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Failure Analysis of Compressor Blade of Typical Fighter-class Aero-engine–A Case Study

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ABSTRACT

Failure of second-stage compressor rotor blade of a typical Russian fighter-class aero-engine has resulted in few accidents and many incidents. Apart from this, during manufacturing stage there was high rejection rate of this rotor blade in vibrational fatigue tests. Metallurgical investigations of the failed rotor blade reveals that the mode of failure is fatigue. The various reasons of this fatigue crack are micro-inclusion, silica embedment and hydrogen attack. This was analysed from the three different approaches, namely, theoretical stress analysis, basic design and quality control. To contain the possibility of silica embedment and hydrogen attack, sand electro-corrundum blasting and measure-replaced blasting have been taken to control hydrogen embedment.

Keywords: Failure analysis, compressor blade, aero-engine, fighter aircraft, rotor blade, stess analysis, quality control

1. INTRODUCTION

Theoretical stress analysis deals with finite element modelling of this compressor rotor blade with concurrent loading to calculate the maximum stress and the critical location of the compressor blade, where more stringent control is required. The basic design study deals with the study of different aero foil profiles considering variation in the profiles to take into account the effect of stress concentration. It also deals with the distribution of material at different sections that affects both the machining and the attainment of resonance frequency, which indirectly affects the failure of this during vibrational fatigue test. The compressor module in a fighter-class aero-engine is generally of a twin-spool axial flow type, and it comprises a disc, a blade and a casing. Blades are of two types, namely, rotor and stator, deriving their nomenclature from its state of position. Stator blades just guide the flow of air, while the rotor blades provide the energy of compression. Hence, a compressor has to work against the pressure gradient, whereas a turbine has to work along the pressure gradient. That is why the compressor module, particularly, the disc and the rotor blades, are severely loaded mechanically. The compressor rotor blade of this typical aero-engine is fitted in the dovetail slot of the rotor disc. This paper deals with the failure analysis of a typical compressor rotor blade which is made of martensitic stainless steel.

2. OBJECTIVE

There were two aircraft accidents and few premature withdrawals because of the failure of

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second-stage compressor rotor blades during service exploitation. Most of the premature withdrawals during service exploitation are due to ultrasonic signals and corrosion pits found during in-service inspection. Apart from this during manufacturing, the rejection rate in vibrational fatigue testing and frequency checking was also quite high. Hence, there was a need from the airworthiness agency point of view to review the manufacturing process and the basic design to analyse the cause of failure and to find the remedial measures.

3. DESIGN OF ROTOR BLADE

The rotor blade of a compressor is designed to work against centrifugal load arising from rotations of the order of 10,000 rpm and gas-bending loads. In addition, it has to survive against corrosion, erosion, and impact from foreign object, if any, and vibrational loads. The other load that acts on the blade is the aerodynamic load arising from the manoeuvring of the aircraft. The failure mode of this blade is of high cycle fatigue. To get such a high fatigue strength with uniform properties, the only manufacturing process is forging. The forged blade made from martensitic stainless steel undergo broaching at the root and milling on the profile, followed by plating to get the finished shape.

3.1 Metallurgical Investigation of Failed Blade

Various reasons for the failure of the rotor blade are inclusion, hydrogen-embrittlement, silica embedment, etc. Most of the failure is of fatigue, originated at the cracks/non-metallic inclusion near the transition radius zone on the pressure surface.

4. THEORETICAL STRESS ANALYSIS

Because of the complex contour of the compressor rotor blade, it is difficult to accurately calculate analytically the stress level, it is subjected to. Hence, FEM modelling has been utilised to model the blade and to calculate the stress level at different ratings of the engine, considering centrifugal load and the gas load on the blades having constraint at the root. The maximum value of the bending stress is found to be 8.78 kg/mm^2 occurring approximately 32 mm from the root of the rotor blade towards the trailing edge of the convex surface. Hence from stress point of view, the section at 32 mm from the root on convex surface is more critical.

5. STUDY OF COMPONENT DRAWING

Critical dimensions of a compressor rotor blade are the centre line thickness, i.e., C_{max} angle of twist, chord length, and root dimension as shown in Fig.1. Linear and angular dimensions of

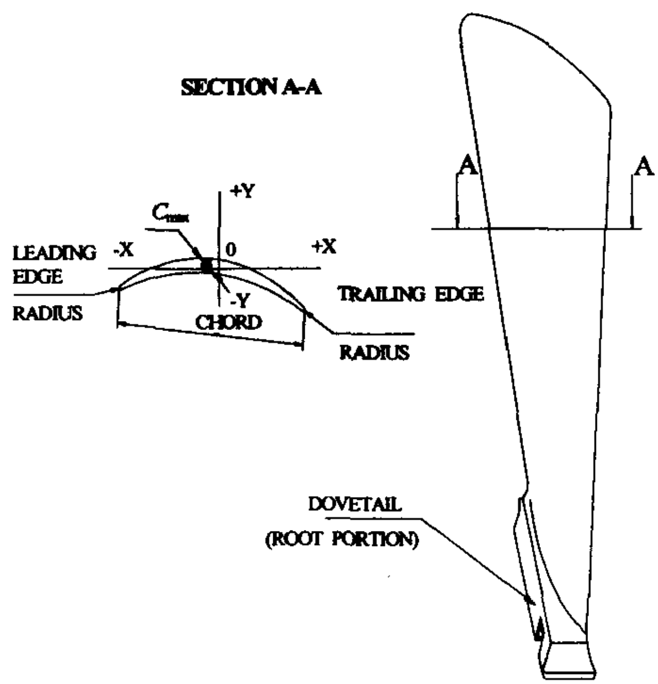

Figure 1. Schematic diagram of typical compressor blade

the blades are to be maintained accurately to obtain identical rates of air flow and identical pressure and temperature on it, without which it will not only reduce the efficiency but also will cause vibration, and their breakdown. Surface finish ($\nabla 8$-$\nabla 10$) is to be maintained both on the root and the working part to increase the fatigue strength and to reduce gas friction losses[1]. Study of drawing reveals that there is maximum change in C_{max} thickness and angle of twist around the sections IV and V which raises the stress concentration factor.

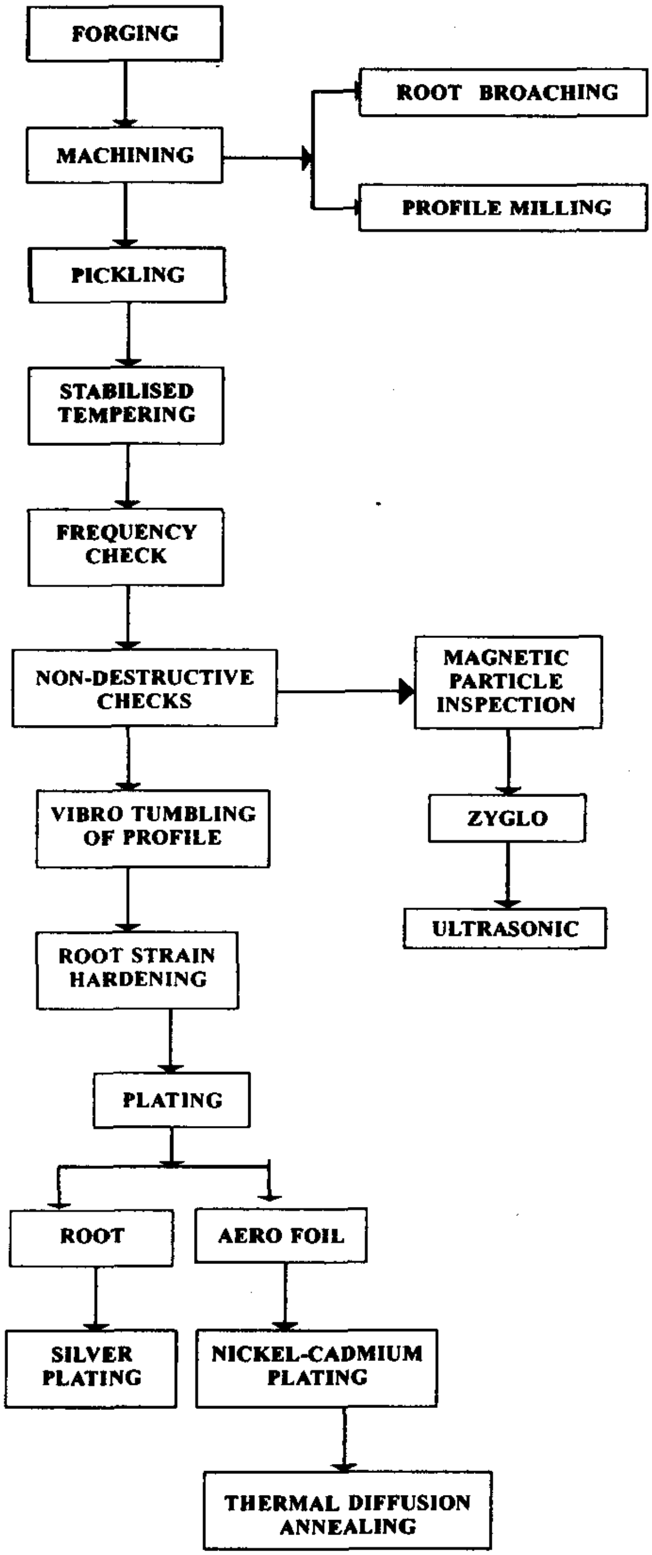

Figure 2. Manufacturing process of second-stage compressor rotor blade.

6. MANUFACTURING PROCESS

Basic manufacturing process of a compressor blade (Fig. 2) mainly consists of forging of billet, machining, and plating.

6.1 Forging of Billet

Rotor blade is made from an electroslag-refined quality martensitic stainless steel. Billet is forged in a closed die forging process with deformation[2] at the top, near the transition radius, and the root section is approximately 19 per cent, 13 per cent and 20 per cent, respectively. Immersion ultrasonic is being carried out in the billet stage to reveal cracks/discontinuity.

6.2 Machining

Machining of the forged blade consists of two steps, namely (i) root machining and (ii) profile machining.

Root machining involves root broaching and slot machining. Profile machining involves profile milling, bell grinding, rough grinding, etc. Material removal during machining amounts to be 75 per cent. Reduction in section thickness along the edges is approximately 83 per cent, while along the centre line[2] is 65 per cent. Material removal at each stage of machining plays an important role because it affects the strength of the rotor blade in terms of overheating/burning. Rotor blades are subjected to magnetic particle inspection, i.e., zyglo, and ultrasonic inspection to reveal surface/subsurface cracks/discontinuity.

6.3 Additional Strengthening Operations

As the dove-tail portion of the root of the blade is highly stressed, strain-hardening by pneumo-dynamic method is resorted to. Vibro-tumbling of blade with steel ball having diameter having daimeter 2-3 mm for 80 min is carried out to strengthen the surface of aero foil of blades by producing a cold-worked layer on the surface for increasing the limit of fatigue strength and to smoothen all roughness[2].

6.4 Plating

Root of a compressor blade is subjected to fretting fatigue because of the unavoidable relative motion between the disc and the blade. Hence to give a cushioning effect and lubrication, the root of this typical blade is plated with silver 3-6 μm thickness. As the profile of the blade is subjected to erosion and corrosion, a sacrificial plating of nickel-cadmium (9-15 μm) is done.

7. TESTS & CHECKS

Evaluation of rotor blade is being carried out in three stages, namely: (i) raw material evaluation, (ii) process evaluation, and (iii) finished component evaluation.

Raw material evaluation is accomplished by mechanical and metallurgical route. Process evaluation comprises mechanical and metallurgical requirements, keeping in view the strength requirement of the finished one. In this case, it deals with the properties of the forged and heat-treated blade. Finished component is evaluated by simulating its assembly and functional requirements. It consists of frequency check, vibratory fatigue check, and engine run.

Rotor blades are subjected to 4^{th}-mode torsional vibrations to check their natural frequency and the minimum limit is 7050 cycles/s. Vibrational fatigue testing is conducted at a stress level of 47 kg/mm^2 for 2×10^6 cycles subject to no-visible flaws during magnetic or zyglo check. Rotor blades are subjected to engine run that comprises initial test and final test to take care of the infant mortality and performance of sliding pairs.

8. DISCUSSIONS

8.1 Problems Related to Service Exploitation

- *Cracks/Inclusion*: Theoretical stress analysis and studying of the component drawing clearly points out that the section around IV and V on the pressure surface is the highly stressed region, and so, more critical. That is why utmost care is to be given not to have any surface discontinuity or inclusion, if any, in this region. Hence, it is suggested to extend the ultrasonic inspection region from the root radius to section IV.
- *Hydrogen embrittlement*: The source of hydrogen in hydrogen-embrittlement may be due to pickup of moisture during plating operation. Insufficient drying during the intermediate operation may be the source for this.
- *Silica embedment*: More angular shape of the silica particle in sand-blasting operation, prior to plating, might have created a notch in which silica particles get embedded and get enveloped by the silver coating during subsequent operation that might have initiated corrosion that led to the failure.
- *Corrosion pits*: To limit corrosion pits, nickel-cadmium plating has been analysed and found that the porous nature of the plating and less adhesive strength may be the cause for this. Additionally, in nickel plating, depending on the thickness, there is a reduction in fatigue strength of the substrate[3], from 3 to 44 per cent on increasing the thickness from 12 μm to 88 μm. Hence, the existing nickel-cadmium plating has been replaced by polymer coating that give favourable results.

8.2 Problems Related to Manufacturing

- *Failure during fatigue testing*: Quality audit of the manufacturing process reveals that during machining operation the material removal during profile milling (rough), profile milling (final), and profile grinding is not followed properly, thereby, excess material is left over for the grinding operation. Surface finish during final profile milling was found to be low, this leads to overheating of the blade that may lead to failure.
- *Frequency mismatch*: Study of component drawing and technology gives the clue that to achieve the desired frequency, dimensions along Y-direction at different sections can exceed the technological limit as follows: section Ia-Ia by 0.07 mm, II-II by 0.13 mm, and IV-IV by 0.2 mm.

Taking trials with the extended acceptance limit, it is found that the blades are meeting the frequency requirements.

9. CONCLUSION

To reduce/eliminate the cracks the C_{max}, edge thickness have been increased, and to reduce the vibrational stresses, the chord length has been reduced. This indirectly meets the frequency requirement. Electro-corrundum blasting in place of sand blasting eliminates the possibility of silica entrapment. To eliminate the corrosion pits, nickel-cadmium plating is replaced by polymer coating. This also enhances the fatigue strength of the substrate. Implementation of all the modifications improves the quality of this rotor blade in particular, and that of the aero-engine, in general.

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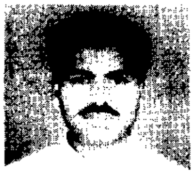

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