Study on water erosion simulation of low pressure last stage blade of nuclear steam turbine

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Abstract. The surface damage and mass loss of two different heat-treatment condition samples of nuclear steam turbine last stage blade 3305YC1 stainless steel were studied by high speed water jet erosion method using numerical simulation analysis and actual test platform. The test results show that the mass loss of both two heat-treatment condition samples was increase as test time added, the quality heat treatment sample was linear relationship, however, the high frequency quenching plus low temperature temper sample displayed an incubation period. The numerical simulation analysis result was correct compared with the actual test value.

1. Introduction
While the Chinese government intensifies effects to optimize the structure of power generation, the nuclear technology developed very rapidly in recent years. The third generation nuclear power plant has started to build such as CAP1400 [1]. For nuclear steam turbine, in order to improve the efficiency and decrease the unit cost, the design length of low-pressure (LP) last stage blade is increasing, which cause the linear speed of blade tip faster and faster. At present, the height of last stage blade profile has reached 1800mm grade, and the linear speed exceed 650m/s [2]. Under this work condition, the last stage blade was confronted with severe water erosion problems. Some technical method like high frequency quenching was carried out at the inlet of blade to alleviate this question for years because of its convenience and operability. Nevertheless, there were few studies on the surface damage and mass loss of water erosion process by numerical simulation and actual platform test.

In this paper, the numerical simulation was used to simulate the water erosion process for two different heat treatment conditions of the 1828mm LP last stage blade 3305YC1 stainless steel, and then test the two heat treatment condition samples for different minutes at the water erosion test platform which was built by Xi’an JiaoTong University, observed the surface morphology and analyzed the law of mass loss and time.

2. Experimental

2.1. Material and sample preparation
The nominal chemical composition of LP last stage blade 3305YC1 steel is shown in Table 1. The size of test coupon is 200x100x10mm. This coupon has been quenched at 1010°C for 2h then oil cooled, tempered at 570°C for 4h then cooled in air (hereafter referred to as condition-1), the hardness of
Condition-1 sample was HV350. After quality heat-treatment, the high frequency quenching was carried out at the edge of coupon about 30mm width which is shown in Figure1. The temperature of high frequency quenching was 1040°C, and then cut the high frequency quenching part and tempered at 275°C for 1h (hereafter referred to as condition-2), the hardness of condition-2 sample was HV480. And then, the 25×25×5mm water erosion test pieces were taken from condition-1 and condition-2 sample respectively.

| Element | C  | Si  | Ni  | Cr  | Mo  | V   | N   | Fe  |
|---------|----|-----|-----|-----|-----|-----|-----|-----|
| Content | 0.10 | 0.15 | 2.5 | 12.0 | 1.5 | 0.30 | 0.03 | bal |

**Table 1.** Nominal chemical composition of 3305YC1 steel (mass%).

**Figure 1.** Test coupon of water erosion (mm).

### 2.2 Water erosion test

#### 2.2.1 Test platform

The water erosion test platform was designed and built by Xi’an JiaoTong University. The test system was mainly constructed by variable speed DC motor, gear accelerator, test section, ultra high pressure water pump, water ring vacuum pump, lubricating oil station, drainage pump and control cabinet. The test section was composed of a rotating shaft, an impeller, sealing device, shell and so on. The 3D model of platform is shown in Figure 2. The test pieces are fasten on the edge of impeller. Figure 3 shows the 3D structure of impeller and spray nozzle. The high-speed water jet is ejected from the spray nozzle and hits the high-speed rotating pieces to simulate the process of water droplets hitting the inlet side of the LP last stage blade of the nuclear steam turbine. The water erosion test parameter is shown in table 2.

**Figure 2.** 3D model of water erosion platform.

**Figure 3.** 3D model of the sample installation.
Table 2. Water erosion test parameter.

| Water hit speed | Water hit angle | Spray nozzle size | Hit time |
|-----------------|-----------------|------------------|---------|
| m/s             | °               | mm               | min     |
| 650             | 90              | 0.15             | 4,6,10,15,20,30,40,50,60 |

2.2.2. Measure method
The surface damage morphology of pieces after different water erosion test time (10min, 20min, 40min, and 60min) was observed by VHX-6000 3D super depth microscope. The mass loss of the test pieces after every hit time were measured by CPA225D precision electronic balance, the range of balance is 100g, and the measurement accuracy is 0.01mg. Before mass loss measurement, the pieces would be demagnetized, and cleaned by acetone in ultrasonic cleaner, and then measured the quantity of piece for three times and take the average value.

3. Numerical simulation

3.1. Simulation model
When built the calculation model, for the process of water jet hitting solid plate, the water jet can be treated as smooth particle hydrodynamic (SPH) method, and the plate was designed as Lagrange finite element method [3]. For the SPH method, the mass was fixed on the coordinate system of particle, it can be classified as Lagrange method. The basic equation required was the basic conservation equation and the constitutive equation of solid material. Because of its mesh less characteristics, the SPH method can avoid the problems of accuracy degradation and negative volume caused by mesh distortion in the case of maximum deformation, and also because it was a Lagrangian method, it can effectively solved the problem of interface between Euler mesh and material, therefore, the SPH method is especially suitable for high-speed impact problems[4]. According to the design parameters of the water erosion platform and assuming that the water jet was a hemispherical cylinder at the top, the SPH particle water jet model was set up as an impulse with a diameter of 0.15 mm, a length of 10 mm, and a velocity of 650 m/s. In order to prevent the initial penetration of the model before calculation, the distance between the jet and the target was 0.1 mm. Because the liquid size was very small compared with the solid target in the actual high-speed liquid-solid impact process, non-reflective boundary conditions were applied on the bottom and four sides of the target, in order to simulate the impact process of an infinite plate. The SPH-FEM coupling calculation model of the 90 degree impact process established in this paper is shown in Figure 4.

3.2. Material model and calculation function
Because the pressure of water droplets in impact was relatively high, in order to study the process better, the effect of compressibility must be considered. Therefore, Mie-Gruneisen equation was used to simulate the process. Initial parameters of water were selected at 20°C under standard atmospheric pressure. The density is 998.2 kg/m³ and the dynamic viscosity coefficient is 1.002×10⁻³ Pa s.

The state equation of water under expansion is:

\[ P = \rho_0 C^2 \mu + (\gamma_0 + a\mu)E \]

When the water is compressed, the equation of state is:

\[ P = \frac{\rho_0 C^2 \mu}{\left[ S_1 - 1 \right] \left( S_1 - S_2 \right) \left( \frac{\mu^2}{\mu + 1} - S_3 \left( \frac{\mu^3}{(\mu + 1)^2} \right) \right] + (\gamma_0 + a\mu)E} \]

(2)
where: \( C \) —— the intercept of \( U_s - U_p \) curve (Shock wave velocity \( U_s \) and particle velocity \( U_p \) curve), equivalent to local sonic speed/m·s\(^{-1}\)
\( \gamma_0 \) —— Gruneisen coefficient
\( \rho_0 \) —— Initial density
\( \mu \) —— \( \frac{\rho}{\rho_0} - 1 \)
\( \alpha \) —— First order correction coefficient of \( \gamma_0 \)
\( E \) —— Initial unit volume internal energy increment
\( S_1, S_2, S_3 \) —— Coefficient of slope of \( U_s - U_p \) curve

These parameter values are shown in table 3.

| \( C \) (m·s\(^{-1}\)) | \( \gamma_0 \) | \( \alpha \) | \( S_1 \) | \( S_2 \) | \( S_3 \) |
|----------------|-------------|---------|------|------|------|
| 1480           | 0.5         | 0       | 2.56 | -1.986 | 0.2268 |

3.3. Simulation results

Figure 5 shows the results of numerical simulation of two different heat treatment conditions of 3305YC1 steel. The numerical simulation of jet impact plate experienced three stages: latent period, accelerated erosion period and stable period. The mass loss of condition-2 sample was better obviously.

4. Water erosion test

4.1. Surface damage results

The 2D surface damage of condition-1 piece after water erosion test for 10min, 20min, 40min, and 60min are shown in figure 6, and figure 7 displays the 3D structure of surface morphology. At 10 minutes, the 3D morphology of the water erosion area had several discrete shallow holes, and the holes were not connected to form a clear boundary erode mark. As the test progressing, the holes became denser, and within 20 minutes the holes in the water erosion area had been joined together to form a clearly erode groove. At the same time, in the water erosion groove, the 3D surface patterns at all times were shown as the discontinuous craters. This phenomenon was mainly due to the formation of local water film in the groove of the jet impingement point due to the movement of the lateral jet, thus weakening the impingement force of the water jet in this area. As the impeller rotated, the impinging point of the water jet moved rapidly, and the water film can only be formed locally due to
the action of the rough surface. Outside the local water film, the jet re-impinges directly on the metal material, resulting in greater impinging force of the jet, thus forming a discrete erosion craters in the water erosion area. With the increase of test time, the width and depth of the erosion groove increased, and the depth of the groove was about 170 microns when testing time was 60 minutes.

**Figure 6.** The 2D surface morphology of condition-1 piece after water erosion test for (a) 10min, (b) 20min, (c) 40min, and (d) 60min.
Figure 7. The 3D surface morphology of condition-1 piece after water erosion test for (a) 10min, (b) 20min, (c) 40min, and (d) 60min.

After erosion test time of 10, 20, 40 and 60 minutes, the 2D surface morphology of the condition-2 piece are shown in Figure 8, and the 3D morphology of the surface damage are shown in Figure 9. In 10 minutes, the surface can be seen that there were several small, shallow holes, and the distance between the holes was larger than condition-1. Then, with the experiment proceeding, the holes deepen gradually, and the distance between the holes decreased slowly. At the time of 20 minutes, the 3D surface morphology shown that the holes on the surface have been roughly connected to form an observable erosion mark. As the test continues, at 60 minutes, there was an erosion groove obviously, which the maximum depth of the groove was about 100 microns.

Figure 8. The 2D surface morphology of condition-2 piece after water erosion test for (a) 10min, (b) 20min, (c) 40min, and (d) 60min.
4.2. Mass loss results
The mass loss curves of the two condition samples are shown in Figure 10. It can be seen that the mass loss of condition-1 specimens was linearly related to the erosion test time. However, there was a water erosion latency of about 15 minutes in the condition-2 specimens. Quality of the high frequency quenching specimens remains basically unchanged during the latency. After the latency, mass loss of the specimens began to appear, the relationship between mass loss and the erosion time were linear too. Comparison the slope of the curves, that was to say, the loss rate of water erosion quality of the samples, it was clearly that the loss rate of condition-1 samples was higher than that of condition-2. The Vickers hardness of the condition-1 and condition-2 specimens was HV350 and HV480 respectively. The hardness of the condition-2 specimens was 1.4 times higher than that of the condition-1 specimens, but the mass loss rate was only 0.5 times.

Figure 9. The 3D surface morphology of condition-2 piece after water erosion test for (a) 10min, (b) 20min, (c) 40min, and (d) 60min.
Figure 10. The mass loss curves of the two condition samples.

5. Conclusions
The mass loss rate of high frequency quenching specimens was smaller than that of quenched and tempered specimens, and the resistance to water erosion was better. There was a linear relationship between the mass loss and time of quenched and tempered specimens in the process of water erosion, while there was a latent period in the process of high frequency quenching test. The numerical analysis model of jet impinging flat plate established by SPH method can well reflect the actual water erosion test.

References
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