Multi-axial High-cycle Fatigue Failure Behavior of 2A12-T4 Aluminum Alloy under Torsion Loading

SHI Xinhong, Zhang Jianyu *, Xiao Qingshan and Fei Binjun

Institute of Solid Mechanics, Beijing University of Aeronautics and Astronautics, Beijing 100191, PR China
* Corresponding author. E-mail: jyzhang@buaa.edu.cn

ABSTARCT *Fatigue experiments with funneled-shape specimens of 2A12-T4 aluminum alloy were carried out to study the multi-axial high-cycle fatigue failure behavior under torsion loading. The torsion S-N curves under different mean shear stress were obtained, including mean shear stress*τm*=0MPa,25MPa,50MPa,75MPa,100MPa. Experiment results showed fatigue life under the same shear stress amplitude reduced gradually with the increase of mean shear stress. However, the reduction of fatigue life when mean shear stress*τm*=75MPa and*τm*=100MPa was not obvious. The micro analysis of specimen fracture appearance was conducted in order to obtain the fracture characteristics under torsion fatigue loading. Fatigue crack initiated in specimen surface and there are clear source region, extension region and final region in the fracture appearance. Obvious abrasion mark appeared and thermal oxidation phenomenon took place due to reversed torsion.*

INTRODUCTION

Aluminium alloys are widely used in the aircraft industry due to the high strength-to-density ratio. Extensive studies have been conducted to understand the fatigue behaviour of aluminium alloys over the years. Most experimental studies on aluminium alloys were concentrated on uniaxial tension-compression loading[1]. However, many components and structures undergo complex multi-axial cyclic loading with mean stress in the fields of aircraft, especially the mean shear stress. About the effect of mean shear stress, Papadopoulos[2] assumes that the effect of the mean shear stress on the fatigue strength is not obvious in the high cycle fatigue, but the effect become obvious in the low cycle fatigue. Davoli et al [3] found that the change of fatigue life is not obvious when mean shear stress increases for 39NiCrMo3 steel. Gadouini [4] suggests that the mean shear stress has no effect on the fatigue limit as long as maximum shear stress is below the yield strength. Susmel et al [5,6] have the same viewpoint that the effect of mean shear stress can be ignored as long as the maximum stress exceed the shear yield strength of the material. However, Wang and

Miller et al [7] found that the presence of mean shear stress makes the fatigue life reduced for 1.99%NiCrMo steel. Kallmeyer et al [8] found that in tension-torsion experiment of Ti-6Al-4V titanium alloy, compared with symmetrical loading, the existence of mean shear stress make the fatigue life decreased significantly.

This paper has discussed effects of mean shear stress on torsion high-cycle fatigue failure. The pure torsion fatigue experiments are carried out in this paper. The change of fatigue life with different mean shear stresses is discussed. The micro analysis of specimen fracture appearance is conducted in order to obtain the fracture characteristics.

EXPERIMENTS

Material and specimens

The material studied in this paper is 2A12-T4 aluminum alloy, and its chemical composition is shown in Table 1. Mechanical properties of the material are shown in Table 2. The solid cylindrical bar specimen is adopted, which machined from the round bar of $\Phi = 40\text{mm}$. The minimum diameter dimension of torsion fatigue specimen is D=18mm. The dimension tolerance is 0.02mm so as to reduce scatter of experiment result. In order to avoid stress concentration, the knuckle radius is greater than 12D. The surface finish of specimen is less than $0.2\,\mu\text{m}$. Shape and dimensions of specimens are shown in Fig. 1.

Table 1. Chemical composition of 2A12-T4 aluminum alloy

Element	Cu	Mg	Mn	Si	Fe	Zn	Ti	Ni
[%]	4.1	1.5	0.66	0.24	0.33	0.08	0.02	0.01

Table 2. Mechanical properties of 2A12-T4 aluminum alloy

	Axial	Torsion
Modulus/GPa	E=76.8	G=29.4
Yield strength/MPa	σ_y =395.1	τ_y =210.5
Ultimate strength/MPa	σ_u =568.4	τ_u =419.8

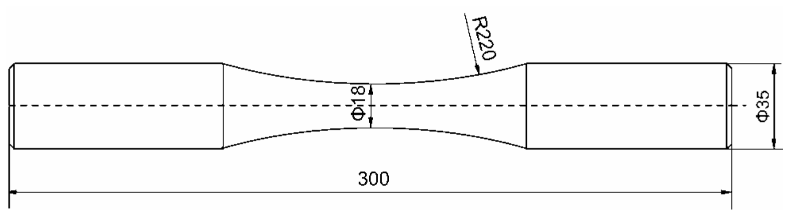


Figure 1. Shape and dimensions of torsion specimen (all dimension in mm)

Experiments of torsion fatigue are executed by sinusoidal waveform at room temperature under constant amplitude loading. Fatigue failure is defined as the complete fracture of the specimen. A PLS-200/1500 servo-hydraulic tension-torsion load frame is used for torsion fatigue experiments. The test system, which has a capacity of 1500Nm 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 is f=3Hz in the experiment.

Determination of mean torsion stress

In the pure torsion fatigue experiment, the test without mean shear stress, i.e. $\tau_m = 0$, is conducted at first. The four stress levels, τ_a = 240*MPa*, 210*MPa*, 190*MPa*, 180*MPa* are selected and 3~5 specimens are tested at each stress level. Afterward, torsion fatigue experiments with different mean shear stresses are carried out and five different mean shear stress, that is τ_m =25*MPa*, 50*MPa*, 75*MPa*, 100*MPa* are selected. Under each mean stress,3~4 stress level are selected.

RESULTS AND DISCUSSION

Pure torsion experimental results without mean shear stress are shown in Table 3.

Table 3. Pure torsion fatigue test results without mean stress

$\tau_{xy,m}$ (MPa)	$\tau_{xy,a}$ (MPa)	Spec. ID	N_f(cycles)	N_{50} (cycles)
0	240	5-2	19,784	25,619
		6-2	12,519	
		3-8	38,940	
		2-1	44,665	
	210	5-1	76,571	82,448
		4-1	101,910	
		3-1	71,823	
	190	3-87	387,302	197,932
		3-48	129,227	
		3-76	107,460	
		3-89	132,494	
		3-58	426,316	
	180	3-2	449,691	374,828
		5-3	515,414	
		11-1	156,138	
		12-1	545,444	

Pure torsion experimental results with mean shear stress are shown in Table 4.

Table 4. Pure torsion fatigue test results with mean stress

$\tau_{xy,m}$ (MPa)	$\tau_{xy,a}$ (MPa)	N_f (cycles)	N_{50} (cycles)	$\tau_{xy,m}$ (MPa)	$\tau_{xy,a}$ (MPa)	N_f (cycles)	N_{50} (cycles)
25	225	40,508	58,094	75	210	20,907	22,880
		65,047				25,545	
		74,410				22,426	
	195	157,198	92,963		180	47,934	97,289
		36,952				98,139	
		138,306				107,476	
50	210	16,162	32,910			177,196	
		183,214			150	545,143	367,896
		17,435				177,537	
		22,722				512,810	
	195	24,258	91,438			369,100	
		126,916		100	210	15,206	30,729
		115,865				34,383	
		195,967				34,585	
	180	272,163	176,058			49,310	
		128,580			180	69,306	63,370
		88,120				76,654	
		311,566				47,901	
	150	>1E+06			150	370,889	428,200
						324,285	
						652,782	

The S-N curve of pure torsion fatigue without mean shear stress, i.e. τ_m=0, is shown in fig.2. From the figure, the life of pure torsion fatigue have obvious scatter. The relationship of fatigue life and stress amplitude is fitted by straight line in double-logarithmic coordinates. The relationship of fatigue lives and stress amplitude can be described by:

$$\lg N = -0.0481 \lg \tau_a - 2.86 \qquad (1)$$

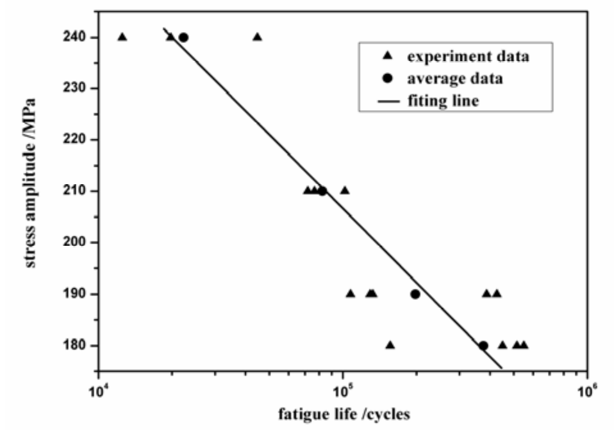


Figure 2. The S-N curves of pure torsion fatigue without mean stress

Results of pure torsion fatigue experiment with mean shear stress are shown in fig.3. From the figure, with mean shear stress increasing, fatigue life decrease gradually, that is the existence of mean shear stress have a negative impact. Based on the *S-N* curves under different mean shear stress, fatigue strength is measured at 4×10^4, 8×10^4, 1×10^5, 2×10^5 and 3×10^5 cycles. Plots of the stress amplitude versus mean stress at different levels of fatigue life are shown in Fig. 4. For each equal-life curves, stress amplitude decreased gradually with increasing of mean stress when mean stress $\tau_m \leq 75$ *MPa*. However, the stress amplitude reduction is no longer obvious when $\tau_m > 75$ *MPa*. In other words, the effect of mean shear stress on the torsion fatigue life is no longer significant. Furthermore, every equal-life curves is parallel and they all don't meet the formula expressed by Goodman, Gerber and Soderberg.

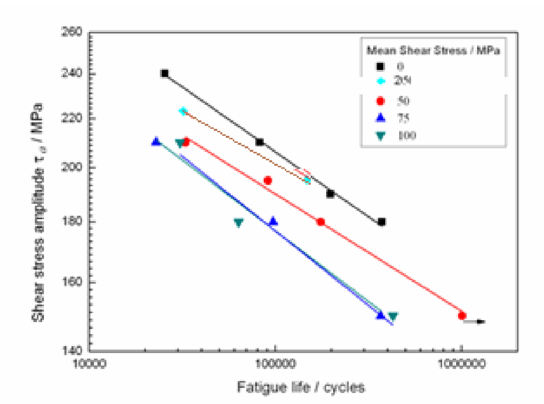


Figure 3. The S-N curves of torsion fatigue with mean stress

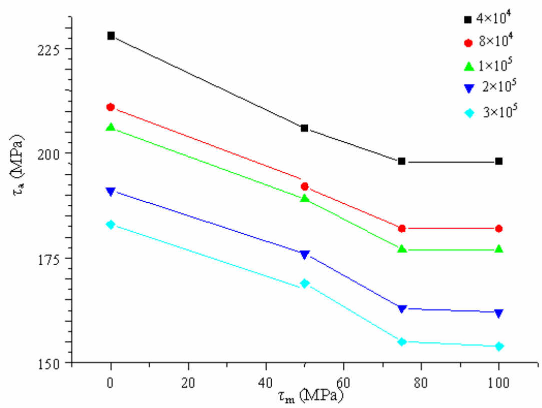
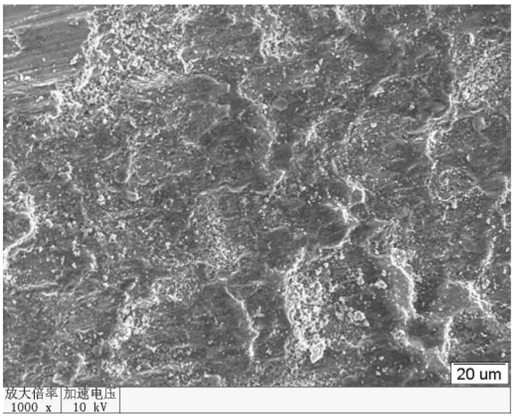
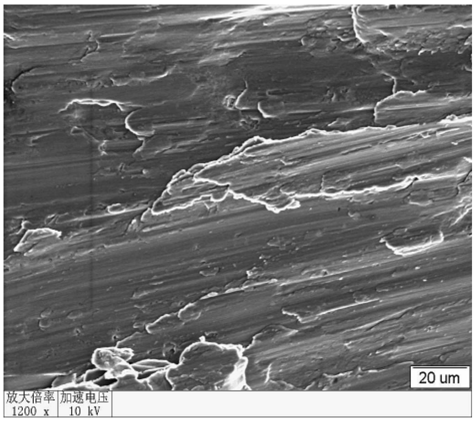


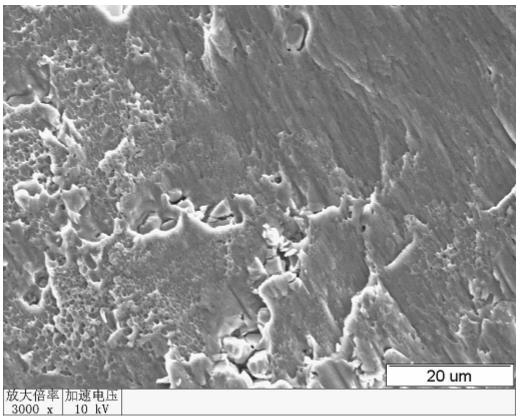
Figure 4. The equal-life curves with different fatigue life

The micro characteristic of origin region, extension region and final rupture region of fracture appearance is shown in fig.5. In the origin region, abrasion mark is obvious and the thermal oxidation phenomenon is severe due to reversed torsion. The broken oxidation particles take place and the emergence of murky gray feather is caused. In the extension region, obvious abrasion mark present on the fracture appearance. At the same time, a large number of white ligaments appear, which shear deformation play a dominant role. In the final rupture region, Elongated dimples are the main feather. Elongated dimples are formed under shear stress and have a parabola shape. In the matching surface of fracture, the dimples are elongated along the opposite direction. This indicates failure mode under pure torsion is shear failure.





a. Origin region　　　　b. Extension region



c. Final rupture region

Figure 5. The micro characteristic of fracture appearance

CONCLUSION

The existence of mean shear stress has a negative impact on the fatigue life. Fatigue life under the same shear stress amplitude reduced gradually with the increase of mean shear stress. However, the reduction of fatigue life when mean shear stress τ_m=75MPa and τ_m=100MPa was not obvious. Fatigue crack initiated in specimen surface and there are clear source region, extension region and final region in the fracture appearance. Obvious abrasion mark appeared and thermal oxidation phenomenon took place due to reversed torsion.

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REFERENCES

1. Zhao T, Jiang Y. (2008) Int. J. Fatigue.30: 834-849
2. Papadopoulos I. V., Piermaria Davoli, Carlo Gorla.(1997) Int. J. Fatigue, 19(3): 219-235
3. Davoli P, Bernasconi A, Filippini M, Foletti S, Papadopoulos I V. (2003) Int. J. Fatigue. 25: 471-480
4. Gadouini H., Nadot Y., Rebours C.(2008) Int. J. Fatigue, 30: 1623-1633
5. Susmel L, Tovo R, Lazzarin P. (2005) Int. J. Fatigue. (27): 928-943
6. Carpinteri A, Spagnoli A, Vantadori S.(2009) Int. J. Fatigue, 31: 188-196
7. Wang C H, Miller K J. (1991) Fatigue Frac. Eng. Mater. Struct. 14(2/3): 293-307
8. Kallmeyer A R, Krgo A, Kurath P. (2002) Transaction ASME, J. Eng. Mater. Tech.124(4): 229-237