Study on the fretting fatigue behavior of alloy ZSGH4169 at different temperatures

Zeyu Xing，Hongjian Zhang*，Haitao Cui，Ziqiang Yu, Xiaodong Yan, Weidong Wen

Aero-engine Thermal Environment and Structure Key Laboratory of Ministry of Industry and Information Technology; Jiangsu Province Key Laboratory of Aerospace Power System; State Key Laboratory of Mechanics and Control of Mechanical Structures; College of Energy & Power Engineering, Nanjing University of Aeronautics and Astronautics Jiangsu, 210016, P.R. China

*Corresponding author: Hongjian Zhang

*E-mail address: zhanghongjian@nuaa.edu.cn

*Postal address: College of Energy & Power Engineering, Nanjing University of Aeronautics and Astronautics, 210016 Nanjing, Jiangsu, P. R. China

Abstract：In this paper, nickel-based alloy ZSGH4169 was used as the test material and the fretting fatigue test of standard test pieces was carried out to study the variation rule of its fretting fatigue life under different temperatures and loads. The results show that the fretting fatigue life of ZSGH4169 decreases with the increase of temperature and load. Through fracture analysis under different working conditions, it can be seen that ZSGH4169 fretting fatigue failure form is basically the same, the crack expands in the form of transgranular fracture propagation. Temperature and load have significant influence on the depth of fretting fatigue crack initiation zone and the fatigue band spacing in the propagation zone, which affects its fretting fatigue life. According to the analysis of crack initiation and propagation path, the crack initiation angle of fretting fatigue crack is mainly affected by temperature. With the increase of temperature, the crack initiation angle increases, however the load has little influence on the crack initiation angle.

Keyword: Nickel-based alloy; fretting fatigue life; fracture analysis; transgranular fracture; crack initiation angle

1 | Introduction

Fretting refers to the movement with very small amplitude (micron magnitude) between the surfaces in contact with each other. In a vibrating environment, two closely matched surfaces are prone to occur fretting damage[1]. Fretting can be divided into three categories: fretting fatigue, fretting wear and fretting corrosion according to different damage forms. Among them, the occurrence of fretting corrosion is relatively rare, and for fretting fatigue and fretting wear, although their damage mechanisms are different, the relationship between the two is close. Generally speaking, fretting wear occurs during fretting fatigue. In fact, in engineering, most of the causes of structural failure are fretting fatigue, and the severity of its consequences often exceeds fretting wear[2], so fretting fatigue is also called ‘industrial cancer’. The main factors affecting fretting fatigue are contact pressure[3,4], slip amplitude[5,6], experimental frequency[7], fretting environment[8,9], contact area material[10], etc.

The nickel-based super-alloy ZSGH4169 has excellent high-temperature mechanical properties, good thermal processing and welding properties, and excellent fatigue resistance. Due to the excellent comprehensive properties of the material, ZSGH4169 alloy is currently the most

widely used and the largest amount of super-alloy material in the fields of aviation and aerospace (accounting for 1/3 of the annual output of super-alloys)[11]. Therefore, it is very necessary to carry out ZSGH4169 fretting fatigue test research.

Due to the particularity of the working environment of aeroengine hot-end components, many scholars have carried out high-temperature fretting fatigue test research and analysis. Hamdy and Waterhouse[12] conducted high-temperature fretting fatigue experiments on TC4 through experiments. Dai[13] et al. used titanium alloy bridge specimens to study the effects of contact stress, relative displacement amplitude and temperature on fretting fatigue life. Jin[14] studied the fretting fatigue behavior of titanium alloy Ti-6Al-4V at a high temperature of 260°C. He found that the coefficient of static friction (COF) increased slightly at the beginning of the fretting cycle and then reached a constant value. The COF value at 260°C and its change with cycle are similar to room temperature. This is because there is no oxide layer formed on the Ti-6Al-4V surface at 260°C.Zhang[15] et al carried out fretting fatigue study on titanium alloy bridge sample by using high frequency fatigue testing machine and self-made high temperature resistance furnace, and analyzed the influence of temperature, contact stress and relative displacement amplitude on fretting fatigue at high temperature. Mall[16] et al. studied the fretting fatigue behavior of Nickel-based super-alloy IN100 at 600°C, and found that fatigue crack initiation and crack growth resistance increased with the decrease of grain size. Komatsu, Okazaki and Miyashita[17] studied the general fatigue and fretting fatigue behaviors of titanium alloys at room temperature, 400°C and 590°C, and calculated the contact stress and relative displacement amplitude by using the finite element method. Wang[18] carried out the fretting fatigue test and theoretical study of titanium alloy dovetail tenon at high temperature. And adopt the combination of dynamic displacement and dynamic strain to detect the initiation of fretting fatigue cracks in time. The influencing factors of fretting fatigue are analyzed, and an equivalent damage parameter considering the influence of temperature is proposed. Peng[19] conducted a torsional fretting test on 7075 aluminum alloy on the basis of a self-designed fretting fatigue test machine, and established the S-N curve of the material. And using three-dimensional profiler, scanning electron microscope and electron probe micro-analyzer to analyze the torsional fretting fatigue damage area. The research results reveal the damage mechanism of torsional fretting fatigue under different conditions, and indicate that the effect of fretting greatly reduces the torsional fatigue life. In addition, the damage analysis results show that as the contact pressure increases, the damage becomes more serious. The oxidation products are mainly Al_2O_3 and $Al(OH)_3$, and the edge of the contact area is more severely oxidized than the contact center. Sangam Sangral[20] studied the fretting fatigue behavior of 6061-T4 aluminum alloy at room temperature and 200°C, and found that the geometry of the contact pad and the test temperature have a significant effect on the fretting fatigue strength. Kong[21] studied the fretting fatigue fracture mechanism of TB6 high-strength titanium alloy under tension-torsion multiaxial stress conditions, and analyzed the difference in fretting fatigue life of lugs with different process conditions under tension-torsion fatigue test stress. The initiation and propagation characteristics of fretting fatigue cracks are discussed, and the mechanism of ear crack initiation is revealed.

In order to explore the mechanism of fretting fatigue damage, Sam Naboulsi et al.[22] introduced the crack analog fretting parameter (CAF) on the basis of the crack analog method (CAM) to study the crack initiation of fretting fatigue. Long Xin[23] et al. studied the evolution of fretting wear behavior and damage mechanism of 690TT alloy under different cycles. The

competition between fretting fatigue crack (FF) and fretting wear (FW) runs through the entire fretting wear process. Before 1.2×10^4 cycles, fatigue crack growth is faster than wear. With the continuous increase of fretting cycles, the wear rate is significantly faster than fatigue crack growth. Tribological transformation structure (TTS) participates in the competition between FF and FW. The gain boundary and dislocations in TTS are suitable ways for crack initiation, propagation and oxygen permeability. Peng[24] et al. conducted a study on the torsional fretting fatigue damage evolution of 7075 aluminum alloy, and the test results revealed the damage mechanism of torsional fretting fatigue in different states, and the fretting effect greatly reduced the fatigue life. The friction coefficient increases with the increase of the torque. When the fretting is operated under a mixed fretting and sliding state, the oxidation of the damaged area near the loading end becomes serious, accompanied by the generation of micro-cracks; while no micro-cracks were generated in the complete slip zone. Sun[25] et al developed a new type of high-temperature fretting fatigue test device to study the high-temperature fretting fatigue mechanism of nickel-based single crystal alloy DD6. The results show that the fretting fatigue life decreases with the increase of axial load and normal load. Metallographic observation showed that the surface peeling and delamination occurred in the contact area. Energy dispersive spectroscopy (EDS) analysis shows that the surface material is oxidized and the oxide will be compacted to the contact surface to form a glaze layer. In addition, many micro-cracks were observed on the contact surface, which were almost perpendicular to the direction of the micro-movement. The combined effect of fretting wear and crystal slip is the cause of fretting fatigue failure. V.Chaudhry[26] et al studied the fretting fatigue damage mechanism of stainless steel (SS316L) and chromium carbide coating. The test results show that the initiation or nucleation of damage in SS316L is caused by severe plastic deformation. The crack propagation is controlled by the strain energy release rate, and its direction is affected by the contact conditions on the contact interface.

In summary, scholars have mainly studied the high temperature fretting fatigue test of titanium alloy and aluminum alloy, but there are few studies on the fretting fatigue test of nickel-based super-alloy ZSGH4169. Therefore, it is of great significance to study the high temperature fretting fatigue test of ZSGH4169. In this paper, the nickel-based super-alloy ZSGH4169 is used as the test material to carry out the fretting fatigue test of the standard test piece. The fretting fatigue life is studied at room temperature, 400°C and 650°C, and the fretting fatigue fracture is analyzed to reveal its fretting fatigue failure form. The parameters obtained by fitting the test results of standard test pieces (selecting four working conditions) are substituted into the high temperature fretting fatigue life prediction model based on continuum damage mechanics, and the life prediction verification of the test results of other working conditions is carried out.

2 | Fretting fatigue test

2.1 | Test materials

The material selected for this experiment is the nickel-based super alloy ZSGH4169, which has excellent high-temperature mechanical properties. ZSGH4169 is a GH4169 forging produced by the direct aging process, which is a poly-crystalline isotropic material. ZSGH4169 is a deformed super alloy in which the matrix is austenite and the strengthening phases are body-centered cubic Ni phase and face-centered cubic $Ni(Al,Ti,Nb)(\gamma')$ phase. The yield strength at 650°C is the highest among the deformed super-alloys. The mechanical properties of the alloy at room temperature, 400°C and 650°C are shown in Table 1[27].

Table 1 Mechanical properties of ZSGH4169 at different temperatures

T / ℃	E / GPa	μ	$\sigma_{0.2}$ / MPa	σ_b / MPa
25	211.5	0.301	1330	1480
400	199	0.318	1180	1320
650	152	0.327	1140	1270

In order to simulate the machining accuracy of real turbine mortise structure to the greatest extent,all the test pieces are formed by slow wire EDM, and the fretting-pad is cut by slow wire, with the machining precision up to 0.01mm.

2.2 | Test piece scheme

In this paper, the axial load of the standard test pieces is 700MPa and 800MPa;the normal load of contact area is 140MPa and 190MPa. During the test, the axial load stress ratio is 0.1, that is, the load valley value/load peak value =0.1, the load frequency is 10Hz.The specific test conditions and the number of test pieces are shown in Table 2,while the specific standard test piece structure is shown in FIGURE 1.

Table 2 Standard test piece test conditions and number of test pieces

T(°C)	Working condition	Axial load	Normal load	Number of test piece
20°C	ZS_1	700MPa	140MPa	3
	ZS_2	800MPa	140MPa	3
	ZS_3	700MPa	190MPa	3
	ZS_4	800MPa	190MPa	3
400°C	ZS_5	700MPa	140MPa	2
	ZS_6	800MPa	140MPa	2
650°C	ZS_7	700MPa	140MPa	2
	ZS_8	800MPa	140MPa	2

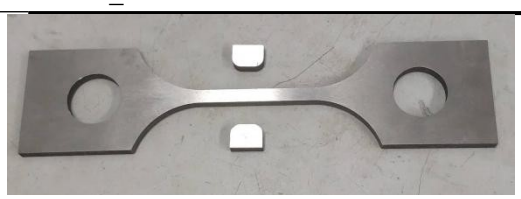


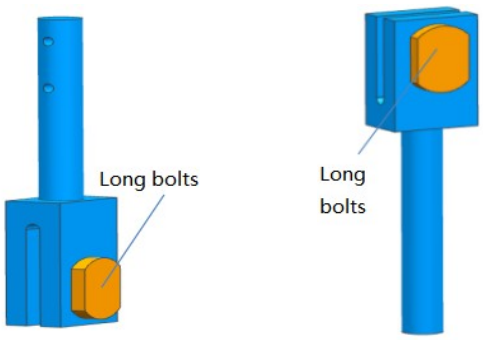
FIGURE 1 Standard test piece

2.3 | Test device

This article uses the model SDS-50 electro-hydraulic servo fatigue testing machine for fretting fatigue test, as shown in FIGURE 2.

FIGURE 2 SDS-50 Electro-hydraulic Servo Dynamic and Static Fatigue Testing Machine

In order to ensure the good neutrality of the test piece during the fretting fatigue test, a transition fixture is needed between the test piece and the testing machine chuck. The fixture is divided into upper and lower parts, holding the two ends of the test piece respectively, and connecting with the test piece by bolts. The structure of the fixture is shown in FIGURE 3. The transition part between the fixture and the testing machine is cylindrical, and it is clamped by a special cylindrical chuck to keep the axial load on the test piece in the vertical direction, because the test needs to be in the vertical direction. It is carried out under high temperature environment, so GH4169 is also selected as the fixture material.



(a) upper part (b)lower part

FIGURE 3 Schematic diagram of test fixture

The fretting fatigue test of the standard test piece requires the application of axial load and normal load to the test piece. Axial cyclic fatigue loads are provided by the testing machine, while normal loads are provided by the stress ring. The structure of the stress ring is shown in FIGURE 4. By tightening the bolts, normal force can be applied to the fretting pad. There are resistance strain gauges on both sides of the stress ring. The strain value of the strain gauges which are connected to the dynamic strain gauge represent the normal load.

FIGURE 4 The stress ring

In order to explore the influence of the working environment temperature on the fatigue life of ZSGH4169, a temperature control device is needed to change the working environment temperature. Due to the need to place a stress ring to apply the normal force, the heating furnace is designed as a split type for heating. FIGURE 5 shows a split heating device.

FIGURE 5 The heating device

3 | Experimental results and analysis

3.1 | The influence of axial force and temperature on fretting fatigue life

By comparing the test results of working conditions ZS_1, ZS_5 and ZS_7 with those of working conditions ZS_2, ZS_6 and ZS_8, and comparing the test life, the influence rule of temperature on the fretting fatigue life can be obtained.

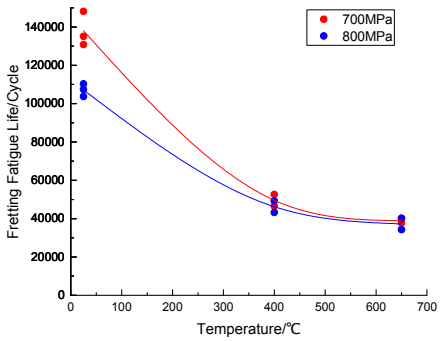


FIGURE 6 Relationship between fretting fatigue life and temperature under different axial stresses

FIGURE 6 shows the influence rule of temperature on fretting fatigue life when the axial

stress is 700MPa and 800MPa.It can be seen from the figure that the fretting fatigue life decreases with the increase of axial load. Under the same axial load, the fretting fatigue life decreases significantly with the increase of temperature. As the axial stress is 700MPa, when the temperature increases from 25°C to 400°C, the fatigue life of fretting fatigue decreases by 64.08%, and when the temperature increases from 400°C to 650°C, the fatigue life of fretting fatigue decreases by 21.43%; as the axial stress is 800MPa, when the temperature rises from 25°C to 400°C, the fatigue life of fretting fatigue decreases by 56.86%, and when the temperature rises from 400°C to 650°C, the fatigue life of fretting fatigue decreases by 19.48%. In addition, as can be seen from the slope of the curve shown in the figure, with the increase of temperature, its influence on the fretting fatigue life shows a downward trend. This is because the higher the temperature is, the more lubricity oxide is generated on the material surface, which reduces the friction coefficient and slows down the wear rate of the test part to a certain extent.

3.2 | The influence of normal force on fretting fatigue life

By comparing ZS_1, ZS_3 and ZS_2 and ZS_4 in working conditions, the influence rules of different normal loads on fretting fatigue life under room temperature can be obtained.

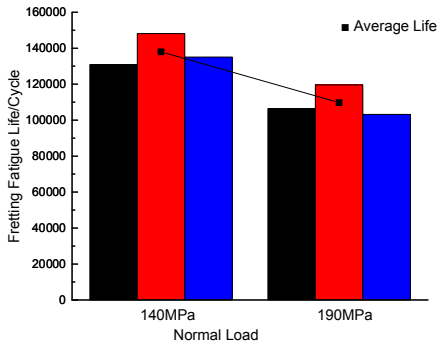


FIGURE 7 Relationship between fretting fatigue life and normal load when axial stress is 700MPa

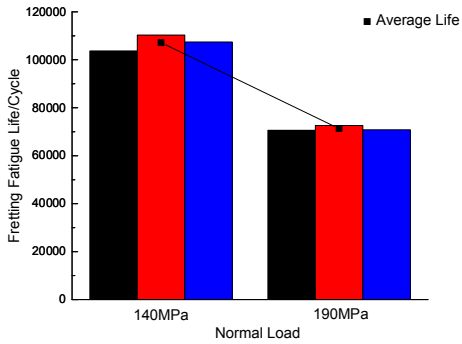


FIGURE 8 Relationship between fretting fatigue life and normal load when axial stress is 800MPa

FIGURE 7 and FIGURE 8 show the relationship between fretting fatigue life and normal load when the axial load is 700MPa and 800MPa at room temperature respectively.It can be seen from the figure that the fretting fatigue life decreases with the increase of normal contact stress.When the axial stress is 700MPa, the corresponding life of 190MPa normal stress is 28.292% less than that of 140MPa normal stress.When the axial stress is 800MPa, the corresponding life of 190MPa of normal stress is 35.802% less than that of 140MPa of normal

stress.It shows that normal stress has great influence on fretting fatigue life at room temperature.

4 | Fracture analysis

In order to explore how temperature, normal load and axial load influence fretting fatigue life, five working conditions (ZS_1, ZS_3, ZS_4, ZS_5 and ZS_7) are selected in this paper for fracture analysis and crack propagation path analysis.The fatigue failure of materials generally undergoes four stages: crack initiation, crack propagation, rapid propagation and transient zone. Since the transient zone has little influence on the fatigue life of fretting, it is not discussed in this paper. FIGURE 9 to FIGURE 13 are fracture SEM images under various working conditions, in which FIGURE(a) is the morphology of the entire fracture, FIGURE(b) is the morphology of the crack initiation area, FIGURE(c) is the morphology of the crack propagation area, and FIGURE(d) is the morphology of the rapid propagation area. By comparing the morphology of the fatigue source area under five working conditions, it can be seen that the fretting fatigue crack initiate from the lower edge of the contact area and its position is random. Cracks always start at one point and expand in a fan shape. Crack propagation are predominantly transgranular propagation. Propagation fracture morphology is relatively flat, while the topography of the rapid propagation zone and the transient zone is fluctuant. In order to compare the effects of temperature and load on crack initiation and propagation better, this paper analyzes the fracture by region.

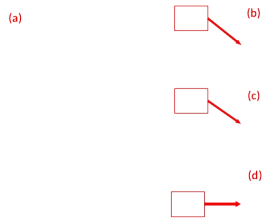


FIGURE 9 Working condition ZS_1 SEM image (Temperature:room temperature Axial stress:700MPa Normal stress:140MPa)

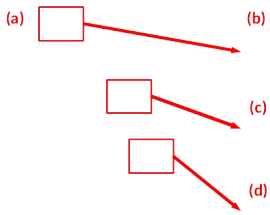


FIGURE 10 Working condition ZS_3 SEM image (Temperature:room temperature Axial stress:700MPa Normal stress:190MPa)

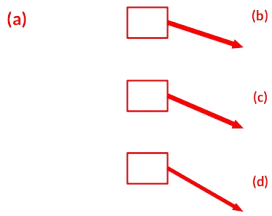


FIGURE 11 Working condition ZS_4 SEM image (Temperature:room temperature Axial stress:800MPa Normal stress:140MPa)

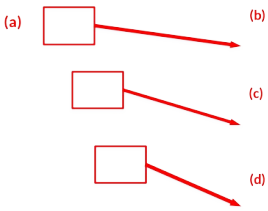


FIGURE 12 Working condition ZS_5 SEM image (Temperature:400°C Axial stress:700MPa Normal stress:140MPa)

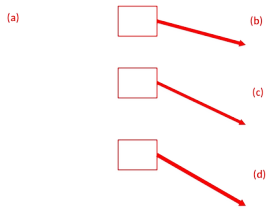


FIGURE 13 Working condition ZS_7 SEM image (Temperature:650°C Axial stress:700MPa Normal stress:140MPa)

4.1 | Crack initiation area

The depth of crack initiation area under five working conditions was measured, and the results were shown in the following table:

Table 3 Depth comparison of fretting fatigue crack initiation zones under different working conditions

Working condition	Depth of crack initiation zone/mm
ZS_1	0.647
ZS_3	0.788
ZS_4	0.803
ZS_5	0.806
ZS_7	1.102

Compared with ZS_1, ZS_5 and ZS_7 working conditions, the influence of temperature on the fretting fatigue crack initiation area was analyzed. Under the same load, with the increase of temperature, the depth of fretting fatigue crack initiation zone increased gradually. The reason for this phenomenon is that at this stress level, high-temperature softening plays a dominant role. Compared with the condition at room temperature, the plastic deformation at high temperature makes it difficult for cracks to expand during the initiation stage, which leads to the increase of the depth of the fretting fatigue crack initiation area.

Compared with ZS_1 and ZS_3 working conditions, the influence of normal stress on fretting fatigue crack initiation area was analyzed. Under the same temperature,with the increase of normal stress, the depth of fretting fatigue crack initiation zone increased gradually. This indicates that with the increase of normal load, the stress concentration is significant, and the plastic deformation in the crack initiation area of the test pieces increases, which also makes it difficult for cracks to expand during the initiation area, thus leading to the increase in the depth of the fretting fatigue crack initiation area.

Compared with ZS_1 and ZS_4 working conditions, the influence of axial stress on fretting fatigue crack initiation area was analyzed. Under the same temperature,with the increase of axial stress, the depth of fretting fatigue crack initiation zone increased gradually. This indicates that with the increase of normal load, the stress concentration is significant, and the plastic deformation in the crack initiation area of the test pieces increases, which also makes it difficult for cracks to expand during the initiation area, thus leading to the increase in the depth of the fretting fatigue crack initiation area.

4.2 | Crack propagation area

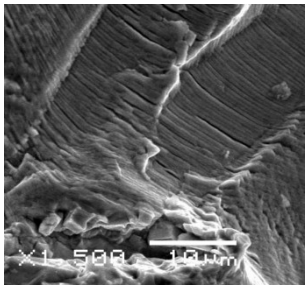
The crack growth areas under five working conditions were measured and converted into a percentage form, and the results were shown in the following table:

Table 4 Comparison of fretting fatigue crack growth area and its proportion under different working conditions

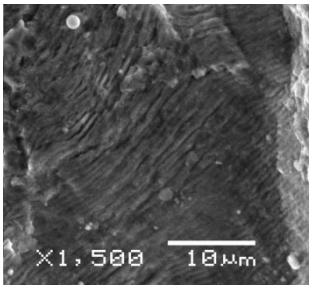
Working condition	Area of crack propagation /mm^2	Proportion of crack propagation area
ZS_1	16.012	64.048%
ZS_3	12.715	50.860%
ZS_4	11.894	47.576%
ZS_5	10.285	41.140%

ZS_7	10.122	40.488%

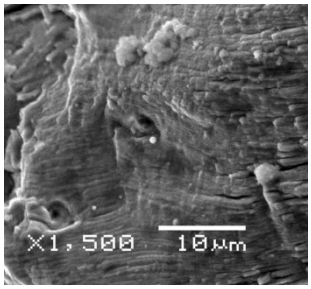
By comparing the working conditions ZS_1, ZS_5 and ZS_7, it can be seen that with the increase of temperature, the area of fretting fatigue crack propagation zone gradually decreases, and the proportion of the area of fretting fatigue crack growth zone decreases; by comparing ZS_1 and ZS_3 under the working conditions, it can be seen that with the increase of normal load, the area of fretting fatigue crack propagation zone gradually decreases, and the proportion of the area of fretting fatigue crack growth zone decreases; by comparing ZS_3 and ZS_4 under the working conditions, it can be seen that with the increase of axial load, the area of fretting fatigue crack propagation zone gradually decreases, and the proportion of the area of fretting fatigue crack growth zone decreases. Enlarge the propagation zone for further analysis, as shown in FIGURE 14.



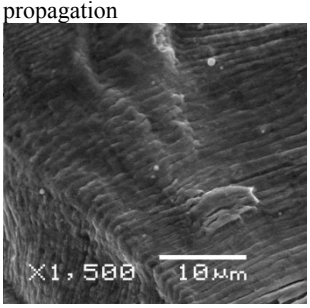
(a) Detail diagram of ZS_1 propagation



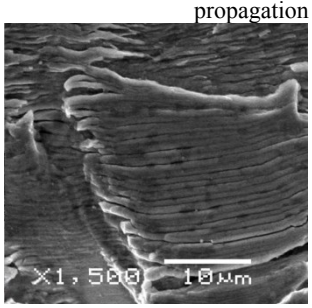
(b) Detail diagram of ZS_3 propagation



(c) Detail diagram of ZS_4 propagation



(d) Detail diagram of ZS_5 propagation



(e) Detail diagram of ZS_7 propagation

FIGURE 14 Detail diagram of propagation area under different working conditions

As can be seen from FIGURE 14, the fretting fatigue crack propagation zone has obvious banded stripes, but the spacing of the fatigue bands is different under different temperatures and loads. The fatigue band spacing can reflect the fretting fatigue crack growth rate. The larger the fatigue band spacing is, the faster the fretting fatigue crack growth rate will be. The sections with clear fatigue bands were selected to measure the spacing of the propagation areas of the above five working conditions. The fatigue bands at three different positions were selected for average processing in each working condition to obtain the final fatigue band spacing, as shown in Table 5.

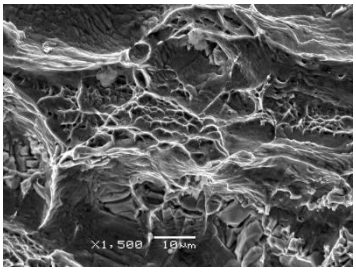
Table 5 Average fatigue band spacing in fretting fatigue crack growth zone under different working conditions

Working condition	Average fatigue band spacing / μm
ZS_1	0.398

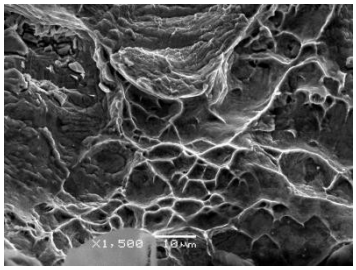
ZS_3	0.502
ZS_4	0.594
ZS_5	0.659
ZS_7	0.807

It can be seen from Table 5 that the fatigue band spacing increases with the increase of temperature, normal load and axial load. This indicates that the higher the temperature is, the faster the fretting fatigue crack propagation rate is; the larger the normal load is, the faster the fretting fatigue crack propagation rate is; the larger the axial load is, the faster the fretting fatigue expansion rate is. This is corresponding to the expansion area area and the proportion of expansion area area in Table 4. The larger the fatigue band spacing is, the faster the fretting fatigue expansion rate is, and the smaller the area and proportion of expansion area are, the shorter the fretting fatigue life is.

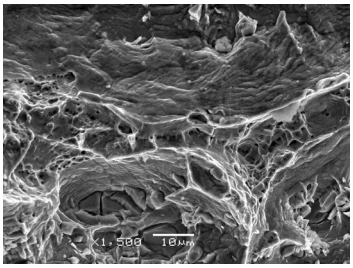
4.3 | Rapid propagation area



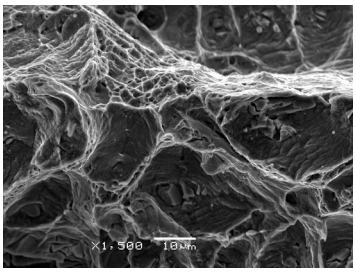
(a) Detail diagram of ZS_1 rapid propagation



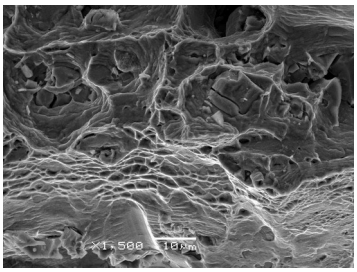
(b) Detail diagram of ZS_3 rapid propagation



(c) Detail diagram of ZS_4 propagation



(d) Detail diagram of ZS_5 rapid propagation



(e) Detail diagram of ZS_7 rapid propagation

FIGURE 15 Detail diagram of rapid propagation area under different working conditions

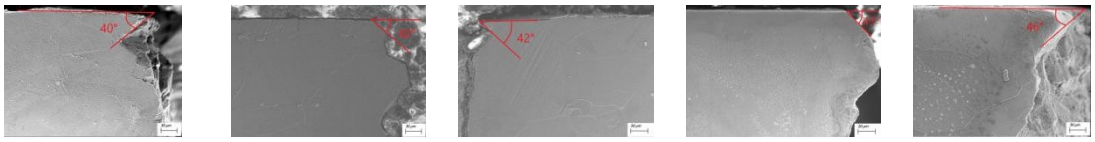
It can be seen from FIGURE 15 that, compared with the crack propagation area, the fatigue bands in the rapid propagation area were significantly reduced and dimples are significantly increased, which were the most important feature of fracture instability. The closer the region is to the transient fault zone, the more dimples there are. Compared with the propagation zone, the area of the rapid propagation zone is small, and the crack quickly enters the transient fault stage and fracture occurs. From the micro morphology, the effect of temperature and load on fretting fatigue crack rapid propagation zone of ZSGH4169 is small.

In summary, the fretting fatigue failure forms of ZSGH4169 under different working conditions are basically the same, and the fretting fatigue crack growth zone is all transgranular.

Temperature and load have significant influence on the initiation and propagation of fretting fatigue cracks. With the increase of temperature, the depth of fretting fatigue crack initiation area increased, the area of fretting fatigue crack propagation area decreased, the fatigue band spacing increased, and the crack propagation rate increased; With the increase of normal load, the depth of fretting fatigue crack initiation area increased, the area of fretting fatigue crack propagation area decreased, the fatigue band spacing increased, and the crack propagation rate increased; With the increase of axial load, the depth of fretting fatigue crack initiation area increased, the area of fretting fatigue crack propagation area decreased, the fatigue band spacing increased, and the crack propagation rate increased. This is reflected in the fretting fatigue life: the fretting fatigue life decreases with the increase of temperature, normal load and axial load.

5 | Crack initiation and propagation path analysis

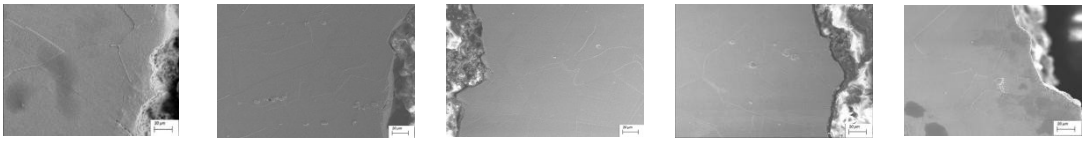
In order to better explain the macro mechanism of fretting fatigue, the initiation and propagation paths of fretting fatigue cracks were analyzed. FIGURE 16 shows the initiation angles of fretting fatigue cracks under different working conditions.



(a)The initial angle of ZS_1 (b)The initial angle of ZS_3 (c)The initial angle of ZS_4 (d)The initial angle of ZS_5 (e)The initial angle of ZS_7

FIGURE 16 Fretting fatigue crack initial angles under different working conditions

FIGURE 16 shows that the fretting fatigue crack initial angle at room temperature was about 40°±2°, and that at high temperature was about 45°±2°. This indicates that the crack initiation angle of fretting fatigue is mainly affected by temperature. With the increase of temperature, the crack initiation angle increases, however the load has little influence on the crack initiation angle.



(a)Crack propagation path of ZS_1 (b)Crack propagation path of ZS_3 (c)Crack propagation path of ZS_4 (d)Crack propagation path of ZS_5 (e)Crack propagation path of ZS_7

FIGURE 17 Propagation path of fretting fatigue crack propagation zone under different working conditions

FIGURE 17 is a schematic diagram of the propagation path of the fretting fatigue crack propagation area under different working conditions. It can be seen from the figure that all the fretting fatigue crack growth under the five working conditions is transgranular, and the growth form does not change with temperature and load, which is consistent with the conclusion in the

fracture analysis in the 4th part.

6 | Conclusion and discussion

(1) Temperature has a great influence on the fretting fatigue life of standard test pieces. Under the same load, as the temperature increases, the fretting fatigue life will decrease significantly.
(2) At the same temperature, the fretting fatigue life is negatively related to the applied load. For the standard test piece, as the axial load increases, the fretting fatigue life decreases; as the normal load increases, the fretting fatigue life decreases.
(3) From the fracture analysis, it can be seen that fretting fatigue cracks always appear at the edge of the contact area, which belongs to the fretting wear slip zone, and the relative slip amplitude is relatively large, and the wear is more serious. From the fracture SEM images under different working conditions, it can be seen that the fretting fatigue failure mode of ZSGH4169 is basically the same. Cracks always start at one point and expand in a fan shape. Crack propagation are predominantly transgranular crack propagation. Temperature and load have significant influence on the initiation and propagation of fretting fatigue cracks. With the increase of temperature, the depth of fretting fatigue crack initiation area increased, the area of fretting fatigue crack propagation area decreased, the fatigue band spacing increased, and the crack propagation rate increased; With the increase of normal load, the depth of fretting fatigue crack initiation area increased, the area of fretting fatigue crack propagation area decreased, the fatigue band spacing increased, and the crack propagation rate increased; With the increase of axial load, the depth of fretting fatigue crack initiation area increased, the area of fretting fatigue crack propagation area decreased, the fatigue band spacing increased, and the crack propagation rate increased. This is reflected in the fretting fatigue life: the fretting fatigue life decreases with the increase of temperature, normal load and axial load.
(4) Temperature has influence on the crack initiation angle of fretting fatigue. The fretting fatigue crack initial angle at room temperature was about 40°±2°, and that at high temperature was about 45°±2°. With the increase of temperature, the crack initiation angle increases, however the load has little influence on the crack initiation angle.

Acknowledgements

This research has been supported by National Natural Science Foundation of China (91860111), National Science and Technology Major Project of China (2017-IV-0012-0049) and Fundamental Research Funds for the Central Universities (No.1002-XBC19007).

Author Contribution Statement

Zeyu Xing is mainly responsible for test data analysis, fracture analysis and article writing.
Hongjian Zhang is mainly responsible for test guidance and article writing guidance.
Haitao Cui is mainly responsible for fund application.

Ziqiang Yu is responsible for room temperature fretting fatigue test.
Xiaodong Yan mainly responsible for high temperature fretting fatigue experiment.

REFERENCES

1. Zhou ZR, LeoVincent, Vincent. Fretting wear. *Science Press*, 2002.

2. Kondo Y, Sakae C, Kubota M, Kitahara H, Yanagihara K. Fretting fatigue under variable loading below fretting fatigue limit. *Fatigue Fract Eng Mater Struct*. 2006;29:183-189.

3. Iyer, Mall S. Effects of cyclic frequency and contact pressure on fretting fatigue under two-level block loading. *Fatigue Fract Eng Mater Struct*. 2000;23(4):335-346.

4. Adibnazari S, Hoeppner DW. A fretting fatigue normal pressure threshold concept. *Wear*. 1993; 160(1):33-35.

5. Stbelkin V, Mall S. Investigation into relative slip during fretting fatigue under partial slip contact condition. *Fatigue Fract Eng Mater Struct.* 2005; 28:809-824.

6. Korkmaz YM, Coker D. Finite element analysis of fretting contact for nonhomogenous materials. *IOP Conference Series: Materials Science and Engineering*. 2018;295(1).

7. Yuki N, Kenkichi S. 20509 Effects of magnetic field and Frequency on Fretting Wear. *Collection of Lecture Papers of the Japanese Machinery Society*. 2007; 13:201-202.

8. Lee H, Jin O, Mall S. Fretting fatigue behaviour of shot-peened Ti-6Al-4V at room and elevated temperatures. *Fatigue Fract Eng Mater Struct.* 2003; 26:767-778.

9. Takeuchi M, Satoh T, Mutoh Y, Waterhouse RB, Kon Y. Fretting fatigue of an austenitic stainless steel in seaweater. *Fatigue Fract Eng Mater Struct.* 1994;17(8):949-958.

10. Sabrina V, Andrea Z. Fretting-fatigue analysis of shot-peened aluminium and titanium test specimens. *Fatigue Fract Eng Mater Struct*. 2020;1-13.

11. Zhu L, Wu ZR, Hu XT, Song YD. Investigation of small fatigue crack initiation and growth behaviour of nickel base superalloy GH4169. *Fatigue Fract Eng Mater Struct.* 2016;39:1150-1160.

12. Hamdy M, Waterhouse RB. The fretting fatigue behaviour of TI-6a1-4v at temperatures up to 600°C. *Wear*. 1979; 56(1): 1-8.

13. Dai ZD, Zhu RP, Pan SC, Wang M. Experimental study on the fretting fatigue characteristics of high temperature stainless steel and titanium alloy. *Acta Aeronautica et Astronautica Sinica*. 1999;(03):3-5.

14. Jin O, Mall S, Sahan O. Fretting fatigue behavior of Ti-6Al-4V at elevated temperature. *Int J Fatigue*. 2005; 27(4): 395-401.

15. Zhang XH, Liu DX. Effects of temperature, slip amplitude, contact pressure on fretting fatigue behavior of Ti811 alloys at elevated temperatures. *Acta Metall Sin-Engl*. 2009;22(2):131-137.

16. Mall S, Kim H, Porter WJ. High temperature fretting fatigue behavior of IN100. *Int J Fatigue*. 2010;32(8):1289-1298.

17. Jayaprakash M,Komatsu D,Okazaki M. High Temperature fretting fatigue behavior of IMI834 titanium alloy. *Transactions of the Indian Institue of Metals.* 2016;69(2):439-444.

18. Wang N, Cui HT, Zhang HJ. High temperature low cycle fretting fatigue test of tenon joint structure. *Journal of Aeronautical Dynamics*. 2018;33(12): 3007-3012.

19. Peng JF, Jin X, Xu ZB, Zhang J, Cai ZB. Study on the damage evolution of Torsional Fretting fatigue in a 7075 Aluminum alloy. *Wear*. 2018;402-403:160-168.

20. Sangral S,Achyuth K, Patel M, Jayaprakash M. Effect of Fretting on Fatigue Behavior of Al Alloys Considering Environmental Effect. *Materials Today: Proceedings*. 2019;15(Pt 1):119-125.

21. Kong HP, Jiang T, Liu CK, Ying SJ, Zhao K. Study on fretting fatigue fracture of TB6 high strength titanium alloy lugs under multi-axis complex stress. *Materials Reports*. 2020;

34(14):14134-14139.
22. Naboulsi S. Applications of crack analogy to fretting fatigue. *Eng Fract Mech*. 2004; 72(10):1610-1623.
23. Xin L, Han YM, Ling LG. The Evolution of Fretting Wear Behavior and Damage Mechanism in Alloy 690TT with Cycle Number. *Materials*. 2020; 13(10).
24. Peng JF, Wang BT, Jin X. Effect of contact pressure on torsional fretting fatigue damage evolution of a 7075 aluminum alloy. *Tribolo Int*. 2019; 137:1-10.
25. Sun SY, Li L, He K, Yue ZF. Fretting fatigue damage mechanism of Nickel-based single crystal superalloys at high temperature. *Int J Mech Sci*. 2020;186
26. Chaudhry V, Satish V. Damage Mechanisms under Fretting of Self-mated Stainless Steel (SS 316L) and Chromium Carbide Coatings. *Procedia Engineering*. 2014; 86:111-115.
27. Material Data Manual for Aeroengine Design. *Aviation Industry Press*. 2010.