Final Report

B787-9, 9V-OJF

Nose Wheel Detached During taxi

Incheon Airport, Korea

18 June 2023

TIB/AAI/CAS.222

Transport Safety Investigation Bureau
Ministry of Transport
Singapore

4 July 2024

The Transport Safety Investigation Bureau of Singapore

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Table of Contents

ABBREVIATIONS

ARAIB	Aviation and Rail Accident Investigation Board of the Republic of Korea
EDS	Energy Dispersion Spectroscopy
EICAS	Engine Indication and Crew Alerting System
FACC	Fukuoka Area Control Centre
FC	Flight cycle
FCTM	Flight Crew Training Manual
FH	Flight hour
FIR	Flight Information Region
FO	First Officer
IACC	Incheon Area Control Centre
ICN	Incheon International Airport
LH	Left hand
MRO	Maintenance and Repair Organisation
NLG	Nose landing gear
PF	Pilot flying
PIC	Pilot-in-command
PM	Pilot monitoring
psi	Pound per square inch
RH	Right hand
SEM	Scanning Electron Microscopy
SPM	Safran Standard Practices Manual
TACC	Taipei Area Control Centre

TSIB Transport Safety Investigation Bureau of Singapore

SYNOPSIS

On 18 June 2023, a Boeing B787-9 operated from Incheon International Airport, Republic of Korea to Singapore Changi Airport via Taoyuan International Airport in Taipei, Taiwan. After arrival at Taoyuan International Airport, the aircraft taxied to the parking bay. At the bay, maintenance personnel found that the left hand (LH) wheel and axle of the nose landing gear (NLG) were missing.

The missing wheel and axle were found along the aircraft's taxi route in Incheon International Airport.

The Korean Aviation and Rail Accident Investigation Board (ARAIB) classified the occurrence as an accident and delegated the investigation to the TSIB. The TSIB conducted an independent assessment of the severity of the occurrence and determined also that the occurrence should be classified as an accident.

AIRCRAFT DETAILS

Aircraft type	:	Boeing B787-9
Operator	:	Scoot
Aircraft registration	:	9V-OJF
Numbers and type of engines	:	Two engines / Rolls-Royce Trent-1000
Date and time of occurrence	:	18 June 2023 at 14:00 UTC
Location of occurrence	:	Incheon International Airport, Republic of Korea
Type of flight	:	Scheduled
Persons on board	:	11 Crew members 343 Passengers

1 FACTUAL INFORMATION

All times used in this report are in Coordinated Universal Time (UTC).

1.1 History of the flight

1.1.1 On 18 June 2023 a Boeing B787-9 operated a scheduled flight from Singapore Changi Airport to Incheon International Airport (ICN), Republic of Korea via Taipei in Taiwan. After arrival at ICN, there was a change of flight crew to operate the return flight from ICN to Singapore via Taipei. The flight crew of the ICN – Taipei – Singapore sector comprised a Pilot-in-command (PIC) and a First Officer (FO). The FO was the pilot flying (PF) and the PIC the pilot monitoring (PM).

1.1.2 A tow tug pushed back the aircraft from parking bay 108 onto Taxiway R9. Before the tow tug turned the aircraft to align it with the centreline of Taxiway R9, the headset man of the pushback team sensed that there was some resistance during the pushback. He stopped the pushback and asked the flight crew if the parking brakes had been released. The flight crew replied that the parking brakes had been released and the headset man resumed the pushback.

1.1.3 When the tow tug was turning the aircraft to align it with the centreline of Taxiway R9, the flight crew felt some vibration. To the flight crew, such vibration was not unusual during ground manoeuvring of aircraft. After the aircraft was pushed back onto Taxiway R9, the tow tug was disconnected.

1.1.4 The FO was to taxi the aircraft to Runway 34R via Taxiways R9, R21, R10, M, M5 and S (see **Figure 1**). During the taxiing, vibrations were felt by the flight crew when the aircraft was turning right from Taxiway R9 to Taxiway R21 and turning left from Taxiway R21 to Taxiway R10. At about midway along Taxiway R10, the PIC took over the taxiing of the aircraft. Thereafter, no vibration was felt by the flight crew. The PIC handed the control back to the FO and the FO performed the take-off. The take-off roll, rotation, lift-off and landing gear retraction were normal.

Figure 1: Taxi route (route in green by FO, route in amber by PIC)

1.1.5 At top of climb, the flight crew carried out an aircraft system check as required by procedure and noted a status message “tire press sys[1]”. On checking the wheel synoptic page on the aircraft’s Engine Indication and Crew Alerting System (EICAS) display, the crew noticed that the tyre pressure of both nose landing gear (NLG) tyres were not displayed. The flight crew discussed and noted that there were three possibilities:

(a) Faulty tyre pressure sensor

(b) Deflation of one nose wheel tyre

(c) Deflation of both nose wheel tyres

In view that the take-off and landing gear retraction were normal, the flight crew felt that it was likely an indication problem. The aircraft continued its flight to Taipei.

1.1.6 In the meantime, the ICN airport authority had found a nose wheel with its tyre

[1] “Tire” is “tyre” in American English. “press” is a short form for pressure and “sys” is a short form for system. During taxiing out and departure, flight crew are not expected to check for status messages such as “tire press sys”.

and debris pieces[2] along Taxiways R9, R21 and R10 and suspected that they had come from the occurrence aircraft[3]. It reported to the air traffic control tower in ICN that a tyre was found and that the tyre was suspected to have come from the occurrence aircraft. The ICN tower reported to Incheon Area Control Centre (IACC) who in turn informed Fukuoka Area Control Centre (FACC) and FACC informed Taipei Area Control Centre (TACC) that there was a tyre issue with the occurrence aircraft.

1.1.7 After the aircraft had established contact with TACC, TACC informed the flight crew that the aircraft might have a tyre issue. The flight crew asked TACC for details about the tyre issue and was subsequently informed that tyre debris were found in ICN and that the debris might have come from their aircraft. In response, the flight crew informed TACC that they had lost both nose wheel tyre pressure indications. They also considered that the worst-case scenario was deflation of both nose wheel tyres. The flight crew referred to the Flight Crew Training Manual (FCTM) but there was no guidance on landing with deflation of both nose wheel tyres. Nevertheless, they noted the FCTM guidance on “Landing on a Flat Tire”[4] and also considered the possibility of stopping on the runway.

1.1.8 The PIC took over control of the aircraft for the landing in Taoyuan International Airport in Taipei. During the approach, the flight crew took the precaution of extending the landing gears while the aircraft was over the water out of consideration that nose wheel tyre debris pieces, if any, would not fall onto populated areas. On final approach, the flight crew requested for the tower to sight the aircraft nose wheels for any anomaly. The tower replied that they were unable to do so due to limited visibility in night condition.

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[2] An aircraft saw the wheel on the taxiway and reported this to the ICN Ground Control who in turn informed the ICN airport authority.

[3] The ICN airport authority determined that, basing on the markings on the wheel, the wheel was from a Boeing B787-8/9 aircraft and that, basing on the aircraft movement record, the wheel likely belonged to the incident aircraft.

[4] The FCTM guidance on landing on a flat tyre is as follows:

(a) The aircraft is designed so that the landing gear and remaining tyres have adequate strength to accommodate a flat nose gear tyre or main gear tyre
(b) Use normal approach and flare techniques and avoid landing overweight and use the centre of the runway
(c) Use differential braking as needed for directional control
(d) In case of a flat nose gear tyre, lower the nose gear to the runway slowly and gently while braking lightly
(e) Use idle reverse thrust when runway length permits
(f) Once nose gear is down, vibration levels may be affected by increasing or decreasing control column back pressure
(g) Maintain nose gear contact with the runway.

1.1.9 According to the PIC, the touchdown was normal and he did not feel any vibration during the landing roll. The PIC requested for Taipei Ground Control to sight the exterior of the aircraft for any anomaly. Taipei Ground Control advised the flight crew that they were unable to do so due to limited visibility in night condition but that an apron vehicle would be escorting the aircraft to the parking bay.

1.1.10 The PIC taxied the aircraft into parking bay B9 without difficulty. At the parking bay, the flight crew were informed by the ground handling staff that the left axle of the NLG had sheared off and the left nose wheel was missing.

1.2 Injuries to persons

1.2.1 There was no injury to any person.

1.3 Damage to aircraft

1.3.1 Nose landing gear (NLG)

1.3.1.1 The left axle of the NLG sheared off at the inboard location but the inner spacer was still in place (see **Figure 2**). The black charred appearance of the fractured axle face at between the 6 and 8 o'clock positions indicated exposure to extreme heat.

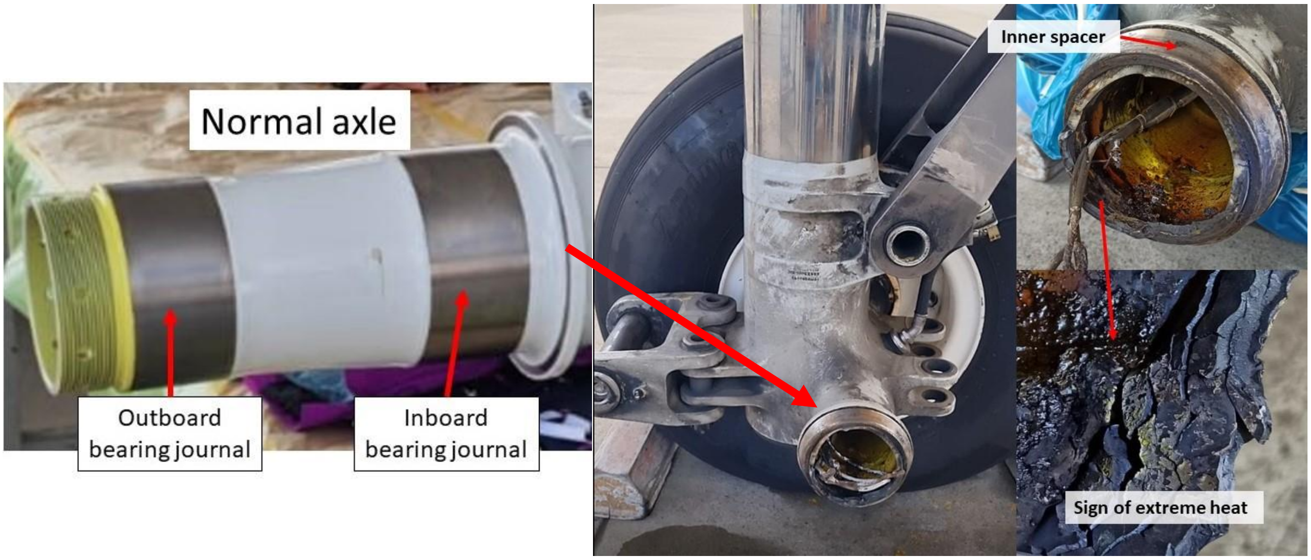

Figure 2: Sheared NLG axle

1.3.2 Left hand (LH) nose wheel and tyre debris

1.3.2.1 The LH nose wheel assembly together with the sheared outboard axle were found in ICN near the turn from Taxiway R21 to Taxiway R10. Debris pieces of the wheel's inboard bearing were also found strewn along Taxiway R9 before the turn to Taxiway R21 (see **Figure 3**). All parts of the inboard bearing were found and recovered except for the retaining clip and some rollers.

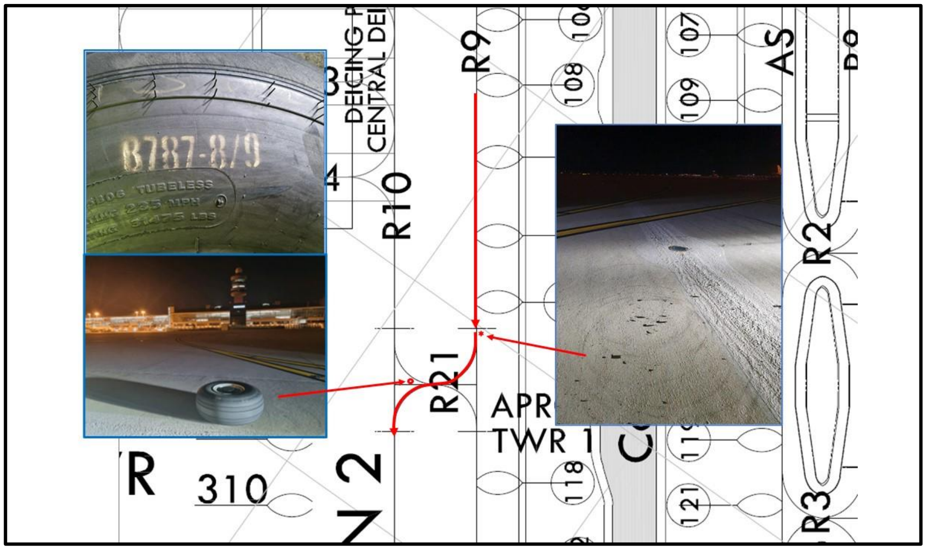

Figure 3: LH nose wheel and tyre debris location

1.3.2.2 The outboard portion of the left axle was found together with the LH nose wheel. The bundle of wires for transmitting LH and right hand (RH) tyre pressure information to the EICAS was severed (see **Figure 4**).

Figure 4: Outboard portion of the sheared off left axle with severed wire bundle

1.4 Other damage

1.4.1 Nil

1.5 Personnel information

1.5.1 PIC

Age	41
Licence type	Air Transport Pilot Licence
Issuing authority	Civil Aviation Authority of Singapore
Licence validity date	19 June 2019
Medical certificate	Class one
Medical certificate validity	Valid till 30 June 2024
Medical operational proviso	Nil
Last Base Check date	15 March 2023
Last Line Check date	20 July 2022
Total flying hours	6000 hr 00 min
Aircraft types flown	Beechcraft G58 Boeing B777 Boeing B787
Total hours on type	4778 hr 16 min
Flying in last 90 days	250 hr 18 min
Flying in last 7 days	18 hr 05 min
Flying in last 24 hours	0 hr 0 min
Duty time in last 48 hours	0 hr 57 min
Rest period in last 48 hours	47 hr 03 min

1.5.2 FO

Age	36
Licence type	Air Transport Pilot Licence
Issuing authority	Civil Aviation Authority of Singapore
Licence validity date[5]	16 December 2021
Medical certificate	Class One
Medical certificate validity	Valid till 31 December 2023
Medical operational proviso	Nil
Last Base Check date	16 March 2023
Last Line Check date	24 July 2022
Total flying hours	3012 hr 00 min

[5] Licence validity date is the date on which the licence is issued to the pilot. The licence remains valid until the expiry date of the Medical Certificate, or when the licence is suspended or revoked.

Aircraft types flown	Piper PA44 Boeing B787
Total hours on type	2811 hr 19 min
Flying in last 90 days	216 hr 41 min
Flying in last 7 days	7 hr 12 min
Flying in last 24 hours	0 hr 0 min
Duty time in last 48 hours	0 hr 57 min
Rest period in last 48 hours	47 hr 03 min

1.6 Aircraft information

1.6.1 Nose landing gear (NLG)

1.6.1.1 NLG information

Manufacturer Serial Number	37119
Total Aircraft flight hours (FH) / flight cycles (FC)	27079.73FH/6004FC
Part Number	520Z1110-502
Serial Number	S00002MP2
Time Since New / Cycle Since New	27079.73FH/6004FC[6]

1.6.1.2 Left hand wheel assembly

Wheel part number	C20598000
Wheel serial number	1811C20598
Wheel installed on aircraft date	2 June 2023
Station installed	SIN
Hours / Cycles since wheel installation	144FH/42FC
Total wheel hours / cycles since new	11933FH/2564FC
Total hour / cycle of inboard bearing (since installed on LH wheel)	9536.9FH/2291FC

1.6.1.3 The NLG assembly had been installed since the aircraft's delivery on 9 October 2015. There was no record of any hard landing since delivery.

1.6.2 Wheel bearing

1.6.2.1 A description of the wheel bearing is in **Appendix A**

1.6.3 Bearing assembly maintenance

[6] The NLG was not due for overhaul.

1.6.3.1 The wheel manufacturer's Component Maintenance Manual contained instructions relating to the maintenance of the wheel bearing assembly. At each tyre replacement in the workshop, when the wheel assembly is dismantled, the outboard and inboard bearings (see construction of the wheel halves in **Figure 5**) are to be visually inspected as follows:

(a) Check that the outer and inner bearing seals are not bent, cracked or nicked and that the rubber lips of the bearing seals are not hardened or too worn to work correctly.

(b) Check that the seal retains its dimension to work correctly.

(c) Check the bearing cups[7] that are fitted on the outer and inner wheel hub halves for presence of corrosion or damage[8].

(d) After the bearing cones are removed and cleaned (to remove the bearing grease), check the bearing cones, tapered rollers and the roller cage (see **Figure B4** in **Appendix B**) for damage[9] by rotating each roller one full revolution.

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[7] Bearing cup is shrink-fitted onto the respective hub half and is normally not removed during the workshop visit unless visual inspection finds corrosion or defects, which will require replacement.

[8] Examples of damage are sign of impact, scores, scratches, notches and nicks on the cups that are deep enough to be felt by a fingernail or tip of a ballpoint pen. When corrosion or damage is found, the bearing cup requires replacement.

[9] Examples of damage found on bearing cones are:

- Nicks and dings, discolouration, sign of wear on the inner diameter of bearing cone
- Tearing, smearing, sharp edges at the finished end of the rollers
- Roller cage that are bent, broken or worn

Surface damage that is deep enough to be felt by a fingernail or tip of a ballpoint pen is considered unsatisfactory. When damage is found, the bearing cone requires replacement.

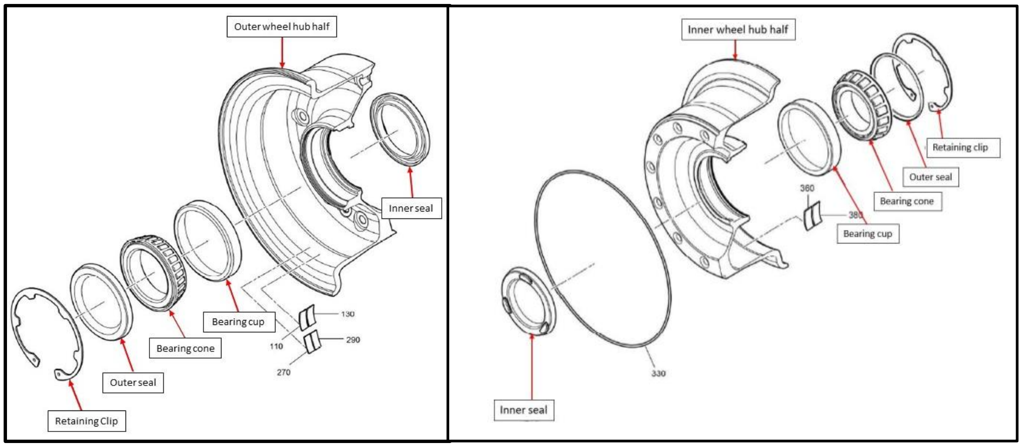

Figure 5: Nose wheel bearing construction (SPM 32-09-01 Safran Landing Systems)

1.6.4 EICAS display of tyre pressure

1.6.4.1 Tyre pressure information is displayed on the aircraft's EICAS. Information of tyre pressure on the LH and RH nose wheels is fed via a common wire bundle. If the wire bundle is severed, there will be no nose wheel tyre pressure information in the EICAS and both nose wheel tyre pressure indications on the Wheel synoptic page will show blank. A status message of "tire press sys" will be generated but there will be no associated alert.

1.6.5 Maintenance history

1.6.5.1 The LH and RH nose wheels were installed by a maintenance and repair organisation (MRO) in Singapore on 2 June 2023. The same set of maintenance crew from the MRO carried out the installation work. The LH nose wheel was installed first, followed by the RH nose wheel.

1.6.5.2 Following the occurrence, the breakaway torque of the RH nose wheel axle nut was checked on site in Taipei in an attempt to estimate the tightening torque that had been applied during the installation on 2 June 2023. However, the wheel manufacturer stated that a breakaway torque measurement is not relevant and is not representative of the tightening torque. The wheel manufacturer does not have a method for determining the torque value that the axle nut has been tightened at the time of wheel installation.

1.7 Flight recorders

1.7.1 The flight data recorder (FDR) was downloaded and contained 25 hours of recording, covering six flights (including the occurrence flight). The recorded data of the event did not indicate any anomaly that could be associated with the shearing of the left axle. In particular, there was no evidence of any excessive de-rotation of aircraft during landing that could have resulted in the NLG experiencing excessive forces.

1.7.2 The cockpit voice recorder was downloaded and contained two hours of recording. However, only the voice recording for the phase of flight from cruise to landing was available.

1.8 Tests and research

1.8.1 A preliminary microscope examination of the sheared-off surface of the NLG left axle by the Aviation and Rail Accident Investigation Board of the Republic of Korea (ARAIB) revealed ductile fracture at the sheared-off surface with small traces of fatigue failure. There was no evidence of corrosion.

1.8.2 For an in-depth examination, the NLG inner cylinder, sheared axle, LH nose wheel (together with its tyre) and parts of the inboard bearings were sent to the aircraft manufacturer's test facility for metallurgical examination.

1.8.3 The aircraft manufacturer provided the investigation team with a report on its examination and a summary of the report is in **Appendix B**. Below are significant points from the examination report:

(a) The axle was lubricated using the correct type of grease for the axle keyway, outboard bearing, and inboard spacer of the sheared axle.

(b) The correct type of corrosion inhibiting compound was used on the inner diameter of the axle. There is no evidence of corrosion on the sheared axle.

(c) The deep roller bearing indentations (parallel to the inner race) on the cone (inner race) of the damaged inboard bearing were consistent with the bearing having experienced high point load with forces exceeding design expectations.

(d) Nital etch inspection of the sheared LH axle cross section at the fractured location revealed the presence of under-tempered martensite (UTM) and over-tempered martensite (OTM), indicating exposure to high temperature due to the heat generated by the seized inboard bearing.

(e) Barkhausen inspection was performed on the sheared LH axle outboard segment's outer diameter. The Barkhausen readings indicated that the surfaces outboard of the inboard journal experienced overheating that would alter the residual stress condition of that area.

(f) The cadmium plating on the inner diameter of the sheared LH axle was found to have melted and re-solidified close to the location of the fractured face with burnt primer.

(g) The fractured surfaces were examined using Scanning Electron Microscope (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). The SEM confirmed the presence of cadmium on the fracture faces and that the failure of the axle was due to intergranular fracture. Cadmium was also found present within the intergranular cracks. This confirmed that the intergranular fracture was a result of cadmium embrittlement.

1.8.4 The wheel manufacturer observed the followings:

(a) The damaged inboard bearing cone (inner race) had several light roller indentations which were at a slight angle (i.e. not fully perpendicular) to the inner race and also a deep roller indentation that was perpendicular to the inner race (see **Figure 6**). The wheel manufacturer opines that the light roller indentations were likely due to skewing of some rollers which were grinding against the inner race during operation, resulting in excessive heat being generated and causing the degradation of the inner race's hardness, and that the single deep indentation was likely due to a subsequent static load on the bearing. The rollers were found deformed and elongated. There was evidence of bearing seizure with signs of overheating on the inboard bearing cone, cup and remaining rollers.

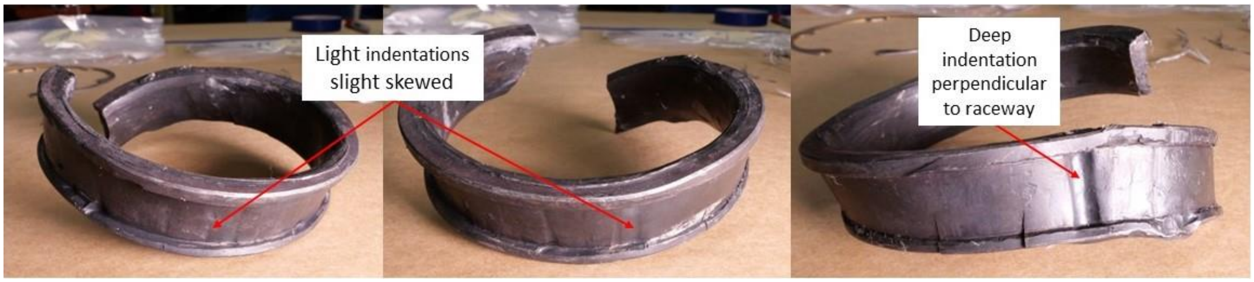

Figure 6: Several light skewed indentations and a deep indentation on inboard bearing cone

(b) There were light traces of corrosion (pitting) on the outboard bearing cup, which were discovered after the layer of grease on the bearing cup was cleaned off.

(c) There was damage on the outboard bearing, indicating that the outboard bearing had been exposed to stress concentration and that it had likely been operated with excessive end play.

1.9 Additional information

1.9.1 Observation by previous flight crew

1.9.1.1 The aircraft had earlier operated the Singapore-Taipei-ICN flight. The flight crew of this flight shared with the investigation team that, after landing at Taoyuan International Airport and while taxing into the parking bay, they heard a scrubbing noise when the aircraft was about 15 metres from the docking position. The flight crew said that the scrubbing noise was similar to the noise made when a wheel skidded over painted strips on a wet tarmac but they could not identify which landing gear the sound was from. As it was dry outside, the flight crew thought that the aircraft might have taxied over some oil spills and reported to the engineer. As the scrubbing noise did not appear to be associated with an aircraft defect, the flight crew did not make any entry in the technical logbook. The engineer inspected all the aircraft landing gears and wheels and did not find any anomaly nor any trace of oil. According to the flight crew, the subsequent take-off from Taipei and landing in ICN were normal. Nevertheless, the flight crew verbally informed the engineer in ICN about the scrubbing noise in Taipei. The engineer in ICN inspected all the aircraft landing gears and wheels and he also did not find any anomaly[10].

1.9.1.2 The engineer in ICN informed the new set of flight crew that was to operate the ICN-Taipei-Singapore flight of the scrubbing noise reported by the previous flight crew and that he had inspected all the landing gears and wheels but did not find any anomaly. The flight crew reviewed the aircraft logs and checked that the aircraft system synoptic displays and status messages were normal. The FO then conducted an external walkaround visual check of the aircraft and he also did not find any anomaly with the landing gears and wheels.

1.9.2 Landing with a missing wheel

1.9.2.1 The aircraft manufacturer's FCTM had guidance on landing on a flat tyre but none on landing with a missing wheel. The aircraft manufacturer indicated to the investigation team after the occurrence that the NLG was designed with redundancy such that landing with one nose wheel missing could be handled just like when there was a deflated nose tyre.

[10] The engineer recalled that no landing gear or wheel components were missing. He was sure that the LH nose wheel retaining clip was in place because he had noticed the shininess of this retaining clip as compared with the RH nose wheel retaining clip which was covered with grease.

2 ANALYSIS

When the left axle of the NLG was sheared off, the wire bundle that transmitted tyre pressure data to the Brake System Control Unit was also severed. The loss of data was logged on the EICAS as a status message without any advisory to alert the flight crew. The flight crew only became aware when they reviewed the EICAS system after aircraft reached the top of climb.

The investigation looked into the following:

(a) Failure of LH nose wheel inboard bearing

(b) Corrosion on bearing cup

(c) Landing with only one nose wheel

(d) Setting a life limit on bearing

2.1 Failure of LH nose wheel inboard bearing

2.1.1 The investigation team explored the following two scenarios:

(a) On the one hand, as mentioned in paragraph 1.8.3(c), the aircraft manufacturer opined that the deep indentation that was perpendicular to the inner race was consistent with a high point load that exceeded design expectations. This deep indentation could have subsequently caused skewing of the rollers which resulted in the seizing of the inboard bearing[11].

(b) On the other hand, as mentioned in paragraph 1.8.4(a), the wheel manufacturer observed that the damaged inboard bearing cone (inner race) had several light roller indentations which were at a slight angle (i.e. not fully perpendicular) to the inner race. The wheel manufacturer

[11] However, the maintenance record for the incident aircraft did not show any instances of hard landing since the installation of the nose wheel on 2 June 2023. As regards the possibility that the high load point was caused by excessive de-rotation of aircraft during landing, the aircraft manufacturer reviewed the FDR data but could not find any instance of excessive de-rotation. It has to be noted, however, that only the last 25 hours of data in the FDR was available for the review.

concluded that some of the rollers were already skewed[12] at a slight angle before the occurrence. These skewed rollers had not been rotating squarely on the inner race, and had been grinding the inner race during taxiing, take-off and landing which generated excessive heat and softened the inner race material. The deep indentation that was perpendicular to the inner race was occasioned by a static load after the inner race material had been softened. This led to the seizure and eventual inboard bearing failure.

2.1.2 The aircraft manufacturer and the wheel manufacturer had different opinion as to the cause of the skewing of the rollers. The investigation team is unable to determine the cause of the skewing but note that both the aircraft manufacturer and the wheel manufacturer shared the view that there was seizure of the inboard bearing.

2.1.3 The investigation team opined that the sequence of failure events leading to the shearing of the left axle of the NLG is as follows:

(a) The seizure of the inboard bearing led to the generation of high heat owing to friction experienced during taxing, take-off and landing.

(b) The high temperature affected the microstructure of the base material at the fractured area of the sheared axle. The heat also caused the cadmium plating in the inner diameter of the sheared axle to melt. The melted cadmium migrated into the grain boundary of the base material causing cadmium embrittlement, thus resulting in intergranular fracture of the axle.

2.1.4 As regards the possibility of bearing defects not having been picked up by visual inspection of the bearing during wheel maintenance, the investigation team noted that the wheel manufacturer's inspection instructions in paragraph 1.6.3.1 are representative of the industry's standard practice in roller bearing inspection. The investigation team also noted that there are challenges in visual inspection in that, given the limited access of the inner race surfaces (see **Figure 7**), an inspector's ability in spotting defects may be subjected to human factors, which could give rise to inconsistent inspection outcome. The

[12] However, the wheel manufacturer was not able to identify the cause of the skewing. As regards the possibility that the nose axle had been subjected to over-torquing during wheel installation, which could compress and skew the cages of the outboard and inboard bearings, and cause skewing of the rollers, the investigation team opines that this is unlikely in view that the LH nose wheel outboard bearing's cage did not show any sign of skewing. The inner bearing's cage was badly damaged and cannot be ascertained if it was skewed.

investigation team believes that there is value in the development of a suitable non-destructive testing (NDT) method to enhance the robustness of the inspection of bearings in addition to visual inspection. There may also be value in imposing a life limit on the bearing assembly to enhance bearing reliability. However, according to the wheel manufacturer, such an NDT method is difficult to be developed.

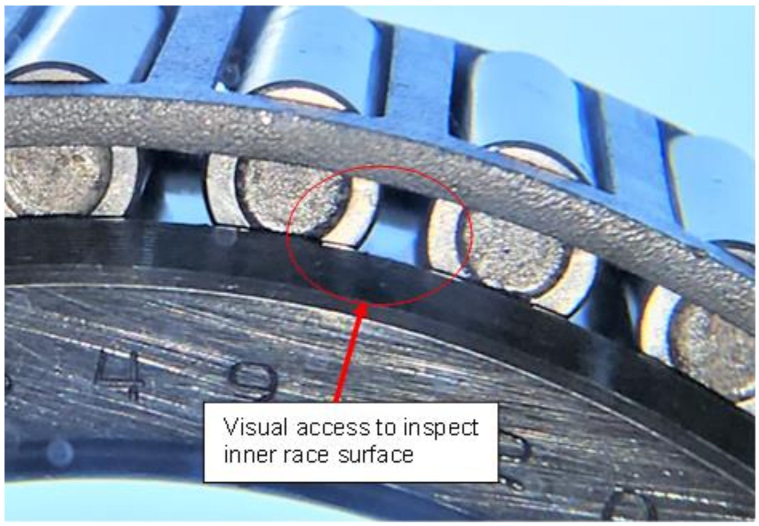

Figure 7: Inspection of inner race surfaces

2.2 Corrosion on bearing cup

2.2.1 During the laboratory inspection, light traces of corrosion (pitting) were found on the outboard bearing cup (see **Figure B6** in **Appendix B**) after the layer of grease on the bearing cup was cleaned off. The investigation team noted the following possibilities but is unable to determine the cause of the corrosion:

(a) The corrosion could have developed between the time the LH wheel was detached from the aircraft and the time it was inspected at the aircraft manufacturer's laboratory. Even though the bearing cup area was smeared with a layer of grease, air and moisture could still have come into contact with some part of the cup surface to start the corrosion.

(b) The corrosion could have occurred prior to the shearing of the axle, due possibly, as suggested by the wheel manufacturer, to inappropriate storage condition during maintenance or storage before it was installed on the aircraft.

(c) The corrosion could also have occurred in service while the wheel was installed on the aircraft and exposed to the elements during operations.

However, the corrosion on the outboard bearing cup could not have caused the inboard bearing failure.

2.3 Landing with a missing wheel

2.3.1 There was no guidance from the aircraft manufacturer on handling a landing with a wheel missing. The aircraft manufacturer indicated to the investigation team after the occurrence that handling a landing with one nose wheel missing was similar to handling a landing with one nose wheel tyre deflated. However, this information was not documented anywhere. There was no evidence that the flight crew of the occurrence flight and the operator were aware of this similarity nor that the operator's pilots had dealt with such a situation in their training.

2.3.2 In order for pilots to be better informed and guided, it is desirable that this information is made available to them.

2.4 Setting a life limit on bearing

2.4.1 According to the wheel manufacturer, the serviceability of the bearing is based on condition of the bearing. As mentioned in paragraph 2.1.4, there are challenges in visual inspection of the bearing in that, given the limited access of the inner race surfaces, an inspector's ability in spotting defects may be subjected to human factors, which could give rise to inconsistent inspection outcome. In view of this, the investigation team felt that setting a life limit on a bearing could be another level of defence against premature bearing failure due to any undetected bearing defects, particularly for a bearing that has accumulated a high number of landings.

2.4.2 However, the wheel manufacturer opined that setting such a limit would be challenging for operators, maintenance organisations and the wheel manufacturer. The bearing manufacturer was also of the same view as the wheel manufacturer, considering that the serviceability of bearing is based on condition assessed during every wheel shop visit and the criteria for assessment in the wheel manufacturer’s component maintenance manual are conservative, requiring the replacement of the bearing or bearing part whenever a defect is detected.

3 CONCLUSIONS

From the information gathered, the following findings are made. These findings should not be read as apportioning blame or liability to any particular organisation or individual.

3.1 The aircraft was operated in accordance with standard operating procedures by the flight crew.

3.2 The aircraft's NLG axle sheared off at the inboard journal location during taxiing in ICN to the take-off runway. The flight crew were not aware of this, and the aircraft took off to Taipei.

3.3 Prior to landing in Taipei, the flight crew was advised by TACC of a possible tyre issue. It did not occur to them that the aircraft had only one nose wheel for the landing in Taipei.

3.4 The aircraft manufacturer indicated that the NLG was designed with redundancy such that landing with one nose wheel could be handled just like when there was a deflated nose wheel tyre.

3.5 While the aircraft manufacturer indicated that landing with a nose wheel missing is similar to landing with a deflated nose tyre, this piece of information is not documented anywhere for the awareness of flight crew.

3.6 There were no injuries to the crew and passengers nor damage to properties other than the nose landing gear axle. The safety of flight was not affected due to the redundancy in design of the nose landing gear.

3.7 There was no evidence of over-torquing of the LH nose wheel during installation.

3.8 Results of metallurgical examinations suggest that the LH nose wheel inboard bearing had seized. This seizure resulted in the generation of high heat and eventually intergranular fracture of the LH axle. The seizure was likely due to roller skewing. However, the cause of the rollers skewing could not be determined.

3.9 Visual bearing inspection is subjected to human factors in the inspectors' ability to spot defects, in particular defects on the inner race surface, given the limited access. This can result in inconsistent inspection outcome.

3.10 The investigation team could not establish the cause of corrosion found on the outboard bearing cup. However, the corrosion was not the cause of the inboard bearing failure.

4 SAFETY ACTIONS

Arising from discussions with the investigation team, the organisations has/have taken the following safety action.

4.1 Following the occurrence, the operator performed a B787 fleet wide nose wheel installation check to inspect the nose wheel axles for signs of heat damage and verify that the spacer and the tang washer are installed.

4.2 The maintenance and repair organisation that provided maintenance support for the aircraft operator has, after this occurrence, issued a Quality Notice to remind all certifying personnel to:

(a) require them to record the torque value applied during wheel installation

(b) remind them of the importance of documenting applied and measured values involved in maintenance tasks.

5 SAFETY RECOMMENDATIONS

A safety recommendation is for the purpose of preventive action and shall in no case create a presumption of blame or liability.

It is recommended that:

5.1 The aircraft manufacturer consider documenting the information that pilots' handling of a missing nose wheel during landing is similar to their handling of a deflated wheel. [TSIB RA-2024-002]

5.2 The wheel manufacturer review and improve the bearing inspection guidance to foster consistent inspection outcome. [TSIB RA-2024-003]

5.3 The maintenance and repair organisation review its procedure to protect bearings against corrosion during maintenance or storage. [TSIB RA-2024-004]

Appendix A

Description of wheel bearing

(1) The wheel bearing is made up of four parts (see **Figure A1**)

(a) Bearing cup or outer race

(b) Cone or inner race

(c) Tapered rollers (33 tapered rollers for inboard bearing and 34 tapered for outboard bearing)

(d) Roller bearing cage

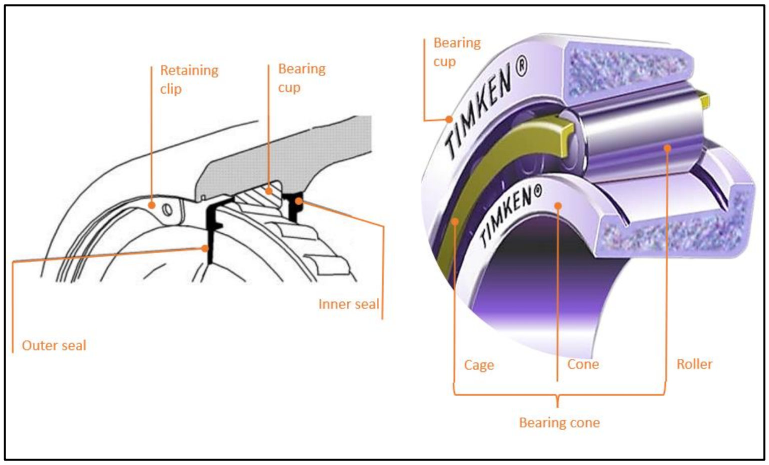

Figure A1: Wheel bearing cross-section

(2) The bearings are precision components that are used on wheels for aircraft landing gear system to support heavy loads at high speed. The bearing cone is installed in the bearing cup, and the bearing cup (outer race) is tight fitted in the half-wheel hub. The bearing cone facilitated rotation movement of the roller bearings that were held in place onto the cone (inner race) by the roller cage. Tapered rollers bearings are used because it carried combined radial and thrust loads.

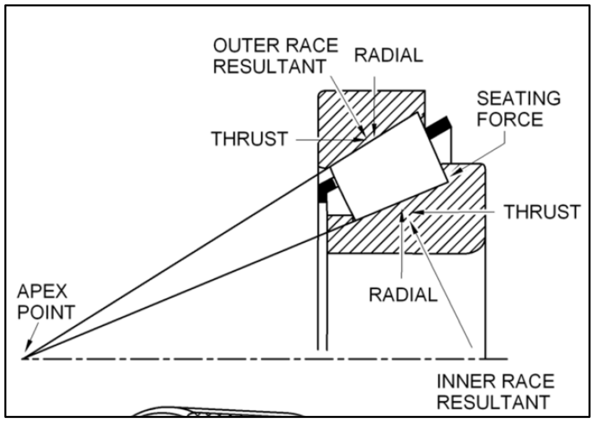

Figure A2: Bearing construction (SPM 32-09-01 Safran Landing Systems)

(3) The bearing seals (inboard and outboard) will keep the bearing grease inside to ensure correct lubrication of the bearing parts and to protect bearing parts from external contamination such as water, particles and dust. The seal and retaining clips on the wheels keep the bearing in their position while pending for wheel mounting on the aircraft axle.

APPENDIX B

Summary of laboratory examination by aircraft manufacturer

(1) The NLG inner cylinder sheared axle and parts of the inboard bearing were sent to the aircraft manufacturer's test facility for metallurgical examination.

(2) The outboard bearing cone (see Figure B1) that was recovered together with the detached LH nose wheel was disassembled and visually inspected. Signs of damage were found on a number of roller bearings (see Figure B2). Damaged marks were found on the cone (inner race) (see Figure B3). Roller cage pockets were found with wear marking caused by roller movements (see Figure B4).

Figure B1: Outboard Bearing Cone

Figure B2: Damage on outboard bearing rollers

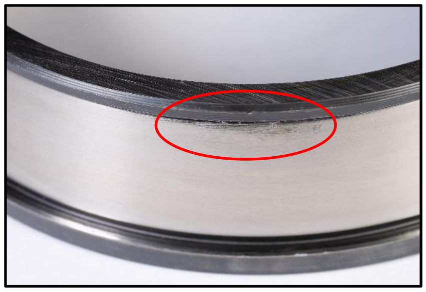

Figure B3: Markings on the cone (inner race)

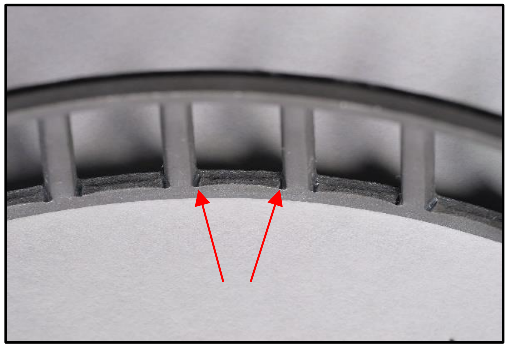

Figure B4: Cage pocket with markings

(3) The aircraft manufacturer performed the following examination on the components recovered:

(a) Visual inspection

(b) Grease and fluid samples taken for test

(c) Nital etch inspection[13]

(d) Barkhausen Noise Analysis[14]

(e) Scanning Electron Microscopy (SEM) and Energy Dispersion Spectroscopy (EDS)[15]

(f) Hardness testing

[13] Nital etch inspection – can determine if overheating has occurred in a part (after final heat treatment) by abusive machining or grinding, or in service that will adversely affect the required properties of the part in question by looking at the grain structure changes due to heat damage.

[14] Barkhausen inspection – to measure noise signal induced by ferromagnetic material due to the impact of heat damage.

[15] Electron microscope that produces image of sample by scanning the surfaces with a focused beam of electrons. SEM instrumentation is equipped with EDS system to perform qualitative analysis of sample material.

(4) The axle was cut off on from the inner cylinder assembly to facilitate examination of the separated LH axle.

(5) Observation from the visual inspection of the separated LH axle

(a) Axle fracture location was at the inboard journal.

(b) Inboard bearing cone (inner race), cage and rollers sustained significant deformation. The cone (inner race) was found with an indentation of a roller bearing. This damage is known as brinelling. (See **Figure B5**) Manufacturer's bearing expert opined that the brinelling marks are consistent with the bearing having experienced high point loading with forces that exceeded design expectations.

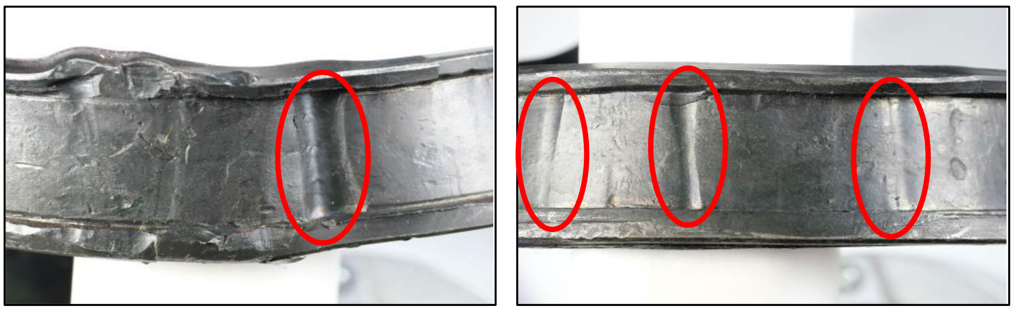

Figure B5: Brinelling marks on inboard bearing cone (inner race)

(c) Heat damage was observed on the outer diameter of the axle extending outboard from the inboard journal with burned off and heat tinted enamel on outboard area of the inboard journal.

(d) Secondary cracks were found along the entire circumference of the axle on the both the inner and outer diameter of axle with most severe cracking found at the bottom of the axle. The axle was deformed with the inboard journal surface bending upwards. (See **Figure B6**)

(e) The primer paint in the inner diameter of the axle was discoloured due to exposure to heat. The cadmium plating on the inner diameter were found to have melted and re-solidified closed to the location of the fractured face with burnt primer. (See **Figure B7**)

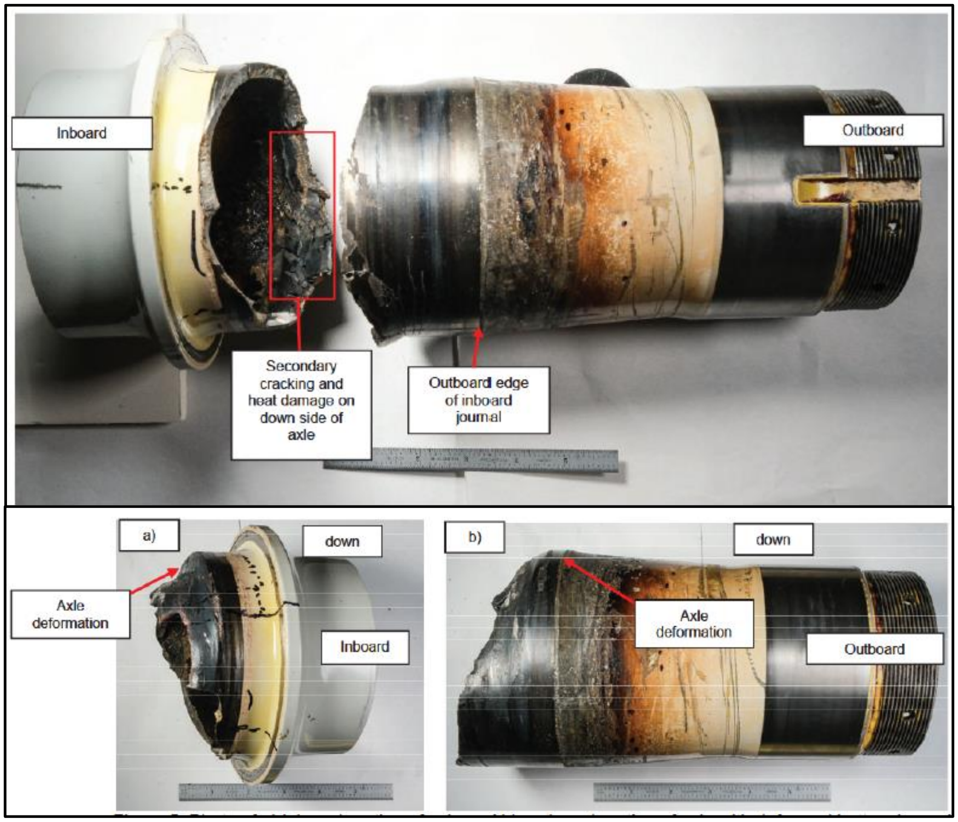

Figure B6: Fracture NLG axle

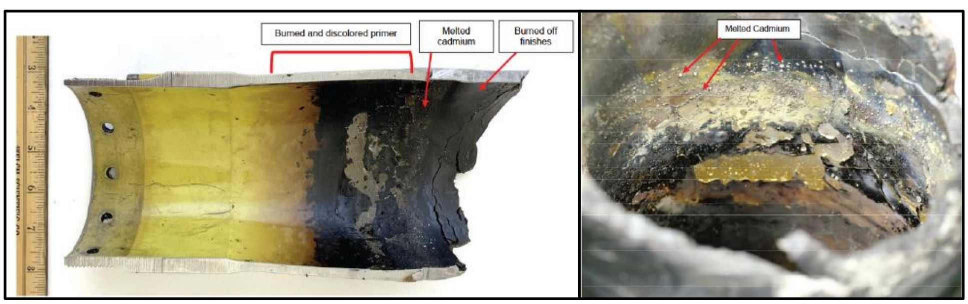

Figure B7: Discoloured and burnt primer with traces of melted cadmium

(6) Grease samples taken from the separated axle keyway, outboard bearing, inboard spacer were chemically analysed, and the grease found to be consistent and matched the type of grease specified by aircraft manufacturer. Corrosion inhibiting compound sample collected from the inner diameter of the axle was found to be consistent match the type of compound specified by the manufacturer.

(7) Barkhausen inspection was performed on the separated LH axle outboard segment's outer diameter. The Barkhausen readings indicated that the surfaces outboard of the inboard journal experienced overheating that has altered the residual stress condition of that area.

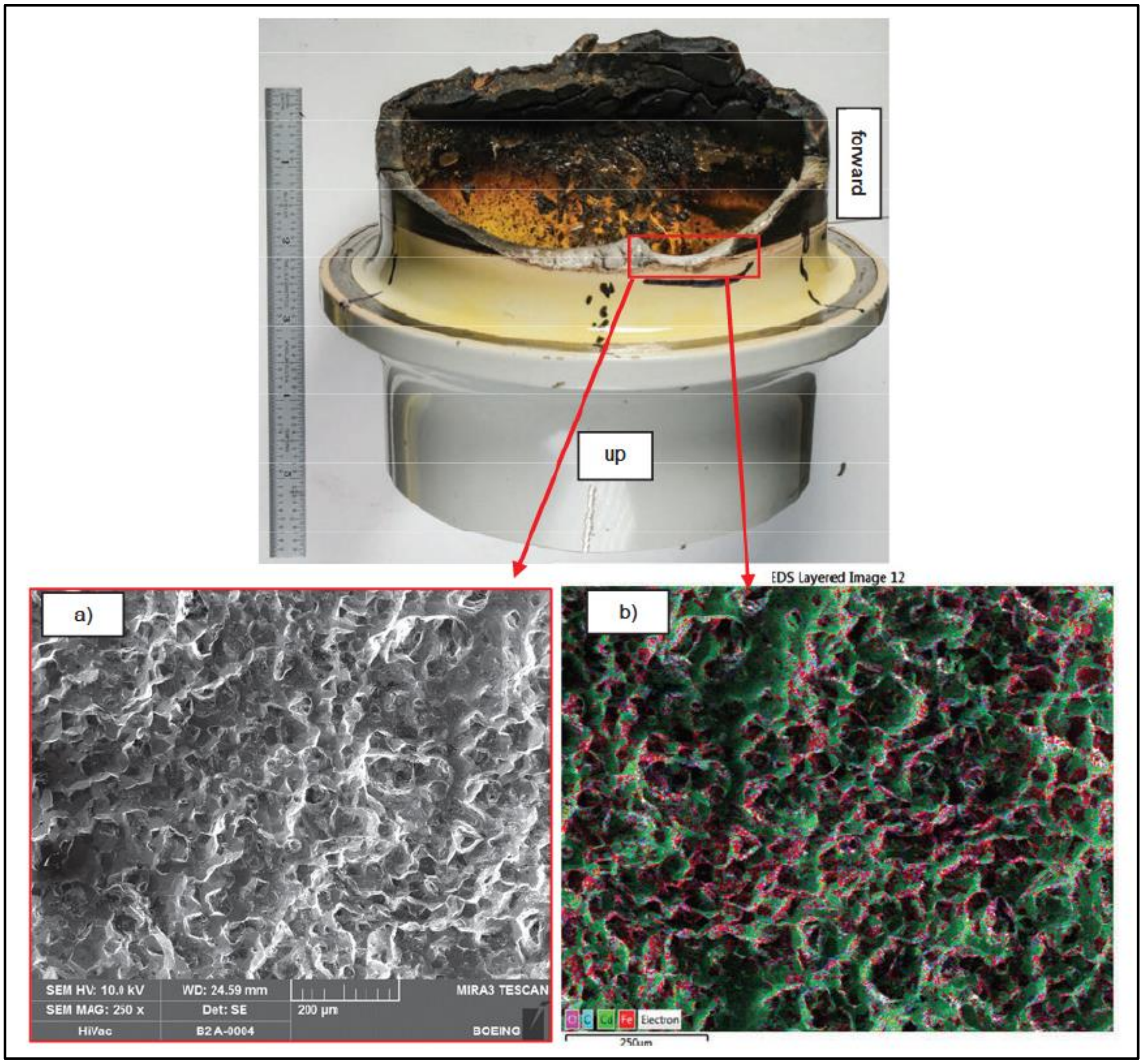

Figure B8: SEM image of fractured surface (near to top of separated axle) with cadmium covering the surface

(8) The inboard portion of the separated LH axle was sectioned, and the fracture surfaces examined by using Scanning Electron Microscope (SEM) and Energy dispersive x-ray spectroscopy (EDS). SEM and EDS examination of fracture surfaces from top, bottom, and forward sections of the axle confirmed the presence of cadmium on the fracture faces. The fractured faces were fully covered by cadmium. A section was taken from the forward part of the axle and cadmium was removed from the fracture face in order to reveal the underlying fracture microstructure. The SEM confirmed that the topography was consistent with intergranular fracture. The presence of cadmium on the fractured surface indicated that the intergranular fracture was a result of cadmium embrittlement. Cadmium was also found within the intergranular cracks in the base material which further confirmed that cadmium embrittlement contributed to the intergranular fracture.

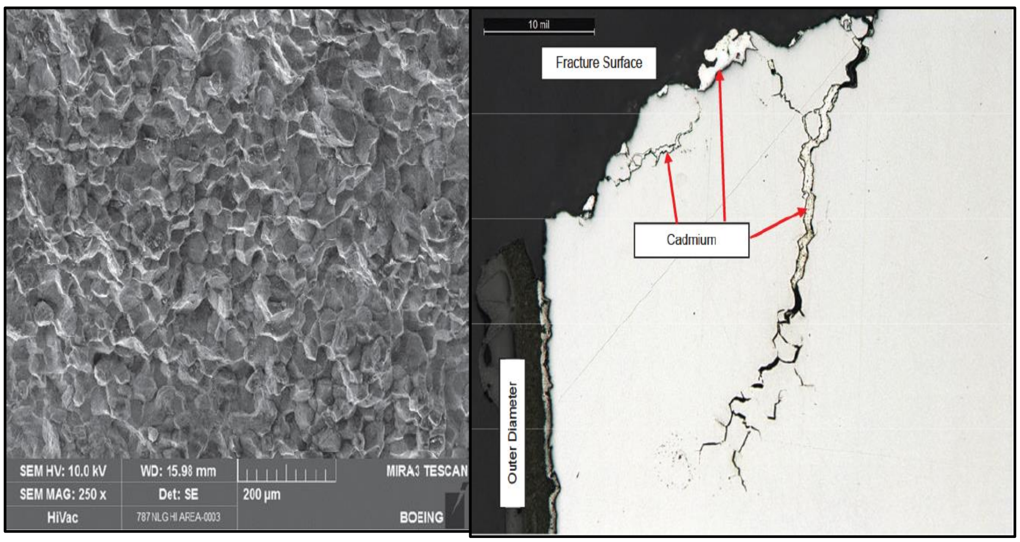

Figure B9: Fracture surface showing intergranular cracks containing cadmium

(9) Another sectioned piece from the forward side of the axle was taken and removed of all the surface finishes and a Nital etch inspection was performed. The Nital etch inspection showed light shades, indicating areas of under-tempered martensite (UTM) and dark shades indicating areas for over-tempered martensite (OTM). The UTM and OTM extended through the thickness of the axle cross section. Microhardness testing was performed on points traversing across the thickness of the specimen section (across the areas of UTM and OTM) and the difference in hardness values corroborated with the microstructure (UTM and OTM)16 indicating that the affected area was exposed to uneven temperature, some parts experienced high enough temperature to affect its microstructure and mechanical properties, in addition to the cadmium embrittlement that resulted in the intergranular fracture.

(10) Additional observations by wheel manufacturer

(a) Inboard bearing cone (inner race), cage and rollers sustained significant deformation. The cone (inner race) was found with several light roller indentations which are at a slight angle (not fully perpendicular) to the raceway and a deep roller indentation that is perpendicular to the raceway. (See **Figure B5**) The wheel manufacturer opined that this is likely due to skewing of some rollers which became seized during operation and resulted in excessive heat being generated. The exposure to excessive heat could have caused the degradation of the raceway material properties in particular its hardness. And a subsequent static load applied to the bearing resulted in the single deep indentation. The remaining rollers of the bearing cone show heavy signs of overheat (deformation and elongation). Several of these rollers are flattened due to wear and grinding effect generated by the skewing.

(b) Some light traces of corrosion (pitting) was observed on the outboard bearing cup (see **Figure B10**) after the layer of grease on the bearing cup was cleaned off. The wheel manufacturer believes that this corrosion could have occurred due to inappropriate storage condition during maintenance or storage before it was installed on the aircraft.

[16] OTM areas exposed to temperature high enough to further tempered the martensite and resulting in lower hardness while the UTM areas likely experienced an even higher that exceeds the austenite transformation temperature with a material brittling effect and thus the hardness is higher.

Figure B10: Outboard bearing cup surface with light traces of corrosion

(c) There were damages found on the outboard bearing indicating that it has been exposed to some areas of stress concentration and there was excessive end play.