Damage comparative analysis of needled C/SiC composite under vibration fatigue loading and monotonic tensile loading

Shaodong Wu¹, Deguang Shang¹*, Linxuan Zuo², Linfeng Qu², Geng Hou¹, Yier Guo¹, Bin Miao¹ and Guocheng Hao¹

¹Faculty of Materials and Manufacturing, Beijing University of Technology, Beijing, 100124, PR China
²Shenyang Aircraft Design & Research Institute, The Aviation Industry Corporation of China, Ltd., Shenyang, 110035, PR China

*Corresponding author’s e-mail: shangdg@bjut.edu.cn

Abstract. Needled C/SiC composite is composed of fiber and matrix, which fatigue limit is related to the vibration loading frequency. A kind of plate specimen made of needled C/SiC composite was tested on a shaking table, and the vibration fatigue life of each specimen was obtained. In addition, the monotonic tensile test of needled C/SiC composite specimen was also carried out. Furthermore, the fracture morphologies from vibration test and monotonic tensile test were compared by scanning electron microscope. And the mechanism causing these differences was also explained.

1. Introduction

The C/SiC composite not only inherit the high temperature resistance of ceramic materials, but also overcome the shortcomings of brittle of ceramic materials. Due to high specific strength and high specific stiffness, C/SiC composite has become ideal material for the thermal protection system of hypersonic aircraft[1-2]. Many scholars have studied the tensile properties of C/SiC composite[3-4]. However, C/SiC composite need to subject aerodynamic heating, aerodynamic loading and high frequency vibration loading for a long time in service. Therefore, it is of significance to investigate the fatigue behavior of C/SiC composite under vibration loading.

Vibration fatigue is a fatigue failure phenomenon caused by resonance when the frequency distribution of dynamic alternating loading (such as vibration, impact, noise) is intersected or close to the natural frequency distribution of structure. Wu[5] carried out vibration tests of C/SiC composite thin-wall plates, and found that due to the particularity of composite micro-structure, the fundamental frequency reduction curve of plates have three different stages. Staehler[6] found that the fatigue limit of C/SiC composite decreases with the increase of vibration frequency, the extensive debonding between fiber matrix interfaces during cyclic loading can cause frictional sliding and internal heating leading to a reduction of cycles to failure. In addition, Shuler[7] and Holms[8] also found that the increasing of loading frequency from 10 to 50 Hz can cause the reduction of cycles to failure. Chawla[9] found that composites with a stronger fiber-matrix interface may show less of a dependence upon frequency.

In this study, a random vibration test of needled C/SiC thin-walled notched specimens with cantilever fixed boundary was carried out on a vibration table, the fatigue lives of the specimens were also obtained. And in order to study the similarities and differences of failure modes of composite
under vibration loading and monotonic tensile loading, the monotonic tensile test of needled C/SiC composite specimen was also carried out. In addition, the fracture morphologies from vibration test and monotonic tensile test were compared by scanning electron microscope (SEM), and the mechanism resulting in these differences were clarified.

2. Material
A needled carbon fiber reinforced SiC matrix composite (a kind of ceramic matrix composite) was prepared by chemical vapor infiltration (CVI) method. The composite is consisted of T700 fiber and SiC matrix. And the orientations of T700 fibers include 0°, 90° and needle direction, as shown in figure 1. The volume fractions of carbon fiber and SiC matrix are 30% and 48%, respectively. The density of the composite material is 1.80–2.1 g/cm³, and the tensile strength is 120–150 MPa.

3. Mechanical tests and results

3.1. Test of vibration fatigue
Figure 2(a) shows the shape and dimensions of the specimen for the vibration fatigue test. We employed plate specimens with a notch, as the stress is concentrated at the notch during the vibration. The thickness of the specimen is 3.5mm, the holes at both ends of the specimen were used to connect with clamp or attachment block by screws. Figure 2(b) shows the setup of the specimen, strain gauge, accelerometer, and clamp on the vibration table. The first-order natural frequency of the specimen is 34.5Hz. The random vibration tests were performed with different acceleration inputs (0.6, 0.65 and 0.7 Grms) within a frequency band of 20-70 Hz at room temperature.

Figure 3 shows the relationship between the applied acceleration and the fatigue life of needled C/SiC composite. And all the specimens fractured at the notch. It can be found that the lives of specimens have a downward trend with the increase of vibration signal strength, and the dispersion of specimen lives is relatively large under the same vibration signal strength.
3.2. Test of monotonic tension

The needled C/SiC composite specimens with dog-bone shape were tested under monotonic tensile loading, which was loaded by the MTS hydraulic servo testing machine, as shown in figure 4. Figure 5 shows the relationship between the displacement and tensile force of the specimen, and it can be seen that the specimen tensile deformation is nonlinear.

(a) Specimen used for testing (measurements are in mm, and general tolerances are ±0.1mm).

(b) Specimen mounting.

Figure 2. Test of vibration fatigue.

Figure 3. Vibration fatigue lives of specimens.
4. Failure modes analysis of composite

The microscopic fracture morphology of failed specimens was observed by SEM, as shown in figures 6-8.

Figure 6 shows that the main damage mode of specimens is tensile failure with fibers pull-out in the axial direction under both vibration fatigue loading and monotonic tensile loading. Comparing with under vibration fatigue loading, the pull-out of axial fibers are longer under monotonic tensile loading. And this may be caused by the different damage mechanisms under above two loading conditions. For under monotonic tensile loading, the specimen was axially stretched, and the axial fibers were broken under the action of monotonic tensile stress after the fiber/matrix interface debonded. But for under vibration fatigue loading, the specimen was subjected to bending stress, and the axial fibers were broken under the action of cyclic bending stress after the fiber/matrix interface debonded, therefore, the fiber will not be pulled out too long.
The fiber bundle can form a neat fracture surface at the place where the fiber bundle adheres closely to the matrix, as shown in figure 7(a), otherwise, the fiber bundle cannot form a neat fracture surface, as shown in figure 7(b). Both neat and non-neat fracture surface can form in axial fiber bundles in vibration test and tensile test. However, the probability of forming neat fracture is higher in vibration test. The reason causing this difference may be that the crack first occurred in the matrix, and when the crack grows to the fiber position, it will cause the fiber/matrix interface debond, after the matrix cracks reach the saturation state, the fibers were damaged gradually under the action of vibration loading. Therefore, the long-time action of vibration load on the fiber bundle makes it easier to form a neat fracture.

Figure 7. Characteristics of fibers fracture surface.

Figure 8 shows that the main failure mode of the needled fibers and the fibers along transverse direction is tearing in both vibration test and monotonic tensile test.

Figure 8. Failure characteristic of the needle and transverse fibers.

5. Conclusions
In this study, both the random vibration test and monotonic tensile test of needled C/SiC composite were carried out. And the fatigue fracture behaviour was analysed by comparing the fracture
morphology under vibration fatigue loading and monotonic tensile loading. The following conclusions are drawn.

1. The lives of specimens have a downward trend with the increase of vibration signal strength, and the dispersion of specimen lives is relatively large under the same vibration signal strength.

2. Comparing with under vibration loading, the length of axial fiber pull-out at the fracture of the specimen is longer under monotonic tensile loading. And comparing with under monotonic tensile loading, the axial fiber at the fracture of the specimen is easier to form a neat fracture under vibration loading.

3. For the composite under vibration loading and monotonic tensile loading, the major failure modes of fibers along needle direction and transverse direction are all tearing.

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