High Temperature Fatigue Properties Research of GH4169 under Multiaxial Cyclic Loading

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Abstract. The high temperature (550°C and 650°C) fatigue properties of GH4169 for thin-wall tube specimen are investigated under uniaxial tension, uniaxial torsion, proportional tension-torsion and nonproportional tension-torsion. All tests are strain-controlled. The results indicate that the shape of the hysteresis loops of uniaxial tension, uniaxial torsion and proportional tension-torsion are similar, but hysteresis loop of non-proportional tension-torsion has distortion; the cyclic softening behavior is shown for GH4169 under uniaxial tension, uniaxial torsion and proportional tension-torsion, but the cyclic hardening behavior is shown for the first several cycles of nonproportional tension-torsion.

1. Introduction

As GH4169 shows high strength, plasticity, durability and fatigue performance below 650°C, this alloy has been extensively used in compressor disk, compressor shaft, compressor blade, turbine disk, turbine shaft, compressor casing and other structural parts of the aircraft engine. GH4169 has an important presence in the field of aviation application [1].

Aircraft engine is often subject to the multiaxial interactive cyclic loads due to its complex structure. In the course of loading, two or three stress (or strain) components will independently experience periodic changes over time. Such changes of stress (strain) components may be in-phase, proportional, or out-of-phase, non-proportional [2, 3]. Present studies on the uniaxial fatigue properties and microscopic failure mechanism of GH4169 [4-6] are relatively developed, but less studies focus on its multi-axial fatigue properties, especially on the high temperature and multiaxial interactive loading. Subject to the high temperature multiaxial loading, the stress-strain relationship tends to show complex properties with changes of loading mode and temperature [3, 7-10]. The present study closely observes the high temperature fatigue properties of GH4169 subject to high temperature uniaxial, multiaxial loading, analyzes its hysteresis loop properties subject to uniaxial tension-compression, uniaxial shear, proportional tension-torsion and non-proportional tension-torsion at different temperatures, and its cyclic softening and hardening properties in different loading paths.

2. Test materials and methods

GH4169 high temperature alloy was selected as the object in this research. Table 1 gives the chemical composition of GH4169. The room temperature tensile properties of GH4169 are shown in Table 2.
Table 1 Chemical composition (Mass Fraction/%)  

|     | C   | Cr | Ni  | Co | Mo | Al | Ti | Nb | B  | Mg |
|-----|-----|----|-----|----|----|----|----|----|----|----|
| C   | 0.023 |    | 17.81 |    | 53.80 | 0.01 | 2.98 | 0.50 | 1.00 | 5.37 | 0.003 | 0.001 |
| Mg  | 0.001 |    | 0.02 |    | 0.04 | 0.01 | 0.001 | 0.02 | 0.001 |    |   |   |

Table 2 Tensile property of GH4169  

| Material | σ_b / MPa | σ_0.2 / MPa | δ_e / % | ψ / % |
|----------|------------|--------------|---------|-------|
| GH4169   | 1370       | 1170         | 18      | 31    |

The test was carried out on the MTS809 tension-torsion machine. Thin walled tubular specimens (uniform gauge length 25 mm) are adopted. Test temperatures and frequencies were 550°C and 650°C, 0.02 Hz, 0.1 Hz, and 0.165Hz, respectively.

The von Mises equivalent stress and strain is:

\[
\varepsilon_{eq} = \left( \varepsilon^2 + \gamma^2 / 3 \right)^{1/2}
\]

(1)

\[
\sigma_{eq} = \left( \sigma^2 + 3 \tau^2 \right)^{1/2}
\]

(2)

where: \(\varepsilon\), \(\gamma\), \(\sigma\) and \(\tau\) are axial strain, shear strain, axial stress and shear stress, respectively. Table 3 shows the loading paths of multiaxial fatigue tests.  

Table 3 Loading paths and parameters

| Test Temperature | Loading path | Strain path | The equivalent strain \(\varepsilon_{eq}\) / % |
|------------------|--------------|-------------|---------------------------------------------|
| 550°C and 650°C  | proportional loading | \(\gamma/\sqrt{3}\) | 1.02 |
|                  | non-proportional loading(90°) | \(\gamma/\sqrt{3}\) | 0.92 |

3. Test results

3.1. Behavior of cyclic stress–strain under proportional loading

Fig.1 is the hysteresis loop of GH4169 subject to high temperature multiaxial proportional loading. It shows that the stress-strain hysteresis loop of the tension-torsion component is smooth without distortion. Its shape is basically the same as that subject to uniaxial loading. However, the tension-compression asymmetry occurs on GH4169 subject to high temperature proportional loading,
namely the absolute value of the maximum compressive stress is greater than that of the maximum tensile stress; although a negative mean stress may occur on GH4169 subject to symmetric strain loading, the mean stress value is small.

Fig. 1 GH4169 proportional loading hysteresis loops for tension and torsion components under different temperature (550°C and 650°C)

3.2. Behavior of cyclic stress–strain under non-proportional loading

Fig. 2 is the hysteresis loop of GH4169 subject to high temperature multi-axial non-proportional loading. It shows that the hysteresis loop of the tension-torsion component is distorted. The distortion on the hysteresis loop of tension-compression component and on the hysteresis loop of torsion component is as a result of the elastic-plastic loading of the axial component and the torsion component, which is affected by sudden reverse loading after the axial strain and the shear strain reaches the maximum value.

(a) Nonproportional loading-tension 550°C  
(b) Nonproportional loading-torsion 550°C
3.3. Cyclic softening or hardening characteristic under non-proportional loading

The changes of the stress on GH4169 subject to high temperature proportional loading are observed. From Fig. 3, it is found that the maximum axial stress and the maximum shear stress tend to decrease gradually as the number of cycles increases, and this process is roughly divided into three stages: Stage 1 (15% lifetime), the stress decreases rapidly as the strain evenly increases; Stage 2 (80% lifetime), the stress decreases slowly as the strain evenly increases; Stage 3 (<5% lifetime), the stress decreases drastically as the strain increases, which might be attributed to the changes of fatigue crack from stable propagation to rapid propagation, so that the axial loading capacity sharply reduces. The above analysis suggests that when GH4169 is subject to high temperature multiaxial proportional loading, in the first 15% cycle number, the axial maximum stress of the specimen decreases rapidly with a high degree of cycling softening, while in the subsequent cycles, the stress response decreases slowly with a minor degree of cycling softening.

Fig. 4 shows the changes of the stress on GH4169 subject to high temperature non-proportional loading. In the initial number of cyclic loading, the maximum shear stress and the maximum axial stress increase drastically, as followed by a gradual decrease of the maximum shear stress and the maximum axial stress. Compared with the cycling softening/hardening subject to the said uniaxial and proportional loading, the initial cycling hardening of GH4169 can be attributed to the non-proportional loading through analysis. After that, the tendency of stress changing with the number of cycles is consistent with that of proportional loading, GH4169 shows cyclic softening. In summary, GH4169 subject to high temperature mainly shows cyclic softening, if subject to non-proportional loading, it shows cyclic hardening in the initial number of cycles.

Fig. 2 GH4169 nonproportional loading hysteresis loops for tension and torsion components under different temperature (550°C and 650°C)
Fig. 4 Change of maximum cyclic stress vs relative cycle numbers under nonproportional loading for GH4169 under different temperature (550°C and 650°C).

4. Conclusion

1) The shape of hysteresis loop for GH4169 subject to high temperature uniaxial tension-compression is basically the same as that subject to high temperature uniaxial shear (pure torsion);
2) The stress-strain hysteresis loop of the tension and torsion component for GH4169 subject to high temperature multi-axial proportional loading is smooth without distortion. Its shape is basically the same as that subject to uniaxial loading;
3) The hysteresis loop of the tension-torsion component for GH4169 subject to high temperature multi-axial non-proportional loading is distorted;
4) GH4169 shows cyclic softening when subject to high temperature uniaxial tension-compression, uniaxial shear and proportional tension-torsion loading, while shows cyclic hardening, then cyclic softening in the initial number of cycles when subject to non-proportional loading.

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