CRACK BEHAVIOR OF THE ALUMINUM ALLOY 2024 UNDER FRETTING CONDITIONS

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Abstract The initial stage of fretting fatigue crack growth is significantly influenced by tangential force induced by fretting action along the contact surface where a mixed-mode crack growth is involved. Fretting crack behavior of aluminum alloy 2024 was studied, taking into account the problem of contact asperities. Finite element was used for the determination of the stress field near the contact surface and the stress intensity factor. The results showed that tensile stress maxima are situated at the trailing edge of the contact zone. Experimental results showed that the crack initiates from the trailing edge of the contact zone too. The crack extension angle was calculated and compared with experimental results at different normal loads. The stress intensity factor increased with increasing friction. The crack initially grows in combined mode I and II before deflecting to mode I plane. Delamination, one of the wear mechanisms, has been observed in our experiments too.

Key Words Fretting Fatigue, Crack Growth, Delamination, Aluminum, Finite Elements

چکیده مرحله اول رشد ترک خستگی سایشی بطرز قابل توجهی تحت تاثیر نیروی مماسی ناشی از عمل سایش در طول سطح تماس، جایی که یک رشد ترک مایل وجود دارد، قرار می گیرد. رفتار ترک خستگی سایشی در آلیاژ آلومینیوم ۲۰۲۴ با در نظر گرفتن مساله زبری سطح تماس مورد مطالعه قرار گرفت. روش اجزاء محدود برای تعیین میدان تنش و ضریب شدت تنش استفاده شد. نتایج نشان داد که تنش کششی ماکزیمم در پشت لبه تماس قرار دارد. آزمایشها نیز نشان دادند که ترک از همان نقطه شروع می شود.ضمنا زاویه رشد ترک نیز برای نیروهای عمودی متفاوت محاسبه گردید و با نتایج تجربی مقایسه شد. ضریب شدت تنش نیز با افزایش اصطکاک افزایش می یابد. ترکها ابتدا بصورت مورب رشد می کنند تا پس از مدتی به حالت عمود بر نیروی محوری در آیند. مکانیزم ورقه ای شدن نیز در آزمایشهای ما مشاهده شد.

1. INTRODUCTION

Fretting is one of the modern plagues of industrial machinery [1,2]. It occurs between contacting surfaces which are subjected to vibration, cyclic stressing or small oscillatory movement. Fretting initiated fatigue failure is frequently observed in a wide range of engineering assemblies [1,3]; the seating of the turbine disc on the drive shaft, fir-tree root of turbine blades and their mating slots, keyways of transmission assemblies, riveted or clamped joints and structures, steel ropes used in mining and in marine environments [4], and in nuclear power plants [5]. It is easy to identify fretting as it produces the well-known red powder in steel [6] and black powder in aluminum contacts [7].

Fretting damage is divided into fretting wear and fretting fatigue [1,2]. Fretting wear starts when particles are detached from the rubbing surfaces. It leads to loss of clearance in many cases but can cause jamming when debris is trapped in the contact. It is common in distributed contacts such as flanged fittings, bearing housings etc. Fretting fatigue starts when cracks are initiated within or at the edge of the contacts. It leads to component failure as cracks propagate. It is found in concentrated contacts such as shaft keys, wire strands etc. Fretting fatigue can reduce the endurance limit of a component by half or more, in comparison to unnotched fatigue. Even though the origin of fretting fatigue and fretting wear are different, both forms of damage often coexist in the same contact zones [8].

Suh has introduced delamination theories of wear by fracture mechanics [9, 10]. The delamination theory suggested that the harder asperities exert a surface traction on the softer surface inducing plastic shear deformation. Due to the deformation and repeated loading, sub-surface cracks and voids are formed. Suh also suggested that cracks nucleate below surface because the compressive stresses inhibit formation of cracks at the surface. Cracks will propagate, joining neighboring ones, to form a sheet-like wear particle.

A finite element analysis by Zhang et al. [11] reveals that, during sliding wear, there exist both surface and subsurface tensile stress fields between the contacting asperities, and the position and magnitude of the stress maxima are affected by the contact ratio and the friction forces . The results indicate that a crack may initiate at the surface if the friction coefficient is large enough to generate a sufficient tensile stress for crack initiation and propagation. The cyclic nature of tension/compression at the contact surface also implies the fatigue phenomenon, but the number of cycles depends on the number of asperities.

The purpose of this paper was to examine the crack behavior due to the problem of contact with asperities, also to investigate the angle of crack orientation. Finite element analysis was used to determine stress, strain along the contact surface. The crack extension angle was calculated and compared with experimental results at different normal loads. Some experimental results also are presented in order to show the effect of normal load on fretting fatigue life and to show that there is a mixed-mode crack growth and cracks are nucleate at trailing edge of the contact zone.

2. EXPERIMENTAL PROCEDURE

Fretting fatigue crack growth behavior of 2024 Aluminum alloy has been investigated under various combinations of axial cyclic loading and constant normal load. The materials properties are the following:

$E=70000$ MPa, $\nu= 0.33$, $\sigma_y=245$ MPa

Fretting Fatigue Testing Apparatus The fretting fatigue tests were performed using a rectangular cross section flat specimen, made from aluminum alloy 2024, providing a wide area for unrestricted crack growth and bridge-type fretting pads, made from steel. The specimen had a width of 20 mm, a thickness of 10 mm and a gage length of 60 mm. The load was transmitted from a calibrated proving ring to the contact area through loading pads, which were attached to the fretting pads by two locating bolts. The load was applied to the center of the loading pad through a solid carbide ball in contact with a loading screw, and was subsequently transferred to the fretting pads by two cylinders located over the center of the fretting pad feet. The bolts were tightened by a torque just enough to hold the pads together in a stable arrangement. Both contacting surfaces were polished with 600 grit silicon carbide paper and cleaned with acetone. The normal force, created by the proving ring was calibrated before testing. Strain gages were bonded to the proving ring and wired to create a Wheatstone bridge circuit to measure the elastic strains induced by loading the ring with a load adjusting screw. A calibration curve of load vs. voltage output was obtained by loading the ring with weights through the axis of the load adjusting screw.

The fretting fatigue tests were conducted on an Instron 60 kN servo-hydraulic fatigue testing machine. The pads were clamped to the specimen by turning the load adjusting screw in the proving ring. When the fretting apparatus was assembled, it was loaded into the fatigue testing machine. Hydraulic wedge grips with serrated clamping faces were used to grip the specimen. Tests were run at a frequency of 10 Hz. Figure 1 shows the experimental apparatus.

Figure 1. The experimental apparatus.

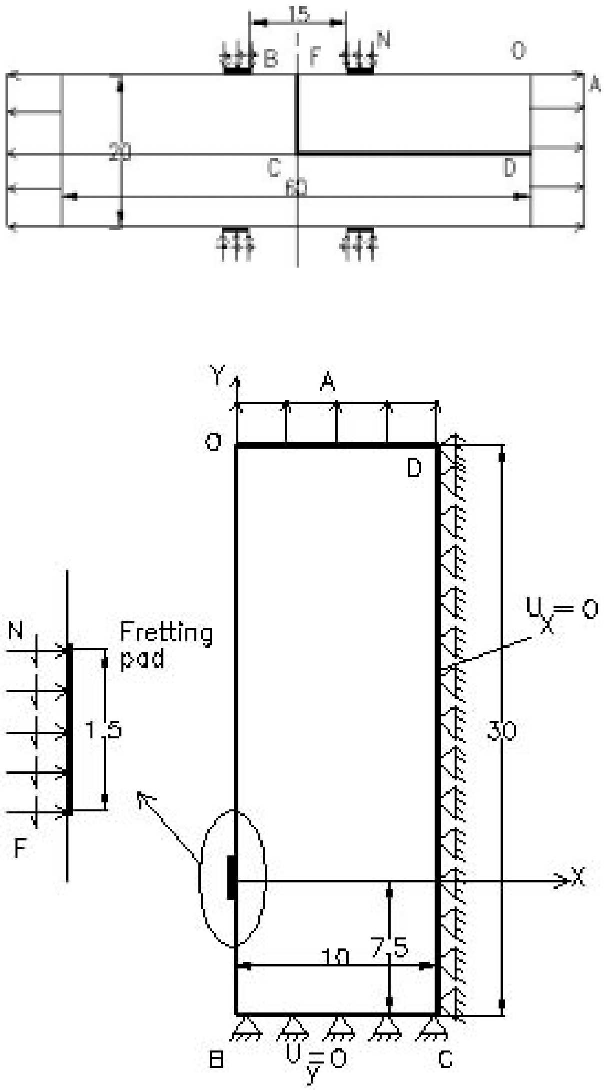

Figure 2. Fretting fatigue configuration.

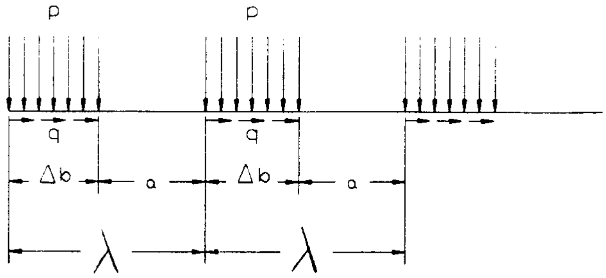

Figure 3. Model of the contact.

3. FINITE ELEMENT MODEL

The finite element analysis was used to simulate a fatigue specimen clamped between two-bridge type fretting pads and loaded using a calibrated proving ring. The finite element model shown in Figure 2 represents a symmetric section of the fretting fatigue configuration. Two dimensional plane strain analysis of a rectangular body in the presence of a crack at the surface was used. Plane strain conditions were applicable because the fatigue specimen thickness is considerably greater than the scar width. Eight nodded biquadratic quadrilateral 2D solid plane strain elements were used.

The assumptions made for the analysis presented in this research are as follows: (i) the localized contact lengths, Δb_i, are equal, (ii) the localized contact areas are periodically distributed across the contact surface, (iii) the contact pressure p on the localized contact area is kept constant.

As illustrated in Figure 3, the periodic distance between the adjacent asperities is denoted by λ. According to the above assumptions, Δb, and p are all constants and can be obtained by taking the ratio of L/n, where n is the number of asperities and L is the contact length. The contact ratio K_o is defined as the ratio of the length of each localized contact area to the periodic interval, i.e. $K_o = \Delta b / \lambda$. therefore, the actual pressure at the localized contact area can be expressed as:

$$P = \frac{N}{L} * \frac{\lambda}{\Delta b} = \frac{P_0}{K_0}$$

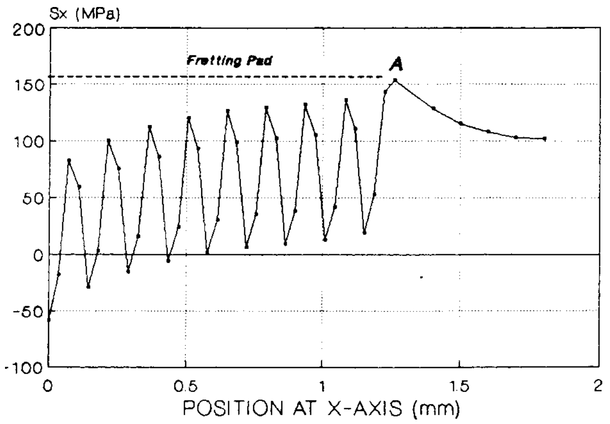

Figure 4. Stress variation (S_x) under the contact area (k=0.5, μ =0.5, N=50 MPa, A=100 MPa).

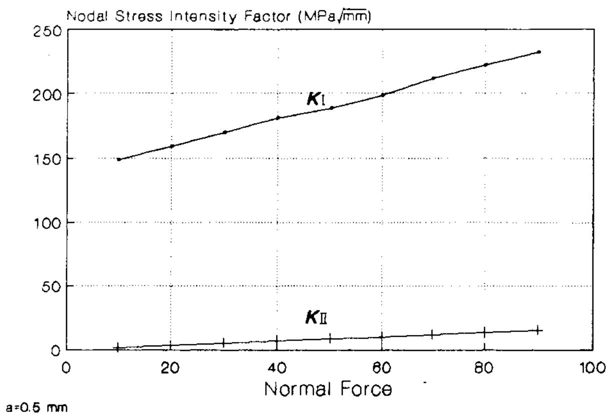

Figure 5. Effect of normal force on stress intensity factor for a surface crack (k=0.5, μ =0.5, A=100 MPa).

where $P_0 = N/L$ is the average normal contact pressure.

The stress intensity factors K_1 and K_{11} were calculated using stress approach [12]. This approach involves a correlation of the finite element nodal or Gauss point stresses with the crack-tip stress equations, as follows:

$$K_I = \lim_{r \to 0} \sigma_x (r, \theta = 0) \sqrt{2\pi r} \qquad K_{II} = \lim_{r \to 0} \tau_{xy} (r, \theta = 0) \sqrt{2\pi r}$$

4. RESULTS AND DISCUSSIONS

Figure 4 shows the stress distribution, S_x, for the overall contact length. For the case of a coefficient of friction μ=0.5 high tensile stresses were observed between the contact asperities on the surface. The figure also implies that the tensile stress on the surface would be minimum at the first asperity of the contact and obtain its maximum at the last asperity of the contact. However, the peak–to–peak values are nearly constant for all asperities. The uneven distribution of the stresses at the asperities is the result of the presence of the traction forces on the surface.

TABLE 1. Fatigue Life as a Function of Normal Load.

Normal load (MPa)	Life (Number of cycles)
0 (pure fatigue)	342500
70	89400
100	59500
120	42000

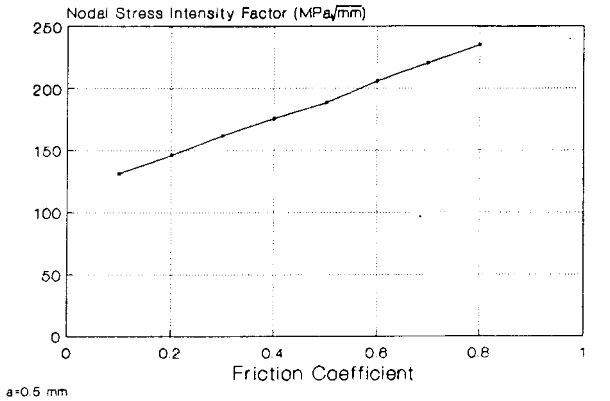

Figure 6. Effect of friction coefficient on stress intensity factor for a surface crack (k=0.5, N=50 MPa, A=100 MPa).

Finite element analysis showed that the maximum tensile stress occurs at the trailing edge of the contact pad where the crack initiates.

Fracture analyses have shown that the crack initially grows in combined mode I and mode II to a size of the order of 0.5-1.0 mm before deflecting to a mode I plane.

Figure 5 shows the effect of normal contact load on the stress intensity factor. It can be seen that K_I is proportional to the normal load.

TABLE 2. Calculated Crack Extension Angle (θ) at Different Normal Load for a Surface Crack.

Normal Stress (MPa)	0	25	50	75	100	200
Crack extension angle, θ	45.00	41.341	40.06	38.56	37.92	36.66

TABLE 3. Calculated Crack Extension Angle (θ) at Depth from the Surface for a Surface Crack.

Depth from the surface (mm)	0.1	0.2	0.3	0.4	0.5
Crack extension angle, θ	41.3	37.5	31.4	22.7	13.8

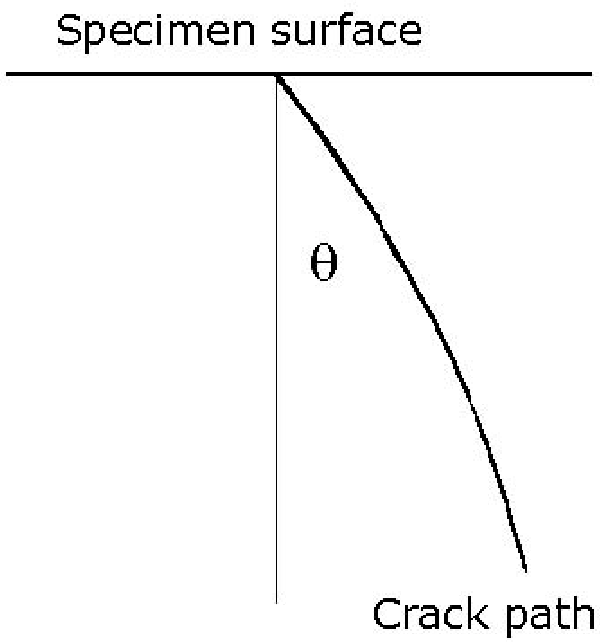

Figure 7. Crack extension angle (θ).

Figure 8. Micrograph showing a fretting fatigue crack growth on Al 2024.

Figure 9. Micrograph showing how wears debris forms due to delamination.

Experimental results showed that specimens had a shorter life at higher normal load (Table 1).

The effect of friction coefficient on the stress intensity factor is given in Figure 6. The results show that the stress intensity factors are proportional to the friction coefficient.

Fellows et al. [13] showed that the crack location from fretting fatigue failures did correlate with the location of the maximum shear stress. Therefore, based on this approach the angle of crack orientation due to the maximum shear stress range was predicted. Table 2 and 3 show the initial crack angle for different contact load and also the incremental crack extension angle at various depths. The results suggest that the crack initially propagates at an angle of 30 to 50 degrees to the surface. The crack propagation path then gradually follows a direction that becomes perpendicular to the surface (Figure 7). This has been confirmed by the Figure 8 which shows the crack extension on a specimen. It can be seen that there is a good agreement between the calculated and experimental results. When the crack direction of crack growth becomes perpendicular to the surface, the effect of friction and normal load and consequently fretting has been terminated. From this moment the crack is influenced only by the axial load (fatigue) until the final fracture and even if the fretting is eliminated from the configuration, nothing will change confirming that fretting is a surface concerned phenomenon. Therefore, surface improvement such as introducing residual stresses [14] may lead to longer life. Figure 9 shows that delamination process is involved in fretting. The figure also shows how a particle delaminates.

5. CONCLUSIONS

From this work the following conclusions may be made:

1. Fracture analysis has shown that the crack initially grows in combined mode I and mode II to a size of the order of 0.5 - 1.0 mm before deflecting to a mode I plane.
2. Finite element analysis showed that the maximum tensile stress occurs at the trailing edge of the contact pad which is in good agreement with experimental observations.
3. The tensile stress on the surface would be minimum at the first asperity of the contact and obtain its maximum at the last asperity of the contact. However, the peak–to–peak values are nearly constant for all asperities.
4. Experimental results showed that specimens had a shorter life at higher normal load.
5. Increasing normal load or friction coefficient increased the stress intensity factor.
6. There was a good agreement between the calculated and experimental results of the initial crack angle for different contact load and also the incremental crack extension angle at various depths.
7. Delamination process is involved in our fretting tests.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. Waterhouse, R. B., "Fretting Fatigue", ***Int'l Materials Reviews***, Vol. 37, No. 2, (1992), 77-97.
2. Waterhouse, R. B., "Fretting Corrosion", Pergamon, Oxford, (1972).
3. Forsyth, P. J. E., "Occurrence of Fretting Fatigue Failures in Practice", In R. B. Waterhouse (Ed.), Fretting Fatigue, Elsevier Applied Science, London, (1982), 77-97.
4. Pearson, B. R., Brook, P. A. and Waterhouse, R. B., "Fretting in Aqueous Media, Particularly of Roping Steels in Seawater", ***Wear 106***, (1985), 225-260.
5. Jones, D. H., Nehru, A. Y. and Skinner, J., "The Impact Fretting Wear of a Nuclear Reactor Component", ***Wear 106***, (1985), 139-162.
6. Farrahi, G. H., Markho, P. H. and Maeder, G., "A Study of Fretting Wear with Particular Reference to Measurement of Residual Stresses by X-Ray Diffraction", ***Wear 148***, (1991), 249-261.
7. Fernando, U. S., Farrahi, G. H. and Brown, M. W., "Fretting Fatigue Crack Growth Behavior of BS L65 4% Copper Aluminum Alloy under Constant Normal Load", ***Fretting Fatigue***, ***ESIS 18***, (Edited by Waterhouse, R. B. and Lindley, T. C.), Mechanical Engineering Publications, London, (1994), 183-195.
8. Vincent, L., Berthier, Y., Dubourg M. C. and Godet, M., "Mechanics and Materials in Fretting", ***Wear 153***, (1992), 135-148.
9. Suh, N. P., "The Delamination Theory of Wear", ***Wear 25***, (1973), 111-124.
10. Suh, N. P., "An Overview of the Delamination Theory of Wear", ***Wear 44***, (1977), 1-16.
11. Zhang, N., Liu, Y., Venugupalan, D. and Rohagti, P. K., "FEM Analysis of Wear Problems by 2-D Elastic Contact with Separation", ***Material Week '89 Wear Modeling Session II***, (1989).
12. Meguid, S. A., "Engineering Fracture Mechanics", Elsevier Applied Science, London, (1989).
13. Fellows, L., Nowell, D. and Hills, D., "On the Initiation of Fretting Fatigue Cracks", ***Wear 205***, (1997), 120-129.
14. Benrabah, Langlade, C., Vannes, A. B., "Residual Stresses and Fretting Fatigue", ***Wear 224***, (1999), 267-273.