Fretting Fatigue in Aircraft Components Made of Ti-Al-V Alloys

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Abstract

This paper presents typical examples of premature fatigue failures originating from fretting damage in aircraft components manufactured from (α+β) titanium alloys, namely, Ti-6Al-4V and Ti-2.5Al-2V. The signatures of fretting damage in the Ti-alloy components with different contacting materials, namely, pure-Ti and a high strength Cr-Mo steel, and the manifestation of the fretting damage in fatigue crack initiation have been discussed. Two examples, one on failure of bolt of main rotor blade fork of a helicopter, and the other on failure of a hydraulic pipeline of an aircraft, have been presented. In the first case, an incident of premature fatigue failure occurred in the blade fork bolt during service, involving fatigue cracking at the flange region of the collar close to the bolt-head. The fretting damage at the flange of the collar was associated with pitting, spalling and sub-surface crack generation at the flange-bush interface. In the case of hydraulic pipeline failure, fretting damage was observed between two titanium alloy tubes in contact. Study showed that the reason for setting-in fretting damage at the joint was due to inadequate closeness of the fit that was formed by swaging.

Keywords: Ti-Al-V alloy; fatigue; fretting; spalling

1. Introduction

Fretting damage occurs between contacting surfaces that are subjected to small amplitude vibration or relative motion [1-3]. The initiation of fatigue cracks in fretted regions depends mainly on the state of stress on the surface and particularly, on the stresses superimposed on the cyclic operating stress. The damage is commonly observed in aircraft components due to superimposed vibrations during service. Fretting damage in aircraft components results in premature fatigue crack initiation and fracture. One of the typical examples of such failures is fatigue crack generation in compressor and turbine blade root regions at the contacting surface with the fir-tree/dove-tail region of the disc. Fretting damages are often encountered in press-fitted components such as shafts, couplings, bearings etc., as well [4]. Titanium alloys are extensively used for aerospace applications in the form of blades and discs in engines, and also as fasteners and hydraulic pipelines. Titanium alloys are known to undergo fretting damage in typical aircraft operating environments, when in contact with...
both similar and dissimilar metals. Under the influence of superimposed vibrations, fretting damage in such components initiate premature fatigue failures. Studies have shown that the contacting materials and the contact shapes have an influence on the extent and nature of fretting damage and in turn, contribute to early fatigue crack initiation. The signatures of fretting damage in Ti-alloys under laboratory test conditions have been studied extensively and are well documented [3, 5-6]. This paper presents two examples of service failures of aircraft components manufactured from different Ti-alloys.

The signatures of damage in the failed components have been used to understand the mechanism of fretting damage and its manifestation in fatigue crack initiation. The paper also brings out the role of manufacturing processes and assembly stresses on the severity of fretting damage in typical aircraft components with specific reference to the failures cited.

2. Case histories

2.1. Fatigue failure in main rotor blade fork bolt of a helicopter

2.1.1. The failure

A crack was observed on the head region of a blade-fork bolt of main rotor of a helicopter during post flight inspection (Fig. 1). The bolt was manufactured from a titanium alloy of nominal composition Ti-6Al-4V. The crack was noticed after the component had performed 143.3 hr of service.

![Fig. 1](a) Photograph showing (a) the cracked bolt, and (b) magnified view of the region marked in (a); note the fretting damage in the vicinity of the crack.

2.1.2. Identification of failure mechanism

Close-up view of the crack on the bolt-head at the flange surface of the collar is shown in Fig. 1(b). Examination revealed fretting damages on the flange of the collar. Fretting damage was found spread nearly over 60% of the flange surface. The extent of damage was more prominent in the vicinity of the crack. Suitable cut was made and the crack was pulled open for fractographic study. Figure 2 shows the mating fracture surfaces. Stereo-binocular examination of the fracture surface revealed well defined beach marks indicating progressive mode of crack propagation. Loss of material in the form of spalling was observed at a few locations along the edge of the fracture surface (marked by rectangular box in Fig. 2(b)).

![Fig. 2](a) Photographs showing (a) the mating fracture surfaces and (b) loss of material from the flange surface (marked by rectangular boxes in (b)).
One of the mating fracture surfaces of the crack was cleaned ultrasonically in acetone and examined under a Scanning Electron Microscope (SEM). A low magnification view of the fracture surface from the crack origin region is shown in Fig. 3(a). SEM examination confirmed progressive mode of crack propagation with well delineated beach marks (Fig. 3(a)). At higher magnification, fracture surface from the progressive crack propagation region showed striations, typical of fatigue failure (Fig. 3(b)). Pitting and sub-surface cracks were observed at a few locations along the edge of the fracture surface and in the fretted region on the flange of the collar (Fig. 4 and 5).

The damage seen on the flange of the collar adjacent to the fractured edge was examined further under SEM. Localized fretting damage and loss of material due to spalling were found present in these regions (Fig. 6). The fretted regions can be clearly distinguished from the virgin surface of the flange wherein the machining marks were intact. Compositional analysis by Energy Dispersive X-ray (EDX) analyzer on the fretted region showed presence of Fe and Cr in addition to the base material elements Ti, Al and V (Fig. 7). In the assembly of the blade-fork, the collar of the bolt was in contact with a steel bush. The presence of the elements Fe and Cr on the fretted region of the collar of the bolt as detected by EDX analyzer was traced to the steel bush, of nominal composition Fe-0.2C-12Cr-1.0Mo-0.3Si-0.4Mn.
2.1.3. Failure analysis and conclusions

From the fractographic features, it is evident that the bolt has failed by fatigue. Fatigue crack had initiated on the flange of the collar at about 3 mm from the chamfered edge. After initiation, the crack had propagated through the thickness of the collar during service. The nature of striations on the fracture surface suggests that the fatigue was of high cycle-low stress type. The contact surface of the collar of the bolt was found damaged and the appearance of the damaged surface was typical of fretting. The reason for fatigue crack initiation was found to be the stress concentration associated with the sub-surface cracks that arose due to fretting damage at the flange-bush interface. Fretting damage was further confirmed by the presence of elements such as Fe and Cr on the flange of the collar. These elements got transferred from the steel bush that was in contact with the flange of the collar during the fretting process involving cold welding followed by de-cohesion. Oxidation of the surface as evidenced by the presence of ‘O’ in the EDX spectrum further confirms fretting damage (Fig. 7). Oxidation is typically noticed in fretted surfaces containing Fe.

2.1.4. Recommendations

Analysis showed that the relative movement between the bolt and the bush during operation had manifested into fretting damage. The stress concentration thus resulted was responsible for the premature fatigue crack initiation on the flange of the bolt. Study showed that relative movement between the flange of the collar of the bolt and the steel bush was unavoidable because of inherent high vibration in helicopter blades. Hence, it was recommended to use solid lubricant such as MoS2 at the interface between these two components to avoid/minimize fretting damages.

2.2. Fatigue failure of a hydraulic pipeline of an aircraft

2.2.1. The failure

An incident of hydraulic pressure drop was noticed while the aircraft was preparing to land. The suspected pipe assembly was removed from the aircraft and subjected to pressure test. During the test, one of the pipelines of the system was found leaking from one of the swaged joints. Subsequent X-ray radiographic examination revealed presence of a circumferential crack on the tube inside the fitting (Fig. 8). The tube in the pipe assembly was made of Ti-3Al-2.5V having 16 mm outer diameter and 1.2 mm wall thickness. The pipeline was fitted with elbow fittings made of commercial pure Ti on both the ends and swaged externally.
2.2.2. Identification of failure mechanism

Suitable cuts were made in the pipe assembly and the end fitting was removed to have access to the crack. The crack in the tube after removal of the end fitting is shown in Fig. 8(b). The crack was found to be present over 60-70% of the circumference of the tube.

Examination revealed a shallow gouge mark on the tube surface over a segment adjacent to the crack (Fig. 9). Under the stereo-binocular microscope, material removal and surface pitting, typical of fretting damage were seen in this region. The crack on the tube was pulled open for further study. The resultant fracture surface is shown in Fig. 10. Examination showed presence of a half-moon shaped region on the fracture surface, indicative of progressive crack propagation. In the half moon shaped region, well delineated beach marks were found present. Tracing back the beach marks, the crack origin was identified on the outer surface of the tube at the stress raisers resulting from the fretting damage. After initiation, the crack had propagated through the tube-wall resulting in two crack fronts, which then propagated progressively either side. Examination of the inner surface of the end fitting also showed fretting damage on the corresponding contacting region. Scanning electron microscopic (SEM) examination revealed roughness, micro-cracks, pits, and oxide particles on the damaged surface of the tube (Fig. 11). These features are typical of fretting on a metal surface. Substantial metal loss was observed in the fretted region leaving behind a depression on the tube surface in the form of a band as seen in Fig. 11(a). The undamaged area was relatively smooth and devoid of pits and/or oxide particles. The fatigue crack origin at the stress concentrator, that is, at the edge of the fretted region is shown in Fig. 9 and 11. After initiation, the fatigue crack had followed the path along this circumferential depression on the tube surface (Fig. 9).
2.2.3. Failure analysis

Fractographic study confirmed that the pipe assembly has failed by fatigue. The fatigue crack had originated on the outer surface of the tube close to the edge of one of the end fittings. The fatigue crack initiation was associated with stress concentrators on the tube surface.

Examination of the tube surface showed signatures typical of fretting damages. The loss of material due to fretting resulted in a circumferential gouge mark on the tube surface. The stress concentrators thus resulted was responsible for the premature fatigue crack initiation. After initiation, the crack had propagated progressively through the tube-wall thickness as well as along the circumferential gouge mark on the tube surface. Once the crack was through thickness, the hydraulic oil leaked out of the system resulting in hydraulic pressure drop.

Generally, in pipe assembly, bending stresses on the tubes are unavoidable. Therefore, once fatigue crack is initiated, its propagation under the fluctuating stresses superimposed with bending stresses takes place at a rapid rate. In the present case, the premature fatigue crack initiation in the tube was promoted due to fretting on the tube surface because of inappropriate swaging of the end fitting.

3. Conclusions

Investigation showed that the closeness of the fit was not adequate enough to eliminate slip between the two contacting surfaces, that is, the tube and the end fitting surfaces. It was, therefore, recommended that the process parameters be set correctly during swaging of the end fittings on to the tube of the pipe assembly.

Acknowledgement

The authors thank Director, NAL for granting permission to publish this paper. The help received from Mr. S. Mallanna for sample preparation during the investigations is gratefully acknowledged.

References