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Experimental investigation of small fatigue crack growth due to foreign object damage in titanium alloy TC4

Lei Zhu[a,b], Xuteng Hu[a,b,*], Rong Jiang[a,b], Yingdong Song[a,b,c], Shoudao Qu[d]

[a] Key Laboratory of Aero-engine Thermal Environment and Structure, Ministry of Industry and Information Technology, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, PR China
[b] Jiangsu Province Key Laboratory of Aerospace Power System, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, PR China
[c] State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, PR China
[d] Herbert Gleiter Institute of Nanoscience, Nanjing University of Science and Technology, Nanjing, Jiangsu 210094, PR China

A R T I C L E I N F O

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A B S T R A C T

The ingestion of runway debris during takeoff, landing and low-flying of aircraft has been a major concern for gas turbine engines. The small craters or notches introduced by particles impacting blades are commonly known as foreign object damage (FOD). The objective of this paper is to identify the initiation and propagation behavior of small fatigue crack originating from FOD crater in titanium alloy TC4. FOD was simulated by firing steel sphere projectile onto the surface of flat specimen at 30°, 60° and 90°. Replication technique based on a two-part silicon mixture was used to observe the initiation and growth process of FOD-initiated crack. The results reveal that all the cracks nucleate from the micronotches at the material pileup of FOD crater rim. The growth process of FOD-initiated crack consists of two stages. In the first stage, the crack propagates merely inside the crater. Once exceeding ~500 μm in length, the crack will grow into the second stage, in which the crack extends rapidly both inside and outside the FOD crater. Moreover, the growth rates of FOD-initiated cracks are lower than naturally-initiated cracks. Of all the three tested impact angles, the 60° impact seemed to lead to the most crucial decline in fatigue resistance. A linear relationship exhibits between the fatigue lifetime and crater cross-section area of FODed specimens.

1. Introduction

Foreign object damage (FOD), which is caused by the ingestion of runway debris during takeoff, landing and low-flying of aircraft, is one of the major concerns for both civil and military engines [1]. FOD mainly occurs as impact damage to the leading edge of fan blade, and takes the form of crater, notch, tear, etc, together with material loss and folding [2]. Such millimeter-sized damage provides preferred sites for the premature initiation of fatigue cracks, thus leading to a serious decline in the fatigue capacity of the blade. The damaged blade in service may even suffer from immediate fracture as a result of the transient airflow dynamics induced high frequency vibratory loads [3]. Due to the flight spectra distinctions between civil and military aircrafts, the primary failure mode in civil engine is low cycle fatigue, whereas high cycle fatigue is deemed as the main failure mode in military engine [4]. For both cases, the stages of crack initiation and small crack growth may exceed 90% of the total fatigue life [5]. Innumerable researches indicate that small crack growth rate can exceed large crack growth rate at the same stress intensity range, and small crack can indeed propagate below the large crack growth threshold [6]. Hence, in order to gain insight into the influence of FOD on the fatigue behavior of the blade and improve the damage tolerance design methodology accordingly, it is crucial to characterize and clarify the initiation and growth mechanisms of small fatigue crack nucleating from FOD.

In the past two decades, considerable efforts have been made to assess the effect of FOD on the fatigue behavior in titanium alloy Ti–6Al–4V, which is a quintessential blade material used in aero-engines. This involves evaluating the FOD-induced stress concentration, microcracking, residual stress gradients and microstructural distortion [1,7–14]. For instance, in a US program regarding high cycle fatigue, Peters and colleagues [1,7–10] used hardened steel spheres to shot flat Ti–6Al–4V surfaces at 200–300 m/s. Two common conclusions could be drawn from their investigations. First, cracks were prone to originate from the vicinity of FOD sites, thus giving rise to that the fatigue strength of FODed specimens was orders of magnitude lower than the

* Corresponding author at: College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, PR China.
E-mail address: xthu@nuaa.edu.cn (X. Hu).

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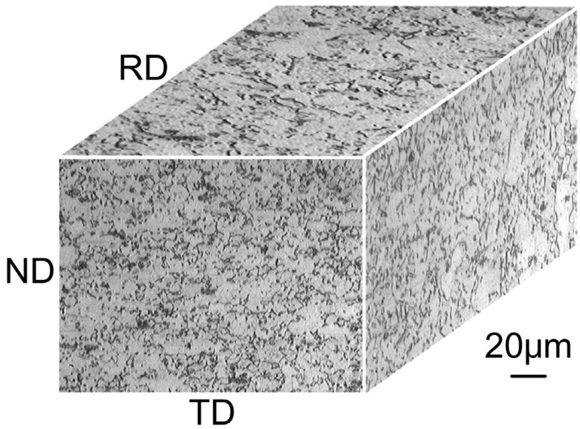

Fig. 1. Microstructure of the TC4 rolled plate (ND: normal direction; RD: rolling direction; TD: transverse direction).

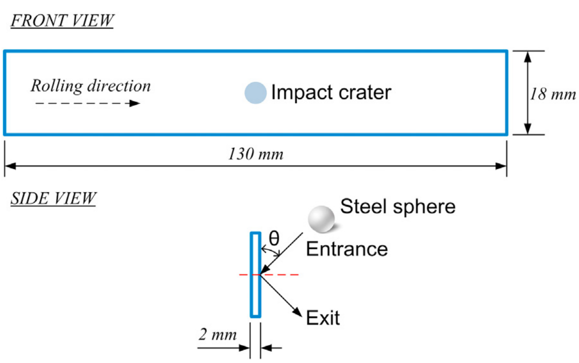

Fig. 2. The geometry of the flat specimen used in the simulation of FOD and illustration of the impact angle θ (not to scale).

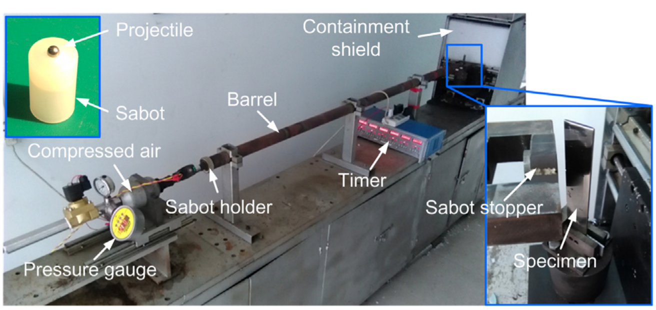

Fig. 3. Photograph of the compressed gas gun and spherical projectile mounted in polyamide sabot.

un-impacted specimens. Second, owing to the interactions of stress concentration, microcracking and residual stress, crack initiation occurred at the base of the impact crater after low-velocity impact (200 m/s) and at the material pileup around the crater rim after high-velocity impact (> 250 m/s), respectively. On the basis of such experimental results, a few researchers [10,13,15] established a modified Kitagawa–Takahashi diagram to describe the failure envelope for FODed blades by using the smooth-bar fatigue strength and the large crack growth threshold. A finite element analysis approach proposed by Chen and Hutchinson [11,12] further delineated the role of FOD-induced stress concentration and residual stress on alternating the critical crack threshold.

However, most of the previous investigations concentrate on the fatigue limit of the FODed blades, while far less information is available for the FOD-initiated fatigue crack behavior, let alone the crack initiation and early growth stages. Experimental data or photographs

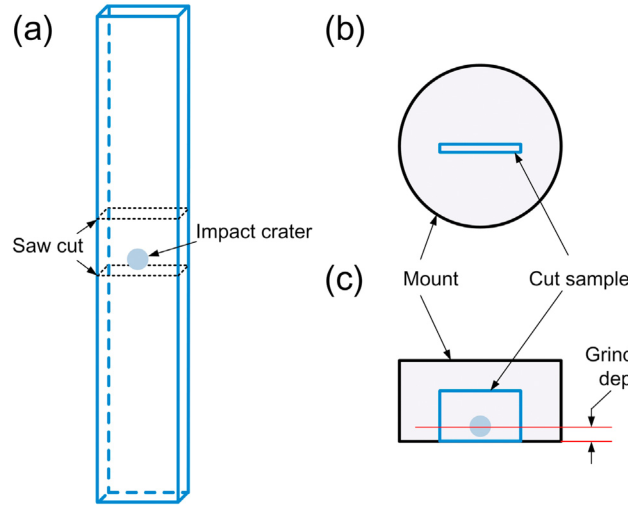

Fig. 4. Schematic of (a) saw cut of the impacted specimen, (b) top view of mounted sample, and (c) profile view of mounted sample.

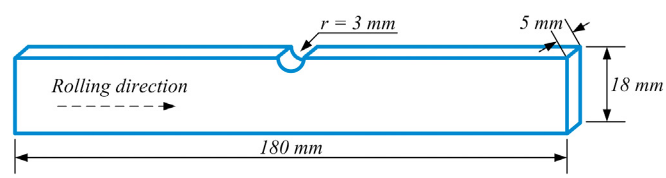

Fig. 5. The geometry of the SENT specimen used in naturally initiated small crack test (not to scale).

manifesting the whole evolution process of small crack nucleating from FOD site have not yet been involved in literature. The main reason is that small crack experiment is more tedious than large crack, especially for crack initiating from irregular FOD surface. Generally, the two major methods applied to quantify the small crack evolution process are in-situ scanning electron microscopy (SEM) [16] and surface replication technique [17]. Although the high-resolution in-situ SEM method is viewed as the most state-of-the-art, it has a relatively limited detecting space due to the nature of the microscope. Thus, it is difficult to identify the location where a crack naturally incubates until the crack length in excess of hundreds of micrometers. With regard to the FOD notch or crater with size of several millimeters, the opportunity to use in-situ SEM to observe the crack initiation and early small crack growth is missed. In contrast, the aforementioned drawback does not exist in replication technique, in which the test is periodically interrupted and the interested area is recorded by using fast-curing replica material [17]. Nevertheless, a vital disadvantage for applying acetyl cellulose film, which is the most widely used replica material, is that it cannot be performed to view uneven surface such as FOD crater. In recent years, a two-part silicon-rubber compound known as RepliSet® has been successfully employed to replace the acetyl cellulose film [18–20]. The RepliSet® material is more convenient to operate and able to solidify within 10 min, which is much faster than acetyl cellulose film [19]. What's more, the RepliSet® material is feasible to duplicate the anomalous FOD surface.

This paper aimed to provide some fundamental information on the initiation and propagation behavior of small fatigue crack originating from FOD crater in titanium alloy TC4 (Ti–6Al–4V). FOD was simulated by firing steel projectile onto the surface of flat specimen. The FODed specimens were fatigued axially in air at room temperature and the RepliSet® based replication technique was used to record the complete process of crack initiation and small crack growth.