

Article

Effect of Foreign Object Damage on the Fatigue Performance of Stainless Steel Blades Under Pre-Corrosion Conditions

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Abstract: Aeroengine blades are prone to corrosion and foreign object damage (FOD) during service, leading to the risk of premature fatigue failure and impacting flight safety. The size of the blade's damage depends mainly on the impact velocity and the size of the foreign object. Therefore, this paper studies the influence of foreign object damage on the fatigue performance of 13Cr stainless steel blades under corrosive conditions by means of experimental exploration. The results are as follows. Pre-corrosion did not alter the blade's damage mechanism, but only reduced its impact resistance. The longer the corrosion time, the more the impact resistance of the blade decreased. Pre-corrosion leads to an increase in damage when the simulated blade is impacted, resulting in decreased fatigue performance of the blade. The fatigue limits of the simulated blades pre-corroded for 24 h, 48 h, and 96 h are reduced by approximately 22%, 23%, and 29%, respectively. The research results of this paper can provide data support for the detection of external field damage of aeroengine blades and provide reference for the design of anti-foreign object damage aeroengine blades.

Keywords: aeroengines; corrosion damage; foreign object damage; fatigue limit; microscopic features



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1. Introduction

13Cr stainless steel possesses outstanding qualities, including high hardness, temperature resistance, and resistance to corrosion. It is widely utilized in various industries, including in chemical equipment, pipelines, steam turbine blades, and medical devices. In particular, martensitic stainless steel and semi-martensitic stainless steel have significant practical value in the field of steam turbine blades. Moreover, the operating environment for aeroengines is complex, encompassing challenging conditions such as the Gobi desert and coastal areas. Aircraft flying in coastal areas are prone to inhaling foreign objects during takeoff, landing, or when flying at low altitudes. This can lead to foreign object damage (FOD) and pre-corrosion damage to the engine blades, especially in warm, rainy, high-temperature, and humid marine climates [1]. FOD will lead to the formation of notches on the impact area of the blade, and corrosion will form a large number of corrosion pits on the surface of the blade [2]. Both types of damage will impact the stress distribution of the entire blade and create a significant stress concentration at the damaged area [3]. The blade experiences centrifugal force and bending vibration loads during rotation. In this state, the

location of damage is prone to initiate cracks, which becomes the primary factor affecting the high cycle fatigue (HCF) of the blade.

1.1. FOD Literature Review

Since the last century, the issue of FOD has garnered the attention of scholars and researchers domestically and internationally. Farahani et al. [4] conducted an experimental simulation of the FOD on the first-stage blade of a gas turbine. At a temperature of 733 °C and a velocity of 300 m/s, hard objects with varying shapes (spherical, conical, and flat) and impact angles (90° and 45° relative to the blade) were used to impact the surface of a Udimet-500 plate specimen. To analyze the morphology of the impact site, they first examined the damage area using a scanning electron microscope. Then, they symmetrically cut the sample and measured the depth of each impact crater using image analysis software. Finally, according to the results, it was found that the maximum and minimum stress concentration factors and the induced microcracks were related to the plane projectile with a 45° impact angle and the spherical projectile with a 90° impact angle, respectively. Arcieri et al. [5] explained the failure mechanism of a 7075-T6 specimen subjected to rotating bending damage using finite element method and fracture observation. The findings indicate that the crack started at the location where the highest residual tensile axial stress occurred after impact. This location also experienced the highest tensile axial stress during the simulated fatigue cycle, and the crack began on the surface of the FOD pit. Discontinuities were observed below the pit, in the compressed area after impact, and during the fatigue cycle. Compared to the undamaged specimen, the fatigue strength decreased by $30 \pm 10\%$. Majidi et al. [6] investigated the impact of FOD on crack initiation and propagation of Ti-6Al-4V at room temperature and 300 °C, comparing it with the material's natural crack initiation behavior at the corresponding temperatures. The test results indicate that the applied stress level affected the crack initiation position, while the temperature did not have a significant impact on the crack propagation rate following FOD. Witek et al. [7] studied the number of load cycles and propagation of crack initiation after hard object injury by a mechanical processing method, as well as the influence of crack size on resonance frequency.

Hongbo Zhang et al. [8] studied the FOD of high strength steel AM355 simulated blade by combining experiment, finite element simulation, and theoretical analysis. The experimental results indicate that AM355 is sensitive to strain rate. When the strain rate is 3864 s^{-1} , the yield strength of AM355 increases by 30.7%. Zhao Zhenhua et al. [9] studied the effect of FOD on the fatigue limit of stainless steel blades using an air gun method and carried out high cycle fatigue tests on FOD specimens. The test results show that the damage after FOD was reflected in extrusion deformation, plastic deformation, and material shear loss at the micro level. At the macro level, the fatigue limit of stainless steel specimens decreased by more than 14% after FOD. Small cracks, notches, and a lamellar structure contribute to this decrease. Additionally, increasing the notch size further decreased the fatigue limit of the test piece. Zhao Zhenhua and colleagues [10] conducted an FOD simulation test on the TC11 plate specimen using the air gun method. They then performed a detailed study of the macroscopic and microscopic impact damage of the specimen and carried out a tensile fatigue test afterwards. The test results indicate that the depth of the notch greatly affects the fatigue limit. Additionally, a higher impact speed leads to a lower fatigue limit. The hard object damage altered the material's microstructure in the damaged area, causing the phase to become elongated and oriented in a specific direction. Zhu et al. [11] investigated the behavior of small fatigue cracks initiated and propagated within the damage pits of TC4 titanium alloy. The test results showed that all the cracks were formed by the nucleation of the micro-area where the hard matter damages

the material accumulation at the edge of the crater. The process of crack propagation caused by damage from hard objects was divided into two stages. In the first stage, the cracks only spread within the crater, while in the second stage, the crack rapidly propagated both inside and outside the remaining structure. The crack propagation rate caused by hard matter damage was lower than that of a natural crack. Yang et al. [12] conducted two types of FOD tests on simulation specimens of TC4 titanium alloy blades, specifically edge impact and face center impact, using a drop weight impact test system. Additionally, they performed vibration fatigue tests on notched specimens and smooth specimens, respectively. The results indicated that the notch width, depth, and volume resulting from the face-centered impact were greater than those resulting from the edge impact, with the average volume of the notch being 46.7% larger. The fatigue crack occurred at the neck shrinkage of the smooth specimen, and at the gap of the damaged specimen. The fatigue limit for blade vibration caused by edge impact was lower than that of face-centered impact. The fatigue limit of the edge impact was 55.8% lower than that of the smooth specimen, and the fatigue limit of the face-centered impact was 35.1% lower than that of the smooth specimen.

1.2. Corrosion Literature Review

The issue of corrosion fatigue has a long history and is widely prevalent in various fields. Therefore, scholars and researchers in the fields of science and engineering, both domestically and internationally, have studied the issue of corrosion fatigue over an extended period. A significant number of experimental studies have been conducted to investigate the deterioration of materials in various corrosion environments, demonstrating the substantial impact of corrosion damage on material fatigue performance [13–29].

In addition, a large number of researchers have conducted studies on corrosion using simulation calculations [30–35]. Han Wang et al. [36] proposed a peridynamics-based CFCG simulation framework and applied to CFCG simulation of 634 stainless steel specimen. This framework explains how corrosion leads to faster crack propagation from the perspective of material performance degradation. The proposed model's effectiveness was confirmed by the simulation results, which aligned well with the experimental results. The effects of corrosion-related degradation function parameters and loading frequency on the CFCG results were discussed. The results demonstrated the flexibility of the simulation method. Yajun Chen et al. [37] investigated the impact of damage and corrosion on the fatigue life of 2198-T8 Al-Li alloy sheets by combining foreign object and corrosion damage. The results indicated that the depth distribution of corrosion pits on the surface of impact dents followed the same trend as the residual stress distribution. For hemispherical punching, the coupling effect of impact damage and corrosion was most obvious at low impact energy. Under high-impact energy, impact damage took precedence over coupling damage. With the increase in salt spray corrosion time and impact energy, the rate of decrease in fatigue life gradually slowed. Impact damage significantly contributed to the early fatigue life of corrosion. Compared to the salt spray corrosion environment at 35 °C, the fatigue life of the specimen at 25 °C increased by a maximum of 50.48% as the impact energy increased from 10 J to 25 J.

In summary, the fatigue properties of materials under corrosion and FOD have been the subject of numerous studies both domestically and internationally. However, there is a lack of research on how foreign object impact affects the fatigue properties of stainless steel under corrosion conditions.

In this paper, the coupling damage mechanism of FOD and corrosion of an engine blade is revealed. Based on the damage mechanism, the effects of coupling damage on high-cycle fatigue of blades were systematically revealed. The mechanism of fatigue crack

initiation and propagation under coupled damage conditions is an important supplement to the research of fatigue properties of stainless steel.

2. Materials and Methods

2.1. Materials and Specimen

In order to study the damage resistance and pre-corrosion performance of 13Cr stainless steel compressor blades, and to give our work practical engineering significance, a simulated blade was designed based on the leading edge geometry of a real service blade and the stress gradient of the dangerous position. The simulated blade is shown in Figure 1.

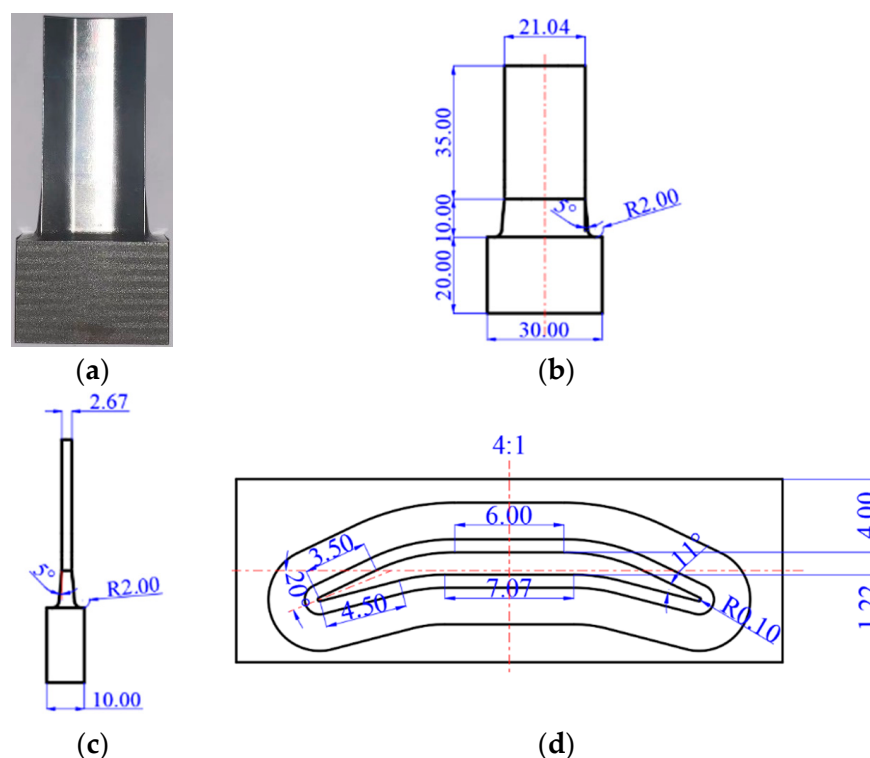


Figure 1. Simulated blade. (a) Simulated blade photograph; (b) Master view of simulated blade design parameters; (c) Side view of simulated blade design parameters; (d) Top view of simulated blade design parameters. Unit: mm.

The material of the simulated blade is 13Cr15Ni4Mo3N stainless steel, or 13Cr stainless steel for short, which has good corrosion resistance, plastic toughness, and high strength. It is evident that the material's metallographic structure is predominantly comprised of lath martensite. The metallography images of materials are shown in Figure 2. This material is commonly used in the production of engine components such as fan shafts, compressor rotor blades, and load-bearing bolts for aeroengines. The material parameters at room temperature are listed in Table 1. The chemical composition of the material is shown in Table 2.

Table 1. Material parameters of 13Cr stainless steel at room temperature.

Density/kg·m ⁻³	Elastic Modulus/GPa	Poisson's Ratio	Elongation Values/%
7870	194.2	0.33	21
Tensile Strength/MPa	Yield Limit/MPa	Bending Fatigue Limits/MPa	
1128	1020	530	

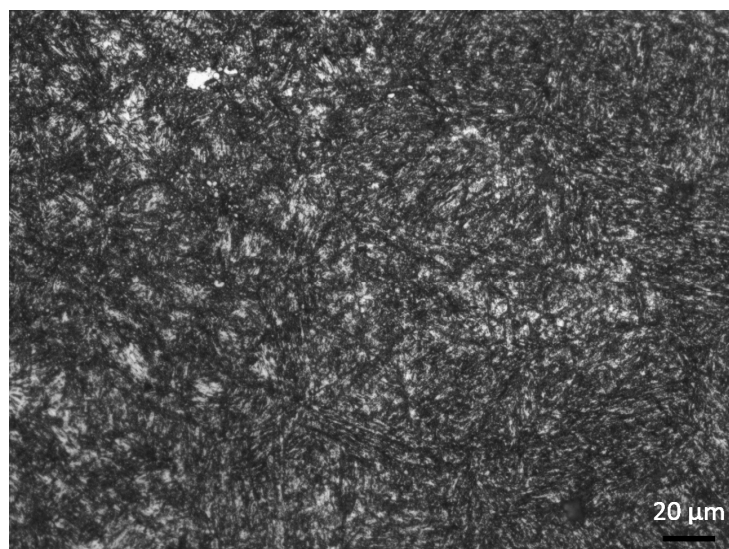


Figure 2. Metallography images of materials.

Table 2. Chemical composition of the material.

Element	Fe	Cr	Ni	Mo	Mn	Si
Mass fraction/%	74.77	17.23	3.76	3.19	0.75	0.30

2.2. Damage Test

2.2.1. Test Area and Conditions

To prevent the leading edge's thickness change from affecting impact damage results and to avoid debate over fatigue failure due to stress concentration from structural changes, the prefabricated FOD position was selected 5 mm above the junction of the straight section and the transition section. The FOD test was performed using an air gun test system. The immersion corrosion method was employed to conduct corrosion tests on simulated blades, and the test equipment was the constant temperature water bath. To prevent the corrosion solution from affecting areas of the test piece other than the corroded area during soaking, we use a method of covering the non-corrosive sections of the test piece with polyvinyl chloride electrical insulation tape. The foreign objects selected for the damage test were steel balls with diameters of 2 mm and 3 mm. The impact velocity was 200 m/s and 300 m/s. The impact velocity was measured using high-speed photography, and the velocity error was within 5%. The angle between the direction of impact velocity and the normal direction of the leading edge was 0°. The FOD system is depicted in Figure 3, including air gun, steel ball, and cartridge. The cartridge was used to deliver steel balls into the air gun. The test area and impact conditions are shown in Figure 4.

2.2.2. Conversion of Laboratory Immersion Corrosion Time to Actual Service Time

In general, the corrosion behavior and corrosion rate of the same material differ even in the same corrosion solutions and temperatures. However, through the experiment, it was found that corrosion pits of different sizes and depths appeared on the surface of the material after corrosion. The corrosion behavior of the samples in the immersion corrosion experiment and the accelerated spectrum experiment under the simulated environment was basically the same, mainly pitting corrosion [38]. Therefore, it can be considered that the corrosion damage mode is not related to the selected corrosion environment. With the formation and expansion of pitting pits, some high-quality materials will be separated from the material body, resulting in the loss of material quality. The size and density of pitting

pits are directly related to quality loss. It is obvious that the larger the number of pits, the greater the quality of material loss, and the corrosion can be evaluated by material quality loss. In different environments, the corrosion rate of the specimen may be different. If the mass loss due to corrosion in the two environments is equal, it can be concluded that the corrosion damage inflicted on the material by both environments is also equal, effectively resulting in similar levels of corrosion.

During the immersion corrosion test, the ambient temperature was 40 °C, and the corrosive solution used was a 5% NaCl solution with a pH value of 4 ± 0.2 . The solution was prepared using deionized water, NaCl crystals, and diluted HCl solution. Three groups of control tests were conducted with different pre-corrosion times: 24 h, 48 h, and 96 h, respectively. According to the above conversion principles, the corresponding actual service time could be calculated as 2, 4, and 8 months, respectively.

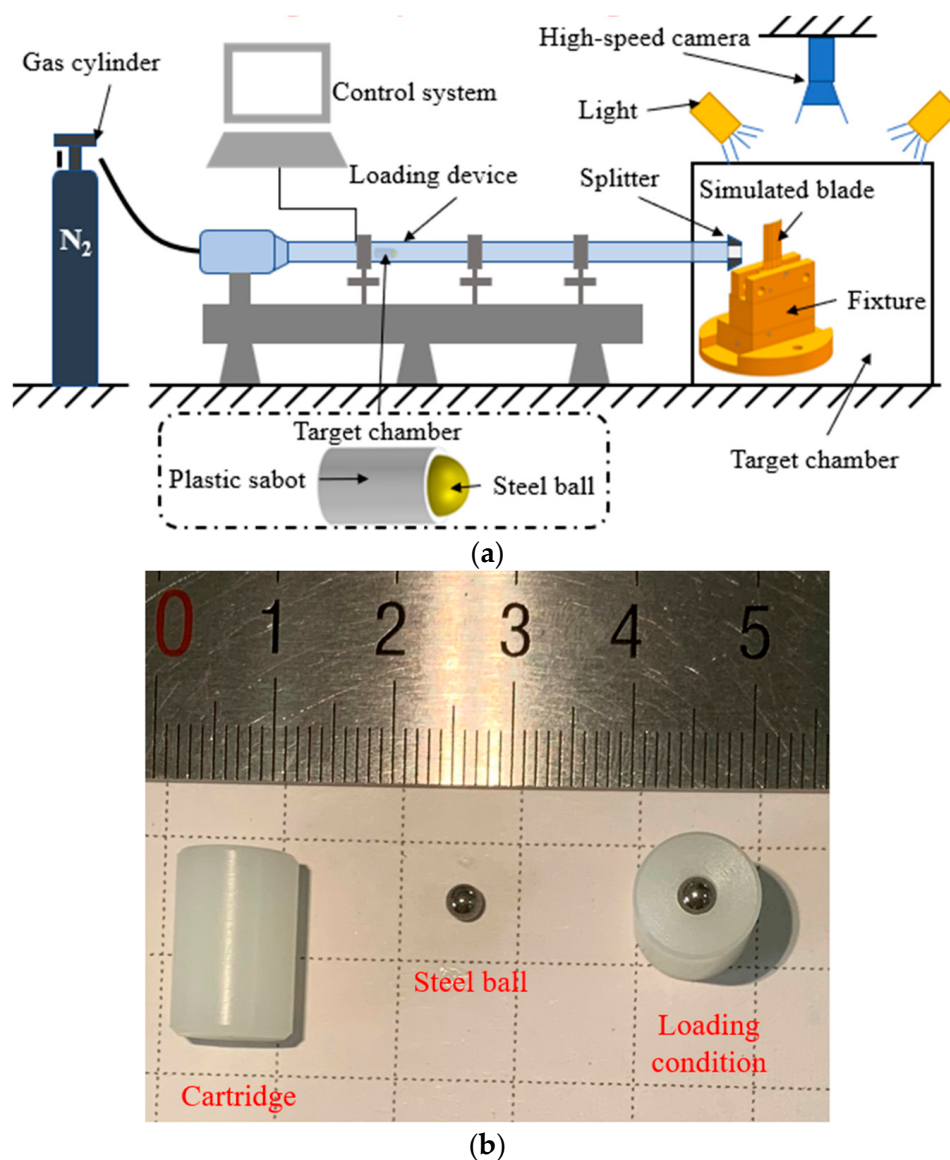


Figure 3. Foreign object damage (FOD) test system. (a) Air gun; (b) Cartridge and steel ball.

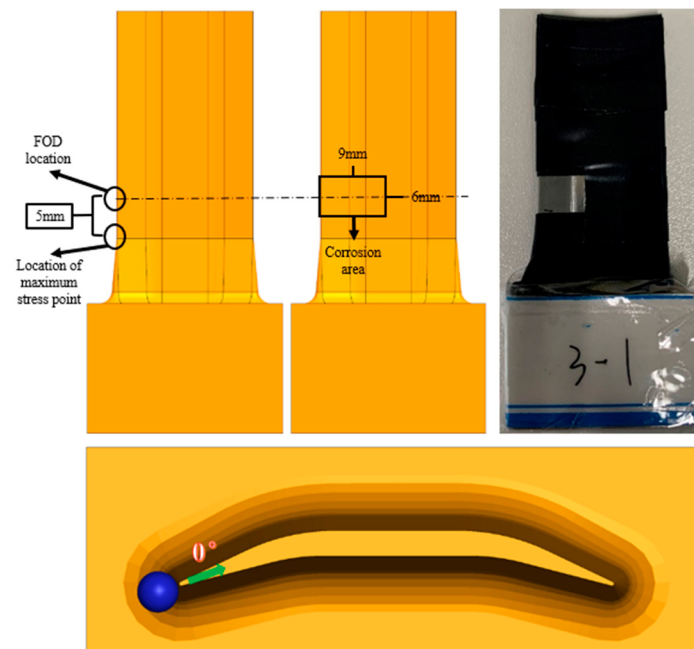


Figure 4. The test area and impact conditions.

2.3. High Cycle Fatigue Test

There are several common methods for determining the fatigue limit, including the group method, lifting method, and single-point method. These techniques are primarily suitable for testing the fatigue limits of multiple specimens under the same conditions. However, the state of specimens is different after foreign object damage and corrosion damage. Therefore, this paper employs the step-by-step loading test method proposed by Maxwell et al. in 1999 [39] to evaluate the fatigue limit of the blade. The fundamental principle of the step-by-step loading test method is to initiate the fatigue test with a lower load. If the specimen does not fail within the specified number of cycles, the load is increased, and the specimen is subjected to the corresponding number of cycles again until fatigue failure occurs.

A digital electric vibration test system (DONGLING VIBRATION, Suzhou, China) was used to perform high cycle fatigue tests on damaged specimens in the first-order bending vibration mode. The clamping method for the simulated blade is illustrated in Figure 5. The test was performed at 1×10^7 cycles with a stress ratio of $R = -1$. The strain measuring instrument was used to collect and record the experimental data, and the laser displacement sensor was used to monitor the test.

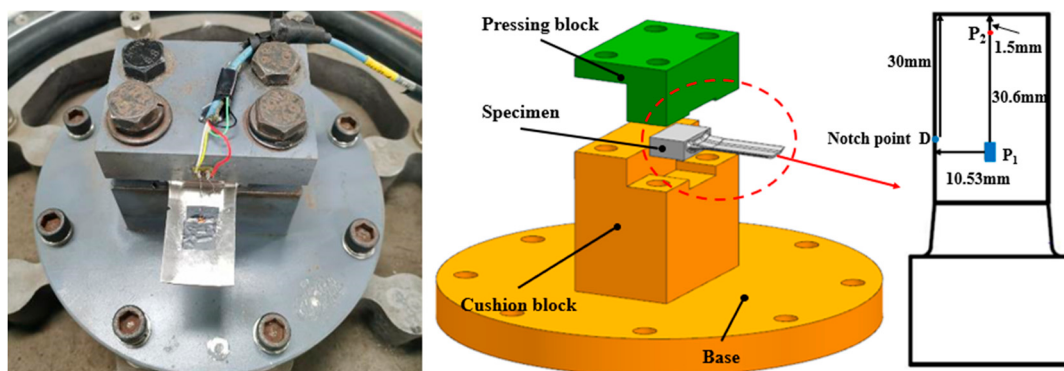


Figure 5. Fixture, specimen, and strain gauge used in HCF test.

In high cycle fatigue testing, stress concentration in the notch area is induced by the FOD, making it impossible to directly monitor the stress and strain conditions at the notch using a strain gauge. Therefore, a strain measuring point P_1 and laser measuring point P_2 outside the damage area must be selected, as shown in Figure 5. Of the two points, P_1 was used to paste strain gauge to collect the strain of the specimen, and P_2 was used to measure the displacement of the specimen.

The equivalent stress at P_1 in the first-order mode calculated by the finite element method is denoted by σ_{P_1} , while the equivalent stress at point D is denoted by σ_D . During the HCF test, the strain ε_{P_1} was obtained by placing the strain gauge at P_1 , and the stress σ'_{P_1} was calculated according to Hooke's law. Therefore, the nominal stress σ'_D at the notch can be calculated by Equation (1).

$$\frac{\sigma_{P_1}}{\sigma'_{P_1}} = \frac{\sigma_D}{\sigma'_D} \quad (1)$$

In order to ensure that the collected strain data accurately reflected the condition of the specimen, the vibration of the blade was calibrated by the amplitude response of the specimen at P_2 . The pre-test was carried out under the condition of identical frequency and amplitude variation. Strain σ'_{P_1} at feature point P_1 and displacement S'_{P_2} at feature point P_2 were recorded, and the coordinate diagram as shown in Figure 6 was established with σ'_{P_1} as the horizontal coordinate and S'_{P_2} as the vertical coordinate.

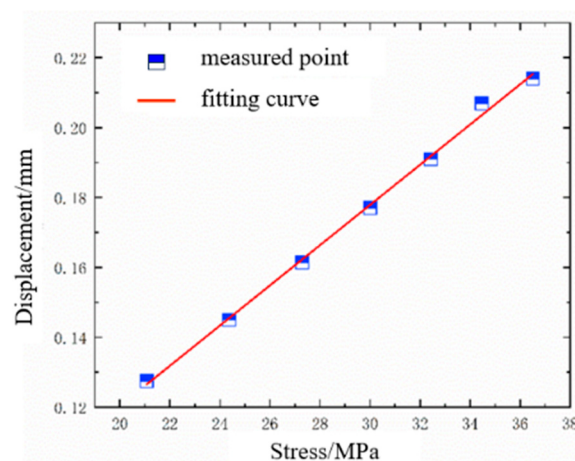


Figure 6. Dynamic stress calibration results fitting curve.

It is evident that the dynamic stress calibration results of the standard smooth test specimen demonstrate a high degree of linearity, with the fitting relationship expressed as follows. It shows that the collected data accurately reflects the state of the specimen.

$$S'_{P_2} = 0.00576 \cdot \sigma'_{P_1} + 0.00521 \quad (2)$$

The fatigue strength of specimens under 10^7 lifetime was tested by the step loading method. In this method, if a given sample is subjected to 10^7 cycles at the initial stress level without fatigue failure, the stress level is increased by 10% and the test is repeated. The test continues until the specimen fails in fewer than 10^7 cycles. According to the material properties of the specimen and previous work [9,10,12], the initial stress level in this experiment was set at 70 MPa. Assuming that fatigue damage accumulates linearly during the last stress stage of specimen failure, the fatigue strength at 10^7 cycles can be calculated as follows:

$$\sigma_e = \sigma_p + \frac{n}{10^7} \cdot (\sigma_f - \sigma_p) \quad (3)$$

where, σ_e is the fatigue strength of the specimen under 10^7 cycles, σ_p is the maximum stress level of the stress step before the failure of the specimen, n is the number of failure cycles of the last stress step, and σ_f is the maximum stress level of the last stress step.

2.4. Test Arrangement

The prefabricated damage test was divided into two categories, comprising a total of four groups. The first category involved simulated blades with only prefabricated FOD. There were 12 specimens in the first category, and these 12 specimens were compiled into the first group. The second type consisted of some simulated blades that had been pre-corroded and subsequently impacted by foreign objects. There were a total of 36 specimens in the second type, which were categorized based on the duration of the pre-corrosion test. The 12 specimens that were corroded for 24 h were assigned to Group 2, the 12 specimens corroded for 48 h were assigned to Group 3, and the 12 specimens corroded for 96 h were assigned to Group 4. After completing the damage test, the simulated blade underwent a high cycle fatigue test. This test was repeated three times for each working condition, and the specific test conditions and the number of specimens are detailed in Table 3.

Table 3. The number of specimens under each test condition.

FOD	Pre-Corrosion			
	0 h	24 h	48 h	96 h
2 mm, 200 m/s	3	3	3	3
2 mm, 300 m/s	3	3	3	3
3 mm, 200 m/s	3	3	3	3
3 mm, 300 m/s	3	3	3	3

2.5. Damage Size Characterization

After completing the FOD test for the simulated blade, the two parameters of notch damage width and notch damage depth were used to characterize the notch after external damage. The damage size along the leading edge was defined as the notch damage width, and the damage size perpendicular to the leading edge was defined as the notch damage depth. The definition of damage depth and damage width are illustrated in Figure 7a. In the laboratory, a KH-7700 three-dimensional stereo microscope from HIROX (Hackensack, NJ, USA) was utilized for measurements, achieving an accuracy level of up to 1 μm .

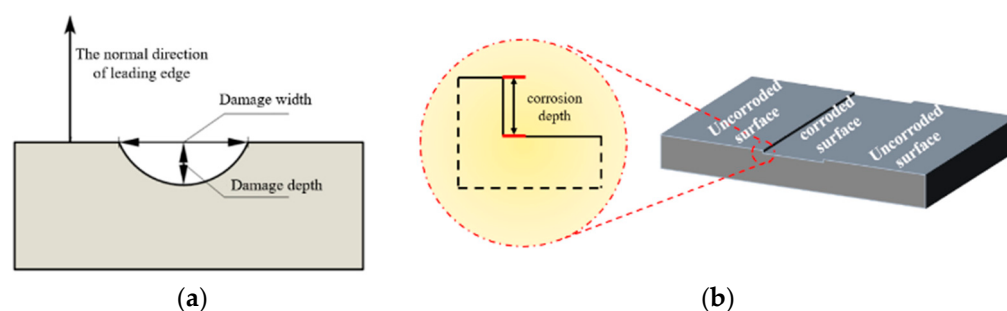


Figure 7. Damage parameter definition diagram. (a) Definition of damage depth and damage width; (b) Definition of corrosion depth.

The pre-corrosion damage test resulted in material loss on the surface, creating a height difference between the corroded and uncorroded areas. The corrosion depth was utilized to characterize the extent of damage, defined as the height difference between the corroded surface and the uncorroded surface. In reality, the corroded surface is not

as smooth as the uncorroded surface because of the presence of corrosion pits. Therefore, for a unified standard, the measured corrosion depth was defined as the distance from the uncorroded surface to the lowest point of the corroded area. The definition of corrosion depth is illustrated in Figure 7b.

Finally, the damage notch and fatigue crack were observed under different conditions by the Quanta 250 electron microscope from FEI company (Hillsboro, OR, USA).

3. Results and Discussion

3.1. Damage Laws

3.1.1. FOD Law

The FOD test was conducted on 12 simulated blades in group 1, with each condition repeated three times to ensure the test's repeatability. Figure 8 illustrates the typical damage to the leading edge of the blade resulting from the impact of steel balls of various sizes and speeds. According to the results of the FOD impact test, the changes of damage width and damage depth with the size of steel ball and impact velocity is illustrated in Figure 9.

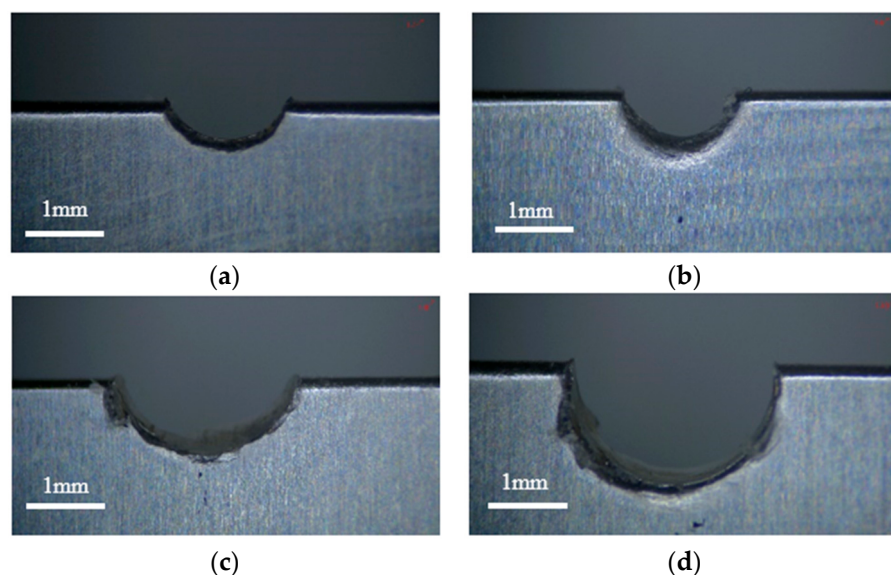


Figure 8. The typical damage of the leading edge of the simulated blade by foreign object impact (a) 2 mm, 200 m/s; (b) 2 mm, 300 m/s; (c) 3 mm, 200 m/s; (d) 3 mm, 300 m/s.

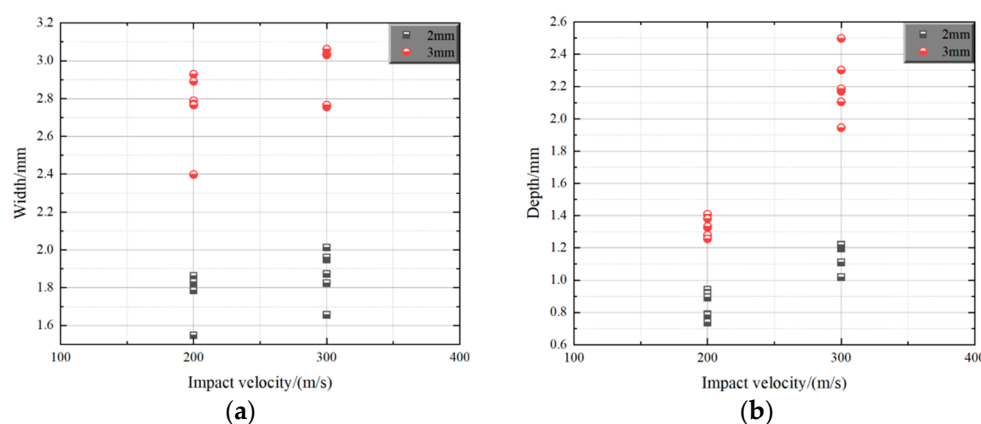


Figure 9. The relationship among the macroscopic size of the FOD, the size of the foreign object, and the impact velocity. (a) The relationship between damage width and impact velocity; (b) The relationship between damage depth and impact velocity.

Evidently, the notch caused by the impact was regular, symmetrical, and U-shaped. When steel balls of varying sizes impacted the leading edge at the same speed, larger diameter balls were associated with greater damage width. When steel balls of the same diameter impacted the leading edge of the simulated blade at varying speeds, the width of the resulting damage remained relatively consistent. This observation suggests that damage width primarily depends on the size of the steel balls. Furthermore, the damage width of nearly all notches was less than the diameter of the corresponding steel balls. When steel balls of varying sizes strike the leading edge at the same impact speed, a larger diameter was associated with greater damage depth. Conversely, when steel balls of the same diameter impacted the leading edge of a simulated blade at different speeds, an increase in impact speed correlated with an increase in damage depth. This indicates that damage depth is influenced by both the size of the steel ball and the impact speed, which together determine the total impact energy. The greater the impact energy, the deeper the resulting damage.

As illustrated in Figure 10, the damage to the notch root of the blade was observed using an electron microscope. The notch root of the simulated blade, formed after impact, featured a significant smooth region, while the edge of the notch root exhibits noticeable ductile deformation. An enlargement of Zone I and Zone II revealed a large number of dimples. It can be concluded that the fracture mode of the simulated blade is ductile fracture when subjected to the impact of steel balls.

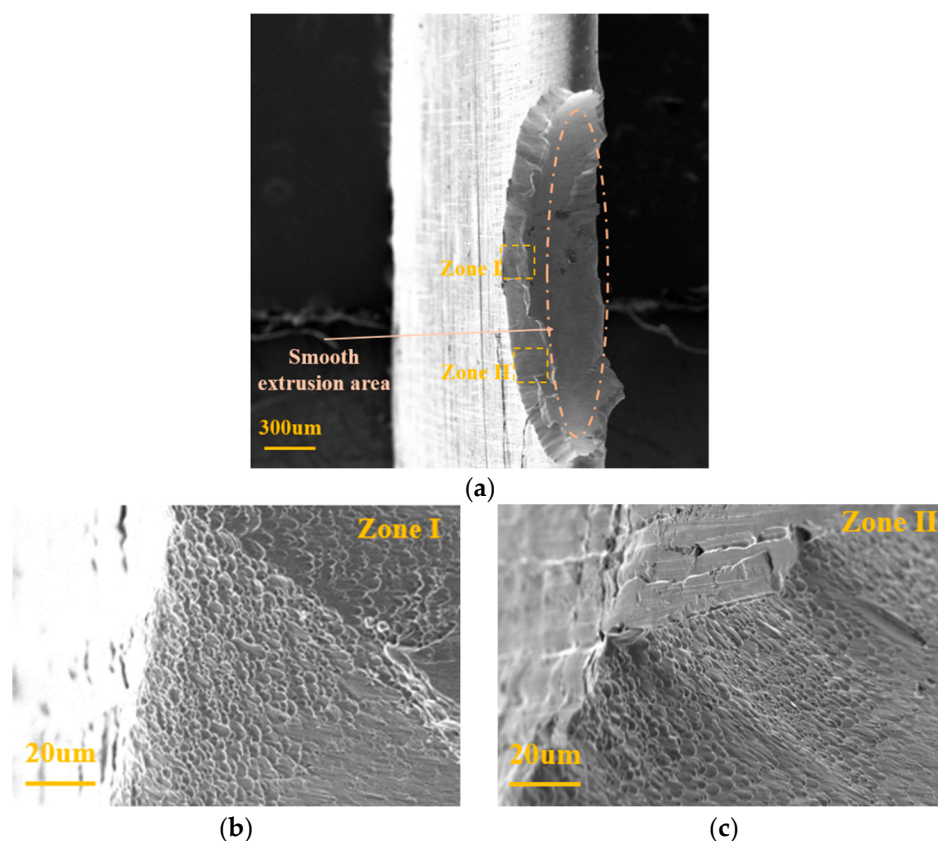


Figure 10. The impact damage characteristics of simulation blades. (a) Global view; (b) Zone I; (c) Zone II.

3.1.2. Corrosion Damage Law

The 36 simulated blades in groups 2, 3, and 4 were subjected to immersion pre-corrosion tests of different lengths, and EDS energy spectrum analysis was performed on the simulated blades before and after corrosion. According to the results of the energy

spectrum analysis, the composition and proportion of the material were determined, and the proportion of each element of the specimen with different pre-corrosion times were compared. The changes for each element are shown in Figure 11. According to the energy spectrum analysis of simulated blades, as the pre-corrosion time increased, the Fe in the simulated blade reacted with oxygen in an acidic environment, existing in various forms such as Fe_3O_4 , Fe_2O_3 , and FeOOH . Therefore, the oxygen content on the surface of the simulated blade continued to increase with prolonged pre-corrosion time. In a hydrochloric acid environment, the enrichment and adsorption of chloride ions on the surface of the simulated blades hindered the growth of the passivation film and compromised its compactness. This disruption made it challenging to form a protective oxide film on the surface of the simulated blades, thereby accelerating the dissolution rate of the metal into the solution [40]. Consequently, the concentration of Fe on the surface of the simulated blades decreased significantly. An anomaly can also be observed in Figure 11, where the surface iron content of the sample after 24 h pre-corrosion is greater than that of the sample after 48 h pre-corrosion. This is inconsistent with the test conclusions, and it is speculated that the effect on the specimen of 24 h and 48 h pre-corrosion is similar. In addition, in the energy spectrum analysis of the specimen, several points in the test area were selected to measure, and the error caused by the selection points is inevitable.

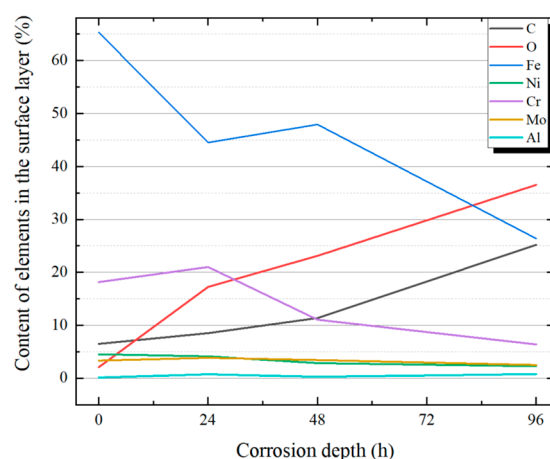


Figure 11. The change of element proportion of simulated blades under different pre-corrosion conditions.

The surface of the test specimen was examined after various pre-corrosion durations, and the relationship between corrosion depth and duration was established. The macroscopic damage caused by corrosion was primarily evident as material loss on the corrosion surface of the simulated blade, as illustrated in Figure 12. This includes both regional uniform corrosion damage and leading edge corrosion notch damage. When the pre-corrosion duration was 24 h and 48 h, the surface of the blade exhibited uniform corrosion across the entire area, with a layer of black corrosion products forming on the surface of the corroded region. When the pre-corrosion duration reached 96 h, the corrosion damage to the leading edge of the blade became more severe. There are two scenarios: one involves the leading edge becoming thinner, accompanied by a significant accumulation of corrosion products in the affected area. The other scenario occurs when the corrosion at the leading edge of the blade causes material loss, resulting in the formation of a notch. Therefore, the surface of the uncorroded simulated blade is relatively flat and smooth. After corrosion, the surface of the blade became uneven and gully-shaped due to the chemical reaction between the corrosive solution and the blade, resulting in the formation of corrosion pits. The longer the pre-corrosion period, the greater the material loss on the blade's surface. The more pronounced the gully-shaped stripes, the greater the density of corrosion pits.

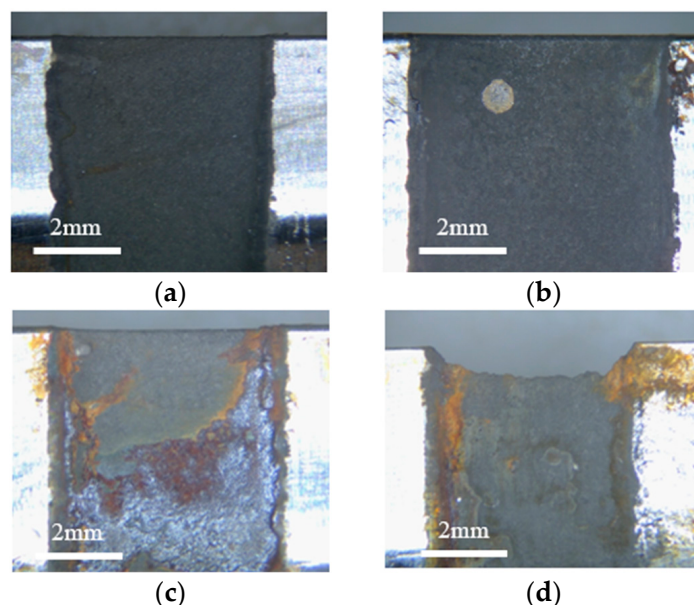


Figure 12. Different pre-corrosion time damage surface characteristics. (a) Pre-corrosion for 24 h; (b) Pre-corrosion for 48 h; (c) Pre-corrosion 96 without notch; (d) Pre-corrosion 96 h (notch).

In addition, damage can be analyzed quantitatively through data. The relationship between corrosion depth and pre-corrosion time is illustrated in Figure 13. Under identical conditions of corrosion solution concentration and temperature, the corrosion depth after 24 h ranges from 0.9 mm to 1.4 mm, after 48 h from 1.2 mm to 1.6 mm, and after 96 h from 1.4 mm to 1.9 mm. It is evident that, for the same duration of pre-corrosion, the difference in corrosion depths does not exceed 0.5 mm, indicating good test repeatability. The longer the pre-corrosion duration, the more extended the reaction time between the material and the corrosive solution, resulting in greater material loss. This loss was evident in the macroscopic size of the damage. The corrosion depth increased with the increase of the pre-corrosion time. Moreover, we observed that the corrosion depth reached approximately 1 mm within the first 24 h. Subsequently, an additional 0.3 mm accumulated every 24 h.

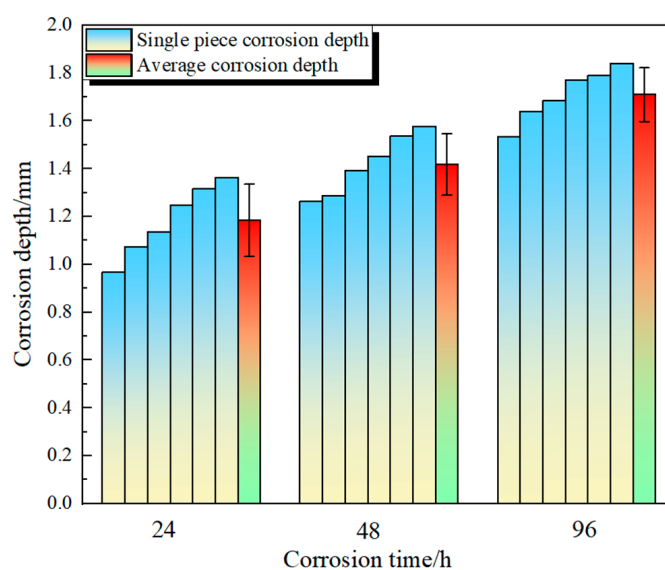


Figure 13. Relationship between corrosion depth and pre-corrosion time.

3.1.3. FOD Law in Corrosive Environment

The FOD test was carried out on 36 simulated blades in the 2nd, 3rd and 4th groups, respectively. Additionally, both macro- and micro-observations of the notch morphology of the simulated blades were performed.

Figure 14 illustrates the comparison of the macroscopic morphology of simulated blade damage subjected to varying pre-corrosion durations while maintaining consistent impact test conditions (3 mm, 200 m/s). From this, it can be observed that under both uncorroded and corroded conditions for 24 h, the damage manifested as a typical ‘U’ notch. Under 48 h of pre-corrosion, the damage manifested as an irregular ‘U’ notch. After 96 h of pre-corrosion, the damage appeared as an irregular notch, with the tip exhibiting irregularities and the bottom forming a U-shaped profile.

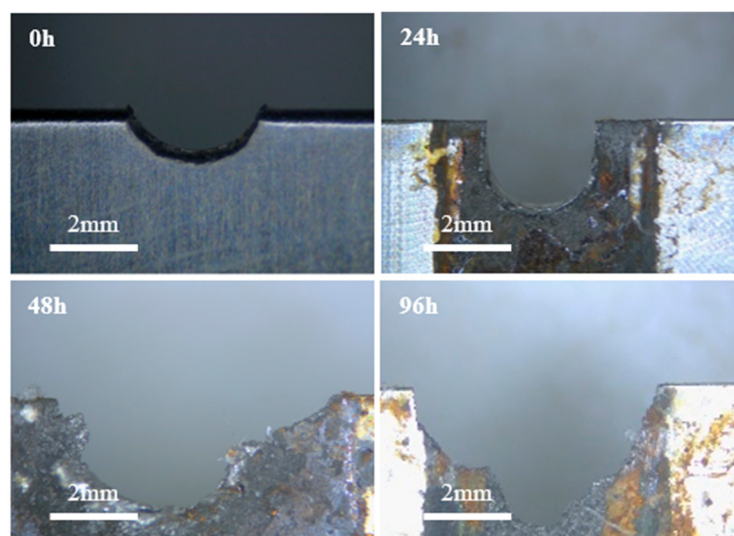


Figure 14. Blade damage caused by foreign object impact after different pre-corrosion times.

The following research on the influence of pre-corrosion on the impact resistance of blades was carried out by quantitative analysis. As illustrated in Figure 15, the relationship between the damage size of the simulated blade and the pre-corrosion time under various working conditions is presented.

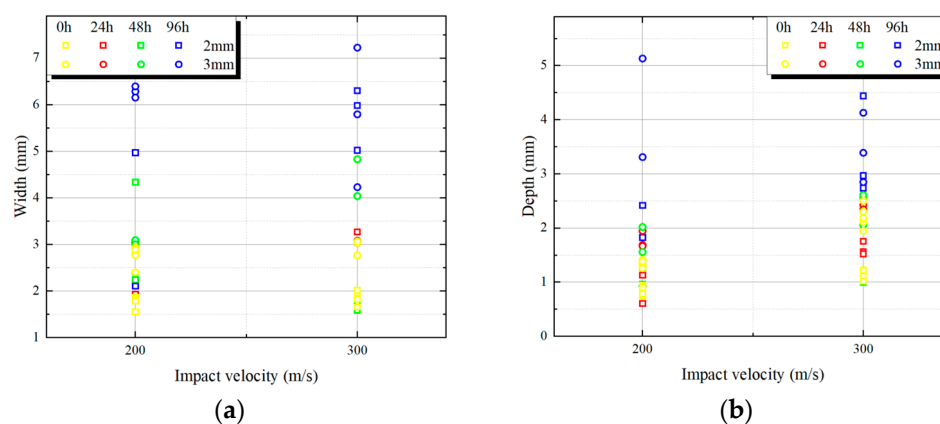


Figure 15. The relationship between damage size and impact velocity of the simulated blade for different pre-corrosion durations. (a) Damage width; (b) Damage depth.

In Figure 15, under the impact condition of 2 mm steel balls, the difference in FOD damage width between 24 h and 48 h after pre-corrosion is not particularly pronounced when

compared to the condition without pre-corrosion. However, after 96 h of pre-corrosion, the width of the damage at the notch increased significantly due to the loss of material from the leading edge in the corroded area. In fact, the damage width nearly matched that of the entire corroded area. The damage depth of FOD after 24 and 48 h of pre-corrosion was slightly greater than that observed without pre-corrosion. However, the damage depth of FOD after 96 h of pre-corrosion was significantly greater.

Under the impact condition of 3 mm steel balls, the width of FOD after 24 h of pre-corrosion was not significantly different from that observed without pre-corrosion. However, the FOD damage width increased with prolonged pre-corrosion time, particularly after 48 and 96 h, with the most pronounced increase occurring after 96 h of pre-corrosion. The width of FOD damage was significantly larger than that of other types of pre-corrosion.

We believe that this is due to the thinning of the leading edge of the blade caused by pre-corrosion and the thinner leading edge producing greater material loss under the impact of the steel ball, which was manifested as a larger damage width on the macro level. From this, we can draw one conclusion. Pre-corrosion reduces the impact resistance of the blade, which leads to greater damage of the blade after pre-corrosion under the same impact conditions, and that damage becoming more serious with an increase of pre-corrosion time.

After conducting a quantitative analysis of the influence of pre-corrosion time on the impact resistance of the simulated blade, the damage to the simulated blade was examined from the perspective of damage morphology. Figure 16 presents the damage characteristic diagram of the impact damage area of the simulated blade subjected to 24 h of pre-corrosion. After 24 h of pre-corrosion, only a few corrosion pits and minimal corrosion products remained on the surface of the simulated blade. Additionally, no signs of corrosion damage were detected at the root of the notch. In Figure 16a, the area to the left of the dotted line is smooth, while the area to the right exhibits a dimpled texture. The fracture in this area is formed by the coexistence of 'brittle fracture' and 'ductile fracture'. Further enlargement of Zone I and Zone II revealed a large area of equiaxed dimples and a small amount of shear dimples. There is obvious epitaxial deformation on the left and right sides of the notch in the figure. Therefore, it can be judged that, on the blade pre-corroded for 24 h, the form of the main fracture after impact with steel balls was ductile fracture. Figure 17 presents the damage characteristics of the simulated blade impact area after 48 h of pre-corrosion. After 48 h of pre-corrosion, the damage of the simulated blade was similar to that of the 24 h pre-corrosion specimen. Both exhibited a smooth extrusion area and rough dimple area at the notch root. Further enlargement of Zone I and Zone II clearly revealed a substantial area of equiaxed dimples and shear dimples. The fracture surface on both sides of the notch had obvious plastic deformation. Therefore, in the case of pre-corrosion for 48 h, the form of the main fracture on the blade after the impact of steel balls was ductile fracture. Figure 18 presents the damage characteristics of the simulated blade impact area after 96 h of pre-corrosion. After 96 h of pre-corrosion, the corrosion marks on the surface of the simulated blade were quite pronounced, and a significant amount of corrosion products and pits are present. It can be seen that, due to the long-term pre-corrosion, the corrosion pits on the blade surface are deeper, but no corrosion products remain at the root of the notch formed by the impact of steel balls. The end of the notch fracture after impact was uneven, exhibiting numerous burrs. Most of the area at the root of the notch was relatively smooth, and obvious plastic deformation was found on the fracture surface on both sides of the notch. The enlarged Zone I and Zone II show characteristics of large area equiaxed dimples. It can be speculated that the form of the blade's impact fracture in the case of pre-corrosion for 96 h is mainly ductile fracture.

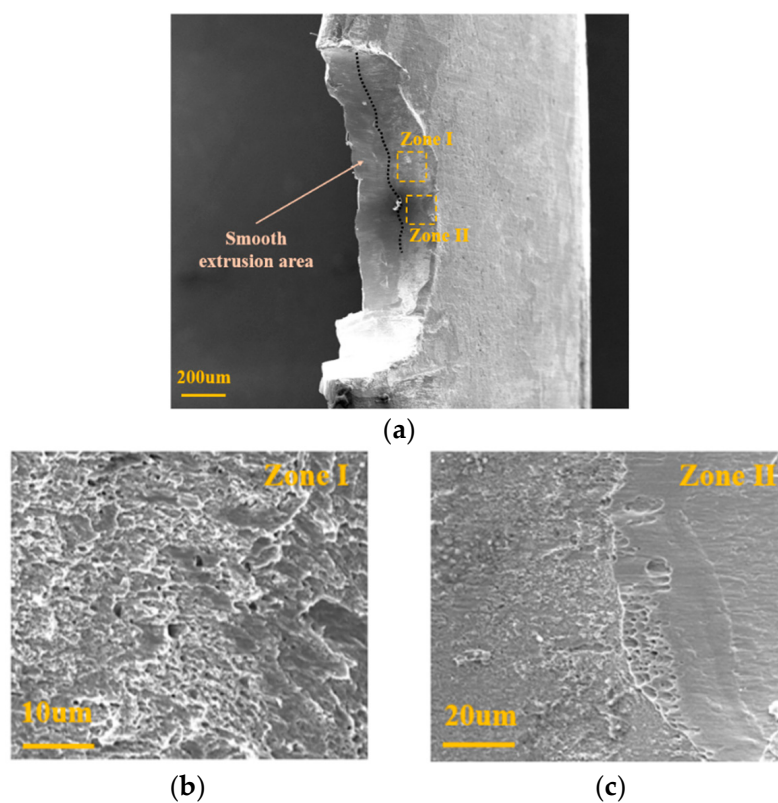


Figure 16. Simulated blade impact damage characteristics for 24 h of pre-corrosion. (a) Global view; (b) Zone I; (c) Zone II.

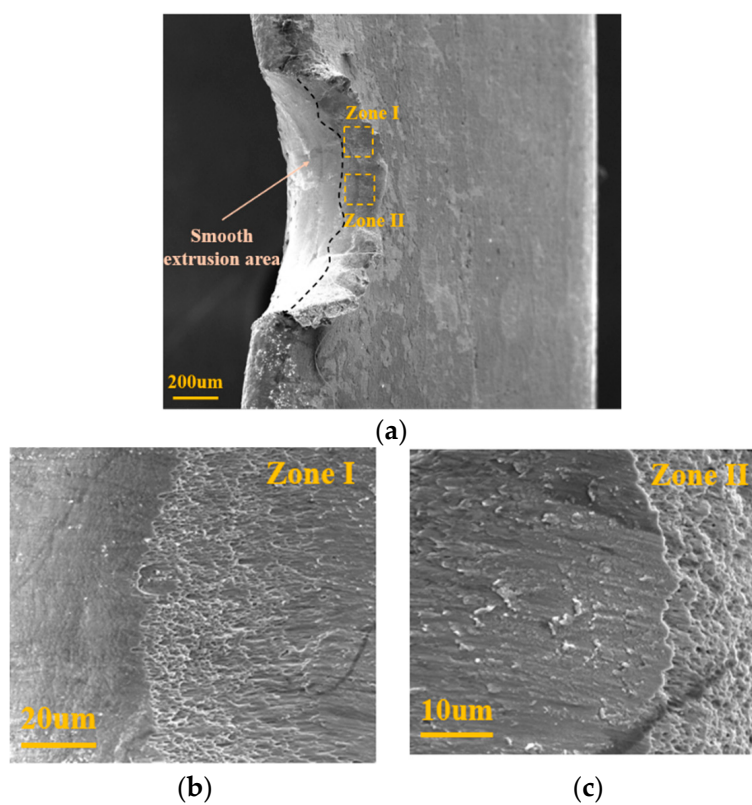


Figure 17. Simulated blade impact damage characteristics for 48 h of pre-corrosion. (a) Global view; (b) Zone I; (c) Zone II.

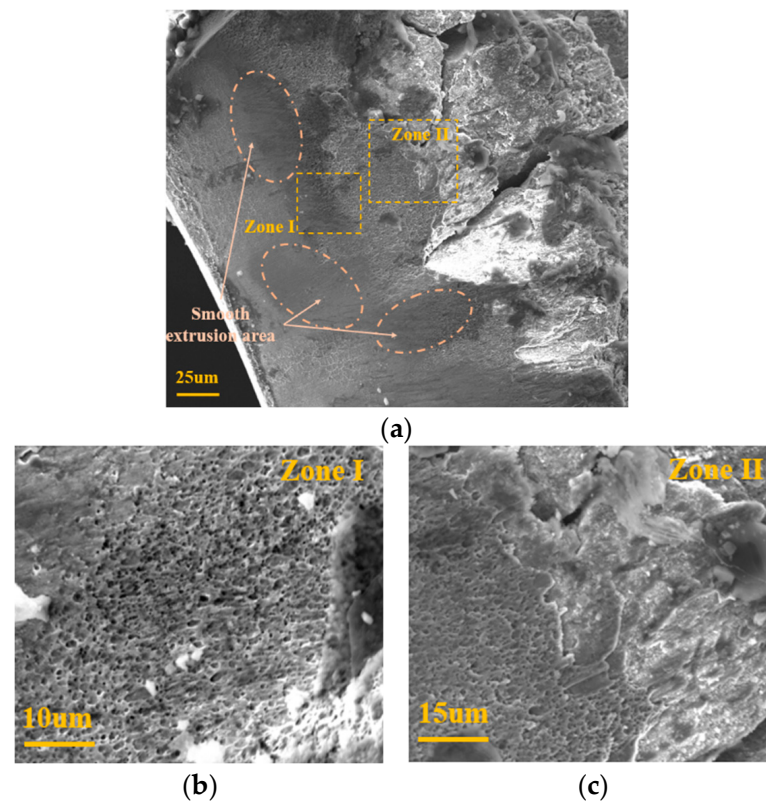


Figure 18. Simulated blade impact damage characteristics for 96 h of pre-corrosion. (a) Global view; (b) Zone I; (c) Zone II.

In summary, the FOD depth of the simulated blade with pre-corrosion increases to a certain extent compared to the FOD depth of the blade without pre-corrosion. Furthermore, the increase in depth is positively correlated with the duration of pre-corrosion. The leading edge of the simulated blade becomes thinner and even some material is lost in the corrosive environment, resulting in a decrease in the impact resistance of the leading edge of the blade. Under the impact of foreign hard objects, the notch in the pre-corroded blade is larger than that in the uncorroded blade. Furthermore, the longer the pre-corrosion time, the more severe the damage to the blade becomes. However, there are no corrosion pits or corrosion products present at the notch root of the simulated blade. There is plastic deformation observed at the notch root of the pre-corroded simulated blade, characterized by microscopic morphological features such as equiaxed dimples and shear dimples. Consequently, the notch formed by the simulated blade after pre-corrosion for 24, 48, and 96 h, when subjected to the impact of foreign objects, continues to exhibit ductile fracture behavior. This observation aligns with the fracture characteristics of the simulated blade under conditions of impact alone. This indicates that pre-corrosion does not alter the damage mechanism of the simulated blade; rather, it merely reduces the impact resistance of the leading edge and exacerbates the damage to the blade's leading edge when subjected to impacts from foreign objects.

3.2. Damage Laws Fatigue Performance of Simulated Blades in Corrosive Environment

3.2.1. The Effect of Pre-Corrosion Time on the Fatigue Performance of Simulated Blades

High-cycle fatigue tests were conducted on the aforementioned prefabricated damaged simulated blades. The frequency of all simulated blades was around 1050 Hz. The results were categorized based on pre-corrosion duration, and the relationship between varying pre-corrosion times and fatigue limits is shown in Figure 19. The fatigue limit of pre-corroded blades was significantly lower than that of non-corroded blades. The fatigue

limit of the simulated blade pre-corroded for 24 h decreased by about 22%; the fatigue limit of the simulated blade pre-corroded for 48 h decreased by about 23%; and the fatigue limit of the simulated blade pre-corroded for 96 h decreased by about 29%. Manifestly, the effects of pre-corrosion at 24 h and 48 h on the fatigue performance of the simulated blade were similar, while the impact of pre-corrosion at 96 h was the most significant. This is because the damage caused by pre-corrosion at 24 and 48 h to the simulated blade was less than that caused by pre-corrosion at 96 h. Therefore, the effects of pre-corrosion at 24 h and 48 h on the fatigue properties of the blades was similar. Beyond this time frame, an increase in pre-corrosion duration leads to a greater decline in the fatigue properties of the simulated blades.

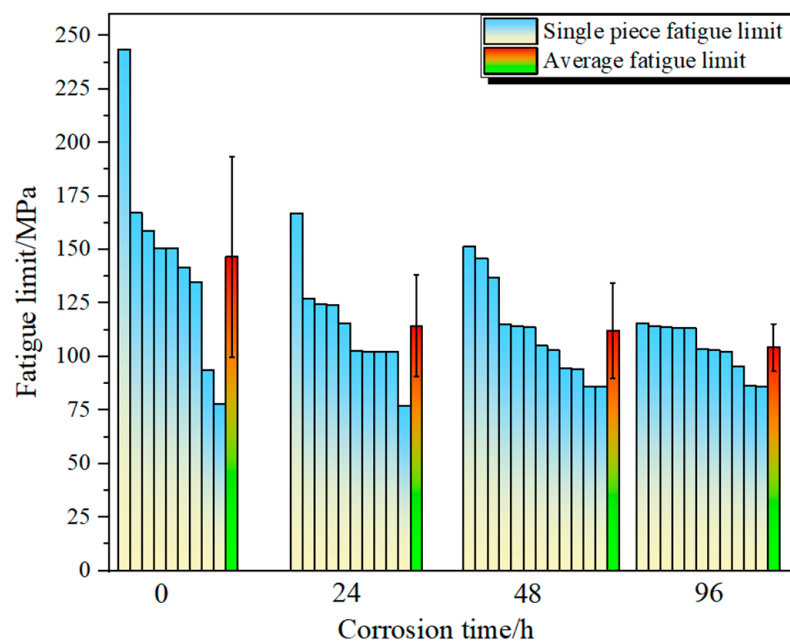


Figure 19. The relationship between fatigue limit and pre-corrosion time of damaged blades.

3.2.2. Study of Fatigue Fracture Observation and Failure Mechanism

The fatigue fractures of simulated blades under various damage conditions were observed. Figure 20 presents a diagram of the fatigue fracture on the simulated blade after fatigue failure. The divergent ridges were only visible at the notch root of the simulated blade, where the impact damage occurred, indicating that this is the area where fatigue originates. The crack originated near the notch root and extended to the opposite side of the blade. The section remained smooth both before and during the crack propagation. At the rear end of the enlarged blade, numerous dimples were visible, and the fracture surface becomes rough, indicating a transient fracture zone.

Figure 21 presents a diagram of the fatigue fracture on the simulated blade after fatigue failure after pre-corrosion. The crack propagation zone appears relatively flat and smooth, and the 'beach strip' feature can be seen. Compared to the fatigue crack source area and the crack propagation area, the backend area of the blade fracture exhibited a significant height difference and featured a shear lip, classifying it as a transient fracture zone. Thus, the fracture of the pre-corrosion simulated blade following external impact can also be categorized into three distinct regions: the fatigue source region, the crack propagation region, and the transient fracture region. It can be concluded that pre-corrosion does not change the damage mechanism of the simulated blade but increases the size of the damage at the leading edge under the same impact conditions. This results in

greater stress concentration at the notch root of the simulated blade, ultimately reducing its fatigue strength.

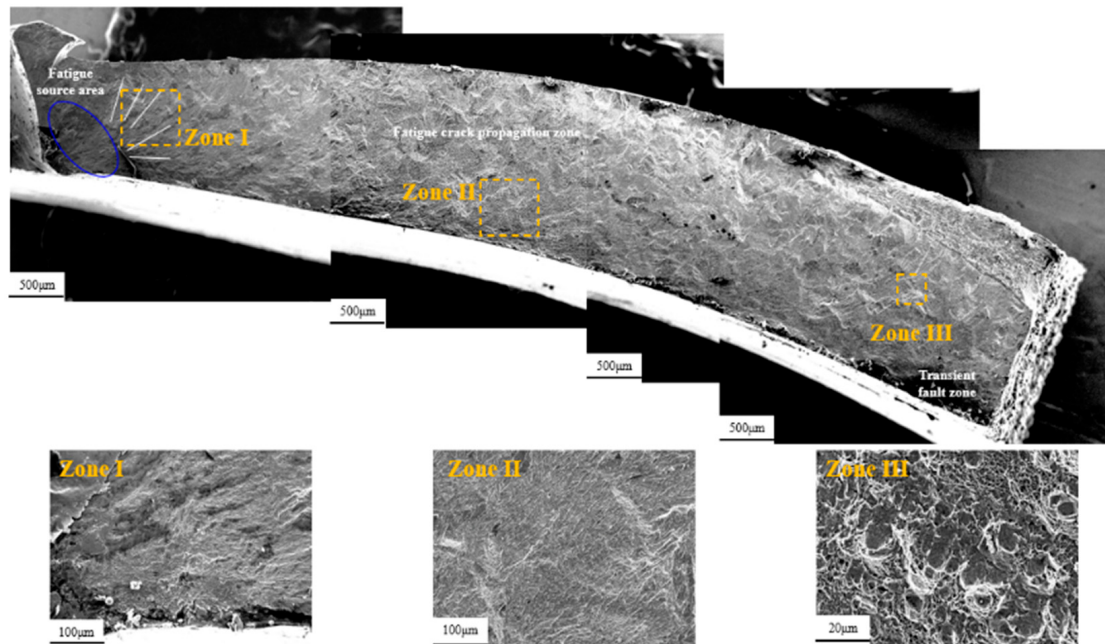


Figure 20. Foreign object impact only simulated blade fatigue fracture diagram.

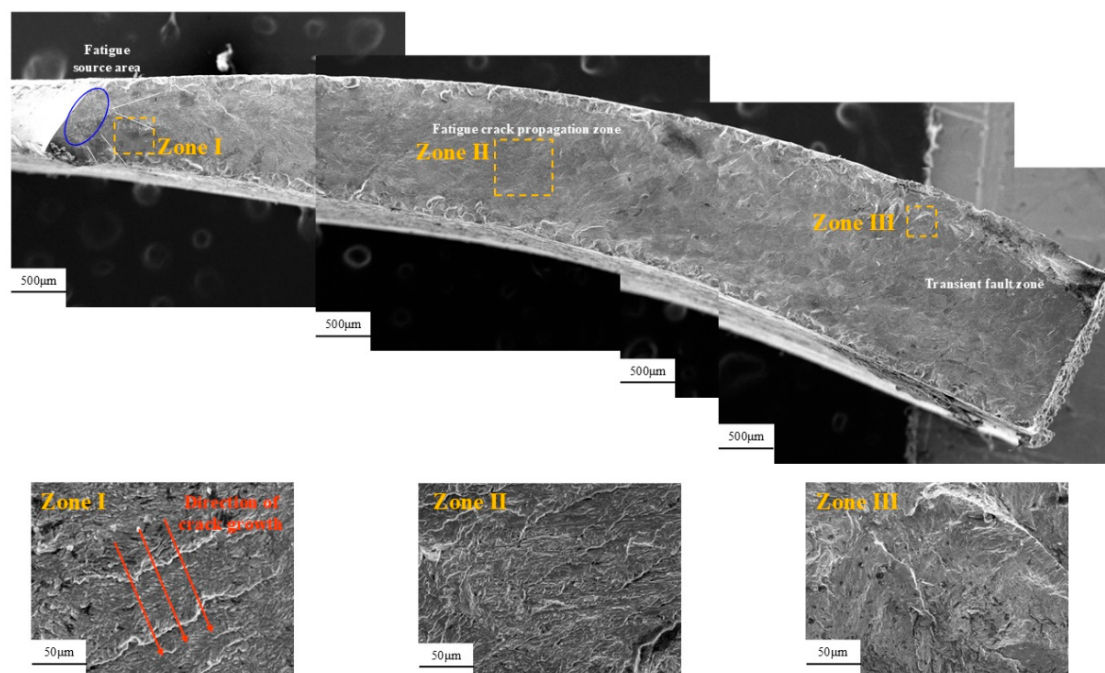


Figure 21. Fatigue fracture diagram of foreign object impact simulated blade after pre-corrosion.

4. Conclusions

In this paper, the effect of foreign object impact on the fatigue performance of 13Cr stainless steel compressor blades after pre-corrosion is studied. The main conclusions are as follows:

- (1) The simulated blade exhibits ductile fracture when subjected to the impact of foreign objects. The shape of the notch is a typical U-shaped notch. The width of the damage

primarily depends on the size of the foreign object, while the depth of the damage is influenced by both the size of the foreign object and the impact velocity.

- (2) After the impact of the pre-corroded damaged blade, the damage degree after 24 h and 48 h was only slightly increased compared to that of the non-corroded blade. However, the damage size increased markedly after 96 h of pre-corrosion. This indicates that the impact resistance of the simulated blade deteriorates significantly as the duration of pre-corrosion increases.
- (3) Pre-corrosion does not alter the damage mechanism of the simulated blade, but increases the damage size of the leading edge of the simulated blade under the same impact conditions, which leads to greater stress concentration at the notch root of the simulated blade and reduces the fatigue strength of the simulated blade.
- (4) Pre-corrosion leads to increased damage when the simulated blade is impacted, which in turn affects the fatigue performance of the blade. The fatigue limit of the simulated blade that was pre-corroded for 24 h decreased by approximately 22%; the fatigue limit of the simulated blade that was pre-corroded for 48 h decreased by about 23%; the fatigue limit of the simulated blade that was pre-corroded for 96 h decreased by roughly 29%.

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References

1. Guan, Y.; Chen, W.; Gao, D. Present Status of Investigation of Foreign Object Damage to Blade in Aeroengine. *Acta Aeronaut. Astronaut. Sin.* **2007**, *28*, 851–857.
2. Huo, W.; Sun, H. Corrosion and Precaution for Blades of Aero-engine Compressor in the Navy Air Arm. *Aviat. Maint. Eng.* **2002**, *6*, 39–41.
3. Mall, S.; Hamrick, J.L. High cycle fatigue behavior of Ti–6Al–4V with simulated foreign object damage. *Mech. Mater.* **2001**, *33*, 679–692. [[CrossRef](#)]
4. Farahani, H.K.; Ketabchi, M.; Zangeneh, S.; Hosseini, M. Characterization of damage induced by impacting objects in udimet-500 alloy. *J. Fail. Anal. Prev.* **2016**, *16*, 629–634. [[CrossRef](#)]
5. Arcieri, E.V.; Baragetti, S.; Božić, Ž. Stress assessment and fracture surface analysis in a foreign object damaged 7075-T6 specimen under rotating bending. *Eng. Fail. Anal.* **2022**, *138*, 106380.
6. Majidi, B. Fatigue Life and Short Crack Behavior in Ti-6Al-4V Alloy; Interactions of Foreign Object Damage, Stress, and Temperature. *Metall. Mater. Trans. A* **2008**, *39*, 772–777.
7. Witek, L.; Bednarz, A.; Stachowicz, F. Experimental Fatigue Analysis of Compressor Blades with Preliminary Defects. *Solid State Phenom.* **2016**, *250*, 263–269.
8. Zhang, H.; Hu, D.; Ye, X.; Chen, X.; He, Y. Numerical and theoretical prediction of foreign object damage on AM355 simulated blade validated by ballistic impact tests. *Thin-Walled Struct.* **2023**, *193*, 111230. [[CrossRef](#)]
9. Zhao, Z.; Chen, W.; Guan, Y.; Ge, N.; Li, Y. Effect of foreign damage on fatigue strength of stainless steel. *J. Aerosp. Power* **2016**, *31*, 1736–1743.

10. Zhao, Z.; Wang, L.; Kainan, L.U.; Li, Y.; Chen, W.; Liu, L. Effect of foreign object damage on high-cycle fatigue strength of titanium Alloy for aero-engine blade. *Eng. Fail. Anal.* **2020**, *118*, 104842.
11. Zhu, L.; Hu, X.; Jiang, R.; Song, Y.; Qu, S. Experimental investigation of small fatigue crack growth due to foreign object damage in titanium alloy TC4. *Mater. Sci. Eng.* **2019**, *739*, 214–224. [[CrossRef](#)]
12. Yang, S.; Zhao, N.; Liang, M.A.; Zhang, G.; Zhang, X.; Du, T. Study on the effect of foreign object damage position on the vibration fatigue of aeroengine blade. *J. Ordnance Equip. Eng.* **2023**, *44*, 97–102+132.
13. Li, X.; Wang, Y.; Zhang, J.; Wang, T.; Duan, Y. Study on Corrosion Resistance of S30403 Stainless Steel in Circulating Water. *Petrochem. Equip. Technol.* **2021**, *42*, 52–56+56+7–8.
14. Meng, L.; Liu, Z.; Xiahou, J.; Gu, J.; Liu, G.; Shi, C. High Temperature Corrosion Behavior of 316H Stainless Steel Base Metal and Weld in Simulated Coastal Atmosphere. *Corros. Prot.* **2024**, *45*, 62–67.
15. McMurtrey, M.D.; Cui, B.; Robertson, I.; Farkas, D.; Was, G.S. Mechanism of dislocation channel-induced irradiation assisted stress corrosion crack initiation in austenitic stainless steel. *Curr. Opin. Solid State Mater. Sci.* **2015**, *19*, 305–314. [[CrossRef](#)]
16. Donahue, J.R.; Burns, J.T. Effect of chloride concentration on the corrosion–fatigue crack behavior of an age-hardenable martensitic stainless steel. *Int. J. Fatigue* **2016**, *91*, 79–99. [[CrossRef](#)]
17. Zhang, D.; Li, Z. Crack propagation Behavior of p100 steel and 13cr stainless steel Under corrosion Fatigue Loading. *Total Corros. Control.* **2019**, *33*, 100–106.
18. Yang, B.; Chen, J.; Geng, Y.; Cui, X.; Gui, W. Corrosion Fatigue Crack Propagation Behavior of 2205 Duplex Stainless Steel in Aqueous Medium. *Corros. Sci. Prot. Technol.* **2018**, *30*, 182–186.
19. Naville, W.; Rodrigo, M.; Isolda, C. Uniaxial plastic strain effect on the corrosion–fatigue resistance of ISO 5832–1 stainless steel biomaterial. *Int. J. Fatigue* **2023**, *173*, 107701. [[CrossRef](#)]
20. Zhao, Y.G.; Lu, Y.H.; Zhang, X.F.; Li, Z.H.; Liu, T.G.; Shoji, T. Effects of dissolved hydrogen on corrosion fatigue crack growth behavior of 316LN stainless steel in high temperature pressurized water environment. *Corros. Sci.* **2024**, *232*, 112041. [[CrossRef](#)]
21. Tan, J.; Zhang, Z.; Zheng, H.; Wang, X.; Gao, J.; Wu, X.; Han, E.-H.; Yang, S.; Huang, P. Corrosion fatigue model of austenitic stainless steels used in pressurized water reactor nuclear power plants. *J. Nucl. Mater.* **2020**, *541*, 152407. [[CrossRef](#)]
22. Zhang, Z.; Zhang, Z.; Tan, J.; Wu, X.; Han, E.H.; Ke, W. Corrosion fatigue crack growth behavior of 316LN stainless steel in high-temperature pressurized water. *Nucl. Eng. Technol.* **2021**, *53*, 2977–2981. [[CrossRef](#)]
23. Amirifard, M.; Hanzaki, A.Z.; Abedi, H.R.; Eftekhari, N.; Wang, Q. Toward superior fatigue and corrosion fatigue crack initiation resistance of Sanicro 28 pipe super austenitic stainless steel. *J. Mater. Res. Technol.* **2022**, *17*, 1672–1685. [[CrossRef](#)]
24. Zhao, C.; Yang, Y.; Kang, S.; Wu, Y. Study on Corrosion Resistance of 316L Stainless Steel in Electrolyte. *Mater. Prot.* **2022**, *55*, 47–52. [[CrossRef](#)]
25. Wang, H.; Bi, Z.; Zhao, Y.; Liu, Y. Analysis of Corrosion Resistance of 2205 Duplex Stainless Steel Coiled Tubing. *Welded Pipe Tube* **2021**, *44*, 1–6. [[CrossRef](#)]
26. Zhao, Y.; He, Z.; Shi, W.; Wu, Q.; Chen, Y.; Luo, Y.; Huang, Y.; Liu, C.; Li, Y. Corrosion Resistance of 317L Stainless Steel in Simulated Marine Environment. *Mater. Prot.* **2021**, *54*, 51–56+149. [[CrossRef](#)]
27. Qin, Y.; Zuo, Y.; Shen, M. Corrosion Inhibition of 316L Stainless Steel in FLiNaKCrF3/CrF2 Redox Buffering Molten Salt System. *J. Chin. Soc. Corros. Prot.* **2020**, *40*, 182–190.
28. Chen, W.; Wang, D.; Niu, D.; Gai, D.; Wang, S.; Shao, S.; Geng, Y. Effect of Aging Practice on Resistance of 304 Austenitic Stainless Steel. *Heat Treat.* **2024**, *39*, 32–34.
29. Miao, H.; Yin, C.; Wang, H.; Gao, Y.; Chen, J.; Zhang, H.; Li, B.; Wu, J.; Xiao, K. Evaluation and Correlation of Environmental Spectra of Stainless Steel Accelerated Corrosion Test in Polluted Marine Atmosphere. *J. Chin. Soc. Corros. Prot.* **2025**, *45*, 449–459.
30. Weng, S.; Meng, C.; Luo, L.; Yuan, Y.; Zhao, L.; Feng, J. Evolution of Corrosion Damage Characteristics of AA7075-T651 Aluminum Alloy Under Mechanical-chemical Interaction Based on Cellular Automata Method. *J. Chin. Soc. Corros. Prot.* **2024**, *44*, 1507–1517.
31. Li, W. FEM Modeling and Simulation of Electrochemical Corrosion System of Typical Steel Materials. Ph.D. Thesis, University of Science and Technology Beijing, Beijing, China, 2023.
32. Zhang, J. Corrosion Simulation of Seawater Pipeline System Under Multi-Physical Field Coupling Condition. Master's Thesis, Liaoning University, Shenyang, China, 2023.
33. Yang, X.; Dai, T.; Zhao, J.; Wang, X.; He, X. Simulation Study on Atmospheric Corrosion and Protection of Aluminum Alloy Shell of Electric Vehicle Motor. *J. Beijing Inst. Petrochem. Technol.* **2022**, *30*, 25–30+41. [[CrossRef](#)]
34. Liu, Q.; Yu, D.; Wang, L.; Xu, Z.; Cheng, X. Acceleration Test and Corrosion Simulation of Aviation Electrical Connectors in Marine Environment. *Equip. Environ. Eng.* **2021**, *18*, 18–27.
35. Cao, W.; Ji, K.; Hu, Z.; Lin, L.; Sun, B. Corrosion Behaviour Simulation of 2A12 Aluminum Alloy in Marine Environment. *Spec. Cast. Nonferrous Alloys* **2020**, *40*, 1218–1223. [[CrossRef](#)]
36. Wang, H.; Dong, H.; Cai, Z.; Liu, Y.; Wang, W. Corrosion fatigue crack growth in stainless steels: A peridynamic study. *Int. J. Mech. Sci.* **2023**, *254*, 108445. [[CrossRef](#)]

37. Chen, Y.; Zhang, Y.; Cui, Z.; Wang, F.; Dong, T.; Meng, X. Effect of impact-corrosion coupling damage on fatigue properties of 2198-T8 aluminum-lithium alloy. *Eng. Fail. Anal.* **2024**, *163*, 108471.
38. Li, Q.; Li, J. Research on the Electrochemical Corrosion Behavior of the 13Cr15Ni4Mo3N Stainless Steel. *Sci. Technol. Inf.* **2023**, *21*, 108–111. [[CrossRef](#)]
39. Maxwell, D.C.; Nicholas, T. A rapid method for generation of a Haigh diagram for high cycle fatigue. In *Fatigue and Fracture Mechanics*; ASTM International: West Conshohocken, PA, USA, 1999; Volume 29.
40. Yuan, Z. The Study of Electrochemical Corrosion Behavior and Passive Film Properties of Nickel-based Alloy and Stainless Steel in Acidic Environment. Master's Thesis, Wuhan University of Science and Technology, Wuhan, China, 2022. [[CrossRef](#)]

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