Fretting damage influence of the fatigue crack initiation and growth in High-Cycle- and Very-High-Cycle-Fatigue areas of peened and unpeened Al-based alloys

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ABSTRACT. *In-service fretting damage influenced the fatigue crack origination in materials under the damaged surface for the very-high-cycle fatigue. Specimens of BS L65 Al-Cu alloy with peened and unpeened surfaces tested under cyclic tension and static compression had the crack initiation on the surface because of fretting damage. The static compression was used to reproduce the fretting damage on the specimen surface. The special methodology was applied to the crack growth analysis in the case of the biaxial stress-state with R=-1.0 for the investigated material. The fretting influence on the fatigue crack propagation was estimated on the basis of the functional correction,* $F(fr)$*, for the stress intensity factor,* K_I*. The fretting damage influence on the fatigue crack growth have been briefly discussed on the basis of the kinetic curves reproduced from the fractographic analysis and the Wöhler diagram described materials behaviour in high- and very-high-cycle fatigue areas.*

INTRODUCTION

In-service cyclic loading of a structural element may induce evolution of its structure on the micro-, meso- and macro-scale levels. Damage is accumulated in the material when stress state, cyclic loads frequency or R magnitudes, etc. may vary in a complicated way, to differ from a laboratory experiment. Storage and dissipation of energy are the two concurrent processes experienced by the material under loading.

In the case of the fretting damage influence on the fatigue crack initiation in a solid media the mechanisms, which take usually place in a material volume have dramatic reduction. Fatigue failure originated by fretting is commonly observed in assemblies where surfaces of two components are in contact and small relative movement can exist between them [1-3], Fig.1. In a fretting situation the stress singularity caused by the contact pressure and the friction force at the edge of the contact patch will speed up the crack nucleation process under the surface in area of very-high-cycle fatigue (VHCF) in the range of cyclic loads (σ_{W1} - σ_{W2}) and accelerate the early phase of crack growth [3,4].

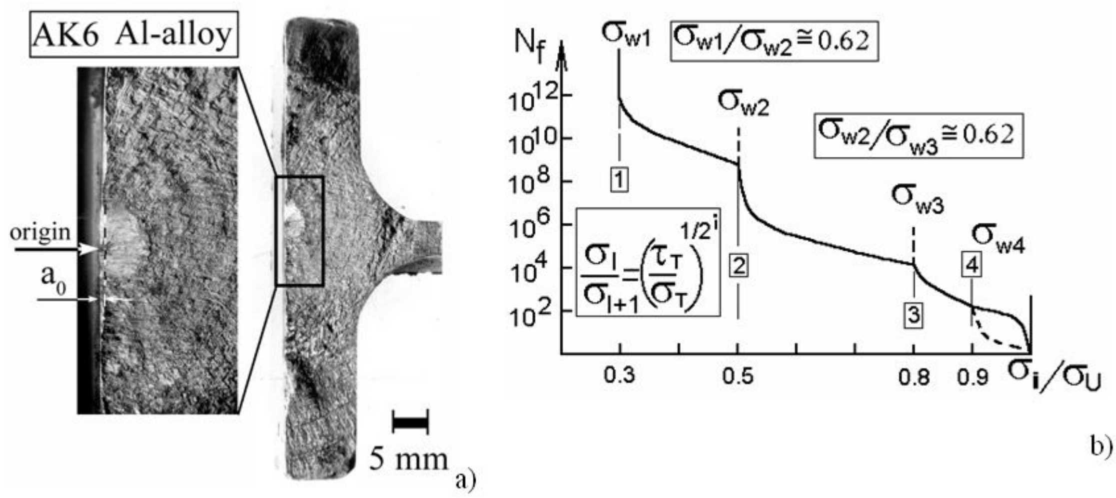

Figure 1. Overview (a) of the fracture surface of the in-service fatigued helicopter longeron in area of 10^{10} cycles because of the fretting damage, and (b) the bifurcation Wöhler diagram: (1-2) VHCF, (2-3) high-cycle-fatigue (HCF), (3-4) low-cycle-fatigue (LCF), and, then, quasi-static fracture. The origin places under the damaged surface in the depth of a_0=0.1mm; τ_T and σ_T – theoretical shear and tension material strength.

Theoretical analysis of fatigue-crack growth and critical assessments of published experimental Paris-type diagrams [4] provide a reason to introduce unified description of fatigue cracks growth (UKC) for Al-alloys on the bases of synergetic approach in the form [3,4]:

$$\delta = [(1-\nu^2)/(12.\pi.E.\sigma_{0.2})]\left\{\begin{matrix} K_e^2 \\ (K_{Is}/K_e)^4 \end{matrix}\right\} \text{ for } \begin{cases} 4.5x10^{-8}m < \delta < 2.1x10^{-7}m \\ 2.1x10^{-7}m < \delta < 4.5x10^{-6}m \end{cases} \qquad (1)$$

In Eq. 1 material constants are the following: υ - Poisson's ratio; E - Young's modulus; $\sigma_{0.2}$ - yield strength; the stress intensity factor, K_{Is}, correlates to the striation spacing, δ, value 2.1x10^{-7} m, and K_e– the equivalent of the stress intensity factor, K_I. It was found by experiment that the stress σ_0 must be used under the conditions of cyclic loads at R≅0.

In the case of the fretting damage influence on the fatigue crack propagation under biaxial simultaneously static and cyclic loads the functional correction, $F(fr)$, for the stress intensity factor, K_I, was used in the form [3]:

$$K_e = K_I F(fr) \qquad (2)$$

The present paper presented analyses of material state evolution under cyclic loads with fretting damage, for various combinations of fretting loading, in correspondence with the fatigue striation spacing increasing for Al-alloy BS L65 to estimate value of $F(fr)$ for different peened and unpeened surfaces.

TEST PROCEDURE

Material properties and equipmen

The material investigated was a fully artificially aged 4% Cooper Aluminium Alloy BS L65, a general-purpose material widely used in aircraft components. The chemical composition for this alloy was the next: 4% Cu; 0.75% Mg; 0.75% Si; 0.8% Mn. Al-remainder. The material had the next mechanical properties: 458MPa - Yield Stress; 504MPa - Ultimate Tension Stress; 9.8% - elongation.

The testing facility used for the present work was the same as in previous investigations. It is described in details in [1]. The loading frame is a Mayes biaxial machine, which provides the normal static load, σ_n, from the fretting pad and the specimen axial cyclic load. The normal load is derived from the vertical actuators. A description of the command control is given in [1].

Specimen and fretting bridge.

The basic dimensions of the specimen section were 8x20 mm.

Sixteen specimens were shot peened by British Aerospace Airbus Ltd, Broughton, UK. The medium Almen intensity of shot peening (8.8A) was used [5]. Shot peened (SP) specimens were separated on two groups (eight in each group). The specimens from one group were polished after shot peening (SP polish), but the specimens from the second group were not polished (SP rough).

Loading conditions and methods of investigation.

Fretting fatigue tests were performed with the axial load amplitude of 100 MPa and various values of σ_n covering the range 10-120 MPa. In all tests cyclic axial load was applied with a sinusoidal waveform of 20 Hz frequency at the R-ratio of –1.0.

Fracture surfaces were cut from tested specimens and subjected to fractographic analysis on a scanning electron microscope EVO-40 manufactured by the "Carl Zeiss", having a resolution of at best 3nm.

The stress intensity factor, K_I, was calculated according to the Newman formula for corner shaped cracks [6]. The ratio between crack axes was determined from the fractographic analysis.

EXPERIMENTAL RESULTS

The fretting fatigue test results have shown that the specimen fatigue life has decrease for the normal pressure, σ_n, increasing for peened and unpeened specimens, Fig.2. In all cases the crack initiation took place on the specimen surface in area of fretting damage. For example, at the normal pressure values for unpeened specimens covering the range 20-120 MPa the lifetime to failure was (75000-190000) cycles, but, the contrary, the lifetime to failure was near to $2\text{x}10^6$ cycles for specimens tested at the σ_n= 10 MPa.

The value of fretting fatigue life at the lowest σ_n=10 MPa for “SP polish” specimen is significantly higher than for rough (approximately two times). The test conditions for low σ_n are close to the plain fatigue conditions, where a high surface roughness decreases the fatigue durability.

The results for both peened surface conditions at the high pressure of 120 MPa are very similar. Obviously the influence of high σ_n reduces the effect of surface roughness on the fretting fatigue life.

The fretting scars in the specimens that were tested under the high σ_n were continuous along the whole width of the specimen. In this case there is little wear as a result of the small slip and high σ_n. The crack initiation area has been seen in all specimens near to the corner, Fig.2. Then the crack propagation was faster along the damaged surface because of fretting.

The striation spacing value was seen from the 0.04 μm to 0.2 μm. In all cases the crack growth rate was faster after the spacing value 0.2 μm. than expressed by the Eq. 1, as is shown in Fig.2.

The functional correction, $F(fr)$, has not regular change in the crack growth direction (see Fig.2). Its value changes from 0.6 up to 1.0 for the striation spacing value less than 0.07 μm, then the $F(fr)$ has drastically increase and after the striation spacing 0.2 μm the functional correction has not principal change. This result takes place because the realised crack growth for the striation spacing value more than 0.2 μm described UKC with the same slope that used in Eq. 1.

The ratio between crack growth period, N_p, and lifetime to failure, N_f, increases for the normal stress, σ_n, increasing, Fig.3, a. It attests that the fatigue crack initiation period, (N_f - N_p), decreases for the normal stress, σ_n, increasing. The ratio N_p/N_f against the lifetime to failure, N_f, has the unified description for peened specimens, Fig.3, b.

The fretting damage influence on the N_f-value in high- and very-high-cycle fatigue areas for various, σ_n, can be summurised as it shown in Fig. 3,c. The normal stress, σ_n, decreased the cyclic stress level, σ_{w2}, of the transition from fatigue crack initiation on the surface because of fretting damages to under the surface.

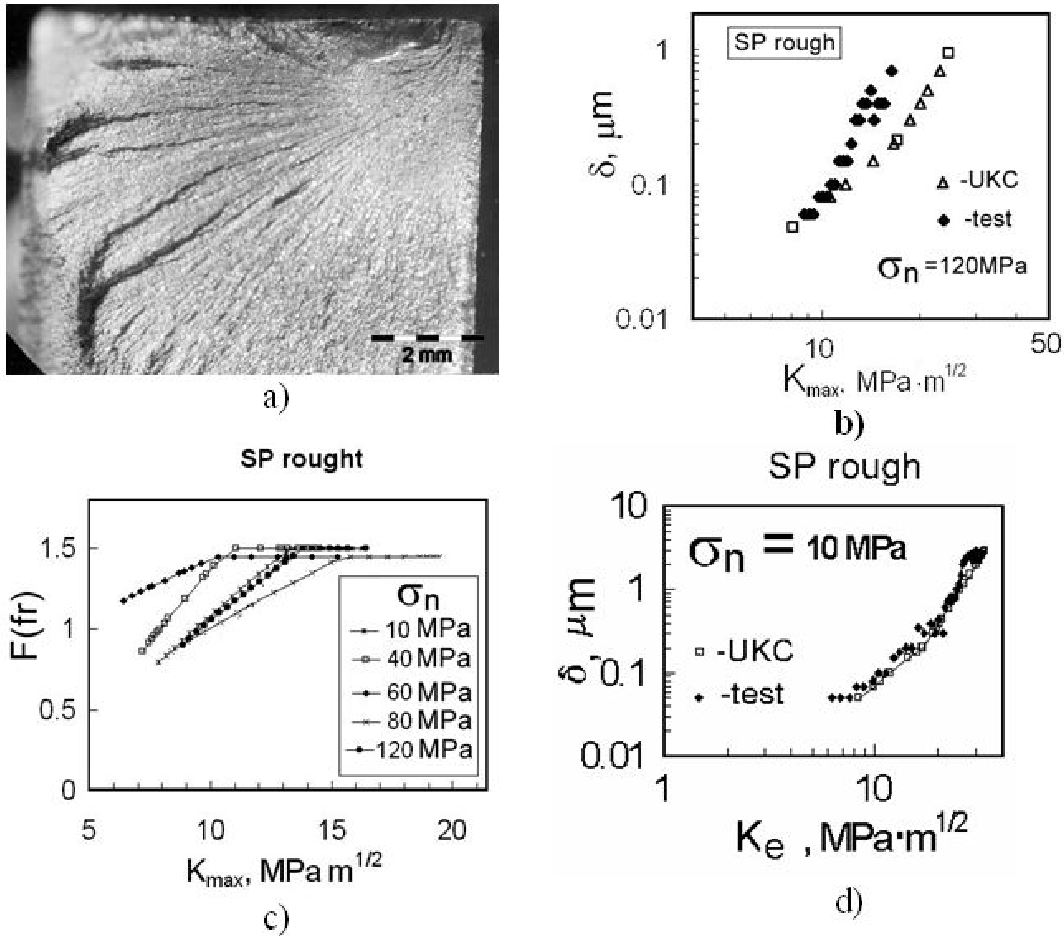

Figure 2. The overview (a) and (b) the striation spacing values, (c) the functional correction $F(fr)$ against the stress intensity factor $K_{\max}$ for the different normal stresses, and (d) the striation spacing value against the equivalent of the stress intensity factor K_e for unpeened and peened specimens and UKC, Eq. 1.

DISCUSSION

The critical through crack length, a_c, was calculated on the basis of the fracture mechanics for the maximum cyclic stress level of 100MPa. This value is approximately 5.5mm for the investigated specimens. The maximum value of the critical length a_c = 5.5mm was discovered for the corner crack in unpeened specimens.

This a_c-value of the corner shaped crack was approximately 8mm for all tested peened specimens. It is approx. 1.45 times more than for the unpeened specimens. This result reflected the residual stress influence on crack growth for hardened specimens. The residual stresses delayed crack front propagation in area of the hardened surface.

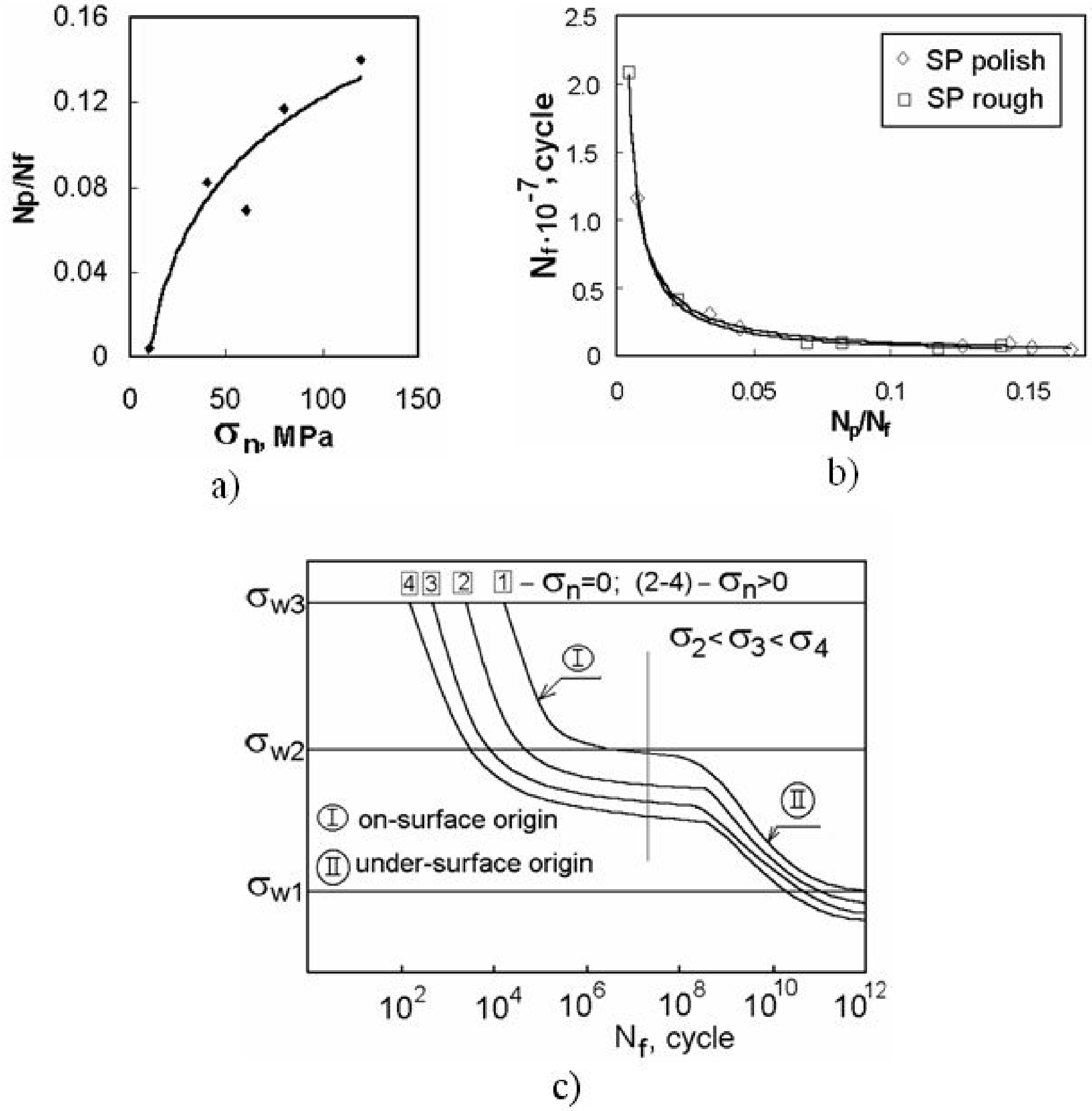

Figure 3. The ratio N_p / N_f against (a) the normal stress σ_n for "SP polish" specimens, (b) the lifetime to failure N_f against the ratio N_p / N_f for "SP polish" and "SP rough" specimens, and (c) the diagram of the N_f-value dependence on the cyclic loads for various normal stresses, σ_n.

Earlier it was shown [4], that for the Al-based alloys the striation spacing increase at R=-1.0 is 1.2 times in comparison to the value for the R=0 at the same crack growth length. The same result was discovered for the unpeened specimen with the through crack. The $F(fr)$-value was approx. 1.07.

The $F(fr)$-value was in the range of 1.4-1.5 for all unpeened and peened specimens with the corner shaped crack for the $0.2\mu m < \delta < 4.5\mu m$ (see Fig.2). The mean value of $F(fr)$ is approx. equal to the ratio 1.45. The $F(fr)$-value increases for the striation spacing increasing in area of $0.045\mu m < \delta < 0.2\mu m$. On the basis of these results and using knowledge about biaxial stress-state influence on the fatigue crack growth for the semi-elliptical and through cracks [4,5] the next explanation of the fractographic measurements can be done. On the first stage of the fatigue crack growth, before the fatigue striations formation, the biaxial stress-state delayed surface crack growth. There is fretting debris on the fracture surface. At the propagated fatigue crack tip can be seen synergetic situation for several parameters of cyclic loads interaction: material stress-state because of static-cyclic loads, residual stress, and fretting process, which influenced the crack closer effect. This synergetical situation has dramatic change in the crack growth direction because the biaxial stress-state decreases when the surface crack has transition to the corner shaped crack.

The crack growth rate increases but the fretting process for the edges interaction can be seen that reflected spherical particles, which were discovered in the fracture surface for the striation spacing values more than 0.2 μm. That is why the biaxial stress-state took place in the discussed area for the crack propagation and its influence on the fatigue cracking process should be estimated by the Eq. 2 on the basis of the K_e-value, and the discovered functional correction $F(fr)$, where K_I should be calculated by the Newman formula, [8], as shown in Fig.2. Performed calculations of the K_e-value have shown good agreement between experimental kinetic curves and UKC introduced for Al-alloys (see Fig.2).

CONCLUSION

The tests showed an increasing in fretting fatigue life of Al alloy BS L65 after SP with medium intensity. The fretting fatigue durability of "SP rough" specimens, is higher than the durability of "SP polish" specimens in the range of contact pressure, σ_n, 20-100 MPa. There is an opposite result at the lower pressure of 10 MPa.

It was shown that the ratio N_p/N_f and fatigue life are significantly dependent on the normal load level for peened and unpeened material, (see Fig.3).

The striation spacing formation process during fatigue crack growth has significant dependence on several factors: the realised stress-state in tested specimens to initiate the material fretting damage during cyclic loading, the fretting process in area of crack initiation and, then, during its propagation because of crack edges interaction, and residual stresses of peened specimens. The synergetics situation can be seen at a crack tip because of these factors interaction during fatigue crack growth. The calculated functional correction $F(fr)$ takes into account this synergetics situation and can be recommended for practice to simulate the fatigue crack propagation or to estimate the crack growth period during fatigue striations formation.

REFERENCES

1. Fernando U.S., Brown M.W., Miller K.J., Cook R., Rayaprolu D. (1994) In: *Fretting fatigue*, *ESIS 18***,** pp.197-209, Waterhouse R.B. and Lindley T.C., (Eds.), Mechanical Engineering Publications, London.
2. Waterhouse R.B. (1985) *Int. Mater. Rev*., **37**, 77-97
3. Shanyavskiy A.A. (2003) Tolerance Fatigue Cracking of Aircraft Components. Synergetics in Engineering Application, Monography, Ufa, Russia.
4. Shanyavskiy A.A. (2005) In: *Materials Structure and Micromechanics of Fracture IV, MSMF-4*, pp.235-238, (Jaroslav Pokluda, Ed.), Trans Tech Publication LTD 482, Switzerland.
5. Champaigne J. (1997) *Almen strip specifications. The Shot Peener* **11, issue 3**, 1-10.
6. Newman J.C., JR., Raju I.S. (1983) In: *Fracture Mechanics: Fourteenth Symposium*, pp. I-238-I-265, Lewis J.C., and Sines G., (Eds.), ASTM STP 791/

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