# ANALYSIS AND COUNTERMEASURE ON AERO-ENGINE BLADE DEFECT

**Zhijun Sun, Zijing Guo, Guoliang Liu**
**AVIC Xi'an Aero-engine (Group) LTD.**

**Keywords**: *turbine blade, nickel superalloy, fluorescence inspection, machining surfaceintegrity, machining damages*

**Abstract:** A large number of finished turbine blades on aero-engine, which were made by deformation nickel superalloy, were found defects on their body, serration and shroud during the finished fluorescence inspection. And the defects were investigated by using macroscopic observation, microscopic observation, surface state analysis, fracture observation, and classification statistical analysis. The results show that the defects can be divided into three categories: 1. Local intergranular attack; 2. Intergranular thermal stress cracks caused by grinding and polishing; 3. Surface machining damage. And the formation mechanisms of the three types defect are analyzed. The qualified rate of finished turbine blade is improved to 95% by new proposed process optimization.

## 1 Instruction

Aero-engine, which is worked at aerodynamic load, mechanical load and high temperature load, is a mechanical thermodynamic product with high durability. Its turbine blade has adverse working environment and high failure probability. It is found that most of the failures on turbine blade are related to the machining surface state by using statistical analysis. To the improvement of the service performance and life of aero-engine, it is important to study the machining surface integrity [1-4].

About 5,000 finished blades on the aero-engine, which are used nickel base were found that there were flake, punctate, reticular and linear fluorescence displays on their bodies, serrations and shrouds.

The mainly technological process of turbine blade is: die forging of blank — electrolysis of profile — solid solution — serration broaching — body polishing — annealing — aging — dry blast — etching by using $FeCl_3$ — fluorescence inspection — luster polish — storage. The serration of turbine blade are produced by using broaching and grinding. And the parameters is shown in table 1. In additional, the shroud is machined by grinding, and the body is polished by wheel and abrasive belt.

In this paper, the fluorescence defects were investigated by using observation, analysis of surface state, fracture observation, and classification statistical analysis. In adding, the improvement measures in engineering were given combined with the manufacturing process of turbine blade.

**Table 1 Parameters of broaching and grinding**

| Processing Methods | Tools | Feed Rate /(mm/min) | Grinding Depth /mm | Linear velocity /(m/s) | Dressing amount of wheel /mm | Dressing wheel velocity /(mm/min) |
|---|---|---|---|---|---|---|
| Grinding | $Al_2O_3$ wheel | 50/90/120 | 1.5/0.3/0.1 | 22 | Dressing amount after the second broach 0.2 | 0.8 |
| Broaching | 5 groups of broach | broaching speed is 1.2 to 1.4/(m/min) | | | | |

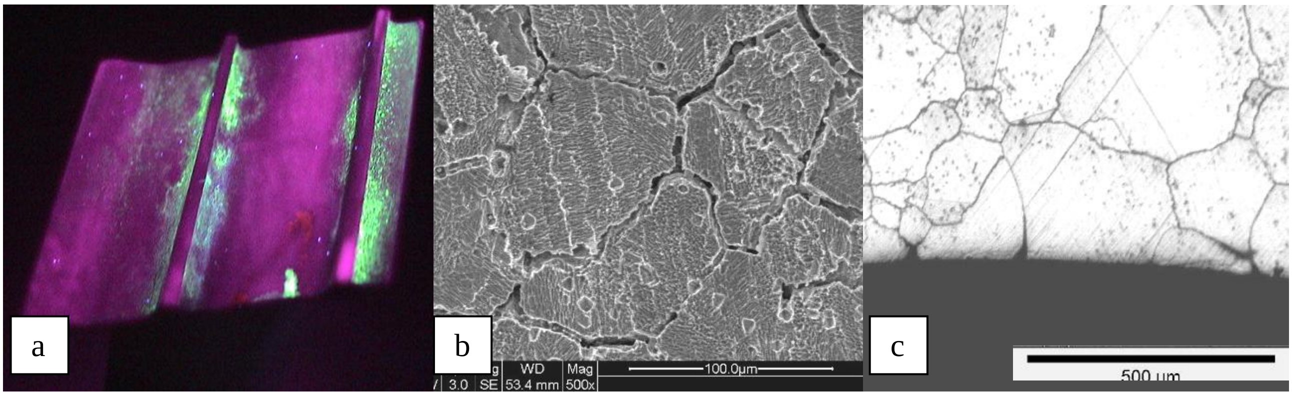
## 2 Testing results and analysis

About 5,000 blades show fluorescence displays, which were mainly distributed at shroud, leading edge and trailing edge of body, and serrations under macroscopic observation. Because of the different processing with different locations, the positions of fluorescence defects can be divided into three categories: (1) shroud, (2) body, (3) serration. Statistics on the occurrence of fluorescence displays, the defects in shroud or body account for 5% of the blades, and the defects in the rest 95% blades are all in the serrations.

2.1 The fluorescence displays in shroud

The shapes of fluorescence displays at shroud, which are located in the middle of top surface and shroud flank, were manifested as linear or reticular.

1) Reticular fluorescence displays: it is found that the distribution of fluorescence displays is clustered flake under fluorescent lamp. Using microscopic observation, there are clearly overstriking network grooves along grain boundaries. And the machining surfaces of grain are became rough with etch pits. Meanwhile it is found that there are tiny intercrystalline cracks extend into the matrix along the grain boundaries. These cracks have larges opens and blunt ends without material and metallurgical defects around them. Also, their length is 0.03mm to 0.06mm, as shown as in Figure 1.

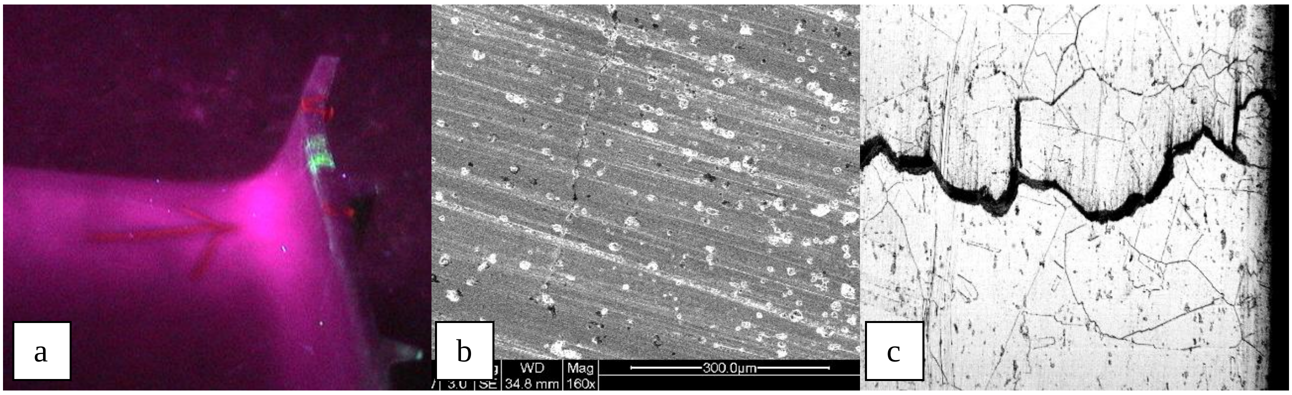



a. **Fluorescence displays at top surface of shroud b. Reticular grooves along grain boundaries**
**c. Metallographic morphology at profile**
**Figure 1 Morphology of reticular fluorescence displays at shroud**

All fluorescence displays are belong to local intergranular attack.

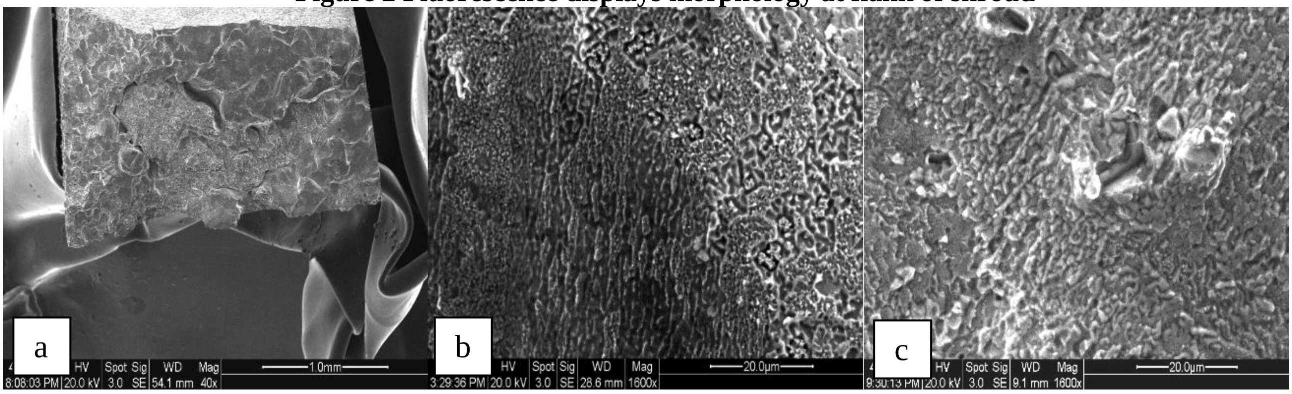
2）Linear fluorescence display: they are single-strip or parallel multi-strip， and with the length from 3mm to 7mm. The fluorescence displays are cracked along the reticular grain boundaries, and perpendicular to the grinding directions. Also, the machined surface has lots of spalling. Observed by using metallographic observation, it is shown that the cracks are reticular and tiny intercrystalline cracks with fine end. Meanwhile, there are secondary cracks with slight oxidation. The length of cracks is 0.2mm to 0.5mm. Especially, individual cracks throughout the shroud with the length of 1mm, as shown as in Figure 2.

Observed the whole fracture after opening the cracks, its characteristic is intergranular fracture. The original crack is black grey with slight oxidation. Its fracture feature is intergranular fracture with dimple. The biggest distance from the cracks to surface is 0.8mm. The photographs are shown in figure 3.




**a. Linear fluorescence displays b. surface morphology of cracks c. metallographic morphology of profile**

**Figure 2 Fluorescence displays morphology at flank of shroud**




**a. Morphology of the whole fracture b. Micrograph morphology of crack fracture**

**c. Micrograph morphology of artificial fracture**

**Figure 3 Fracture morphology of shroud cracks**

These types of fluorescence displays belong to the grinding cracks.

2.2 Fluorescence displays at trailing edge on bodies

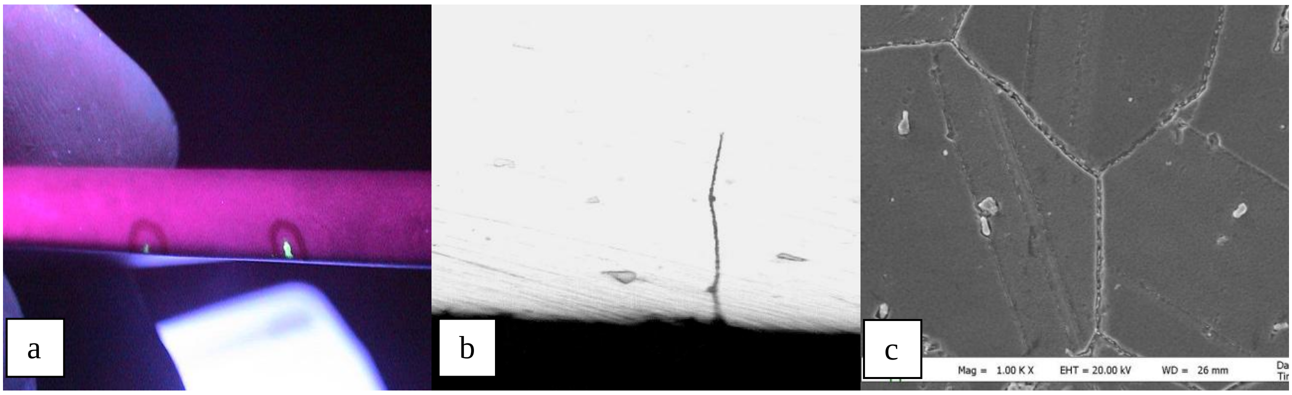
The distribution of the most of the fluorescence displays on bodies is linear or densely punctate at the leading edge and trailing edge. And the analysis results show that the fluorescence displays on bodies can be divided into three categories:

1) Thermal stress cracks caused by grinding or polishing: the fluorescence displays are intercrystalline cracks by using microscopic observation. Metallography observation indicates that there are lots of tiny, grayish black intercrystalline cracks with fine end and the length of 0.17mm. And there are chain carbides precipitated on the grain boundaries. Compared the crack fracture with artificial fracture, the crack fracture is dark brown, and the artificial fracture is sliver gray. There is a obviously boundary between both of them. In additional, the crack fracture is similar to the grinding crack in 2.1(Figure 3b), and its fracture feature is the intergranular fracture with dimple.

All of these fluorescence displays belong to the thermal stress crack caused by the grinding or polishing overheats on body.

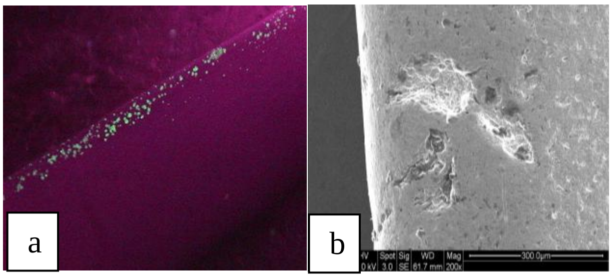
2) Local intergranular attack: it shows overstriking grain boundaries and etching micro-pits on machining surface. On the profile, it is the tiny cracks with blunt ends.

3) Machining damage on body surface: there are obvious flake peeling on the body. Meanwhile, there are lots of micro-pits on the surface. Both of them are caused by machining, as shown as in figure 5.




**a. Linear displays b. Morphology of crack profile c. Chain carbides precipitated on the grain boundaries**

**Figure 4 Fluorescence displays on body**




**a. Reticular or densely punctate b. Machining damages**

**Figure 5 Fluorescence displays on bodie**

2.3 Fluorescence displays on serration

2.3.1 Surface morphology of fluorescence displays on serration

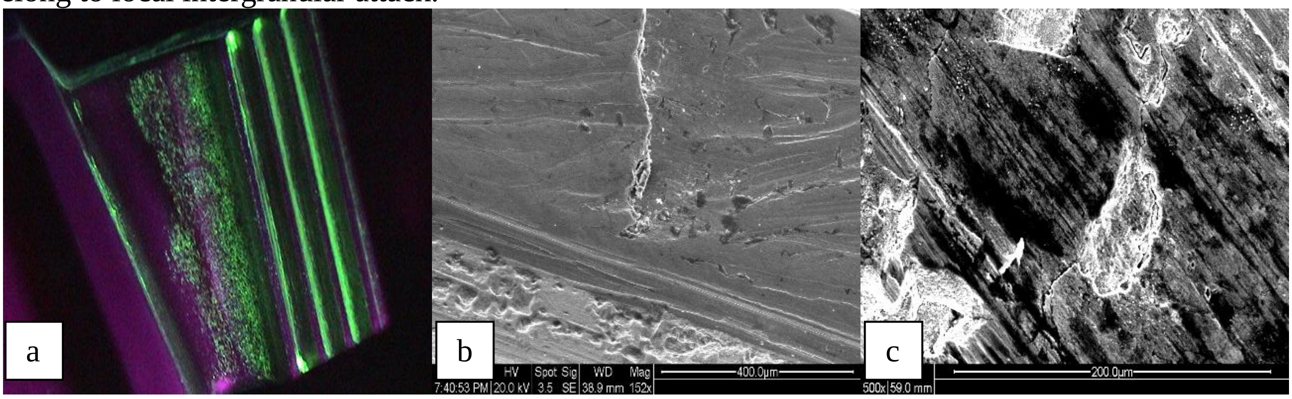
The fluorescence displays on serration is green, densely punctate or reticular.

1) Reticular displays: The few displays belong to local intergranular attack.

2) Machining damages on serration surface: The fluorescence displays on serration are densely punctate in most of blades. Microscopic observation results show that these damages are machining mark, flaking, peeling, step, surface micro-pit, or laps, which are damages caused by the broaching or grinding， as shown as in figure 6. All of these displays belong to the machining damage on serration surface.

2.3.2 Metallographic evaluation of machining damage on serration surface

To the fluorescence displays on the serration, chosen two turbine blades with punctate displays, and sectioned on transverse and longitudinal. The metallographic evaluation of machining serration surface was performed, the results as shown as in Table 2.




**a. Fluorescence Displays b. Step c. Peeling**

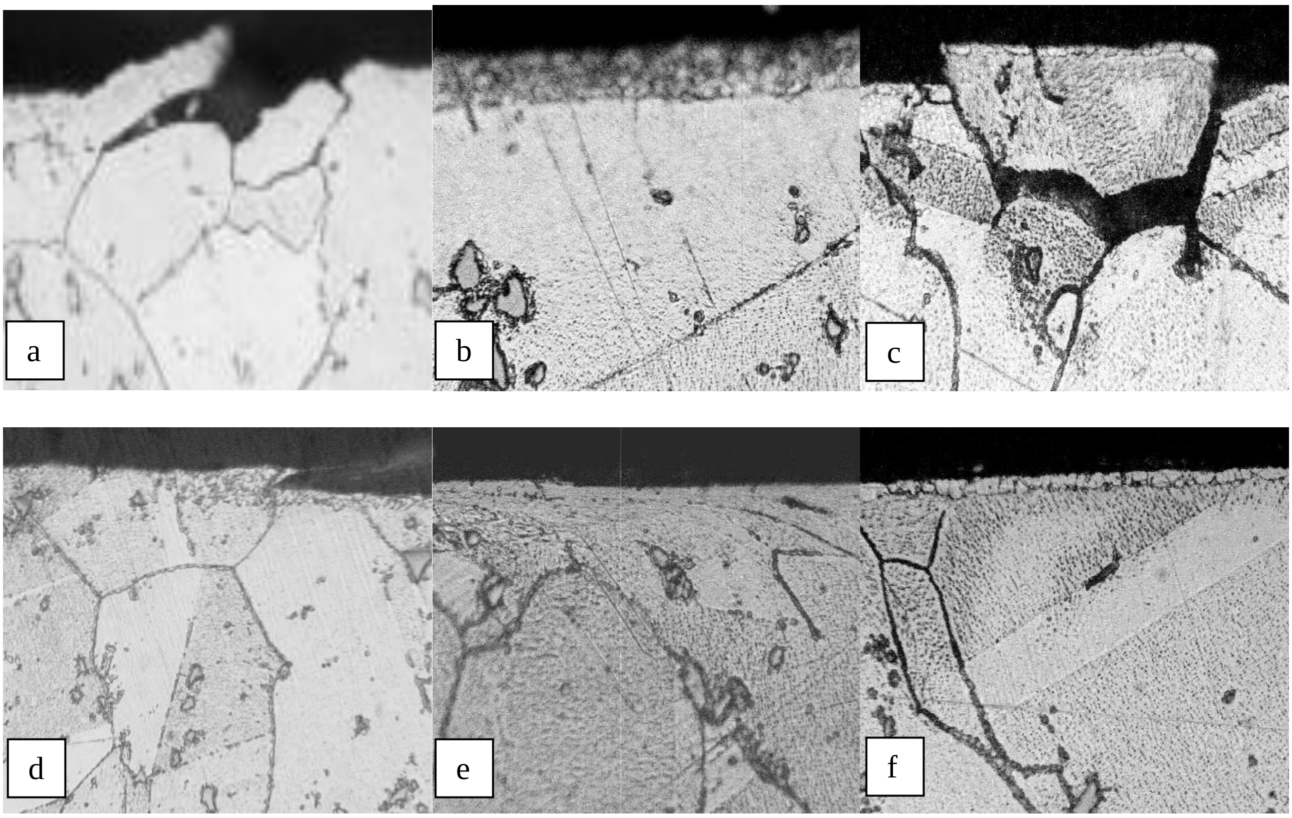
**Figure 6 Fluorescence displays on serration**

**Table 2 Evaluation results of surface state (mm)**

| Testing Item | Broaching | | Grinding | |
|---|---|---|---|---|
| | Longitudinal | Transverse | Longitudinal | Transverse |
| White layer | None | None | None | None |
| Re-deposited layer | None | Partial 0.017 | None | Partial 0.016 |
| Puckering | Individual 0.01 | None | None | None |
| Plucking | Individual 0.02 | None | Individual 0.01~0.031 | None |
| Cracks/Tear | None | None | None | None |
| Strain（Working hardening） | 0.014 | 0.006 | 0.012 | 0.006 |

The testing results show that the existences of work hardenings are distributed on the whole machining surface of serration. And local or individual positions exist the re-deposited layer, plucking, laps. Especially, there are grain loosening or peeling in individual positions, as shown as in figure 7.

The discontinuity of surface, which was caused by re-deposited layer, plucking, laps and grain loosening on the serration surface, leads to the fluorescence displays. And the machining hardening and recrystallization not only show the surface damage degree, but also show the quality of machining parameters.




**a. Plucking b. Re-deposited layer c. Grain peeling**

**d. Laps e Working hardening f. Recrystallization**

**Figure 7 Machining damage on serration surface**

## 3 Analysis and discussion of results

As mentioned as above, all of the fluorescence displays can be divided into three categories:

3.1 Local intergranular attack

This type of fluorescence displays is distributed at shroud, serration and trailing edge of body. And it accounts for 3% of the damaged blades. Grinding is used to manufacture the flank and top surface of shroud. Too large feed and inadequate cooling will lead to the local overheat on surface. If the incorrect polishing is used, it also lead to the local overheat. After the blades machining are finished, $FeCl_3$ etching will be performed for fluorescence inspection. Because of the local overheat on shroud and body, the electrochemical corrosion is inhomogeneous. Under the same etching medium and time, the overheat position caused by polishing will form the preferential intergranular attack. Therefore, at the prescriptive etching time, there has different etch state. At the overheat position, it is reticular overstriking grain boundaries and local intergranular attack. In adding, the displays on serration is related to poor protection.

3.2 Intergranular cracks

The intergranular cracks, which cover the 2% of total defective blades, include grinding cracks and thermal stress cracks. Because of the poor thermal conductivity of superalloy, there are two processes could form local friction heat: one is incorrectly grinding operation, too big feed, and inadequate cooling during shroud grinding; the other is too long polishing time, inadequate cooling during polishing. With the stack of thermal stress and structural stress, and the stress concentration and redistribution caused by chain carbides on grain boundaries, the grain boundaries became weakly, and formed intergranular cracks [7].

3.3 Machining damage of surface

Both of the body and serration have this type machining damage, which account for 95% in all of the damaged blades. And the machining damages on serration are representative. The test results in 2.3 show that these damage are surface damages caused by machining, such as flaking, peeling, heavily machining mark, surface micro-pits, step, loosening and peeling of grain, working hardening, surface working hardening(twist grain boundary and surface recrystallization layer), surface re-deposited layer, plucking, tears and laps. The formation of all these damages is related to the wrong machining parameters. Take grinding for example, the feed rate 50 mm/min, 90 mm/min, 120mm/min with wheel linear velocity of 22m/s, corresponding to the grinding depth 1.5mm, 0.3mm and 0.1mm, respectively. Using this processing parameter, the removal amount is 1.5mm after the first grinding. It will induce the deeply working hardening on serration surface. Also, too large material removal depth will produce more machining heat, and increase the damage of machining surface. The damage could affect the subsequent processing, decrease the processing capacity of metal, cause the adhesion of metal and wheel, and form the local flaking, plucking and re-deposited layer. In additional, the coolant flow was not specified in the processing guideline. It is unacceptable for the processing of intractable metals.

Analysis on the combination of related references and processing, the possible forming reasons of each defects are summarized [8-10].

1) White layer: lack of lubricant, high feeding speed, blunt tool, overheating;

2) Surface deformation layer: lack of lubricant, high feeding speed, blunt tool, overheating;

3) Redeposited layer: tool wear, chip embedded, chip entrainment, tool loosening;

4) Foreign material: embedding of tools or other foreign materials;

5) Plucking: too large cutting depth, tool wear/damage, embedding of chips;

6) Peeling: Too large cutting depth, tool wear/damage, embedding of chips;

7) Laps: the materials or burrs, which are plucked by machining, are pressed back to the surface in next process;

8) Work hardening/Strain line: Severe distortion on the surface which is induced by rapidly or excessively material removal.

9) Cracks: Excessive distortion on surface induced by overheat or too large strain.

All of the machining damages, which can induce severe reduction of fatigue property, belong to machining surface integrity. Therefore, the optimization of machining parameters to improve machining surface integrity not only solve the fluorescence defects on serration, but also improve the fatigue life of turbine blades.

## 4 Solving countermeasures

Aiming at the formation mechanisms and the corresponding process of the three types of defects, the combination of preventive measures were performed.

1) Because the local intergranular attack and the two types of intergranular crack relate to the local overheat induced by grinding or polishing, the following measures are carried out during the grinding, polishing and etching of blades.

i) To prevent local overheat and thermal stress cracks, the grinding feed is decreased and the coolant flow of grinding is increased;

ii) During polishing, increasing the feed frequency with the decreasing of feed, to prevent the local overheat and thermal stress crack caused by excessive polishing;

iii) Using rubber to protect the serration during etching.

As mentioned as above, this problem is solved effectively.

2) According to the formation position and processing of the machining surface damages, two methods are used.

i) Machining damages of serration mainly come from the processing of grinding and broaching, and relate to the machining tools, cooling and feed parameters. If using broaching processing, unchanging broaching structure, and fixing cutting speed and feed, the possible factors affected the machining surface state are:

a) Hardness difference of blades: mainly induced by the tiny difference in material compositions and heat treatment processing. When the components were broached at solid solution state, the difference in hardness is about 50HB. It will decrease the processing adaptability, and leads to the bad surface state.

b) Wear and damage of tools will lead to local chip embedding, plucking, flaking, step, severe distortion on surface, and laps.

c) Cooling flow in machining: sufficient cooling can prevent overheat and provide enough lubrication.

For the same bathes of material, the occurrence probability of machining defects is higher when the tools is too old or too new. So, the main formation factor of defects is related to the broach, which include coping angle, hardness, minimal defect of cutting edge, and so on. The secondly formation factor of defects is the tool adaptability to hardness difference (50HB). Controlling of solution temperature and cooling rate can reduce the difference, but cannot eliminate the difference.

According to the above mentioned analysis, this problem was solved by modifying the front angle of broach, improving the sharpness of tools, increasing the cooling medium flow, and determining the tool service life (acceptance amount of broaching blade).

Machining damages of body: these damages can be solved by using high frequency and low feed in grinding and polishing.

## 5 Conclusion

There are three types of fluorescence displays on the turbine blades: (1) local intergranular attack; (2) intergranular thermal stress cracks caused by grinding or polishing; (3) surface machining damage. The qualified rate of finished turbine blade is up to 95% by new proposed process optimization. And the solutions are only an apotheosis of study on lean machining. With the increase in engine performance, the service environment of components becomes worsening. Also, the manufacturing cost is increased. Hence, the control on surface integrity is research focus in future, because the lean machining could decrease the cost and improve the service reliability.

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Contact Author Email Address
Mailto: mar002@163.com

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