Experimental and finite element analysis of stress amplitude on fretting fatigue behavior of Al-Zn-Mg alloy

XIAOSONG JIANG*, JINGRUI LI, WANXIA LIU, DEGUI ZHU
School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu Sichuan 610031, China

Fretting fatigue behavior of Al-Zn-Mg alloy is investigated with experimental and finite element analysis. Fretting fatigue tests are systematically performed for Al-Zn-Mg alloy, and effects of stress amplitude on fretting fatigue characteristics and fretting fatigue lives are emphatically researched. The results indicate when its contact stress is 180MPa, with increasing of stress amplitude, the degree of cyclic softening increases, and fretting fatigue lives decrease with increase of stress amplitude. Based on fretting fatigue test apparatus with point contact, ANSYS finite element analysis is used to analyze stress distribution by numerical study using 2D finite element method. The calculation results indicate that there are sticking region, sliding region and opening region on contact surface with stress amplitude changing during other test parameters are invariable. The sticking region, sliding region and opening region change with stress amplitude changing. The tensile stress and shear stress change very fiercely at the mixing region between sticking region and sliding region where the propagating cracks would nucleate at the region. The predicted fretting fatigue behavior of Al-Zn-Mg alloy show good agreement with experimental results.

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Keywords: Al-Zn-Mg alloy, Fretting fatigue, Finite element analysis, Point contact, ANSYS

1. Introduction

Fretting Fatigue is phenomenon of fatigue crack initiation, propagation and final fracture which is caused by repeated loadings between contacting bodies [1]. Fretting fatigue is found widespread in assemblies of machinery, transportation, electric power, aerospace, etc. [2-4]. So that it is highly concerned because of widespread presence and serious hazards of fretting fatigue phenomenon. As an extrusion structure and light weight material, Al-Zn-Mg alloy has been extensively used in aerospace, automotive, rail transportation and other engineering fields [5]. While fretting fatigue is widespread in the application process, even sometimes cause unimaginable disaster consequences. Currently, researchers focus more on factors affecting fretting fatigue crack initiation and propagation, whereas analysis of its macro-mechanical properties and tribological properties less [6-8]. In this study fretting fatigue behavior of Al-Zn-Mg alloy by experimental and numerical simulationare presented. Based on the experimental and numerical simulation results of fretting fatigue of Al-Zn-Mg alloy, macro-mechanical properties and tribological characteristic of Al-Zn-Mg alloy are intensively analyzed.

2. Experimental materials and methods

The alloy investigated in this research is Al-Zn-Mg alloy and its chemical composition mainly for, 5.76% Zn, 1.21% Mg, 0.32% Fe, 0.13% Ti, 0.66% Si, 0.02% Mn, 0.05% Cu and 0.02% Cr. Al-Zn-Mg alloy is subjected to a T6 heat treatment which consists of an 8 hour solid solution heat treatment at 500°C followed by water quench at 60°C−100°C and 4 hours of artificial aging at 150°C, then furnace cooling. The yield strength (σ_s) and ultimate tensile strength (σ_b) of Al-Zn-Mg-T6 alloy are 372 MPa and 402 MPa. The treated material is machined to a desired size and the specimen's surface has been polished to a surface roughness (Ra ≤ 0.16) which are shown in Fig. 1 [9]. Material and heat treatment methods of the fretting bridge are consistent with specimens. Each specimen is tested under uniaxial cyclic loadings using MTS 809 system which a point contact configuration is added for the fretting fatigue testing [9].Cyclic loading stress amplitude are 132MPa, 192MPa, 252MPa, 312MPa and 372MPa with frequency of 9 Hz, a sine wave form and a stress ratio of -1, 200 MPa Hertz contact stress. The surface damage characterization is observed by Quanta 200 FEG-SEM machine.

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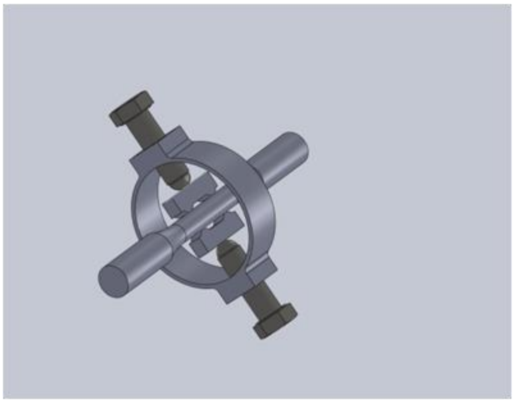

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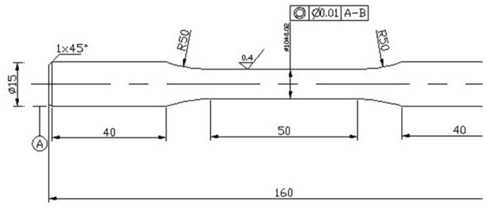

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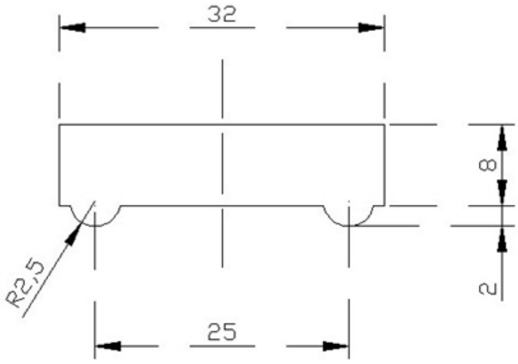


(d)

Fig. 1. System and specimen for fretting fatigue test (a) The MTS 809 system,(b)Configuration for test, (c)Smooth specimen for fretting fatigue test, unit:mm, (d)Pad for fretting fatigue test, unit:mm

3. Results and discussion

3.1. Effect of stress amplitude on the contact surface partition and stress distribution

A commercial finite element code, ANSYS is used to analyze the specimen under the same condition as experimental. This analysis is done in order to predicate the contact surface partition and stress distribution which can suggest the contact surface partition and stress distribution corresponds with certain rules. The finite element model for point contact is shown in Fig. 2. Note that only one-quarter of the test configuration is considered due to double symmetry with respect to the X and Y axes. Plane strain quadrilateral element PLANE42 modeling is used to model specimen and fretting bridge. The minimum size of the contact area grid is 4.57E-04mm. Among them, specimen unit are 19800 units and nodes unit are 20096 units, bridge unit are 11167 units and nodes unit are 11409 units, contact elements unit are 592units.

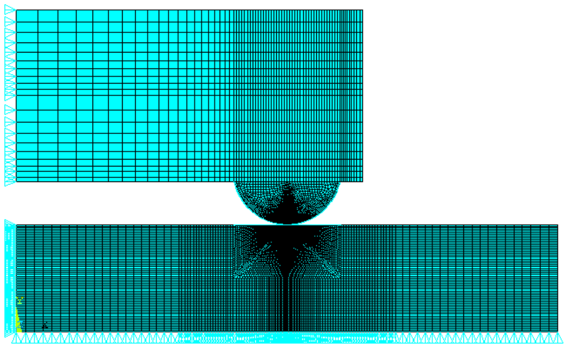
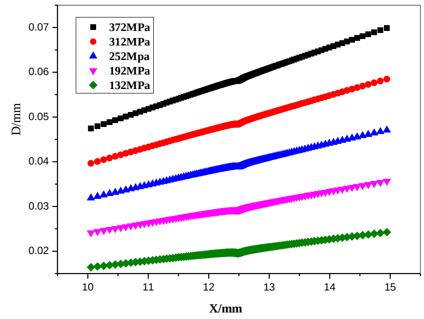


Fig. 2. Two-dimensional fretting -contact analysis finite element model

In order to study effects of cyclic loadings on the local fretting-contact stress distribution, two-dimensional finite element analysis model is used to calculate fretting-contact surface of the sticking region, sliding region and opening region with distribution of contact stress distribution when nominal contact stress is 180 MPa and coefficient of sliding friction is 0.4(μ = 0.4) while stress amplitude is 132MPa, 192MPa, 252MPa, 312MPa, 372Mpa, respectively [10]. In this way effect of nominal stress amplitude on the local fretting-contact pressure can be discussed.

As can be seen from results of Fig. 3, contact surface can be divided into sticking region, sliding region and opening region. When cyclic loading is relatively small, contact surface is in sticking state, then sticking state changes to partial sliding state with increasing of cyclic loading. Asymmetrical distribution of normal contact stress σ_n and tangential contact stress σ_t leads to partial sliding. When $\sigma_t<\mu\sigma_n$, it's at sticking state, if $\sigma_t>\mu\sigma_n$, it's at partial sliding state, where μ is the coefficient of friction. According to hertz contact theory, compressive stress has a maximum value and shear stress has a minimum value in the center of the contact region. With cyclic loading increasing, contact stress is reduced in the center and shear stress of the edge increases gradually. When $\sigma_t=\mu\sigma_n$, junction of sliding region and sticking region appears. With the increase of cyclic loading, sticking region is decreasing with the increase of cyclic loading, while sliding region and opening region is increasing with the increase of cyclic loading. There is a mutation of tensile stress and shear stress at the junction of slipping region and sticking region so that crack initiation at the junction of the sliding region and sticking region.

Fig. 3(a) reveals sliding distance changing with the stress amplitude variations. It can be seen from the results that under different stress amplitude, sliding distance distribution of the entire contact edge is similar. With increasing of the stress amplitude, the sliding distance of entire contact edge reduces gradually. Fig. 3(b), 3(c) and 3(d) are tensile stress, compressive stress and shear stress distributions, respectively. All of tensile stress, compressive stress and shear stress have break between sticking region and sliding region. This shows scalability crack can easily initiate between sticking region and sliding region [11]. Tensile stress controls the early initiation of micro-cracks and shear stress results in plastic deformation of contact surface. Because formation of fretting cracks is in that the alternating plastic deformation [12]. Therefore, formation of fretting cracks is determined by shear stress of the contact surface while compressive stress is almost no effect on the position of cracks. From these results it can be concluded that cracks initiate at the junction of sliding region and sticking region or opening region.



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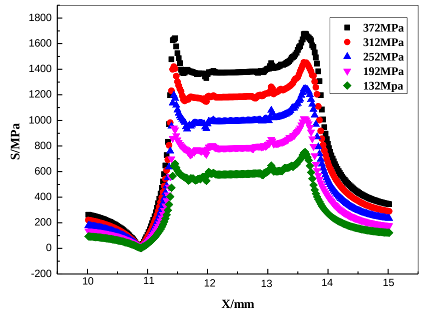

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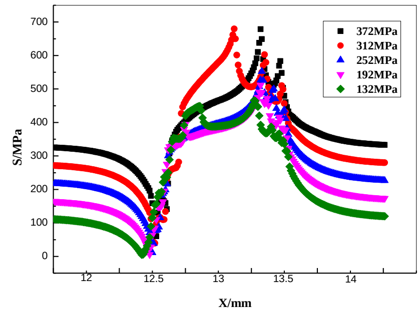

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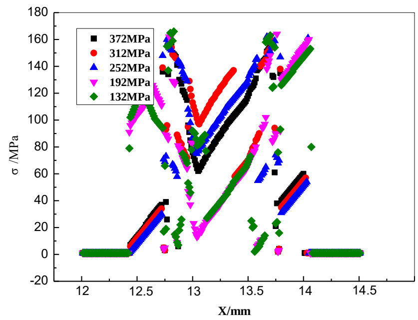
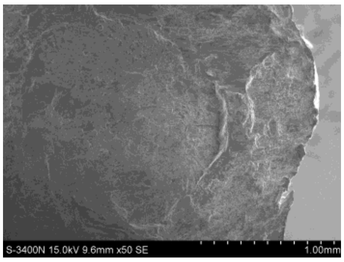


(d)

Fig.3. Sliding distance changing with the stress amplitude variations curve and contact stress distribution curve: (a) Sliding distance changing with the stress amplitude variations, (b) Tensile stress distribution curve, (c) Compressive stress distribution curve, (d) Shear stress distribution

Fig. 4 is Al-Zn-Mg alloy's SEM results of the mixing region of the fretting scar when stress amplitude is 252MPa and contact stress is180MPa. Can be seen from Fig. 4, mixing region has characteristics of sliding region and sticking region because there is ring-shaped morphology with sticking phenomena in the middle and wearing phenomena outside. Obvious abrasions and scratches can be observed in the center of fretting scar due to there is minor injury as relative slipping does not occur. Significant wear can be seen in ring-shaped slipping region as furrow and plastic flow morphology appear, that's because exfoliative material comes off surface due to abrasion and at the same time the flaking can give birth to a large number of micro-cracks around the release agent between sliding region and sticking region. In addition, due to presence of debris, clear microscopic furrows phenomenon can be observed at the mixing region.



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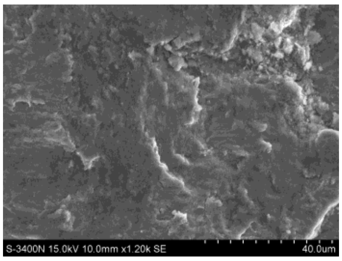

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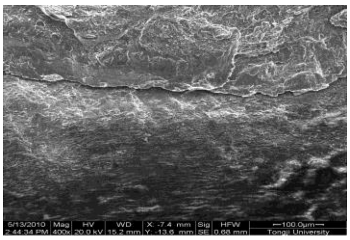

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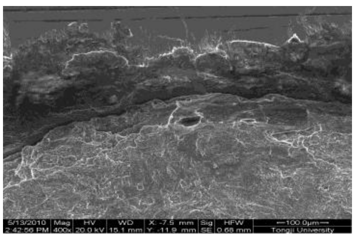
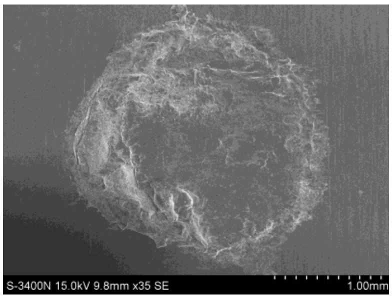


(d)

Fig. 4. SEM results of the fretting scars (σ_3=252MPa): (a) Panorama of the fretting scars, (b) Edge of the fretting scars, (c) Crack of the fretting scars, (d) Crack of the fretting scars

Just like finite element simulation results, fretting fatigue crack initiates in the fretting -mixing region which can be explained by friction cyclic stress mechanism [13]. Crack initiation and fracture results are shown in Fig. 5. When fretting bridge and specimen contact and then fretting fatigue generates, frictional force generated by contact stress can causes tangential tensile stress generating to jog the rear material in the direction of movement while tangential compressive stress is generated in corresponding front direction. Then movement direction reverses, tensile stress and compressive stress direction reverse accordingly. Consequently cyclic stresses will generate in this area and this is the source causes that micro-crack initiate in the mixing region. At the same time stress concentration caused by stress applied to specimen due to fretting bridge can promote micro-crack initiates in the mixing region.



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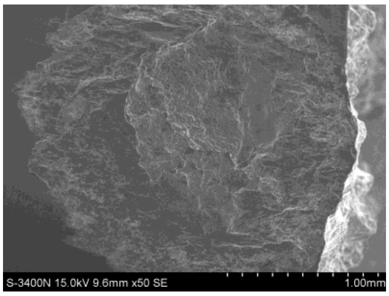


(b)

Fig. 5. Results of micro-crack initiation and fracture at the mixing region: (a) SEM result of fretting scar, σ_3=252MPa, (b) SEM result of fracture at the mixing region, σ_3=252MPa

3.2. Effect of stress amplitude on the behavior of fretting fatigue

To study effects of stress amplitude on elastic-plastic deformation characteristic of Al-Zn-Mg alloy, fretting fatigue cyclic stress-strain curve of Al-Zn-Mg alloy under different stress amplitudes are shown in Fig. 6. The figure shows that when the stress amplitude is132MPa, the stress-strain curve approximately comes into being a straight line. This is evidence that there is almost no plastic deformation of Al-Zn-Mg alloy and elastic deformation dominates [14].When the stress amplitude increases to192MPa, the stress-strain curve is not a straight line any more but surrounded by a smaller area. It illuminates Al-Zn-Mg alloy has been under obvious plastic deformation. When the stress amplitude is increased to 372MPa, Al-Zn-Mg alloy is more obvious under plastic deformation. As can be seen from Fig. 6, area enclosed by the hysteresis loop significantly increases with the increasing of stress amplitudes. With the cyclic stress amplitudes increase gradually, Al-Zn-Mg alloy shows more obvious characteristics of transformation of elastic deformation to plastic deformation and increasingly severe plastic deformation.

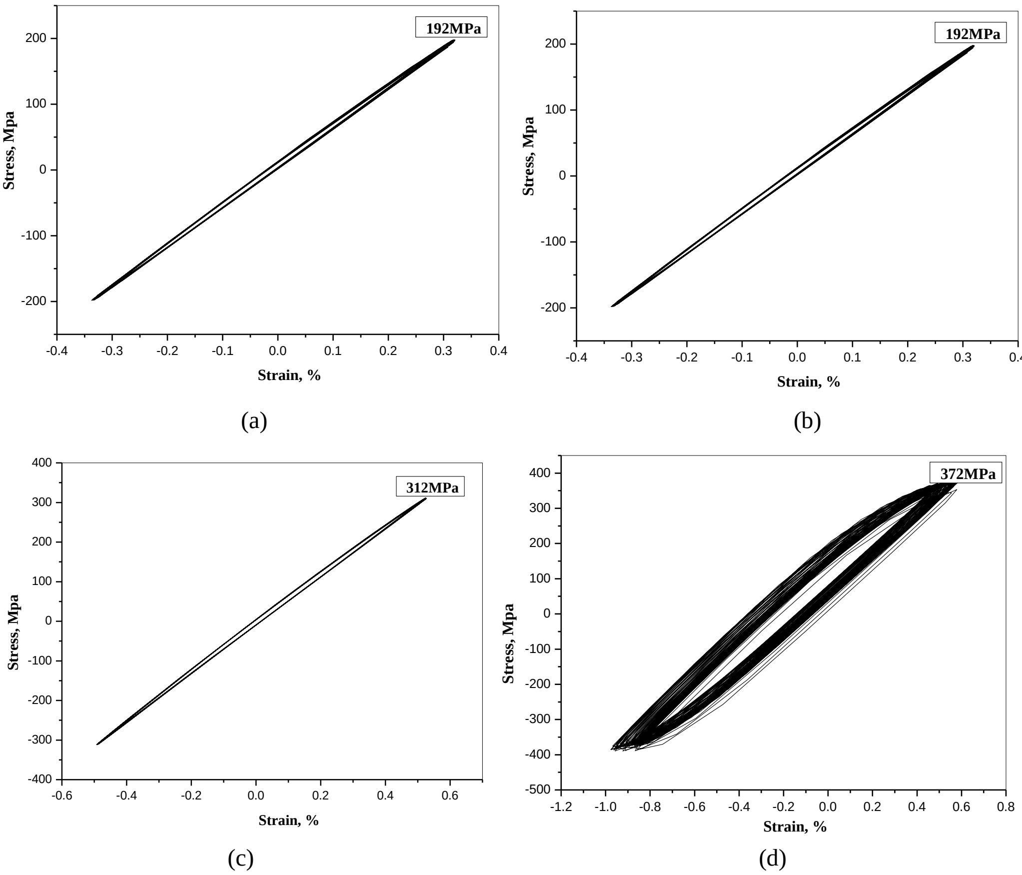
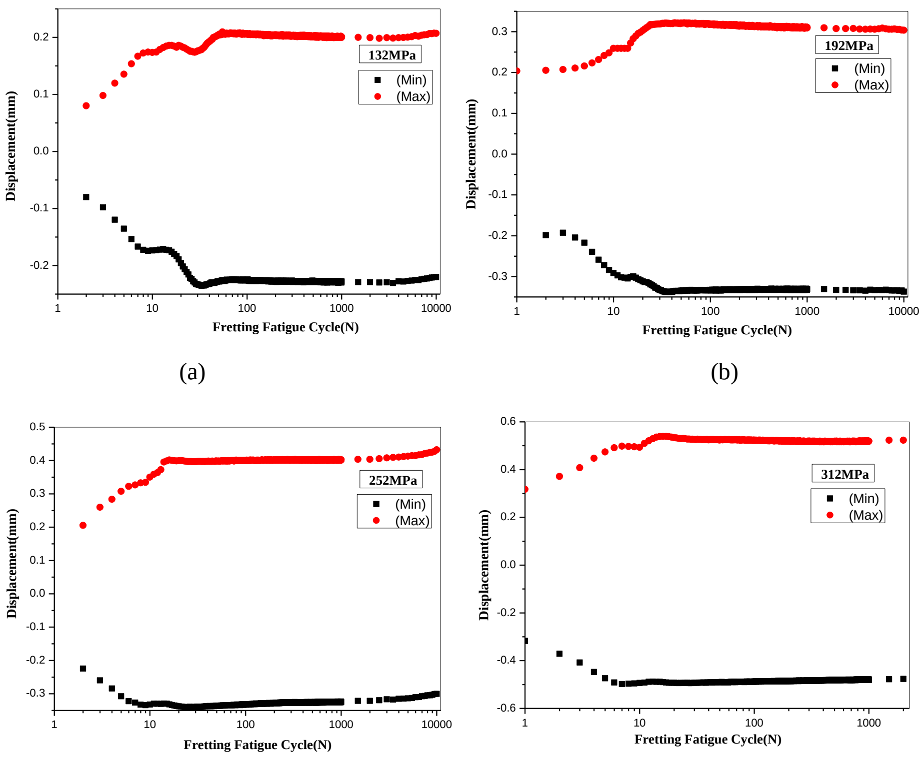


Fig. 6. Fretting fatigue hysteresis loop of Al-Zn-Mg alloy specimens under different stress amplitude: (a) σ_1=132MPa,p=180MPa, (b) σ_2=192MPa,p=180MPa, (c) σ_4=312MPa,p=180MPa, (d) σ_5=372MPa,p=180MPa

To study effect of stress amplitude on fretting fatigue properties of Al-Zn-Mg alloy, Al-Zn-Mg alloy's cyclic characteristics are shown in Fig.7. Cyclic characteristics of materials are greatly dependent on the strain amplitude because increasing strain amplitude enhances result in cyclic hardening/softening degree and hardening /softening rate increasing. As can be seen from Fig. 7, displacement amplitude increases rapidly with increasing of cycles within the first 10 cycles and then in constant increase stabilize data bout10 cycles. During10 cycles to 30cycles, displacement amplitude is still increasing with the increase of cycles, but the rate of increasing is less than the first10 cycles in that the reason of displacement amplitude increasing is mainly due to cyclic softening. After 30 cycles displacement amplitude reaches stability and can maintain at a constant value. At the same time, with stress amplitude increasing from132MPa, 192MPa, 252MPa to 312MPa, displacement amplitudes increase from 0.2mm, 0.3mm, 0.4mm to 0.5mm. Therefore displacement amplitude varies with changing of stress amplitude as cyclic softening of material has been more serious with increasing of stress amplitude [15]. Accordingly, the relationship between displacement amplitude and cycles is related to cyclic softening of material. In addition, fretting friction also affects the displacement amplitude changing.



(b) (d)

Fig.7. Displacement amplitude-cycle curve of Al-Zn-Mg alloy specimens under different stress amplitude: (a) σ_1=132MPa,p=180MPa, (b) σ_2=192MPa,p=180MPa, (c) σ_3=252MPa,p=180MPa,(d) σ_4=312MPa,p=180MPa

Fretting fatigue lives of Al-Zn-Mg alloy are shown in Fig. 8. As can be seen from Fig. 8, fretting fatigue lives of Al-Zn-Mg alloy are sensitivity to stress amplitude. With increasing of the stress amplitude, the general trend of decline in fretting fatigue lives of Al-Zn-Mg alloy changes because fretting fatigue lives decrease with increasing of different stress amplitude. In the process of fretting fatigue, specimens are subjected to cyclic loading and contact pressure results in the joint action of fretting wear and fretting fatigue which causes damage accumulation. Simultaneity, fretting-wear continues to accumulate with increasing of cycles. With increasing of stress amplitude, micro-crack initiation increases and micro-crack propagation speeds which can reduce fretting fatigue lives. In the lower levels of stress amplitude, the joint action of fretting wear and fretting fatigue causes long time action on specimens so that the magnitude amplitude's reduction of fretting fatigue lives is very large with stress amplitude increasing. In the higher stress amplitude level, the joint action of fretting wear and fretting fatigue only in a short time on specimens so as to cause cumulative damage effect is not obvious.

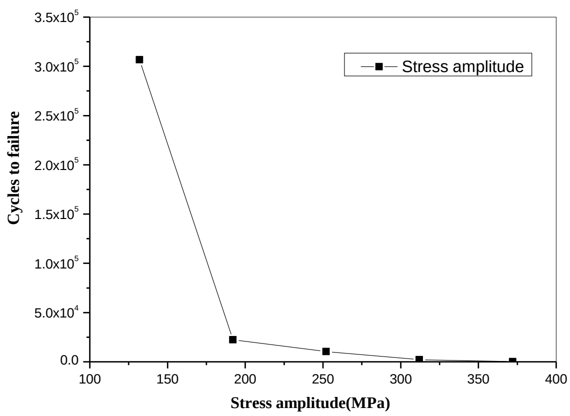


Fig. 8. Fretting fatigue lives of Al-Zn-Mg alloy under different stress amplitude

4. Conclusions

1. Fretting fatigue contact surface can be divided into sticking region, sliding region and opening region. There is a mutation of tensile stress and shear stress at the junction of sliding region and sticking region so that crack initiation at the junction of the sliding region and sticking region.

2. With the cyclic stress amplitudes increase

gradually, Al-Zn-Mg alloy shows more obvious characteristics of transformation of elastic deformation to plastic deformation and increasingly severe plastic deformation. The relationship between displacement amplitude and cycles is related to cyclic softening of material, simultaneity fretting friction also affects the displacement amplitude changing.

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*Corresponding author: xsjiang@yeah.net