The effect of mean stress on tension-torsion high-cycle fatigue failure of 2A12-T4 aluminum alloy

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ABSTRACT. *The aim of present paper is to study the effect of mean tensile stress and mean shear stress on multi-axial fatigue failure. Fatigue experiments with funnel-shape specimens of 2A12-T4 aluminium alloy are carried out to investigate the effects of mean tensile stress and mean shear stress on the multi-axial high-cycle fatigue failure under proportional and non-proportional loading conditions. Loading is given by Soderberg rules in the experiments of mean tensile stress. The results show that fatigue lives reduces gradually with the increase of tensile stress ratio and the reduction are more significant under non-proportional loading, which indicates that for the multi-axial high-cycle fatigue, the effect of mean tensile stress is more severe than that in unaxial fatigue. With increasing of mean tensile stress, the direction of initiation and expansion of crack remain basically unchanged, however, the transverse step increases gradually. The experiment results on the effect of mean shear stress show that there are no remarkable effects on fatigue lives under proportional loading. However, the existence of mean shear stress makes a significant reduction of fatigue lives under non-proportional loading. With the increasing of mean shear stress, the black and brilliant feather in the initiation region becomes apparent. The direction of initiation and expansion of crack remain basically unchanged. Different from the previous, there is no transverse step.*

INTRODUCTION

Most of the structural components suffer multi-axial cyclic loading. There are many loading factors e.g. stress amplitude ratio, phase angle and mean stresses of tension and torsion, affect the multi-axial fatigue lives. The effect of these loading parameters on multi-axial fatigue failure is so complicated that no widely accepted agreements have been reached, especially the effect of mean stresses [1-7]. Currently, studies show that mean tensile stress has a negative impact and mean compression stress has a beneficial effect on multi-axial fatigue lives, which is the same as the uniaxial failure [8, 9]. The relationship between stress amplitude and mean tensile stress can be correlated by Goodman and Gerber rules as long as the maximum stress does not exceed the yield stress of material in multi-axial fatigue [10, 11]. About the effect of mean shear stress, Wang and Miller et al [12] found that the presence of shear stress makes the fatigue

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lives reduced for the 1.99% NiCrMo steel and Kallmeyer et al [13] give the same point. However Davoli et al [14] found that for 39NiCrMo3 steel, the change in fatigue lives is not obvious when mean shear stress increases but does not exceed the shear yield strength of the material; Susmel [15] presented the same result.

The objective of this paper is to study the effect of mean tensile stress and mean shear stress on multi-axial high-cycle fatigue failure. The tension-torsion fatigue experiments of different mean tensile stress and different mean shear stress are conducted. The change of fatigue lives and fracture appearance with different mean tensile stress and different mean shear stress are discussed.

EXPERIMENTS

The material tested is 2A12-T4 aluminum alloy, which is usually used in aircraft. The chemical composition and content of 2A12-T4 is: Cu (4.1%), Mg (1.5%), Mn (0.66%), Si (0.24%), Fe (0.33%), Zn (0.08%), Ti (0.02%), Ni (0.01%), Al (the rest). The mechanical properties are as follows: tensile modulus is 76.8GPa, tensile yield strength is 395.1MPa, tensile ultimate strength is 568.4MPa; shear modulus is 29.4GPa, shear yield strength is 210.5MPa, shear ultimate strength is 419.8MPa. The funnel-shaped specimen is adopted and the minimum dimension of diameter is D =18mm. The configuration of the specimen is shown in fig1.

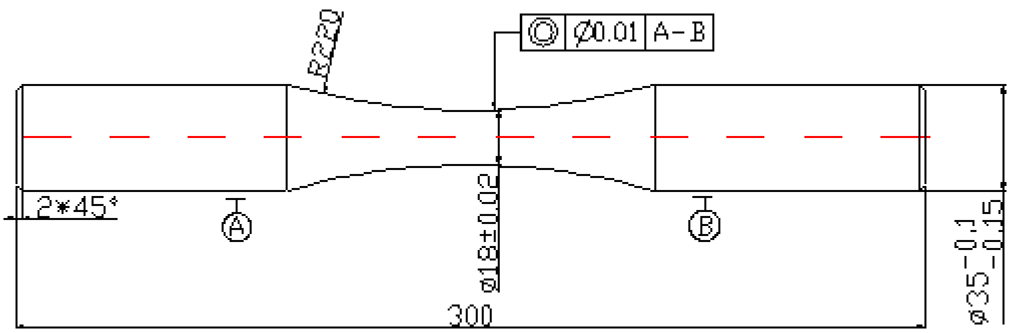


Figure 1. Dimension of the specimen

The experiments of multi-axial fatigue are executed by simusoidal waveform at room temperature under constant amplitude loading in PLS-200/1500 servo-hydraulic testing machine. Loading frequency is f =3Hz. Fatigue failure is defined as the complete fracture of the specimen. The axial and shear stress are controlled at the same time when loading.

Determination of mean tensile stress

The experiment about effect of mean tensile stress on multi-axial high-cycle fatigue is carried out at the circumstance of $\tau_m = 0$. The waveform of loadis as follows:

$$\sigma = \sigma_a \sin \omega t + \sigma_m$$
$$\tau = \tau_a \sin(\omega t - \varphi) \tag{1}$$

Where, σ 、 σ_a 、 σ_m is the alternate stress, stress amplitude and mean stress of axial loading respectively; τ 、 τ_a 、 τ_m is the alternate stress, stress amplitude and mean stress of shear loading respectively; φ is phase angle of axial and shear loading. The Von-Mises stress is adopted as the equivalent stress. The stress amplitude ratio is defined as the ratio of the amplitude of shear stress and axial stress. That is:

$$\sigma_{eq} = (\sigma^2 + 3\tau^2)^{1/2}$$
$$\lambda = \tau_a / \sigma_a \tag{2}$$

According to the achievements in uniaxial fatigue, in which stress amplitude and mean tensile stress is correlated by using either ultimate or yield strength, such as rules proposed by Goodman, Gerber and Soderberg, correlative studies show that the effect of mean tensile stress in multi-axial fatigue is same with that of uniaxial fatigue. Since 2A12-T4 is a kind of plastic material and its yield strength is the sign of damage, the loading is given by Soderberg rule, Eq. (3), in the tension-torsion experiment when studying the effect of mean tensile stress.

$$\sigma_a = \sigma_{-1}(1 - \sigma_m / \sigma_s) \tag{3}$$

In the experiments, $\sigma_{eq} = 330\text{MPa}$, $\lambda = 1$ is selected when tensile stress ratio is $R_\sigma = -1$, that is $\sigma_a = \tau_a = 165\text{MPa}$, and other tensile stress ratio is $R_\sigma = -0.1$, 0.2, 0.5 to study the changes of fatigue lives under proportional loading when the mean tensile stress is increased. In addition, the experiment results of $R_\sigma = -0.1$ in $\varphi = 0^\circ, 90^\circ$ are compared in order to study the difference of proportional and non-proportional loading.

Determination of mean shear stress

The experiments about effect of mean shear stress on multi-axial high-cycle fatigue are conducted at the circumstance of $\sigma_m = 0$. The expression of loading is:

$$\sigma = \sigma_a \sin \omega t$$
$$\tau = \tau_a \sin(\omega t - \varphi) + \tau_m \tag{4}$$

In the experiments, $\sigma_{eq} = 330\text{MPa}$, $\lambda = 0.5$ is selected when $\tau_m = 0$, that is σ_a=249.46MPa, τ_a=124.73MPa. The Soderberg rules is considered when mean shear stress is selected. However, fatigue lives obtained are more than 500,000 cycles. Therefore, the axial and shear stress amplitude is fixed and diffrent mean shear stress is given to assure that the maximum shear stress is no more than the shear yield strength of the material when loading, which consults on correlative studies[14]. The chosen mean shear stress is $\tau_m/\tau_{0.3}$=0, 0.12, 0.24, 0.36, where, $\tau_{0.3}$ is the yield strength. The maximum stress is $\tau = 0.95\tau_{0.3}$ when $\tau_m/\tau_{0.3} = 0.36$. The experiment results of $\tau_m/\tau_{0.3} = 0.36$ in $\varphi = 0^\circ, 90^\circ$ are compared in order to study the different effects of mean shear stress under proportional and non-proportional loading.

RESULTS AND DISCUSSION

Results and discussion of mean tensile stress

The experimental results of different mean tensile stress are shown in table 1. It can be seen form table 1 that with increasing of mean tensile stress, fatigue lives decreased under proportional loading, i.e. the fatigue lives corresponding to $R_\sigma = -1$ is the longest while the fatigue lives under $R_\sigma = 0.5$ is the shortest. Comparing the experimental results of $R_\sigma = -1$, $R_\sigma = -0.1$ under $\varphi = 0^\circ$, which are proportional loading conditions, with the results under $\varphi = 90^\circ$, which is non-proportional loading, it can be seen that the reduction of fatigue lives under non-proportional loading is more serious than that under proportional loading.

Table 1. Test results under mean tensile stress

φ (°)	σ_a (MPa)	σ_m (MPa)	R_σ	Spec. ID	Experiment life (cycles)	Median life (cycles)
0	165.00	0.00	-1	3-56	112,295	125,706
				3-79	142,202	
				3-96	124,395	
	122.98	100.62	-0.1	3-26	111,572	87,411
				3-93	96,761	
				3-46	61,864	
	101.45	152.17	0.2	3-32	32,122	32,122
	73.24	219.72	0.5	3-73	13,275	12,924
				3-68	11,381	
				3-67	14,289	
90	165.00	0.00	-1	3-21	250,479	275,103
				3-40	400,143	
				3-39	207,731	
	122.98	100.62	-0.1	3-50	33,118	34,308
				3-95	44,071	
				3-78	27,668	

When mean tensile stress increases, the change of fatigue lives under proportional loading is shown in fig.2. The relationship of fatigue lives and tensile stress ratio can be described by:

$$\log N = k_2 + \log(c_2 - R_\sigma / t_2) \qquad (6)$$

where， k_2、 c_2、 t_2 is the fitting coefficients. The correlation coefficient is 0.90486.

The previous description shows that the effect of mean tensile stress in multi-axial high-cycle fatigue under proportional loading is more serious than that in the uniaxial fatigue. Therefore, the prediction by Soderberg expression is somewhat dangerous. Because the tensile ultimate strength is used in Goodman and Gerber rules, fatigue lives predicted by them will be more dangerous than that predicted by Soderberg rule.

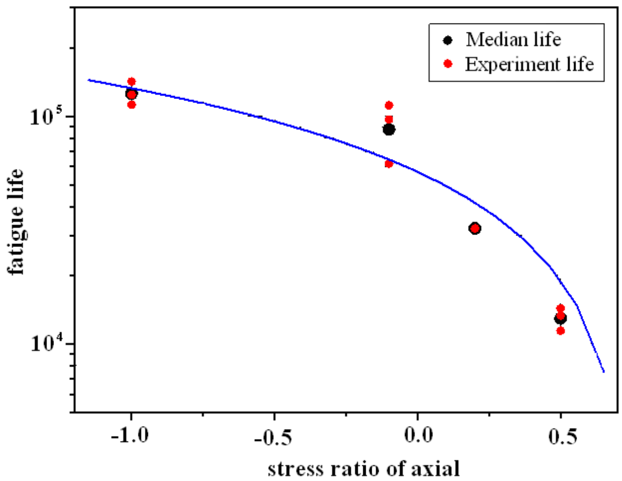


Figure 2. Change of fatigue lives with different mean tensile stress

(a) R_σ=-1 (b) R_σ=-0.1 (c) R_σ=0.2 (d) R_σ=0.5

Figure 3. Fracture appearance with different mean tensile stress

When mean tensile stress increases, fracture appearance under proportional loading is shown in fig.3. It can be seen from fig. 3 that there are clear initiation region, extension region and final region in the fracture appearance. With increasing of mean tensile stress, the direction of initiation and expansion of crack remain basically unchanged, however, the transverse step increases gradually.

Results and discussion of mean shear stress

The results of different mean shear stress are shown in table 2. with increasing of mean shear stress, the changes in fatigue lives under proportional loading are not significant. However, the effect of mean shear stress under non-proportional loading is different and fatigue lives is shorter when $\tau_m / \tau_{0.3} = 0.36$ than that when $\tau_m / \tau_{0.3} = 0$ in $\varphi = 90^\circ$.

Table2 test results under mean shear stress

φ (º)	$\tau_m / \tau_{0.3}$	τm (MPa)	Spec. ID	Experiment life (cycles)	Median life (cycles)
0	0	0.0	3-20	114,319	91,891
			3-44	86,330	
			3-19	78,622	
	0.12	25.0	3-86	107,993	107,993
	0.24	50.0	3-15	105,347	94,110
			3-28	69,734	
			3-18	113,460	
	0.36	75.0	3-66	127,184	111,087
			3-31	134,827	
			3-98	79,943	
90	0	0.0	3-75	105,917	128,757
			3-36	105,697	
			3-18	190,669	
	0.36	75.0	3-43	33,115	42,264
			3-45	44,955	
			3-88	50,711	

When mean shear stress increases, the change of fatigue lives under proportional loading is showed in fig.4. It can be seen from fig.4 that the fatigue lives remains basically unchanged, about 1.0×10^5, with the increasing of mean shear stress as long as the maximum shear stress does not exceed the shear yield strength of the material. This shows that under proportional loading, the effect of mean shear stress is no obvious.

Comparing the experimental results of $\tau_m/\tau_{0.3}=0$, $\tau_m/\tau_{0.3}=0.36$ under $\varphi=0^\circ$, which are proportional loading conditions, with the results of $\varphi=90^\circ$, which is non-proportional loading, it can be seen that when $\varphi=90^\circ$, fatigue lives of multi-axial high-cycle fatigue decreases with increasing of mean shear stress. This shows that the effect of mean shear stress on fatigue lives under non-proportional is more serious than that ~~of~~ under proportional loading.

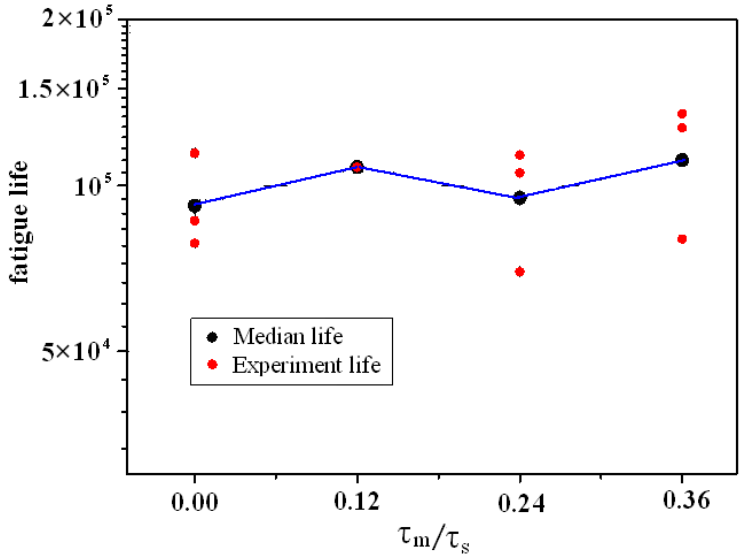
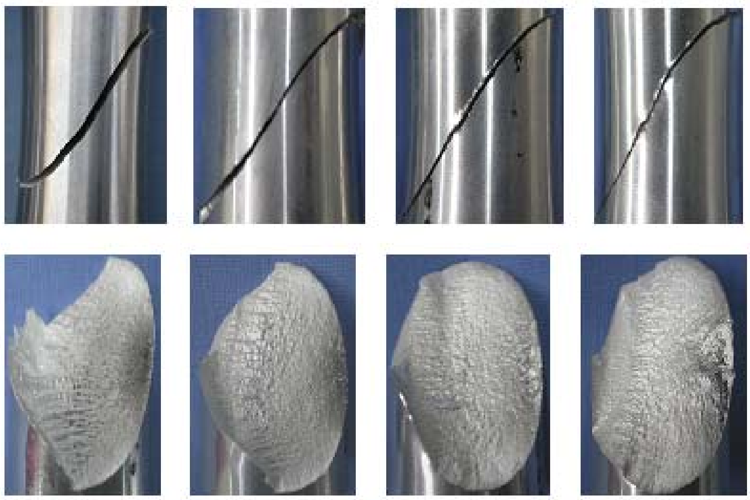


Figure 4. Change of fatigue lives with different mean shear stress



(a) $\tau_m/\tau_{0.3}=0$ (b) $\tau_m/\tau_{0.3}=0.12$ (c) $\tau_m/\tau_{0.3}=0.24$ (d) $\tau_m/\tau_{0.3}=0.36$

Figure 5. Fracture appearance with different mean shear stress

Fracture appearance of different mean shear stress under proportional loading are shown in fig.5. Clear initiation region, extension region and final region in the fracture appearance can be find from fig.5. With the increasing of mean shear stress, the black and brilliant feather in the initiation region become apparent. The direction of initiation and expansion of crack remain basically unchanged. Different from the previous, there is no transverse step.

CONCLUSION

The effects of mean tensile stress and mean shear stress on multi-axial high-cycle fatigue of 2A12 aluminum alloy are investigated experimentally in this paper. Following conclusions can be draw.

(1) With increasing of mean tensile stress, fatigue lives reduced gradually under proportional loading and the reduction are more significant under non-proportional loading. This indicated that in multi-axial high-cycle fatigue, the effect of mean tensile stress is more severe than that in uniaxial fatigue.

(2) There are no obvious mean shear stress effects on fatigue lives under proportional loading, however, the existence of mean shear stress make a significant reduction of fatigue lives under non-proportional loading.

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