On the use of the [?]area$^{a}ndthethree -$ $parameterpowerfunctiontoestimatefatiguelifeofTC17titaniumalloy$

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Abstract

This paper examined the ability of [?]area$^{u}singthematerialfatigue-lifecurvesinestimatinghigh-cyclefatiguelifeconsideringmicroscratch.Ultra$
$parameterpowerfunction.Reasonableagreementsareobservedbetweenthemodelpredictionsandtheexperimentalvalues.Whatismore, accordingtoth$

NOMENCLATURE

σ_t ultimate tensile strength

σ_s yield stress

E Young's modulus

HV Vickers hardness

m , c material parameter

W_i width of scratch i

D_i depth of scratch i

R fatigue loading stress ratio

$\sqrt{\text{area}}$ fatigue damage parameter for micro scratch

σ_w fatigue strength

$\sigma_{w,}$ conditional fatigue strength for micro scratch

a_0 initial defect size

$\frac{\mathrm{da}}{\mathrm{dN}}$ fatigue crack growth rate

N_f experimental fatigue life

N_P predicted fatigue life

Keywords: TC17 titanium alloy, micro scratch, high cycle fatigue life, three-parameter model.

1 | Introduction

In the aerospace industry, titanium alloy compressor blades are the critical parts of an aero engine. The rotor blades are subjected to severe mechanical loads such as centrifugal force, moment load during the operation. Moreover, high-frequency vibration generated by the surge, resonance, and flutter make it prone to fatigue failure.[1,2] Titanium alloy has sensitivities for surface integrity, which make it easy to produce various damages, especially micro scratch. Operation at extreme conditions, micro scratches are sufficient to induce early initiation and propagation of fatigue cracks, leading to premature fatigue fracture of blades. [3,4]Thus, it will exert potential risk of fatigue failure to the aircraft if have the scratched blade continue to serve.

Fatigue behavior affected by scratches has been a subject of great interest to demand for the development of safe fatigue design, damage assessment and fatigue life prediction. Wiryolukito [3]investigated the cause of failure on compressor blade of X-gas turbine in service prior the schedule for overhaul at 40,000 hour. The evidences indicate the scratch has an important role to initiate fatigue crack on blade root chamfer. Gourdin[5] found that the fatigue crack growth of natural cracks initiating from scratches without residual stresses is identical and similar to the long crack growth behavior of a nickel based superalloy. Inchekel and Talia[6] revealed that the fatigue life decreased sharply as the scratch depth increased and an edge scratch is more detrimental than a center scratch. Mayer [7] investigated fatigue life of bainitic bearing steel under fully reversed tension-compression loading at cycling frequency 20 kHz. They found that surface cracks are initiated at surface defects produced during machining and deep scratches (approximately 8 μm) can be considered as pre-cracks. Poulain[8] also pointed out that the location and the growth of fatigue cracks in the early stages are controlled by the presence and the geometry of grinding scratches. It can be concluded that once scratched blades continue to serve, there will be huge potential safety hazards to the aircraft.

The fatigue life of scratched structures can be predicted using dynamic analysis of scratch generation combined with the continuum damage mechanics based fatigue damage model[9]. A new method to calculate the fatigue life and defect tolerance for a30CrMnSiA steel specimen with artificial scratches was proposed.[10]Xu[11] estimated the fatigue limit curve for highspeed railway axles with surface scratch using Murakami theory. The sensitivity of the HCF and VHCF strength to small scratches under torsional and rotating bending fatigue tests can be evaluated by parameter model. [12]

Traditionally, surface roughness parameter such as Ra , Rzcan be a common method to evaluation on surface condition. Stylus method is commonly employed to collect surface morphology data. But stylus method cannot aim at the specific scratches directly, and actual depth and width maybe not reflected by surface roughness. Researches have pointed out that surface roughness cannot be applied directly to express the relationship between fatigue failure performance and the surface defects.[13-15] There are also few parameters on expressing fatigue damage quantitatively caused by actual micro scratch.

In previous work, we proposed a parameter $\sqrt{\text{area}}$ to describe fatigue damage caused by micro scratch.$\sqrt{\text{area}}$ is inspired by Murakami theory and developed for actual micro scratch. The ability of $\sqrt{\text{area}}$ in conditional fatigue strength prediction was verified by high strength steel FV520B-I and Ti-6Al-4V.[16] Prediction error is below 10% for the two material. Using actual scratch depth and width of micro scratch of EA4T steel from Xu [17], prediction error is also lower than 10%.[18] For the scratch with a depth from 10-45μm, the error can be lower than 5%.

Using roughness profiles from stylus method can be an alternative method to determine scratch depth and width in current study.[19,20] Considering the practical situation that scratch direction and length own the characteristic of randomness, this method may obtain inaccurate actual scratch geometry parameters. Facing with this problem, we modified the surface location parameter in Murakami fatigue strength model to $1.06C$ for stylus method.[16] Prediction error of modified fatigue strength model is below 6%.

Fatigue life prediction are crucial for the design and maintenance process of components. Two major types of methodologies are available for fatigue life prediction. One approach is the classic fatigue theory based on the material fatigue-life curves (e.g., S–N curves or ε–N curves) and a damage accumulation rule, which is the focus of the current study. The other approach is based on the fracture mechanics and crack growth analysis. $\sqrt{\text{area}}$ can be used as fatigue damage parameter, also as equivalent initial defect size for micro scratch. Its rationality and validity of $\sqrt{\text{area}}$ in fatigue life prediction was checked by fracture mechanics.[18] A fine prediction result was obtained under the combination of Paris law and $\sqrt{\text{area}}$.

The present study attempts to prove the validity of$\sqrt{\text{area}}$ in the field of the classic fatigue method, e.g., material fatigue-life curves. The ultrasonic fatigue tensile experiment was performed to obtain fatigue data, and fracture properties are observed by SEM (Scanning Electron Microscope). Combined with the condition fatigue strength model modified by $\sqrt{\text{area}}$and the three-parameter model, an HCF life model for TC17 is established. The model was verified being effective to the fatigue life prediction of TC17. What is more, the application of$\sqrt{\text{area}}$ combined with current fatigue theories in fatigue strength and fatigue life analysis was also discussed.

2 | Brief introduction of $\sqrt{\text{area}}$

Murakami and Endo proposed the parameter $\sqrt{\text{area}}$ as fatigue damage size for the prediction of the fatigue limit of specimens with surface defects. [21,22] $\sqrt{\text{area}}$ is defined as the square root of the area obtained by projecting a small defect or crack onto a plane perpendicular to the maximum principal stress. It is an useful and simple method to express fatigue damage caused by scratch[11,23], micro notch[24], hole, micropore[25] and non-metallic inclusions[26].

Micro scratch has tens of microns along the surface, and a depth of a few micrometers with a length of potentially several millimeters. Compared with the size of artificial defect in Murakami experiment[27], the studied scratch size has microscopic geometric characteristics, as can be seen in Fig. 2 below. What is more, its direction and length own the characteristic of randomness. This is because that the impact angle and time of foreign objects on the component surface are random and uncontrollable.

Thus, it seems that Murakami theory cannot applied to micro scratch directly in estimating the projected area. Unreasonable result may be produced in condition fatigue strength prediction if both scratch direction and length considered at the same time. Nevertheless, we found that if only take section area of micro scratch into consideration, better predicting results will obtained. Thus, we proposed the two principles that there may be no obvious influence of scratch direction and length on fatigue life.

Inspired by Murakami theory, also for considering the particularity of geometrical size of micro scratch, we proposed the fatigue damage parameter $\sqrt{\text{area}}$ for micro scratch, which is defined as the square root of triangle area of scratch section:

$$\sqrt{\text{area}_i} = \sqrt{\frac{W_i\ D_i}{2}}, \ (1)$$

whereW_i and $D_i$are defined as the width and depth of scratch i . If there are multiple scratches on the detected surface, $\sqrt{\text{area}}$ is determined by the maximum value of Equation 1 due to larger scratch has more severe stress concentration. Detailed discussion about$\sqrt{\text{area}}$ can be found in Ref. [18]. $\sqrt{\text{area}}$ only take depth and width of micro scratch as fatigue damage control factors.

3 | Material and experiment

3.1 | Material and experiment

With a requirement of aero-engine with high thrust-weight ratio, the design and manufacture of blisk has been regarded as the key technology by many countries. TC17 Titanium alloy has attracted more and more attention in blisk manufacturing due to its outstanding mechanical performance, such as high-strength, excellent corrosion resistance and excellent toughness.

TC17 Titanium had the following mechanical properties: ultimate tensile strengthσ_t=1108 MPa, yield stress σ_s=1060 MPa, and Young's modulus E =111.5 GMPa, Vickers hardnessHV= 356 Kgf/mm^2.

The specimen used in the experiment is the hourglass type as shown in Fig. 1.

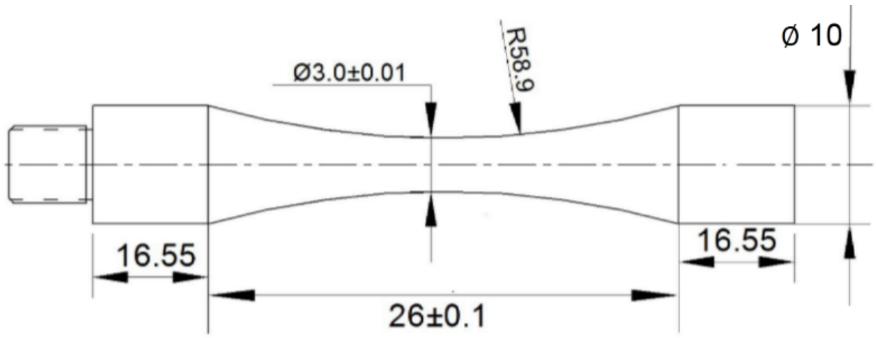


FIGURE 1 Specimen.

To study the effect of micro scratches on fatigue life of TC17, rough specimens were prepared. The machining defect, mainly micro scratches, were not eliminated by fine grinding and polishing in last process step.

Because of the extremely small size at micron level, optical interferometer is the most suitable method of measuring the scratches. ZYGO 3D optical profiler instrument owns numerous advantages: high measurement precise, non-contact surface measurement, and nanoscale surface features. The surface topography of specimens, along with the essential geometric parameter such as depth and width of scratches can be observed and measured by ZYGO accurately.

As shown in Figs. 2A-D, micro scratches are the main morphological characteristics for the specimens. Table 1 gives the measurement results of actual micro scratch depth and width by ZYGO along with $\sqrt{\text{area}}$ of each specimen. For each scratch, there cross-sections are measured and take the average value as the final depth and width. For each specimen with multiple scratches, only three largest scratches are observed and measured. Specific measurement methods and precautions are listed in Ref. [18].

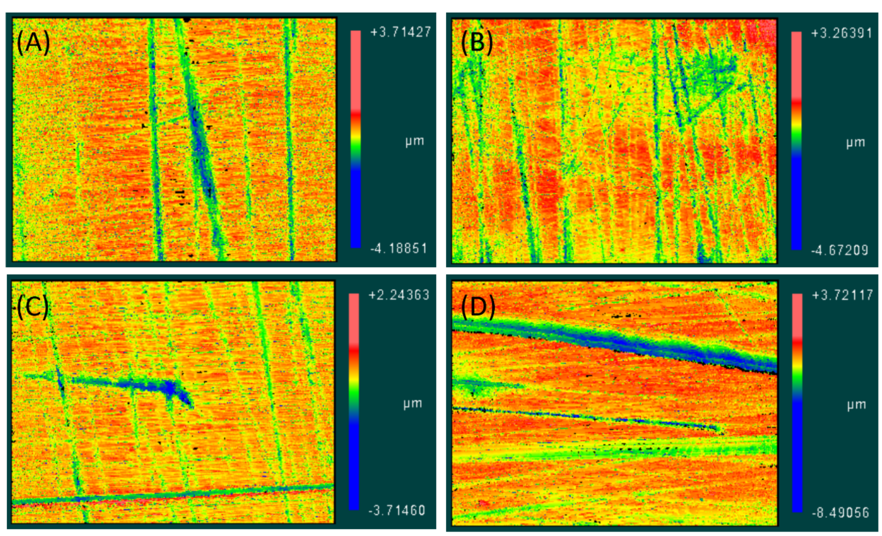


FIGURE 2 Surface topography of specimen (Measuring dimensions: 0.353×0.265mm):

Loading frequency shows no effect on fatigue life of TC17 at R = -1, 0.1, 0.5 and 0.7.[28] Therefore, USF-2000 ultrasonic tensile fatigue test system with a load ratio of R = -1is used because of its high efficiency and low energy consumption.[29] A cooling system is adopted to keep the testing environment at room temperature (20) to avoid the material behavior affected by the internal heat generation. The minimum stress amplitude is

600 MPa, increasing interval is 15 MPa in this experiment. Characteristic of the fatigue fracture morphology was observed by SEM.

TABLE 1 Data of width and depth (μm)

Specimens	Scratch 1	Scratch 1	Scratch 2	Scratch 2	Scratch 3	Scratch 3	$\sqrt{\text{area}}$
	W	D	W	D	W	D	
1	9.8	1.23					2.45
2	36.40	7.84	40.33	4.18			11.95
3	22.73	4.68	17.20	4.77	18.37	3.91	7.29
4	26.27	3.40	15.83	3.14			6.68
5	22.07	4.06	17.50	3.10	17.90	3.85	6.69
6	26.27	3.40	15.83	3.14			6.68
7	20.30	1.68	25.37	1.85			4.84
8	12.53	2.39	11.05	2.20			3.87
9	13.27	5.96	16.77	5.13	19.90	5.08	7.11
10	25.77	1.72	26.33	1.49			4.71
11	36.93	5.68	31.10	4.21	19.43	2.86	10.24
12	12.73	1.57	13.50	1.76			3.45
13	30.35	2.15	18.30	3.55	38.35	2.10	6.35
14	19.77	2.90					5.35
15	9.80	1.35	11.60	1.52			2.97
16	30.57	6.41					9.90
17	26.70	4.16	30.75	3.83	28.17	4.39	7.86
18	12.70	1.02	14.35	1.88			3.67
19	16.93	3.46	24.85	3.07			6.18
20	20.80	4.85	20.07	3.93	18.80	4.93	7.10
21	19.80	5.93	39.90	5.29			10.27
22	41.35	7.10	33.13	5.04	40.33	7.37	12.19
23		1.26	25.0	1.30			4.03

3.2 | Experiments results

The distribution of stress amplitude σ_a and experimental fatigue lifeN_f is portrayed in Fig. 3. If a specimen exceeds 10^9cycles, it was defined as "run out".

Fatigue life mainly concentrates on the HCF regime$10^4 < N_f < 10^6$. The transition between high cycle fatigue and very high cycle (VHCF) fatigue is shown as a broken line. Although the loading level begins to decrease, fatigue life will not be reduced readily. Only under fatigue strength, fatigue life can reach to VHCF immediately. Therefore, it can be deduced that the existence of micro scratches significantly reduced fatigue life, which means that TC17 possesses a high sensitivity to micro scratches in this experiment.

That is to say, it is indeed a potential danger for TC17 blade to continue service under the harsh service environment once the part with accidental micro scratches. Fatigue life of the rough blade can be significantly reduced, even cannot satisfy a whole service cycle because of the scratches. Consequently, a model to estimate the fatigue life of TC17 blade with micro scratches can be quite necessary to guarantee service safety.

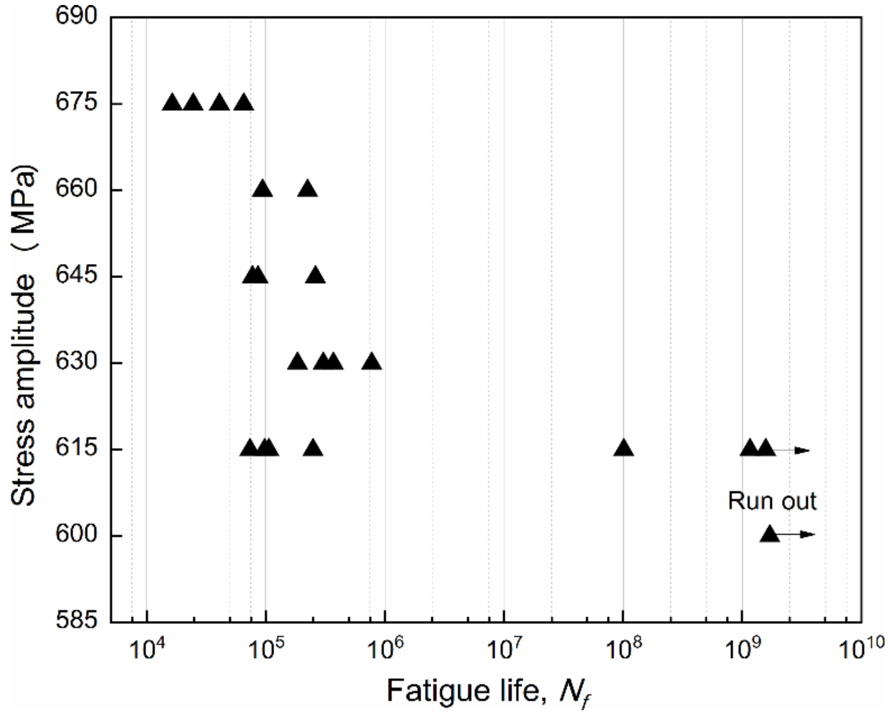


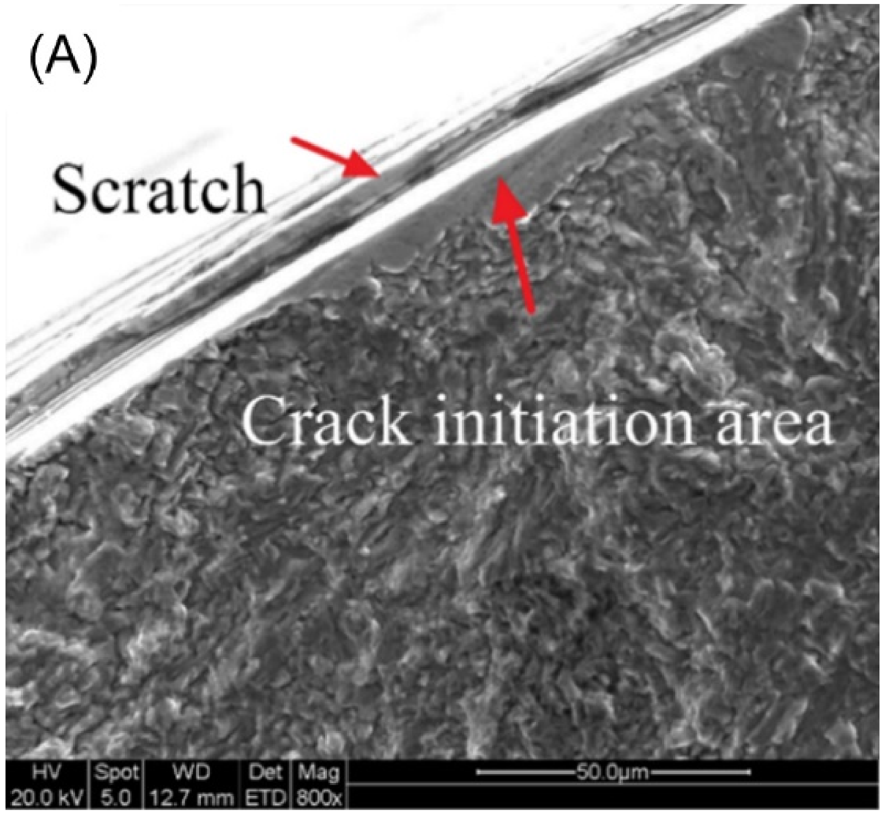
FIGURE 3 The distribution of fatigue lifeand stress amplitude.

3.3 | Fracture observations

Fatigue failure of all the specimens occurred from the surface scratches in this experiment, verified by the observation of SEM. And no facets were observed in the initiation area of all the specimens.

Figs. 4A-B show two typical examples of fatigue crack initiated from the root of scratch. It can be observed that scratch in Fig. 4A is distributed along the circumferential direction and the one in Fig. 4B is along the axial direction of the specimens. Both the two cases have the same failure mode.

Surface scratches can serve as stress concentrators and produce localized stress concentration at the surface. Micro scratch can push crack to the stage of propagation stage in a short time. Small crack propagation can be ignored. Thus, it can be regarded as the equivalent initial crack. At these positions around scratches where cyclic plastic deformation is higher than the average, which caused fatigue failure.[30]


(A)
Scratch
Crack initiation area
HV 20.0 kV
Spot 5.0
WD 12.7 mm
Det ETD
Mag 800x
50.0μm

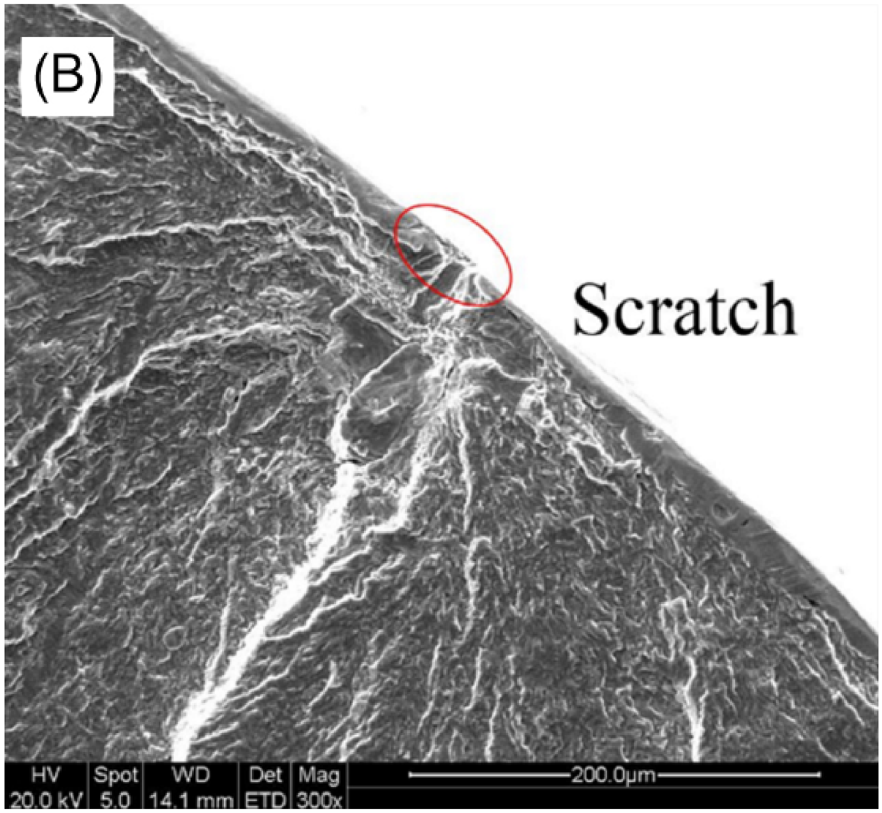


FIGURE 4 Observation of fracture by SEM:

4 | Fatigue life prediction based on micro scratches

4.1| Condition fatigue strength model

The well-known condition fatigue strength model proposed by Murakami has been widely verified and applied to describe the effect of surface defect on fatigue strength:

$\sigma_w = \frac{1.43(HV+120)}{\sqrt{\text{area}}^{1/6}}$, (2)

where HV is Vickers hardness, and C =1.43 for the surface defect. For a certain material, the projected area is the critical factor that control fatigue strength.

4.2 | Three-parameter model

Classic fatigue analysis theory depends on the S -N curve. On the basis of being widely recognized by scholars, mathematical expression of S -N curve can be classified into four types as follows: Basquin model [31], Langer model[32], Weibull three-parameter model[33] and Manson-Coffin model. [34] The effect of fatigue strength on S -N curve can be reflected by the three-parameter model. The introduction of three parameter make it much more flexible and accurate in describing S -N curve under a given R :

$N_P = C(\sigma_a - \sigma_w)^{-m}$, (3)

Where N_P is the predicted life, σ_a is stress amplitude; σ_w is fatigue strength, m and $c$are constant which related to material, R and loading mode.

4.3 | Fatigue life prediction

It should be pointed out that it is the smooth specimen without surface defect that is used in the experiment to obtain fatigue strengthσ_w. σ_w is constant for a certain material under required experimental conditions. In the aeronautical practice, the parts would inevitably have surface defects, especially micro scratches. Fatigue strength will be reduced due to the serious stress concentration, and different geometric size of micro scratches can lead to different fatigue strength. Thus, the traditional fatigue strength would be not applicable in the three-parameter model for parts containing micro scratches.

In order to introduce the effect of micro scratch into fatigue strength, combined with the proposed $\sqrt{\text{area}}$, the modified condition surface conditional fatigue strength with the consideration of micro scratches is obtained as:

$\sigma_{w,} = \frac{1.43(HV+120)}{\sqrt{\text{area}}^{1/6}}$, (4)

In this paper, condition fatigue strength is introduced to in the three-parameter model to describe the effect of micro scratches on HCF life of TC17:

$N_P = C(\sigma_a - \sigma_{w,})^{-m}$, (5)

Equation 5 derives from the combination of Murakami theory and the three-parameter model, which establishes the link between surface fatigue damage caused by micro scratches and HCF life of TC17 in HCF regime. But two parameters for micro scratches, m and Ccontinue to be undetermined. There is no reference to the unknown parameters in the current literature, especially relating to micro scratches. The two parameters can reflect the effect of micro scratches on HCF life of TC17, so it can be obtained from the designed fatigue experiment data. The fitting algorithm uses continuous curves or analytical expressions to represent discrete data and the functional relationship between the variables. By using of the experiment data, the results of the parameter are estimated as $m = 1.8,\ C = 9.33E + 8$.

Then substitute the obtained parameters m and C into Equation 5, the HCF life model of TC17 with the consideration of micro scratch can be obtained:

$N_P = 9.33E + 8\left(\sigma_a - 680.68/\sqrt{\text{area}}^{1/6}\right)^{-1.8}$, (6)

Fig. 5 present the result of fatigue life prediction. The predicted life values mainly fall into the scatter band of factor 2. In general and despite of some dispersion, a fair correlation between the experimental and predicted value is achieved, indicating that the$\sqrt{\text{area}}$ is also applicable to classic fatigue theory.

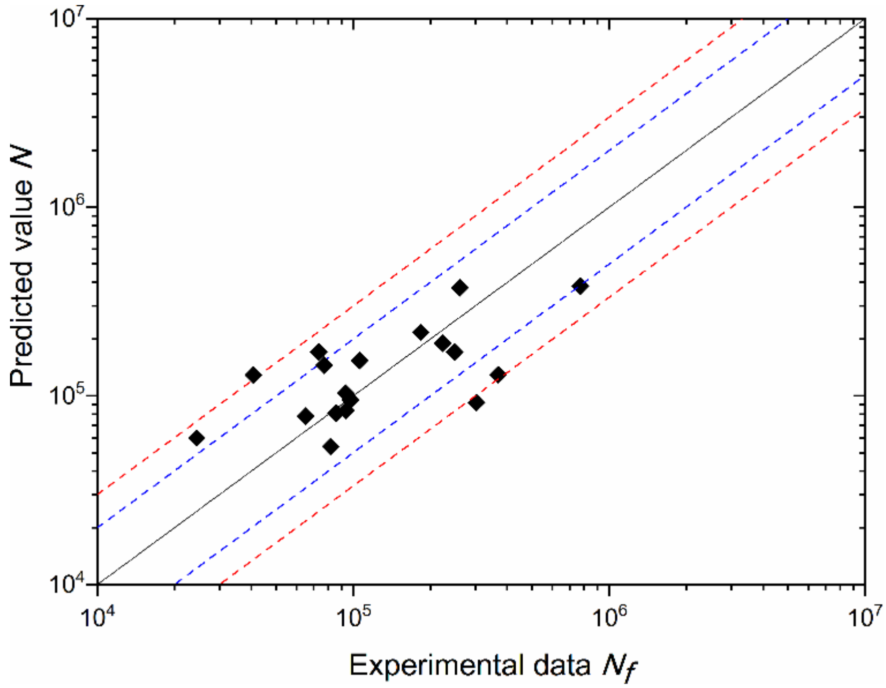


FIGURE 5 Result of fatigue life prediction

5 | Discussion

Surface condition such as different processing methods[35] or surface roughness[36,37] has a critical effect on fatigue strength and fatigue life. It should be pointed out that in most cases it is the micro scratch that finally affects fatigue behavior among different processing methods or surface roughness. Micro scratch is one of the most concerned problems in structure service. $\sqrt{area}$ brought Murakami theory into micro dimension level, which aimed at actual micro scratch in order to provide an effective parameter for fatigue damage estimation.

To examine fatigue strength of component with micro scratches, the depth and width of detectable scratches should be collected. Fatigue damage parameter $\sqrt{area}$ can be calculated using Equation 1. Combined with Vickers hardness of material, conditional fatigue strength can be achieved by Equation 4. The accuracy of $\sqrt{area}$in conditional fatigue strength prediction was checked by FV520B-I, Ti-6Al-4V and EA4T steel using Equation 4.[16,18]Prediction error is lower than 10%.

Classic fatigue-life curve method can provide essential parameters of material fatigue properties for infinite fatigue life design. Obviously, the presence of micro scratch can reduce fatigue properties including fatigue strength and fatigue life. $\sqrt{area}$ can be applied to describe fatigue damage caused by micro scratch quantitatively. The relationship between fatigue life and stress amplitude affected by micro scratch can be revealed by modify fatigue strength using $\sqrt{area}$. According to Fig. 5, acceptable result was also achieved combining with three-parameter model and $\sqrt{area}$.

Crack growth analysis in fracture mechanics is mainly adopted for damage tolerance design. Fatigue life of component with initial defect generated by manufacturing or assembly process can be assessed using fatigue crack growth rate $\frac{\mathrm{da}}{\mathrm{dN}}$. A problem in the fracture mechanics-based life prediction is to determine the equivalent initial defect size a_0 for crack growth analysis. Because of the presence of micro scratch, the initiation and propagation life of small cracks can be ignored. In such a situation,$\sqrt{area}$ provide another method to estimate equivalent initial defect size a_0 for component with micro scratch. Reasonable fatigue life result was examined its ability in the combination with the fracture mechanics and crack growth analysis of TC17 titanium alloy[18].

Since a new fatigue damage parameter for micro scratch is obtained, more attempts can be made to combine $\sqrt{\text{area}}$ with the existing fatigue analysis theories to study the fatigue behavior affected by micro scratch. These results support the validity of $\sqrt{\text{area}}$ in fatigue analysis, even though it is evident that more work has to be done in this area to more deeply investigate its accuracy and reliability.

Facing with the characteristics of random length and direction of micro scratch, $\sqrt{\text{area}}$ highlights the effect of depth and width on fatigue damage estimation. This is proved to be useful and convenient to service safety concerned with surface condition. To a certain extent, it can facilitate the engineering application in dealing with fatigue problem affected by micro scratch.

Due to the small size at micron level, there may be some obstacles in measuring the actual dept and width of micro scratch. To a certain extent, optical profiler instrument can reflect the actual geometric parameters of micro scratch. As a traditional and widely method, stylus method can present an alternative method to determine the approximate size scratch. Other measuring methods such as 3D mapping technology[38,39] and powder filling method[11] are also recommend for micro scratch to guarantee prediction accuracy. Multiple scratch on the surface of component is general situation in engineering practice, the principle of measuring the maximum scratch and cross-section should be followed

6 | Conclusions

This paper summarizes an attempt to estimate fatigue life of TC17 titanium alloy considering micro scratch, based on the use of the three-parameter model combined with $\sqrt{\text{area}}$. Conclusions can be drawn as follows:

1. Fatigue failure mode for TC17 is that surface failure without facets in this study. TC17 possesses a high sensitivity to micro scratches in this experiment.
2. With the assistant of $\sqrt{\text{area}}$, an HCF life model of TC17 based on micro scratch is established by the combined application of modified surface condition fatigue strength and the three-parameter model. With the accuracy of prediction result, it can be concluded that $\sqrt{\text{area}}$ has the rationality and validity in combination classic fatigue-life curve method.
3. Reasonable results are obtained in conditional fatigue strength and fatigue life prediction using $\sqrt{\text{area}}$ in combination with current fatigue theories. $\sqrt{\text{area}}$ has potential applicability as a useful parameter to study fatigue behavior affected by micro scratch.

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