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Failure investigation of pure titanium bleed air ducts in jet fighters

Bokwon Lee [a,*], Garrett Nygren [b], Ryan L. Karkkainen [b], Jinyi Lee [c]

[a] ATRI (Aero Technology Research Institute), Korea Air Force, Ayang-ro, Dong-gu, Daegu 41052, Republic of Korea
[b] University of Miami, Department of Mechanical and Aerospace Engineering, Coral Gables, FL 33146, USA
[c] Research Center for IT-based Real Time NDT, Chosun University, Gwangju 501-709, Republic of Korea

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A B S T R A C T

This paper describes the failure investigation of in-flight failures of bleed air ducts in jet fighters. Severe rupture had occurred at the bleed air duct during the flight that had caused the emergency landing situation. The tubular duct was manufactured using commercially pure titanium. An inspection revealed that all cracks occurred in the central portion of the bleed air duct. Examination of the fractured surfaces by using electron microscopy revealed that cracks initiated at multiple corrosion pits in the inner surface of the duct and these propagated by brittle cleavage cracking with occasional areas of fatigue striations induced by in-service cyclic pressure. Fractography, chemical analysis, and metallographic analysis confirmed that brittle fracture involved the ingress of hydrogen into a duct surface. The hydrogen effectively decreased the ductility of the duct which contributed to brittle fracture. The final destructive rupture of the duct can be explained by fracture mechanics. The critical crack size and stress induced by conditions at or near the operating load were estimated based on computational fracture analysis to explore the fracture mechanism. As a consequence, a novel nondestructive inspection method has been developed to prevent such failures in future.

1. Introduction

There has been a series of in-flight failure of bleed air ducts in jet fighters. The failed air duct is a connecting tube made of pure titanium from engine bleed air to the cabin, which is used for maintaining cabin air condition, pressurization, and anti-icing. In some cases, failure of the ducts has compromised aircraft safety by damaging internal systems induced by hot pressurized gas leaking from the duct. The bleed air system is an essential component of the aircraft's environmental control system (ECS). The ducts supply pressurized hot air from the engine compressor to other subsystems. The functioning of the bleed air system plays a vital role in flight safety, ground operations, and coordination with other existing systems. Leakage in bleed air ducts has been one of the major causes of duct rupture. During operation, the duct experiences significant cyclic loading at high temperatures and pressure differentials. In addition, vibrations are induced in the duct, making the duct susceptible to crack propagation.

Among the various metallic materials suited for the ducts, titanium is preferred because of its favorable characteristics, such as high strength-to-weight ratio, corrosion resistance, good formability and appropriate mechanical properties [1].

* Corresponding author.
E-mail address: lbwzippo@gmail.com (B. Lee).

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Commercially pure titanium is indicated for application in the air distribution lines, primarily for parts requiring strength up to 205 °C and oxidation resistance up to 315 °C [2]. A number of in-flight failures of titanium pneumatic ducts, all of them associated with cracking adjacent to welds, have been described in technical literature [2,3].

Several failures of the bleed air ducts of jet fighters have been experienced in the last decade. All failures occurred in the middle of the tube located on the dorsal area while reported failures of the duct have been associated with cracking adjacent to welds. All failure cases showed identical features as shown in Fig. 1. There is a straight center portion of the crack which then bifurcated helically both forwards and backwards. This kind of "X" shape cracking is characteristic of dynamic pressure loading-driven tube failure [5]. In some cases, failures of the ducts in the dorsal area has compromised flight safety by damaging fuel lines or wirings, blowing cover panels from the aircraft, and disabling air conditioning in a cockpit and avionics system. The bleed air duct had fractured through the longitudinal direction and helically bifurcated forward and backward. In the present paper, a detailed examination of recent duct failures is described. It is concluded that crack growth in service occurs mainly by environmentally assisted cracking. Due to the severe effect on the safety of the flight, a novel non-destructive inspection (NDI) method has been developed to prevent these failures in future.

2. Failure analysis

2.1. Macro observation

This section presents the failure analysis procedure employed to identify the root cause of the duct failure in jet fighter. The overall fractured shape of the components are shown in Fig. 2. The external insulation tube was completely fractured into several fragments. The failed ducts are 50 mm in diameter with wall thickness (t) 0.45 mm, and are generally manufactured from pure titanium ASTM B265 grade 1. In service, the ducts carry pressurized air 689 kPa (100 psi), initially at 20 °C and then increasing to 295 °C. For the failure of the case C, which is the most recent failure described in detail as follows, the duct had been in service for 5244 h and routine proof pressure testing at 620 kPa had been carried out after 5039 h. In order to investigate the fractured surface at low magnification, the segment of the fracture surface which contains the center straight crack was cut off from the duct and observed using stereoscope. Fig. 3 shows the fracture surface of the straight portion of the crack in the case C. Measured length of the center crack of the case C is 28 mm. Also, the center crack sizes of case A and B (indicated in Fig. 1) are 31 mm and 29 mm, respectively. It is inferred that the crack propagation in the failed ducts are highly associated with crack propagation process in ductile metals rather than material defects. The fracture surface exhibited a rough, dull texture. In particular, it presented clearly visible steps between regions propagating from different sites on slightly different planes, which suggests multiple defects linking together. Most cracks initiated at the bottom side of the tube. Metallographic specimens were taken perpendicular to the fracture surface, at the location which approximately corresponds to the center of the straight portion of the crack (section A-A indicated in Fig. 3). This examination of cross section A-A of the fractured surface revealed the presence of multiple pits likely produced during service life. These pits served as stress raisers under cyclic operating loads. There was no noticeable evidence of macroscopic plastic deformation in the central crack. The pressurized hot gas wave traveled from right to left. As the wave propagated past the surface initial defects, the hoop stress opened the defects into a through-wall crack from inside to outside of the duct. The crack fronts

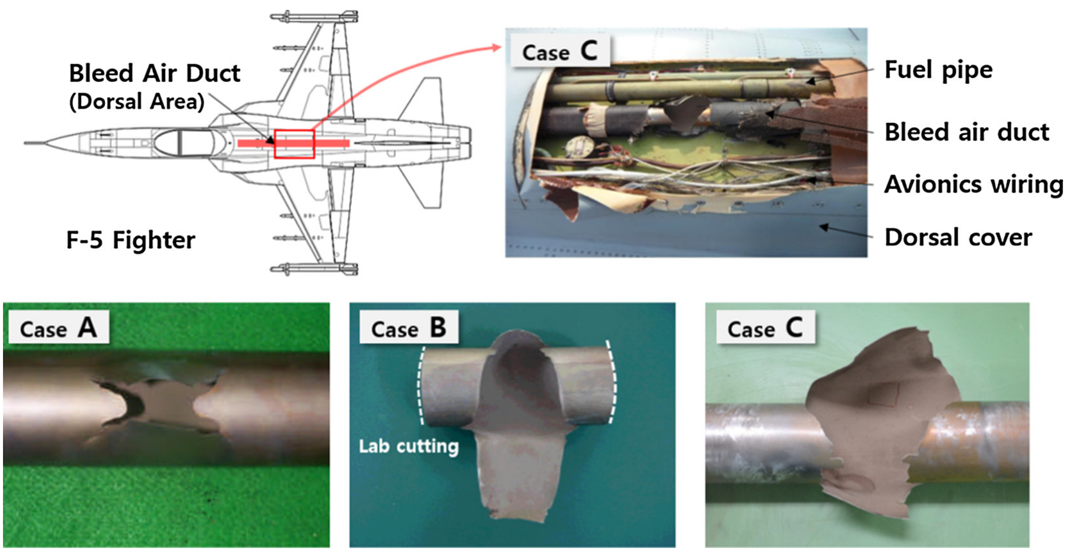

Fig. 1. Failed commercially pure titanium ducts with location of the bleed air duct.