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Formation of hole-edge cracks in a combustor liner of an aero engine

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ABSTRACT

A combustor liner from an aircraft engine, which is made of a wrought Ni-based superalloy GH3039, was investigated after service exposure of 1600 engine operating hours. A series of experiments, including macroscopic examination and microscopic examination, fractography observation and thermal exposure experiments, were conducted to investigate the formation mechanism of hole-edge cracks. The results show that microstructural degradation and thermal fatigue should be responsible for the formation of hole-edge cracks in complementary combustion zone (CCZ) of the combustor liner. CCZ is the highest temperature area instead of primary combustion zone (PCZ) during service, which results in significant microstructural degradation, e.g., the stripping of coating and intergranular oxidation, in the hole-edge in CCZ. The cracks initiate at the hole-edge due to coating microstructure degradations and intergranular Al_2O_3-type oxidation under the coating, and then propagate under the action of thermal fatigue, which results in final failure of the combustor liner.

1. Introduction

As the place where fuel atomizing, air–fuel mixing and fuel burning take place, the combustor liner is one of the most important components in aero-engine combustion chamber. During service time, the combustor liner is exposed to very complicated and severe conditions, including high temperature, gas corrosion and vibration, readily leading to crack formation, local fracture, even malfunction and failure [1,2]. Accordingly, research on the microstructure degradation and damage behavior of the combustor liner under these conditions is an important issue.

Previous reports have shown that the combustor liner expands and shrinks rapidly, namely thermal fatigue, is one of the main reasons for failures [2,3]. Most of these studies on the thermal fatigue were based on the fracture analysis, and the working temperature distribution of the combustor liner was usually determined by using a numerical modeling method [2]. However, the experimental data coming from the practice service is still in shortage, leading to an imperfectly understanding of the mechanism on initial cracks formation and propagation in the combustor liner.

In this work, a failure combustor liner due to hole-edge cracks is investigated through a failure analysis method combined with microstructure degradation imitation by thermal exposure. The thermal exposure experiments on the original material are conducted to examine the thermal effects on microstructure and evaluate the service temperature of the combustor liner. The reasons for hole-edge crack formation will be discussed.

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2. Experimental procedure

The investigated combustor liner was taken from a serviced aircraft engine, which had been in service for 1600 engine operating hours. The combustor liner is made of a wrought Ni-base superalloy GH3039, with an enamel coating on its inside and outside surfaces. Chemical compositions of the combustor liner are presented in Table 1.

The outside surface profile of the investigated combustor liner is shown in Fig. 1. Corresponding to the combustion characteristics and the size of the dilution hole, the combustor liner can be orderly divided into three zones from the head to the tail, which are primary combustion zone (PCZ), complementary combustion zone (CCZ) and cooling zone (CZ). There are totally 10 rows of dilution holes in the combustor liner. Generally, Rows 1-3 are included in PCZ, while Rows 4-6 and Rows 7-10 are included in CCZ and CZ, respectively.

The samples in transverse section were cut from neighborhood of the holes in PCZ, CCZ and CZ, respectively, as shown in Fig. 1. Two positions in the samples were observed to investigate the matrix microstructure and coating microstructure, as shown in Fig. 2. Location A was used for matrix microstructure examination while location B was used for coating microstructure observation. The samples with hole-edge crack propagation and tip were sectioned and observed. The crack fracture surface was also investigated after the sample was intentionally ruptured along propagation direction.

The thermal exposure experiments were conducted in order to examine the thermal effect on microstructural degradation and speculate service temperature of the combustor liner. Since the head of the combustor liner was far away from the combustion gas and the service temperature here was much lower than that in CCZ, the microstructure in the head was almost unchanged during service and considered as an unserviced one. Therefore, the original samples for the thermal exposure experiment were sectioned from the head of the combustor liner. The samples were exposed in an air-circulated furnace for a period of 100 h at 600, 650, 700, 750, 800 and 850 °C or for periods of 500, 1000, 1500 and 2000 h at 750 °C, respectively.

The metallographic specimens were characterized after mechanically polished and etched in a solution of 30 ml HCl, 10 ml HNO_3 and 10 ml $C_3H_8O_3$. The microstructural examinations were performed using a ZEISS SUPRA 55 field-emission scanning electron microscope (FE-SEM). The compositions were analyzed by the energy dispersive X-ray spectroscopy (EDS) detector on FE-SEM. Thicknesses of coating were measured from about five areas and obtained by calculating the mean value of the measurements on each coating microstructure sample. The fracture surface of hole-edge crack was treated by immersing in a hot solution of 10 g $KMnO_4$, 20 g NaOH and 100 ml H_2O to remove the oxide scale.

3. Experimental results

3.1. Macroscopic inspection and fracture surface observation on hole-edge cracks

Macroscopic inspection was conducted to investigate surface crack and macro damage of the combustor liner. No obvious geometric deformation or severe corrosion attack was observed on the outside surface. Different colors along axial direction were observed on the inside surface, as shown in Fig. 3a. The inside surface of CZ and PCZ exhibits light green, which is the color of enamel coating, but that of CCZ exhibits dark grey. Additionally, totally 21 hole-edge cracks were observed in CCZ while no cracks were observed in PCZ and CZ. Typical hole-edge cracks morphology is shown in Fig. 3b. Some of the cracks connect two holes. The cracks growth directions are almost parallel to the axial direction of the combustor liner and the length of the cracks is about 5–10 mm.

Fig. 4 shows the SEM fractographs of typical hole-edge fracture surface. The fracture surface profile consists of three distinguished regions, which are marked I, II and III in Fig. 4a. In Region I, the fracture surface is relatively rough and mainly characterized by intergranular fracture, as shown in Fig. 4b. The grain size of fracture surface is about 40–80 μm. In Region II, however, the fracture surface has a smooth appearance. Typical fatigue striations in different directions were observed at higher magnifications, as shown in Fig. 4c. Region III is intentionally broken but not the region of original hole-edge crack propagation.

3.2. The coating examination

Fig. 5 presents the thickness and typical microstructures of hole-edge coating at different locations along axial direction of the combustor liner. The coating thickness is about 16–20 μm in PCZ and about 8–16 μm in CZ. The coating is relatively in a good preservation in both the two zones, compared with that in original sample (15–21 μm). However, there is no residual coating at the hole-edge of CCZ, as shown in Fig. 5.

Table 1
Chemical compositions of the investigated combustor liner (wt.%).

Elements	Ni	Fe	Si	Mo	Al	Ti	Nb	Cr	S	C	Cu	Mn	P
Contents	73.13	0.85	0.28	2.13	0.64	0.66	1.10	20.58	0.005	0.055	0.014	0.13	0.0059