Study on the short fatigue crack initiation and propagation behavior of 42CrMo

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Abstract
A micro-tensile fatigue test of 42CrMo alloy steel was carried out. The result shows that the crack initiation and propagation of the material could be characterized with randomness and localization. There existed two sorts of short fatigue crack propagation behaviors for the tested material, that is, self-propagation and joint propagation with other short cracks. A short fatigue crack growth rate function was built considering the propagation characteristics. Moreover, a simulation model of short fatigue crack evolution was built. Total three samples were tested and simulated. The experimental result was in good consistent with that from simulation, both showing that the crack growth rate accelerated first and then decelerated during propagation.

Keywords
Microscopic fatigue test, crack behavior, crack simulation, crack growth rate, 42CrMo

Introduction
Regardless of service conditions of engineering parts, fatigue damage process generally means that defect nucleates in an undamaged region and then propagates steadily until a sudden break occurs. A few previous studies have shown that there existed transient acceleration or deceleration characteristics related to the subcritical growth of short fatigue cracks. The retardation or stagnation phenomenon of short fatigue crack during propagation indicates that there is a threshold of short fatigue crack growing, which is different from that of long fatigue crack. This threshold is supposed to be independent of crack growth rate obtained by Linear Elastic Fracture Mechanics (LEFM) and crack size. Generally, the behaviors of different short cracks vary greatly, so it is very limited to study the behavior of a single short crack only. In the process of short crack growing, fatigue damage depended largely on the interaction of many cracks. The differences of microstructure growth conditions at the crack tip are considered to be the root reason of the randomness of damage nucleation and short crack initiation. The stochastic analysis method for fatigue crack propagation mainly includes mathematical model and physical simulation method.

At present, the micro-mechanism of fatigue damage has not been fully and systematically understood, and the rules of short fatigue cracks growing and population evolution need to be further clarified. Therefore, in the current study, a micro-fatigue short crack test was carried out, the group behavior of fatigue short cracks...
cracks was analyzed, and a simulation model of fatigue short crack evolution was built and verified.

**Experimental details**

Fatigue failure usually originates on the surface of samples. The micro-fatigue testing device can observe the initiation and propagation of surface cracks in real time at metallographic level. The chosen material of the micro fatigue test is 42CrMo. The measured chemical composition of the material in wt.% includes: 0.42 C, 0.31 Si, 0.57 Mn, 0.20 Mo, 0.95 Cr, 0.03 P, 0.016 S, 0.105 Cu. After annealing, the metallographic structure of the material is ferrite and pearlite, and the average grain diameter is $d_0 \approx 20\mu m$. The metallographic structure is shown in Figure 1. The mechanical properties of the material are as follows: Elongation 14%, Section shrinkage 50%, Impact energy 70J, Yield strength 760 MPa, Hardness 20HRC.

The sample profile and dimensions are shown in Figure 2. For easy observation under microscope, two small notches with dimension of 0.5 mm × 0.2 mm were pre-cut on both sides of sample before test to induce crack initiation. The samples were finely ground and polished to facilitate online monitor. After the test was completed, the sample surface was slightly corroded by 3% nitric acid alcohol solution for metallographic morphology observation.

The fatigue test device used in the experiment was similar to that in Yang et al. The prepared samples was fixed on the fatigue test device. A microscope was fixed above the sample for real-time observation. The loading frequency was kept at 1 Hz with a stress ratio of 0.1. The test was carried out at room temperature in air. Total three samples were tested. The loading conditions are listed in Table 1.

During the test, the testing device came to a halt after running 300–1000 times loading cycles. The test process data was recorded by a camera installed above the microscope. A computer was connected to the camera to perform real-time observation and data recording. During each halt, the metallographic structures and fatigue cracks of the samples were observed under a microscope. Meanwhile, some interesting images were saved for further analysis.

**Characteristics of short fatigue crack initiation and propagation**

The nucleation of fatigue short cracks is often due to the presence of slip bands, grain boundaries and inclusions where short cracks are initiated due to stress concentration. After undergoing an initial several thousand cycles, at about the life fraction $N/N_f = 10\% \sim 20\%$, new cracks continued to initiate, but the lengths of existing short cracks hardly changed. Therefore, during short crack initiation stage, the lengths of short cracks did not change significantly but the amount of cracks increased with increasing fatigue cycles. The size of short cracks initiated at this stage is smaller than the average grain size and thus belongs to Micro-structurally Short Cracks (MSC).

| Sequence Number | Stress level ($\sigma/\sigma_s$) | Maximum load (N) | Minimum Load (N) | Overload protection (N) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1               | 0.58            | 1650            | 165             | 1900            |
| 2               | 0.54            | 1550            | 155             | 1800            |
| 3               | 0.48            | 1400            | 140             | 1600            |
According to the observation and analysis of crack localization characteristics in micro-fatigue tests, the evolution of short fatigue cracks was usually characterized by localization. During crack initiation and propagation process, denser short fatigue cracks appeared in a few regions, while there was little damage occurred in other regions (Figure 3). According to the theory of damage mechanism, this uneven damage was caused by differences in local structures of the material. As the strength of pearlite is higher than that of ferrite (about 560 MPa for ferrite and 820 MPa for pearlite), the crack mainly propagated along the grain boundary or through ferrite. Previous study also reported that cracks were found to propagate inside ferrite, pearlite and their boundaries. Within experimental scope, pearlite was the least sensitive to crack propagation, followed by ferrite, and grain boundaries were the worst, therefore crack was most likely to propagate grain boundaries.

On one hand, the grains and grain boundaries in local region of metallic materials might act as natural physical barriers to crack growth. On the other hand, short cracks might also be caused by inconsistent plastic deformation, which were easy to converge with local dominant cracks, and thus promoting rapid crack growing, that is, local micro-structure might serve to promote or hinder crack growing instead.

Observation of the short fatigue cracks on the sample surface reveals that the crack behavior had the following characteristics:

1. The initiation of short fatigue cracks was random. Short cracks originated in the stationary slip bands inside ferrite grains and ferrite-pearlite grain boundaries, but the short cracks at these locations tended to become non-propagating cracks, while short cracks at the grain boundaries or at the material defects were more likely to become propagating cracks. It was difficult to control the micro-local plastic deformation during the crystallization process of material preparation, and the micro-roughness of surface could not be eliminated by subsequent processing. Therefore, the initiation conditions of short cracks were random.

2. The initiation of short fatigue cracks was characterized by localization. There were a large number of cracks in the short crack stage. However, the group cracks of the test material were not uniformly distributed on the surface of the material, but concentrated in some ferrite regions in the form of resident slip bands.

3. The propagation of short fatigue cracks was localized. Certain localities of the test material might be favorable for the initiation of cracks and the early initiation of short cracks, but might not be conducive to crack propagation. Others, on the other hand, might be detrimental to crack initiation, but the short crack propagated faster in this region. Therefore, sometimes short cracks in unfavorable localities might propagate faster in the later stage and became locally dominant cracks beyond the initial cracks.

4. Short fatigue cracks presented two modes of propagation: self-propagation and convergence with other short cracks. In general, the crack growth rate had the characteristics of acceleration first and then deceleration. The crack propagation tended to slow down when the crack tip met grain boundary or pearlite, and the direction of propagation changed accordingly. When the crack tip encountered a randomly distributed short crack concentration area, the confluence of the cracks accelerated crack growing and the direction of propagation turned after the confluence. Therefore, from the microscopic point of view, the rate and direction of crack growth changed significantly after being hindered by grain boundaries or being converged with other short cracks.

The above evolution characteristics of short fatigue crack illustrated the particularity and complexity of short crack behavior. Although there have been several micro-damage mechanisms to explain the transient anomaly of short crack initiation and propagation,
how to visualize the random physical damage process and non-linear behavior of short crack at a micro level still needs to be further investigated.

**Fatigue short crack evolution model**

**Local dominant crack characteristics**

The study of the evolution of short cracks revealed the relationship between the physical process of micro-damage and the mechanical properties of the damaged material. The parameter of crack number density was often used to describe fatigue short crack damage, which reflected the contribution of crack number to fatigue damage in multi-crack specimens. In the existed studies, the initial evolution of short fatigue crack population was thought to be sparse and have little interaction between cracks. Literature gave an ideal short crack model to analyze the early stage of short crack evolution by combining the number and length of cracks. In fact, although the short fatigue cracks of smooth plate specimens had group behavior characteristics, the fatigue damage did not develop uniformly inside material. According to the results of micro-fatigue test, there was almost no damage being found in some areas where were unsusceptible to crack, while there were dense short fatigue cracks in areas where were prone to crack. Therefore, the evolution of short cracks was characterized by dominant cracks with obvious local evolution.

However, localized fatigue damage did not develop linearly. The localized damage process could be divided into two stages: Localized ideal short crack stage and locally dominant crack control stage. First, in the initiation stage of a short fatigue crack, some regions, such as grain boundary defects and grains at slip lines, were considered as susceptible sites of crack initiation. At this time, there was almost no interaction between cracks. The nucleation and propagation of short fatigue cracks were independent. The damage extent of short fatigue cracks could be described by an ideal short crack system evolution model. With the propagation of fatigue process, the short fatigue crack initiation stage entered the locally dominant crack control stage. At this stage, the interaction between cracks in the areas far away from the damage concentration area was weak, and the fatigue damage caused by short cracks in these areas had little or no influence on the damage process and amount. The interaction between cracks in the damage concentrated region had a strong influence on the initiation and propagation of cracks and was easy to form Dominant Local Field Short Cracks (DLFSC). DLFSC and its damage-affected zones should be key considerations when building fatigue shortcrack damage model since they could more easily evolve into “long cracks” that finally cause part failure. The two stages of localized damage process had different characteristics in terms of crack growth rate. The boundary of the two stages could be related to crack length. When crack length was less than a threshold value \( a_l \), the short crack was in the localized ideal short crack stage. When the crack length was greater than \( a_l \), the short crack was in the localized dominant crack control stage.

Unlike long cracks, the propagation of DLFSC was more influenced by the length, amount and microstructure of short fatigue cracks around it. Since crack initiation at the initial stage of damage was controlled by many factors, the location of crack initiation was random, and the area where the damage was concentrated was sparsely distributed, so there were many DLFSCs. The stress concentration in the tip region of DLFSC resulted in grain boundary cracking and intra-grain slip. As a result, more short cracks tended to form in crack tip regions. DLFSC was further propagated by combining these short cracks. The amount, length and orientation of initiation cracks in the crack tip region (including grain boundary and intra-grain) were random due to the differences in local microstructure of materials, and the growth behavior of DLFSC was also random.

**Fatigue short crack propagation model**

**Hypotheses.** Based on the analysis of the micro-mechanism of random propagation of DLFSC, the hypotheses of locally dominant crack damage model are proposed:

1. In the initial stage of damage, the short crack initiation process is very short, and its effect on material damage and life can be neglected.
2. After the formation of local dominant crack, it becomes the main factor of material damage.
3. There is a concentrated area of short cracks at the local dominant crack tip, in which the characteristics of short cracks are the same as those of the ideal short crack system.
4. The locally dominant crack propagates through itself and its connection with the existing short crack in the tip region.

**Formula analysis of fatigue short crack growth rate.** Based on the above assumptions and the research results of fatigue short crack growth law, the formula of fatigue short crack growth rate is obtained:

\[
\frac{da}{dN} = \begin{cases} 
A \sigma^{n_1} r_{msc} & 0 < a < a_l \\
B \sigma^{n_2} r_{psc} & a_l < a
\end{cases} 
\]

Where \( \frac{da}{dN} \) is the growth rate (\( \mu m \cdot cycle^{-1} \)), \( \sigma \) is the stress level (MPa), \( A, B, n_1, n_2 \) are the material constants, and \( a_l \) is the critical crack length for the growth
rate of short cracks (μm), \( r_{\text{rmsc}} \) and \( r_{\text{pisc}} \) is the size of plastic affected zone of Micro-structurally Short Cracks (MSC) and Physically Short Cracks (PSC) (μm).

Following gives a detail description of the above parameters:

1. Formula (1) describes the two stages during fatigue short crack growing. There existed a critical threshold for crack length (referred as to \( a_1 \)). When the crack length was less than \( a_1 \), the crack experienced a steady growing stage. Furthermore, crack growing might even decelerate at grain boundaries. However, when some cracks propagated across grain boundaries, crack length increased over the threshold \( a_1 \), the grain boundaries could not hinder crack growing any more, and thus crack grew again with a steady speed or even accelerated. Therefore, the growth of short fatigue cracks have the characteristics of first decelerating and then accelerating before becoming into “long cracks.” It was established that the critical threshold \( a_1 \) was related to grain size \( d_0 \),\(^{25} \) which was generally determined as \( a_1 = 3d_0 \sim 5d_0 \) (being set as 3.5\( d_0 \) in the current study).

2. Equation (2) reflects that the growth rate of short fatigue crack is affected by the level of loading stress. Short crack growth rate increases when the stress level is high, and decreases when the stress level is low.

3. The sizes \( r_{\text{rmsc}} \) and \( r_{\text{pisc}} \) of plastic affected zone for micro and physical short cracks represent the size of plastic affected zone for crack tip, which is related to the size of crack, the position of crack tip and the average size of grains.

### Size analysis of plastic impact zone based on local microstructure.

Metal materials show varying degrees of immunity to the initiation and propagation of Fatigue Short Cracks in different localities, and the number and size of cracks in each locality reflect the extent of local damage. Generally speaking, when the cracks in the adjacent area of the DLFSC tip are too sparse, that is, the size of the plastic affected zone at the crack tip is very small, and when the cracks in the adjacent area of the DLFSC tip are too dense, the plastic affected zone at the crack tip is very large. Therefore, the density of short cracks in the local region of the short crack tip can be regarded as a certain value, and the sizes \( r_{\text{rmsc}} \) and \( r_{\text{pisc}} \) of the plastic influence zone of the crack tip are intrinsic physical quantities reflecting the degree of local damage.

Corresponding to the existing law of fatigue short crack growth, the dimensions \( r_{\text{rmsc}} \) and \( r_{\text{pisc}} \) of plastic influence zone at crack tip can be divided into the following situations:

1. \( r_{\text{rmsc}} = 1 \), \( r_{\text{pisc}} = a \). By substituting \( r_{\text{rmsc}} \) and \( r_{\text{pisc}} \) values into equation (1), the formula of crack growth rate for short fatigue crack is obtained:

\[
\frac{da}{dN} = \begin{cases} 
Aa^{m_1} & 0 < a < a_1 \\
Ba^{m_2} & a_1 < a 
\end{cases}
\]

(2)

The duplication technique is used to observe short cracks.\(^{26} \) When the crack length is less than the threshold, the crack growth rate is independent of crack length and only changes potentially with stress level. When the crack length exceeds, the crack growth rate is proportional to the crack size and potentially related to the stress level. However, this conclusion is obviously different from the existing understanding of the fatigue short crack growth rate, possibly due to inaccurate observation of the test process.

2. \( r_{\text{rmsc}} = \frac{1}{a^{m_2}} \), \( r_{\text{pisc}} = a^{m_2} \). By substituting \( r_{\text{rmsc}} \) and \( r_{\text{pisc}} \) values into equation (1), the formula of crack growth rate for short fatigue crack is obtained:

\[
\frac{da}{dN} = \begin{cases} 
Aa^{m_1} & 0 < a < a_1 \\
Ba^{m_2} & a_1 < a 
\end{cases}
\]

(3)

Where \( m_1 \) and \( m_2 \) are indices reflecting the influence of crack length on crack growth rate.

Considering the characteristics of fatigue short crack that crack growth decelerates first and then accelerates, when the length of short crack is less than the critical scale \( a_1 \), the crack growth rate is inversely proportional to the crack size and potentially related to the stress level. When the crack length exceeds \( a_1 \), the crack growth rate is directly proportional to the crack size and potentially related to the stress level. The

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**Table 2. Parameters for crack growth rate calculation.**

| No. | Stress level (σ/σ_s) | A    | \( n_1 \) | \( m_1 \) | B    | \( n_2 \) | \( m_2 \) |
|-----|----------------------|------|----------|----------|------|----------|----------|
| 1   | 0.58                 | 0.03361 | 0.20025  | 0.85770  | 0.00226 | -0.10453 | 0.70265  |
| 2   | 0.54                 | 0.02203 | 0.11680  | 0.23013  | 0.00056 | -0.39360 | 1.33514  |
| 3   | 0.48                 | 0.01942 | 0.09600  | 0.35425  | 0.00019 | -0.29052 | 1.16596  |
coefficients in the above equations, including $A$, $B$, $n_1$, $n_2 m_1$, and $m_2$ were determined from experimental results, which are listed in Table 2.

(3) $r_{\text{msc}}$ and $r_{\text{psc}}$ considering randomness. The fatigue short crack growth process is also random due to the randomness of local microstructure. To reflect the randomness of the micro-process of fatigue damage, a random function is introduced to modify the deterministic formula (2) and formula (3) for fatigue short crack growth rate. According to the analysis of the influence of grain size and yield strength of local microstructure at crack tip on the density of cracks,\cite{27,28} the plastic influence zone sizes $r_{\text{msc}}$ and $r_{\text{psc}}$ of crack growth tip should be a function of crack size $a$, material grain size $d_\text{0}$ and local strength of ferrite/pearlite $\sigma_{\text{YS}}$. Considering the above factors, $r_{\text{msc}}$ and $r_{\text{psc}}$ can be expressed as:

$$\begin{cases} r_{\text{msc}} = \omega(x) V(x) & 0 < a < a_1 \\ r_{\text{psc}} = \omega(x) a^{m_2} V(x) & a_1 < a \end{cases}$$  \hspace{1cm} (4)$$

Where $V(x)$ is a random coefficient reflecting local damage; $\omega(x)$ is the correction factor of the size of plastic affected zone.

Local damage randomness coefficient $V(x)$ is a numerical measure of the sensitivity of local materials to crack initiation and propagation, indicating the random factors that hinder or promote crack growth in the damage concentration region at the crack tip, and is $V(x) \in [0, 1]$. The closer the $V(x)$ $Q$ is to 1, the more likely the crack is to become a propagating crack, and the closer the $V(x)$ is to 0, the more likely it is to become a non-propagating crack. The correction factor $\omega(x)$ is related to the grain size and the strength of phase (ferrite/pearlite) located at the locally dominant crack tip (locally). The larger the grain is, the more short cracks are generated in the grain, and the greater the possibility that the locally dominant crack meets the short crack. The larger the strength of phase, the more difficult the crack propagates. Therefore, $\omega(x)$ is directly proportional to grain size $d_\text{0}$ and inversely proportional to $\sigma_{\text{YS}}$.

The formula for fatigue short crack growth rate based on local randomness is obtained by substituting equation (4) with equation (1):

$$\frac{da}{dN} = \begin{cases} A a^{n_1} \omega(x) V(x) & 0 < a < a_1 \\ B a^{n_2} \omega(x) a^{m_2} V(x) & a_1 < a \end{cases}$$  \hspace{1cm} (5)$$

Formula (5) reflects the unity of randomness and certainty of local main crack growth. It can be used to simulate the evolution of fatigue short crack and reproduce the local characteristics of non-expanding initiation crack, crack growth rate, and crack damage.

**Short fatigue crack evolution simulation**

**Simulation method of fatigue short crack evolution**

Monte Carlo simulation provides a convenient method to investigate the initiation of fatigue crack at a micro-scale.\cite{29} Here, a simulation method was proposed based on Monte Carlo simulation. Following gives a detail description of calculation process.

(1) Simulation of material microstructure: A hexagon grain background diagram was constructed as a two-dimensional microstructure diagram of the material. The sizes of hexagon was determined by the average grain size $d_\text{0}$.

(2) A certain number of “crack initiation sites” are randomly set in the grain. Cracks randomly originate at the sites and the lengths of the cracks cannot exceed the grain size, which is considered as non-propagating short cracks. The crack initiation sites includes grain slip zones, grain boundaries, inclusions, etc. The amount of sites $n$ represents the degree of influence of material defects.

(3) The crack initiation sites are randomly set at the edge of the material. The short cracks initiated from these sites are DLFSC.

(4) The characteristic pattern of crack determines the growing rate of crack.

(5) When the crack tip reached grain boundary, it will continue to grow or stop growing temporarily according to the characteristic pattern. Every time a crack crosses the grain boundary, it is no longer considered the original crack, but its descendants. The new characteristic pattern of the offspring crack is inherited from its predecessor.

(6) The different local damage randomness coefficient $V(x)$ at each local position of a given material reflects the local difference of crack propagation, indicating the resistance of the local immunity to crack propagation damage.

(7) It is assumed that when the distance between adjacent cracks reaches the mandatory crack connection condition,\cite{30} the cracks converge: $x = a_1 + a_2 - \sqrt{a_1^2 + a_2^2}$ ($a_1$ and $a_2$ are the length of adjacent cracks respectively). The connecting path is the connecting line between the two crack tips. Crack confluence determines the characteristic type of crack after confluence according to the biogenetic law.

(8) When the DLFSC reaches a certain size, crack propagation enters the long crack stage, and the simulation ends.
Simulation and verification of 42CrMo micro fatigue test

The hexagonal grain background map was built according to the average grain size ($d_0 = 20\mu m$). Meanwhile, grain orientations were supposed to be normal distribution random data according to Monte Carlo theory. It is assumed that the orientation distribution of short crack initiation and propagation is the same as the grain orientation. Since the grain orientation is random, the direction of short crack propagation changes randomly with the grain orientation. The propagation rate of locally dominant crack is determined according to equation (6), and is affected by the following three factors: (1) The effect of hindering the expansion of DLFSC on grain boundaries. (2) Acceleration effect of DLFSC propagation at the confluence of cracks. (3) The characteristic pattern changes after the cracks converge. These factors make the expansion rate of DLFSC also have the characteristics of randomness.

Figures 4 to 6 are the simulation results of DLFSC growth rate with crack length at loading stress levels of 1400, 1550, and 1650 N, respectively. It can be seen that the simulated $da/dN=a$ curve is in good agreement with the curve from experiment. In the simulation of single DLFSC, the effects of grain boundary and the convergence of random short Cracks on crack growth rate were taken into account. Even if other design parameters remain unchanged, the growth rates, and paths of DLFSC from different simulations are still random. In summary, the long crack suitable for LEFM analysis is developed from DLFSC that initiated at the initial damage stage. The initiation and propagation of DLFSC is strongly affected by grain boundaries, inclusions and MSc group behavior. Therefore, at the initial stage of fatigue damage, the behavior of DLFSC is random, resulting in the randomness of macro fatigue performance.

Conclusions

(1) Based on the analysis of fatigue short crack propagation characteristics, a formula of fatigue short crack growth rate was established. The fatigue short crack growing process could be divided into two stages: micro short crack stage and physical short crack stage. Although the crack propagation had different features in...
the two stages, both were related to the short crack length and the dimension of plastic influence zone of crack tip.

(2) A simulation method for fatigue short crack evolution has been designed. The simulation was based on the hypothesis the crack sources were distributed at random inside material. The method takes into account the effects of material microstructure, non-propagating cracks on the propagation behavior of DLFSC, as well as the local characteristics of crack damage. The experimental observation from the 42CrMo micro-fatigue test proved the fidelity of the simulation.

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References
1. Castelluccio GM and McDowell DL. Mesoscale modeling of microstructurally small fatigue cracks in metallic polycrystals. Mater Sci Eng A 2014; 598: 34–55.
2. Sadananda K, Nani Babu M and Vasudevan AK. A review of fatigue crack growth resistance in the short crack growth regime. Mater Sci Eng A 2019; 754: 674–701.
3. Elamurugu S, Sudarshan Rao G, Biju S, et al. Fatigue crack growth rate studies on high-strength low-Alloy steel under different loading conditions. Trans Indian Inst Metals 2019; 72: 1527–1531.
4. Shlyannikov V and Fedotova D. distinctive features of crack growth rate for assumed pure mode II conditions. Int J Fatigue 2021; 147: 106163.
5. Hong Y, Lu Y and Zheng Z. Orientation preference and fractal character of short fatigue cracks in a weld metal. J Mater Sci 1991; 26: 1821–1826.
6. Hong YS and Fang B. Micro-process and theory of initiation and development of short fatigue cracks. Adv Mech 1993; 23: 468–486.
7. Burchill M, Barter S, Chan LH, et al. Microstructurally small fatigue crack growth rates in aluminium alloys for developing improved predictive models. MATEC Web Conf 2018; 165: 13004.
8. Zhu L, Song YD and Chen J. Modeling of multi-scale fatigue crack growth in titanium alloy TC4. Iran J Sci Technol Trans Mech Eng 2021; 45: 153–163.
9. Omishore A. Stochastic modelling and prediction of Fatigue Crack propagation based on experimental research. Mater Sci Eng 2019; 471: 102037.
10. Busc C, Palmert F, Sjödin B, et al. Evaluation of the crystallographic fatigue crack growth rate in a single-crystal nickel-base superalloy. Int J Fatigue 2019; 127: 259–267.
11. Yuan H, Zhang W, Castelluccio GM, et al. Microstructure-sensitive estimation of small fatigue crack growth in bridge steel welds. Int J Fatigue 2018; 112: 183–197.
12. Cui C, Xu YL and Zhang QH. Multiscale fatigue damage evolution in orthotropic steel deck of cable-stayed bridges. Eng Struct 2021; 237: 112144.
13. Musinski WD and McDowell DL. Simulating the effect of grain boundaries on microstructurally small fatigue crack growth from a focused ion beam notch through a three-dimensional array of grains. Acta Mater 2016; 112: 20–39.
14. Cheng LF, Wei GQ, Hu K, et al. Life simulation of microscopic short crack nucleation and early propagation of weld toe. J Mech Strength 2021; 43: 1436–1441.
15. Pan JZ. A new fatigue test method-microscopic fatigue test. J East China Unis Sci Technol 1995; 21: 58–64.
16. Yang B, Ma BQ, Zhao YX, et al. Short Fatigue Crack growth at different maintenance times for LZ50 Steel. Strength Mater 2015; 47: 114–121.
17. Stratulat A, Duff JA and Marrow TJ. Grain boundary structure and intergranular stress corrosion crack initiation in high temperature water of a thermally sensitised austenitic stainless steel, observed in situ. Corros Sci 2014; 85: 428–435.
18. Boeff M, Hassan HU and Hartmaier A. On the numerical modeling of nucleation and growth of microstructurally short cracks in polycrystals under cyclic loading. J Mater Res 2019; 34: 3523–3534.
19. Azeez A, Norman V, Eriksson R, et al. Out-of-phase thermomechanical fatigue crack propagation in a steam turbine steel—modelling of crack closure. Int J Fatigue 2021; 149: 106251.
20. Yang B, Feng B, Li YF, et al. Influence of surface micro shot peening on short fatigue crack behavior of CuNi2Si alloy. J Traffic Transport Eng 2021; 21: 163–171.
21. Zhang ZL, Xia S, Cao W, et al. Effects of grain boundary character on intergranular stress corrosion cracking initiation in 316 stainless steel. Acta Metallurgica Sin 2016; 52: 313–319.
22. Cheng LF, Wei GQ, Hu K, et al. FIP-based simulation of behavior of short crack on weld toe. Trans China Welding Inst 2020; 41: 7–12.
23. Zhang YB, Guo RX, Xia HY, et al. Effect of particle and microstructure on fatigue crack initiation and growth behavior of Cu/wcp Composites. Mat Rep 2017; 31: 85–91.
24. Chen L, Huang TL and Zhou H. Stochastic modelling of metal fatigue crack growth using proportional Paris law and inverse Gaussian process. Eng Mech 2021; 38: 238–247.
25. Xu H and Wu ZX. Formation and propagation of short fatigue cracks in 45 steel. Acta Metallurgica Sinica 1995; 18: 85–89.
26. Ke FJ, Bai YL and Xia MF. Characteristics of evolution of ideal microcrack system. *Scientia Sinica (Mathematica)* 1990; 12: 621–631.

27. Goto M and Knowles D. Initiation and propagation behaviour of microcracks in Ni-base superalloy udimet 720 Li. *Eng Fract Mech* 1998; 60: 1–18.

28. Zhao YX, Yang B and Gao Q. Initiation and early propagation of short fatigue cracks on weld metal of 1Cr18Ni9Ti pipes. *Nucl Power Eng* 2003; 24: 127–132.

29. Al-harthi MA, Khokhar ZH and Abdulazeez A. Monte Carlo simulations of crack propagation at Tee Joint along Pipe. *Int J Eng Res Dev* 2012; 5: 82–86.

30. Hong Y, Zheng L and Qiao Y. Simulations and experiments of stochastic characteristics for collective short fatigue cracks in steels. *Fatigue Fract Eng Mater Struct* 2002; 25: 459–466.