



Australian Government

Australian Transport Safety Bureau

TECHNICAL ANALYSIS INVESTIGATION REPORT

Report No. 16/05

Task No. BE/200400012

Occurrence No. BO/200401353

Examination and analysis of a failed turboprop engine bull gear

1 FACTUAL INFORMATION

1.1 Introduction

On 16 April 2004, during a scheduled passenger flight from Melbourne, Vic to Mount Gambier, Vic. the right engine of a BAe 3200 Jetstream aircraft (registered VH-OAE) failed, necessitating a single-engine approach and landing at Mount Gambier. The flight crew reported that the failure was associated with a sharp bang from the engine, loss of thrust and the sound of a hard object impacting against the aircraft fuselage.

Preliminary inspection of the engine revealed an uncontained failure of the propeller reduction gearbox, with associated evidence of debris being liberated from the gearbox and striking the forward right side of the aircraft fuselage.

Commencing on 29 April 2004, the failed engine underwent a strip and examination at the workshops of Tenix Aviation, Adelaide, under the supervision of representatives from the Australian Transport Safety Bureau (ATSB), the Civil Aviation Safety Authority (CASA), the aircraft operator and the engine manufacturer. During that examination, it became evident that the engine failure had resulted from the loss of a segment of the bull gear rim that had broken away from the web and precipitated extensive mechanical damage to the reduction and accessory gear train. Fragments of the bull gear rim had escaped the reduction gearbox housing through a hole punctured in the engine inlet shroud. Those fragments had impacted the aircraft fuselage, leaving characteristic gear tooth pattern witness marks in the aluminium skin.

1.2 Examination brief

The failed bull gear, its partner high speed pinion gear and associated gear tooth fragments were retained from the engine strip examination and forwarded to the ATSB Technical Analysis laboratories for detailed examination and analysis. That work was carried out during the period 26 – 29 May 2004 and was observed by representatives from CASA and the engine manufacturer.

1.3 Items received

- Bull gear, part number 3108295-1, serial number 02P15415. The gear had been installed as a new item¹ on 23 December 2002 and had subsequently operated through 1,199 hours and 1,523 cycles at the time of the subject failure.
- High speed pinion gear, part number 3101741-2, serial number 02P16161. The pinion gear had also been installed as a new item on 23 December 2002 with the bull gear. Several teeth evidently fractured from the pinion gear were also received.

¹ To achieve compliance with CASA airworthiness directive AD/TPE 331/57 Amdt 1.

1.4 Examination findings

1.4.1 Bull gear

The part number 3108295-1 bull gear acted as the first-stage speed reduction gear from the turbine output stage. The conventional external spur gear had a solid web that transitioned to a central hub and drive through to the planetary gear train (second-stage speed reduction & propeller drive).

1.4.1.1 Failure

The bull gear received had failed by the liberation of a 142 mm circumferential section of the gear rim, representing approximately one-sixth of the total gear periphery (figure 1). Fracture had occurred around the base of the transition between web and rim, turning radially outward near each end to release the rim section (figure 2). At one end of the separated section, cracking continued for approximately 30 mm beyond the point of rim separation. Near the centre of the circumferential fracture was a single curved crack that turned through approximately 180 degrees as it extended into and through the gear web (figure 3). At several discrete points along the fracture and crack pathways were regions of discolouration and 'bluing', typical of localised heating. There was no evidence of that effect at any location away from the fracture paths.

Figure 1: Rear face of failed bull gear showing the extent of rim liberation



Figure 2: Forward face of the bull gear showing the primary fracture path and associated cracking. Arrow indicates direction of gear rotation

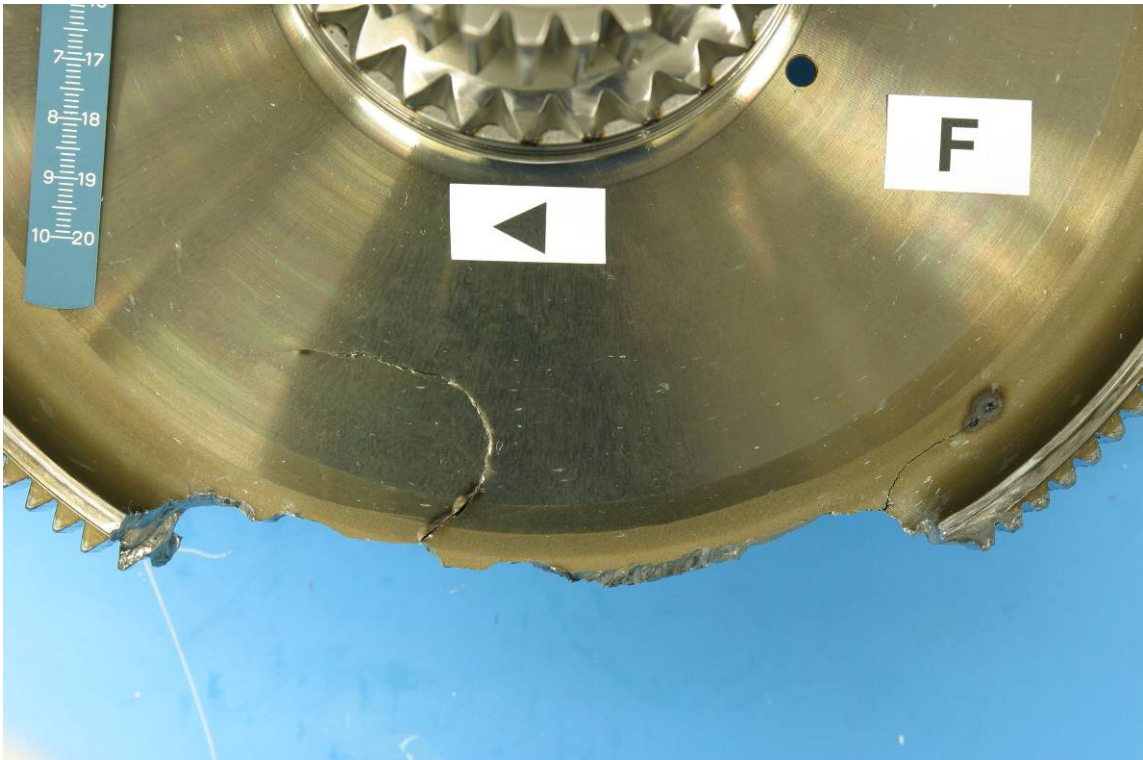


Figure 3: Detailed view of the web crack path

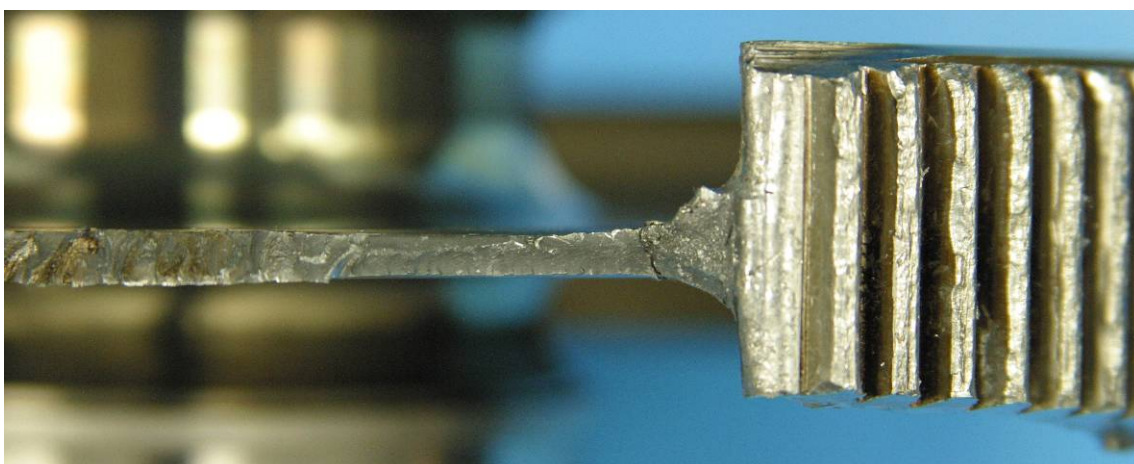


The majority of the exposed fracture surfaces had sustained varying degrees of mechanical rubbing and surface metal flow as the crack surfaces moved against each other before the rim section separated (figure 4). Evidence of progressive crack growth was noted in areas along the fracture surfaces, presenting as bands of parallel markings running through the web and rim of the gear. An area of fracture extending through the web and into the rim at one end did not exhibit rubbing and metal flow features and was characterised by a dull, uniform morphology (figure 5) that was typical of final overload failure of the web as the rim section was released.

**Figure 4: End of the primary fracture where the cracking intersected the gear rim.
Note the extent of fracture surface rubbing and metal flow**



Figure 5: Opposite end of the rim fracture to Figure 4 above. Web fracture was characteristic of ductile overload



1.4.1.2 Crack origins

To investigate the origin of the cracking that had propagated through the gear web, a section was made through the flange to intersect the end of the curved crack (figure 6). Fluorescent magnetic particle inspection was performed before the sectioning to determine the full extent of the crack growth. After sectioning and separation of the crack surfaces, clearly visible progression marks confirmed the propagation of cracking by a fatigue mechanism and indicated the origin to have been located at the very end regions of the web crack (figure 7). An area of ‘bluing’ discolouration that lay along the separated crack path was observed extending onto the fracture, with the surrounding surfaces showing the effects of heavy rubbing and contact. Removal of material at the crack origin by the sectioning process prevented further examination of that area.

Figure 6: Section removed from the gear to allow investigation of crack propagation. Origin was identified at the arrow and direction of crack growth shown



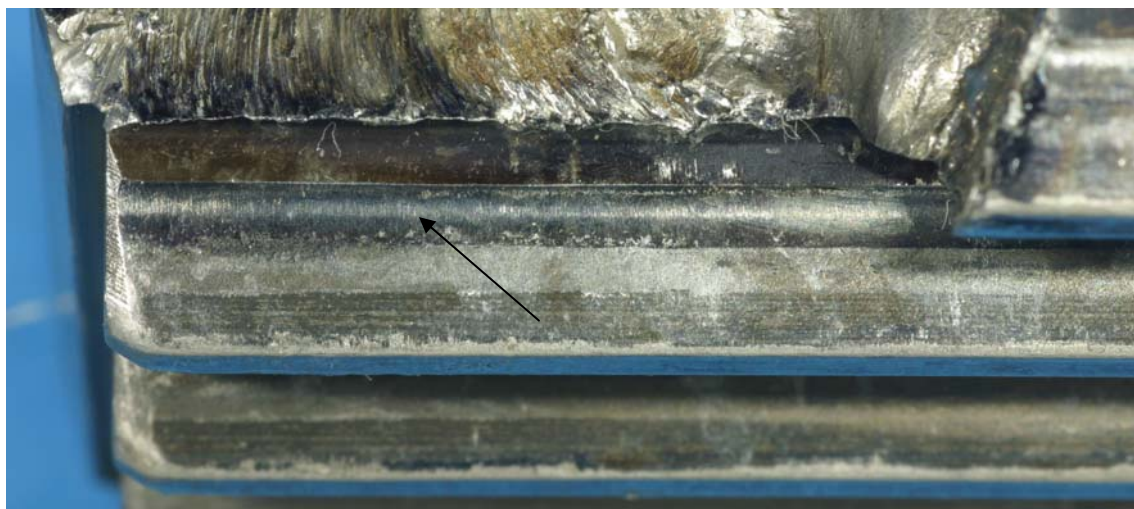
Figure 7: Fatigue crack progression markings evident on the crack surfaces exposed in the boxed area shown in figure 6 above



1.4.1.3 Tooth profile

The teeth remaining on the bull gear showed a band of localised wear and polishing extending across the driven face (figure 8). Visibly around 2.5 mm wide, the band was centred below the pitch line position of the teeth and extended to within 1 mm of the tooth root radius.

Figure 8: Wear bands evident across the contact surfaces of the bull gear teeth



1.4.1.4 Microstructure

Two specimens for metallographic examination were prepared from sections taken through the gear rim and were located approximately 6 mm inboard from the forward and rear rim edges respectively. Both sections were oriented parallel to the plane of gear rotation. The bulk (core) microstructure of the gear presented by both specimens was uniform tempered bainite (figure 9), transitioning to a shallow case structure of very fine martensite, typical of a case-carburised component (figure 10).

From the metallographic sections, the extent and depth of the localised tooth wear was established (figures 11, 12). Presenting as a uniform depression, the wear extended for around 1.25 mm down the tooth face and to a maximum depth of 0.041 mm (41 μ m). There were no anomalous microstructures or other atypical features associated with the localised wear or at any other location across the sections examined.

Figure 9: Typical bainitic microstructure of bull gear core (1% Nital etch)



Figure 10: Case – core microstructure transition region of the bull gear (1% Nital etch)



Figure 11: Cross-sectional view through a bull gear tooth, illustrating the visible region of wear on the tooth driven face (1% Nital etch)

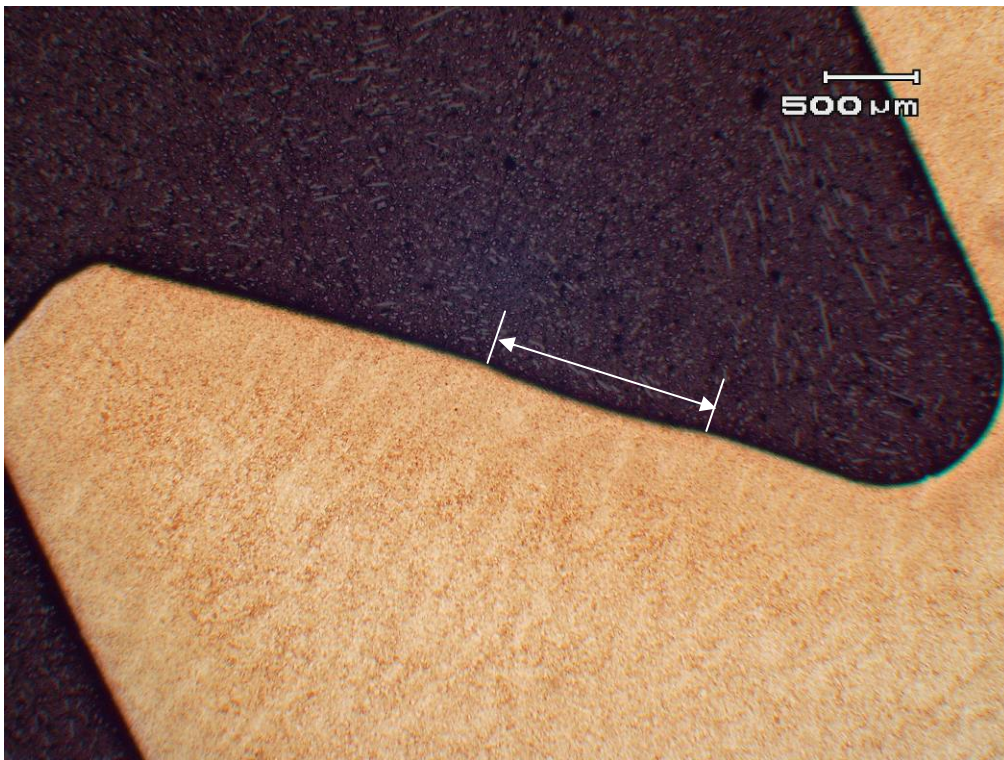


Figure 12: Closer view of the region of wear shown in figure 10 (1% Nital etch)



1.4.1.5 Hardness

A series of hardness measurements were carried out within the core and case regions of the bull gear rim tooth profile to characterise the material properties and allow a comparison against the manufacturer's specifications.

Region	Measurement
Rim Core	407 – 418 HV ₂₀ (approx 42 HRC)
Tooth case	613 – 633 HV ₂₀ (approx 56 – 57 HRC) on cross-section
Case depth	0.75 mm (0.030") to ~ 50 HRC

Core hardness and case depth measurements complied with the manufacturer's requirements for the component. Measured case hardness values fell below the specified minima; however consideration must be given to the influence of measuring the hardness on a cross-sectional plane, as opposed to a direct surface test. Cross-sectional tests will typically return lower nominal values than direct surface tests when evaluating surface or case hardened components.

1.4.2 High speed pinion gear

The part number 3101741-2 high speed pinion gear was coupled to the turbine output shaft and engaged with the bull gear. As received, the pinion had fractured transversely through the shaft immediately adjacent to the rear support bearing (figure 13). Evidence of continued rotation after the failure presented as extensive metal smearing and flow across the fracture surfaces as they moved relative to each other after the failure. The majority of the pinion teeth had been lost from the gear body, with the heavily flowed fractures implying gross mechanical interference and mis-meshing of the teeth during final failure. Several teeth from the pinion gear were recovered during the engine strip process – all showed failure at or about the root transition region, with all fractures typical of ductile shear under overloading conditions (figure 14). The contact surfaces of the failed teeth showed bands of heavy wear and deformation that were comparable to the damage shown by the bull gear teeth.

Figure 13: Fracture and post-failure distress exhibited by the high speed pinion drive



Figure 14: One of the high speed pinion teeth recovered from the reduction gearbox



1.4.2.1 Microstructure

Metallographic sections through several of the liberated pinion gear teeth revealed microstructures comparable to those of the bull gear (figure 15). Planes of deformation-induced microstructural transformation were noted around the base of the teeth, around the areas associated with the shear failure and along the deformed driving surfaces of the teeth.

Figure 15: Metallographic cross-section through a high speed pinion tooth, showing the cracking and deformation induced microstructural transformation associated with gross overloads sustained during failure (1% Nital etch)



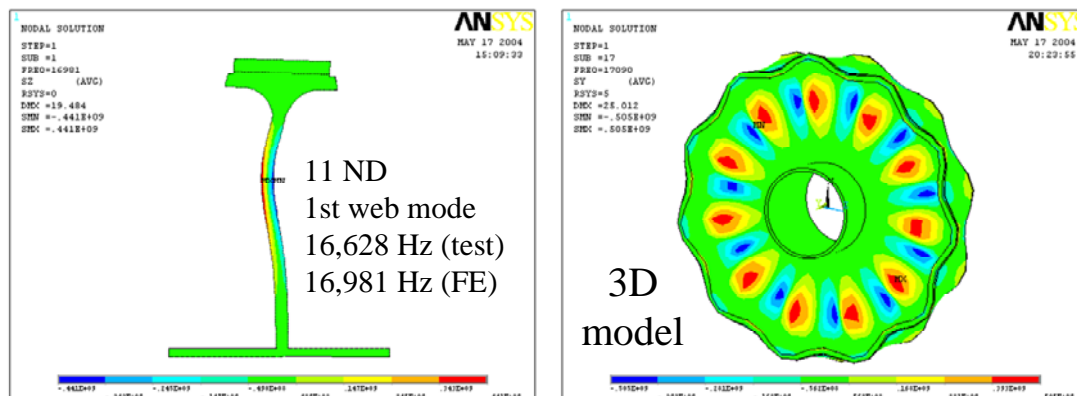
1.5 Previous failures

The TPE 331-12 turbopropeller engine bull gear has a significant history of failure by rim separation. Since January 1995 there have been 19 confirmed bull gear failures, of which six have been failures of the part number 3108295-1 gear as fitted to the subject engine. The 3108295-1 gear was referred to by the manufacturer as a ‘generation 3’ component and was introduced into service in April 1999. The gear contained a number of engineering changes from earlier designs, aimed at reducing the incidence of fatigue cracking within the tooth roots, gear web and hub splines. The first service failure of the 3108295-1 gear occurred in June 2000 at a life of 1,372 hours and 1,771 cycles.

The manufacturer determined that the prime cause of historical bull gear failure was the wear of gear teeth, increasing the dynamic loading and bending stresses in the gear tooth roots and increasing the resonant stresses at other locations in the gear (figure 16). Those increased stresses led to the initiation of high-cycle fatigue cracking² at the tooth roots, web and hub splines. Gear misalignment, high tooth contact stresses and sliding velocities and the lack of proper tip relief were cited as the direct causes of gear wear, with misalignment from housing distortion and gear teeth rework also identified as contributing causes.

² High-cycle fatigue cracking is that where the dominant driving stress varies rapidly in relation to the stresses that are induced as a product of the characteristic flight-cycle of the aircraft, engine or component. Vibratory stresses are the typical drivers for high-cycle fatigue cracking

Figure 16: Manufacturer's stress analysis³ of an earlier gear design, illustrating the resonant response within the web section. The areas highlighted red represent peak tensile stress levels and hence the regions most likely to initiate fatigue cracking under vibrational excitation



1.6 Redesign

Resulting from the deficiencies identified during its earlier analyses, the engine manufacturer released Alert Service Bulletin (SB), SB TPE 331-A72-2114 in August 2004. That SB introduced several changes to the design of the bull and high-speed pinion gear assembly to address the root causes of rim separations. Those changes included:

- adoption of a helical tooth pattern to lower intermeshing tooth contact stresses and reduce surface sliding
- improvement of lubrication feed and increase in lubricant flow to reduce operating temperatures
- increased rim thickness to reduce likelihood of root-initiated cracks from causing rim separations
- increased web thickness to reduce bending stresses.

The manufacturer indicated the new gear design had achieved certification by the US Federal Aviation Administration (FAA) in May 2004.

³ 1995 strain gauge analysis conducted by Honeywell Engines, Systems & Services

2 ANALYSIS

2.1 Bull gear failure

The ATSB laboratory examination confirmed the failure of the part number 3108295-1 bull gear to have resulted from the progressive propagation of high cycle fatigue cracking through the gear web and rim transition region, allowing the liberation of a section of the gear rim as the cracking reached critical length⁴. The origin of fatigue cracking was identified within the gear web and corresponded closely with the regions of peak tensile stress identified by the engine manufacturer during analysis of the resonant web vibration modes excited during gear operation. The resonant behaviour of the gear was also implicated in the formation of the localised zones of discolouration along the crack paths, which were produced as the effects of frictional heating as the crack surfaces vibrated against each other.

The examination found no evidence of deficiencies in the material or physical manufacture of the bull gear that could be implicated in the premature failure of the component.

2.2 Gear tooth wear

The examination identified several bands of non-uniform wear and polishing across the contact surfaces of the bull gear teeth. The metal loss had been sufficient to produce measurable localised depressions within the contact faces, however it was not possible to directly ascertain the time frame over which the wear had occurred, or indeed whether the wear was exacerbated during the development of the gear cracking. Wear of the extent sustained would be expected to contribute to the elevation of tooth root stresses and the excitation of resonant vibration in the manner identified by the manufacturer during its previous analyses of bull gear failures.

⁴ Critical crack length is defined as the length of a propagating crack that reduces the remaining cross-section of the affected component to below that capable of sustaining the operationally induced loads. The result is typically final overload failure of the remaining section.

3 CONCLUSIONS

3.1 Summary

The bull gear failure sustained by the right engine of VH-OAE was found to be a recurrence of a known failure mechanism to which the assembly was susceptible and which the engine manufacturer was in the late stages of addressing by way of design changes to the gear assembly. The examination did not identify any evidence of anomalous operating conditions, maintenance practices or other events that may have contributed to the development of the gear failure.