

SP 0614

Fatigue Fracture of Bevel Gear of an Aeroengine Gearbox

.... the 1000th investigation at NAL



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Hearty congratulations to the Failure Analysis & Accident Investigation Team and the supporting groups of Materials Science Division on the successful completion of their 1000th investigation. The Laboratory has been rendering yeoman service to the aeronautical community in the country using their expertise, built over four decades of dedicated work, to analyse and identify causes of failures of engineering structures and of aircraft accidents. This has led to a better understanding of the behaviour of the system under operational environment. The Team's work received

international recognition through the publication of some of their selected works as an ASM International publication just last year. This event of completion of the 1000th investigation is very creditable indeed, and is a major milestone on the path of investigation science and engineering.

I compliment the team on this occasion and wish them all the success.

*A.R. Upadhya
Director*

Service failures of engineering components, and aircraft and industrial accidents have great impact on society and its economy. Failures and accidents lead to loss of machine time, loss of production and above all loss of human lives in many instances. It is only by a systematic analysis of failures that factors responsible for an incident/accident can be determined and thereby preventive actions can be initiated. The Failure Analysis & Accident Investigation Group of NAL's Materials Science Division, has, over the years, built up the necessary expertise to fulfill this task. It is heartening to note that the Group has completed the 1000th investigation recently. This has been possible because of sustained efforts of many scientists who have worked in this activity for more than three decades. It is appropriate to place on record the contributions of former colleagues Dr. V.S. Arunachalam, Dr. V. Ramachandran, Dr. A.C. Raghuram, Dr. R.V. Krishnan, Mr. S. Radhakrishnan, Mr. R. Rangaraju, Dr. T.A.

Bhaskaran, Mr. M.A. Parameswara and Mr. B.D. Rao in laying down a strong foundation for the Failure Analysis & Accident Investigation activity at the Materials Science Division of NAL. Failure analysis and accident investigation is, by its very nature, interdisciplinary and a team work. A number of scientists contributed to this activity. Today, the activity would not have been in this position but for the active support of all past Heads of the Division, and Directors of the laboratory. Last but not the least, I wish to thank the external organizations for continuing to repose their faith and confidence in the Group. I am happy to note that the 1000th investigation is being brought out as a special publication of NAL. My hearty congratulations to all the members of the team and I wish them the very best in the coming years.

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Head, Materials Science Division*

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Information

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Executive Summary

A few failed components of engine gearbox (with modified PTO shaft and EBW bevel gear) were sent to the laboratory for investigation. Examination revealed that the bevel gear assembly has failed by fatigue. There was multiple fatigue crack initiation at the weld as well as the spur gear spline roots. Investigation showed that generation

of these cracks was independent of each other and hence, they need to be addressed separately. Both metallurgical incompatibility at the weld and high stresses on the spur gear splines have contributed to the present failure. A detailed analysis of the failure is presented and a few recommendations have been suggested.

1. The Incident and Background Information

There was an incidence of failure during endurance test (run No.28) of an engine gearbox on April 24, 2006. It was reported that noise/vibration level suddenly increased when the test was going on under about 80% of the rated load at maximum RPM (NH 16035). Following this, the test was terminated and on opening the gearbox, failure was noticed in the gearbox components. The damaged components, viz., bevel gear assembly and the bevel pinion were sent to the laboratory for analyzing the cause of failure. The details of the gearbox components are given in Table 1.

The bevel gear assembly in question was a modified one. The design modifications were carried out following a failure in the gearbox earlier (ref.1). In the modified design, the bevel gear and the spur gear were joined together by Electron Beam Welding (EBW) to form an integral part.

2. Failure Identification

2.1. Visual and stereo-binocular examination

The gearbox components received for investigation are shown in Fig. 1. The bevel



Figure 1. Damaged components of the engine gearbox.



Figure 2. Fracture surface of the bevel gear assembly.

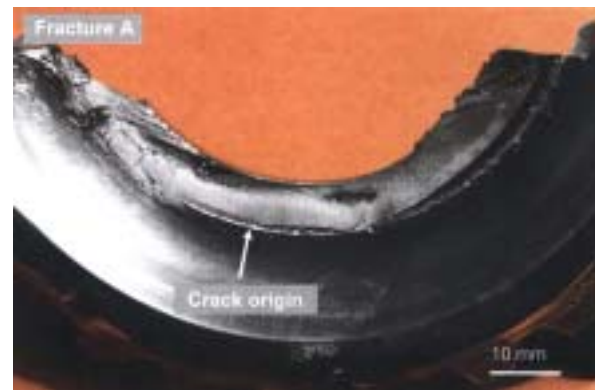


Figure 3. Close-up view of fracture A (refer Fig.2); note the beach marks' orientation.

Table 1. Details of the components received for investigation

Description	Drawing No.	Serial No.	Remarks
Bevel gear assembly	KL 36100	-	Modified design wherein bevel gear and spur gear were joined together by EBW and the assembly has logged on for 11 hr 20 min in endurance test facility
Bevel gear	KL 36002 'C'	034	Before modification: logged on for 137 hr 40 min After modification: logged on for 11 hr 20 min in EGB endurance test facility
Spur gear	KL 36003 'F'	004	Logged on for 11 hr 20 min in endurance test facility
Bevel pinion	KL 80301 'C'	025	Logged on for 149 hr on engine and test rig

gear assembly was found to have fractured into two pieces. A sector of the bevel gear containing 12 teeth had fractured and fallen off in the gearbox. The fracturing has taken place along the weld. The teeth on this sector were in tact and free from any damages. About 11 teeth on the other part of the gear were almost completely shaved off. The bevel pinion did not have any major damages except for some dent marks caused under impact load. These damages are believed to have occurred after fracture in the bevel gear.

2.2. Fractographic examination

Figure 2 shows the fracture surface of the bevel gear. For ease of explanation, the fracture surface has been divided into three parts and denoted as fracture A, B and C. The fracture A is on the hub of the gear, while fractures B and C are on either side of fracture A and on the

teethed region. Close-up views of these three regions are shown in Fig.3 to 5. Beach marks, typical of fatigue failure were found present on the fracture surface. Tracing back the beach marks, it was possible to identify the crack origins. For fracture A, the crack was found to have originated at the weld as shown in Fig.2 and 3. For fractures B and C, the cracks appeared to have two origins each, one at the spline root and the other at fracture A (Fig.4 and 5). Observations did not reveal any mechanical abnormalities at the fatigue crack origins.

Based on the above observations, the three fracture surfaces A, B and C can now be associated with three independent cracks, viz., cracks A, B and C. The independent nature of these cracks is confirmed through Fig.6 and 7. The progressive propagation of crack A in the hub of spur gear can be seen. Similarly, a



Figure 4. Close-up view of fracture B (refer Fig.2); note the beach marks' orientation.



Figure 5. Close-up view of fracture C (refer Fig.2); note the beach marks' orientation.



Figure 6. Progressive propagation of crack A in the hub of spur gear.



Figure 7. Crack A and extension of a crack at spline root.

propagating crack from root of a spline can also be seen. Following this observation, the spline roots of the spur gear were examined. All the spline roots were found to have cracks of varying lengths (Fig.8 and 9). Minor deformation and wear were also observed on the splines.



Figure 8. Fatigue cracks at the spline roots.

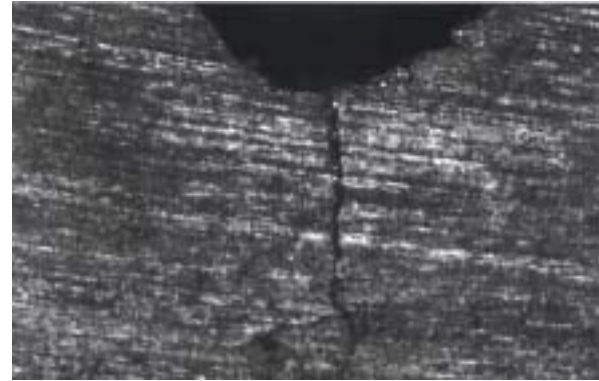


Figure 9. Magnified view of the crack marked in Fig.8.

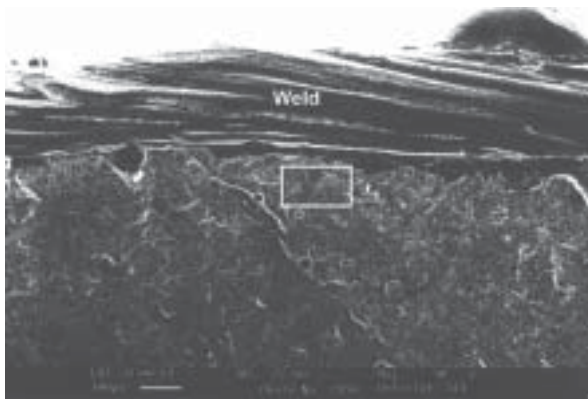


Figure 10. SEM fractograph at the crack origin region on the fracture surface A.

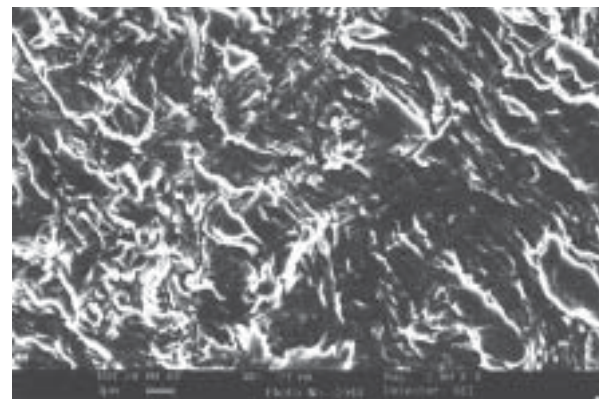


Figure 11. Magnified view of the rectangular region marked in Fig.10 showing fatigue striations.

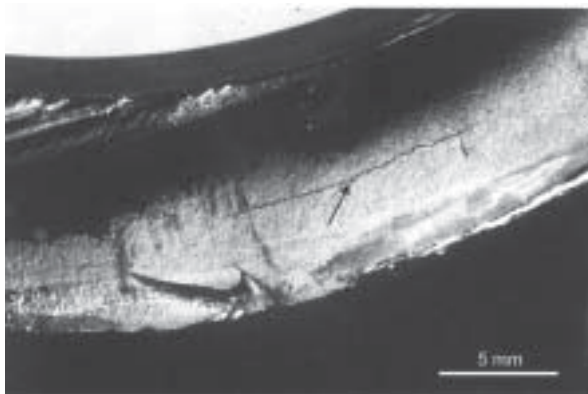


Figure 12. A crack on the fracture surface A (arrow).

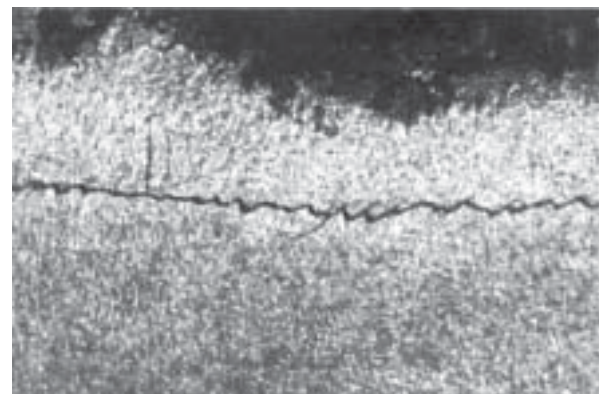


Figure 13. Close-up view showing zigzag nature of the crack.

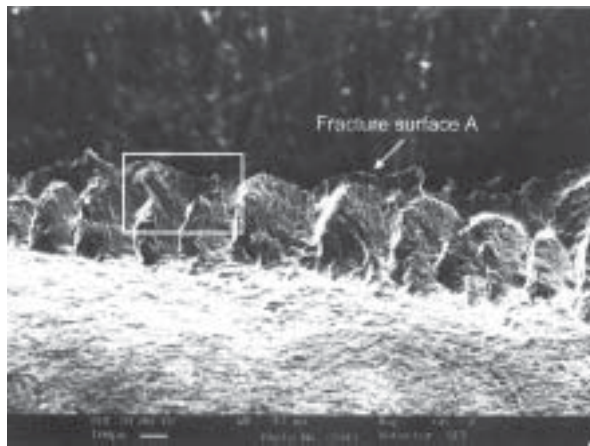


Figure 14. SEM fractograph of the crack shown in Fig. 13.

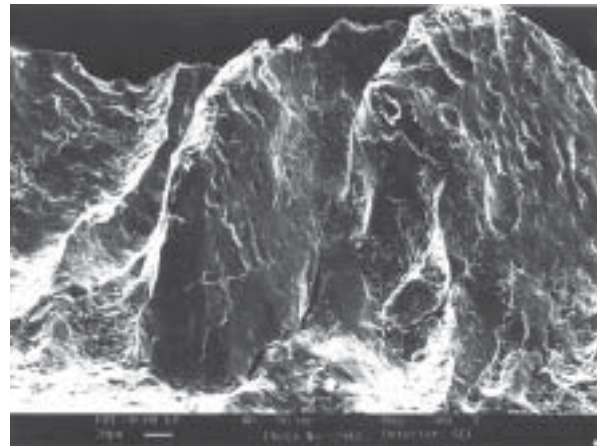


Figure 15. Magnified view of the rectangular region marked in Fig. 14 showing intergranular fracture.

Observation revealed a 15 mm long crack on the fracture surface of the dislodged sector of the gear assembly (Fig.12). But no such crack was observed on the mating fracture surface. The crack was oriented in the circumferential direction and perpendicular to the fracture surface. It was found to follow a zigzag path (Fig.13). Fractographic study showed that the crack was predominantly intergranular in nature (Fig.14 and 15).

3. Materials Characterization

3.1. Microstructural study

Suitable samples were cut from the bevel gear assembly, metallographically prepared, etched with 2% Nital solution and observed under an

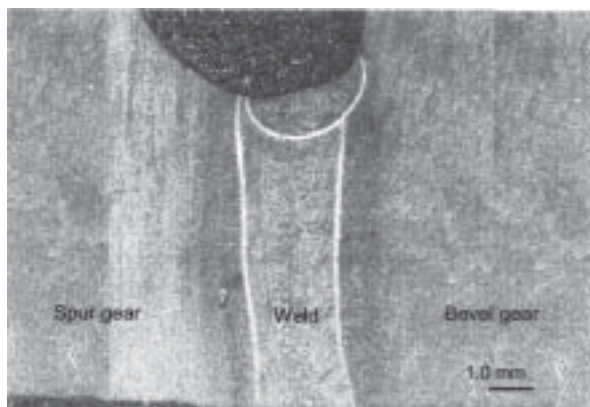


Figure 16. Optical micrograph showing the weld profile; etched in 2% Nital solution.

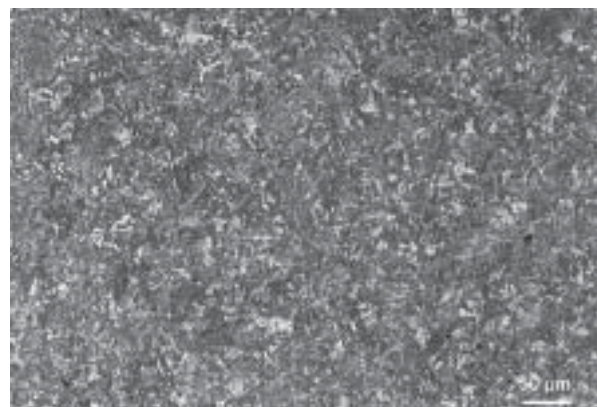


Figure 17. Optical microstructure of bevel gear material consisting of tempered martensitic structure; etched in 2% Nital solution.

optical microscope. Figure 16 shows the weld profile. The weld pool had a width of about 2 mm. The weld did not have any defects like voids or porosity. The weld – parent metal interfaces were clearly distinguishable from the weld as well as parent metal (Fig.16).

The microstructure across the weld was examined in detail. The microstructure of bevel gear and spur gear material was found to be identical and it consisted of tempered martensitic structure (Fig.17 and 18). On the contrary, an untempered martensitic structure was observed in the weld (Fig.19). The weld structure was very coarse compared to that of the parent material of the gear. The microstructural variation across the weld was found to be significant. The teeth/splines of

the gears showed satisfactory carburised/ carbonitrided structure (Fig.20).

A suitable sample was cut across the crack

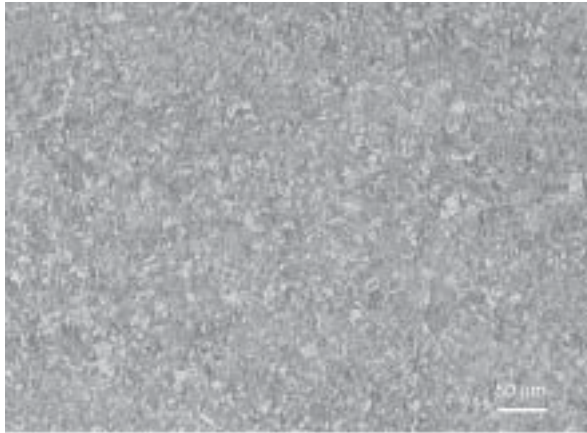


Figure 18. Optical microstructure of spur gear material consisting of tempered martensitic structure; etched in 2% Nital solution.

shown in Fig.12 and 13, mounted on the cross section, metallographically prepared for identification of the crack origin. Examination revealed that the crack had emanated from the

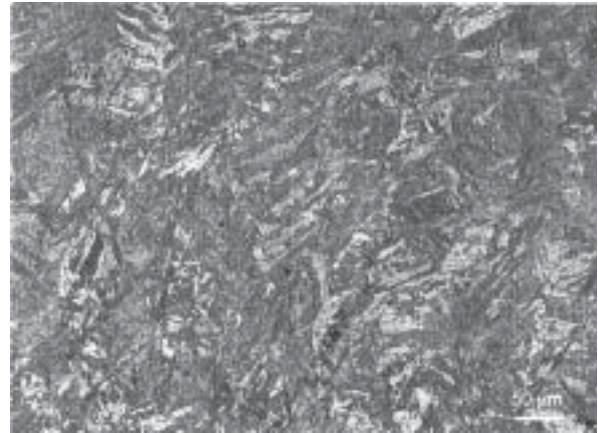


Figure 19. Optical microstructure of weld consisting of martensitic structure; etched in 2% Nital solution.



Figure 20. Optical microstructure of the bevel gear teeth case, showing typical carburised structure; etched in 2% Nital solution.



Figure 21. Photograph showing crack at the weld; etched in 2% Nital solution.

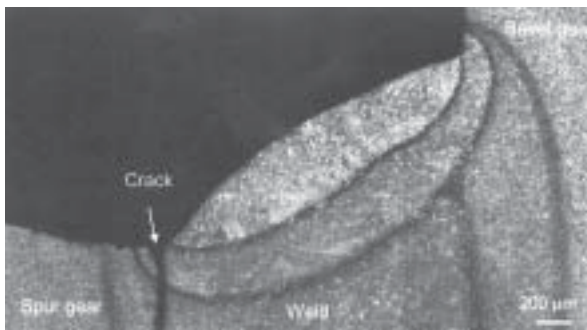


Figure 22. Optical microstructure showing crack emanating from the weld; etched in 2% Nital solution.

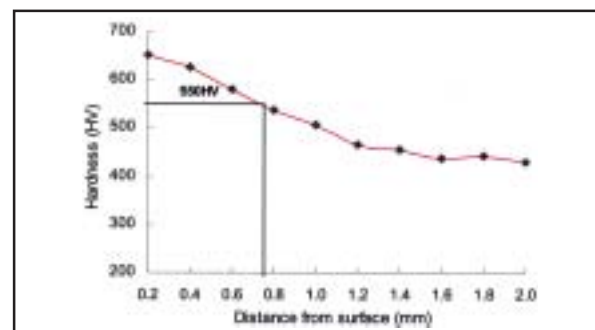


Figure 23. Hardness distribution across the bevel gear tooth thickness.

weld and propagated in the spur gear hub (Fig.21 and 22).

3.2. Hardness survey

Hardness survey was carried out on metallographically prepared samples using a microhardness tester at a load of 500 g. The hardness profiles on the gear teeth/splines and across the weld are shown in Fig. 23 to 26. The results obtained are summarized in Table 2.

The core hardness of the bevel gear and the spur gear was measured to be in the range 430 to 435 HV (~ 44 R_c). The case depth at 550 HV on the gear teeth and splines was measured to be in the range 0.7 to 0.8 mm and 0.36 mm respectively. The hardness variation across the

weld was quite significant (Fig.26). The hardness of the weld was as high as 500 HV (49 R_c) while that at the weld interface was as low as 328 HV (33 R_c).

3.3. Compositional analysis

The composition of the gear material was determined by Energy Dispersive X-ray analyzer (EDX) attached to a Scanning Electron Microscope (SEM). Both bevel gear and spur gear material was found to conform to E16NCD13 steel specification (Table 3).

4. Failure Analysis

Fractographic examination showed that the bevel gear assembly has failed by fatigue.

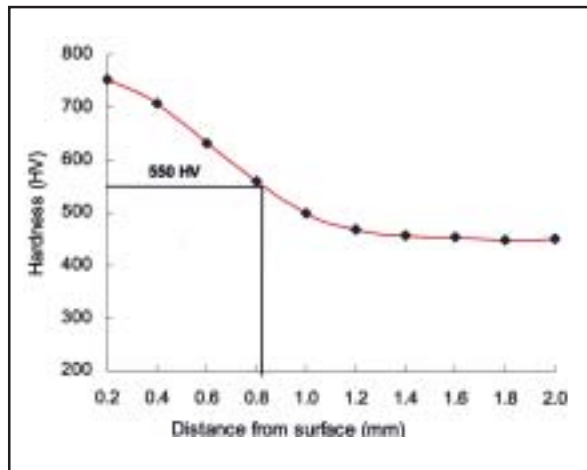


Figure 24. Hardness distribution across the spur gear tooth thickness.

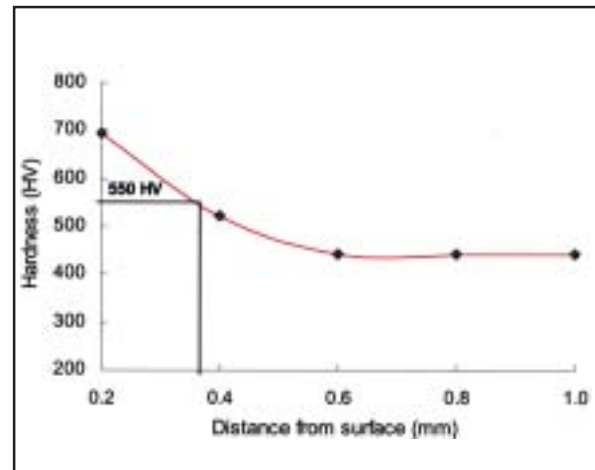


Figure 25. Hardness distribution across spur gear spline thickness.

Table 2. Hardness survey; measured at a load of 500 g

Component	Description	Hardness/case depth at 550 HV	
Bevel gear (teeth)	Core	430 HV	
	Case	0.7 mm	
Spur gear	Teeth	Core	435 HV
		Case	0.8 mm
	Splines	Core	445 HV
		Case	0.36 mm

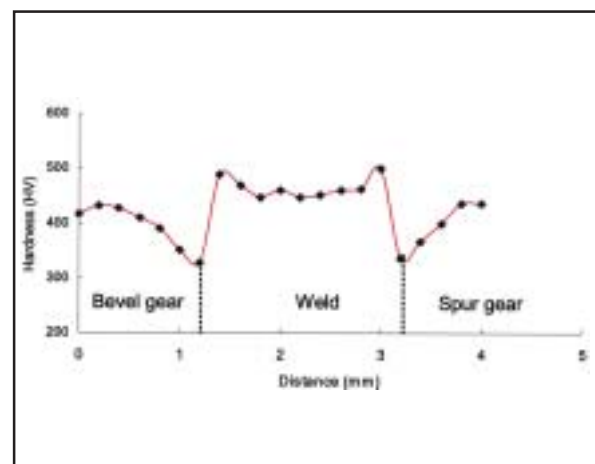


Figure 26. Hardness distribution across the weld.

Table 3. Semiquantitative compositional analysis by EDX analyzer*

<i>Element</i>	<i>Component</i>		<i>E16NCD13 specification</i>
	<i>Bevel gear</i>	<i>Spur gear</i>	
C	-	-	0.12-0.17
Cr	1.1	1.0	0.8-1.1
Ni	3.6	3.0	3.0-3.5
Mn	0.5	0.5	0.3-0.5
Mo	0.3	0.5	0.25-0.30
Si	0.4	0.4	0.15-0.40
Fe	balance	balance	balance

* Carbon cannot be determined accurately by EDX analysis

There were multiple fatigue cracks in the component and the initiation of these cracks was found to be independent of each other. For example, initiation of cracks in the spur gear spline roots, and at the weld between the bevel and spur gear is not related. This implies that in the absence of any one of them, the other would have initiated independently. There were no evidences to suggest that the cracks had initiated due to stress concentrations arising from any mechanical abnormalities. The microstructure, hardness and case depth of the teeth of bevel and spur gears were found to be satisfactory. As far as the spur gear splines and the weld are concerned, these aspects are discussed later in this section.

The major crack, which led to the fracturing of bevel gear assembly, has been identified as crack A (refer Fig.2). This crack has initiated at the weld and propagated progressively in the spur gear hub across the thickness as well as in the circumferential direction of the gear assembly (refer Fig.6 and 7). Simultaneously, a number of cracks have initiated at the spline roots of the spur gear and have propagated progressively into the hub (refer Fig.7 to 9). When crack A and the cracks from the spline roots have interacted, new crack fronts such as cracks B and C have been generated and propagated progressively in the flange of the bevel gear leading to the fracturing of a part of the bevel gear (refer Fig.2). This argument is substantiated by the fact that the cracks B

and C had two fatigue crack origins each; one from the spline roots and the other from the fracture surface A.

After the fracture, the sector A of the bevel gear had fallen off in the gearbox. Hence, the teeth on this sector were in tact and undamaged. Following this, the bevel pinion had pounded onto the bevel gear resulting in shaving off of about 11 teeth. The fragments generated had resulted in minor damages in the bevel pinion as well.

The presence of fatigue crack in most of the spline roots of the spur gear needs special attention. It may be recalled that in the earlier failure (ref.1), excessive stresses on the splines of the bevel gear were found to be responsible for the fatigue crack initiation. Also, there were severe deformation and wear on the flank of the spur gear splines. In the post-mod gear assembly, the wear and deformation on the flank of the splines have reduced significantly. This is due to introduction of surface hardening in the splines. But the design modifications carried out in the splines, if any, does not appear to be adequate in reducing the effective stresses on the splines to a significant extent. Fatigue crack initiation in every spline root clearly suggests that the stresses in the post-mod gear assembly are still on the higher side.

As far as the initiation of crack A is concerned,

the metallurgical factors appear to have played an important role. The hardness survey across the weld showed unusually low hardness at the weld interface. Also, the hardness of the weld pool is very high compared to that of the parent material (refer Fig.26). This implies that no post weld heat treatment has been carried out. This was also confirmed by microstructural study wherein untempered martensitic structure was observed in the weld (refer Fig.19). The untempered martensitic structure has substantial residual stresses.

Welding of hardened materials involves compromises and should be avoided whenever possible. For instance, the heat-affected zone usually contains areas with hardness 10 to 20 Rockwell C points lower than that of the base material. In addition, if the weld contains untempered martensite as seen in the present case, localized stresses are developed at the weld interface, which is often termed as metallurgical notch in the material (ref.2). This notch is equivalent to any mechanical notches/stress raisers and hence, vulnerable for fatigue crack initiation. The fatigue crack initiation at the weld in the present gear assembly is also due to presence of a metallurgical notch resulting from EBW. The situation was further aggravated due to no post weld heat treatment.

The presence of a crack on the fracture surface A (refer Fig.12 and 13) also points towards high residual stresses in the weld. Microstructural study confirmed that this crack had initiated at the weld and propagated in the hub of the spur gear (refer Fig.21 and 22). The intergranular fracture features suggest that the crack has been generated and propagated instantaneously (refer Fig.14 and 15). The confinement of the crack in one of the mating fracture surfaces is noteworthy. This implies that the crack has been generated only after the crack A has passed through and in the process, the residual stresses in the weld have been relieved.

5. Factors Responsible for Failure

The bevel gear assembly has failed by fatigue. There was multiple fatigue crack initiation at the weld and the spline roots of the spur gear. The primary crack leading to fracturing of the bevel gear assembly had initiated at the weld between the bevel and spur gear. The factors responsible for fatigue crack initiation are

- metallurgical notch/residual stresses at the weld and
- excessive stresses on the spur gear splines.

6. Suggested Remedial Action

- Metallurgical notches/residual stresses are unavoidable while welding hardened materials. In view of this, it is suggested that the gear assembly be fabricated from a single stock.
- If welding is continued, the following is recommended to minimize residual stresses.

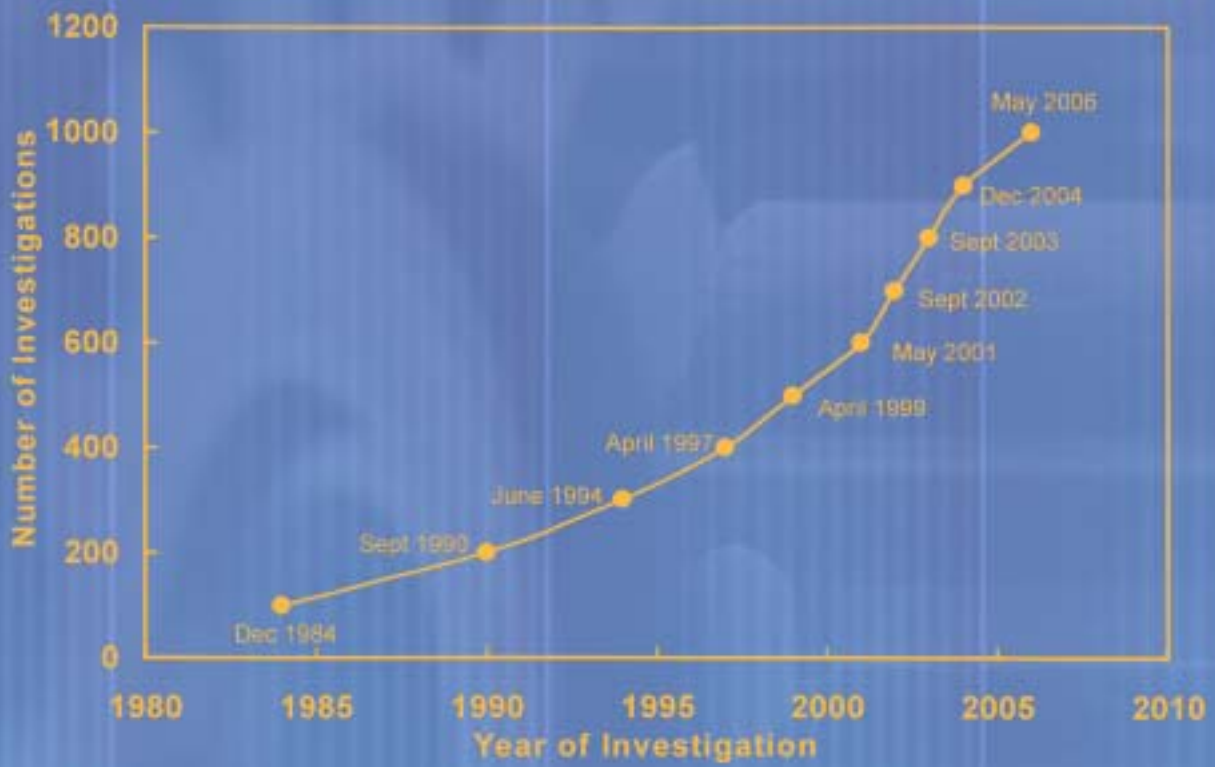
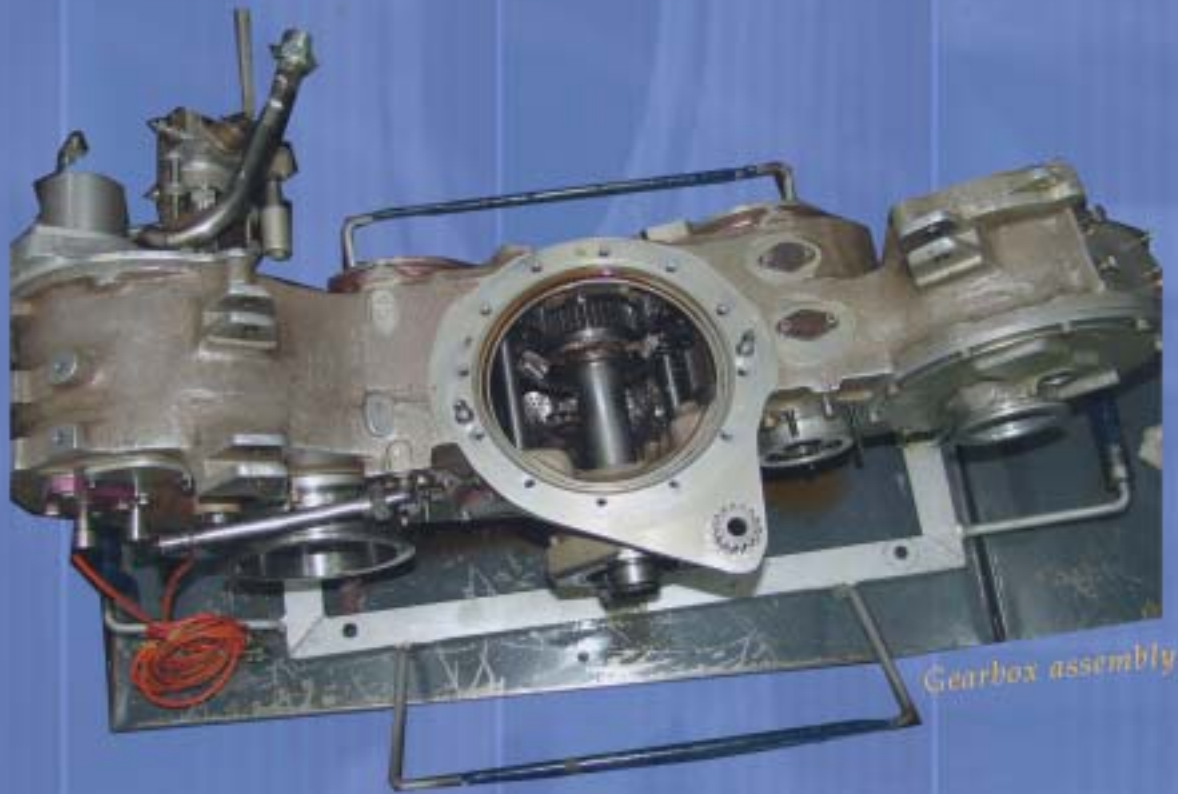
The material should be slowly cooled after welding and then tempered immediately, using a temperature slightly lower than the original tempering temperature of the bevel and spur gears.

- In spite of design modifications, the stresses on the spur gear splines are on the higher side. This needs to be reviewed.

7. References

1. *Analysis of failed/damaged components of an engine accessory gearbox*, Technical Report No. MT-FA-865-07-2004, Materials Science Division, National Aerospace Laboratories, September 2004.
2. *Failure of shafts*, Failure Analysis and Prevention, ASM Metals Handbook, Vol.10, 8th edition, 1975, pp.373-397.

Note: The damages seen on the bevel pinion were secondary in nature and subsequent to the failure in the bevel gear assembly. Hence, no destructive test was carried out on the bevel pinion.



Photography by D Freddy, A B S Vijai