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An investigation of fretting fatigue in a circular arc dovetail assembly

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ABSTRACT

The fretting fatigue of a fan blade–disk attachment in aircraft gas turbine engines was investigated, in which a sub-scaled specimen with one circular arc dovetail root at each end and its fixture were designed and tested under cyclic loading, and the stress distribution in the contact zone and its variation during loading were determined by use of the finite element method. Based on the critical plane method, an approach taking the cyclic strain range and the stress gradient into consideration was developed to predict the fatigue life of specimens, which is verified by the experiments and can be applied to real structures.

1. Introduction

Dovetails or single-tooth assemblies are widely used to secure fan or compressor blades to disks in gas turbine engines. Currently, a special fan disk assembly incorporated with a circular arc dovetail root and slot has been widely used for the high bypass ratio turbofan engines. This novel feature will help decrease the hub radius and thus increase the airflow through the fan blades. However, Fretting fatigue may occur in such a component, due to relatively high contact stresses and relatively small displacements that develop in the blade–disk interface, which always results in premature failure such as wear or cracking. The failure induced by fretting fatigue has gradually become a prominent issue for aero-engine during long time service, in some cases, micro slip at the edge of contact zone can reduce life by as much as 40–60% [1].

There are many complexities of the dovetail assembly conditions, for example, the contact geometry, loading conditions, surface treatments and so on, influencing the failure mode and the amount of damage incurred at the blade–disk interfaces [2,3]. Engineers always have to take these factors into consideration when design such components. One of the considerable challenges for the designers is to simulate the contact situation in a real dovetail assembly experimentally, because the interfacial normal and shear stresses are oscillatory under real working conditions. However, representative experiments could still be conducted. One such experimental fixture was designed by Ruiz and co-workers [4], in which a biaxial rig fixture was developed to simulate the centrifugal force and the remote disc loading, respectively. The advantage of their fixture is that it is very similar to the real dovetail joints in gas turbine engines. More recently, Rajasekaran and Nowell [5] developed a similar biaxial experimental fixture which could simulate the combined effects of centrifugal loading, disk expansion force and blade vibration. A disadvantage of these two experiments, however, is that it can be relatively expensive to perform a single test. The other type of dovetail assembly experiment was developed by Conner and Nicholas [6], in which the fixture held removable contact pads rather than using a conformal contact geometry as in the Ruiz's fixture [4]. Similar fixture was designed by Golden and Calcaterra [7] to evaluate the effect of flank angle on the fretting fatigue performance of dovetail specimens. Obviously, this kind of set-up has easily replaceable fretting pads and is quite rigid, which results in very reproducible alignment. However, the removable contact pads produce a shorter contact length compared with the real dovetail configuration, which may reduce the fretting fatigue life and cause differences between the test and the actual structure.

With the importance and complexity of understanding fretting fatigue, numerical analysis of fretting fatigue is also conducted, which consists of addressing two key issues: the first is to solve the contact stress as accurately as possible. However, the stress

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analysis of dovetail assemblies is not without challenges. The difficultly may stem from the high stress magnitudes as well as the contact nonlinearities. Although analytical and quasi-analytical formulas based on the Hertzian solution [8] can be used to calculate the contact stresses for some specific contact geometries [9,10], due to the complexities of geometries and loading conditions, finite element method (FEM) is the most widely used approach in industry, but it is often essential to perform a verification analysis to examine the convergence of contact stresses when using FEM. Sinclair et al. [11] systematically analyzed the contact stresses in a dovetail assembly. They found out that the solution accuracy is highly dependent on the density of finite element (FE) mesh, which indicates that the contact regions must be carefully tracked when using the FEM to carry out the stress analysis. More recently, Wei et al. [12] analyzed the convergence of elastic–plastic stresses by establishing a series of FE models with different mesh density and tried to suggest the minimum mesh quality to be used. Once the stress field is obtained, the second key issue is to develop suitable life prediction approaches. A number of life prediction models have been developed and applied over the last decades. A well-known empirical parameter is the fretting fatigue damage parameter (FFDP) proposed by Ruiz et al. [4]. It has been proved that this parameter is capable of predicting the crack initiation location. However, this parameter is lack of a clear physical interpretation and only a vague qualitative correlation with fatigue life has been obtained [13]. Due to the fact that the fretting loads induce multiaxial stress field and severe stress gradient in the contact zone, critical plane based fatigue parameters such as the Smith–Watson–Topper (SWT) [14], Fatemi–Socie (F–S) [15], McDiarmid [16] and Findley [17] parameters have been widely used to predict fretting fatigue lives [13,18]. Additionally, noticing that there are some quantitative equivalences between the stress field close to the edge of a flat rigid punch and that at the tip of an elastic crack, some investigators [19,20] have employed a crack analogue approach to fretting fatigue based on asymptotic analysis. A recent asymptotic approach intended to permit matching of prototypical fretting problems to simple laboratory tests was developed by Hills and Dini [21].

The approaches (or parameters) outlined above generally offer a means of correlating the stress/strain field with experimental observations, but it is now recognized that the high stress gradients close to the contact surfaces can favor the formation and initial growth of small cracks. Thus local multiaxial fatigue criterions may provide over-conservative predictions for they do not account for the sharp stress gradient effects [22]. A number of prediction approaches have been developed to take the stress gradients into account which can be broadly divided into two categories, namely (i) non-local approaches such as theory of critical distance (TCD) [23], volume averaging approach [24,25] and weight function method [26]; (ii) short crack arrest methods [27,28] based on the linear elastic fracture mechanics. The TCD which has been widely used for notched specimens in plain fatigue can be used in conjunction with any conventional multiaxial fatigue criterion. The most important parameter to correctly apply such a theory is the so-called material characteristic length which is related to the threshold of the stress intensity factor and the plain fatigue limit. Attempts of applying the TCD to fretting fatigue have been made in the last few years [29,30]. Volume averaging methods have also been widely used to account for the stress gradient effects. Araújo and Nowell [22] developed two non-local averaging methods in extending the critical plane approaches to cope with the existence of stress gradients. The predictions of both averaging methods show that a critical averaging dimension of the order of the material grain size (i.e. Al 4% Cu and Ti–6Al–4V) appears to give realistic estimations. Similar method was adopted by Naboulsi and Mall [25], in which they computed the averaged values of parameters (i.e. the crack initiation parameter and the state of stress/strain) over a process volume. It was quite a successful attempt to average the parameters of life equation (i.e. Shear Stress Range (MSR), SWT and Findley), since it encompassed the combined effect of both stress and strain gradient. The weight function method is to modify the life equation by introducing a weight function which is stress gradient dependent, and it is usually accompanied by employing analytical or semi-analytical formulas [31–33] to calculate the stresses and the stress gradients. The expression of weight function is dependent on life prediction models. For example, the weight function developed by Fouvry et al. [26,34] depends on the mean gradient of hydrostatic pressure. While the weight function introduced by Heredia et al. [35] is characterized by the mean principal stress gradient between the surface and a distance of 100 μm below the contact surface. As an alternative approach, the concept of short crack arrest firstly proposed by Araújo and Nowell [27] has been applied to deal with the stress gradient effect. A comparative analysis between the multiaxial stress and the stress intensity factor based short crack arrest methodology was carried out by Araújo and Castro [28]. This approach is somewhat attractive since it relies only on standard material parameters obtained from plain fatigue experiments. In fact, there is not much fundamental difference between the volume averaging approach and the short arrest method in dealing with the stress gradient feature, since both approaches require a critical distance to sustain the high level of stress.

The present work is concerned with the analysis of fretting fatigue in dovetail assemblies. Firstly, a circular arc dovetail specimen was designed and corresponding fatigue experiments under cyclic loading were conducted. The experimental fixture was connected to the testing machine by two pairs of orthogonal pins and lugs to help reduce the additional bending moment in the experimental process. Further, finite element analysis (FEA) was carried out based on the contact configuration. The stress distribution in the contact zone and its variation were analyzed in details. In the end, an approach based on the critical-plane SWT model was developed to take the stress gradient into account. This approach was established by introducing a weight function which is stress/strain gradient dependent. The developed method was used to predict the fatigue life of the dovetail specimens and the predictions are in good agreement with the experimental counterparts.

2. Circular arc dovetail assembly experiments

2.1. Material and specimen

Titanium alloy TC4 is the material chosen for the dovetail specimen in our experiments since it is commonly used in aerospace application such as fan blade and disk. As a medium strength alloy, TC4 consists of two phases α and β, which contains 6% Al as the α stable element and 4% V as the β stable element. The chemical composition of the material is given in Table 1 [36]. The material was subjected to the following heat treatment: 730 °C for 1.5 h and then air cooling [37]. TC4 has an elastic modulus of 109 GPa, Poisson ratio of 0.34, density of 4440 kg/m^3, yield strength of 880 MPa, and ultimate tensile strength of 938 MPa.

In order to investigate the fretting fatigue behavior of the circular arc dovetail root used in turbofan engines. A sub-scaled dovetail specimen is designed as shown in Fig. 1(a). The specimen consists

Table 1
The chemical composition of TC4 (wt.%) [36].

Al	V	Fe	Si	C	N	H	O	Ti
5.5–6.8	3.5–4.5	0.30	0.15	0.10	0.05	0.01	0.20	Balance