Research and analysis of fluorescent magnetic particle inspection of steam turbine rotor blade

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Abstract. The operating conditions of turbine rotor blades are complex and changeable, and the probability of defects is high, which puts forward higher requirements for the professionalism, safety, stability and convenience of magnetic particle inspection personnel. How to find the deficiencies in the magnetic particle inspection of blades and improve it to better adapt to the field inspection has become the focus of attention. This paper mainly describes the process of fluorescent magnetic particle inspection, compares the similarities and differences of magnetization specifications in three domestic standards, analyzes the problems found in the process of fluorescent magnetic particle inspection and makes corresponding improvement, and adopts reasonable optimization scheme to improve the reliability of fluorescent magnetic particle inspection. After demonstration test and field application, the improved fluorescent magnetic particle inspection can give full play to its advantages, achieve the purpose of rapid, accurate inspection and continuous improvement; on this basis, different inspection platforms can be established to inspect different parts, improve the universality and inspection efficiency of magnetic particle inspection, which is conducive to the promotion and application of magnetic particle inspection in the field of nuclear power.

1. Introduction

In November 2012, the turbine low-pressure cylinder rotor blade failure and fracture caused emergency shutdown maintenance in a power plant, which caused people to attach great importance to the non-destructive inspection of the last three stage blades of the steam turbine rotor. According to the material and technical characteristics of the steam turbine blade, the inspectors carried out the technical demonstration of the previous inspection, and passed several surface non-destructive inspection methods (permeability, magnetic powder, etc.) performance By comparison, it is found that the fluorescent magnetic particle inspection technology has the advantages of simple equipment, convenient operation, fast speed, intuitive defect observation and high inspection sensitivity, and has a good detection rate for complex shape parts, which is very suitable for the application of non-destructive inspection of turbine rotor blade surface and near surface.

The basis of fluorescent magnetic powder inspection is the magnetic interaction between the leakage magnetic field at the defect and the fluorescent magnetic powder. The principle is that after the ferromagnetic material and the workpiece are magnetized, due to the existence of discontinuities, the
magnetic field lines on the surface and near the surface of the workpiece are locally distorted. The leakage magnetic field absorbs the fluorescent magnetic powder applied on the surface of the workpiece to produce magnetic marks. The fluorescent magnetic marks can emit bright yellow-green fluorescence under the irradiation of ultraviolet rays, and have a high contrast with the purple background formed on the surface of the workpiece. Discontinuous position, shape and size are shown, so the defect magnetic mark is easy to observe in a dark environment, and the inspection sensitivity is high.

2. The Working Environment of the Inspected Object and the Characteristics of Defects

2.1. The working environment
The low pressure cylinder rotor blade of steam turbine is made of Martensite Precipitation Hardening Stainless steel, and its operation conditions are complex and changeable. It operates at high temperature and high pressure (absolute pressure 0.747 mpa, temperature 265 °C). The stress of steam turbine rotor in the process of rotation concentrates on the connection between blade root and rotor groove, and is washed by saturated steam medium for a long time, which makes it easy to produce in operation cracks, corrosion, cavitation and other defects lead to blade root fracture.

2.2. Characteristics of defects
The secondary last stage and last stage blades of steam turbine rotor are fir tree type. During operation, the stresses on blade root mainly include centrifugal tensile stress, steam bending stress and eccentric bending stress. Therefore, in the process of turbine rotation, the first tooth is easy to produce defects, especially in the inlet side and outlet side. In addition, according to the location of defects found in the NDT of several major repairs of a power plant, the root defects of turbine rotor blades are transverse cracks extending from the inlet side to the first key groove, as shown in Fig. 1. Therefore, in order to maximize the safety of the operation of the steam turbine rotor blades, the key inspection area of the fluorescent magnetic powder of the steam turbine rotor blades is the rotor blade groove and the steam inlet and outlet end faces of the blades, as shown in Fig. 2, and all of them can achieve 100% full coverage of the rotor blades.

![Figure 1. Defects on the inlet side of the steam (fluorescent magnetic powder)](image1)

![Figure 2. Key inspection area-the root groove of the rotor blade and the steam inlet and outlet end faces](image2)
3. Selection of Inspection Process

In two sections with different permeability, the direction of the magnetic induction line will change, which is similar to the refraction of light and radio waves, which is called the refraction of magnetic induction line. If the permeability of the two media is very different, such as iron and air, the magnetic induction line refracts into the air and is almost perpendicular to the interface, thus causing the change of the magnetic field path, resulting in part of the magnetic flux leakage on the surface of the workpiece, forming a magnetic leakage field. The distribution of the magnetic leakage field at the discontinuity is shown in Fig. 3.

![Figure 3: Magnetic flux leakage distribution at discontinuities](image)

1-leakage magnetic field 2-crack 3-near surface air hole 4-scratch 5-internal air hole 6-magnetic line of force 7-workpiece

3.1. Preliminary preparation

Equipment connection, site water source power supply preparation, illumination verification, auxiliary equipment confirmation (black light lamp, black and white illuminance meter, measuring ruler, etc.), magnetic suspension preparation (1:35).

3.2. Pretreatment

The surface condition of the picked-up workpiece has a great influence on the operation and inspection sensitivity of the magnetic particle inspection. At the same time, the surface of the steam turbine rotor blade is working in a poor environment, and there is a lot of dirt on its surface, especially in the root keyway, so the surface to be inspected For pretreatment, it is required that the tested surface is exposed to metallic luster, and there is no solvent or oil that affects the wetting of the water-borne magnetic suspension.

3.3. Magnetization (selection of magnetization specification)

Determine the magnetization method, magnetization current type and effective magnetization area according to the material, size, shape, surface state, heat treatment state, magnetic characteristics, and the type, location, shape and size of the defect to be detected, and select the corresponding magnetization specification. Standards have different magnetization specifications for coil magnetization. The comparison of the three standard magnetization specifications is shown in Table 1.
Table 1. Comparison of magnetization specifications of NB/T47013, ASME and RCC-M.

| Standard project | NB/T 47013.4-2015 | ASME V Volume (2004) | RCC-M (2000) |
|------------------|-------------------|----------------------|--------------|
| Low fill factor coil method | When magnetization is placed eccentrically, it is calculated according to Equation (1): \[ I=45000\div N \( L/D \) \] When magnetization is placed in the middle, it is calculated according to Equation (2): \[ I=1720R\div N\left\{ 6 \( L/D \) - 5 \right\} \] | The magnetic field strength is based on the length L and diameter D of the part, and the calculation is carried out according to the following (a), (b) and (c). The long part should not exceed 18in. (457mm) for inspection and calculation. When, L is 18in. (457mm). For non-cylindrical parts, D takes the diagonal of the largest cross section: (a) Parts with L/D ratio greater than or equal to 4, magnetized ampere-turn: Ampere-turn=35000/(L/D+2) (b) Parts with L/D ratio less than 4 but not less than 2, magnetization ampere-turn: Ampere-turn=45000/(L/D) (c) If the magnetization range is expanded to more than 6in. on either side of the coil, the appropriate magnetic field shall be determined by a magnetic field indicator such as a pie-shaped magnetic field strength indicator, an artificial injury test piece or a Hall effect tangential field probe. |
| High fill factor coil method | \( I = \frac{35000}{N \left( \frac{L}{D} \right) + 2} \) | |
| Medium fill factor coil method | \( I = \left( N/10 - Y \right) + \left( N/2 - 5 \right) \) | |

Remarks:
1. It is stipulated in NB/T 47013.4-2015 that when the cross-sectional area of the coil is greater than or equal to 10 times of the cross-sectional area of the workpiece to be inspected, it is a low filling factor, less than or equal to 2 times the high filling factor, and more than 2 times and less than 10 times the medium filling factor;
2. In the formula: I -- magnetizing current applied to coil, unit: Ampere (a); N -- coil turns; L -- blade length, unit: mm; D -- equivalent diameter of blade (maximum dimension on cross section of blade), unit: mm; R -- coil radius, unit: mm.

By comparing the requirements of three kinds of standard magnetization specifications and combining with the actual site conditions, the magnetization specification in the standard NB/T 47013.4-2015 is selected. The tested area must be magnetized at least twice, and the magnetic lines of force of the two magnetizations should be approximately perpendicular to each other. The magnetic suspension should be evenly sprayed at the same time of magnetization. The magnetization can be stopped at least 3S after the magnetic powder is applied.

3.4. Apply magnetic suspension
Apply the magnetic suspension while magnetizing. The magnetic suspension should be evenly sprayed on the surface of the blade to be inspected. When spraying the magnetic suspension, the impact water flow should not damage the solidified magnetic powder display.
3.5. Magnetic trace analysis
When there is a display trace, it must be determined whether it is a true defect display trace or a false defect display trace. If it cannot be determined, a re-examination should be performed. The position, shape and size of defects that meet the recording standards should be recorded.

3.6. Demagnetization
There is still a certain amount of residual magnetism after magnetization of the blade, which will cause trouble in the subsequent use process and even cause safety accidents in serious cases. Therefore, demagnetize the inspected blade. The remanence in the blade after demagnetization should be less than 0.3mt (3G), otherwise it is unqualified.

3.7. Post treatment
Remove the redundant magnetic suspension on the tested surface and remove the fluorescence to the background value. Ultrasonic wave or high pressure washing is recommended.

4. The Working Environment of the Inspected Object and the Characteristics of Defects

4.1. Analysis and improvement of problems in the inspection process
Existing problems: The original magnetizing coil is 3 turns, and it is 570mm * 380mm rectangular. The number of turns of the coil is small, resulting in serious heating and scalding after working for 1-2 hours, and it needs to be shut down for 30 minutes to 1 hour; in addition, the rectangular coil will produce uneven distribution of magnetic force lines on the four corners of the coil, resulting in weak magnetic field strength of the four corners, which will affect the magnetization effect.

Improvement measures: The number of turns of magnetizing coil is changed to 6 turns and the shape is changed to round. One rectangular magnetizing coil is changed into three circular coils with inner diameter of 200 mm, 400 mm and 600 mm respectively. The magnetic particle inspection of blades of grade 5, 6 and 7 is used respectively. After the improvement, the equipment almost has no hot and hot phenomenon. The coil can work for 4-8 hours, which greatly improves the working efficiency and is replaced by circular coil In addition, three coils are used to improve the specificity and applicability of the equipment, and different coils are suitable for different objects to be inspected, and the defect detection rate is improved.

4.2. Analysis and improvement of sensitivity calibration
Existing problems: The original sensitivity calibration uses a1-30 / 100 standard test piece to check the sensitivity. The side with artificial groove is closely attached to the surface of the largest cross-section of the blade, and the position of the weak magnetic field in the magnetization process is shown in Fig. 4. This sensitivity calibration method will cause excessive accumulation of magnetic medium in the strong magnetic field position, resulting in the fuzzy display of large defects, which is easy to be missed, and in the calibration process the key inspection areas of defects, i.e. the end face of inlet and outlet side and the first key groove, are ignored.

Improvement measures: Place the A1-30/100 standard test piece for sensitivity calibration with the artificial groove on the side of the air inlet and outlet of the blade close to the surface of the first key groove, and perform two sensitivity calibrations at the weak and strong magnetic fields. The improved
calibration not only focuses on the air inlet and outlet side end faces and the first keyway, it will not cause excessive accumulation of magnetic media at the location of large defects due to excessive magnetic field, and will not affect the evaluation of large defects, nor will it cause small defects due to too small magnetic field. No accumulation of magnetic media and small defects are missed.

4.3. Analysis and improvement of magnetization specification
Existing problems: The size of the original magnetizing coil is fixed, but the tested blades are Grade 5, 6 and 7. The sizes of the three blades are different. When the three different sizes of blades pass the inspection of the size fixed coil, three different magnetization specifications will be produced, namely, eccentric placement with low filling coefficient, medium filling factor and high filling factor. When the number of turns is fixed, the magnetization current will fluctuate greatly, the test effect is poor.

Improvement measures: Three kinds of coils with different sizes are used to magnetize the blades of three different sizes, and the magnetization specifications are unified. Either the low filling coefficient is eccentric placed, or the filling coefficient is medium or high. The normalization of the three kinds of blade magnetization specifications is realized. The selection of magnetizing current is convenient and quick with small fluctuation. In addition, the mutual transformation of NB / T47013, ASME and RCC-M can be realized. It is equivalent to each other to improve the universality and compatibility of magnetization specifications and equipment.

4.4. Analysis and improvement of magnetic suspension
Existing problems: When the magnetic suspension is recycled, the suspension will produce foam after five or six hours. It will affect the inspection and replace the new magnetic suspension. The evaporation of water will make the magnetic suspension thicker.

Improvement measures: Add defoaming agent to the magnetic suspension according to a certain proportion, track and calibrate the magnetic suspension with sensitivity test piece in time, and dilute the magnetic suspension. If it is found that the magnetic suspension does not meet the requirements, it shall be replaced in time.

4.5. Demagnetization problem analysis and improvement
Existing problems: Due to the special-shaped structure of the turbine rotor blade, there are keyways in the blade root and Stellite Alloy at the blade end. During demagnetization, it is found that the demagnetization effect of some parts is poor, especially the demagnetization effect of stellite alloy part and blade root keyway part sometimes fails to meet the demagnetization requirements, that is, the remanence in the blade after demagnetization should be less than 0.3mt (3G)

Improvement measures: The demagnetized blade is placed for 30 minutes, and the demagnetization is conducted again after the magnetic domain returns to the natural state (equilibrium state), or the demagnetization is carried out with special demagnetization equipment (such as CT-650 demagnetization machine). The demagnetization effect is obviously improved when the secondary demagnetization and special demagnetization equipment are used.

5. Defect Display of Fluorescent Magnetic Particle Inspection
The cracks on the inlet side end face of turbine rotor blade root and stellite alloy cutter withdrawal groove detected by fluorescent magnetic particle inspection technology are shown in Fig. 5. The defects on the blade surface can be quickly inspected by fluorescent magnetic particle inspection, with intuitive display, accurate positioning and good repeatability.
6. Conclusion

(1) The fluorescent magnetic particle inspection of steam turbine rotor blades has the advantages of simple equipment, convenient operation, fast speed, intuitive defect observation and high inspection sensitivity. The comparison and selection of three kinds of standard magnetization specifications can optimize the selection of magnetization specifications and improve the inspection sensitivity. Fluorescent magnetic particle inspection can replace penetrant inspection in some fields.

(2) The analysis and improvement of problems in the inspection process can promote the optimization and continuous improvement of inspection process and equipment, highlight the advantages of fluorescent magnetic particle inspection, which can not only improve the defect detection rate and inspection efficiency, but also improve the professionalism and compatibility of inspection;

(3) A new inspection platform is proposed, which makes the equipment modular operation, which can be compatible with the current magnetic particle inspection system, and improve the overall stability and safety of the equipment. At the same time, the establishment of a new mode of inspection platform is conducive to the promotion of practical application of fluorescent magnetic particle inspection.

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