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Failure Analysis of Gas Turbine Blades

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Abstract

The failure analysis of gas turbine blades made of nickel-base alloy was carried out in two discrete sections:

- Mechanical analysis
- Metallurgical analysis

Using ANSYS Workbench 11.0 software (advanced CFD section), a steady state gas flow analysis was carried out, and the pressure and temperature distributions and velocity vectors and streamlines were delineated. Then, by mapping these results on the other section of it (simulation section), equivalent stresses and total deformation were determined.

The metallurgical investigation was carried out using visual examination, photographic documentation, non destructive testing (NDT), optical microscopy, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS). The surface of the blades are diversely colored, which may have represented the presence of some metal oxides, sodium, and sulfur. Also, these blades suffered both types of corrosion and erosion. DPI testing showed that there was a crack on both sides of a failed blade coating.

A detailed microstructural analysis of all elements that had influence on the failure initiation were carried out. Namely, micro-cavities were found on fracture surfaces that served as an origin of a creeping failure mechanism (the appearance of the fracture surfaces in the failed blade resembles a dimple-like fracture); decreasing of alloy ductility and toughness due to carbides precipitation in grain boundaries (formation of continuous films and dispersed particles of carbides); and degradation of the alloy γ' phase (irregular growing of γ' particles). It is found that the cracks in the coating act as an initiator for the thermal fatigue crack. The substrate intergranular crack initiation and propagation were due to a creep mechanism. Also, due to operation at high temperatures, many annealing twins were observed at different regions.

Introduction

Blade failures can be caused by a number of mechanisms under the turbine operating conditions of high rotational speed at elevated temperatures. In general, blade failures can be grouped into two categories: (a) fatigue, including both high (HCF) and low cycle fatigue (LCF) [1–6]; and (b) creep rupture [6–8]. Researches on evaluating the thermomechanical behavior for turbine blade materials that are made up of Ni base superalloys have garnered increased interest in recent years. These superalloys are the standard material for hot stages of gas turbines, where vanes and blades are subjected to high mechanical stresses and aggressive environments [9–23]. In Ni base superalloys, the presence of chromium is essential to assure high-temperature oxidation resistance, whereas other alloying elements are important to guarantee high-temperature strength, especially creep resistance. Other elements, such as aluminum and titanium, enable the precipitation of the γ' phase $(Ni_3(Al, Ti))$ during heat treatment, which strengthens the face centered cubic matrix (γ phase) [24–27]. Another kind of phase is also very important for the mechanical properties of nickel base superalloys (carbides). These particles are present in these alloys because it is very difficult to remove carbon during refining and because carbon is added on purpose to form carbides, which improve creep properties [24, 27].

The aim of this work is to evaluate the creep-fatigue properties of the first and second stage blades under cycling duty. To identify this, a complete metallurgical investigation with mechanical analysis was carried out.

Background

The blades used in a gas turbine were damaged during servicing. The accumulated service time of the blades is more than 10 years. The blade material is specified as IN738LC alloy (Cr: 16; Co: 8.5; Ti: 3.4; Al: 3.4; Fe: 0.3; Mo: 1.75; W: 2.6; Ta: 1.7; Si: 0.1; balance: Ni). Figures 1 and 2 show the rotor and stator of this turbine, respectively. The first stage blades were badly damaged, while the second stage blades remained relatively whole.

Visual Inspection

The macroscopic features of the blades were observed by visual examination and photographic documentation. These inspections showed the different regions on the surface of the blades at the convex and concave sides.

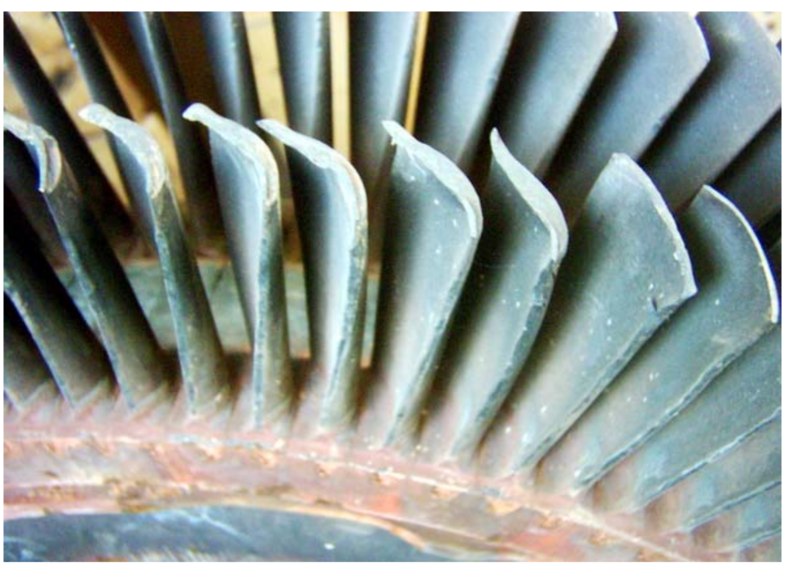

Figure 1: Deformation of Rotor Blades

Figure 2: Failed Stator Blades

As can be seen from Figure 3, in the vicinity of the platform both sides of the blades were rough and exhibited diverse colors, especially reddish, greenish, and dark brownish regions. Using X-ray diffraction (XRD) and X-ray fluorescence (XRF), Khajavi et al. found that these colors represented the presence of iron oxides, Cr_2O_3 and NiO, as well as Na and S [28–31]. Loss of materials and thickness (that may have been caused by interaction of different mechanisms such as hot corrosion, or erosion, and creep or fatigue [30]) was observed at the whole of the blades. Also, dye penetrant inspection (DPI) testing found that there was a crack on both sides of the failed blade coating.

Experimental Procedure

The chemical composition of the material was determined by energy dispersive spectroscopy (EDS). The microstructure of the blades was observed by optical microscopy and scanning electron microscopy (SEM). For these investigations, we prepared several longitudinal and transverse sections from the blades. These specimens were polished by standard techniques and were etched by solution of 5ml $CuSO_4$, 50ml H_2O, and 50ml HCl.

Microstructural Evaluation

Metallographic prepared sections were initially examined in an optical microscope and, subsequently, evaluated in a scanning electron microscope equipped with an EDS spectrometer.

Figure 4 shows that the coarsening of grain boundary precipitates in the top section of service exposed second stage blades because of creeping degradation that was taken by optical microscopy. The distribution and morphology of strengthening phase γ' precipitates in the top section of the second stage blade, as shown in Figure 5. As can be seen from this figure, the coarsened γ' size is in the range of 0.5–2 μm in this section. Moreover, the large size coarsened γ' precipitates are surrounded by the γ' denuded zone (darker regions), devoid of secondary γ' precipitates. Figures 6 and 7 show carbides precipitation in grain boundaries that is represented in the formation of continuous films (including 39.8 percent Cr) and dispersed particles (include 9.6 percent Ti) of carbides, respectively. Carbides precipitation results in decreasing of alloy ductility and toughness.

Figure 3: The Rough Surface Shows Diversely Colored

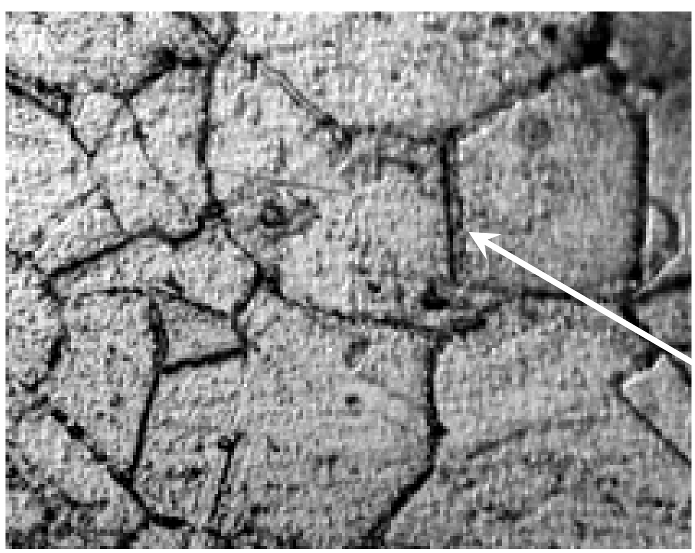

Figure 4: Coarsened Grain Boundary Precipitates ($200\times$)

Crack Evaluation

There were a large number of cracks at different regions of blades because of operation at high temperatures and stresses over a long period of time. Some of these cracks are shown in Figures 8–11. In Figure 8, we observe an intergranular crack on fracture surface. The appearance of the fracture surface in Figure 9 resembles a dimple-like fracture. The dimple-like appearance can be attributed to the microcavities, which could be related to intergranular decohesion of carbides [29, 32]. These microcavities serve as the origin of a creep failure mechanism [29, 33, 34].

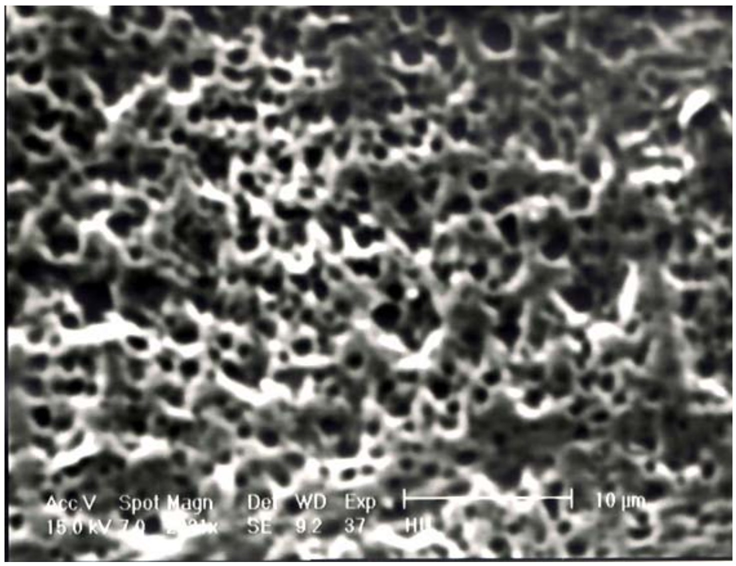

Figure 5: The Large Size of Coarsening-Coalescence of γ' Phase

Figure 6: Continuous Films of Carbides Precipitates

Figure 7: Dispersed Particles of Carbides Precipitates

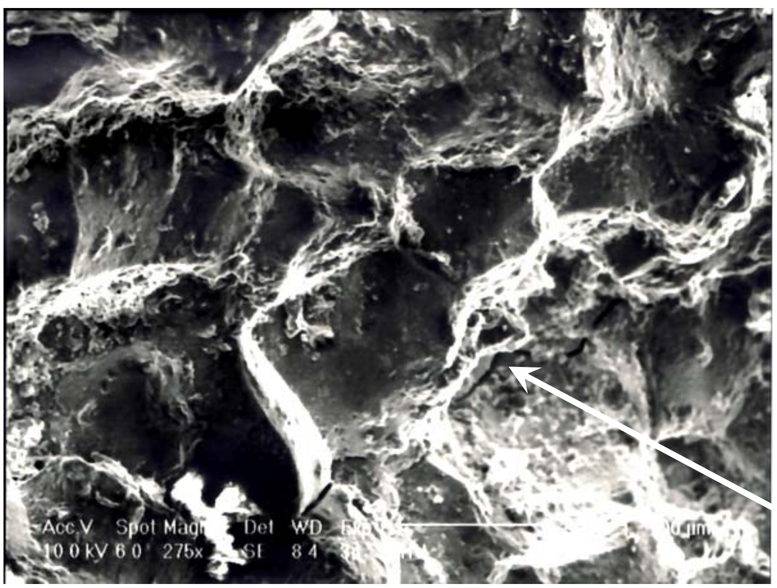

Figure 8: Intergranular Fracture Morphology (There is a crack on fracture surface.)

Also, we observed an intergranular crack on the first stage blade coating (Figure 10) and several intergranular cracks that were located on transverse section of the blade surface (Figure 11). The coating crack initiation was probably due to a thermal fatigue mechanism, as a result of high thermal transient loads (i.e., trips, start-ups, and slow-downs) and crack grain boundary initiation and propagation in the substrate by a creep mechanism (high steady state loads) [33].

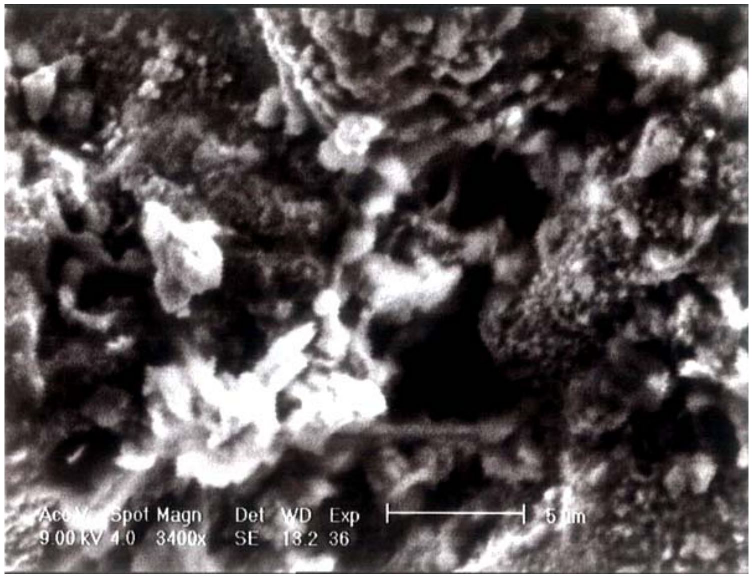

Figure 9: Dimple-like Microcavities Found on Fracture Surface

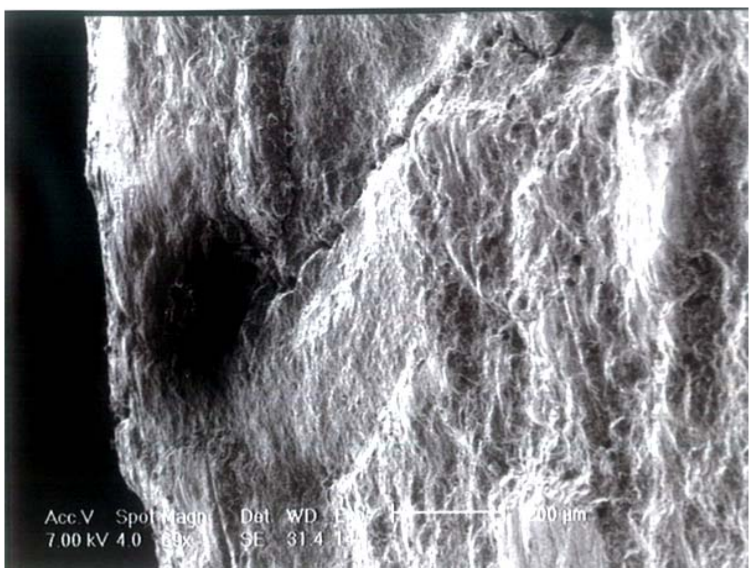

Figure 10: Intergranular Crack on the Coating

As the other result of the creep failure mechanism, we found grain detachment in the second stage blade that is shown in Figure 12. As seen in this figure, there were several macrocracks on grain boundaries.

One of the important deformations in metals is the process known as twinning. Twins may be produced by mechanical deformation or as the result of annealing following plastic deformation. The first type is known as mechanical twins, and the latter are called annealing twins [35]. In this study, many annealing twins (Figure 13) were observed at different regions.

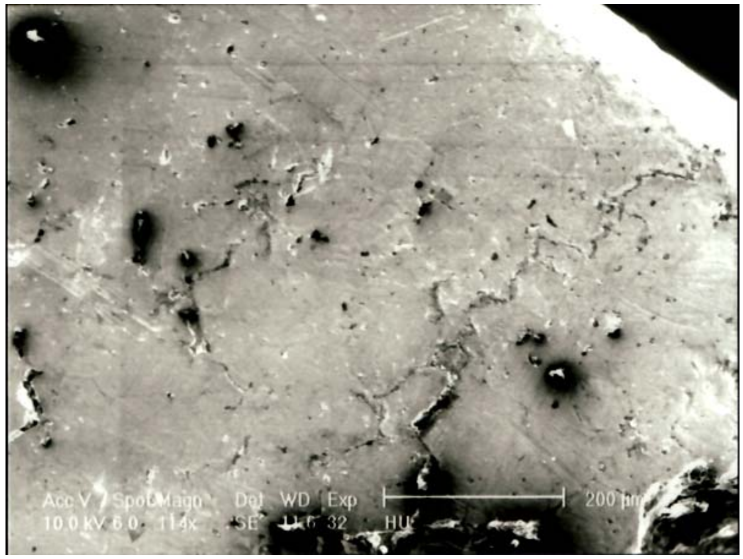

Figure 11: Several Intergranular Cracks on Transverse Section of the Blade Surface

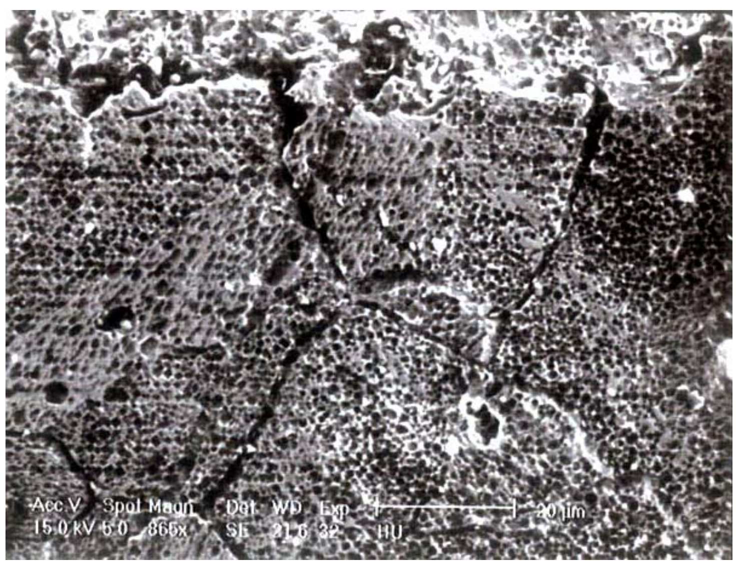

Figure 12: Several Macrocracks on Grain Boundaries Due to Creep Mechanism

Mechanical Analysis

A steady state gas flow analysis was carried out by means of Advanced CFD, which is a section of the ANSYS Workbench 11.0 software; then, by mapping these results on the simulation section, the stress analysis was carried out. Since the rotor and stator of this turbine had 83 and 76 blades, respectively, a complete modeling solution took a long time, so we modeled two blades of rotor and stator with consideration of correct boundary conditions.

Temperature and pressure contours showed consistence with real conditions (Figures 14, 15, 16, and 17). Note that at these figures, the stator and rotor blades were located left to right, respectively. Figures 18 and 19 show the magnitude and direction of flow velocity by use of velocity vectors and streamlines, respectively. The stress analysis simulated the steady state behavior of the rotor first stage blade under service conditions where the centrifugal load, gas pressure load, and thermal expansion are present. The equivalent stresses and total deformation plots for a blade are shown in Figures 20 and 21, respectively. The peak stress of the blade occurred at the bottom firtree, not at the topsection of the blade where failure occurred. It is, therefore, unlikely that blade failure was directly related to centrifugal and gas loading.

Figure 13: Annealing Twins Taken by Optical Microscopy ($200\times$)

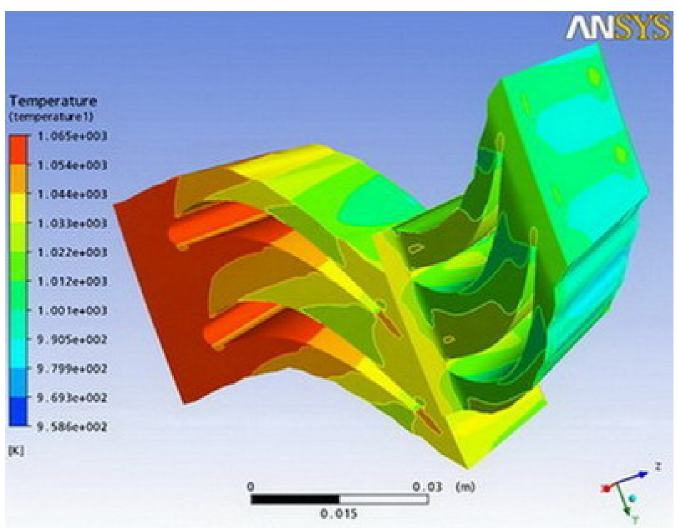

Figure 14: Fluid Flow Temperature Distribution around the First Stage Blades

The cause of the rotor blade failure may be increases in blade length and contact between blade tip and casing as a consequence of creep after an extended period in service.

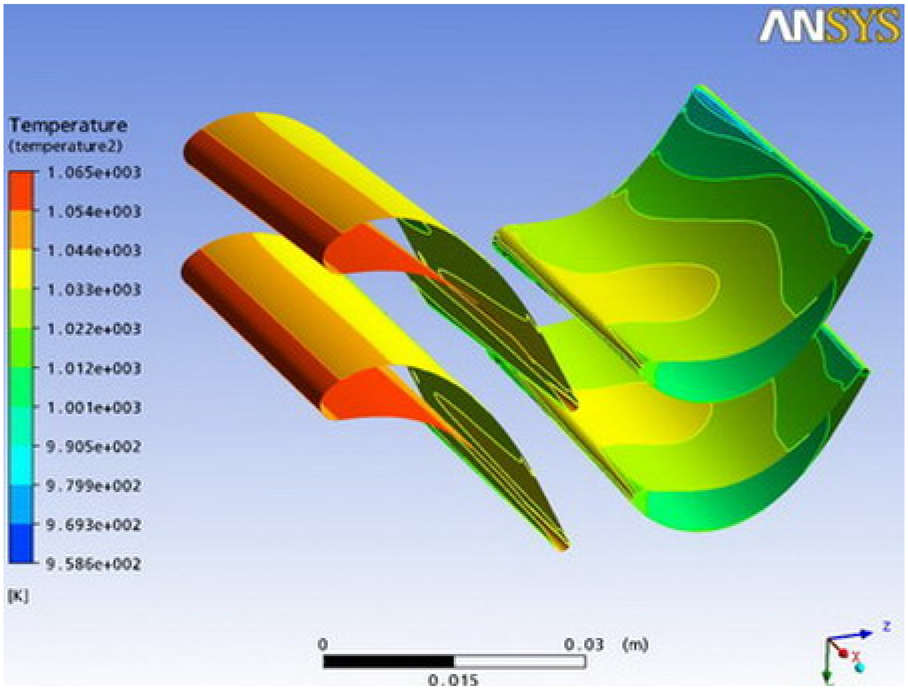

Figure 15: Fluid Flow Temperature Distribution on the Stator and Rotor Blades

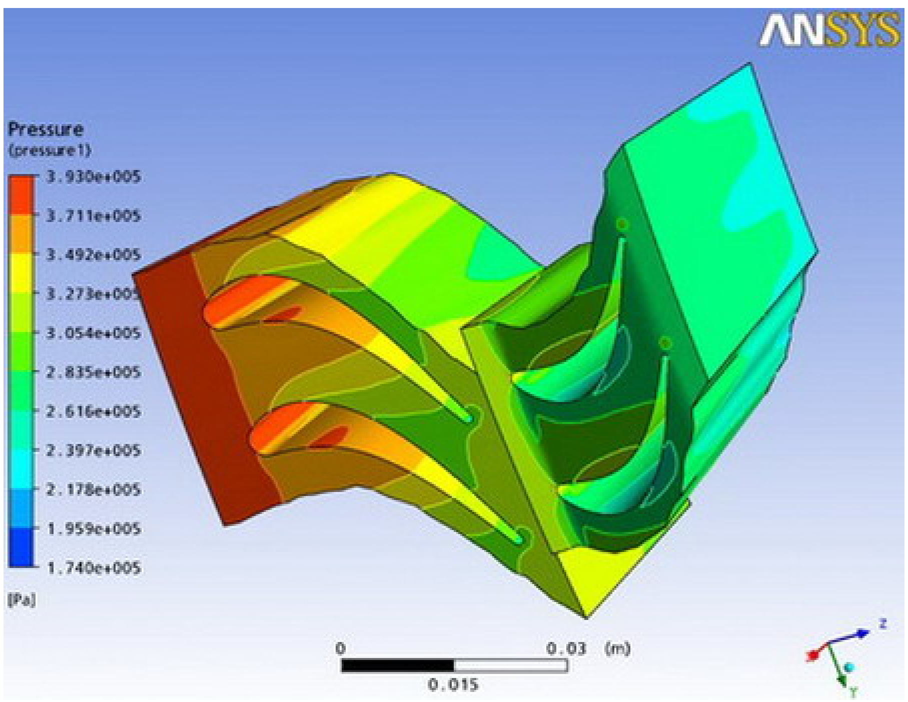

Figure 16: Fluid Flow Pressure Distribution around the First Stage Blades

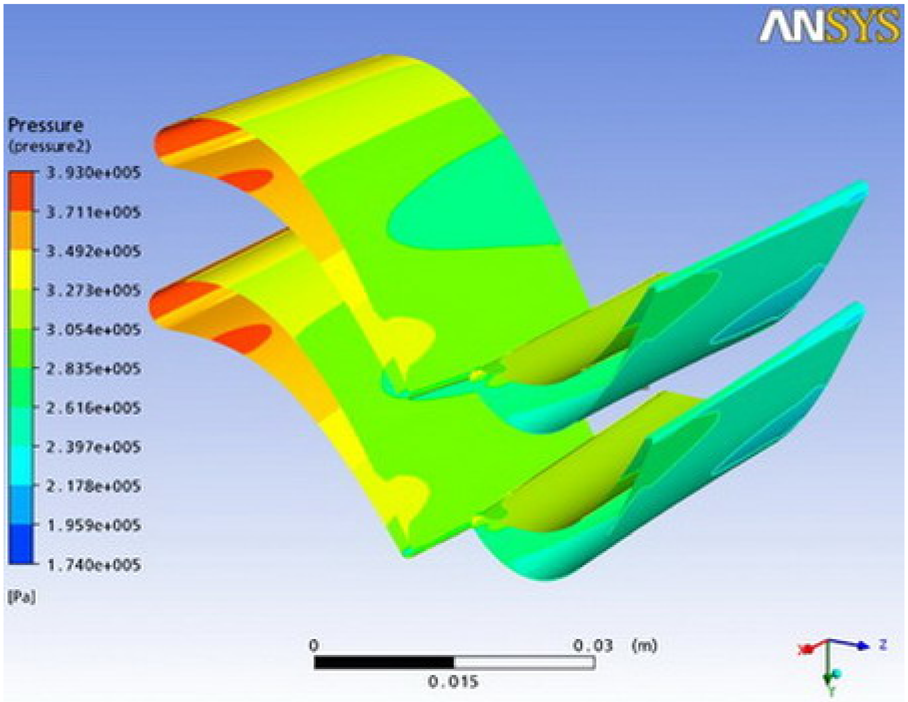

Figure 17: Fluid Flow Pressure Distribution on the Stator and Rotor Blades

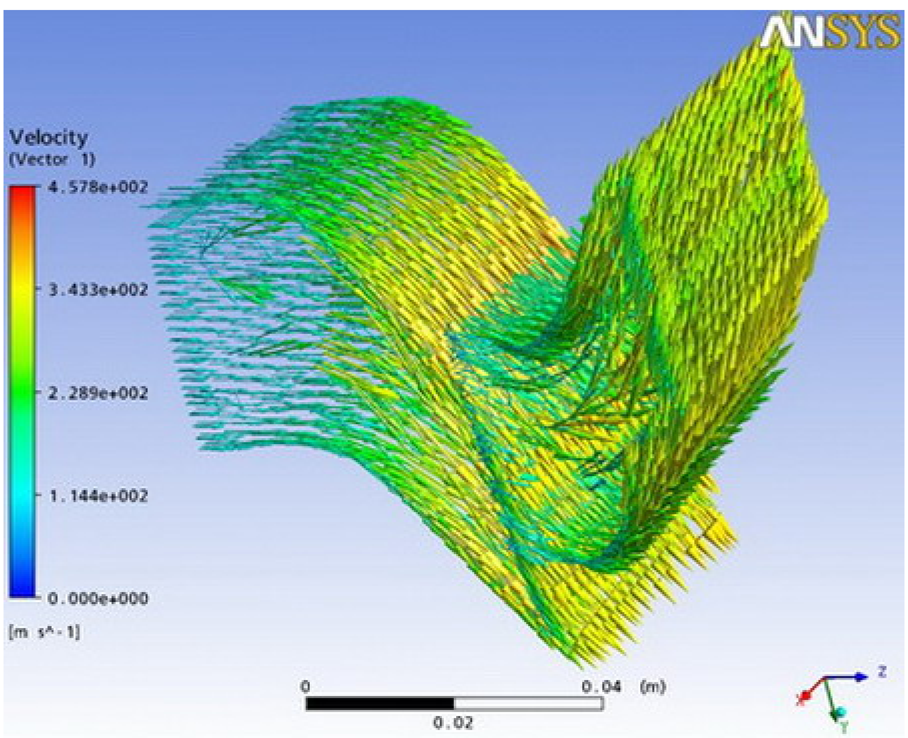

Figure 18: Fluid Flow Velocity Vectors

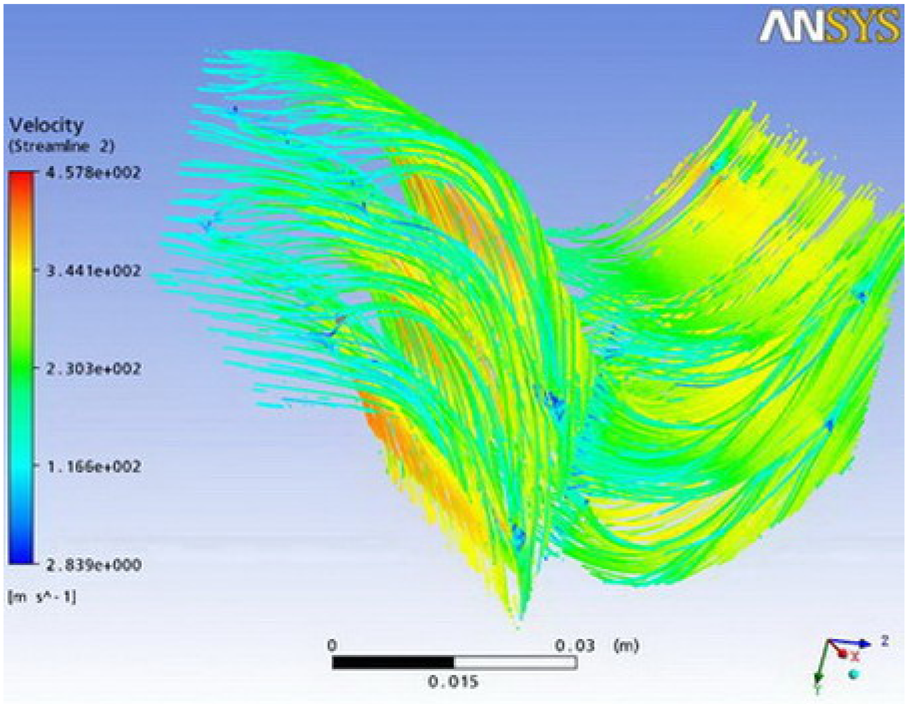

Figure 19: Fluid Flow Velocity Streamlines

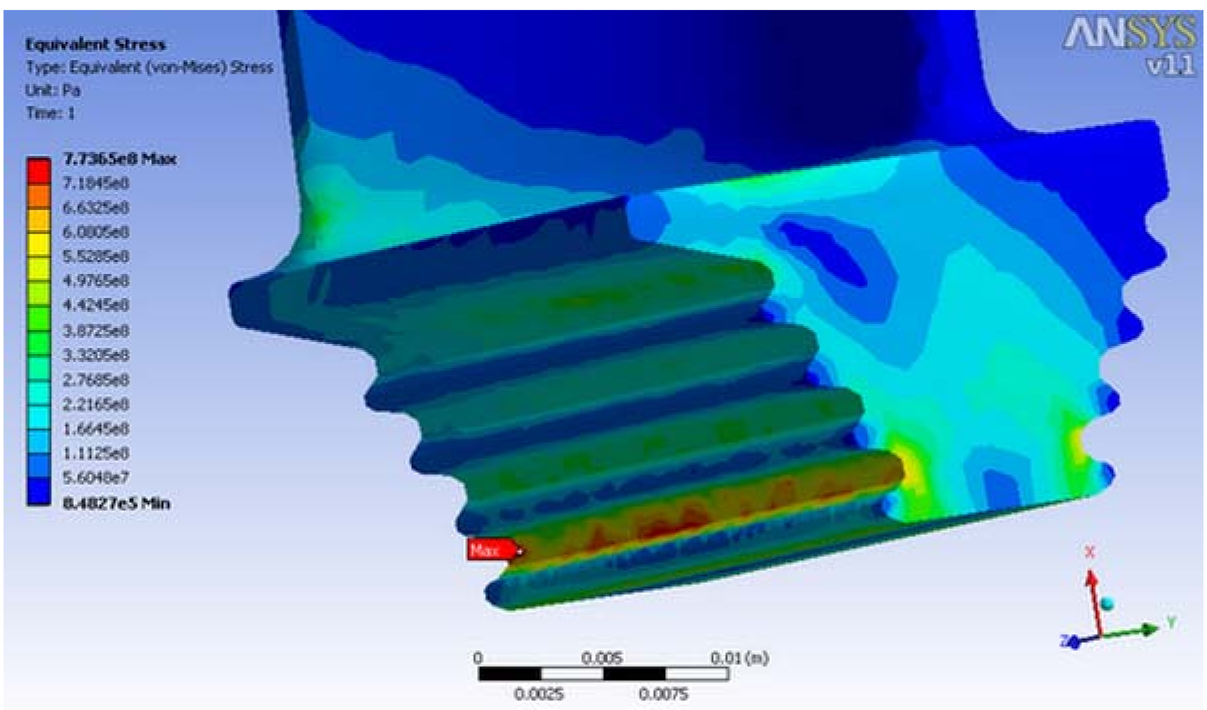

Figure 20: Resultant Stress Distribution for the Rotor Blade

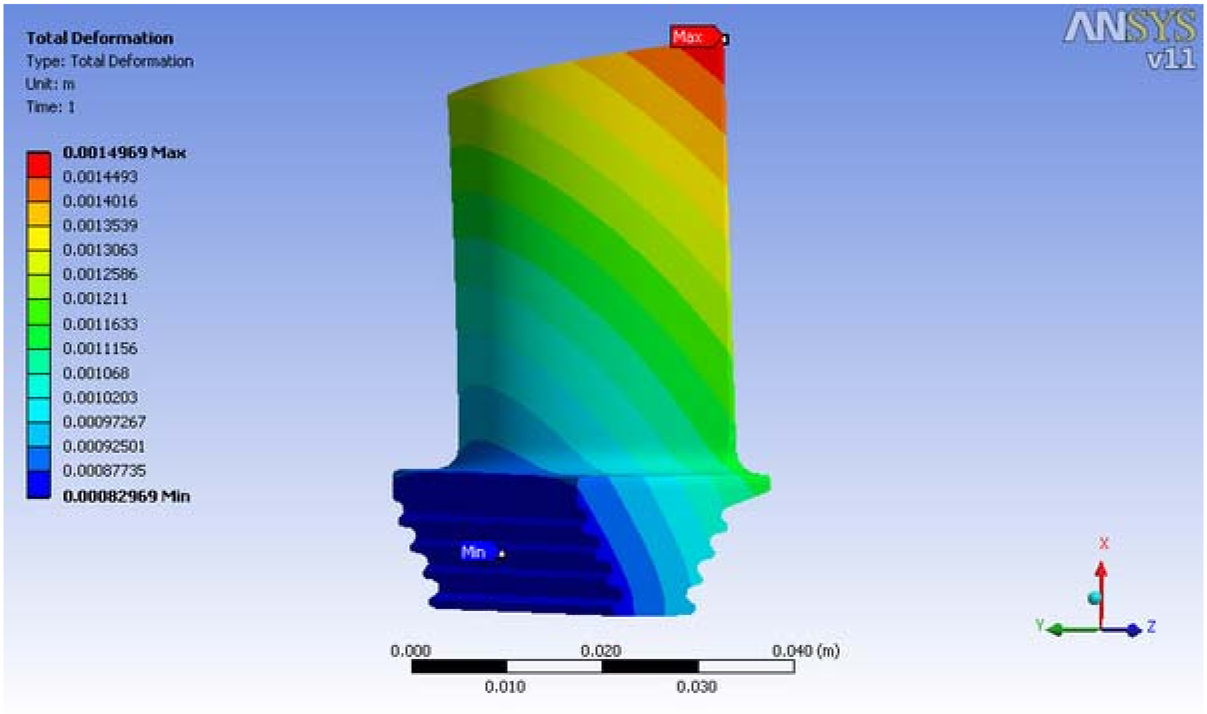

Figure 21: Total Deformation of the Rotor Blade

Conclusion

The failure analysis of a gas turbine with first and second stage blades made of nickel-based alloy was investigated. The accumulated service time of these blades is more than 10 years. This investigation was carried out by mechanical and metallurgical analysis.

After visual examination and photographic documentation, it is found that the surface of the blades exhibit diverse colors that may have represented the presence of iron oxides, Cr_2O_3 and NiO, Na, and S. Also, in the vicinity of the platform, both the convex and concave sides of these blades were very rough and appeared to have corrosion and erosion. The microstructural investigation of the blades revealed the presence of continuous and dispersed films of carbides in grain boundaries and coarsened γ' precipitates resulting from exposure to extreme temperatures and subsequent operation. There were a large number of cracks at different regions of blades because of operation at high temperatures and stresses for a long period of time. An intergranular crack was found on the failed blade coating; there were some micro-cavities on the fracture surface that served as the origin of a creep failure mechanism; there were several intergranular cracks on transverse section of the first stage blade surface. Also, due to operation at high temperatures, many annealing twins were observed.

A steady state gas flow analysis was carried out by means of Advanced CFD, which is a section of Workbench ANSYS 11.0 software. Then, by mapping these results on the simulation section of this software, the stress analysis was carried out. Temperature and pressure contours and the magnitude and direction of flow velocity showed consistency with

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real conditions. It is found that the blade failure was not directly related to centrifugal and gas loading. Finally, it is thought that the cause of the rotor blade failure may be increased in blade length and contact between blade tip and casing as a consequence of creep after an extended period in service.

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Biography

Mehdi Tofighi Naeem is currently a postgraduate student at K. N. Toosi University of Technology. He joined the university in the Department of Mechanical Engineering in September 2005. He is currently working on his thesis.

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