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Crack Growth Simulation in D16T Al-Alloy Subjected to Variable Biaxial Stress Ratio, Principle Stress, and R-Ratios.

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Abstract: *Multiparametric variations of external cyclic loads influence on the fatigue crack growth under biaxial stresses-state investigated in the cases when loads interaction effects are visible were produced on crusiform specimen from Al-alloy D16T. The unified kinetic diagram and correction function used to simulate fatigue crack growth after simultaneous changing of principle stress level, biaxial stress ratio, and stress ratio, R. Values of correction function that discovered in the case of regular cyclic loads were corrected for investigated cases of irregular cyclic loads. Results of fatigue crack growth simulation are briefly discussed.*

Notation

a	semi-crack length
da/dN	crack growth rate
E	Young's modulus
K_I	mode I stress intensity factor
K_e	equivalent mode I stress intensity factor
$F(\lambda,R)$	stress intensity factor K_I as a function of cyclic parameters λ and R
R	stress ratio ($\sigma_{min}/\sigma_{max}$)
λ	biaxial stress ratio (σ_2/σ_1)
δ	striation spacing
ν	Poisson's ratio
$\sigma_{0.2}$	0.2% offset yield strength
σ_1	tensile stress opening the fatigue crack
σ_2	tensile or compressive stress acting in a perpendicular direction to the σ_1 direction

Introduction.

In service aircraft components subjected to various external multiaxial cyclic loads. Fatigue cracks are created in faces of components, and some of them may large enough to make the components lose their load capacity and bring about a great loss in economy. So, problems of fatigue cracks growth simulation to prevent the components failure have great value, not only in theoretical but also economic aspects.

For service cracks growth simulation problems are complex, they involve many factors, such as transient stresses, biaxial stress ratio, $\lambda=\sigma_2/\sigma_1$, taking place on the component face, environments changes from flight to flight and others. Because the fatigue crack growth is a transient problem and involves many factors, there are many difficulties in the quantitative analysis work. That work in the case of cracks growth under various multiaxial stresses is important to introduce in practice a non-destructive testing of components provided economically utility inspection's period. In the recent investigation the interaction effect of various cyclic loads was analysed in the case of biaxial stresses state at various R ratios. The equivalent mode I stress intensity factor, K_e, and the developed unified kinetic diagram [1], [2] were used to simulate fatigue crack growth.

On the basis of experiments, and based on a synergetic analysis [2] of multiparametric effects on fatigue crack growth during Stage II (tensile mode I crack growth) and making allowances for fractographic peculiarities during Stage II when the self-organised processes of fatigue striations formation are dominant, a unified description of fatigue crack growth in Al-alloys was proposed in the next form [2]:

$$\begin{array}{ll} \delta = C_s K_e^2 & \text{at} \quad \delta < 2.14 \text{ x } 10^{-7} \text{ m} \\ \delta = C_2 K_e^4 & \text{at} \quad \delta > 2.14 \text{ x } 10^{-7} \text{ m} \end{array} \qquad (1)$$

In the above equations the proportionality factor for the through cracks are $C_s = [1-\nu^2][12\pi E\sigma_{0.2}]$, and $C_2 = C_s/K_{es}^2$. Here K_{es} corresponds to the value of K_e when the growth rate of 2.14 x 10^{-7} m/cycle is reached. This value of growth rate characterised the transition to more complicated mechanisms of metal fatigue, i.e. shearing, facet rotations, and static fracture processes but fatigue striation formation mechanisms after the transition were dominant.

Any of the values of K_e determined by assuming similarity of the crack growth process under any one of the previously discussed external action parameters adds to our understanding of a material's behaviour. This has been realised in uniaxial pulsating cyclic tension tests where a corrective function for independent variations of the parameters λ and *R* can be presented by a polynomial equation. In our studies of crack growth under pulsating uniaxial cyclic tension ($\lambda=0$ and $R=0$) the correction function equals 1 [1,2].

The function values for Al-alloy D16T for different λ and *R* ratios were obtained in the case of regular biaxial cyclic loads from the relationship between proportional factors by the relation [1]:

$$F(\lambda,R) = [(C_s)_{\lambda,R}/(C)_{\lambda=0,R=0}]^{1/2} \qquad (2)$$

Comparison of fatigue striation spacing δ and crack growth increment per cycle of loading, da/dN, reveals that their evolution can be described in a similar way [2] using Eqs. (1) and (2), and crack growth period can be simulated, but the values of the correction function $F(\lambda,R)$ for growth rates is different from the function for striation spacings because crack growth in the interior and on the exterior of specimens is different [1,3].

Below is given a comparative analysis of crack growth for various irregular biaxial cycle loading conditions. The function correction, $F(\lambda,R)$, discovered in the case of regular biaxial cyclic loads, was optimised to have a good agreement between simulated and experimental data for irregular cyclic loads.

Experimental procedure.

Tests were developed on the cruciform specimens, having a sheet thickness t=4.9mm, from the D16T Al-Alloy. The specimen geometry, the especial test bed for biaxial cyclic loads, material composition, and properties were the same as described in paper [1].

The several series of cyclic loads sequences were developed:

I. Blocks of cyclic loads of three levels σ_1 were acting during 50 cycles: $(\sigma_1)_2=1.5(\sigma_1)_1$, - during 25 cycles; $(\sigma_1)_3 = 1.8(\sigma_1)_1$ - during 15 cycles. Biaxial stress ratios were: -0.7;+0.2;+0.7 at frequency 10Hr, and $(\sigma_1)_1 = 140$MPa.

II. Blocks of modulated cyclic loads by sinuous low of amplitudes variation with period of 12 cycles at frequency 8Hr. The mean loads level was constant but the load amplitude in the block was varied in two times for biaxial stress ratios +0.2 and +0.7 at σ_1 = 140MPa.

III. Blocks of various λ ratios in the next sequences per block:-0.2;-0.4;-0.7;-1.0;-1.4, and +0.2;+0.4;+0.7;+1.0;+1.4. There were produced $4x10^3$ cycles of each λ value in a block at R=0.1. The frequency and the stress level, σ_1, were 10Hr and 115MPa respectively.

IV. One time transition from one combination of λ_i; R_i; σ_i to another. The two or three parameters were simultaneously changed in the ranges $-1.4 < \lambda < +1.4$, $0.2 < R < 0.7$, and $120 < \sigma_1 < 240$MPa. The test frequency was 10Hr.

After the test, fracture surfaces were cut from the specimens and subjected to fractographic analysis on a scanning electron microscope, CDS-50, having a resolution at best of 50A.

Results and discussion.

Fractographic analyses.

There were only two blocks of striations with different mean spacing value in a block on the fatigue surface for I-sequence of cyclic loads. The striation spacing increases in 3.0 times for the principle stress level, σ_1, increasing in 1.2 times. The reversion to the less level of σ_1 decreased the striation spacing on the same factor. The minimum stress level didn't produced any striation. There was the line of the small width from the cyclic loads produced by the stress, $(\sigma_1)_1$, on the fatigue surface between two blocks of striations of 20 cycles per each block, Fig 1. So, the correspondence of striation spacing with the crack increment per cycle of loading remains near 1 to 1 for any λ ratio and stress level σ_1 if the stress levels variations in a block produced in the range $1 < (\sigma_1)_i/(\sigma_1)_{i+1} < 1.5$.

The possibility to use the unified kinetic diagram to simulate crack growth in the case of this cyclic loads sequence was analysed on the bases of the relation:

$$\delta_i/\delta_{i+1}=[(\sigma_1)_i/(\sigma_1)_{i+1}]^n \qquad (1)$$

Because the crack length, a, and the biaxial stress ratio, λ, were the same for measured striation spacings in any block, the spacing ratio δ_i/δ_{i+1} only depended on the stress levels in a block. In the investigated case for used $[(\sigma_1)_i/(\sigma_1)_{i+1}] = 1.2$ the value of $n = 6$. The correction function $F(\lambda,R)$ therefore is not the same for various stress levels in the block. It value should have optimisation according to the unified description of fatigue crack growth (1) by the relation [1]:

$$\delta_i/\delta_{i+1} = \{[(\sigma_1)_i/(\sigma_1)_{i+1}].[F(\lambda_i,R_i)/F(\lambda_{i+1},R_{i+1})]\}^4 \qquad (3)$$

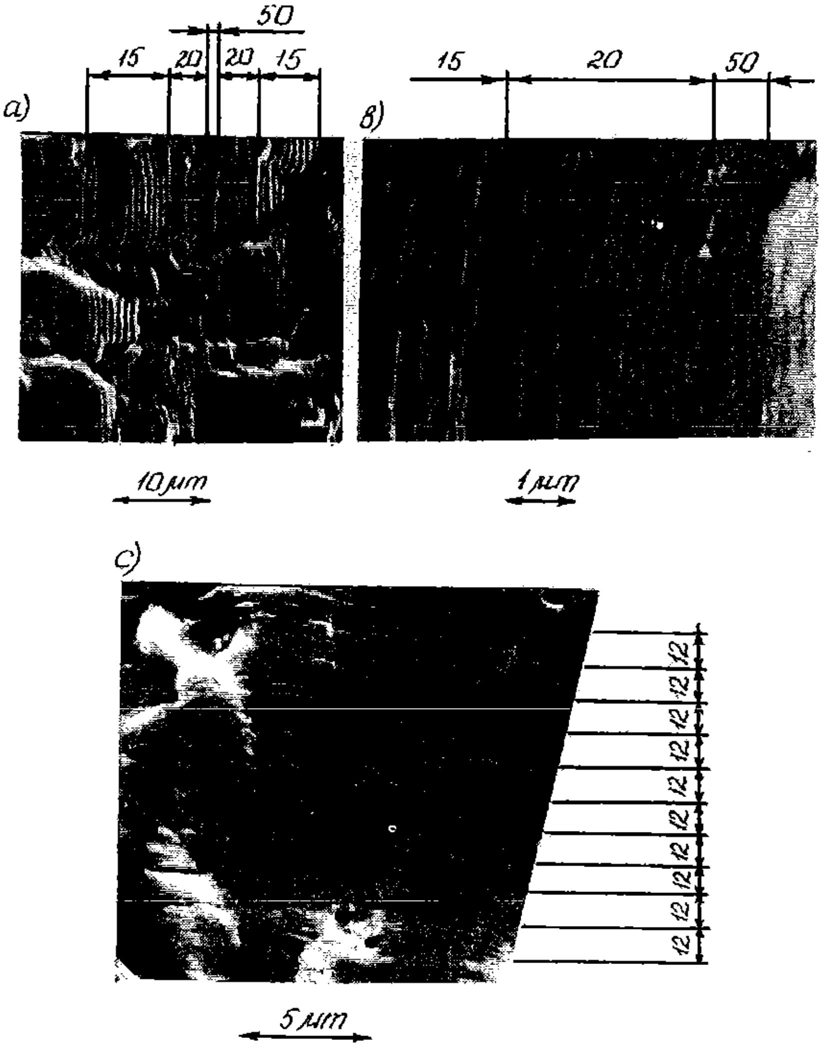

Fig.1 Blocks of fatigue striations for (a,b) I-sequence and (c) II-sequence of cyclic loads.

In the Eq.(3) the correction function F(λ,R=0) equals to F(λ) for the I-sequence of cyclic loads in a block. The function, F(λ), value changes in approx. 1.1 time, have increasing or decreasing in dependence on the stress level increasing or decreasing in the block respectively. This value of correction function characterised interaction effect of cyclic loads when any striation disappeared after the stress level decreasing.

Striations were not produced under the minimum stress level reduced in 1.5 time. This variation of cyclic loads did not delayed crack growth in the case of uniaxial loads [4]. Therefore, the interaction effect of biaxial cyclic loads influenced growth rate more intensively than the uniaxial cyclic loads variation [4].

Variation of the stress amplitude during 12 cycles in the II-block produced only 5 striations under the maximum stress's amplitude, Fig.1. The 7 cycles produced roughed line had a small size in width. There is approximately the same relation between stresses amplitude $(\Delta\sigma_i)/(\Delta\sigma_{i+1})=1.5$ that prevented the fatigue striation formation as was discovered in the case of the stress level decreasing for the I-block of cyclic loads at R=0.

Mean values of the crack increment, Δ, per any block of two loads sequences, measured on the fatigue surface, had good correspondence with the crack growth rate determined in tests as value of a crack increment , Δa, per a number of blocks, N_i, as shown in Fig.2.

Variations of the λ-ratio in blocks of III-sequences of the cyclic loads produced approximately $4x10^3$ striations for many λ ratios but not for the λ = -0.2 and λ = 0.2, because transitions from λ= -1.4 and λ = 1.4 to λ = -0.2 and λ = 0.2 respectively delayed crack growth. The calculated number of striations is near to the number of cyclic loads prtoduced in test for any λ ratio if the interraction effect not delayed crack growth. The λ ratio influence on the growth rate was analysed in the case of regular cyclic loads [1]. The crack growth was more intensive for the λ = +1.4 and λ = -1.4 than for the λ = 0.2 and -0.2 respectively. In the investigated case it was only transition from λ = −1.4 to λ = -0.2 that delayed crack growth, as shown in Fig.3. There is black wear debris following the crack front on the fatigue surface. Therefore, there were residual stresses increasing ahead of a crack tip within the plastic zone those delayed crack growth after the transition to λ ratio decreasing up to 0.2 or increasing up to -0.2.

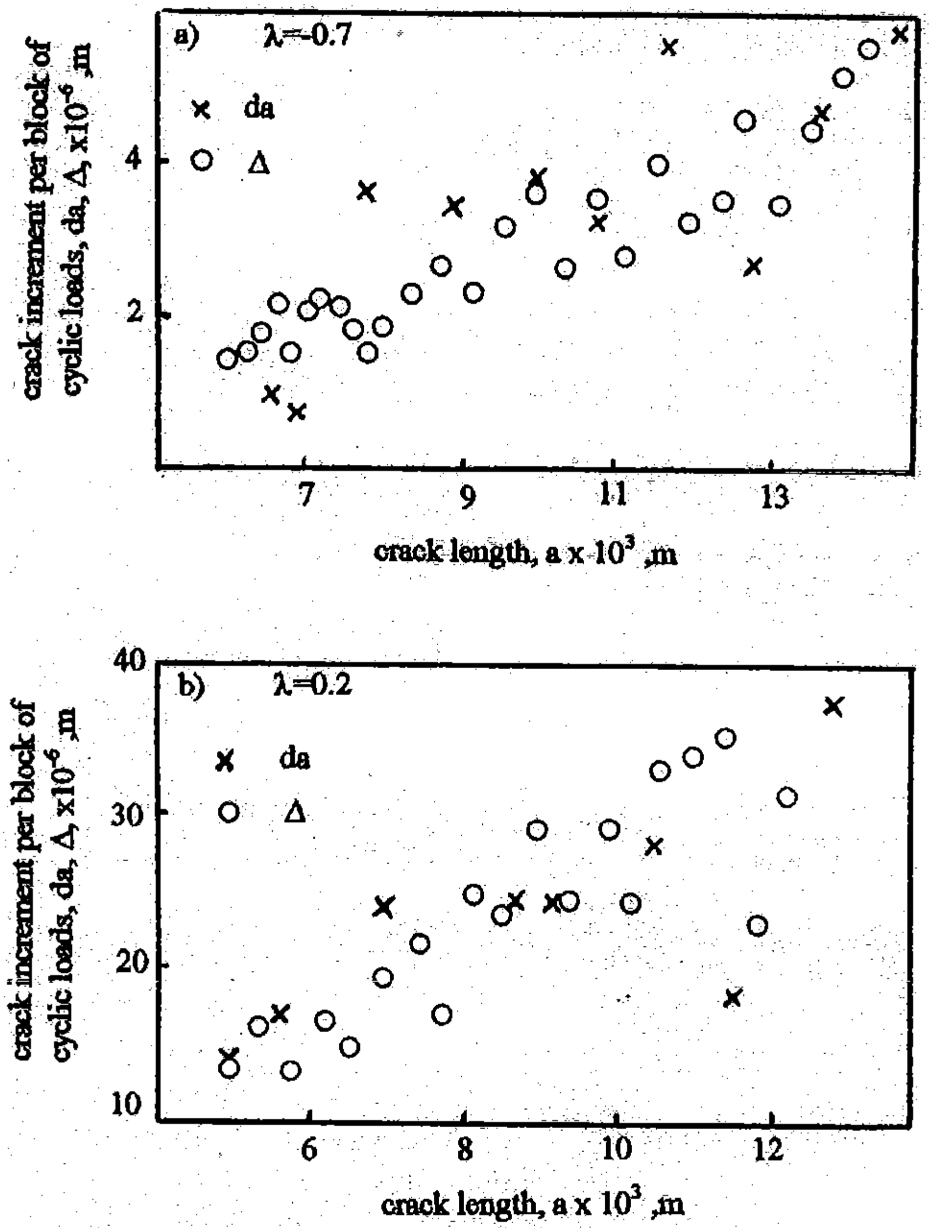

Fig.2 Dependencies of the mean value of the crack increment per block on crack length of (a) I-sequence and (b) II-sequence of cyclic loads determined in test, da/dN, and from the fractographic analysis, Δ.

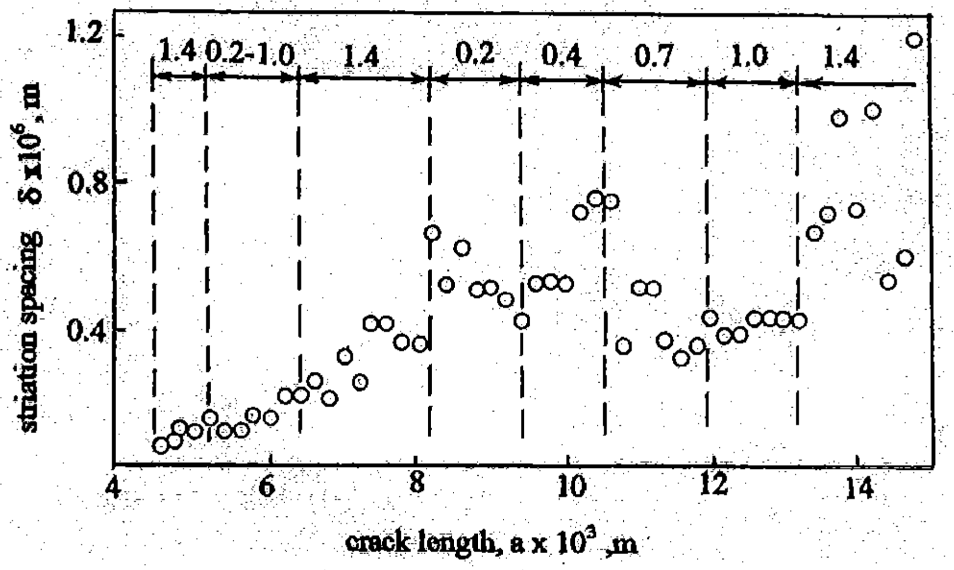

Fig.3 **Striation spacing dependencies on crack length in the case of III- sequence of cyclic loads.**

Variations of cyclic loads in the IV-sequence did not produced the crack retardation. A number of calculated striations had approximately correspondence to cycles number that specimens have subjected to biaxial loads after any transition to the new values of λ_i; R_i; $(\sigma_1)_i$. The stress level increasing from 150 MPa to 200 MPa was compensated by the λ ratio conditions were realised in test when the striation formation mechanism is dominant variation from 0.4 to 0.7 or -1.4 at R = 0.3, as shown in Fig.4. The similarity in fatigue crack growth before and after any transition from one combination of biaxial cyclic loads parameters to another reflected the self-organised principal of fatigue fracture process in metals [2]. The external cyclic loading parameters can only decrease or increase the crack length's interval into which the striation spacing formation process is dominant. Any situation of crack growth under any test condition can be related to the case of simple uniaxial cyclic tension at R = 0 during Stage II, when the fatigue striations are firmed. Each kinetic curve describes the same process of fatigue crack development for any parameters of cycle loading before and after investigated transitions because similar.

Fractographic analysis showed the self-organised and similar fatigue crack propagation behaviour in the D16T Al-alloy for any combinations of investigated parameters. This conformed the unique stage-by-stage processes of fatigue fracture that developed surface features on different scale levels for crack increment in metals. During Stage II of the growth rate (4.74 to 450)x10 $^{-8}$ m/cycle the fatigue striation formation mechanism is dominant. The external cyclic parameters can only decrease or increase the crack length interval into which that dominant mechanism is realised. For all cases the K_e value can be written as $K_e = K_I.F(\lambda,R,...X_i)$ for the cyclic parameters $(\lambda,R...X_i)$. Therefore, the crack growth can be simulated in the case of irregular cyclic loads on the bases of an equivalent mode I stress intensity factor K_e and unified kinetic diagram, Eq. (1), when a number of striations corresponded to a number of cycles near 1 to 1.

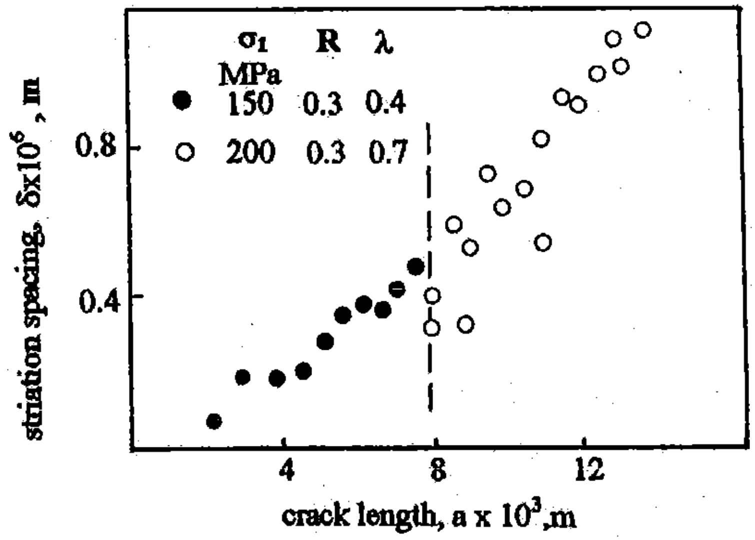

Fig.4 Striation spacing dependence on crack length for the IV-sequence of cyclic loads.

Crack growth simulation.

The fatigue crack growth was simulated for investigated cases when the mainly fatigue striations formation mechanism was realised. The unified kinetic diagram, Eq.1, was used in these cases with the same correction function values those were calculated for regular cyclic loads [1].

There was slowed real crack growth along the crack length than simulated crack developing by the Eq.1 for most combinations of $\lambda_i;R_i;(\sigma_1)_i$ after any transition to new values of these parameters This result is explained by the analysed cyclic loads interaction effect that was discovered in the case of the I-sequence of cyclic loads. The simulated data and experimental data did not have an error that exceeded 15% when the λ ratio was increased from 0.4 or -0.4 to 1.4 especially for simultaneous increasing of principle stress, σ_1, from 150 MPa to 200 MPa. The values of biaxial stress ratio had approximately the same influence on the crack growth that was discovered for the regular cyclic loads [1]. That is why, the interaction effect had not principal influence on the crack growth after the transition from one λ ratio value to another one.

So, a special optimisation of the correction function values was required. The technology of optimisation was the same as for the regular cyclic loads [1]. First of all, the crack growth calculation was used for the value of the correction function discovered for regular cyclic loads. The a new calculation was made by decreasing the function value to decrease difference between the calculated crack growth period and that registered in test. The calculation was stopped automatically after the difference did not exceeded +2%. Results of this optimisation are shown in Table. It is evidently that the transition to a more intensive decreasing of the growth rate needs in a less value of the correction function than was discovered for the same parameters values of the regular cyclic loads. The stress level, σ_1, variation in 1.5...2.0 times had more intensive influence on the growth rate than the simultaneous λ ratio variation in many times.

Table

Values of cyclic loads parameters λ, R, σ_1 before (i) and after (i+1) of their change during crack growth, and the correction function values before (j) and after (j+1) of their optimisation.

nn	$(\sigma_1)_i/(\sigma_1)_{i+1}$ MPa/MPa	λ_i/λ_{i+1}	R_i/R_{i+1}	$F_j(\lambda/R)$	$F_{j+1}(\lambda/R)$
1.	120/200	-0.4/0.4	0.3/0.3	0.60178	0.463
2.	120/200	-0.4/0.4	0.4/0.2	0.71258	0.317
3.	150/120	0.4/0.4	0.3/0.3	0.60178	0.535
4.	150/120	0.4/0.2	0.3/0.3	0.65489	0.520
5.	150/150	-0.4/0.4	0.3/0.3	0.60178	0.300
6.	150/150	-0.4/1.4	0.3/0.3	0.23457	0.240
7.	150/150	0.7/-0.7	0.3/0.3	0.80997	0.543
8.	150/150	0.4/1.4	0.3/0.3	0.23457	0.257
9.	150/150	0.2/0.4	0.4/0.2	0.71258	0.400
10.	150/200	0.4/1.4	0.3/0.3	0.23457	0.203
11.	200/150	-0.7/0.7	0.3/0.3	0.50941	0.315
12.	200/150	-0.7/0.4	0.4/0.4	0.47305	0.163
13.	200/150	0.7/0.4	0.3/0.4	0.47305	0.315
14.	200/200	-0.4/0.4	0.4/0.4	0.47305	0.189
15.	200/200	-0.7/0.4	0.4/0.3	0.60178	0.215
16.	200/200	-0.7/0.4	0.4/0.4	0.47305	0.297
17.	200/200	-0.7/0.4	0.4/0.4	0.47305	0.297
18.	200/200	-0.4/0.4	0.4/0.2	0.71258	0.300
19.	240/150	0.4/-0.4	0.3/0.3	0.77353	0.539
20.	240/150	0.4/-0.7	0.3/0.3	0.80997	0.513
21.	240/150	0.4/-0.7	0.4/0.3	0.80997	0.410

Conclusions

(1) The fatigue fracture process under varied biaxial cyclic loads parameters λ; R; σ_1 is qualitatively similar to the process develops under uniaxial cyclic loads varied parameters. The simultaneous changes of these parameters in the opposite direction can be seen to be mutually compensatory. As a result, an increase of one of them and simultaneous decrease in the other may create no effect on crack growth, if it is compared with the crack development under uniaxial pulsating cyclic loading.

(2) A similarity in the fatigue fracture mechanisms attest to the possibility of characterising the formation of fatigue striations and growth rates by unified kinetic diagram based on F(λ,R), The crack growth decreases more intensively in the case of irregular cyclic loads than for the regular loading when variations of λ; R; (σ_1) didn't delayed crack growth.

(3) The new values of the F(λ,R) correction function were determined for investigated variations of cyclic loads parameters when was only produced one time transition from any combination of the λ; R; (σ_1) to another. The simulated data and the experimental data did not have an error that exceeded 15% applicable to investigated specimens.

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