TWO-PARAMETER MODEL OF FRETTING FATIGUE CRACK GROWTH IN STRUCTURAL ALLOYS

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ABSTRACT

A fretting fatigue crack growth (FFCG) model is proposed accounting for the effects of tribological parameters of contacting materials and biaxiality of contact and bulk loads upon FFCG rate and direction in the fretting zone subsurface layers. Basing upon this model a new technique is developed providing fatigue life and fatigue limit prediction of aluminium alloy AMg6N and titanium alloy VT9 for given fretting conditions. For the above cases FFCG behaviour predicted by use of the proposed model is in good correlation with the experimental results.

KEY WORDS

Multistage fracture, fatigue crack, crack growth criterion, fretting conditions, fatigue life prediction, Mode I, Mode II, crack propagation curves, finite element method

INTRODUCTION

The principal trend of these studies is application of fracture mechanics to fretting fatigue life prediction of structural alloys. Service conditions of machine parts joints afford oscillatory movement of their contacting surfaces promoting fretting processes. Nonempirical consideration of fatigue limit decrease induced by fretting and of suitable palliative measures calls for physical interpretation of surface fracture different aspects, e.g. nonstationary compressive stress field conditions of crack initiation and propagation; biaxiality of crack tip loading by surface and bulk stresses, etc. Those factors promoting early growth of inclined microcracks in subsurface layers of fretting zone, thus reducing crack initiation stage fraction to 5-10% of the total life, FFCG behaviour turns into a main objective of mathematical representation in state-of-the-art techniques of fretting fatigue life prediction.

Solutions of Rooke and Jones (1977) has shown that inclined crack growth is attributed to two-axiality of subsurface layers loading in the fretting zone which is due to normal and tangential surface stresses interaction with bulk stress cyclic components what leads to generation of cyclic stress intensity factors K_I and K_{II} of variable ratio in the growing fretting fatigue crack tip.

The inclined crack tip stress state definition being rather intricate in case of two-axial loading, most available techniques of FFCG prediction based upon fracture mechanics approach, e.g. (Edwards, 1981; Tanaka et al., 1985) used the simplified scheme of FFCG behaviour: the surface crack propagation is postulated to occur in plane normal to the surface of the contact with no account taken of the parameter K_{II} effect upon the FFCG current rate and direction. The given simplification may cause significant discrepancy between the predicted and the experimental fretting fatigue life values.

Thus in the present study an attempt is made to provide FFCG behaviour prediction for inclined microcrack in fretting zone by means of step-by-step calculation of crack path and current rate of growth in terms of fracture mechanics using the FFCG model of Troshchenko et al. (1988) proposed for steels. For the model application to fretting fatigue life prediction for structural alloys a complex of experimental procedures is developed providing the required material parameters and relations controlling fretting fatigue processes, e.g. tribological curves of the contacting surfaces and parameters of fatigue crack propagation curves for Mode I, Mode II and mixed-mode types of fracture. Aprobation of the indicated techniques with aluminium alloy AMg6N and titanium alloy VT9 and the obtained data incorporation in the design provides fretting fatigue curves prediction for various contact conditions as well as their correlation with the corresponding test results.

EXPERIMENTAL DETAILS

Materials and Specimens. The materials used were aluminium alloy AMg6N and titanium alloy VT9. The mechanical properties of the two alloys are given in Table 1.

Table 1. Mechanical properties

Alloy	Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)	Reduction in area Φ (%)
AMg6N	343	430	7	21
VT9	1030	1140	7	30

Plain specimens of AMg6N and VT9 alloys of configuration shown in Fig. 1 were machined, respectively, from as-received 20 mm thick sheet and 25 mm dia. bar. Cylindrical contact pads of

5 mm dia. and 10 mm length were machined from workpieces of the same alloys and both the specimens and the two contact pads were polished with fine emery papers and with buff-polishing on the smooth surface.

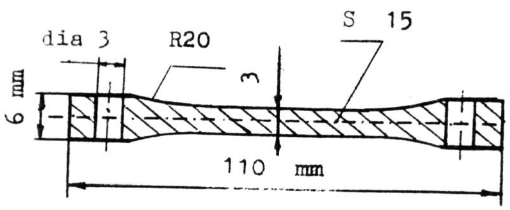


Fig. 1. Specimen dimensions

FFCG Procedure. The developed procedure provides fretting fatigue conditions in cyclic contact of the described specimen with two cylindrical pads in push-pull test what is aquired by use of the fixture shown in Fig. 2.

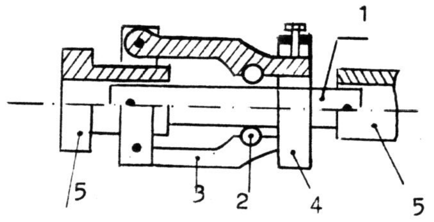


Fig. 2. Configuration of FFCG fixture : 1 - specimen ; 2 - contact pad; 3 - loading arm; 4 - calibrated ring; 5 - test machine clamp.

The normal contact load, P, is controlled by use of the calibrated ring of the described fixture. Specimen with clamped pads is subjected to regular push-pull test in the electromechanic test machine with 36 Hz frequency and the constant stress ratio, R=-1.

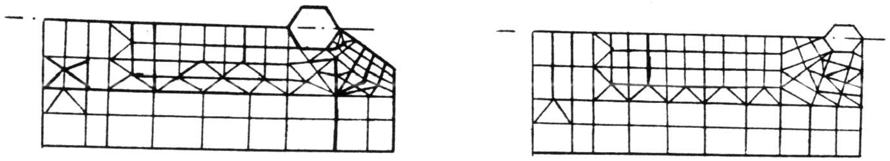
The monitoring optic system ensures detection of the through fretting fatigue crack of 0.1 mm depth. The corresponding number of cycles is taken for crack initiation stage. Further crack rate and configuration monitoring provides experimental data for FFCG curves. The other material parameters required for FFCG modelling are determined by the following techniques.

Determination of the Tribological Relations. For the assessment of the surface forces induced by a relative slip of the contacting surfaces, the corresponding value of the current coefficient of friction, M, should be determined for the same loading conditions. In the present study that was achieved by use of the above FFCG fixture for different slip conditions. During tribological tests cyclic movements of the active clamp are set and the slip amplitude is measured using a stroboscopic illumination miscroscope. The friction force, F, is measured using strain gages. Setting different values of the slip amplitude, the corresponding values of friction force, F, and the coefficient of friction, M (M = F/P), are determined. Experimental relations between the coefficient of friction and the slip amplitude are assessed for each of the investigated contacting materials.

Mode II Crack Propagation Test Procedure. Mixed-mode fatigue crack propagation conditions occuring in machine parts during their service loading, safety design calculations require experimental crack propagation data in Mode I and Mode II loading conditions. A test procedure is proposed providing simple experimental technique of Mode I and Mode II crack propagation testing of plane specimen (Fig.1.) with an additional single notch of 3 mm depth machined in the middle of the working part. The proposed procedure is a modification of the four-point bending scheme of Otsuka et al.(1985) by use of the original fixture (Tsybanev et al.,1992) which is applicable for arbitrary stress ratio values. Reactive loads induced in specimen parts clamped in the fixture influence stress intensity factor calibration of the modified scheme. Therefore finite element method (FEM) was used to evaluate K.. values for edge cracks of different lengths of the given specimen configuration in cases of point or distributed loading providing shear conditions in normal edge crack plane.

FINITE ELEMENT FFCG MODELLING

The two-dimentional FEM algorithm (Tsybanev et al.,1992) integrating the virtual crack growth approach and the singular element model of stress- strain singularity in the crack tip was realized: a singular hexagonal element containing edge crack tip was used for calculation of the parameters K and K both in shear loading tests and in FFCG tests. The FEM mesh including izoparametric rectangular or finite elements (336 in the former case and 370 in the latter case) while the both meshes included a hexagonal singular element containing the crack tip which is illustrated by Fig.3.



(a) (b)

Fig.3. FEM mesh configurations (fragment):
(a) Mode II edge crack in shear test;
(b) Mixed-mode fretting fatigue crack.

FEM solution for the present modified scheme is

$$K = \{(1.549-4.809x+16.061x^2-10.244x^3+0.222x^4)*QY/(tb^{\frac{1}{2}})\} \quad (1)$$

where Q is shearing force, t is specimen thickness, b is specimen width and X is normal edge crack relative length. The above calibration is used for the experimental Mode II crack propagation curves plotting.

Fretting fatigue edge crack FEM calculations provide elastic solutions for K_I and K_{II} parameters for the particular input parameters of FFCG test (crack configuration, loads, etc.).

RESULTS AND DISCUSSION

Crack Propagation Curves. Using the proposed shear test technique and the standard single edge crack propagation test procedure, Mode I and Mode II results for the stress ratio R=-1 were obtained for aluminium alloy AMg6N and titanium alloy VT9 and presented in Fig.4.

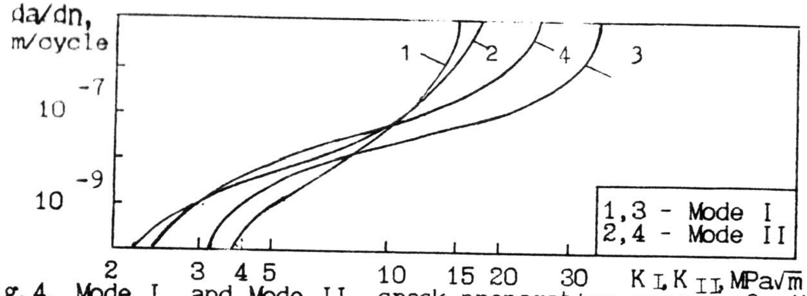


Fig.4. Mode I and Mode II crack propagation curves of AMg6N alloy (lines 1,2) and VT9 alloy (lines 3,4).

Mode II crack growth in the middle section of crack propagation curves is unstable which results in frequent crack bifurcation or deviation into maximal normal stress plane. In the investigated cases K_{II} parameter threshold values are shown to be lower than those of K_I parameter while their relation is in good correlation with von Mises criterion.

Tribological Relations. Experimental tribological relations determined for two pairs of the same contacting materials (AMg6N - AMg6N and VT9 - VT9) are presented in Fig.5. The experimental curves contain a linear, a nonlinear and a saturation sections which are usually related to different slip mechanisms (partial slip, microslip, macroslip, etc.). Analytical representations of the corresponding curves are incorporated in the following assessment of K I and K_{II} values in specific loading conditions realized in fretting fatigue crack propagation tests.

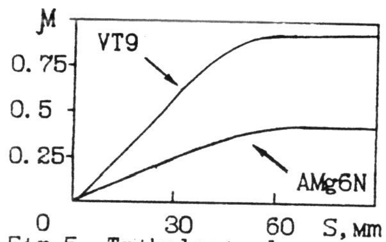


Fig.5. Tribological curves.

FFCG Behaviour. In FFCG tests 15 specimens of AMg6N alloy and 12 specimens of VT9 alloy were investigated with constant nominal values of normal contact stress: 80 MPa for VT9 and 100 MPa for AMg6N alloy. Tests provided the experimental data of FFCG behaviour (Fig.6) as well as fretting fatigue curves (those are analyzed later in Fig.8). In the investigated cases the initial crack of 0.01 mm length occured in the outer border of contact after no more than 8-10% of the total life.

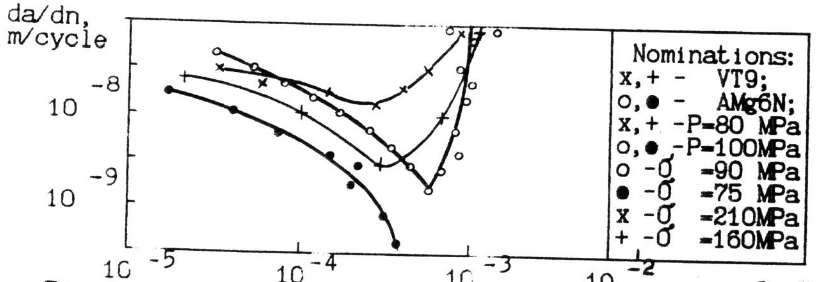


Fig. 6. FFCG curves for VT9 and AMg6N alloys.

As the initial cracks had different inclination angles (from 45 deg to zero) variating with growth, the corresponding rates were assessed in the current FFCG directions. In Fig.6 two branches of FFCG may be seen: significant decrease of FFCG rate in the initial stage is either followed by crack arrest or by enhanced growth in case of higher bulk load levels.

FEM calculations of parameters K_I and K_{II} in the crack tips for several of the investigated FFCG cases were realized by incorporation of experimental bulk and contact loads into FEM representation of experimental inclined edge cracks. Thus the kinetics of the parameters K_I and K_{II} variation with an increase in crack length was investigated in several specific cases. The calculated values of K_I and K_{II} given in Table 2 suggest that only one of those factors dominates in the early FFCG stage but the situation changes with crack growth.

Table 2. FEM calculations of K_I and K_{II} for FFCG tests

Alloy	AMg6N	AMg6N	AMg6N	AMg6N	VT9	VT9	VT9
Stress amplitude, MPa	90	90	75	75	210	210	160
Slip amplitude, мm	24	24	15	15	16	16	12
Friction coefficient	0.16	0.16	0.12	0.12	0.32	0.32	0.28
Edge crack length, mm	0.08	0.26	0.08	0.26	0.09	0.12	1.08
Inclination angle, deg	23	18	30	30	43	28	14
Parameter K_I, MPa $\sqrt{m}$	0.35	1.96	0.23	0.37	0.58	0.75	9.53
Parameter K_{II}, MPa $\sqrt{m}$	6.09	4.33	5.72	2.44	6.07	5.46	0.03

The indicated tendency of the calculated parameters K_I and K_{II} variation with edge crack length increase is illustrated by Fig.7. The determined scheme suggests change of crack growth modes from Mode II to Mode I which may be taken into account by use of the following two-parameter FFCG model.

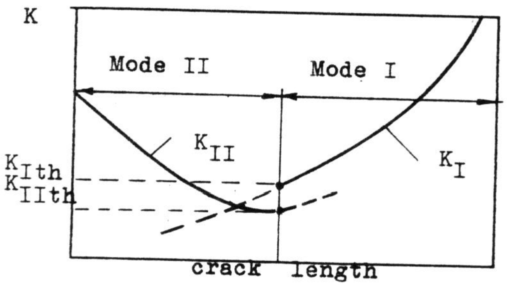


Fig. 7. K_{II} and K_I variations in FFCG.

The Proposed Model. In order to describe FFCG behaviour in the investigated cases of mixed-mode loading condition the model of Otsuka et al.(1985) was used and modified (Troshchenko et al., 1986). The model postulates the following stages of fatigue crack growth in mixed-mode loading conditions: the nucleated microcrack grows initially in the plane of maximal tangential stresses at stage I and then it deviates into the plane of maximal normal stresses at stage II. One of the following two parameters controls the crack growth at each of the two stages: the maximal tangential stress intensity factor K_τ and the maximal normal stress intensity factor K_σ , where

$$K_\sigma = \cos(\theta/2)[K_I \cos^2(\theta/2) - 1{,}5 K_{II} \sin\theta] \quad (2)$$

$$K_\tau = (1/2)\cos(\theta/2)[K_I \sin\theta + K_{II}(3\cos\theta - 1)]; \quad (3)$$

Crack propagation rate in the plane of maximal normal stress is controlled by the parameter K_σ and may be correlated with the Mode I crack propagation curve of the same material, while in the general case it is disputable which of the two parameters, K_σ or K_τ controls the initial fatigue crack growth in the plane of the maximal tangential stresses.

In the present study this model was refined and applied to FFCG in alloys. As has been shown in the investigations of Kaneta et al. (1986) , fretting fatigue cracks initiate and develop in the plane of maximum tangential stresses. The present FEM analysis showed that in the initial stage of FFCG (stage I) the values of parameter K_τ may exceed the corresponding value of K_σ by an order of magnitude due to the significant influence of the contact stresses , as a result of which the crack propagates in the plane of maximum tangential stresses controlled by the parameter K_τ With crack growth the contact stress-induced constituents of the stress intensity factors diminish and therefore the fatigue crack growth rate drops. According to Fig.7, if the parameter K_τ drops to its threshold value K_{IIth} and the value of K_σ at this moment still does not reach the threshold value K_{Ith} , then a nonpropagating crack is formed. From the condition of fatigue crack nonpropagation it is possible to evaluate the fatigue limit in the particular fretting fatigue conditions. In case of contact and bulk stresses combination exceeding the value corresponding to fretting fatigue limit, a change in the FFCG mechanism occurs (and stage II begins) while further FFCG rate and direction are controlled by the parameter K_σ.

FFCG Life Prediction. The above model was incorporated into the software for FFCG life prediction providing step-by-step FEM calculation of the resultant parameters K_τ and K_σ for the current crack configuration and loading conditions, consequent integration of the experimental Mode I and Mode II curves and loading cycles calculation for the growing inclined edge crack. In Fig.8. the predicted fretting fatigue curves of AMg6N and VT9 alloys are compared with the available experimental data, a close correlation between those being provided by the model.

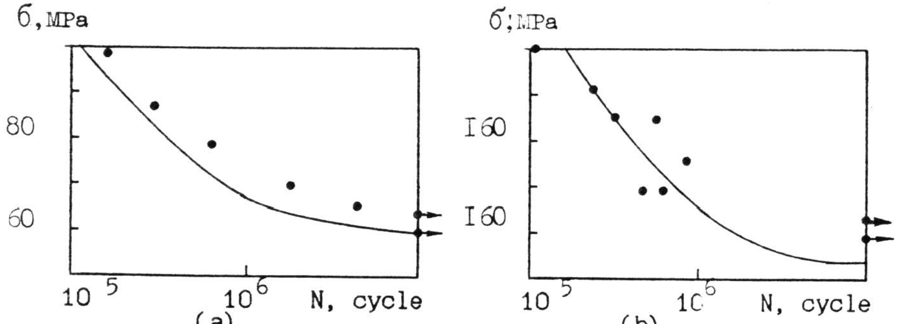


Fig. 8. Experimental data and predicted fretting fatigue curves: (a) AMg6N alloy; (b) VT9 alloy.

CONCLUSIONS

Following conclusions are drawn based on the present work:
(1) The proposed model provides FFCG behaviour prediction by use of the maximal tangential stress intensity factor K_τ and the maximal normal stress intensity factor K_σ as parameters controlling FFCG at stage 1 and stage II, respectively.
(2) A new FFCG prediction technique is developed, verified and shows close correlation with the experimental results.

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