Simulation Calculation of Strip Descaling Based on Birth-Death Element Method

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Abstract. In order to more accurately simulate the descaling process, a three-dimensional finite element model is established by ABAQUS based on the birth-death element method (BDEM). The model simulation results show that with the help of BDEM decision rules, the scale layer elements are continually deleted after reaching the failure threshold, and descaling process is accurately simulated. The maximum Mises stress at different times shows the law of random fluctuation, which is consistent with the working principle of BDEM. Increasing the number of iterations of the model and refining the local mesh can improve simulation effect of the model, but it will also increase the total amount of operation and total operation time.

1. Introduction
In the process of high temperature hot rolling, the strip steel will inevitably contact with air, and a layer of brittle mill scale (commonly known as scale layer) will be produced on its surface [1-2]. In order to ensure surface quality and mechanical properties of cold rolled or coated final products, this brittle scale layer must be completely removed before the next process. Traditional descaling method is pickling, which uses chemical reaction capacity of acid solution to the scale layer. The pickling line is generally located in a cold rolling workshop, with huge pickling equipment, large floor area, expensive initial investment and slow production speed. In addition, due to the use of acid solution, discharge of spent acid pollutes the environment, and volatile gas of acid solution is easy to corrode the surrounding mechanical equipment, which is also harmful to the health of workers. It is difficult to accurately control the chemical reaction speed of acid solution. Under pickling or over pickling are common in pickling production, and hydrogen embrittlement and other defects are easy to occur [3].

Acidless descaling is a process technology that does not use acid to remove the scale layer on the surface of strip steel. The main technical feature of Acidless descaling is green and pollution-free. Scholars at home and abroad have been committed to the research of Acidless descaling technology for a long time, and have made great achievements in some fields. At the same time, some new green and environment-friendly descaling equipment have been put into operation. However, there are still many deficiencies when these equipment are in service in production lines. For example, EPS (Eco-Pickled Surface) [4] in the United States has high investment cost, high treatment cost per ton of steel, and complex filtration and circulation systems. Abrasive water jet descaling system [5] has high energy consumption, and the nozzle will be worn under continuous operation, so regular shutdown and replacement are necessary; the plunger pump providing high-pressure water has strict requirements for sewage filtering and recycling equipment after descaling, which increases the initial investment and
operation cost of enterprises. The descaling mechanisms of EPS, abrasive water jet and shot blasting are similar. The technical means adopted by them are to accelerate continuous impact of a solid medium on the surface of strip steel to break and remove the brittle scale layer. Solid media used for EPS, abrasive water jet and shot blasting are steel sand, quartz sand and spherical steel shot respectively. Because the scale layer is very thin (10-20 μm), and impact velocity of these solid media is very high (about 50 m/s), so the descaling process is completed in almost $10^{-6}$ seconds. Obviously, it is difficult to observe the specific descaling process in industrial sites. Scholars [6-8] used finite element software for simulation calculation, and made some breakthroughs, but there are also many problems. For example, some scholars did not set a scale layer and only simulated the impact force [6]. Some scholars set a too thick scale layer in finite element model (0.5 mm), which is deviated from the actual situation [7]. Some scholars focused on the analysis of abrasive mixing mode [8], and did not simulate the descaling action. In order to simulate the descaling process more accurately, the research team established a three-dimensional finite element model based on Birth-Death Element Method (BDEM) and by using ABAQUS software, and simulated and analysed the descaling process.

2. BDEM

2.1. Introduction to BDEM

In fields of NC Lathing and milling damage, BDEM has achieved good results [9] in simulation calculation. The basic working principle of BDEM is introduced as follows:

During the operation of finite element model, when a physical quantity of a certain element meets a certain set condition ($\sigma \leq 200$ MPa), the element is “alive” and continues to exist in subsequent finite element calculation. On the contrary, when a physical quantity of certain element does not meet the set condition ($\sigma > 200$ MPa), the element is “dead” and removed from the finite element model, moreover, it no longer transmits stress/strain. Figure 1 shows the application process of BDEM, as follows:

1. After the finite element modeling, select an element group of which birth/death is to be determined, and set birth/death determination rules.

2. The first step is to begin iterative operation of finite element method. After the operation, determine the birth and death of the set element group in combination with the operation results, and delete all elements determined to be “dead” from the model.

3. The next step is to continue iterative operation of the finite element method. After the operation, determine the birth and death of the set element group in combination with the operation results, and delete all elements determined to be “dead” from the model.

4. Continue to cycle the above (3) until the finite element operation is completed. After the operation, all elements judged as “dead” are deleted from the model.

In order to more accurately simulate the descaling process, BDEM is used in the descaling model.
2.2. Principle of simulating descaling with BDEM

Based on the above BDEM setting and calculation process, the simulation process of model descaling is described. As shown in Figure 2, all elements of scale in the finite element model are set as the element group to be determined by the BDEM. Under the impact of projectile, the scale layer and its underlying matrix deform on a certain scale and accumulate stress/strain.

In the process of finite element iterative calculation, after a certain step of operation, the projectile surface contacts with elements 3, 4, 5 and 6 of scale. Based on the data obtained from the operation and through the BDEM, it is determined that elements 3, 4 and 5 are “dead” and all other elements are “alive”. After that, elements 3, 4 and 5 are immediately deleted from the model, while other elements are retained, as shown in Figure 3.

As shown in Figure 3, in the next iterative operation, the space of elements 3, 4 and 5 originally under the projectile becomes a vacuum. The interaction between these dead elements and surrounding elements also disappears. At the same time, new contact surfaces are generated on the right side of element 2, the left side of element 6, and the upper side of elements 8, 9 and 10.

As time goes on, the finite element model continues to carry out the above operations. After each operation, the BDEM will delete the elements which are determined as “dead” by it. In this way, the process of successively deleting elements is used to simulate the descaling process.

3. Finite element modeling

3.1. Model dimensions and material properties

A three-dimensional finite element model of descaling is established by ABAQUS software. The model consists of projectile, iron matrix and scale layer. Dimensions of each part of the model are as follows:

(1) The scale layer is a semi cylinder with a diameter of $d_1=2$ mm and a thickness of $h_1=0.015$ mm. The upper surface of the scale layer is set as the XOY surface of three-dimensional coordinate system.

(2) The iron matrix is also a semi cylinder, with a diameter of $d_2=2$ mm and a thickness of $h_2=0.985$ mm, located below the scale layer (negative direction of Z-axis). The upper surface of the iron matrix and the scale layer are connected by the “TIE” command.

(3) The projectile is hemispherical with a diameter of $d_3=0.6$ mm. The sphere center of the projectile is located on the positive half axis of the Z-axis and tangent to the scale layer at the origin of the coordinate system.

The material properties of each component are set as follows:
(1) The scale layer is set as a brittle material without shaping, with density \( \rho_1 = 7.75 \times 10^3 \text{ kg/m}^3 \), elastic modulus \( E_1 = 210 \text{ GPa} \) and Poisson’s ratio \( \mu_1 = 0.29 \).

(2) The iron matrix is set as an elastic-plastic material with high density \( \rho_2 = 7.8 \times 10^3 \text{ kg/m}^3 \), elastic modulus \( E_2 = 200 \text{ GPa} \) and Poisson’s ratio \( \mu_2 = 0.288 \).

Considering that descaling is a process of instantaneous large deformation, Johnson-cook model is selected for iron matrix [10]. Model parameters: \( A = 244 \text{ MPa}, B = 899.7 \text{ MPa}, n = 0.94, C = 0.0391, T^* = 0 \).

(3) The projectile is set as an analytical rigid body without deformation, with density \( \rho_3 = 7.7 \times 10^3 \text{ kg/m}^3 \), elastic modulus \( E_3 = 150 \text{ GPa} \) and Poisson’s ratio \( \mu_3 = 0.3 \).

3.2. Operation setting of model

The projectile element shall be of C3D10M type. C3D8R type is selected for scale layer and matrix element. Mesh refinement is carried out for some areas of scale layer and iron matrix. The finite element model after mesh generation is shown in Figure 4.

![Figure 4. Finite element model after meshing.](image)

In order to simulate the damage of scale layer under projectile impact, all scale layer elements are classified to be determined by BDEM. BDEM decision rule [10-11] is set as follows:

1. When strain of an element \( \varepsilon < 0.08\% \), the element is retained;
2. When strain of an element \( \varepsilon \geq 0.08\% \), the element is dead and will be deleted from the model.

The velocity of the projectile is \( v = 50 \text{ m/s} \), the direction of which is located in the fourth quadrant of XOZ coordinate system and forms an included angle of Z-axis is \( \theta = 45\degree \) with the negative square.

4. Simulation calculation and analysis

4.1. Simulation results

The descaling model is simulated on a computer. After the first iterative operation \( (t = 7.918 \times 10^{-8} \text{ s}) \), the local Mises stress nephogram of the model is shown in Figure 5. The gray area in the figure is projectile. The two layers of element below the projectile (as shown between the red and purple lines in the figure) are scale layers. The elements below the scale layer are iron matrices.

The scale element in the yellow box in Figure 5 has disappeared. It is because under the impact of projectile, strain of the element exceeds the decision value of BDEM and is deleted by the finite element model. The 10 elements on the left of the element were “killed” by the finite element model for the same reason. In order to better show the descaling process, the projectile at the end of the first iterative operation is hidden from the model, and the Mises stress nephogram shown in Figure 6 is obtained. It can be clearly seen from Figure 6 that some elements in the 6 rows in the Y-axis direction have been deleted. It can also be seen from Figure 6 that the maximum Mises stress at the end of the first iterative operation is 338.7 MPa.
As time goes on, the model simulation calculation continues. After the second iterative operation (t=2.377×10^{-7}), the local Mises stress nephogram of the model (the projectile has been hidden) is shown.

Figure 5. Mises strain diagram containing projectiles.

Figure 6. Mises stress diagram at t=7.918×10^{-8} s.

Figure 7. Mises stress diagram at t=2.377×10^{-7} s.
in Figure 7. Compared with Figure 6, it can be seen that scale elements in a larger area in Figure 7 are deleted by the finite element model. Several scale layer elements of the second layer in the negative direction of Z-axis marked by the red box in Figure 7 have also been deleted. This indicates that with time, the downward movement of the projectile has contacted the scale layer of the second layer and impacted it, resulting in its destruction. It can also be seen from Figure 7 that the maximum Mises stress at the end of the first iterative operation is 334.6 MPa. Compared with Figure 6, the maximum Mises stress in Figure 7 is reduced. This is because that some scale elements are deleted, so they cannot continue to transfer stress/strain to the surrounding. This result is consistent with previous description of the working principle of BDEM.

Figure 8. Mises stress diagram at t=3.167×10^{-7} s.

Figure 9. Mises stress diagram at t=3.963×10^{-7} s.

As time goes on, the descaling process under the action of projectile continues. Figures 8 and 9 are the model Mises stress nephograms at t=3.167×10^{-7} s and t=3.963×10^{-7} s respectively. It is not difficult to see that more and more scale elements are deleted by the model over time. It should be noted that the maximum Mises stress in Figure 8 is smaller than that in Figure 7, but the maximum Mises stress in Figure 9 is larger than that in Figure 8. However, it cannot be simply considered that the maximum Mises stress must be reduced after elements are deleted. After deletion of these elements, the projectile will continue to move and contact with other scale elements or matrix elements to transfer stress/strain.
Therefore, the maximum Mises stress should show the law of random fluctuation. This rule is consistent with the working principle of BDEM described above.

Figure 10 is a nephogram of Mises stress after finite element calculation ($t=9.5 \times 10^{-6}$ s). It can be seen from Figure 10 that the projectile has rebounded and left the iron. Under the impact of the projectile, scale layers in a certain area on the surface of the iron is removed. In addition, obvious deformation occurs in the local part of the matrix, showing the shape of “meteorite crater” as a whole.

It can also be seen from Figure 10 that the descaling area is larger than the area of the crater. This is because the iron matrix is an elastic-plastic body, which can transmit stress/strain to a long distance; the stress/strain is transmitted to the surface scale layer through the joint surface, resulting in fracture of the scale layer.

In Figure 10, there are also some blue scale elements “splashing” from the matrix surface. Taking element A in the yellow wireframe in the figure as an example, with the impact of the projectile, all elements around element A were broken and lose efficacy, that is, they were deleted from the model according to the BDEM decision rules. In this way, no stress/strain is transferred to element A. At a certain moment, after element A is impacted by other scale elements, it will appear as a “splash”.

4.2. Application effect and improvement method of BDEM

Due to high impact velocity of the projectile (about 50 m/s), the thickness of scale layer is very thin (about 15 μm). Therefore, it is difficult to observe the action of damage to scale layer in industrial field. From the above ABAQUS calculation, it can be seen that BDEM simulates the descaling process well: the elements determined as dead by BDEM are gradually deleted with the model calculation process. It should be noted that the deletion of a certain element will inevitably affect the stress/strain of surrounding elements, because the deleted element will no longer transmit the stress/strain. In this case, it will interfere with the accuracy and stability of model operation, and even cause element distortion, thereby leading to failure and termination of finite element model operation.

In the finite element simulation calculation, the research group explored schemes to reduce interference factors. The first one is to increase the number of iterations and reduce durations of two adjacent iterations, that is, increase the number of birth and death decisions. The second one is local mesh refinement. Both schemes can improve simulation effect, but at the same time, they will also increase the total amount of server operation and total operation time.

5. Conclusion

The descaling process is completed in almost $10^{-6}$ s, and therefore it is difficult to observe the specific descaling process in the production line or laboratory. There is no doubt that the research on descaling
process is very key to improve the system efficiency. Using finite element modeling and simulation calculation is an important research approach. The main conclusions of this paper include:

1. A three-dimensional finite element model is established based on BDEM, and descaling process is simulated. With the help of the decision rules of BDEM, the scale elements reaching the critical state are gradually deleted by the model, and the descaling process is accurately simulated. The maximum Mises of the finite element model at different times shows the law of random fluctuation. This is consistent with the working principle of BDEM.

2. Increasing the number of iterations and local mesh refinement can reduce element distortion and improve simulation effect, but it will also increase total amount of operation and total operation time.

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