



Crack initiation and early propagation plane orientation of 2A12-T4 aluminum alloy under tension-torsion fatigue loading including mean tensile stress

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ABSTRACT. The specimen fractures appearances are analyzed to investigate the effects of mean tensile stress on the fatigue crack initiation and early propagation plane orientation under axial-torsion fatigue loading for 2A12-T4 aluminum alloy. The fatigue crack initiation and early propagation plane orientations are measured by optical microscope, the results of macro-analysis show that both the maximum shear stress amplitude and normal mean stress have effects on the orientations of crack initiation and propagation plane orientation, which are close to the plane of the maximum shear stress amplitude plane. With increasing the mean tensile stress, more cracks are inclined to initial and propagate on or near the maximum shear stress amplitude plane with larger normal mean stress, and the angle of deviation from the plane of maximum shear stress amplitude increases. The predicted plane orientations based on critical plane methods are compared with experimental measured results.

KEYWORDS. Multiaxial fatigue; Mean tensile stress; Crack initiation and propagation plane; Critical plane orientation; Aluminum alloy.

INTRODUCTION

In practice many engineering structures are subjected to fatigue loading, especially multiaxial fatigue loading, and that many of the structures undergo tensile mean stress due to external static load, weight or residual stress [1]. So many multiaxial fatigue failure criteria based on critical plane approach have been proposed and applied to determine the

fatigue failure conditions or predict the fatigue life [2] as the critical plane approach has clear physical meaning. Once the fatigue damage plane is selected, then the stress or strain history on the critical plane is calculated and converted into cumulative fatigue damage. So the research on multiaxial fatigue crack initiation and propagation plane orientation contributes to the selecting of critical plane and determining the fatigue failure mode. Fatigue crack initiation and propagation are affected by material type, structure, size and load paths [3]. Although the effects of mean stress and multiaxial loading paths on fatigue life are considered by many criteria, the study of mean stress on the crack initiation and propagation plane orientation in middle and high cycle fatigue is fewer.

Fatigue crack initial generally at the site of the highest stress or the place which has a defective. Then crack propagate into the material, this progress can be divided into two stages: stage I is in the direction of the maximum shear stress, which is dominated by shear stress and controlled by the microstructure within individual grains. After propagating several grains diameters, stage II crack growth begins and propagates perpendicular to the maximum normal stress at the macro point of view, which is controlled by the maximum normal stress. The crack propagates usually 2 to 5 grains diameters in stage I, but contributes to a large proportion of the fatigue life [4]. However, the definition of crack initiation size is not clear. The nucleation of flaws along persistent slip bands is considered as the crack initiation stage by material scientists, while a detectable crack size by engineers [5]. The crack initiation approach consists of microscopic growth and small crack growth up to a length of about 1mm [6].

In this paper the stress state on planes and fatigue fracture surface under tension-torsion loading with different mean tensile stress is analyzed for 2A12-T4 aluminum. Experiment had been carried out in order to study the effect of mean tensile stress on crack initiation and early propagation plane orientation. Optical microscope is used to measure crack initiation and early propagation plane orientation (stage I) on specimen fracture. The predicted plane orientations based on critical plane models are compared with experimental measured angles.

EXPERIMENTS

Material and specimens

The material studied in this paper is 2A12-T4 aluminum alloy, which is usually used in aircraft. The shape and dimensions of specimens used in axial-torsion fatigue experiment are shown in Fig. 1.

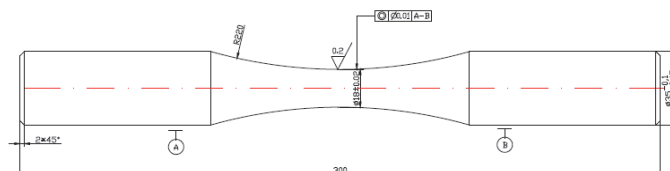


Figure 1: Specimen geometry for tension-torsion loading.

A PLS-200/1500 servo-hydraulic tension-torsion load frame was used for tension-torsion fatigue experiments. The test system, which has a capacity of 1500N·m in torque and 200kN in axial load, is equipped with the electronic control, computer control, and data acquisition. The axial and shear loading are controlled at the same time. Loading frequency was $f = 3\text{Hz}$ in the experiment. In order to investigate the effect of mean tensile stress, the tension-torsion fatigue experiment is carried out. The waveform of load is as follows:

$$\begin{aligned} \sigma_x &= \sigma_{x,a} \sin \omega t + \sigma_{x,m} \\ \tau_{xy} &= \tau_{xy,a} \sin(\omega t - \varphi) + \tau_{xy,m} \end{aligned} \quad (1)$$

The test is conducted at the circumstance of $\tau_{xy,m} = 0$, $\tau_{xy,a} = 165\text{MPa}$, so the mean shear stress and shear stress amplitude is fixed. And the phase angle of axial between shear loading $\varphi = 0^\circ$, so the effect of non-proportional loading is excluded. The chosen mean tensile stress is $\sigma_{x,m} = 0\text{MPa}$, 50MPa , 100MPa and 150MPa .

Then the macro-fractures of the tested specimen were observed by optical microscope, and fatigue crack initiation and early propagation plane orientations were measured at a magnification about 30 times. The angle between the axial



direction of the specimen and the direction normal to the crack initiation and early propagation plane is defined as critical plane orientation, ϕ , which is shown in Fig. 2, where the origin O of the coordinate system is at the surface of the minimum diameter dimension of specimen, the x direction is the longitudinal direction of the specimen and the y direction is the direction circumferential to the surface of the specimen.

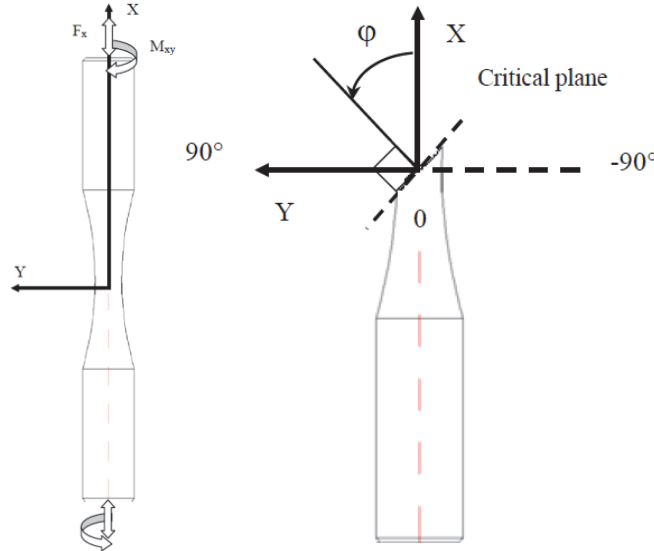


Figure 2: Definition of the crack initiation and early propagation plane orientation ϕ

The crack path under different mean stress is shown in Fig.3. The position of the crack initiation and early propagation plane orientation is marked in the figure.

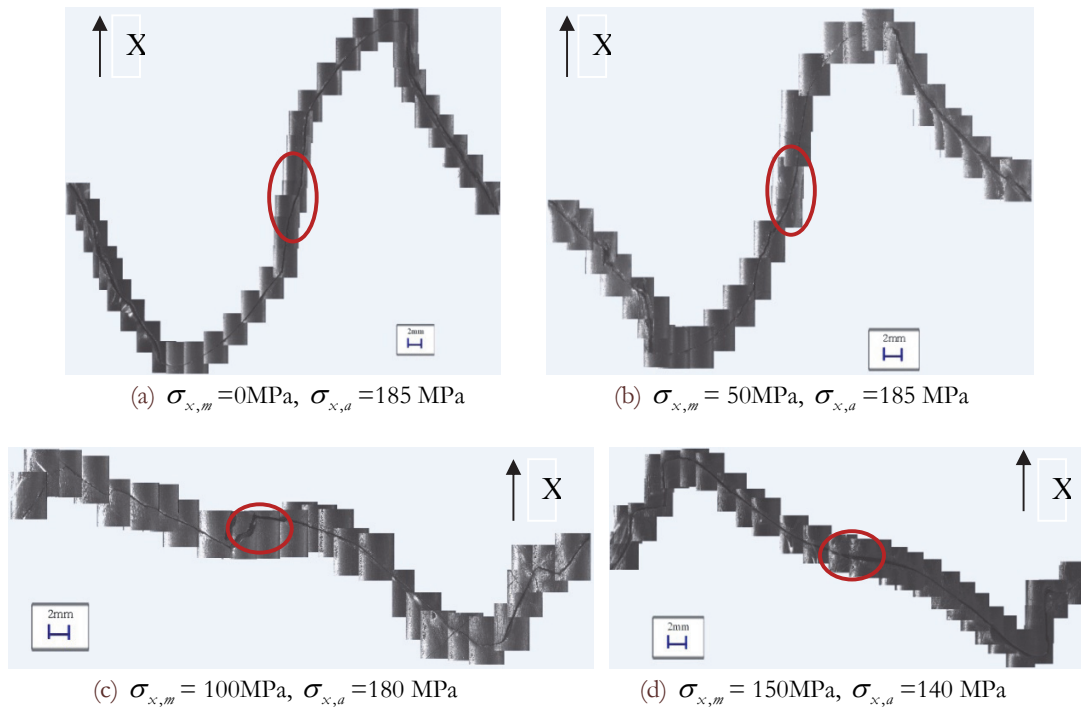


Figure 3: crack path under different mean stress.

DISCUSSION AND ANALYSIS

Macroscopic fracture analysis

The fractures of tension-torsion fatigue with mean stress are shown in Fig. 4 - Fig. 7. Meanwhile the measurement of crack initiation and early propagation plane orientation, and analysis of stress element are conducted. The macroscopic fracture and analysis of stress element is representative of each level of mean stress. The fatigue crack origin, propagation and final rupture region can be identified in the fracture appearance. As the stage of crack initiation and early propagation contributes to most of the fatigue life, only the effect of mean stress on crack plane orientation is investigated on the crack initiation region.

The fracture surface, measurement of crack initiation and early propagation plane orientation, and stress element under tension-torsion loading for $\sigma_{x,m}=0\text{MPa}$ are shown in Fig.4. The regions of crack initiation, propagation and final rupture can be identified from the fracture surface. The crack surface in the initiation region is suffered repeated normal stress and shear stress, and then it shows gray and black caused by the friction between the surfaces. In the propagation region the fracture surface is bright. In the final rupture region there is a large area occupied by a rough surface. From the analysis of stress element, there are two maximum shear stress amplitude planes separated by 90° and the values of shear stress amplitude and normal stress amplitude on both planes are equal, respectively. Meanwhile the normal mean stresses on both planes are zero. One of the two planes is nearly parallel to the direction of specimen axial, but the other is nearly 80° apart with the direction of specimen axial. While the crack initiation and early propagation plane orientation is close to the front plane of maximum shear stress amplitude.

The fracture surface, measurement of crack initiation and early propagation plane orientation, and stress element under tension-torsion loading for $\sigma_{x,m}=50\text{MPa}$ are shown in Fig.5. The regions of crack initiation, propagation and final rupture can be identified from the fracture surface, too. On the whole the entire fracture area has been reduce than the area for $\sigma_{x,m}=0\text{MPa}$. It is still gray and black in crack initiation region, and bright in propagation region. The values of shear stress amplitude and normal stress amplitude on both maximum shear stress amplitude planes are equal, respectively. But the values of normal mean stress on them are not equal, and are both smaller than the values of normal stress amplitude. One of the two planes with larger normal mean stress has a larger maximum normal stress; the other plane with smaller normal mean stress has a smaller maximum normal stress. However, the crack initiation and early propagation plane orientation is close to the back plane.

The fracture surface, measurement of crack initiation and early propagation plane orientation, and stress element under tension-torsion loading for $\sigma_{x,m}=100\text{MPa}$ are shown in Fig.6. On the whole the entire fracture area has been reduce than the area for $\sigma_{x,m}=50\text{MPa}$. In crack initiation region the gray and black is significantly reduced, and the fracture surface in propagation region is flat. It can be noted that the characteristics of stresses on both maximum shear stress amplitude planes are nearly the same as $\sigma_{x,m}=50\text{MPa}$, except that the values of normal mean stress on both planes have been increased. The value of normal mean stress is less than that of normal stress amplitude on the plane, which is nearly 80° apart with the direction of specimen axial; however it is approximately equal to the value of normal stress amplitude on the other plane. The crack initiation and early propagation plane orientation is different from the orientation for $\sigma_{x,m}=50\text{MPa}$, but is closer to the maximum shear stress amplitude plane with larger normal stress.

The fracture surface, measurement of crack initiation and early propagation plane orientation, and stress element under tension-torsion loading for $\sigma_{x,m}=150\text{MPa}$ are shown in Fig.7. There is a small amount of gray and black in crack initiation region, it becomes more flat in propagation region and the area of final rupture is further reduced. With the increasing of axial mean stress, the normal mean stress on both maximum shear stress amplitude planes is increasing. The value of normal mean stress is much smaller than that of normal stress amplitude on the maximum shear stress amplitude plane, which direction is nearly 80° apart with the direction of specimen axial. Meanwhile it is much greater than the value of normal stress amplitude on the other plane. Observation shows that crack initiation and early propagation plane orientation is closer to the maximum shear stress amplitude plane with larger normal stress.

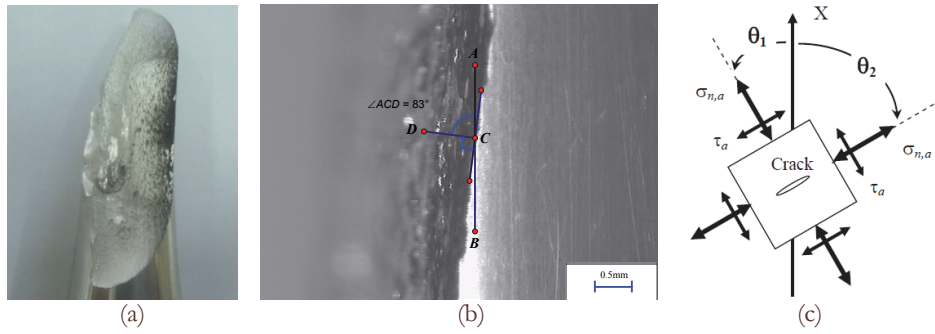


Figure 4: Tension-torsion fatigue for $\sigma_{x,m}=0\text{MPa}$, $\sigma_{x,a}=185\text{MPa}$: (a) fracture surface, (b) measurement of crack initiation and early propagation plane orientation, (c) stress element.

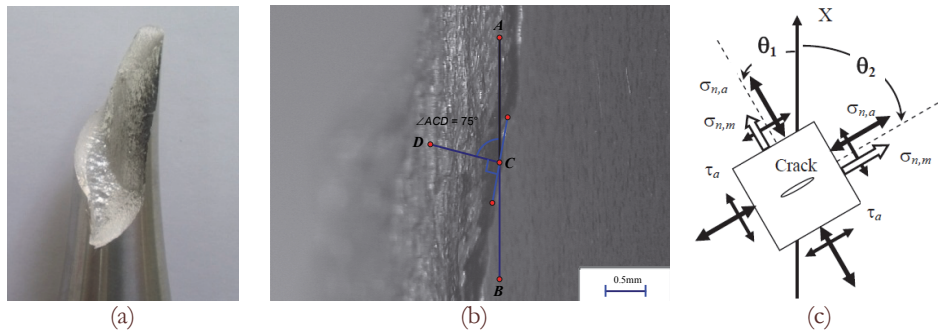


Figure 5: Tension-torsion fatigue for $\sigma_{x,m}=50\text{MPa}$, $\sigma_{x,a}=185\text{MPa}$: (a) fracture surface, (b) measurement of crack initiation and early propagation plane orientation, and (c) stress element.

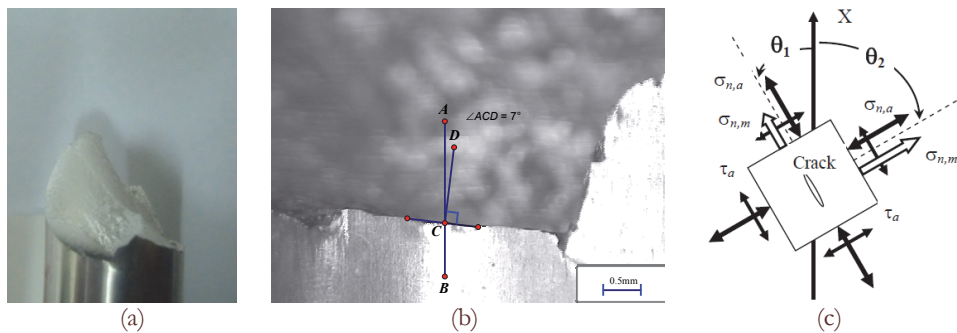


Figure 6: Tension-torsion fatigue for $\sigma_{x,m}=100\text{MPa}$, $\sigma_{x,a}=180\text{MPa}$: (a) fracture surface, (b) measurement of crack initiation and early propagation plane orientation, and (c) stress element.

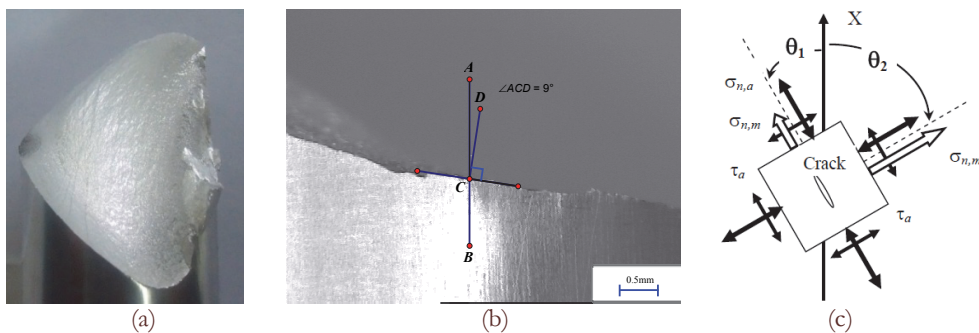


Figure 7: Tension-torsion fatigue for $\sigma_{x,m}=150\text{MPa}$, $\sigma_{x,a}=140\text{MPa}$: (a) fracture surface, (b) measurement of crack initiation and early propagation plane orientation, and (c) stress element.

Orientation predictions of different approach

The comparison of measured crack angle with the predictions based on the maximum shear stress amplitude[7], Findley parameter[8] and Fatemi-Socie parameter [9] for different mean stresses is shown in Fig.8. The abscissa represents the specimen, and vertical coordinates represent the value of measured angle. Black solid round dots are representative of measured angles. Hollow dots, triangles and squares are representative of the predicted angles based on the maximum shear stress amplitude, Findley parameter and Fatemi-Socie parameter, respectively.

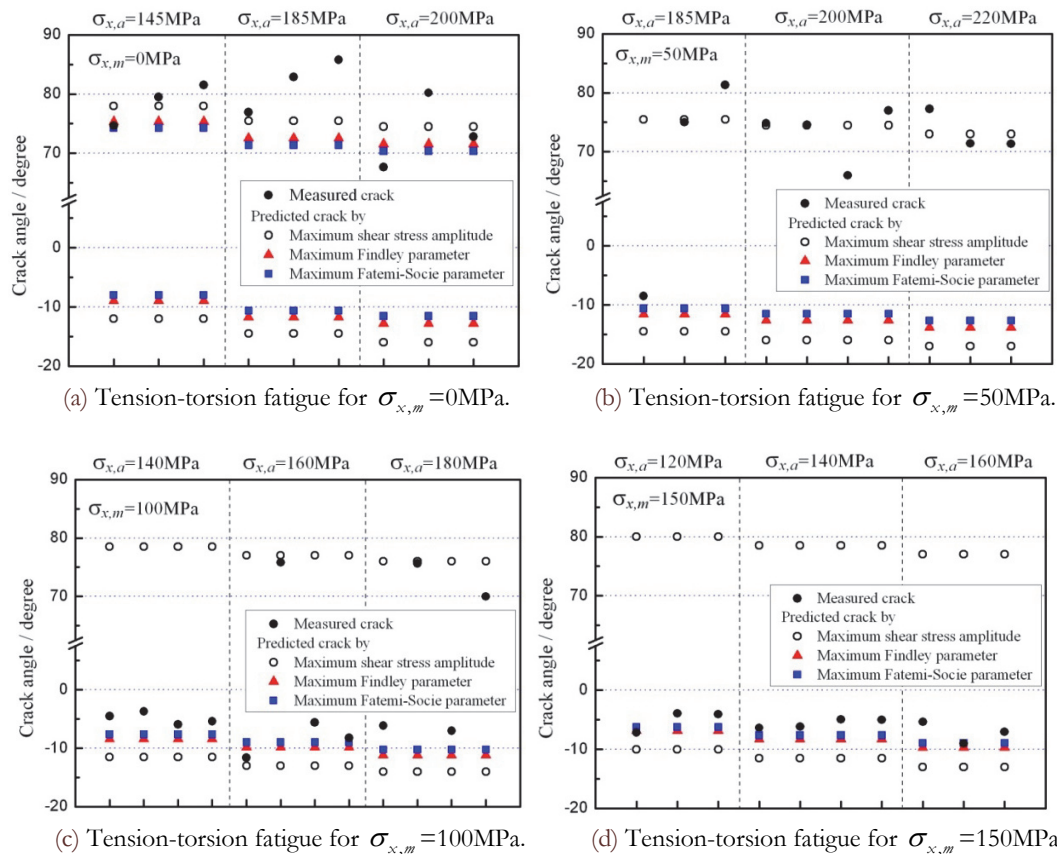


Fig.8.Comparison of measured crack angle with the predictions for different mean stresses

The measured angles and predicted angles based on three parameters under tension-torsion loading for $\sigma_{x,m}=0\text{MPa}$ are shown in Fig. 8(a). There are three groups of different axial amplitudes but the axial mean stress and torsion stress are all the same. Although there are two equal values of maximum shear stress amplitude planes and the normal mean stress on both planes is zero, all of the measured angles are in the side of the maximum shear stress plane, which direction is nearly 80° apart with the direction of specimen axial. Most of the measured angles are larger several degrees than the predictions made by the maximum shear stress amplitude. All the predictions made by Findley parameter and Fatemi-Socie parameter are smaller several degrees than the predicted value by the maximum shear stress amplitude.

The measured angles and predicted angles based on three parameters under tension-torsion loading for $\sigma_{x,m}=50\text{MPa}$ are shown in Fig. 8(b). There is normal mean stress on both the maximum shear stress amplitude planes, and the value of normal mean stress is larger on the plane which direction is around -15° . But all of the measured angles are still in the side of the maximum shear stress plane with smaller normal mean stress. All the predictions made by Findley parameter and Fatemi-Socie parameter are in the side of the maximum shear stress plane with larger normal mean stress. And their values are nearly 5° smaller than the predictions made by the maximum shear stress amplitude.

The measured angles and predicted angles based on three parameters under tension-torsion loading for $\sigma_{x,m}=100\text{MPa}$ are shown in Fig. 8(c). Most of the measured angles are in the side of the maximum shear stress amplitude plane with larger normal mean stress, which direction is close to perpendicular to the specimen axis. The difference between most of measured angles and hollow dots corresponding to the maximum shear stress amplitude is 5° or more. Only three



measured angles are in the other side of the maximum shear stress amplitude plane. The predicted angles made by Findley parameter are close to coincident with predictions made by Fatemi-Socie parameter. And most of the predicted crack angles are in the middle part of the measured angles and hollow dots corresponding to the maximum shear stress amplitude.

The measured angles and predicted angles based on three parameters under tension-torsion loading for $\sigma_{x,m}=150\text{MPa}$ are shown in Fig. 8(d). In this situation all of the measured crack angles are in the side of maximum shear stress amplitude plane with larger normal mean stress. The direction of this plane is about -10° apart with the direction of specimen axial, and is smaller 5° than predicted angles corresponding to the maximum shear stress amplitude. All of the predicted crack angles based on Findley and Fatemi-Socie parameters are close to the hollow dots corresponding to the maximum shear stress amplitude. With increasing of normal mean stress on both maximum shear stress amplitude planes, more cracks are becoming to initial and propagate from the side of maximum shear stress amplitude plane to the other side of maximum shear stress amplitude plane with larger normal mean stress. And the angle of deviation from the plane of maximum shear stress amplitude increases.

CONCLUSION

The experiment and analysis of stress components on plane orientations under tension-torsion fatigue with different axial mean tensile stress for 2A12-T4 aluminum alloy were conducted, the plane orientation in macroscopic fracture are studied. The following conclusions can be drawn:

- (1) Under the tension-torsion loading, both of the maximum shear stress amplitude and normal mean stress have effect on the crack initiation and early propagation plane orientation. Fatigue cracks initial and early propagate on the plane which is close to the plane of the maximum shear stress amplitude plane. This characteristic is not changed by the presence of mean stress. With increasing of mean tensile stress, more cracks are inclined to initial and propagate on or near the maximum shear stress amplitude plane with larger normal mean stress, and the angle of deviation from the plane of maximum shear stress amplitude increases.
- (2) When axial mean stress is $\sigma_{x,m}=0\text{MPa}$, there are two predicted plane angles separated by 90° but only one crack plane exists. When axial mean stress is $\sigma_{x,m}=50\text{MPa}$, the predicted angles are not coincident with the crack plane orientations which are not the planes with larger normal mean stress. When axial mean stress is $\sigma_{x,m}=100\text{MPa}$, the differences between most of predicted angles and crack plane orientations with larger normal mean stress is nearly 5° . When axial mean stress is $\sigma_{x,m}=150\text{MPa}$, the predicted angles are close to the crack plane orientations.

NOMENCLATURE

- σ_x axial stress
- $\sigma_{x,a}$ axial stress amplitude
- $\sigma_{x,m}$ axial mean stress
- τ_x shear stress
- $\tau_{xy,a}$ shear stress amplitude
- $\tau_{xy,m}$ mean shear stress
- τ_a shear stress amplitude on the critical plane
- $\sigma_{n,a}$ normal stress amplitude on the critical plane
- $\sigma_{n,\max}$ maximum normal stress on the critical plane
- $\sigma_{n,m}$ mean normal stress on the critical plane
- $\Delta\gamma$ shear strain range
- σ_y yield tensile strength
- G shear modulus



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