Destructive behavior of iron oxide in projectile impact

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Abstract. The damage strain values of Q235-A surface oxide scale were obtained by scanning electron microscopy (SEM/EDS) and universal tensile testing machine. The finite element simulation was carried out to study the destruction effects of oxidation at different impact rates. The results show that the damage value of the oxide strain is 0.08%. With the increase of the projectile velocity, the damage area of the oxide scale is increased, and the damage area is composed of the direct destruction area and the indirect failure area. The indirect damage area is caused by the stress/strain to the surrounding expansion after the impact of the steel body.

1. Introduction

In the hot rolling and subsequent cooling process, the surface of strip steel will form a dense, brittle oxide scale (commonly known as scales). Before the cold rolling production, the strip steel should pass acid washing process to remove the surface oxide scale and ensure that the finished product quality[1-2]. As the acidity general have the problems of less-pickling, over-pickling and etc, the discharge of waste liquid causes serious pollution to the environment, which is not the intention of the green manufacturing[3-4].

Projectile impact descaling is a typical acid-free descaling mode, and its operation mechanism is from the difference of the iron oxide and iron Body material properties, which is, brittle iron oxide sheet will fractures in the impact of direct cracking, while iron Body will produce a certain elastic-plastic deformation[5-7]. Iron oxide skin damage strain is an important parameter of the projectile impact decaling process, and scholars have done a lot of research in this area. Evans and Robertson[8-9] argue that the evolution of the internal defects of the oxide layer is the root cause of the damage, and based on the fracture mechanics theory they proposed iron oxide skin failure strain calculation formula. Nagl[10] experimentally analyzed the relationship between the fracture behavior of the oxide layer and the thickness of the oxide scale, and found that the failure stress/strain decreases with the increase of the thickness, and the larger the thickness of the oxide layer is, the larger the defect length is, and the experimental results Evans and Robertson[8-9] theoretical derivation is consistent.

On the production line as a large number of projectile impact at the same time high-speed, and damage the strip surface, while the oxide layer is very thin, and it is difficult to capture the behavior of the bullet impacting the scales. The finite element software is used to simulate the impact of single shot pills and some experience results are received. However, the model is generally very simple. For example, the finite element model proposed by the scholar Gao Zhi[11] does not set the oxide layer, only analyzed the impact of projectile towards steel, failing to get scaling damage principles; in the
finite element model proposed by the scholar Ren Yujun[12] the scale is too thick(0.5 mm), and the
direction of the impact is vertical, which deviates from the actual field.
This paper mainly carried out the following three aspects of the work:
(1).The damage strain value of Q235-A surface oxide scale was obtained by universal tensile tester
and scanning electron microscope (SEM/EDS).
(2).Based on the destructive strain value obtained in Step 1, the model of projectile impact failure
was established. The damage behavior of strip scale was calculated numerically according to different
impacting speed.
(3).The damage effect of the oxide scale on the surface of the strip was observed by using the shot
blasting experiment and the 4XB-TV metallographic microscope.
These work provides fundamental support for the design and optimization of projectile descaling
process parameters.

2. Stretch experiment
The experimental material is the Q235-A hot-rolled narrow strip, coil width is 200mm, and thickness
is 3.5 mm. The following samples are taken from the central position of the original coil, the chemical
composition shown in Table 1.

| Element | C   | Mn  | Si  | S   | P   |
|---------|-----|-----|-----|-----|-----|
| w/\%    |     |     |     |     |     |
| C       | 0.216 | 1.250 | 0.183 | 0.041 | 0.0398 |

(1).Sectional observation test method
The samples were prepared with the length and width of 10 mm. The surface of the sample was
cleaned with ultrasonic cleaning instrument, washed with alcohol, dried and cross sectioned. The cross
section was observed by ZEISS ULTRA 55 scanning electron microscope.
(2).Tensile test method
The tensile test specimen was prepared by line cutting. The length direction (drawing direction) of
the sample was in the rolling direction. The specific shape and size were shown in Figure 1. A specific
strain was applied to the specimen using a US MIT MTS universal tensile tester. The displacement
was controlled to be 0.01 mm/min, held for 1 min after the preset strain was reached. The sample was
removed and the surface was wiped with an alcohol cotton swab. The surface morphology was
observed by a plate-type metallographic microscope. Strain rises from 0.04%, with the step size of
0.005%.

![Figure 1. Tensile specimen dimensions (mm)](image)

(3).Sample Cracking Observation Method
The tensile test specimens were measured to line cutting using an optical microscope to prepare a
tensile test specimen with a length and a width of 10 mm. The surface of the sample was cleaned with
an ultrasonic cleaner and washed with alcohol, and then dried. Then utilize a ZEISSL ULTRA 55
scanning electron microscope to observe the surface of the sample.

3. Tensile Experiment and Discussion
3.1. Observation of cross section of iron oxide skin
Figure 2 shows the cross-sectional topography of Q235-A iron oxide under the scanning electron
microscopy. The cross-sectional morphology of iron oxide skin shows: iron oxide skin has no obvious
stratification, the thickness is relatively uniform, about 10 μm, the structure is relatively dense, and the
Body is better[13].
3.2. Tensile cracking behavior of iron oxide

The rupture behavior of iron oxide skin on the surface of each sample was observed by 4XB-TV metallographic microscope (200 times). When the strain was less than 0.08%, the surface oxide scale was not cracked, and the strain was obviously broken when the strain reached 0.08%.

When the specimen is cracked, multiple cracks occur simultaneously. Figure 3 shows a microscopic topography (10 000 times) of a 0.08% tensile strain observed by scanning electron microscopy. It can be seen from the micro-topography that the crack width is about 2.5 μm, the lines are neat and the debris that is peeled off during cracking. Obviously, the Q235-A iron oxide skin critical damage strain is 0.08%.

4. Finite Element Modeling

The 3D model of single projectile impact strip was established by ABAQUS/CAE finite element pretreatment software. The model has three parts: projectile, surface scale and strip. The radius of the projectile is 0.2 mm, the thickness of the surface is 0.02 mm, the radius is 0.5 mm, the thickness of the strip is 0.28 mm and the radius is 0.5 mm. Considering the symmetry of the whole structure, a 1/2 finite element model is established. In the unit style setting, the C3D10M type unit is applied for the projectile, the C3D8R type element is applied for the scale layer and the Body, and the TIE order[14] between the scale layer and the Body is bonded. After the grid is optimized, the finite element grid is shown in Figure 4.
In this model, the projectile is set as ideal rigid material, ignoring its irregular effects and deformation during striking. The scale is set to be brittle material without plasticity, and the failure criterion is ABAQUS brittle fracture failure[15]. The Body is set as an elastoplastic material, using the Johnson-Cook strength model[16]. The model is an empirical constitutive equation, and the Von Mises equivalent stress is a function of the equivalent plastic strain, the equivalent plastic strain rate and the temperature. The model equation[16] is shown in equation (1)

\[ \bar{\sigma} = (A + B \bar{\varepsilon}^p)(1 + C \ln \bar{\varepsilon}^p)(1 - T^m) \]  

(1)

In this equivalent: A, B, n, C, m are material parameters with no units, and \( \bar{\sigma} \) is equivalent stress; \( \bar{\varepsilon}^p \) is equivalent plastic stress; \( \bar{\varepsilon}^p \) is equivalent plastic strain rate with no units; \( T^* \) is temperature with no units, and its expression is

\[ T^* = \frac{T - T_r}{T_m - T_r} \]  

(2)

Here, \( T_r \), \( T_m \) are the reference temperature and the melting point of the material respectively, \( T \) is current temperature. The parameters of the model are shown in Table 2[17]. The simulation parameters and failure criteria are shown in Table 3[16,18].

**Table 2.** Parameters of Johnson-Cook models of Q235 steel.

| A/Mpa | B/Mpa | n   | C   | m   |
|-------|-------|-----|-----|-----|
| 244.8 | 899.7 | 0.94| 0.0391 | 0   |

**Table 3.** Simulation parameters

|          | density / (kg·m\(^{-3}\)) | Elastic Modulus /Gpa | Poisson's ratio | direct stress after cracking /Mpa | Direct stress damage strain /% |
|----------|-----------------------------|----------------------|----------------|----------------------------------|-------------------------------|
| Projectile | 7700                          | 150                  | 0.3            | -                                | -                            |
| Body     | 7800                          | 200                  | 0.288          | -                                | -                            |
| Scales   | 7750                          | 210                  | 0.29           | 180                             | 0.08                          |

The impact speed was set as 5 m/s, 10 m/s, 20 m/s, 30 m/s, 40 m/s and 50 m/s, respectively, with the impact angle (the angle between the projectile velocity direction and the strip surface for simulation) is 60°.

5. **Introduction Finite Element Modeling**

5.1. **Effect Damage of Projectile Velocity on Scale**

Figure 5 shows the impact of different projectile speed after the impact of strip surface damage layer cloud effect. In the calculation, the strain of the scale unit to break the strain is removed. Compared with the effect of scale damage at different speeds, the damage area increases with the increase of velocity. Under the impact of small speed, the model damage area is roughly semicircular, the damage area is very small. When the speed is 20 m/s, the semicircle of the damaged area begins to show "whisker-like crack" to the surrounding area, and the stress in the area of the "crack" is larger. When the velocity reaches 50 m/s, the larger scale is destroyed, and the "whisker" in the failure zone is close to the edge of the model.
Figure 5. The final destruction effect of the scale layer after impact of different blasting velocity
There are two types of failure unit. One is the unit direct failure, which is that the strain of the scaly cell itself is critical to the critical strain (in this model, the partially deactivated unit has been removed from the model after the calculation).

The second type is the failure of the scale unit group, these unit groups due to the failure of the surrounding units and the formation of a "island"; although these unit group stress/strain does not reach the critical strain value, but in the subsequent projectile impact or matrix deformation and other external forces Under the action of the "island" as a whole and the strip out of the matrix, as shown in Figure 5(f) in the blank area of the blue unit group.

5.2. Energy utilization rate

The define of energy utilization rate is $\varepsilon$:

$$\varepsilon = \frac{S}{E_K}$$  

Here, $S$ is the direct destruction area, $E_K$ is the energy of the projectile.

As can be seen from the formula, the energy utilization rate ($\varepsilon$) characterizes the area of the scale that one unit energy can be removed from.

![Energy utilization rate](image)

**Figure 6.** Energy utilization rate at different projectile impact speed

Figure 6 shows the relationship between energy utilization rate and projectile velocity. As can be seen from Figure 6, the energy utilization rate ($\varepsilon$) decreases as the projectile velocity increases.

On the actual descaling production line, the smaller the speed of the project, the slower the processing speed, which means, the time required to process a roll of steel is longer. With respect to various conditions, the ideal range of projectile impacting velocity is 20 m/s-30 m/s.

5.3 Deformation caused by body deformation

Figure 7 shows the stress cloud at different moments of the impact of the projectile at 25 m/s.

As can be seen from the Figure 7, as time goes, under the impact of the substrate more and more obvious deformation of the elastic-plastic is achieved, the stress quickly spreads among the surrounding area of radiation. Strip surface of the initial stress line is roughly circular, late was "star" to expand around.
Figure 7. Body stress at different time

Figure 7(c) and Figure 7(d) are body stress map and surface layer failure map at the same time (t = 1.2×10^{-6} s). After comparison of the two figures, the followings can be concluded:

1. The better elastomeric body is rapidly exposed to the surroundings after impact, and the same size strain is transmitted to the surface layer (a tear effect) with the contact surface, which results in a scaly strain that is far from the direct impact zone, and fail to reach the damage value.

2. As shown in Figure 7(c), since the iso-parametric lines of the late-stage steel strip are "star-shaped" outward, resulting in farther damage area spreading out as "whisker cracking" (figure d), "star-shaped" sharp corners of the stress line correspond to the "extension" of the failure zone of the scale.

If the "epitaxial zone" in Figure 7(d) is an indirect descaling zone, it is obvious that the scales in the area are easily destroyed by the subsequent impact of other pellets.

6. Conclusion

1. Hot rolled strip Q235-A surface oxide scale is compact and has a good structure with the substrate, the thickness is about 10 μm, the critical damage strain is 0.08%.

2. With the increase of the impact speed of the projectile, the damage effect of the scale layer is stronger. The fractured area of the scale has two parts, one is the direct impact damage area, and he other is the indirect tearing damage area caused by the body deformation. The indirect tearing is due to the large deformation of the iron body due to the impact of the iron body, and the strain is transferred to the surface oxide scale by means of the contact surface, causing the scale of the farther region.

3. The bigger the shot speed, the lower the energy utilization rate. Taking into account the actual production situation, a reasonable impact speed should be 20m/s-30m/s.

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