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A Method for Low-Cycle Fatigue Life Assessment of Metallic Materials under Multiaxial Loading

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A new method of fatigue life assessment under multiaxial low-cycle regular and irregular loading is proposed, which is based on the modified Pisarenko–Lebedev criterion, the linear damage accumulation hypothesis, and the nonlinear Manson approach. The results of low-cycle fatigue tests of titanium alloy VT9 under irregular proportional and non-proportional biaxial loading are given. The tests were carried out at three Mises strain levels (0,6, 0,8, and 1,0%) with various combinations of proportional and non-proportional strain paths. All the tests were carried out at room temperature. The proposed method turned out to be effective and to allow for such factors as strain state type, strain path type and loading irregularity.

Keywords: multiaxial low-cycle fatigue, irregular loading, titanium alloys, damage accumulation, limit state criteria.

Introduction. Machine and construction elements often undergo irregular multiaxial cycle loading. Though multiaxial fatigue of materials has been studied for a long time and sufficient experimental data has been accumulated, the problem of including a loading irregularity in a low-cycle fatigue area is still important. Numerous attempts to describe fatigue damage process have been made, resulting in the development of a large number of damage accumulation models.

The most generally employed is the linear damage accumulation concept proposed by Miner, whereby damages D per cycle at a variable loading amplitude are added linearly and the failure happens when $D=\sum_i n_i/N_{fi}=1$, where n_i is the number of one-level loading cycles and N_{fi} is number of cycles to failure under a given loading level. This approach is easy to use but it fails to give an adequate estimation of life in many cases.

There have been many attempts to develop a model based on the nonlinear accumulation of fatigue damage, but most of them disregarded the complex influence of such factors as the stress state type, loading path, previous stress history in the process of fatigue damage accumulation. Fatemi and Yang [1] have carried out a substantial survey of the existing models, proposed a classification thereof, discussed advantages and disadvantages of each model.

In the paper, the influence of sequential loading effects is studied on VT9 titanium alloys under tension–compression, torsion and 90° out-of-phase non-proportional loading. The life estimation method is proposed both for regular and irregular multiaxial loading. A damage model is put forward, which considers the nonproportional effects arising at a change of the loading regime.

Experimental Procedure. A high-temperature titanium alloy VT9 of the Ti–Al–Mo–Zr–Si system belongs to two-phase $(\alpha+\beta)$ martensitic alloys. The chemical composition (in wt.%) of the material is given in Table 1. The microstructure of the material of the specimen billets consists of $(\alpha+\beta)$-phases of equiaxial structure and corresponds to the second type in the nine-type scale for bar materials according to Instruction No. 1054-76 of the All-Union Institute of Aircraft Materials.

Table 1

Chemical Composition of VT9 Alloy

Al	Mo	Si	Fe	Zr	H_2	N_2	C
6.50	3.40	0.30	0.081	1.58	0.006	0.018	0.06

Specimens were made from as-delivered rolled bars 25 mm in diameter. The mechanical properties of the material, which were determined by tensile testing of 125-mm-long solid cylindrical specimens at room temperature, have the following mean values: proportional limit 758 MPa, yield strength 865 MPa, ultimate strength 973 MPa, elongation 17%, reduction of the cross-sectional area 45%, and elastic modulus 118 GPa.

For the purpose of providing a stress-strain state close to a homogeneous one, tubular specimens with an outer diameter of 11 mm, wall thickness of 0.5 mm, gauge length of 20 mm were used. The realized strain paths are shown in Fig. 1.

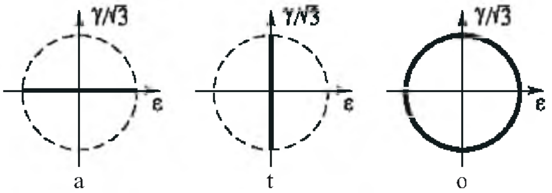

Fig. 1. Schematics of strain paths used.

For the VT9 titanium alloy the test program as given in Table 2 was implemented. The basic modes were as follows: tension–compression, alternating torsion, and 90° out-of-phase loading. The first stage of the program was the block axial loading and/or torsion moment test with given strain ranges. During this test the strain path remained constant. The second stage of the program involved testing of the specimens with changing of the strain path. A transition from one strain path to the other was conducted when the D value reached 0.5 and then the specimen was cycled to failure. At the third stage the test with a multiple strain path change was carried out.

Proposed Method. It was previously mentioned that the application of the Pisarenko–Lebedev modified criterion for the fatigue life assessment of the VT1-0 titanium alloy under regular nonproportional loading shows a good agreement between the predicted and test data due to the complex consideration of the strain state type and nonproportionality of loading [3]. Therefore it is recommended to apply the Pisarenko–Lebedev modified criterion as well as the chosen damage accumulation hypothesis for assessing the VT9 titanium alloy fatigue life. In this study, the two damage accumulation hypotheses were analyzed: the linear hypothesis and the Manson approach with the Pisarenko–Lebedev equivalent strain in both cases, according to which the damage curve is a nonlinear function of the relative fatigue life,

$$D_i = (n_i / N_{fi})^q,$$

where $q = (N_{fi} / N_{fr})^{\alpha}$; α is the material constant to be calculated from the test data for sequential double-level loading, and N_{fr} is the number of load cycles to failure at a "reference" loading level.

Analyzing Figs. 2 and 3 one can see that during the application of the Pisarenko–Lebedev modified criterion and the linear damage accumulation hypothesis the best correlation between the predicted and test data is obtained for alternating torsion (paths t_01 and t_02).

Table 2

Strain Peak Values and Number of Cycles to Failure for VT9 Titanium Alloy

Test type		ε_a	$\gamma_a/\sqrt{3}$	n_i	N_f
		%		cycle	
a_01	a	0.8	–	157	293
	a	1.0	–	136	
a_02	a	1.0	–	98	245
	a	0.8	–	147	
a_03	a	0.6–0.8–1.0–0.8	–	50	519
a_04	a	1.0–0.8–0.6–0.8	–	50	491
oatota	–	0.8	1.0	50	475
oa	o	1.0	1.0	77	218
	a	1.0	–	141	
atat_1/5	a	1.0	–	40	423
	t	–	1.0	130	
atat_1/3	a	1.0	–	65	510
	t	–	1.0	219	
t_01	t	–	0.8–1.0–1.2–1.0	50	601
t_02	t	–	1.2–1.0–0.8–1.0	50	528
at	a	1.0	–	97	398
	t	–	1.0	301	
ta	t	–	1.0	398	603
	a	1.0	–	205	
ao	a	1.0	–	98	184
	o	1.0	1.0	86	
to	t	–	1.0	282	390
	o	1.0	1.0	108	
ot	o	1.0	1.0	80	384
	t	–	1.0	304	

As a result, one can come to a conclusion about the linearity of damage accumulation process for a given loading type. The combined application of the Pisarenko–Lebedev modified criterion and of the Manson's approach showed a high level of correlation between the predicted data and test results for all the loading programs except the alternating torsion. So, the following modification of the Manson approach is proposed:

$$D_i = (n_i/N_{fi})^{\beta(\omega)}, \tag{1}$$

where $\beta(\omega) = \left(\dfrac{N_{fi}}{N_{fr}}\right)^{\alpha} + \dfrac{2\omega}{\pi}\left[1 - \left(\dfrac{N_{fi}}{N_{fr}}\right)^{\alpha}\right]$, ω is the strain path orientation angle, which determines the dominating type of the strain state, $\omega = \arctan\left(\dfrac{\gamma_a}{\varepsilon_a}, \dfrac{\varepsilon_{fs}}{\gamma_{fs}}\right)$, ε_{fs} and γ_{fs}

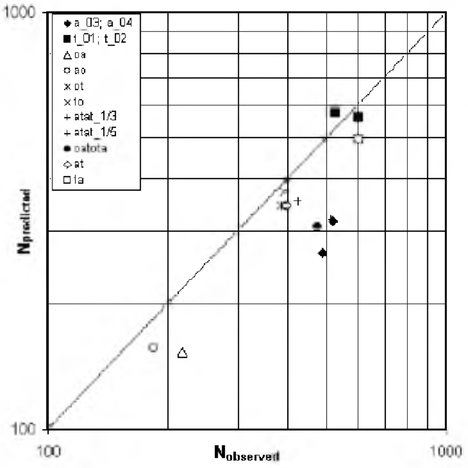

Fig. 2

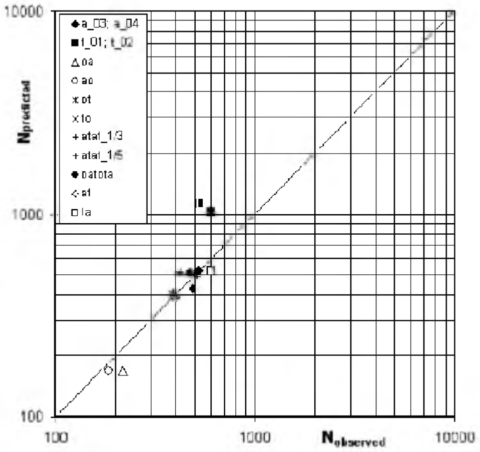

Fig. 3

Fig. 2. Comparison between the fatigue lives predicted by the modified linear damage rule and the experimental fatigue lives.

Fig. 3. Comparison between the fatigue lives predicted by the modified damage curve approach and the experimental fatigue lives.

are the fatigue strength coefficients for a finite life N_f in the uniaxial and torsional loading cases.

Thus, the damage accumulation during the alternating torsion is linear, during the tension–compression is calculated using the Manson approach, and during the biaxial proportional and non-proportional loading is assessed by their linear interpolation.

The application of formula (1) resulted in the best agreement between the predicted and experimental data as shown in Fig. 4.

Conclusion. The proposed method of fatigue life assessment under multiaxial low-cycle regular and irregular loading, which is based on the Pisarenko–Lebedev modified criterion, the linear damage accumulation hypothesis, and the nonlinear Manson approach proved to be effective and to allow for such factors as the strain state type, strain path type, and loading irregularity.

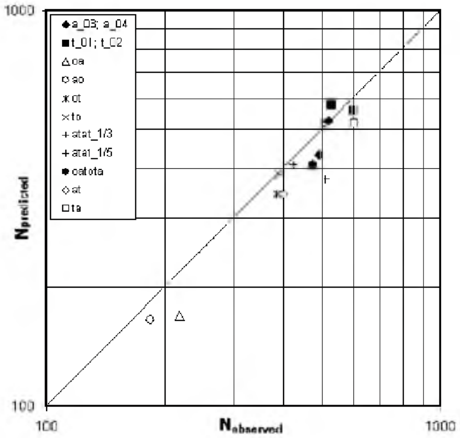

Fig. 4. Comparison between the fatigue lives predicted by the proposed approach and the experimental fatigue lives.

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