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Thermal Analysis and Microstructural Evaluation of Inconel 738LC Superalloy Gas Turbine Blade

M. Rayatpour[1], Z. Lalegani[1,*]

[1]Niroo Research Institute (NRI), Tehran, Iran.

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Abstract

The operational temperature of a gas turbine blade made of IN738LC superalloy was investigated. The component under evaluation was a first stage blade of a 25MW power plant gas turbine with the gas temperature of 943℃ in the first stage nozzle at the base load. The evaluation was carried out after 16000 h of operation in the mode of base load. To analyze the temperature distribution of the component, three 3D-models of the blade were prepared, meshed and analyzed using CFD software. The results indicate the higher temperatures in the upper section of the leading edge during steady state operation of the blade.To evaluate the reliability of this analysis, intermetallic$\acute{\gamma}$ coarsening behavior was examined as the most important microstructural changes of the alloy after long term service exposure. This metallographic analysis also approves increasing in temperature with height of the airfoil section.

Keywords: Gas Turbine, IN738LC Superalloy, Gamma Prime Coarsening.

1. Introduction

The IN738LC alloy is an intermetallic$\acute{\gamma}$ precipitation-strengthened nickel base superalloy, which is widely used as turbine blades in hot sections of gas turbine engines due to its outstanding strength properties at high temperatures as well as excellent hot corrosion resistance [1,2]. The microstructure of IN738LC superalloy, like other Ni-base superalloys, includes a non-magnetic γ matrix and precipitates which are mainly$\acute{\gamma}$, MC, and $M_{23}C_6$ carbides [3-5]. The turbine blade damage during the operation of power generation gas turbines can have a metallurgical root. Some factors affect the lifetime of the blade, such as temperature, load level, and thermal transient loads [5].

The information about temperature distribution of different parts of the blade is very important to evaluate the type and the amount of damages which can reduce the life of the component. This helps inspectors to determine the critical points of the blade for lifetime estimation. So, studying the operational temperature of the blade is one of the primary steps in various lifetime estimation techniques. An exact thermal analysis can lead into a more reliable remaining life prediction [6]. The conventional method for determining the blade temperature distribution is using the computational fluid dynamics (CFD) software.

Using the outputs, it is possible to have a thermal-mechanical analysis using finite elements method (FEM) to determine the mechanical and thermal stresses. Besides, understanding the correlation between microstructural degradation and changes in mechanical properties is necessary for deterioration evaluation of the blade alloy [5].

The major microstructural changes during long-term service operation of turbine blades include $\acute{\gamma}$ coarsening, changing in the morphology of $\acute{\gamma}$ particles, the formation of continuous $M_{23}C_6$ carbides along grain boundaries and needle-like phases within the grains. Among the mentioned changes, $\acute{\gamma}$ coarsening investigation is the most conventional method to examine the amount of damages [7].

In this paper, we evaluate the IN738LC superalloy first stage blade of a gas turbine with a 25 MW power plant and 750℃ gas inlet temperature.

The evaluation was carried out after 16000h of operation in the mode of base load. After temperature analyzing using suitable software, microstructure was studied to evaluate the reliability and the accuracy of these predictions.

Finally, the relations between software analysis and $\acute{\gamma}$ coarsening behavior are discussed. The turbine has 4 stages of nozzles and buckets.

The first stage buckets are made of IN738LC superalloy by using the investment casting and coated with thermal barrier coating (TBC).

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[*] *Corresponding author*
Email address: z.lalegani@ut.ac.ir

Table. 1. Chemical composition of IN738LC alloy (wt. %).

C	Cr	Ni	Co	Mo	Ta	Nb	Ti	Al	B	Zr	W
0.110	15.900	Bal	8.470	1.750	1.700	0.900	3.280	3.220	0.010	0.060	2.600

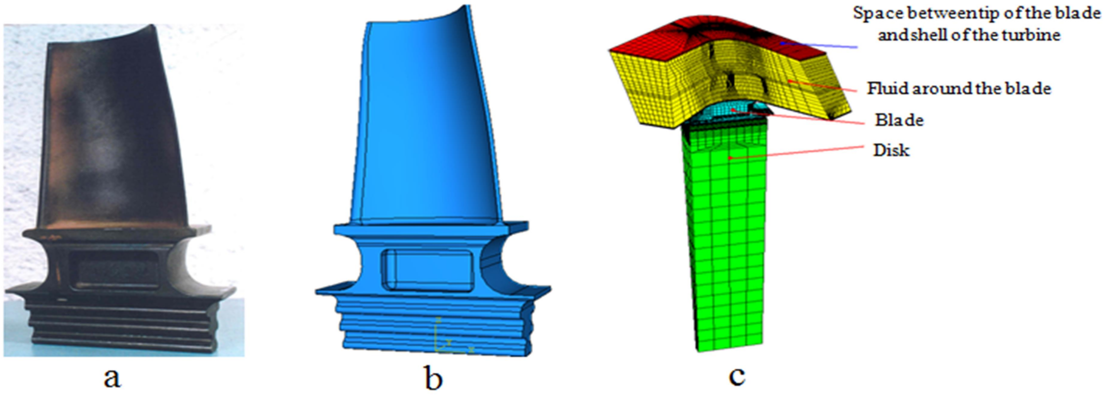

Fig. 1. a) A turbine blade, b) 3D model of turbine blade, and c) meshing model of blade, fluid and disk.

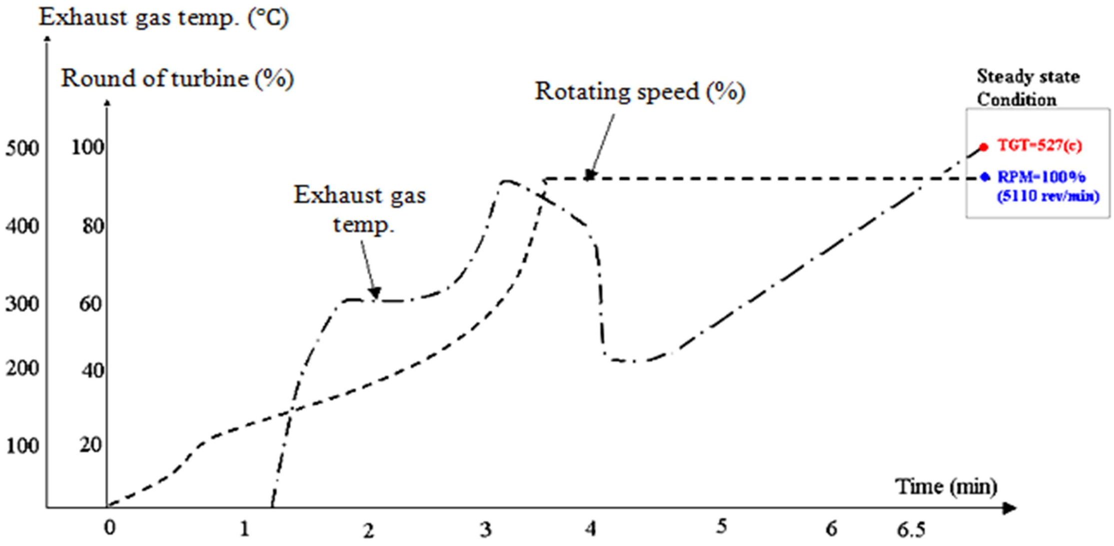

Fig. 2. Start up cycle of GE-Frame5 turbine to the end of loading stage.

2. Materials and Methods

Table. 1. given the chemical composition of this superalloy. At first, the 3D model of the turbine blade, turbine disk and the gas flow around the blade were prepared. The model was meshed using PATRAN software which allows applicants to work with very complicated geometrical models such as a turbine blade. Fig. 1. shows a typical turbine blade, its 3D geometrical model and the meshing model of the blade. After meshing, physical and mechanical properties of IN738LC superalloy and the properties of gaseous fluid were extracted. It was supposed that the mechanical and physical properties of the alloy and the fluid were time dependent. Afterward, according to start-up the cycle of the turbine to the end of the loading stage, the initial and boundary conditions for thermal analysis were extracted using the start-up cycle of the blade shown in Fig. 2. To determine the temperature distribution of the metal temperature, CFD analysis was performed using FLUENT software including transient and steady state conditions. The analysis was carried out from sparking stage to the steady state condition and the temperature distribution in all cross sections of the turbine blade was extracted versus time. To evaluate the microstructural changes of the blade after certain hours of operation, selected samples were cut from different parts of the blade. Samples were polished and etched using a solution of 10% perchloric acid and 90% water and then studied by a scanning electron microscope (SEM). Furthermore, the size of intermetallicγ' precipitates was determined by image analyzer software, and the average size of 30 particles was reported as the γ' size (diameter), in each area.

3. Results and Discussions

The Temperature distribution of 3D model of the whole blade and on its trailing and leading edge resulted from the thermal analysis were studied separately. Fig. 3. demonstrates the temperature contour of the blade in 4, 100 and 240 seconds after start-up and at steady state condition.

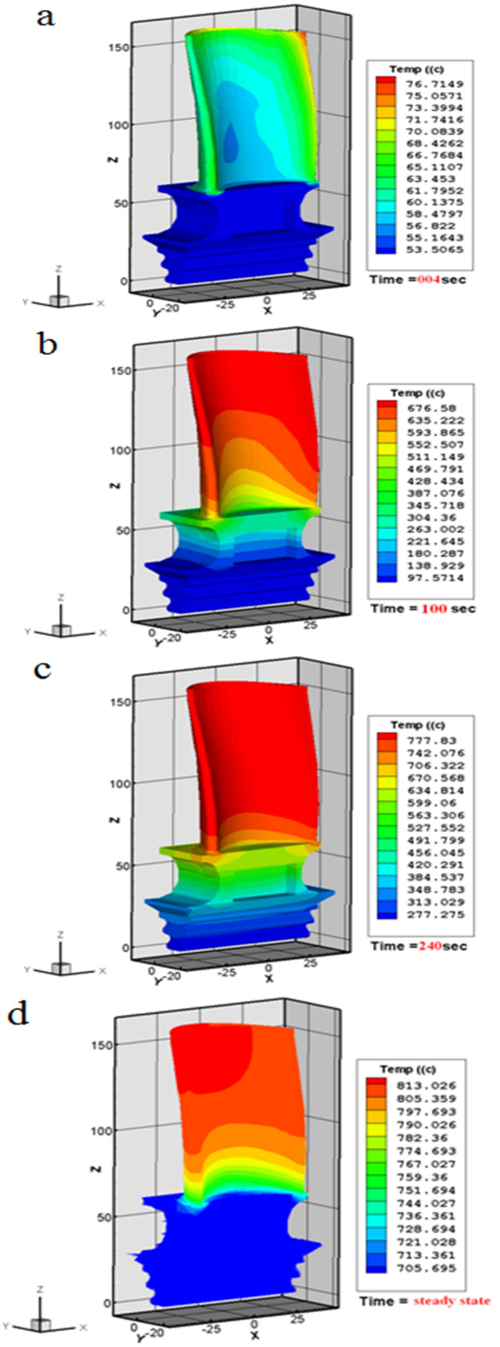

Fig. 3. Temperature distribution in blade surface a) after 4 sec., b) after 100 sec., c) after 240 sec., and d) in steady state condition.

According to the obtained results, it seems that during start-up, a thermal gradient is occurred in the blade which could result in thermal stresses due to the local tension and compression stress.

Also, in steady state condition, the maximum temperature takes place in the leading edge and in the 91mm to 96mm height of the platform that is estimated about 822℃.

Approximately, 50% of the airfoil (upper parts) is in the temperature range of 800℃ to 820℃. The temperature of the leading and trailing edge are demonstrated in Fig. 4. and Fig. 5. versus time. According to the temperature values of different parts of the edge of the blade, it can be concluded that the thermal stability of the trailing edge is more than the leading edge. To increase the reliability of the thermal analysis, studying the microstructural changes of the blade during operation which is proportional to its temperature, can be a useful way.

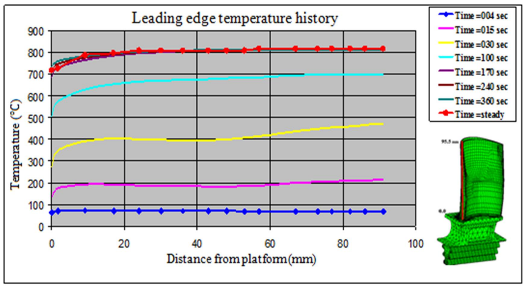

Fig. 4. Leading edge temperature vs. time.

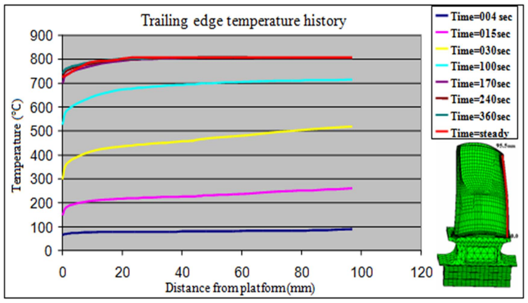

Fig. 5. Trailing edge temperature vs. time.

There can be various microstructural changes that take place in a blade made of Ni-based superalloy during service operation. These include: ý coarsening [8], changing in the morphology of ý from cubic to spheroid [9],the formation of the diffuse layer between superalloy and its coating which thickens with time [10],the formation of the continuous $M_{23}C_6$ carbides along grain boundaries, the formation of detrimental needle-like phases [11], and the changes in the chemical composition of the coating [10].

In another article, more and useful discussion about intermetallic ý precipitates in Ni-based superalloys is available [12].

In this case, γ́ coarsening with increasing the operating time can be a good indicator to determine the temperature changes in different parts of the turbine blade. The results of various investigations on superalloys in high temperatures after long-time operation indicate that precipitates drag solute atoms from the matrix and become larger. γ́ growth follows LSW model shown in Eq. (1). [8]:

$$r^3 - r_0^3 = kt \qquad \text{Eq. (1).}$$

Where r is the diameter of γ́ particles after service, r_0 is the diameter of γ́ before service (initial diameter in standard heat treatment condition), t is the duration of operation, and k is a value that is constant in a certain temperature [13,14]. As the growth of γ́ precipitates is a diffusion process, the value of k increases with temperature, and coarsening of γ́ particles after long-time exposure shows that the temperature could have been higher in those sections. Comparing the microstructures of different sections of the blade demonstrates that γ́ precipitates become larger than the sample which is selected in the root area. As the root temperature is lower than the value which can cause any detectable microstructural changes, this area could be a reference for the conditions of the alloy before exposure [15]. The microstructure of different parts of the blade is demonstrated in Fig. 6.

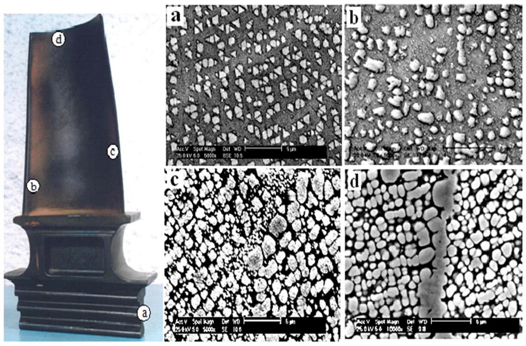

Fig. 6. Microstructure of different parts of the blade.

Fig. 7. shows the changes of γ́ size in different areas of the blade, such as the leading and trailing edge and the root area. These results are in a good agreement with those obtained from the thermal distribution analysis. Moreover, detailed examination shows that the sharp edges of the precipitates have disappeared in the root area of the airfoil. These results are also in agreement with other works on deformation of γ́ from edged particles to sphere, in IN738LC after long-time aging. In fact, the alloy moves toward lower internal energies after exposing in higher temperatures [16].

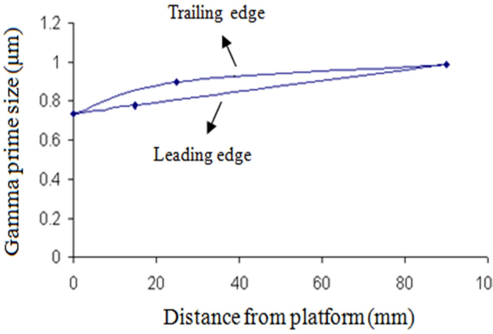

Fig. 7. Gamma prime size in different areas of the blade.

4. Conclusions

The operational temperature distribution of a gas turbine blade was simulated using a CFD software. Metallographic studies were carried out to implement the software analysis. Furthermore, microstructural evaluations were carried out to examine the reliability of thermal analysis. The results are as follows:

1. The results of thermal analysis indicate the increase in operational temperature moving toward the upper part of the airfoil and, the maximum temperature is estimated about 822℃ which is obtained in the leading edge.
2. Microstructural studies indicate that intermetallicγ́ precipitates have larger sizes in the upper area of the leading edge than the root and lower areas of the leading and trailing edge, which approves the results of thermal analysis using software.
3. The rate of disappearing the γ́ sharp edges in different part of the airfoil is higher in compare with those in the root area.

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