Numerical Simulation of Erosion of Valve Sealing Surface by High Speed Water Flow Based on ALE Method

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Abstract. With the development of modern industry, more and more valves need to be serviced under severe working conditions. Due to the high-speed flushing of working media, the failure of valve sealing surfaces is not uncommon. Based on the ALE (Arbitrary Lagrange-Euler) algorithm, LS-DYNA is used to simulate the erosion of the valve sealing surface material Stellite21 by high-speed water flow, and the damage degree of grid unit is judged by the damage parameter D. At the same time, the parameters of Stellite21 in the Johnson-Cook material model were first calibrated. In this paper, the impact dynamics simulations of different impact angles and different impact velocities were carried out and the material behaviour under different operation parameters of water jet is studied. It is found that with the increase of impact velocity, the erosion rate of materials has a significant increase. As impact angle increases, the erosion damage rate increases first and then decreases, and material has the maximum erosion damage rate at the impact angle of about 40°.

Keywords. ALE, erosion damage, fluid-solid coupling, Stellite21.

1. Introduction
Erosion damage is a metal damage caused by high-speed relative motion between the metal surface and the fluid. Valves, piping systems, steam lines, etc., are most susceptible to erosion damage. Failure cases of power plant valves due to high-speed fluid scouring is very common. During the start-up process of the thermal power unit, condensed water in the steam pipeline needs to be discharged, thereby improving power generation efficiency and protecting the safe operation of related equipment. The drain valve is the main equipment for draining. During the draining process, due to the high pressure difference between the inside and outside of the valve, the condensed water will cause serious flushing damage to the valve sealing surface material, affecting the sealing performance of the valve, leading to steam leakage, causing a large amount of energy waste and even the consequences of downtime. Therefore, it is important to study the erosion resistance of the valve sealing surface material and the valve structure.

Liu et al [1] studied cavitation and particle erosion using the butterfly valve coupling erosion model, and verified the effectiveness of the coupled model through experiments and simulations. Noleberg et al. [2] carried out simulation analysis and experimental research on the wear of the throttle valve, and found that the calculation model and particle rebound speed have a direct impact on the accuracy of the calculation results. Wang et al. [3] verified the accuracy of the discrete phase model and the semi-
empirical material loss model by comparing the valve wear distribution area with the mass loss in numerical simulation and liquid-solid erosion test. In addition, scholars at home and abroad have conducted related research on fluid mechanics such as matrix materials and flow rate \[4, 5\], impact angle \[6, 7\], temperature \[4, 8\], and chemical composition \[9, 10\]. However, there are few reports on the numerical simulation of erosion damage caused by pure water to metals.

In this paper, the Y-type drain valve provided by a company is used as the research object. The LS-DYNA is used to simulate the erosion of the valve sealing surface material Stellite21 by high-speed water flow, which realizes that the jet source can continuously generate high-speed water flow. At the same time, the physical properties of Stellite21 in the Johnson-Cook material model were firstly calibrated, and the erosion resistance and erosion damage of Stellite21 were studied.

2. Material models

The material model has a crucial influence on the accuracy of the simulation results. Therefore, based on the existing water and air material model, the material model parameters of the valve sealing surface material Stellite21 are calibrated experimentally.

2.1. Material model for water and air

The GRUNEISEN equation of state is used to provide pressure for water. The pressure is given by:

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

(1)

The material model parameters of water \[11\] are shown in Table 1.

| ρ (g/cm³) | μ (Pa •us) | C/(cm/s) | S₁ | S₂ | S₃ | γ₀ | α | E |
|----------|-----------|----------|----|----|----|----|---|---|
| 1.05     | 8.5e3     | 0.148    | 2.56 | 1.986 | 0.2268 | 0.5 | 0 | 0 |

The linear polynomial equation of state for air, is linear in internal energy. The pressure is given by:

\[
P = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_5 \mu + C_6 \mu^2)E
\]

(2)

The material model parameters of air \[12\] are shown in Table 2.

| ρ(g/cm³) | μ (Pa •s) | C₀ | C₁ | C₂ | C₃ | C₄ | C₅ | C₆ |
|----------|-----------|----|----|----|----|----|----|----|
| 1.29     | 1.67×10⁻⁵ | 0  | 0  | 0  | 0  | 0.401 | 0.401 | 0 |

2.2. Material model for Stellite21

The valve sealing surface material is Stellite21, which is described by Johnson-Cook material model and failure model. This model is generally used to describe the ultimate strength and failure processes of metallic materials in large strains, high strain rates, and high temperatures.

Johnson and Cook express the flow stress as

\[
\sigma_{eq} = (A + B \varepsilon_{eq}^p)(1 + Cln\varepsilon_{eq}^p)(1 - T^m)
\]

(3)

Where, A, B, c, n, and m are material model parameters; \(\varepsilon_{eq}^p\) is effective plastic strain; \(\varepsilon_{eq}^*\) is normalized effective plastic strain rate; T* is homologous temperature;

The strain at fracture is given by
\[
\varepsilon_f = [D_1 + D_2 \exp(D_3 \sigma^*)](1 + D_4 \ln \dot{\varepsilon}_{eq}^*) (1 + D_5 T^*)
\]

(4)

Where \( \sigma^* \) is stress triaxiality, \( D_1\sim D_5 \) are failure model parameters. Fracture occurs when the damage parameter \( D = \sum \Delta \varepsilon_f / \varepsilon_f \) reaches the value of 1.

The Stellite21 alloy is widely used in the valve field to resist the impact of erosion damage. Its chemical composition is shown in Table 3.

**Table 3.** Chemical composition of Stellite21 used in this study (in wt. %)

| C   | Si  | B   | P   | S   | Fe  | Mo  | Ni  | Co  | Balance | Cr  | Mn  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|---------|-----|-----|
| 0.22| 0.77| 0.002| 0.009| 0.002| 2.01| 5.40| 2.82| Balance| 25.97| 0.025|

In order to determine the model parameters of constitutive relation and fracture criterion, four series of material performance tests were carried out. The Table 4 shows the basic scheme of testing. The Fig. 1 shows the geometry and size of the experimental samples. The experiment was conducted by universal testing machine, INSTRON 8032.

**Table 4.** Survey of experimental program

| Series | Coefficient to be determined | Specimen geometry | Test type |
|--------|------------------------------|-------------------|-----------|
| 1      | A,B,n                        | Fig.1(a)          | Tension at 25°C and reference strain rate |
| 2      | m,D_5                        | Fig.1(a)          | Tension from 25°C to 500°C at reference strain rate |
| 3      | C,D_4                        | Fig.1(a)          | Tension at 25°C and different strain rate |
| 4      | D_1,D_2,D_3                  | Fig.1(a),(b)      | Tension at 25°C and reference strain rate |

The strain rate of quasi-static tensile test of smooth cylindrical specimens is \( 2.5 \times 10^{-4} \) s\(^{-1} \). The experimental results are shown in Fig. 2, 3 and 4.

**Figure 1.** Geometry and dimensions of specimens (in mm)

**Figure 2.** Tensile test at different temperatures

**Figure 3.** Tensile test at different tensile velocities

**Figure 4.** Load-displacement curve of notched tensile test
According to the experimental results, combined with Equation 3 and 4, the Johnson Cook model parameters of Stellite21 material are calibrated by control variable method. The fitting results are shown in Fig. 5-10. The summary results of the fitting parameters are shown in Table 5.

### Table 5. Johnson-Cook model parameters of Stellite21

| A/MPa | B/MPa  | n    | C    | m    | D₁    | D₂    | D₃    | D₄    | D₅    |
|-------|--------|------|------|------|-------|-------|-------|-------|-------|
| 404.2 | 2865.1 | 0.518| 0.0133| 1.636| 0.0121| 0.0521| -1.625| 0.110 | 1.467 |

3. Modelling

3.1. ALE algorithm description

The ALE algorithm combines the advantages of the Lagrange method and the Euler method to effectively track the motion of the boundary of the material structure and can also make the internal grid unit independent of the physical entity. Not only is it difficult to perform numerical calculations due to severe distortion of the grid, but dynamic analysis of fluid-solid coupling can be achieved. Therefore, it is very suitable to use the ALE method to study the interaction between high-speed fluid and structure.

3.1.1. Fluid governing equations in ALE algorithm. Suppose that \( v \) is velocity of matter, and \( u \) is velocity of the mesh, introducing a relative velocity \( w \), and let \( w = v - u \). The governing equation of ALE algorithm can be given by the following equations:

1. **Mass conservation equation**

   \[
   \frac{\partial \rho}{\partial t} = -\rho \frac{\partial v_j}{\partial x_j} - w_i \frac{\partial \rho}{\partial x_i} \quad (5)
   \]

2. **Momentum conservation equation**

   \[
   \frac{\partial v_j}{\partial t} = \sigma_{j,i} + \rho \beta_i - \rho w_i \frac{\partial v_j}{\partial x_j} \quad (6)
   \]

3. **Energy conservation equation**

...
\[
\rho \frac{\partial E}{\partial t} = \sigma_{ij} v_{i,j} + \rho b_i v_i - \rho w_i \frac{\partial E}{\partial x_j}
\]  

(7)

Where \( \rho \) is material density, \( \sigma \) is stress tensor, \( b \) is unit body force, and \( E \) is specific total energy.

3.1.2. Fluid-solid coupling method. In this paper, LS-DYNA software is used to realize the erosion simulation of the valve material Stellite21 by high-speed water flow. The program uses the keyword *CONSTRAINED_LAGRANGE_IN_SOLID to realize the coupling between structure and fluid. When building geometric models and performing finite element meshing, the mesh of structures and fluids can overlap. When using the fluid-solid coupling method to simulate, it is often necessary to constrain the Lagrange structure and transfer the relevant parameters of the structure to the fluid unit. Fluid-solid coupling can also be achieved by combining interface nodes of fluids and structures and contact algorithms.

3.2. Modeling description

The numerical simulation process of water erosion damage is a nonlinear collision dynamic coupling problem between high-speed water flow and structure. In this paper, ANSYS APDL parametric modeling is used to establish a simulation model for high-speed water flow scouring of Stellite21 cobalt-based alloy samples. The entire model is divided into three sections: the jet source, the air domain, and the target, as shown in Fig. 11.

The high-speed water flows out from the waterjet source and impacts the target plate through the airspace. The model dimensions of the numerical simulation are shown in Table 6. The water jet impacts the sample at an angle of 25°, 40°, 65° and 90°. The size of the air domain is adjusted according to the change of the impact angle of the impact, and is designed to improve the calculation efficiency and accuracy to cover the area mainly in contact with the sample. Figure 12 shows a 40° impact angle mesh model. For fluid-solid coupling, the ALE mesh (water and air) needs to overlap with the Lagrangian grid (target plate).

| Jet diameter | Target distance | Impact angle | Length of target | Width of target | Height of target |
|--------------|----------------|--------------|------------------|----------------|-----------------|
| 0.85mm       | 16mm           | 25°, 40°, 65°, 90° | 16mm            | 16mm          | 32mm            |

3.3. Boundary conditions

(1) In order to reduce the calculation time, considering the symmetry of the model, a symmetric boundary condition is used to establish a 1/2 model.

(2) Fixed boundary conditions at the bottom of Stellite21 cobalt-based alloy sample

(3) The boundary of the air domain is subject to free boundary conditions.
(4) The jet source defines the initial condition that the water flow flows out at a fixed speed, and the high-speed water flow can be continuously generated to realize the continuous jet.

When the LS-DYNA solver is used to solve the problem, the deformation of the material increases with the impact of the high-speed water flow on the sample, and the damage parameter D of the mesh unit increases accordingly. When D = 1, the material is eroded and destroyed, and the grid unit fails.

4. Result and discussion

Based on the above material model and ALE algorithm, the simulation of different operating parameters is carried out in this paper: (1) Simulation of different impact velocities of 150 m/s, 382 m/s, 600 m/s and 800 m/s at 40° impact angle. (2) Simulation of different impact angles of 25°, 40°, 65°, and 90° at an impact velocity of 800 m/s. The erosion resistance and erosion damage of Stellite21 materials under different operating parameters were studied.

4.1. Simulation results and discussion under different impact speeds

4.1.1. Distribution of the von-Mises stresses. The same unit of the same position (A385122 unit) changes in stress at different impact speeds, as shown in Fig. 13. It can be seen from the figure that the A385122 unit is destroyed at 240us at an impact speed of 800m/s. Before the unit is destroyed, the faster the impact speed, the greater the stress the unit is subjected to. The faster the water flow, the greater the kinetic energy it has, and the greater the pressure that is converted into impact when the sample is impacted. Therefore, the larger the impact velocity corresponds to the higher the stress level when the grid unit experiences the same flushing time.

![Figure 13. Stress curve of different impact speeds of the same unit](image)

The stress changes of different depth units under the operating conditions of an impact angle of 40° and an impact velocity of 382 m/s are shown in Fig. 14. Units A385122, B383074, C378979, D374882, and E370786 correspond to positions of depths of 0.125 mm, 0.375 mm, 0.875 mm, 1.375 mm, and 1.875 mm, respectively.

![Figure 14. Stress curve of different depth units](image)
The units C378797, D374882 and E370786, which are farther from the surface, are subjected to the same stress as expected. The farther away from the surface, the smaller the stress, and the trend of stress changes is basically the same. For the unit near the surface, the surface unit A385122 is subjected to the greatest stress at the beginning stage, and as the scouring time increases, the stress of the unit B383074 having a depth of 0.375 mm after 2500 μs becomes maximum. The study by Kyriaki [12] also reached similar conclusions.

4.1.2. Erosion process at different impact speeds. The erosion morphology of the Stellite21 sample after 5000 us scouring at different speeds is shown in Fig. 15. It can be clearly seen that at the same scouring time, the higher the impact velocity, the deeper the erosion depth of the sample. The change in erosion depth is shown in Fig. 16. The change of mass loss with time at different speeds is shown in Fig. 17. It can be seen from the 800 m/s impact velocity curve that as the scouring time increases, the mass loss rate of the sample generally increases first and then slows down. This is because as the water accumulates in the erosion pit, it will play a certain degree of buffering effect, weakening the penetration ability of the high-speed water flow, thereby reducing the erosion damage rate.

![Damage parameter distribution](image)

**Figure 15.** Erosion morphology at different impact speeds

![Erosion depth variation](image)

**Figure 16.** Variation of erosion depth at different scouring speeds

![Mass loss](image)

**Figure 17.** Mass loss at different impact speeds

4.1.3. Damage parameter distribution. The distribution and variation of damage parameter D were analyzed by using 40° impact angle and 800m/s impact velocity simulation as an example. Fig. 18 shows the damage morphology and the corresponding damage parameter D distribution at different times. Through numerical simulation, we can more clearly observe the entire destruction process of the sample under high-speed water flow.

The larger the damage parameter D of the grid unit is, the closer it is to 1, the more the material tends to fail. Fig. 19 shows the variation of the damage parameter D of different depth units. It can be found that when D=1, the grid unit is destroyed and deleted, which is equivalent to the mass loss. The sooner the grid element is closer to the surface of the sample, the earlier it fails. Through the value and
change of D, the time of failure of the unit and the degree of damage can be known. In addition, through
the numerical simulation of this paper, we can more deeply understand the application of the failure
criterion defined by the Johnson-Cook failure model in finite element calculation.

4.2. Simulation results and discussion under different impact angles

4.2.1. Erosion quality loss analysis. The effect of speed on mass loss has been discussed previously,
and the effect of different impact angles on mass loss is now discussed in accordance with Fig. 20. After
5000us high-speed water scouring, the mass loss of the sample increases first and then decreases with
the increase of the impact angle. The erosion damage rate changes with time, and it starts to be faster,
then slows down, indicating that Stellite21 material is more resistant to positive impact. In actual valve
application, it should avoid the oblique impact of about 40°.

![Figure 18. Erosion morphology and damage parameter D distribution over time](image)

![Figure 19. Variations of D in different depth units](image)

![Figure 20. Mass loss at different impact angles](image)
4.2.2. **Erosion morphology analysis.** At the impact speed of 800 m/s, after 5,000 us high-speed water flow impact, the erosion topography at different impact angles is shown in Fig. 21. The degree of damage of the sample, as the impact angle increases, first rises and then falls, reaching a maximum at about 40°, and substantially no damage at 90°. The erosion pit of the sample showed a narrower side and a wider side. The erosion pit on the incident side of the high-speed water flow is narrow, and the erosion pit on the reflection side of the water flow is wider. Small-angle impact erosion pits are relatively narrow; large-angle impact erosion pits are relatively concentrated.

5. **Conclusion**

Based on ALE method, the numerical simulation of valve sealing material Stellite21 under high-speed water erosion is carried out. The main conclusions are as follows:

1. The Johnson-Cook material model parameters of the Stellite21 material were first calibrated by mechanical properties experiments.

2. Combining numerical simulation to judge material failure by changing the damage parameter D, and deeply understanding the application of Johnson-Cook failure model in finite element simulation

3. At the 40° impact angle, the same as the impact speed, the greater the mass loss of the sample, the faster the erosion damage rate. However, as time increases, the rate of mass loss generally increases first and then slows down.

4. Stellite21 material is most susceptible to erosion damage caused by high-speed water flow at an impact angle of around 40°, and is more resistant to 90° positive impact.

The Stellite21 material parameters measured in this paper can provide a certain degree of reference for researchers who carry out related numerical simulations and experimental studies. For valves using stellite21 as the sealing surface material, it is conceivable to combine the flow field simulation to improve valve structure and avoid high-speed fluid flushing valve sealing surface at a 40° impact angle.

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