C), thus tempering occurs. Once tempering occurs, the welding is forcibly interrupted, which directly affects the quality of the weld.

A special anti-tempering device is designed. The installation of anti-tempering device is simple and reliable, which effectively improves the service life of welding torch and avoids tempering phenomenon. The anti-tempering device is as in Figure 2.
5. Welding Process Optimization

5.1. Flame parameter optimization
In order to improve the weld strength, carbonized flame welding should be used in the process of surfacing welding, and the flame proportion must be controlled within a certain range[3]. Moreover, the carbonation flame will produce a reduction atmosphere in the high temperature area of the molten pool and protect the high temperature metal in the weld zone.

After repeated tests, we found that using a certain proportion of gas, the content of carbon elements in deposited metal can be increased to an ideal range. At the same time, it is found that when the carbon content of the deposited metal is within a certain range, the weld hardness is within a HRC40-HRC47 range. Therefore, the optimized carbonization flame ratio can effectively guarantee the welding quality.

5.2. Optimization of torch parameters
Because of the small size of the latch parts, the welding capacity is large. The heat input of welding will affect the residual stress of welding, so the appropriate type of welding nozzle must be selected. However, the residual stress can not be evaluated directly through the test. In this paper, the full size physical model is established in the finite element software, and the indirect coupling analysis method is used. Advanced thermal analysis calculates the temperature field distribution of the workpiece, and then applies the temperature field calculation results to the stress calculation process in the form of load, and calculates the residual stress of different welding nozzle types[4][5].

![Figure 3: the residual stress field](image)

The results show that the peak temperature of the butt welding parts is 740.4℃, and the peak temperature of the butt welding parts is much higher than that of the butt welding parts 1181℃. Figure 3 shows the residual stress field of the two kinds of welding nozzles.

In order to reduce the heat input, the welding pin hole can make up for the heat flux lost in the air and improve the melting efficiency, while the welding nozzle is used in the surfacing tooth surface, which can help to reduce the total energy of the system.

6. Test validation
Use special welding equipment and welding optimization process to weld test parts. The hardness test, metallographic test, liquid permeation test and thermal life test were carried out.

6.1. Hardness testing
Ten hardness measurement points are selected on the surfacing layer, as shown in Figure 4. The results show that the HRC hardness values of each measuring point are between the HRC41~HRC45 values, and the difference between the the maximum and the the minimum values is not more than HRC5, which meets the design requirements and the uniformity is very good[6].
6.2. Metallographic and other examinations

6.2.1 Metallographic examination
It can be seen from the metallographic photos that there are no visible defects on the surfacing layer, and the surfacing layer is well combined with the base metal. Carbides are mainly formed on grain boundaries. With the increase of the number of carbides, the eutectic region on grain boundaries becomes thicker and the resistance to deformation is stronger. Even if the second phase on the grain boundary is smaller, the hardness of the alloy is.

![Metallographic examination images a) 200X and b) 500X](image)

6.2.2 Phase analysis - X diffraction (XRD)
The carbides mainly exist in the form of (Cr, M) 7C3, and the Co matrix structure is face-centered cubic structure. After heat treatment, some Co matrix undergo fcc→hcp transformation. The amount of carbides increases with the increase of C content. So the higher the carbon content, the greater the hardness of the alloy. The location and pictures are shown in Figure 6, and Figure 7.

![X diffraction (XRD) chart](image)
6.3. Liquid penetration testing
The improved welding equipment reduces the difficulty of welding operation and effectively ensures the stability and consistency of the welding process. After the penetration detection of the parts, the reasonable detection rate is about 80%-90%, which meets the expected goal.

6.4. Life test
The ultimate life test of 15 million steps is carried out, and the wear and hardness of the latch after life test are tested. Before and after the test, the surface hardness of the parts has no obvious change. The wear data are compared in Table 1.

It can be seen from the test results that after completing the 6.5 million step life test, the top width of the tooth is still 1/3 of the wear, which fully meets the 6 million step life requirement of the control rod driving mechanism of the third generation pressurized water reactor. And 15 million step limit life test can still work normally.

| Step/million | Cylindrical dimension/mm | Wear in Tooth height/mm | Wear in Tooth width/mm |
|-------------|--------------------------|--------------------------|------------------------|
| 6.5         | 0                        | 0                        | 1.12                   |
| 15          | 0.1                      | 1.3                      | >1.7                   |

7. Conclusions
In order to meet the requirements of the third nuclear power reactor for CRDM equipment, a special latch welding device is developed and the welding process is optimized. Latch product process performance is good, welding controllability is good. The hardness of latch surfacing layer is in the range of HRC41~HRC45, and the difference between the maximum and the minimum value is not more than HRC5; the test piece has completed the 15 million step limit life test, which is the longest service life CRDM in the world at present.

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