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Failure analysis of an aircraft APU exhaust duct flange due to low cycle fatigue at high temperatures

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ABSTRACT

Considerable crack-like-defects were observed in an auxiliary power unit (APU) exhaust duct flange area in a jet aircraft with 900 cumulative flying hours. A detailed investigation of crack-induced fracture surface was conducted using Scanning Electron Microscopy (SEM) and computer aided thermal-stress analysis. The results showed that failure of the flange occurred due to the combined effects of the flange constraint and the cyclic thermal stress of the duct. The failure analysis in this study calls for the need for improvement in structure design and installation method of the APU duct system in order to reduce the damage resulting from the creep and fatigue crack during the early stages of service.

1. Introduction

An auxiliary power unit (APU) in a vehicle is a device that performs various functions except for propulsion [1]. Different types of APUs are found in aircrafts, as well as in large ground vehicles. The primary purpose of an aircraft APU is to provide power to start the main engines. A typical gas turbine APU in an aircraft consists of a jet fuel starter and an emergency power unit.

APU has a power section to generate gas and produce all the power for the shaft. It also has a duct system to guide and deliver airflow. APU exhaust duct is the final section of a duct system that allows the gas to exit the aircraft. APU exhaust duct is usually attached to the aircraft skin structure through a flange. The duct and flange are connected through brazing during manufacturing. During operation, an APU system is exposed to periodic heating environment.

A considerable amount of crack damage has been observed around the APU exhaust duct flange area in a jet aircraft after 900 cumulative flying hours. In an aircraft, the structural components and major mechanical systems have to meet the design requirements of the overall durability or design service life over several thousands of flying hours. A number of critical parts such as main engine components are subject to periodic inspections and maintenance to ensure functional integrity. The APU exhaust duct component, however, has not been categorized as a primary group that requires a periodic maintenance plan.

In this paper, visual inspection, analysis of fractorgraph, and finite element analysis have been conducted for failure analysis of the crack damaged APU. It shows that cyclic thermal stress as well as excessive mechanical constraints has contributed to the formation of fatigue cracks in the flange. It is anticipated that this study would provide confirmation of the necessity for the improvements in the design for APU.

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2. Investigation details

Visual observation of the crack-damaged area identified the crack length, its initiation location and propagation path as well as any surface topography features. Subsequently, that section was cut to expose the damaged surface induced by cracks. The fractograph was acquired using a Scanning-Electron Microscopy (SEM: Hitachi SU-70) with analytical energy-dispersive X-ray spectrometer (EDS) to further analyze and find the crack initiation location, its propagation pathway, damage types and/or overall failure characteristics. Thermal-stress analysis was conducted on the crack-damaged area to determine whether any environmental effects (heat) played a role. The overall features of the APU exhaust duct are shown in Fig. 1. APU exhaust duct has a flange, which was attached to the upper part of the fuselage structure. It has a circular type and includes guided outlet vanes that assist the gas to exit the aircraft. The figure shows cracks and damage in the flange.

3. Results and discussion

3.1. Visual inspection

Visual inspection of the damaged duct reveals cracks and chafing sites around the duct flange and its fillet as shown in Fig. 2. Two major cracks exist along the duct flange fillet as shown in Fig. 2A. The crack lengths are approximately 13 cm and 10 cm. In addition, there is considerable chafing developed on the flange (Fig. 2B), and the chafing sites are very close to crack sites.

The existence of chafing reveals that there is an extensive wear by friction between contacted surfaces of flange and the corresponding structure. Then the duct and flange were cut away to find the brazing state and its quality as shown in Fig. 2C. Brazing is a typical process for joining metals using a filler metal [2]. A careful observation of the brazing area was performed to find any defects from structures or associated filler metal. It shows that there is no considerable defect on the brazing joint and manufacturing quality of brazing may not have any connection with this failure.

A closer visual inspection of duct and lower surface of flange shows that there is a considerable discoloration around the crack as shown in Fig. 3A. The discoloration of metallic surface usually means that the part has been exposed to high temperature condition. The APU gas flows through the duct for exit and the temperature of gas reaches up to 600 °C when fully developed. Another observation is that there is a distributed trace of scratch on the lower surface of flange as shown in Fig. 3B. It has been reported from manufacturers that those scratches can be made possible during the removal process of beads that were created during brazing work. Overall visual inspection of the damaged duct shows that cracks, heat, and chafing may have an effect on the failure of APU exhaust duct.

3.2. Fracture surface inspection

Fig. 4 shows fracture surface of flange created by the crack. Visual observation of fracture surface shows that the surface is mainly divided into two parts by different crack propagation. The entire area of the upper part is much bigger than that of the lower part. In addition, a ratchet mark appears. Ratchet marks usually occur on a surface where high stress concentration is present [3]. It also means that the crack has been initiated from multiple origins [4,5]. Many crack initiation sites were found under a closer observation.

A more detailed fracture surface investigation has been conducted using the Scanning Electron Microscopy (SEM). There are creeps on the flange upper surface and fatigue crack propagations (striations) on the fracture surface as shown in Fig. 5. Creep is a slow deformation phenomenon under stress condition in solid materials below yield strength [6]. Creep damage is

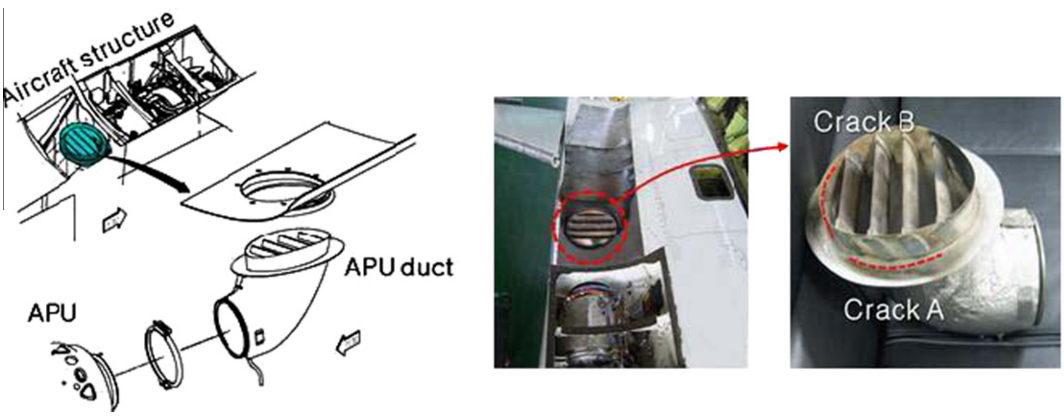

Fig. 1. Overall features of the APU exhaust duct.

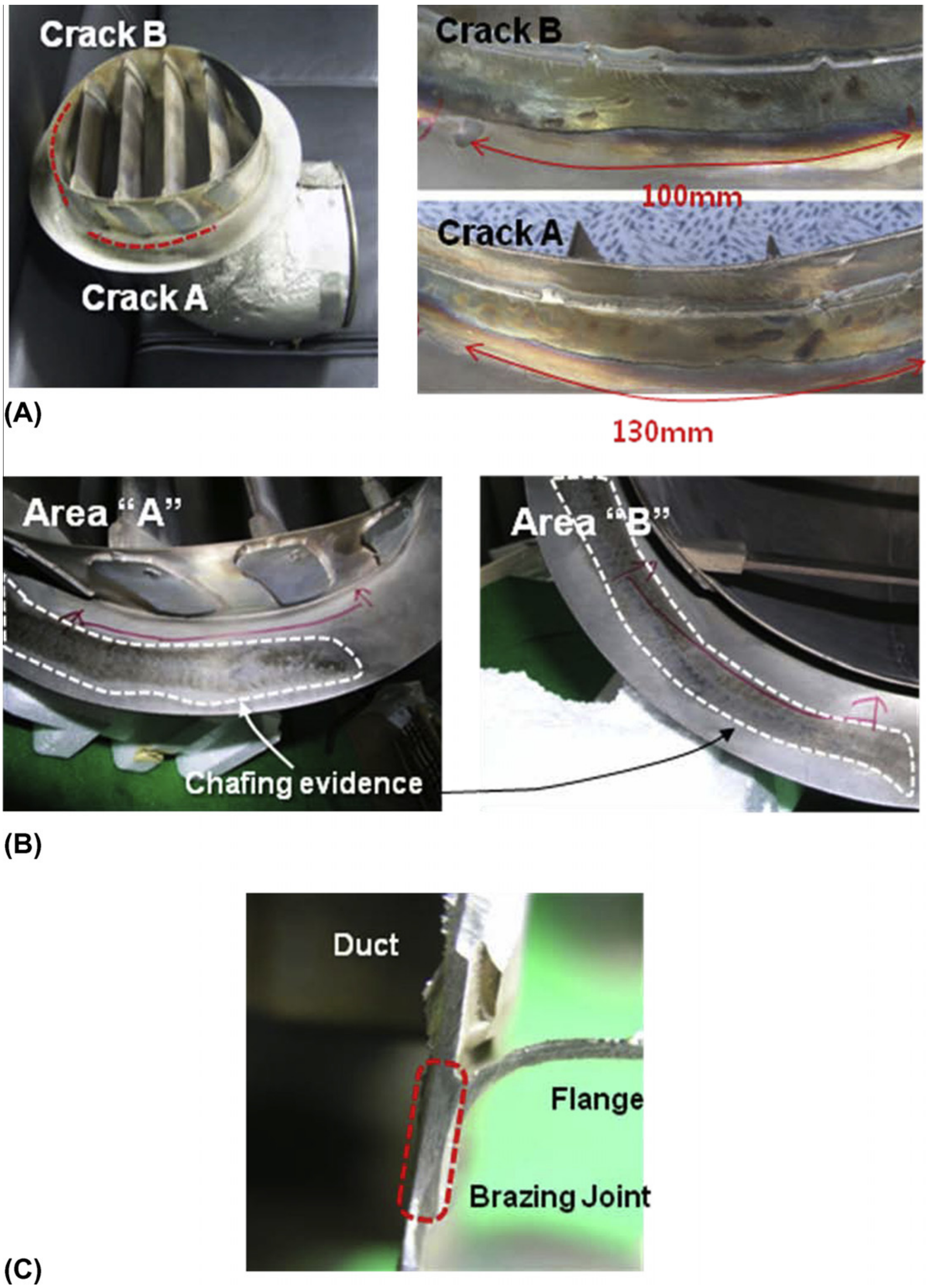

Fig. 2. Visual inspection of the failed duct (A) cracks, (B) chafing and (C) cut-away.

widely distributed on the flange surface. It implies that a uniform load has been consistently applied to induce cracking. Chafing sites, as shown in Fig. 2B, give evidence that there exists mechanical contact between two solids. It may occur during APU operation. Widely distributed chafing area and creep damage area are very close and it can be said that chafing condition is closely related to creep situation. Fracture surface in Fig. 5 clearly shows striations by fatigue. It indicates that cycle

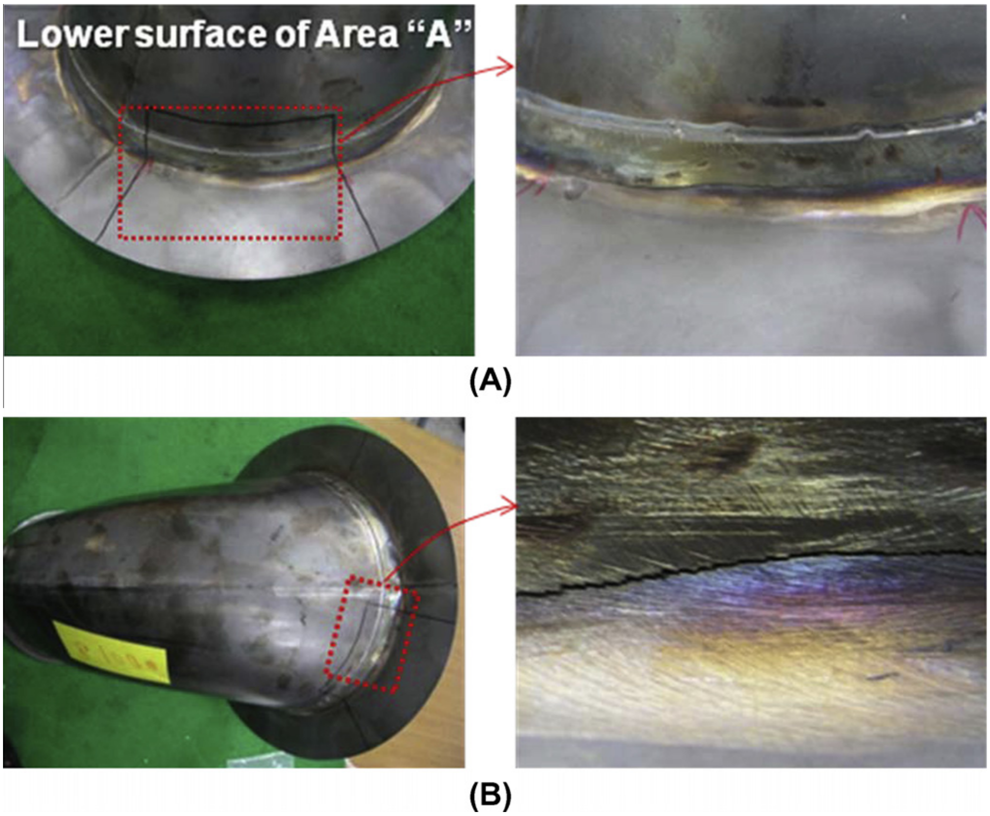

Fig. 3. Visual inspection of lower surface of the flange (A) discoloration and (B) scratches.

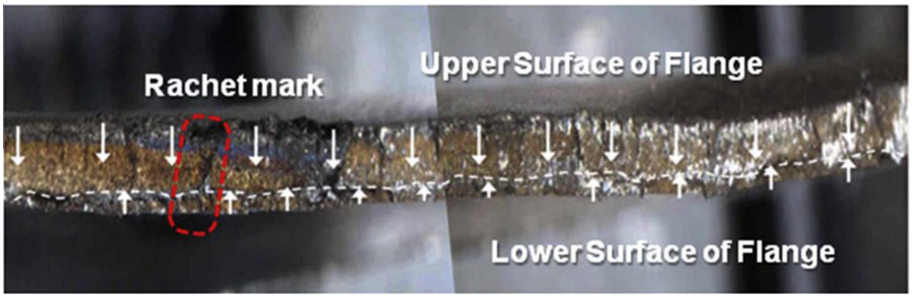

Fig. 4. Macroscopic investigation of the fracture surface.

loads were applied on the flange and that the fatigue cracking direction is from top to bottom. It also means that the fatigue cracks originated from the flange upper surface, where creep damage is found.

Fig. 6 shows scratches on the flange lower surface and fracture surface. Many scratches are widely distributed on the surface and they have arbitrary directions as shown in Fig. 2A and B. However, only two macro-scale fatigue crack initiation points can be seen in circumferential direction. It implies that the fatigue cracks are mainly induced and developed by mechanical loading and has little connection with scratches.

Striation density of fatigue crack was calculated and the result is shown in Fig. 7. Striation means a line mark left on a fatigue fracture surface as a result of the growth of the fatigue crack with one load application [7]. The striation density decreases as it becomes more distant from crack origin. Overall trend of striation density reveals a typical low cycle fatigue where stress level is relatively high. Such trends are usually dominant in plastic deformation processes [8–11]. From this point of view, it can be said that creep environment may have close relations with low cycle fatigue.

In addition, creep crack and fatigue crack formations shown in Figs. 5 and 6 look transgranular dominant in crack growth or propagation stage. Creep crack extension shows relatively beeline zigzag formations and fatigue crack fracture surfaces

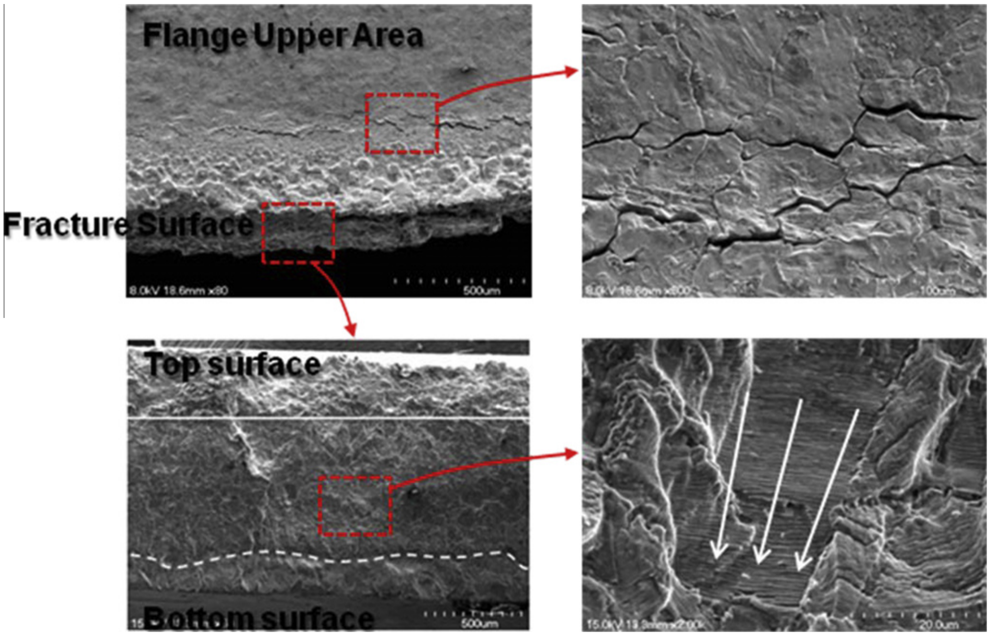

Fig. 5. SEM image of the upper surface and fracture surface.

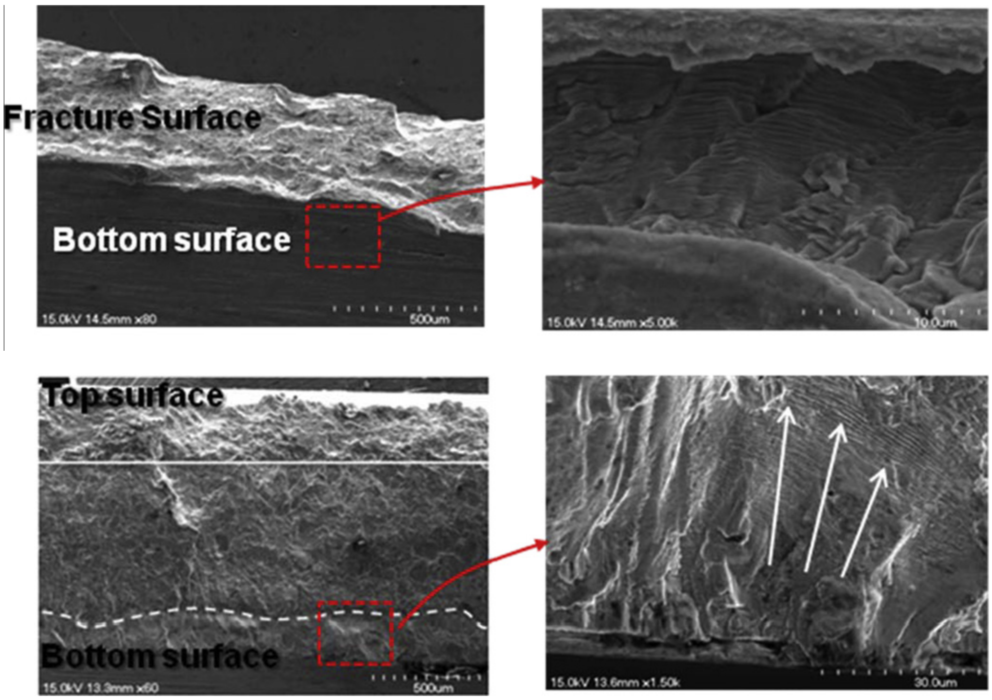

Fig. 6. SEM image of the lower surface and fracture surface.

are relatively flat and they have well defined striations. Striation density in Fig. 7 tells that there may be a typical situation for low cycle fatigue with high stress and large strain. Duct and flange material is Hastelloy X, which has good qualities for furnace applications because of its special resistance to oxidation under high temperature conditions [12,13]. Actually, the temperature of gas that flows through the duct reaches up to 600 °C when fully developed. It is reported that Hastelloy X material exhibits transgranular dominant crack growth characteristics under high temperature creep conditions [14,15].

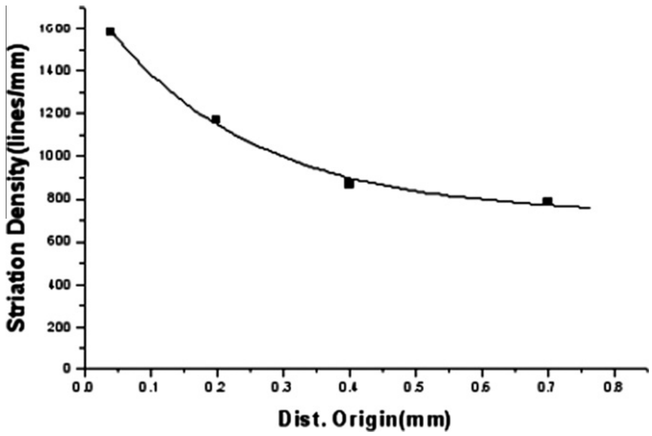

Fig. 7. Striation density of fatigue crack B.

Table 1
Material properties of Hastelloy X [16].

Temperature (°C)	*E* modulus (GPa)	Poisson's ratio	Density (g/m^3)	Thermal conductivity (W/m K)	CTE (μm/°C)	Specific Heat (J/kg K)
20	196	0.29	8.22	9.7	15.3	486
600	158			20.6	15.7	582

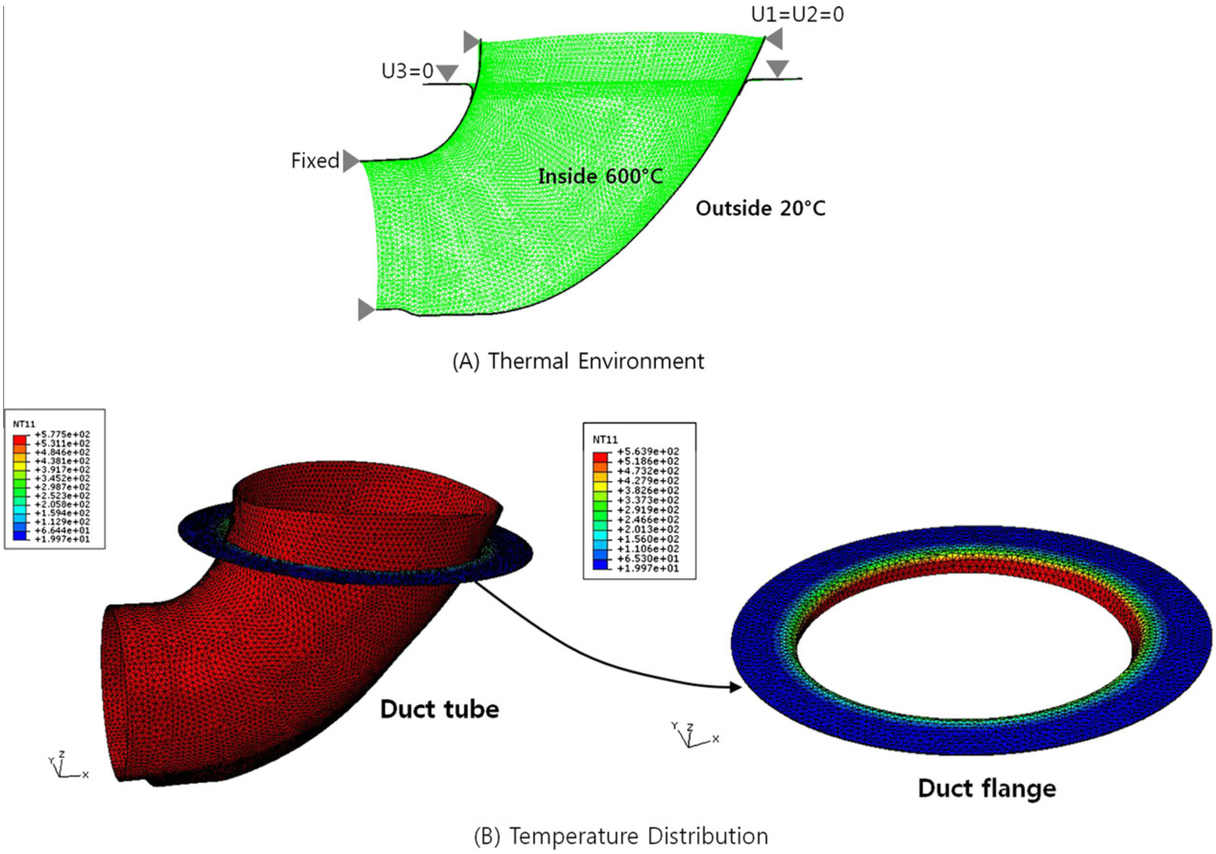

Fig. 8. Temperature profile of the APU duct (A) thermal environment and (B) temperature distribution.

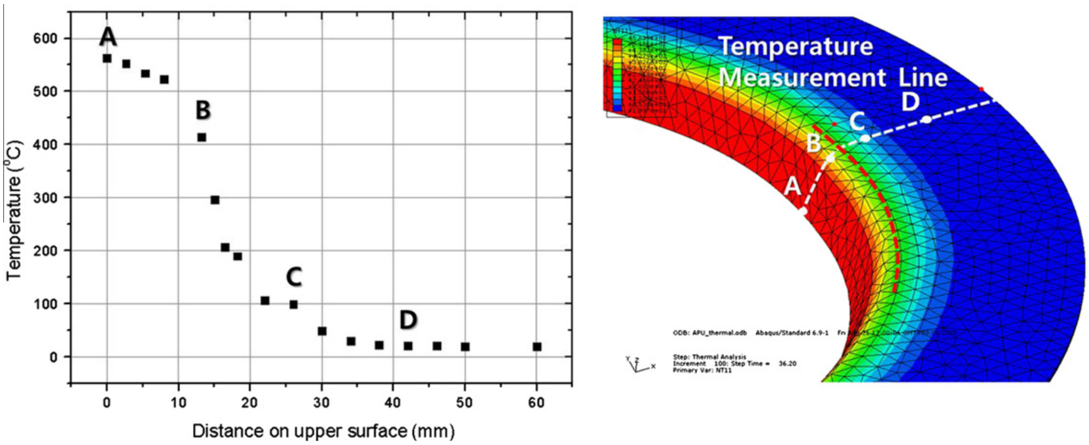

Fig. 9. Temperature distribution along the flange corner.

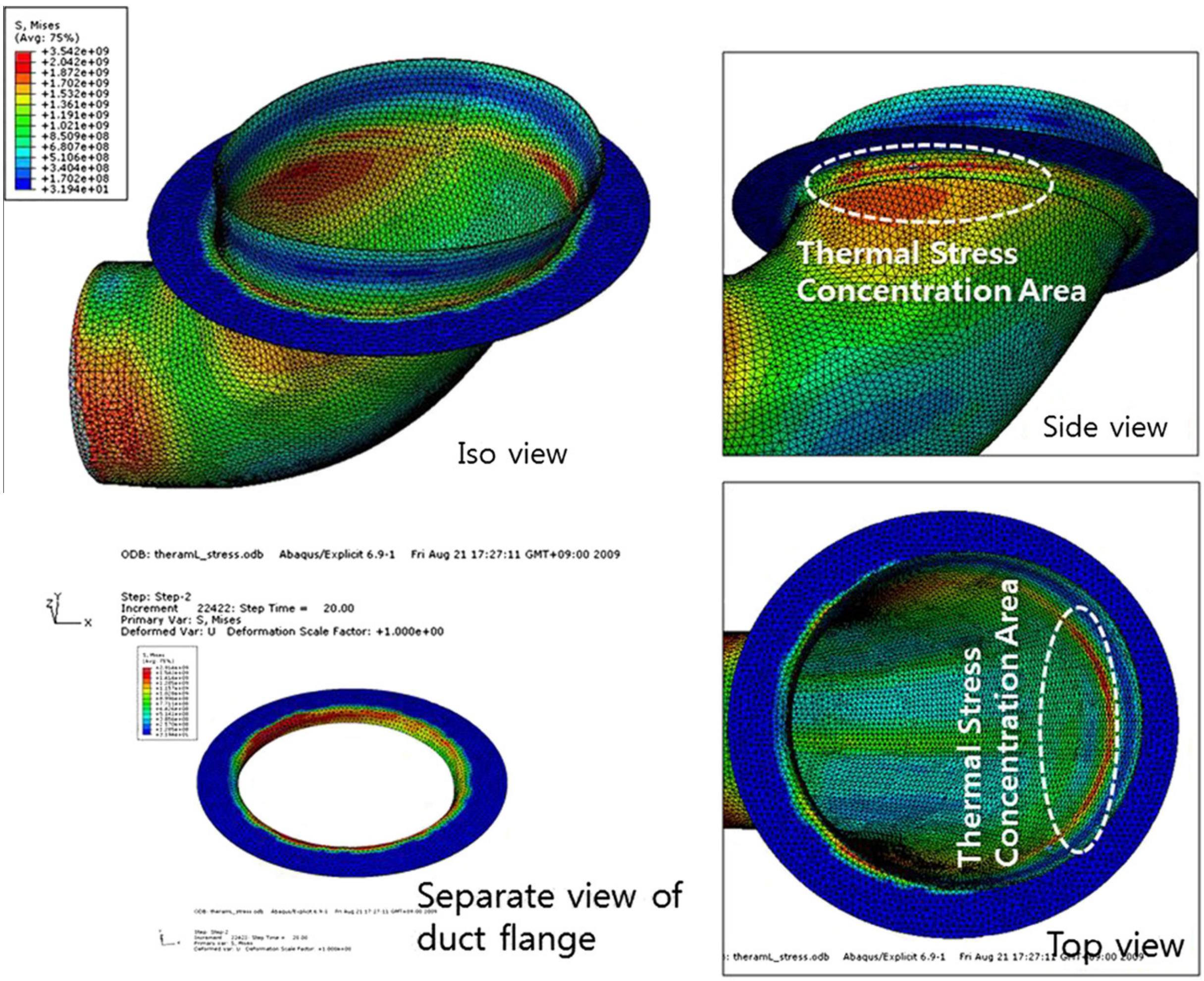

Fig. 10. Thermal stress distribution of the APU duct.

However, there might be intergranular and/or mixed mode of intergranular and transgranular crack formation during crack initiation and/or final fracture stages including rapid crack growth depending on strain range, temperature and duration hold time. More detailed study can be conducted from the metallurgical point of view.

3.3. Failure mechanism analysis

The thermal stress analysis was conducted to look into the failure and deformation behavior of the APU duct. The numerical stress analysis was performed using a FEA code, ABAQUS/standard 6.9. Table 1 shows mechanical and thermal properties of Hastelloy X [16]. The temperature field used in computational analysis was obtained from the field usage environment. A mesh convergence study was carried out to ensure the convergence of mesh model of the duct with 5% tolerance. A 4-node thermally coupled tetrahedron (C3D4T) was used and a total of 66,682 elements were used for the model.

Fig. 8 shows the boundary conditions and temperature distribution of flange under constant internal temperature of 600 °C for 10 min, which is the typical temperature of the actual exhaust gas for real running time while normal main engine's start up. Fig. 9 shows the temperature profile of flange along the calculation line (A–D). The highest temperature gradient zone ranging from 408 °C to 102 °C is located on the curved surface between point B and point C. This area is exactly corresponding to the area where actual fatigue cracking occurs. The upper surface of the flange was constrained to simulate actual installation conditions. The result shows that the temperature gradient associated with this constraint may cause thermal stress situations on the curved surface of the flange.

Fig. 10 presents von-Mises stress resulting from the temperature distribution. The result shows that the high thermal stress on the curved surface of the flange creates asymmetric stress concentration along the circumference of the flange. It is mainly due to the geometrical feature of the duct. Moreover, those stress concentration areas are identical to the location where actual damage occurred. It can be concluded that the temperature gradient caused by exhaust gas, which flows through the duct, plays a major role in raising stress on the failed structure. Also, additional mechanical stress as a result of cyclic thermal expansion associated with constraints makes subsequent contributions to fatigue crack acceleration.

4. Conclusion

The investigation and analysis of the aircraft APU duct failure showed that cyclic stress from thermal as well as mechanical environments mainly caused discoloration and creep and fatigue cracks of the flange. The exhaust gas of 600 °C, which flows inside the duct, induced thermal expansion of the duct. Operations of APU system played a role for the periodic expansion and corresponding cyclic stress. The flange that was constrained and held down by a fixed seal attached to the skin structure was exposed to creep and fatigue situations under high thermal stress. Consequently, the cracking failure of the flange occurred due to the combined effects caused by the flange constraint and the cycle thermal stress of the duct. The failure analysis in this study calls for the need for improvement in structure design and installation method of the APU duct system in order to reduce the damage resulting from the creep and fatigue crack during the early stages of service and operation.

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