

Article

Study on the Tensile and Fatigue Properties of the FH36 Ship Steel Plates at Room and Low Temperatures

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Abstract: This study investigated the tensile properties and fatigue behavior of FH36 steel plates subjected to alternating rolling processes in different directions, as well as their performance at room temperature and -60°C . The results revealed that by employing sequential rolling in both the rolling and transverse directions, the disparities in the mechanical properties between these two directions were eliminated, resulting in nearly identical tensile performances. The macroscopic features of the high-cycle and low-cycle fatigue fractures at both room temperature and at -60°C were similar, with high-cycle fatigue fractures exhibiting oblique shear features and low-cycle fatigue fractures exhibiting cup-cone shapes. The crack initiation zones were consistently located on the surface of the specimens. As the maximum stress increased, the area of the high-cycle fatigue crack propagation zone decreased, while the area of the final fracture zone, the number of dimples, and the proportion of low-angle grain boundaries all increased. Under -60°C conditions, the critical crack length for high-cycle fatigue, the maximum stress limit for the onset of high-cycle fatigue, and the fatigue limit were all higher than those at room temperature, indicating a superior low-temperature fatigue performance.

Keywords: ship plate steel; tensile properties; fatigue limit; fracture observation



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1. Introduction

In the field of shipbuilding and operation, ship plate steel is a crucial material that is subjected to various mechanical and environmental loads. Therefore, the study of the performance of ship plate steel was of utmost importance, especially in terms of their tensile strength and fatigue properties.

Extensive and systematic research has been conducted on the tensile and fatigue performance of ship plate steel. Various grades of ship plate steel, such as A, D, E, and F grades, have been studied. For example, Wang et al. [1,2] conducted a comprehensive study on the tensile and fatigue properties of EH36 ship plate steel in the temperature range from -60°C to 20°C . They found that as the temperature decreased, the yield strength and ultimate tensile strength, resistance to low-temperature crack initiation, and crack propagation of the steel plate all increased to varying degrees, but the plasticity decreased and the brittleness increased. As the stress ratio increased from 0.03 to 0.3, the fatigue crack propagation rate increased, while the fatigue crack propagation threshold value decreased. Regarding research on different types of ship plate steel, differences in their performance have been observed. Taking EH36 and FH36 ship plate steel as examples, Wang et al. [3] assessed the fatigue crack propagation rates of EH36, DH36, and FH36 ship plate steels at

room temperature, and found that EH36 steel had a higher fatigue crack propagation rate than the other steel types due to its higher carbon content and smaller grain size.

Xu et al. [4] studied the fatigue crack growth process of AH36 steel and found that with the increase in the stress amplitude and mean stress, the fatigue life of the steel significantly decreased. As the stress ratio increased, the crack tip opening displacement (CTOD) value gradually increased, while the fatigue life decreased. Wang et al. [5] simulated the relationship curve between the stress intensity factor amplitude and the fatigue crack length of FH36 steel using ANSYS 23.1 software, which was consistent with the experimental results. They confirmed that the fracture mechanism of FH36 steel was microporous aggregation fracture and that it had large and deep dimples.

Regarding fatigue crack growth, several researchers have employed modified theoretical models for prediction. For instance, Le et al. [6] studied the fatigue crack propagation of AH36 steel using the modified Irwin equation to calculate the plastic zone size at the crack tip in the residual stress range and the modified Wheeler model to predict the fatigue crack propagation process under various stress levels. Their results showed that the theory underlying the plastic zone size could describe the fatigue crack propagation behavior of the steel well, and their predicted results were in good agreement with the experimental data. Jiang et al. [7] studied the low-cycle fatigue behavior of shipbuilding steel 945. Through the cyclic stress–strain curve and the strain–life relationship, it was verified that the steel belongs to cyclic softening materials and had typical Masing behavior.

In addition to the aforementioned studies, new findings have emerged regarding fatigue failure. For example, it was generally believed that the high-cycle fatigue failure of the 65Mn steel components was caused by internal factors, while Li et al. [8] found that surface cracks can also lead to a high-cycle fatigue failure. Wang et al. [9] investigated the effects of two different specimen thicknesses on the fatigue crack propagation rate of shipbuilding steel through finite element simulation and experiments. They found that under the same maximum stress, the plastic zone at the crack tip of the thin specimen was significantly larger than that of the thick specimen, and the stress intensity factor at the crack tip was significantly greater than the theoretically calculated value.

In conclusion, several studies have been conducted both domestically and internationally on the fatigue crack propagation rate, fatigue life, and other aspects of the ship plate steels, such as FH36. However, there is a lack of research reports available on the ambient and low-temperature cyclic fatigue behavior and the mechanisms underlying the ship plate steels, as well as the fatigue phenomena that arise when these steels were subjected to extreme conditions of high alternating stress. Therefore, in this study, FH36 steel was subjected to tensile performance tests, and based on these tests, ambient and low-temperature fatigue behaviors of FH36 steel were investigated when it was subjected to maximum cyclic stresses exceeding the tensile strength. The aim was to understand the fatigue behavior and fatigue limits of this steel under extreme loading conditions. Furthermore, through fatigue fracture morphology and texture analysis and comparison, further investigations were conducted on the ambient and low-temperature fatigue behavior and their differences. This research was expected to be beneficial for the safety design and assurance of the ship plate steels under extreme loading conditions and for ensuring their service performance.

2. Materials and Methods

FH36 steel ingot was prepared through basic oxygen furnace (BOF) steelmaking with aluminum deoxidation and continuous casting process, with dimensions of $250 \times 1550 \times 1550$ mm. The chemical composition of the steel ingot is shown in Table 1. The Ti and Nb elements in the ingot were able to form finely dispersed (Ti and Nb; C and N) precipitates during the continuous casting process, which was conducive to grain refinement and thus improved the steel's fatigue performance. Subsequently, the ingot was uniformly heated at 1200 °C for 4–5 h, followed by the application of a new commercial thermo-mechanical controlled process (TMCP) technique. During the TMCP, it underwent 4 passes of the first-stage rolling along the transverse direction

(TD) to a thickness of 108 mm, with a reduction rate of 57%. Then, it was rotated by 90° and underwent 3 passes of the second-stage rolling along the rolling direction (RD) in the austenite–ferrite two-phase region, finally reaching a thickness of 54mm with a reduction rate of 50%, followed by water cooling. This rolling process can improve the performance along the TD and reduce the anisotropy in the steel plate [10]. The main parameters of the TMCP can be found in Table 2. The final dimensions of the steel plate were approximately 54 × 3100 × 3100 mm.

Table 1. Chemical composition of the FH36 steel plate (wt.%).

Chemical Composition												
C	Si	Mn	S	P	Nb	V	Ti	Al _s	Cu	Cr	Ni	Fe
0.08	0.17	1.42	0.002	0.012	0.03	0.040	0.013	0.030	0.10	0.16	0.35	Bal.

Table 2. TMCP parameters of the FH36 steel plate (°C).

First-Stage Rolling Temperature	Second-Stage Rolling Temperature	Final Rolling Temperature	Water Inlet Temperature	Self-Tempering Temperature
1050	820	790	760	500

According to the tensile testing standard GB/T 228.1-2010 [11], three specimens were taken along the RD and TD at the 1/4 thickness position of the FH36 steel-rolled plate (see Figure 1a). The dimensions of the tensile specimen are shown in Figure 1b. Tensile tests were conducted on the above specimens using the SUNS universal testing machine with a tensile rate of 1 mm/min to obtain the stress–strain curves at room temperature. The specimen was cut 10 mm away from the fracture surface and polished with SiC papers. The ZEISS Sigma 500 field emission scanning electron microscope (SEM) and Bruker XFlash 6l,100 energy spectrometer were used to observe and analyze the fracture morphology and inclusion composition, respectively.

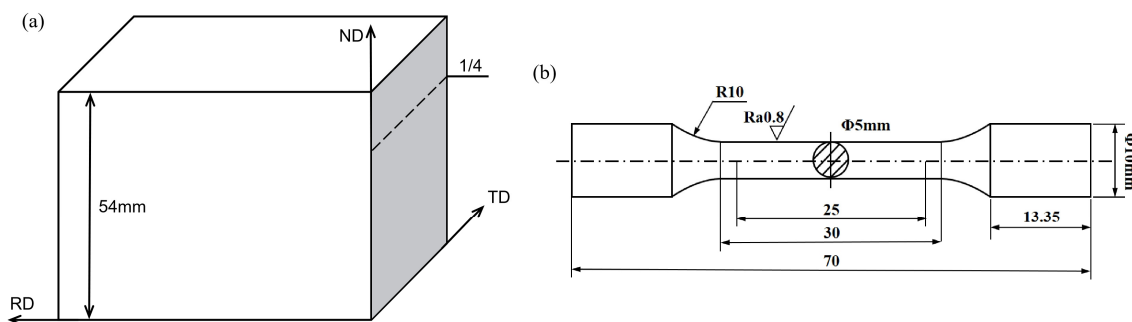


Figure 1. Tensile specimen (a) location and (b) size. ND—normal direction.

According to the fatigue testing standard GB/T 3075-2008 [12], specimens were taken along the RD of the steel plate and subjected to tension–tension fatigue tests at room temperature and −60 °C using a GPS50 high-frequency fatigue testing machine. The specimens dimensions are shown in Figure 2. The stress ratio R was set to 0.1 and the number of cycles N was 10^7 for both room temperature and −60 °C low-temperature tension–tension fatigue tests. The test specimens were considered to have completed the test when the number of cycles reached N or when they failed.

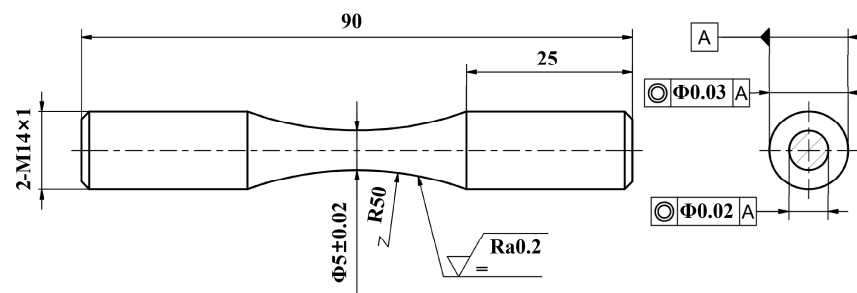


Figure 2. Size of the fatigue specimen.

The fatigue limit test at a room temperature of 25 °C was conducted using the staircase technique, in which the maximum cyclic stress of the first specimen was set to 500 MPa, and the stress increment $\Delta\sigma$ was determined as 4% (20 MPa) of the tensile strength. If the previous specimen did not fail after N cycles or failed before completing N cycles, the stress of the next specimen was increased or decreased by $\Delta\sigma$ accordingly. The frequency of the test was 150 Hz. The fatigue limits were determined using the staircase method at a low temperature of −60 °C. The maximum cyclic stress levels that were applied were 480, 500, 520, 540, 560, and 590 MPa, respectively, with a frequency of 120 Hz.

It was well known that the empirical formulas of the S–N curve included the power function Basquin model, the exponential function model, the three-parameter model, etc. [13,14]. The Basquin model was only suitable for medium to low fatigue life, while the three-parameter model was suitable for fitting the S–N curves in the low fatigue life zone and also had application value in fitting the S–N curves in the medium and high fatigue life zones and the overall fitting effect was good [15,16]. Therefore, we used the three-parameter model to fit the S–N curve during the low-temperature fatigue test. The parameters in this model were commonly determined using the least squares method by researchers. For instance, Little et al. [17] used linear regression to fit the logarithmic mean S–N curve of the life specimens and solve the parameters. Ling et al. [18] estimated the parameters in the model using the maximum likelihood and moment methods. Zheng et al. [19] employed the direct modeling method of GM (1,1) in the gray system theory to determine the three parameters in the model. Xie et al. [20] fitted the experimental data using a double-weighted least squares method. Gao et al. [21] used the linear correlation coefficient as the objective function and determined the parameters through BASIC programming, which resulted in a better fit of the S–N curve experimental data. Therefore, in this study, the method proposed by Gao et al. was adopted, and the relevant parameters were determined using MATLAB programming.

After the fatigue test, the fracture surface was cut 10 mm away from the fracture position of the fatigue specimen, ground flat using SiC papers, and then observed using a SEM. The energy spectrometer was used to determine the composition of the fracture inclusions. In addition, wire cutting was used to cut a 10 mm length along the tensile direction and a 2 mm thickness perpendicular to the tensile direction from the fracture surface of the fracture specimens and the center of the unfractured specimens at room temperature to obtain the longitudinal cross-sections for observation. The sections were mechanically polished using SiC papers, and then vibration polishing was used to remove the stress layer. The morphology of the above sections was observed using a SEM. The grain boundaries and texture for these sections were analyzed using a SEM equipped with an Oxford SYMMETRY EBSD detector and Aztec Crystal 6.0 software.

3. Results and Discussion

3.1. Observation of the Microstructure

Figure 3 displays the optical microscope (OM) images of the ND–TD section of FH36 steel. From this figure, it can be seen that the steel plate's microstructure is primarily composed of polygonal ferrite (PF), acicular ferrite (AF), and granular bainite (GB). Notably,

the presence of AF and GB should contribute to enhancing the steel plate's strength and impact toughness [22]. The grains exhibited elongation along the TD. This phenomenon was due to the adoption of a cross-rolling and longitudinal-rolling alternate rolling process, with the TD being the initial RD of the steel plate. From the 1/2 thickness of the plate to the surface, there was a gradual trend of grain refinement, which was associated with the increasing cooling rate.

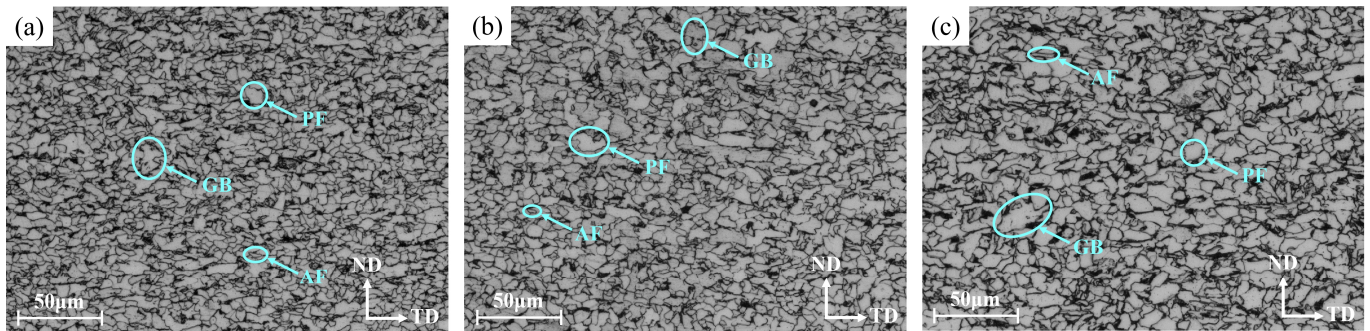


Figure 3. OM images for the ND–TD section at different locations. (a) Surface, (b) 1/4 thickness, and (c) 1/2 thickness.

3.2. Analysis of the Tensile Property Test Results and Morphological Observations

3.2.1. Analysis of the Tensile Property Test Results

Figure 4 shows the stress–strain curves of the FH36 steel plate along the RD and TD at 1/4 thickness. From this figure, it can be seen that the repeatability of the curves was good, and the positions of the curves for the two types of specimens were relatively close. Figure 5 displays the strength and plasticity data of the two types of specimens that were calculated from Figure 4. It can be seen from this figure that the mechanical performance data of the FH36 steel plate at 1/4 thickness in the RD and TD both met the performance requirements of the standard GB/T 712-2011 [23], and that the data of the RD and TD were quite close. The yield strength in the RD was slightly lower than that in the TD, but the toughness was slightly higher than that in the TD, and the difference between the two was very small. This was related to the steel plate being rolled first in the TD and then in the RD, so that the rolled plate underwent deformation in both the TD and RD, thereby essentially eliminating the performance differences between the TD and RD [24].

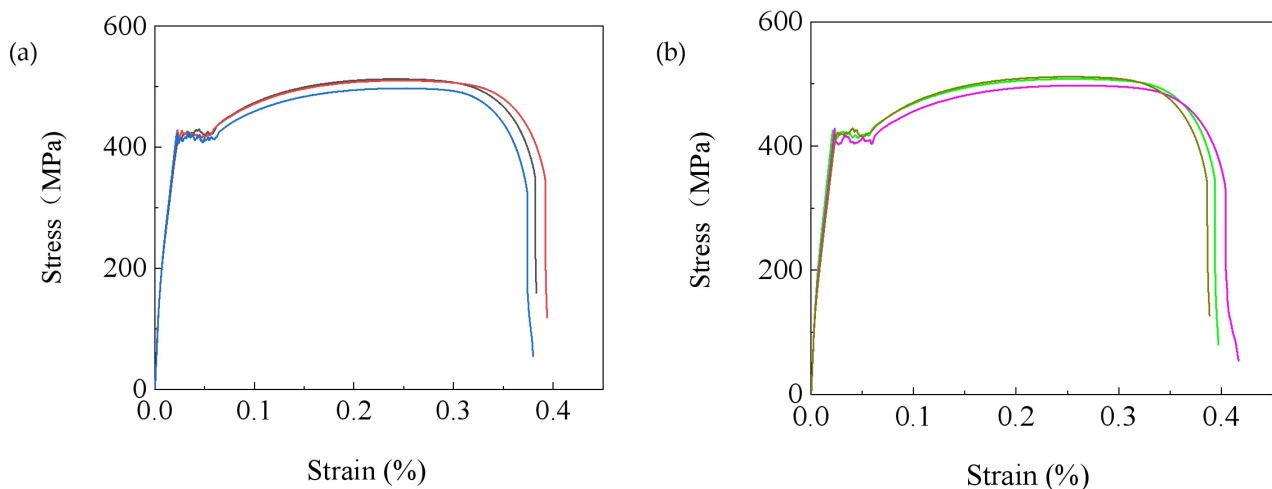


Figure 4. Tensile stress–strain curves of the steel plate. (a) RD. (b) TD.

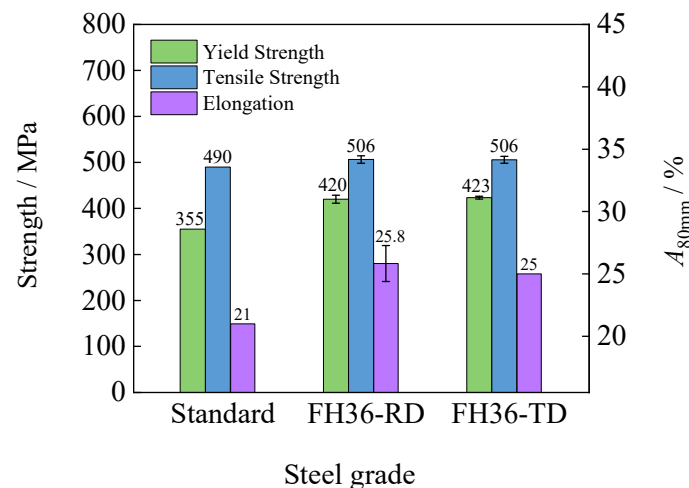


Figure 5. Tensile test results of the steel plate.

3.2.2. Tensile Test Fracture Surface Observation

Figure 6 shows the tensile fracture macroscopic morphology (a,d), fiber zone morphology (b,e), and shear lip morphology (c,f) of the FH36 steel plate at 1/4 thickness. From Figure 6a,b, it can be seen that the tensile fracture surface was cup- and cone-shaped, with the center of the fracture being a rougher fiber zone and the edges being a smoother shear lip zone. No obvious radical zone was observed, indicating that the deformation constraint was small and that the plasticity was good [25,26]. The shear lips were oriented at a 45° angle to the main stress. The proportion of the fiber zone of the specimen in the RD was larger than that in the TD, indicating better plasticity in the RD, which was consistent with the plasticity results in Figure 4. The shear lips in the TD were less symmetric, smooth, and complete compared to the RD [24].

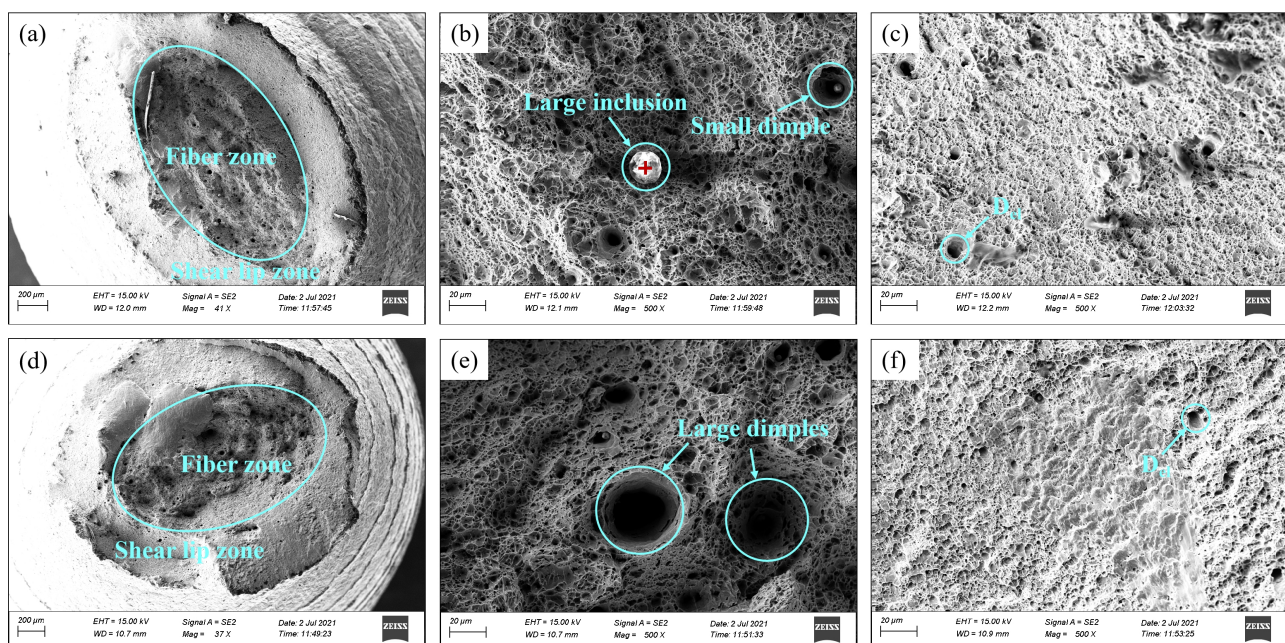


Figure 6. Tensile fracture morphology. (a–c) RD. (d–f) TD.

From Figure 6b,e, it can be seen that there were both equiaxed dimples (D_{eq}) and spherical inclusions in the fibrous area of the fracture surfaces in the RD and TD. Typically, the large dimples nucleated at the location of inclusions, while the small dimples nucleated at the location of carbides. Compared to Figure 5b, there were more large dimples in

Figure 5e, indicating a higher content of inclusions and lower plasticity and toughness of the specimen [27]. Additionally, a large-sized spherical inclusion with a diameter of up to 20 μm was observed in Figure 5b.

Table 3 presents the energy spectrum analysis results for the inclusion at the location indicated by the red cross. Based on the elemental composition ratio and simulated calculation using the JMatPro 7.0 software, it can be inferred that the inclusion was a composite inclusion primarily consisting of $\text{Al}_2\text{O}_3\text{-CaO}$, with small amounts of SiO_2 , CaS , MnS , TiC , and NbC [28–30]. Generally speaking, oxide inclusions that existed in the molten steel can act as nucleation sites for the precipitation of sulfides and other compounds. Therefore, it was common to find oxide inclusions enveloped by a layer of sulfide inclusions and other constituents in steel, forming composite inclusions [31].

Table 3. Composition of the large inclusion in Figure 5b (wt.%).

Chemical Composition											
C	O	Al	Si	S	Ca	Ti	Mn	Fe	Nb	Ni	Cu
5.30	28.35	23.04	0.83	2.40	21.77	1.96	0.33	15.53	0.45	0.02	0.03

3.3. Fatigue Test Results and Analysis at Room Temperature

3.3.1. Fatigue Test Results at Room Temperature

The results of the room temperature fatigue tests for the steel plate are shown in Table 4.

Table 4. Fatigue test results at room temperature.

Specimen No.	Maximum Stress/MPa	Cycles/N	Result
RT1	500	10,000,000	Pass
RT2	520	23,695	Failure
RT3	500	10,000,000	Pass
RT4	520	23,659	Failure
RT5	500	292,586	Failure
RT6	480	4,787,073	Failure
RT7	460	10,000,000	Pass
RT8	480	3,388,534	Failure
RT9	460	10,000,000	Pass
RT10	480	10,000,000	Pass
RT11	500	167,802	Failure
RT12	480	537,316	Failure
RT13	460	10,000,000	Pass

The fatigue limit was calculated using the following formula based on the above data:

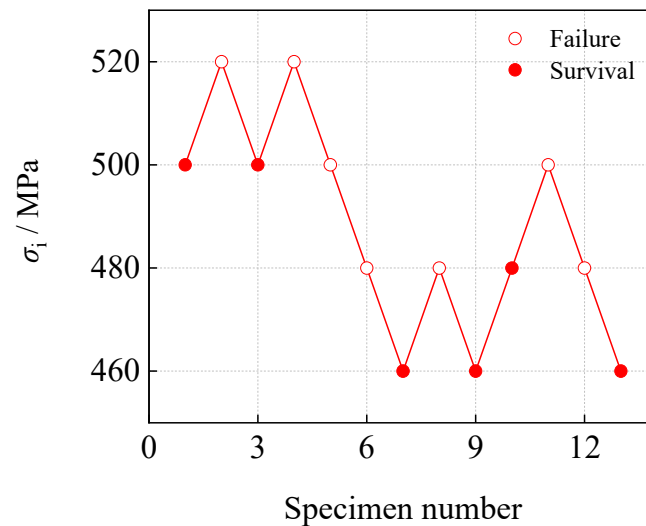
$$\sigma_R(10^7) = \frac{1}{m} \sum_{i=1}^n V_i \sigma_i \quad (1)$$

where m is the total number of valid test cycles, R is the stress ratio, σ_i is the maximum stress for the i -th level, and V_i is the number of valid cycles at the maximum stress for the i -th level.

The fatigue limit, $\sigma_{-1}(10^7)$, calculated from the formula was 488 MPa. The specimen did not fail under the maximum stress of 460 MPa, while it failed under the maximum stress of 480 MPa and 500 MPa, but with a cycle number greater than 10^5 for both. However, when the maximum stress was 520 MPa, the specimen failed with a cycle number of less than 10^5 . Therefore, it can be inferred that high-cycle fatigue occurred at the maximum stress of 500 MPa and below, while low-cycle fatigue occurred at 520 MPa and above, as shown in Table 5. Figure 7 displays the up-and-down diagram that was constructed based on the test results.

Table 5. Fatigue failure types under different maximum stress levels at room temperature.

Temperature	Maximum Stress/MPa			
	460	480	500	520
20 °C	High-cycle fatigue	High-cycle fatigue	High-cycle fatigue	Low-cycle fatigue

**Figure 7.** Fatigue test up-and-down diagram.

3.3.2. Fatigue Test Fracture Morphology Observation and Analysis

Figure 8 displays the macroscopic morphology of the fatigue fracture surface of the failed specimens under different maximum stress levels, as listed in Table 4. From Figure 8a,b, it can be observed that there was no significant plastic deformation near the fracture under the maximum stress levels of 480 MPa and 500 MPa, and that the fracture formed was a oblique shear fracture. This fracture showed a static fracture zone caused by crack propagation, indicating good plasticity [32]. From Figure 8c, it can be seen that due to the maximum stress of 520 MPa being greater than the material's tensile strength, there was a significant level of macroscopic plastic deformation near the fracture surface. As a result, the effective cross-sectional area decreased, and an overload fracture occurred, resulting in a cup-and-cone-shaped fracture with good ductility, similar to the fracture surface of a tensile specimen [33].

**Figure 8.** Fatigue specimens at room temperature under different maximum stress levels at (a) 480 MPa, (b) 500 MPa, and (c) 520 MPa.

Fatigue fracture surfaces typically consist of three zones: the flat and shiny crack initiation zone (CIZ), the crack propagation zone (CPZ), with fan-shaped fatigue striations, and the rough fast fracture zone (FFZ), as shown in Figure 9. The size of the CPZ was related to the critical crack length, a_c , for crack propagation, and when the crack length reached a_c , the specimen began to undergo a fast fracture [34].

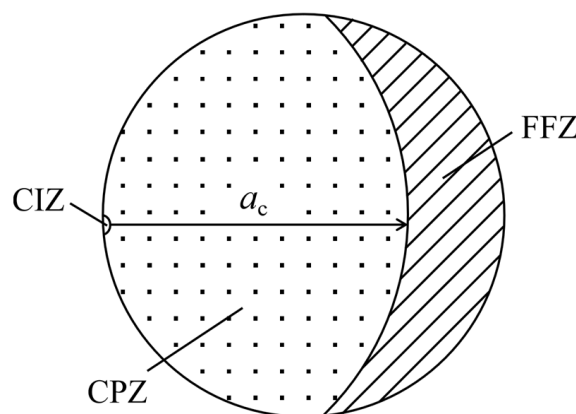


Figure 9. Illustration of the division of the fatigue fracture zones and the critical crack length, a_c .

Figure 10 displays the fatigue fracture surface of specimens RT6, RT8, and RT12 under the maximum stress level of 480 MPa from Table 4. It can be seen from this figure that all the fracture surfaces consisted of the CIZ, CPZ, and FFZ. From Figure 10a,d,g, it can be observed that the CIZ was located at the surface of the specimens. This was due to the fact that under cyclic loading, the highest stress in the specimen was applied on the surface. The defects, such as slip bands, grain boundaries, and inclusions, which existed in the surface, subsequently developed into severe stress concentration positions. Fatigue fracture was very sensitive to the positions; thus, micro-cracks first formed in the surface [35,36]. Meanwhile, the surface where the fatigue crack was initiated was relatively smooth; subsequently, the fracture surface displayed a single fatigue source. According to Figure 9, the estimated a_c values for the CPZ of the RT6, RT8, and RT12 specimens in Figure 10 were 2.0 mm, 2.3 mm, and 2.3 mm, respectively. The average a_c value was approximately 2.2 mm. The characteristic of the fatigue striations in the CPZ was that the width increased as the distance from the CIZ increased [37]. In addition, there were also significant fatigue steps in this zone, which were formed through the intersection of the different fracture surfaces, and the direction of the striations was generally consistent with the normal direction of the fatigue striations [38]. For the FFZ, under tension–tension fatigue test conditions, the dimples were almost circular and equiaxed, and there were spherical and irregular cotton-like inclusions located near the dimples (see Figure 9c,f,i).

Figure 11 shows the fatigue fracture morphology of specimen RT5 under the maximum stress level of 500 MPa, as listed in Table 4. From Figure 11a, it can be seen that the CIZ was located at the surface. As the maximum stress was higher than 480 MPa, the a_c value was about 1.9 mm, significantly lower than the 2.2 mm under the maximum stress of 480 MPa. Therefore, the range of the CPZ was smaller, the range of the FFZ was larger, and the fatigue striations were finer and less obvious [39]. From Figure 11b, it can be seen that the CPZ was mainly characterized by cleavage fracture with a river-like pattern. From Figure 11c, it can be observed that there were more dimples in the FFZ compared to that under the maximum stress of 480 MPa, and that the diameter of the larger dimples was also larger.

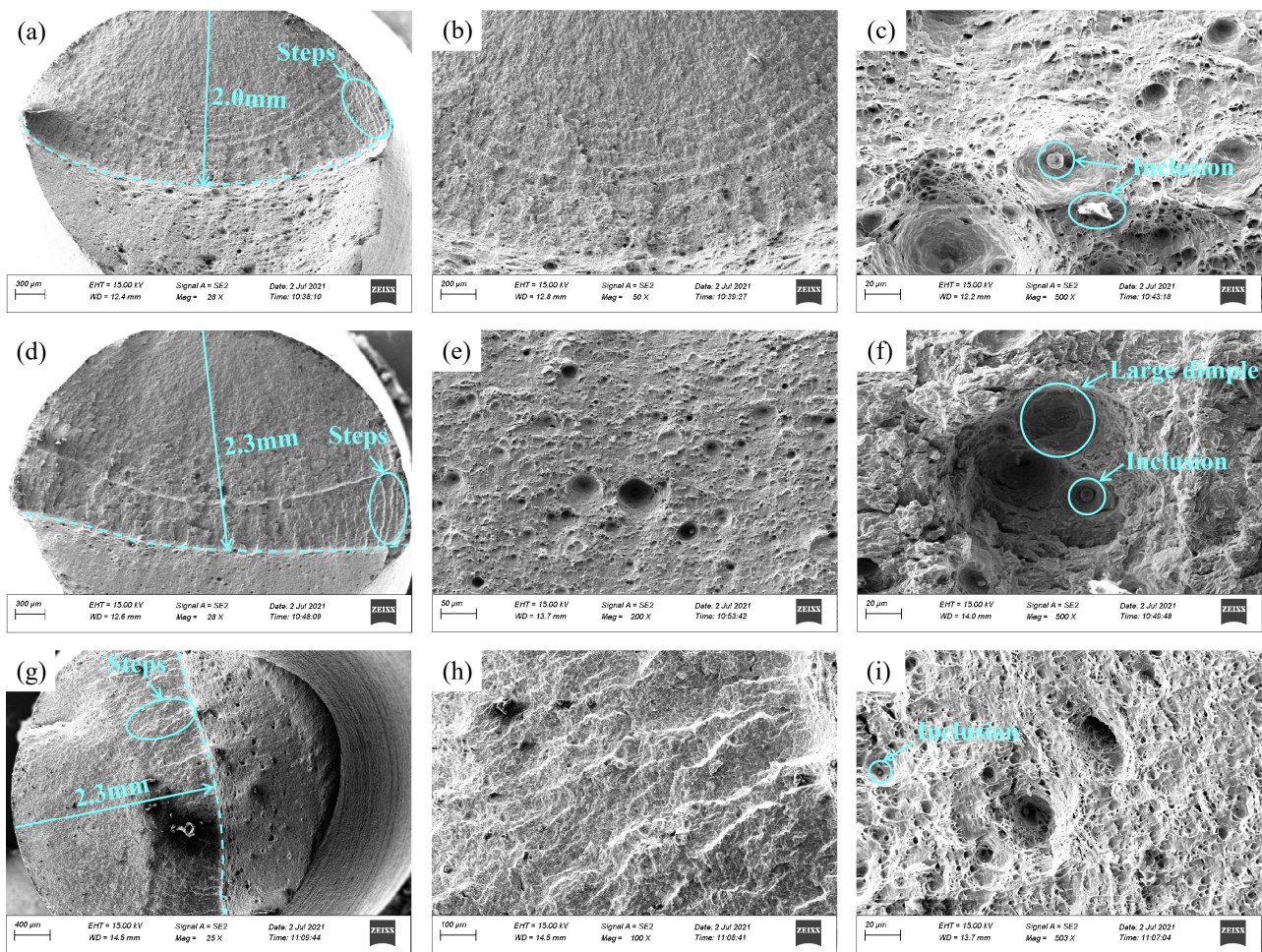


Figure 10. Fatigue fracture morphology of the specimens under the maximum stress level of 480 MPa. (a,d,g) Macroscopic morphology. (b,e,h) The CPZ. (c,f,i) The FFZ.

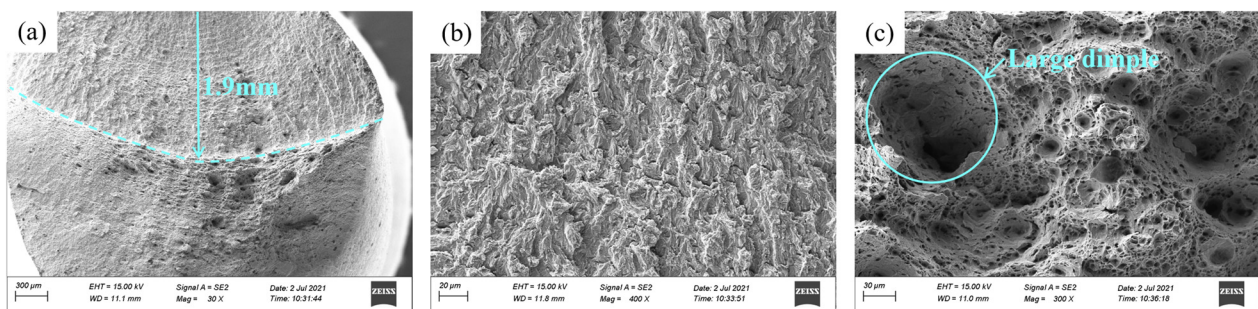


Figure 11. Fatigue fracture morphology of the specimen under the maximum stress of 500 MPa. (a) Macroscopic morphology. (b) The CPZ. (c) The FFZ.

Figure 12 shows the fatigue fracture morphology of specimens RT2 and RT4 from Table 4 under the maximum stress level of 520 MPa. As shown in Figure 12a,d, it can be seen that the cross-sectional area near the fracture was much smaller due to significant plastic deformation (as shown in Figure 7c) than that under the low maximum stress (as shown in Figure 10a). The microstructure of the fracture surface was similar to that of the tensile fracture, with a fiber zone and a shear lip zone, but no clear CIZ and CPZ. From Figure 12b, it can be seen that the elongated dimple (D_{el}) appeared in the shear lip zone on the edge. From Figure 10e, it can be seen that there were circular fatigue striations in the shear lip zone, with river-like patterns as well as irregular inclusions. From Figure 12c,f, it can be seen that there were many D_{eq} in

the fiber zone, but the size of the large dimples (as seen in Figure 12c) was not as large as that under 500 MPa (see in Figure 10c). There were cotton-like and spherical inclusions of various sizes inside the dimples (as shown in Figure 12c,f).

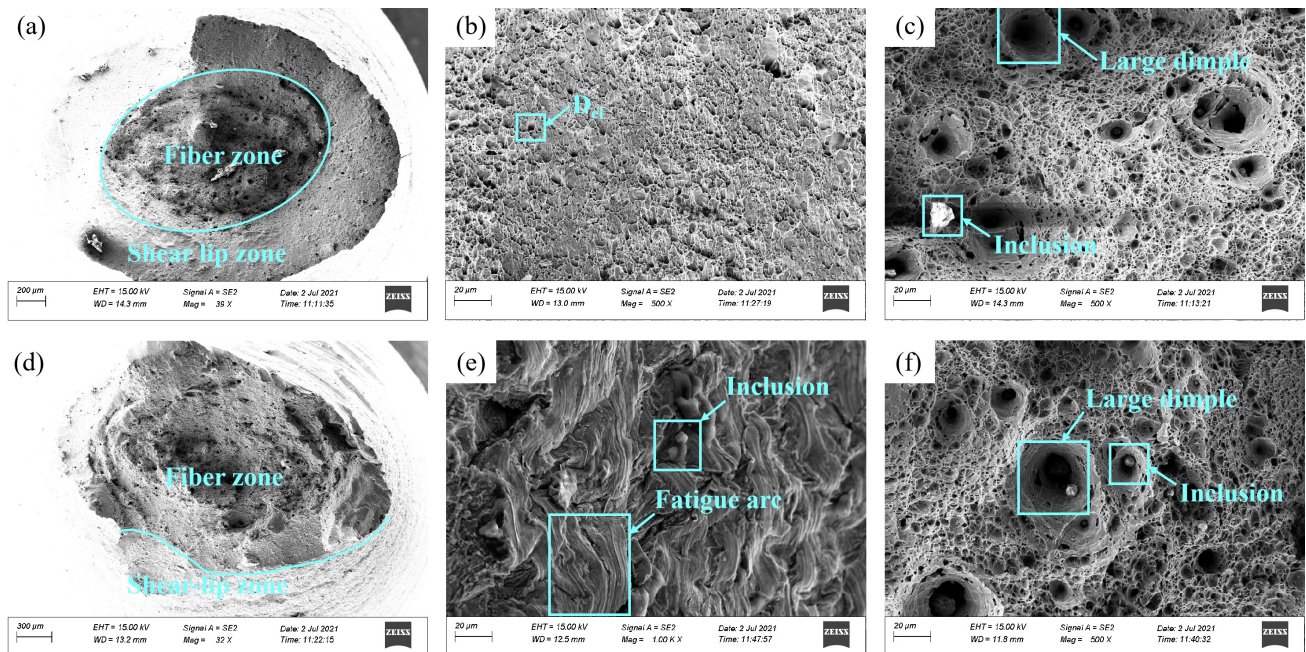


Figure 12. Fatigue fracture morphology of the specimen under the maximum stress of 520 MPa. (a,d) Macroscopic morphology. (b,e) Shear lip zone. (c,f) Fiber zone.

3.3.3. Analysis of Grain Boundaries in Fatigue Fracture at Room Temperature

Figure 13 shows the inverse pole figure (IPF) maps of the fatigue fracture surface at different maximum stress levels of 480 MPa and 520 MPa, as well as the original microstructure. Compared with the original microstructure (see Figure 13a), the grains of the specimen under the maximum stress of 480 MPa (see Figure 13b) were still irregular polygons. In addition, it can be seen that secondary cracks propagated along $\langle 001 \rangle$ orientation. For the specimen under the maximum stress of 520 MPa, the grains were elongated along the loading direction. The grain sizes of the two specimens were 2.41 µm and 1.06 µm, respectively. The proportion of low-angle grain boundaries (LAGBs) for the two specimens was 62.2% and 59.4%, respectively, which was significantly higher than the 13% for the original steel plate. It can be inferred that the fatigue process would lead to an increase in the proportion of LAGBs in the steel plate.

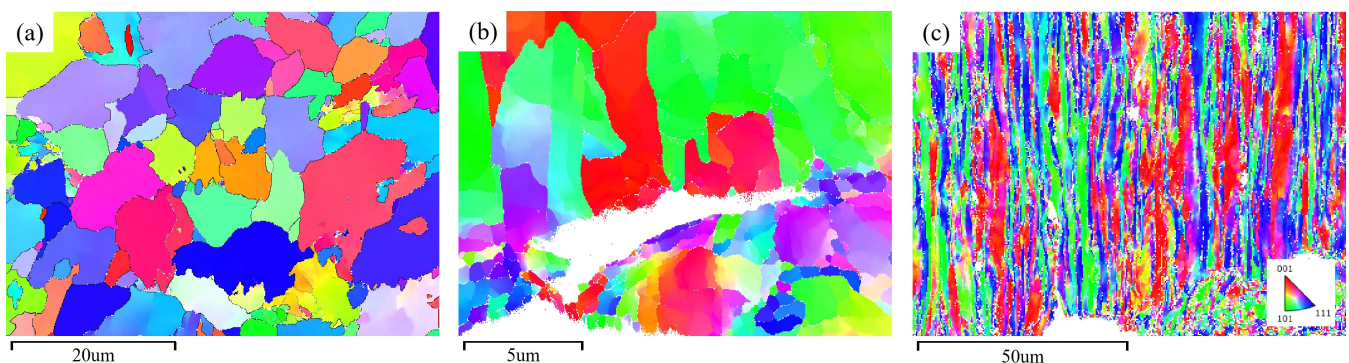


Figure 13. IPF maps of (a) the original, (b) and (c) fatigue fracture cross-sectional specimens under the maximum stress levels of 480 MPa and 520 MPa.

3.3.4. Texture and Orientation Difference Analysis of Fatigue Fracture at Room Temperature

Figure 14 shows the texture components and kernel average misorientation (KAM) maps of the fatigue fracture surfaces of the specimens under the maximum stress levels of 480 and 520 MPa. According to Figure 15a,b, the texture components included S, brass, Dillamore, $\langle 111 \rangle \parallel X$, $\langle 110 \rangle \parallel X$, and $\langle 001 \rangle \parallel X$, where X represents the rolling direction. Under the maximum stress of 480 MPa, the texture components were relatively evenly distributed, while under the maximum stress of 520 MPa, the texture was mainly $\langle 110 \rangle \parallel RD$, with a volume fraction of 80.6%. Other texture components were mainly distributed around the defects. The crack in the specimen under maximum stress of 480 MPa propagated along the $\langle 001 \rangle \parallel X$ texture and was inhibited by the $\langle 110 \rangle \parallel X$ texture. From Figure 14c, it can be seen that under the maximum stress of 480 MPa, the fracture surface was mainly distributed along the LAGB, and the orientation difference value around the crack was relatively high. As shown in Figure 14d, under the maximum stress of 520 MPa, the cracks that formed in the specimen were of a smaller size and had not yet propagated. The crack formed near the spherical inclusion of about 2 μm in the middle and propagated around the inclusion, and the voids formed above the inclusion were also relatively large. However, the crack was suppressed by the $\langle 110 \rangle \parallel X$ texture, and the crack below the inclusion was also suppressed, and the matrix was not completely separated. Under the maximum stress of 520 MPa, due to the plastic deformation, the KAM values of the cross-section were relatively high, and the KAM values near the inclusions and crack edges were higher than those observed in other areas.

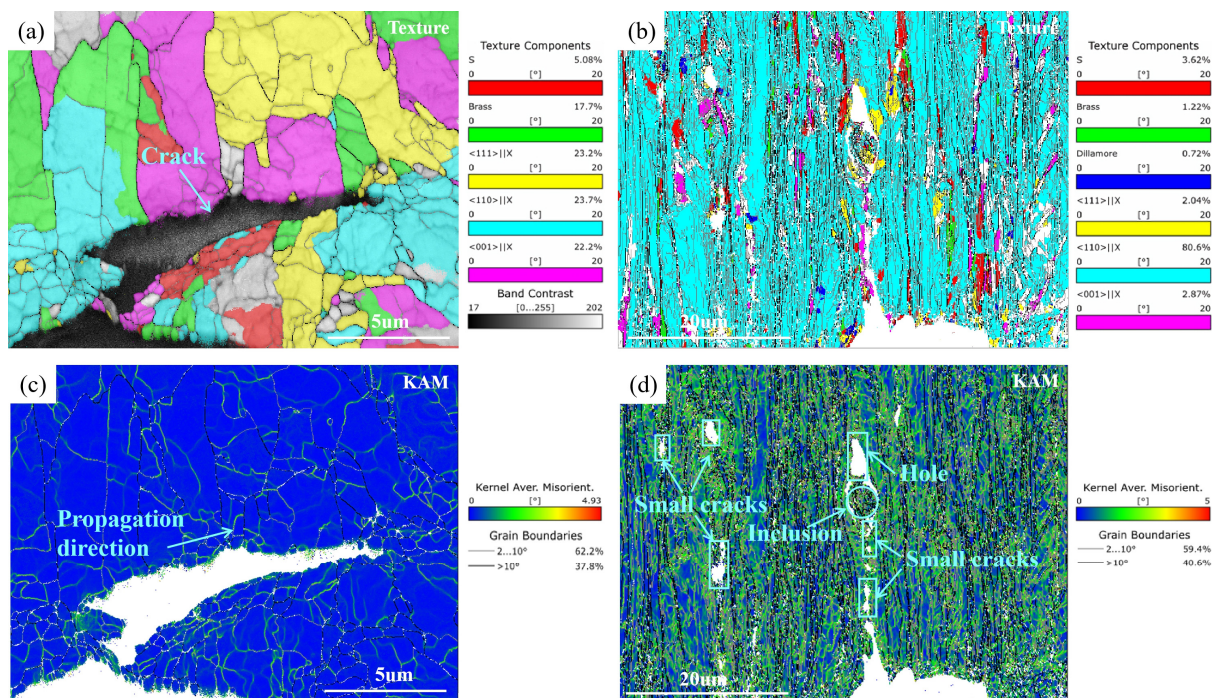


Figure 14. Texture components and KAM maps of fatigue fracture cross-sections under the different maximum stress levels of (a,c) 480 MPa and (b,d) 520 MPa.

Figures 15 and 16 illustrate the common orientation distribution function (ODF) of the cubic crystal system with a ϕ_2 angle of 45° , and the ODFs of the fatigue fracture surfaces under the maximum stress levels of 480 MPa and 520 MPa, respectively. Comparing these two figures, it can be seen that the main textures presented in the fracture surface under the maximum stress of 480 MPa were $\{011\}\langle 211 \rangle$, $\{100\}\langle 490 \rangle$, and $\{112\}\langle 111 \rangle$, with a maximum texture intensity of 7.85. For the maximum stress of 520 MPa condition, the main

textures were $\{100\}\langle 011\rangle$, $Y\{111\}\langle 112\rangle$, and Goss $\{011\}\langle 100\rangle$, with a maximum texture intensity of 12.77, as shown in Figure 16.

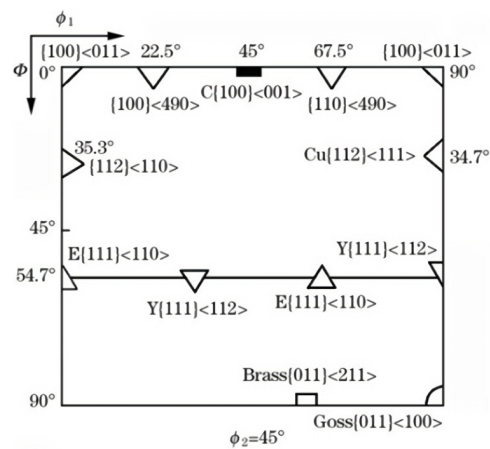


Figure 15. Common orientation map for the cubic crystal system with a ϕ_2 angle of 45° .

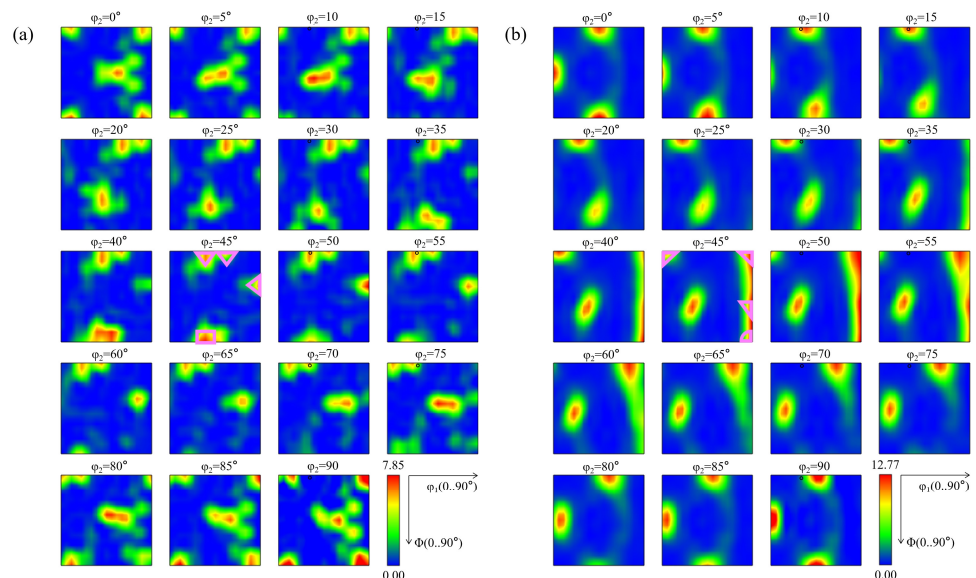


Figure 16. ODF figures of the fatigue fracture cross-sections under the different maximum stress levels of (a) 480 MPa and (b) 520 MPa.

Figure 17 displays the pole figures of the low-cycle fatigue fracture cross-section under the maximum stress level of 480 MPa. It can be observed that a strong $\langle 110\rangle$ // RD fiber texture was formed.

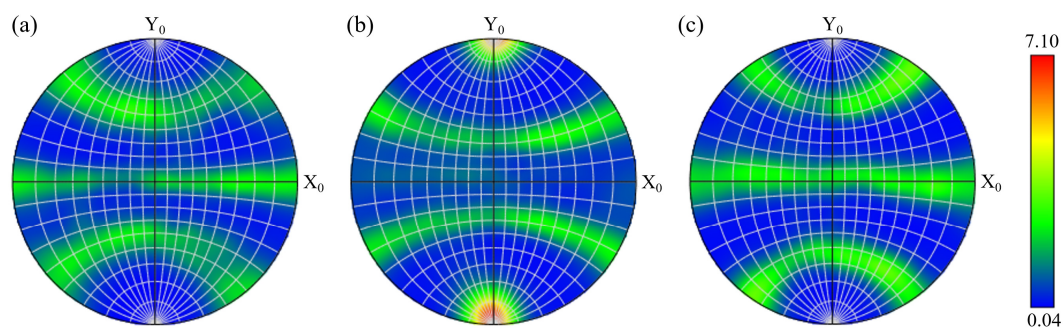


Figure 17. Polar figures on the cross-section of the low-cycle fatigue fracture (a) (001); (b) (110); and (c) (111).

3.4. Low-Temperature Fatigue Test Results and Analysis

3.4.1. Low-Temperature Fatigue Test Results

After the low-temperature fatigue tests were completed, a total of 30 sets of valid data were obtained, and the results are shown in Table 6.

Table 6. Low-temperature fatigue test results.

Specimen No.	Maximum Stress/MPa	Cycles/N	Result
LT1	480	10,000,000	Pass
LT2	480	10,000,000	Pass
LT3	480	10,000,000	Pass
LT4	500	8,718,127	Failure
LT5	500	10,000,000	Pass
LT6	500	10,000,000	Pass
LT7	500	897,629	Failure
LT8	500	634,092	Failure
LT9	500	10,000,000	Pass
LT10	500	654,200	Failure
LT11	520	928,427	Failure
LT12	520	10,000,000	Pass
LT13	520	1,105,590	Failure
LT14	520	785,297	Failure
LT15	520	651,789	Failure
LT16	520	266,784	Failure
LT17	540	540,968	Failure
LT18	540	227,497	Failure
LT19	540	399,912	Failure
LT20	540	242,145	Failure
LT21	540	208,273	Failure
LT22	560	914,834	Failure
LT23	560	218,731	Failure
LT24	560	460,801	Failure
LT25	560	157,670	Failure
LT26	560	254,022	Failure
LT27	590	92,206	Failure
LT28	590	21,273	Failure
LT29	590	17,219	Failure
LT30	590	99,197	Failure

This table revealed that the number of cycles leading to the failure of the specimens under maximum stress levels of 480, 500, 520, 540, and 560 MPa were all higher than 10^5 cycles, while the number of cycles leading to the failure of the specimen under the maximum stress of 590 MPa was less than 10^5 cycles. It can be concluded that high-cycle fatigue occurred when the maximum stress was 560 MPa and below, while low-cycle fatigue occurred when the maximum stress was 590 MPa and above, as shown in Table 7.

Table 7. Low-temperature fatigue failure types under different maximum stress levels.

Temperature	Maximum Stress/MPa					
	480	500	520	540	560	590
−60 °C	High-cycle fatigue	High-cycle fatigue	High-cycle fatigue	High-cycle fatigue	High-cycle fatigue	Low-cycle fatigue

According to the literature [40], the expression for the three-parameter model was as follows:

$$(S_{\max} - S_f)^m N = C \quad (2)$$

where S denotes the maximum cyclic stress, N represents the fatigue life, m and C are parameters related to the material properties and the specific loading conditions, respectively, and S_f represents the fatigue limit of the material.

Taking the logarithm of Equation (2), we obtained the following:

$$\lg N = \lg C - m \lg(S - S_f) \quad (3)$$

where we took $x = \lg(S - S_f)$, $y = \lg N$, $a = \lg C$, and $b = -m$. Subsequently, we obtained the following equation:

$$y = a + bx \quad (4)$$

For a series of S_i and fatigue life N_i ($i = 1, 2, 3, \dots, 30$), using the method of least squares, we obtained the following:

$$\begin{cases} a = \bar{y} - \bar{x}b \\ b = L_{xy}/L_{xx} \end{cases} \quad (5)$$

where L_{xx} denotes the total sum of squares, which represents the sum of squares of the differences between the x and $\bar{x}$, and L_{xy} represents the regression sum of squares, which denotes the sum of squares of the differences between the predicted values from the regression model and $\bar{y}$.

The square of the linear correlation coefficient R was defined as follows:

$$R^2 = \frac{L_{xy}^2}{L_{xx} \cdot L_{yy}} \quad (6)$$

where L_{yy} denotes the residual sum of squares, which represents the sum of squares of the differences between the observed values and the predicted values from the regression model.

In order to obtain the best linear correlation, it was necessary to maximize the absolute value of R . Thus, we obtained the following equations:

$$\frac{d(R^2)}{dS_f} = 0 \quad (7)$$

That was:

$$\frac{d(R^2)}{dS_f} = \frac{L_{xy}^2}{L_{xx} \cdot L_{yy}} \left(\frac{2}{L_{xy}} \cdot \frac{dL_{xy}}{dS_f} - \frac{1}{L_{xx}} \cdot \frac{dL_{xx}}{dS_f} \right) \quad (8)$$

where

$$\frac{dL_{xy}}{dS_f} = -\frac{1}{\ln 10} \left[\sum_{i=1}^n \frac{y_i}{S_i - S_f} - \frac{1}{n} \cdot \left(\sum_{i=1}^n y_i \right) \cdot \left(\sum_{i=1}^n \frac{1}{S_i - S_f} \right) \right] = -\frac{L_{y0}}{\ln 10} \quad (9)$$

$$\frac{dL_{xx}}{dS_f} = -\frac{2}{\ln 10} \left[\sum_{i=1}^n \frac{x_i}{S_i - S_f} - \frac{1}{n} \cdot \left(\sum_{i=1}^n x_i \right) \cdot \left(\sum_{i=1}^n \frac{1}{S_i - S_f} \right) \right] = -\frac{2L_{x0}}{\ln 10} \quad (10)$$

where S_i represents the applied maximum stress for the i -th fatigue test. L_{y0} is the intercept parameter in the regression equation, which represents the predicted value of the dependent variable y when the independent variable x is zero. L_{x0} is the slope parameter in the regression equation, which represents the effect of a unit change in the independent variable x on the predicted value of the y .

Substituting Equations (8)–(10) into Equation (7), we obtained the following equation:

$$H(S_f) = \frac{L_{y0}}{L_{xy}} - \frac{L_{x0}}{L_{xx}} \quad (11)$$

By solving the nonlinear equation system, $H(S_f)$, we were able to obtain S_f . Accordingly, after substituting S_f into Equations (5) and (6), we were able to obtain a and b . Subsequently, we obtained the following equation:

$$\begin{cases} C = 10^a \\ m = -b \end{cases} \quad (12)$$

Equation (2) can be rearranged into the following equation:

$$S = S_f + \frac{a^*}{N^{b^*}} \quad (13)$$

where

$$\begin{cases} b^* = 1/m \\ a^* = C^{b^*} \end{cases} \quad (14)$$

According to a series of S_i and N_i , a nonlinear fitting of Equation (13) was performed using the MATLAB programming language, and the related parameters were calculated as follows: $S_f = 499.87$, $m = 1.2566$, and $C = 2.66 \times 10^7$. According to the three-parameter model, the expression for the S-N curve was:

$$(S_{\max} - 499.87)^{1.2566} N = 2.66 \times 10^7 \quad (15)$$

Therefore, it can be concluded that the fatigue limit $S_f(10^7)$ of the steel plate at -60°C was approximately the maximum stress of 500 MPa. Shiozawa and Lu [41,42] summarized the characteristics of the S-N curves as follows: in the high-stress range below 10^6 cycles, the S-N curve was attributed to the initiation and propagation of the surface cracks, and the critical stress that prevented surface crack growth was referred to as the fatigue limit. According to Table 6, when the maximum stress was greater than or equal to 500 MPa and the number of cycles to failure was less than 10^6 cycles, the crack would initiate and propagate on the surface.

Figure 18 shows the predicted S-N curve that was obtained using the expression above. Compared to the curve, fatigue data had a significant scattering. In general, even when using the same batch of specimens and identical test conditions, variations in the test results can still occur. In this study, several factors influencing the scatter of the fatigue test results were considered, including the inconsistency of the test materials, variations in specimen processing and rolling processing, and accidental changes in the test environment [43]. Compared with room temperature, $S_f(10^7)$ at -60°C was increased to some extent, indicating that the fatigue performance of the steel plate was better under low temperatures. This was determined to be due to the fact that the crack propagation mechanism within the temperature range from -60°C to room temperature was based on the dislocation slip mechanism. When the temperature decreased, the yield strength of the steel plate increased. Dislocations were only able to move when they were subjected to a stress level that was greater than the yield strength. Therefore, the level of stress required for the driving dislocation motion was increased, and dislocations were less likely to slip, which made it difficult for the cracks to propagate and thus increased the fatigue limit [44,45]. Furthermore, as the temperature decreased, the grain boundaries were strengthened and less prone to cracking. This was also an important reason underlying why the fatigue limit increased when the temperature decreased.

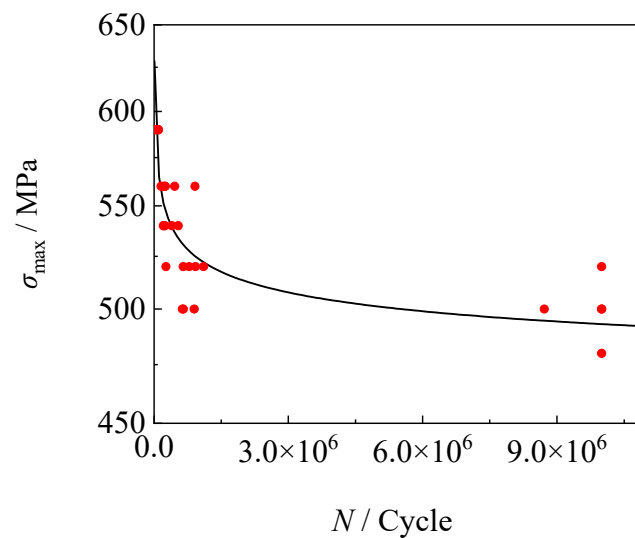


Figure 18. S–N curve of the three-parameter model. Red dots—fatigue data.

3.4.2. Observation of Fracture Surface in Low-Temperature Fatigue Tests

Figure 19 shows the photographs of the fatigue fracture specimens under different maximum stress levels at room temperature. From Figure 19a–d, it can be seen that the fractures of these specimens were all oblique shear fractures, without obvious plastic deformation. The specimen in Figure 19d had a crack perpendicular to the direction of the applied stress. According to Figure 19e, it can be seen that the fracture surface of the specimen was a cup-cone shape, with a shrunken cross-section and obvious plastic deformation.

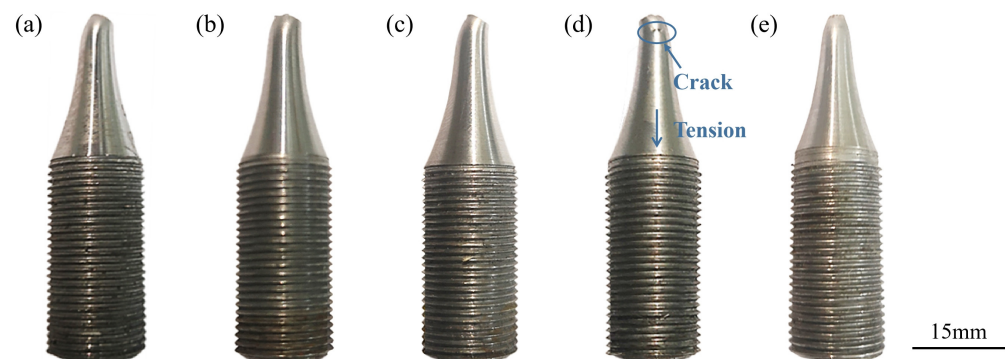


Figure 19. Low-temperature fatigue-fractured specimen under the different maximum stress levels of (a) 500 MPa; (b) 520 MPa; (c) 540 MPa; (d) 560 MPa; and (e) 590 MPa.

Figure 20 displays the SEM image of the crack on the side of the specimen in Figure 19d, where the direction of the applied cyclic tensile stress was perpendicular to the crack's surface. From this figure, it can be seen that under tensile stress, the two surfaces were pulled apart, and the crack propagation mode was the opening type. While the crack propagated inwardly along the specimen, it also propagated upward along the machining scratch on the right side of the specimen. Based on the local magnified image in Figure 20b, it can be seen that there was a crack source that had not yet propagated on the machining scratch, indicating that these cracks were prone to initiate on surface defects, such as machining scratches under high stress conditions [46].

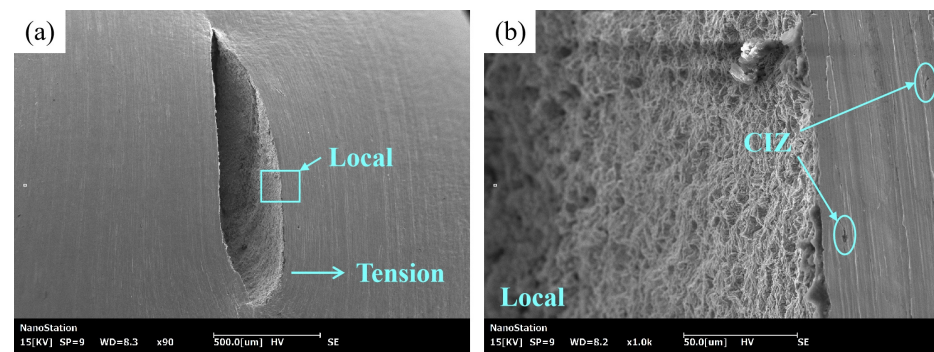


Figure 20. (a) Side crack and (b) magnified view of the local area of the fatigue specimen.

Figure 21 displays the fatigue fracture morphology of the specimen under different maximum stress levels. It can be seen from this figure that the fracture morphology was composed of the CIZ, CPZ, and FFZ, and the CIZ was located at the surface. When comparing Figure 21a,d,g,j, it can be seen that the fracture surface was relatively flat under maximum stress levels of 500 MPa, 520 MPa, and 540 MPa, and the boundary between the CPZ and the FFZ was clear. However, under the maximum stress of 560 MPa, the boundary was less clear than under other maximum stress levels. When comparing Figure 2c,f,i,j, it can be seen that the FFZ under the maximum stress levels of 500 MPa, 520 MPa, and 540 MPa contained a certain number of D_{el} and larger D_{eq} . In comparison, under the maximum stress of 560 MPa, the FFZ contained more D_{el} and larger D_{eq} . The a_c value in Figure 21a was about 2.2 mm, which was higher than the value of 1.9 mm at room temperature, as shown in Figure 10a, indicating that the N value under low temperature was relatively higher than that at room temperature [47].

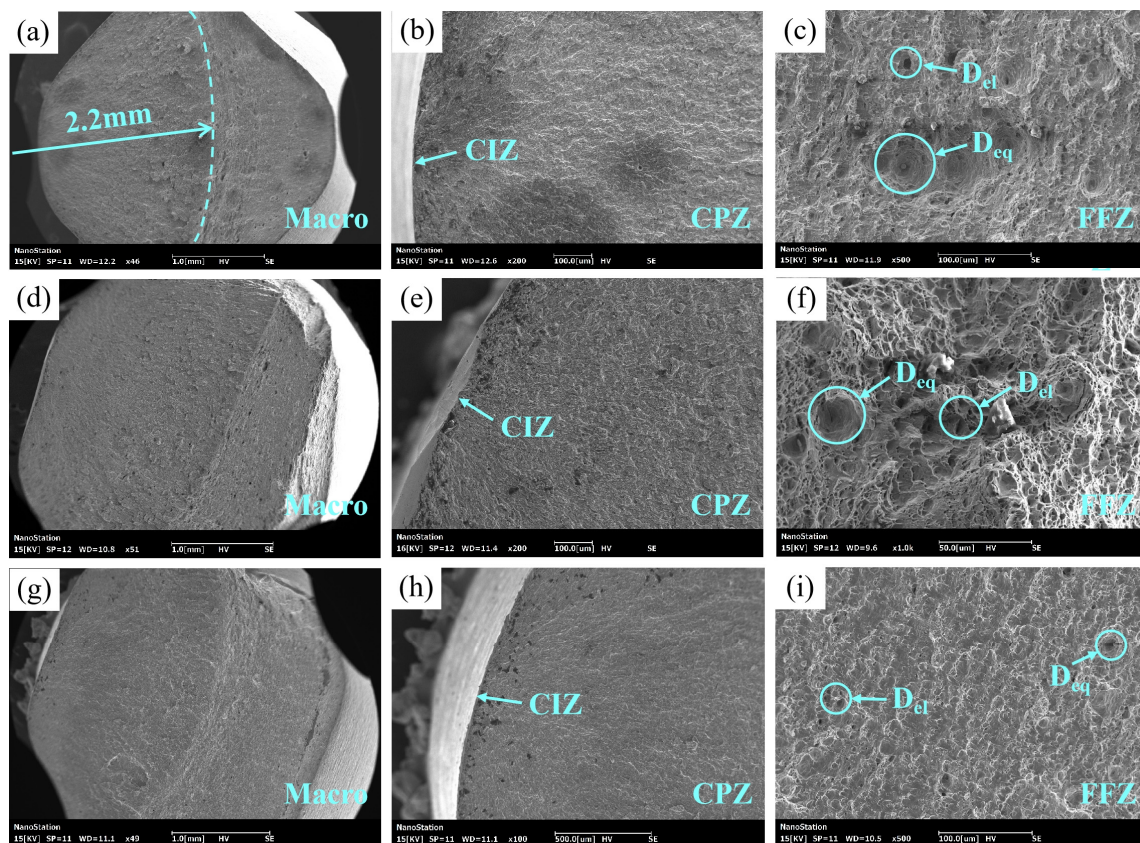


Figure 21. Cont.

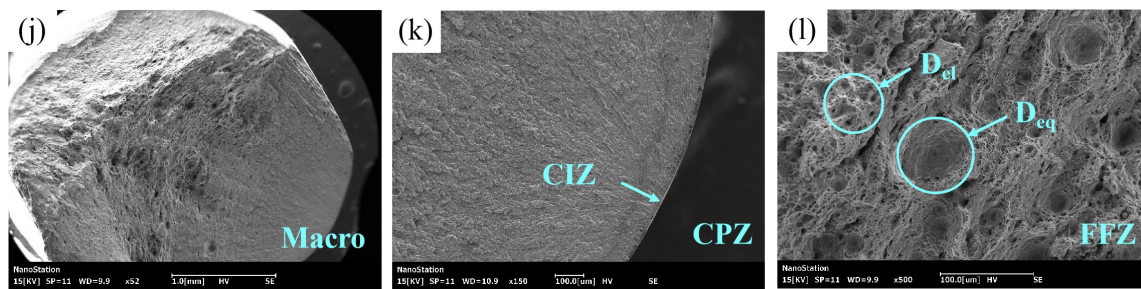


Figure 21. High-cycle fatigue fracture morphology under the different maximum stress levels of (a–c) 500 MPa; (d–f) 520 MPa; (g–i) 540 MPa; and (j–l) 560 MPa.

Figure 22 displays the fatigue fracture morphology of the specimen under the maximum stress of 590 MPa. From Figure 22a, it can be seen that the fracture surface showed plastic deformation and shrinkage, and there were multiple fatigue sources on the surface. The zone where the crack propagated inwards was the CPZ, and the center was the fibrous FFZ. From Figure 22b, it can be seen that the fatigue source zone was relatively smooth without the formation of dimples. At the boundary between the CIZ and the CPZ, there were D_{eq} , while D_{el} were present in the CPZ. From Figure 22c, it can be seen that the FFZ also mainly consisted of D_{el} .

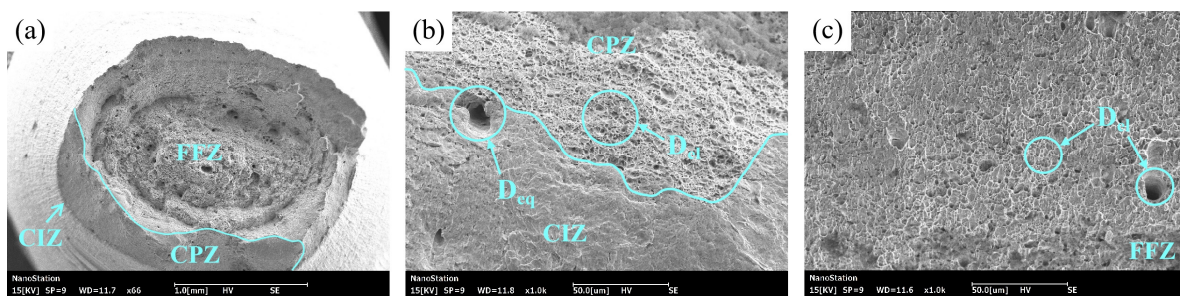


Figure 22. Fatigue fracture morphology of the specimen under 590 MPa maximum stress. (a) Macroscopic morphology. (b) The CIZ and the CPZ. (c) The FFZ.

Figure 23 displays the morphology of the inclusions at locations one, two, three, four and five in the CIZ and the CPZ. From this figure, it can be seen that the inclusions at locations one, two, and three were of an irregular block shape, with sizes between 25–40 μm , while the inclusions at locations four and five were ellipsoidal and spherical, with diameters between 6–10 μm , with the former being much larger than the latter. Table 8 shows the energy spectrum analysis results of the inclusions at different locations in Figure 23. The K element in the table was likely a component of the protective slag used in the crystallizer. The Mg element may have originated from the refractory material of the ladle. The Fe element could have formed as a result of X-ray penetration through the inclusions into the steel matrix, leading to its presence during EDX analysis. The high C element content in the inclusions at positions one, two, and three may be related to surface contamination by certain organic substances. Based on the percentage content of the other elements in the table, it can be inferred that the inclusions at positions one, two, and three were composite inclusions consisting of CaO , SiO_2 , TiO_2 , and CaS [31,48]. The location and content of these inclusions were relatively close, which may have been due to a large block inclusion undergoing deformation and splitting into three smaller inclusions because of the stress concentration during the fatigue test, becoming the source of fatigue failure in the steel [49,50]. The inclusion at position four was speculated to be primarily composed of SiO_2 along with small amounts of Al_2O_3 and TiO_2 . It was suggested that this inclusion was mainly formed due to the secondary oxidation of silicon and the precipitation of dissolved oxygen during the steel refining process, resulting in the formation of glassy silicate inclusions rich in SiO_2 . The inclusions in position five were primarily composed of

Al_2O_3 and CaO , with small amounts of MgO_2 , TiO_2 , and MnS . These were fine composite inclusions. [51].

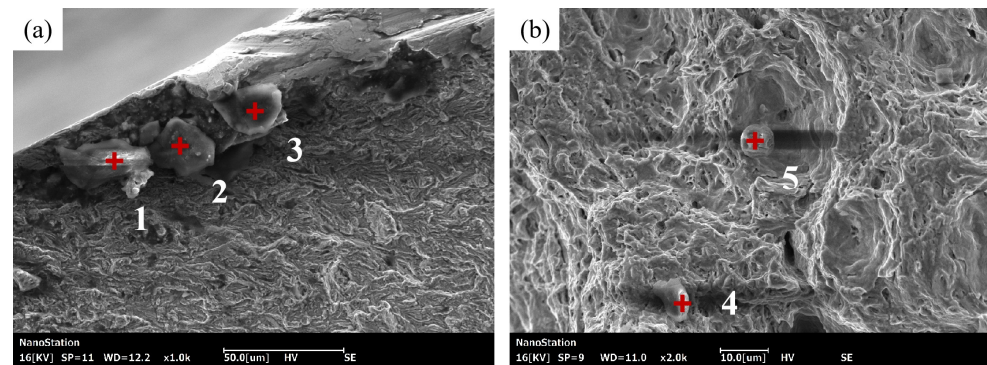


Figure 23. Inclusions in different zones of fatigue fracture under the maximum stress of 590 MPa. (a) The CIZ. (b) The CPZ. “+”—Energy spectrum analysis position.

Table 8. Energy spectrum analysis results of inclusions in Figure 23 (wt.%).

Position	Chemical Composition											
	Fe	C	O	Ti	S	Ca	Si	K	Cl	Al	Mg	Mn
1	4.18	70.57	21.13	0.29	1.15	0.35	0.88	0.45	0.72	0.27	-	-
2	1.32	64.44	29.88	0.33	0.78	0.72	0.56	0.28	1.70	-	-	-
3	5.74	72.68	16.52	0.24	1.24	0.39	0.80	0.73	1.66	-	-	-
4	4.51	16.24	53.16	0.11	-	-	22.02	1.17	-	2.79	-	-
5	3.71	18.41	38.61	0.58	0.33	10.02	-	-	-	27.27	0.77	0.32

4. Conclusions

This study focused on the TMCP process of FH36 ship plate steel. Through tensile tests in both the RD and TD, fatigue tests at room temperature (20 °C) and low temperature (−60 °C), and analysis and comparison of the morphology, grain boundaries, and textures of the tensile and fatigue specimens, the following main conclusions were drawn:

1. By adopting the process of first rolling in the RD and then rolling in the TD, the differing properties of the steel plate in the RD and TD were effectively eliminated, resulting in almost identical tensile properties in the RD and TD at a thickness of 1/4 of the rolled plate. The yield and tensile strength of the steel plate were approximately 420 MPa and 506 MPa, respectively, and the elongation was approximately 25%.
2. The fatigue limit of the steel plate at room temperature was 488 MPa. When the maximum stress was below 500 MPa and above 520 MPa, the specimens failed under high-cycle and low-cycle fatigue, respectively. The high-cycle fatigue fracture exhibited an oblique shear fracture, while the low-cycle fatigue fracture was a cup-cone shape, and the CIZs were both on the surface of the specimens. As the maximum stress increased, the area of the CPZ for high-cycle fatigue decreased, while the area of the FFZ increased, and the number of dimples in the FFZ increased. The proportion of the LAGBs in the fracture surfaces of the high- and low-cycle fatigue specimens had significantly increased.
3. The fatigue limit of the steel plate at −60 °C reached 500 MPa, which was higher than the fatigue limit at room temperature, indicating that its low temperature fatigue performance was better than that at room temperature. This was related to the increase in the yield strength as the temperature decreased, which subsequently led to an increase in the resistance to crack propagation. The specimens showed high-cycle and low-cycle fatigue failure when the maximum stress was below 560 MPa and above 590 MPa, respectively. The fatigue cracks were prone to initiate on the surface defects of the specimen, such as the machining scratches under high stress conditions.

The surface of the high-cycle fatigue fracture was flat, and the CIZs were all located on the surface of the specimen. As the applied maximum stress increased, the boundary between the CPZ and the FFZ became less distinct, and the number of dimples in the FFZ increased. The low-cycle fatigue fracture surface exhibited significant plastic deformation and multiple CIZs.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Abbreviation	Full Meaning
BOF	Basic oxygen furnace
CTOD	Crack tip opening displacement
TMCP	Thermo-mechanical control process
SEM	Scanning electron microscope
RD	Rolling direction
TD	Transverse direction
ND	Normal direction
OM	Optical microscope
AF	Acicular ferrite
PF	Polygonal ferrite
GB	Granular bainite
CIZ	Crack initiation zone
CPZ	Crack propagation zone
FFZ	Fast fracture zone
IPF	Inverse pole figure
LAGBs	Low-angle grain boundaries
KAM	Kernel average misorientation
ODF	Orientation distribution function

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