Defence Science Journal, Vol 49, No 4, August 1999, pp. 311-316

Failure Analysis towards Reliable Performance of Aero-Engines

T. Jayakumar, N.G. Muralidharan, N. Raghu, K.V. Kasiviswanathan and Baldev Raj
Indira Gandhi Centre for Atomic Research, Kalpakkam - 603 102.

ABSTRACT

Aero-engines are critical components whose reliable performance decides the primary safety of an aircraft/helicopter. This is met by rigorous maintenance schedule with periodic inspection/nondestructive testing of various engine components. In spite of these measures, failure of areo-engines do occur rather frequently in comparison to failure of other components. Systematic failure analysis helps one to identify root cause of the failure, thus enabling remedial measures to prevent recurrence of such failures. Turbine blades made of nickel or cobalt-based alloys are used in aero-engines. These blades are subjected to complex loading conditions at elevated temperatures. The main causes of failure of blades are attributed to creep, thermal fatigue and hot corrosion. Premature failure of blades in the combustion zone was reported in one of the aero-engines. The engine had both the compressor and the free-turbine in a common shaft. Detailed failure analysis revealed the presence of creep voids in the blades that failed. Failure of turbine blades was also detected in another aero-engine operating in a coastal environment. In this failure, the protective coating on the blades was cracked at many locations. Grain boundary spikes were observed on these locations. The primary cause of this failure was the hot corrosion followed by creep damage.

1. INTRODUCTION

Gas turbines or combustion turbines are used to convert heat energy of combustion to mechanical energy of rotation. The turbines have three main parts, viz., a compressor, a combustor and a turbine. Ambient air is drawn into the compressor and pressurised. The compressed air flows into the combustion section where the fuel is injected and burnt. The hot gases are expanded through the turbine section. The turbine section of the gas turbines are made of nickel or cobalt-based superalloys designed to withstand extreme conditions of high temperature and stresses. The desire to achieve increased output with increase efficiency has paved way for the development of advanced alloys and surface coatings for turbine blades. The turbine blades used in aero-engines are also subjected to complex loading conditions at elevated temperatures. The extreme operating conditions demand materials capable to sustain complex stress cycles of the engine operating at temperatures between ambient and about 1500 K. However, the stresses imposed by elevated temperatures produce a continuous strain in the component resulting in creep damage. In spite of adequate care in material selection and optimised operating parameters, failures do occur due to a variety of reasons. Problems with materials encountered in the turbine section can be broadly categorised as (i) mechanical property related, (ii)

Received 03 June 1999

corrosion related, and (iii) service-induced due to microstructural degradation. Creep, creep-fatigue interaction and thermal fatigue are the primary mechanical to property related to damage mechanisms. Hot corrosion and corrosion-fatigue also reduce their life considerably. Cracking or spalling of high temperature protective coating on the turbine blades can lead to premature service-induced degradation and ultimately leading to failure.

This paper highlights the failure investigations on two aero-engine turbine blades.

2. FAILURE ANALYSIS OF TURBINE BLADES

2.1 Turbine Blades Failure due to over Temperature Exposure

Failure of turbine blades in the hot zone was reported in one of the aero-engines. The engine has a compressor and a free-turbine with rotor bearing assemblies and has a common gas flow path. During full power, the bladed wheels of both the compressor and free-turbine rotated at 21,200 rpm and 12,000 rpm, respectively. The blades of the compressor turbine were made of nickel-based superalloy and had a protective aluminised coating to withstand high temperature operation (about 1200 K). The combustion chamber was also provided with a number of thermocouples to measure the compressor inlet gas temperature. At the time of failure, abnormal sound was heard followed by the engine failure, and the speed of the compressor came down to 2 per cent and the gas temperature also reduced drastically. Strip out examination revealed total failure of the shroud tips of all the 61 blades in the first stage and 71 blades in the second stage (Fig. 1). In addition to this, partial melting of the thermocouple heads fitted to the first nozzle diaphragm assembly was also noticed. The casing appeared bluish, and the blade debris was found strewn throughout the casing. The failed shroud tips were found blunt.

2.1.1 Results of Examination Techniques

Metallographic examination were conducted on the failed blades, unused blades and partially-used (500 hr blades). Examination of the failed blades revealed a lot of creep cavities as shown in Fig. 2 The protective aluminide coating was also found to have spalled and dislodged from the surface as shown in Fig. 3. The etched surface revealed grain coarsening; absence of gamma prime precipitates in the gamma matrix and grain boundary carbides as shown in Fig. 4. Cracking of the grain boundary carbides was also seen on a number of places. The microstructure of the

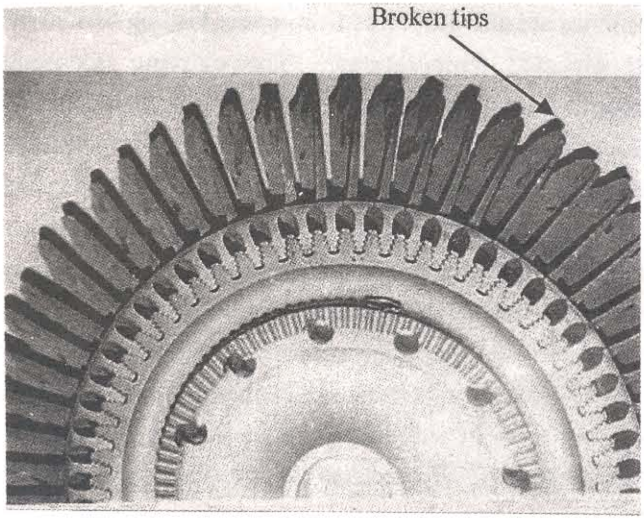

Figure 1. Failed turbine blades

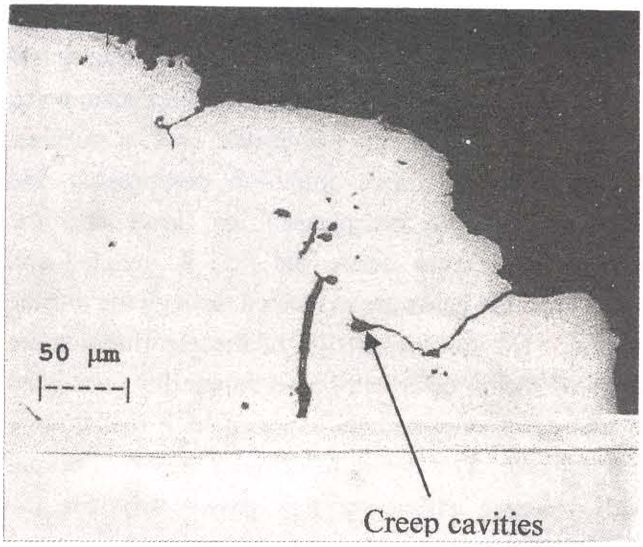

Figure 2. Polished first stage blade showing creep damage

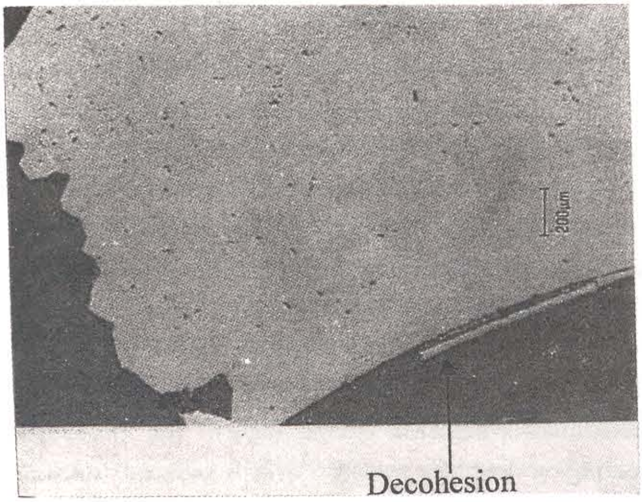

Figure 3. Photomicrograph showing decohesion of protective coating.

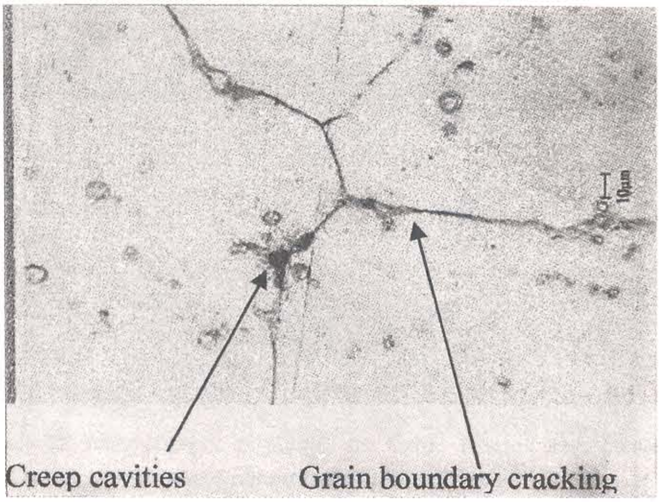

Figure 4. Photomicrograph showing creep cavities and cracking of grain boundary carbides.

partially-used blade revealed coarsening of grains and gamma prime precipitates. The microstructure of the fresh blades was, however, found to have very fine gamma prime precipitates in the gamma matrix.

The microhardness measurements revealed reduction in the hardness value of the failed blades. The microhardness of the fresh blade and the failed blade were 410 VHN and 370 VHN, respectively.

2.1.2 Observations & Conclusion

The total absence of the strengthening precipitates in the matrix of blades, presence of creep cavities on the grain boundaries, excessive grain growth and cracking of grain boundary carbides confirm[1,2] over temperature exposure to approximately 1313-1373K. The dislodgement of the protective coating and melt down of the thermocouples confirm that the temperature was not within the normal operating range. Creep occurs readily at an elevated temperature due to reduction in strength by the dissolution of gamma prime precipitates and also due to grain coarsening. As a result of overageing, there was appreciable grain growth and segregation of carbides at grain boundaries.

The spalling/decohesion of the aluminide coating observed could have led to the microstructural changes seen in the blades. The blunt shroud tips of the failed blades confirmed that they had accommodated the creep strain within the permissible limits. When there was an accelerated creep strain, the blades could not resist it and suffered failure at the minimum ligament area. Failure of the blades in the first stage brought about the cascade damage to all the blades in the first and the second stages of the aero-engine. The failure had occurred due to over temperature exposure, which is attributed either to the faulty temperature controller or the cooling system.

2.1.3 Recommendations

Temperature monitoring device is to be augmented to detect excess heating of the aero-engine beyond the acceptable limits. Better quality control of the protective coatings during overhauls is recommended to avoid over temperature exposure leading to microstructural changes during service.

2.2 Turbine Blades Failure due to Hot Corrosion

The first stage turbine blades of an aero-engine, made of nickel-based superalloy operating in a saline atmosphere, completed around 2900 hr of total operation and about 1000 hr after its first overhaul, failed prematurely, even though these had been designed for a total life of 4000 hrs.

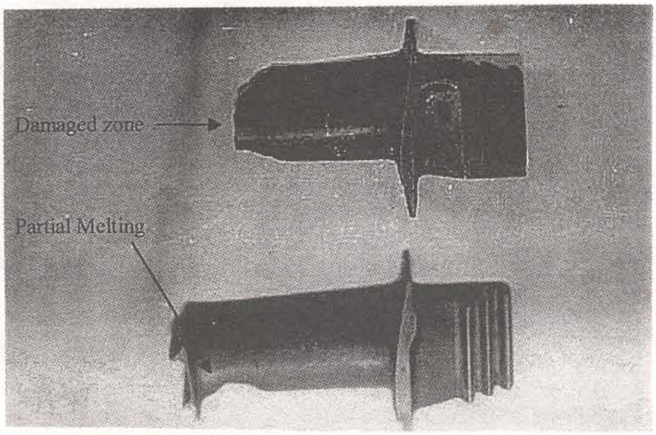

Figure 5. Failed turbin-blade

2.2.1 Results of Examination Techniques

Visual examination of the failed turbine blades revealed that the failure was adjacent to the shroud tip area (Fig. 5). The fractured surface was found to be heavily oxidised with no indication of plastic deformation. The external surface of the blade was free from any deterioration like scaling and pitting. Metallographic examination revealed grain boundary spikes and disruption of the protective surface coating as shown in Fig. 6. These areas were also seen to have matrix-depleted zones, below the protective coating on the blade surface. Creep voids and cracking were observed at many locations and the protective coating had also cracked at many locations.

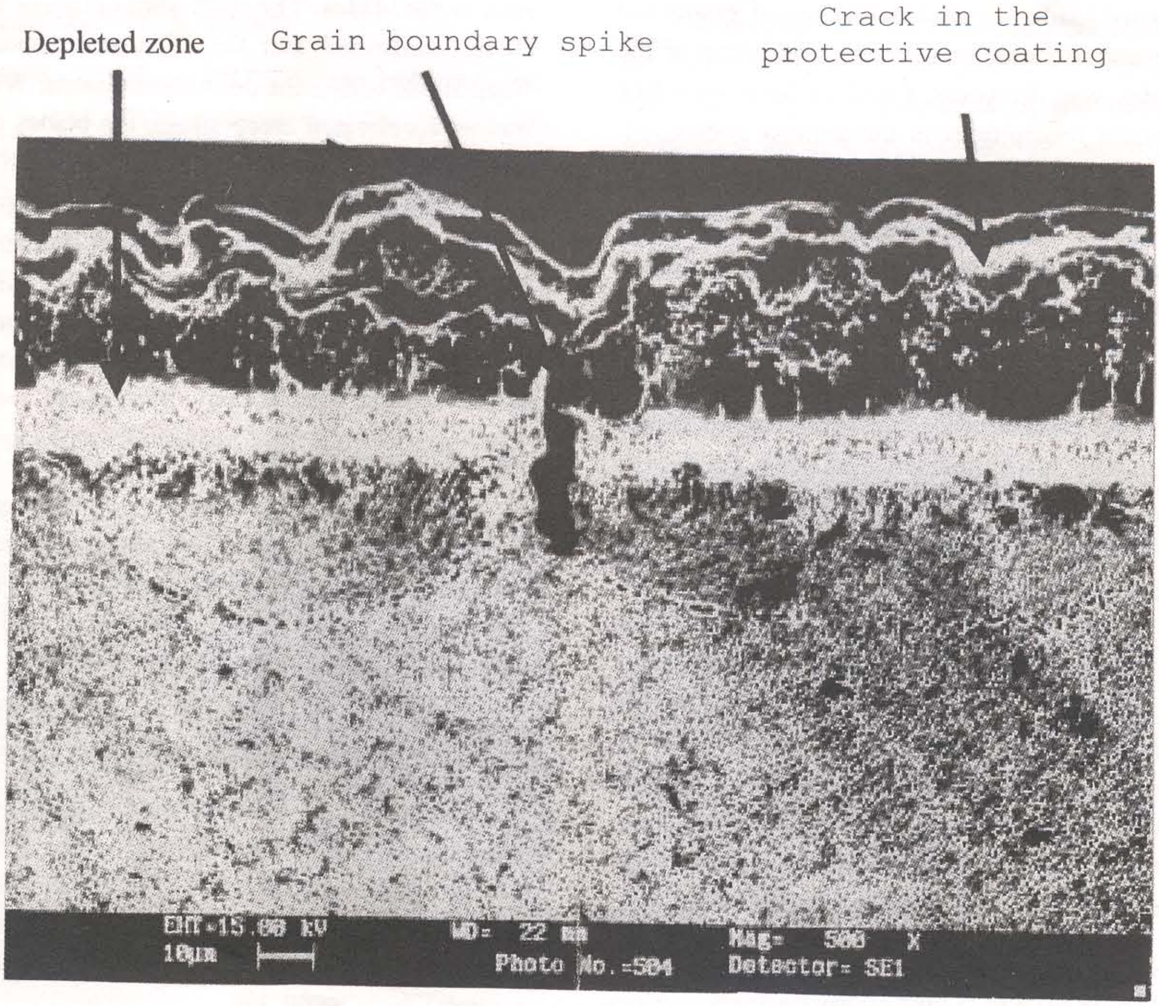

Figure 6. SEM photomicrograph showing hot corrosion damage

2.2.2 Observations & Conclusion

Metallographic observations revealed that the failed turbine blade had undergone non-layer form of hot corrosion damage due to combined action of oxidation and sulphidation[3]. The high temperature form of hot corrosion is attributed to the action of condensed salts deposits formed by the combustion between the sulphur in the fuel and the sodium present either in the fuel or in the ingested air. Presence of grain boundary spikes and matrix-depleted zones along with cracks in the coating are typical indications for non-layer form of hot corrosion.

Hot corrosion damage leads to loss of cross-sectional area due to corrosive material wastage. The superalloys used under this service condition gets weakened due to depletion of hardening elements and gamma prime precipitates. The corrosion-induced changes in the surface morphology and the alloy microstructure facilitate creep-crack initiation and its propagation. The reduction in fatigue strength and endurance limit are mainly due to corrosion-induced surface changes, such as pits, notches, precipitate-depleted weak zone, grain boundary spike, etc. and facilitate fatigue-crack initiation.

2.2.3 Recommendations

Limitation of sulphur and alkali contents in the fuel through careful control of specification is recommended. Stringent specifications for the quality control of protective surface coating during manufacture and subsequent inspection overhauls can significantly reduce the failure incidents.

3. CONCLUSIONS

As can be seen from the failure investigations, most of the failures in the aero-engine turbine blades are due to microstructural changes at elevated temperatures, hot corrosion and degradation of mechanical properties leading to creep and creep-fatigue interaction. Spalling and decohesion of the high temperature coatings on these blades accelerate damage to the material due to elevated temperature. Based on the failure investigations, the adoption of the recommendations, as part of in-service inspection methodologies would prevent premature failure of the blades.

ACKNOWLEDGEMENTS

The authors are thankful to Dr Placid Rodriguez, Director, Indira Gandhi Centre for Atomic Research, Kalpakkam, for his constant encouragement and support. They are also thankful to their colleagues in DPEND for their contributions.

REFERENCES

1. Betterridge, W. & Heslop, J. The nimonic alloys. Ed. 2. Edward Arnold, UK., 1974.
2. Sims Chester, T. & Hagel, William C. The superalloys. John Wiley & Sons, U.K., 1972.
3. Viswanathan, R. Damage mechanisms and life assessment of high temperature components. ASM International, 1989.

Contributors

Dr T Jayakumar obtained his Dr Ing. from University of Saarland, Germany. Presently, he is heading Nondestructive Testing and Evaluation Group of Indira Gandhi Centre for Atomic Research, Kalpakkam. He is the recipient of *National NDT Award* from the Indian Society of Nondestructive Testing (ISNT), in 1996.

Mr NG Muralidharan is working as Scientific Officer in the Metallurgy and Materials Group of Indira Gandhi Centre for Atomic Research, Kalpakkam. Presently, he is engaged in the post-irradiation examination of nuclear fuels and structural materials from the Fast Breeder Reactor. His research areas include: metallography, mechanical testing and failure analysis. He has published a large number of papers in national and international conferences.

Mr N Raghu is working as Scientific Officer in the Metallurgy and Materials Group. Presently, he is engaged in post-irradiation examination of nuclear fuels and structural materials from the Fast Breeder Reactor. His research areas include: metallography and failure investigation.

Mr KV Kasiviswanathan, Scientist, is heading the Post-Irradiation Examination Group as well as Remote handling Group of Indira Gandhi Centre for Atomic Research, Kalpakkam. He has vast experience in setting up the hot cells and post-irradiation examination of irradiated materials. His areas of research include: design and development of components, materials testing, miniaturised specimen testing and failure investigations. He has also designed and developed robots for their use in nuclear laboratories. He has published a large number of papers in national and international conferences.