Paper 134,ENG108

Analysis of Metallurgical and Mechanical Failure of a Centrifugal Compressor

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Abstract

The present paper reports the investigation of a sudden failure of a two stage centrifugal compressor that was used in the oil industry. This study is composed of two sections: metallurgical and mechanical. The first section was carried out in the laboratory, and in the second one, the impeller was modeled by Mechanical Desktop (MDT) and analyzed by Ansys Workbench software. Then, the results of both sections were compared and validated.

The impeller was subjected to a series of examinations, including a visual inspection, photographic documentation, non destructive testing (NDT), optical microscopy, scanning electron microscopy (SEM), and quantometer. Samples from the longitudinal and transverse sections of the disc were prepared for metallography. The morphology of the fracture surfaces and fatigue striations are shown through the use of SEM. It is observed that the fracture surface created by the fatigue crack is smooth, but the initial crack looks coarse.

On the fracture surface, there are curved lines called chevron markings that seem to converge near mid-thickness of the fracture surface. Investigation shows that because of long periods of operation and cyclic loads, the impeller was subjected to fatigue damage. Fatigue cracks grew to a critical size and caused the catastrophic failure of the impeller; also, creep mechanisms accelerated this phenomenon. A visual inspection and photographic documentation of the second stage impeller have revealed the presence of many cracks of different lengths at different regions of the damaged impeller, on both the disc and cover. It is observed that cracks originated from the junction of the disc and blade, where there is stress concentration. Then, these cracks propagated and caused the fracture of the impeller.

In the software analysis, pressure, thermal, and stress distributions under operating conditions were identified, and critical points were found.

Introduction

Apparently, the most common mode of failure in metallic parts is fatigue. Determination of a maintenance policy after the occurrence of a fatigue failure in service is based on finding the number of loading cycles that caused the failure [1]. The compression of gas within a plant is integral to the oil industry, too. It is thus of the utmost importance that premature failure of these pieces of equipment be avoided [2]. The rupture of metal parts is a complex phenomenon that depends on the nature of the material (composition, structure, and morphology), temperature, the deformation or excitation mode (traction, flexure, fatigue, etc.), and the rate at which strain is applied [3, 4]. An examination of the fracture surfaces can provide information regarding the origin and cause of the fracture; these causes may include the apparent heterogeneity, ductility, and, sometimes, the grain size. When a metal piece breaks, two major questions should be answered: what are the modes and speed of rupture, and what is the origin of the damage (metallurgical failure, manufacturing defects, etc.) [3]?

Damage tolerant fatigue design methods for critical rotating components, such as discs and shafts in gas turbine engines, are well established. These address crack propagation through the application of fracture mechanics, assuming defects are present in the material. The prediction methods have limitations; but at lower temperatures, these are conservative. It is not clear, however, if similar conservatism is valid at higher temperatures where additional failure modes due to creep and environment interact with those arising from fatigue [5].

In this study, we focus on a two stage centrifugal compressor that failed during the operation. Failure analysis is carried out to delineate the cause of failure. This compressor is made of low alloy steel by quenched and tempered treatment. The rotor is composed of two impellers, one of them for the first and the other for the second stage. The impellers have been constructed by welding the blades to the cover, and all of these parts were made by forging.

Visual Inspections

After the compressor disassembling and the rotor removal, it was evident that the second stage impeller was catastrophically broken. A visual inspection of the second stage impeller revealed the presence of many cracks, on both the disc and cover (Figures 1 and 2).

Fortunately, the crack often leaves a series of fracture markings in its wake that may indicate the relative direction of crack motion. For example, the curved lines (called chevron markings) that seem to converge near mid-thickness of the fracture surface (shown in Figure 3) have been shown to point toward the crack origin. It is believed that, within the material, localized separations ahead of the crack grow back to meet the advancing crack front and form these curved tear lines. All one needs to do is follow the chevron arrow. When a crack initiates in a large component, it sometimes branches out in several directions as it runs through the structure. Although the chevron markings along each branch will point in different directions relative to the component geometry, it is important to recognize that the different sets of chevron markings all point in the same relative direction—back toward the origin. Chevron markings grow radially from an internally located origin [6].

The assembly of the compressor was dismantled. Dye penetrant inspection (DPI) and magnetic particles tests were carried out to detect the defects on the impeller (Figure 4). Since cracks and failures were so clear, even without using these tests, all of them were noticeable.

Figure 1: Fracture on Cover

Figure 2: Fracture on Disc

Figure 3: One Sample of Impeller and Chevron Markings on its Fracture Surface

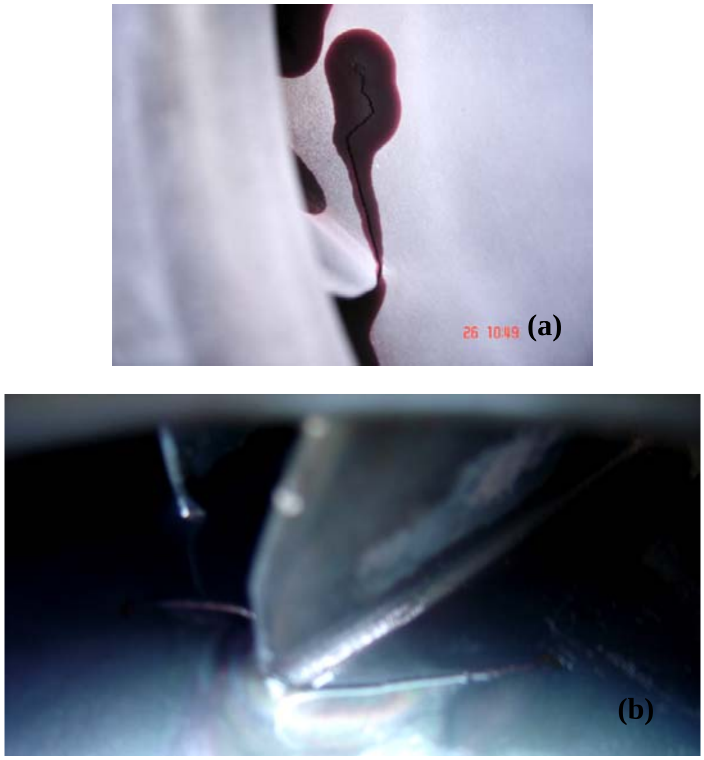

Figure 4: Crack around the Blade, (a) DPI, (b) Magnetic Particles

Chemistry

The chemical composition analysis of the failed impeller using the quantometer shows that it is similar to ASTM A514 Steel, grade F, as shown in Table 1. Also, the composition and mole fraction of the inlet gas to the compressor are illustrated in Table 2.

Table 1: Chemical Composition of the Impeller

Composition	Impeller	ASTM A514 Steel, grade F
Fe	96.3	97
C	0.0887	0.1-0.2
Si	0.214	0.25
Mn	0.820	0.8
P	0.0114	
S	0.0243	
Cr	0.527	0.48
Mo	0.487	
Ni	0.968	0.85
Al	0.0461	
Co	0.0139	
Cu	0.305	0.33
Nb	0.002	
Ti	0.0354	
V	0.0594	0.06

W	0.0150	
Pb	0.0250	
Sn	0.0020	
B	0.0026	0.0030
Ca	0.0010	
Zr	0.0020	
As	0.0050	

Table 2: Chemical Composition of Inlet Gas

Composition	CH_4	C_2H_6	C_3H_8	n-C_4H_{10}	I-C_4H_{10}	C_5H_{12}	C_6H_{14}	H_2S	CO_2	N_2
Mole fraction%	87.3	5.74	2.42	0.8	0.41	0.52	0.14	0.07	2.51	0.09
Molecular weight	16	30.1	44.1	55.1	58.1	72.2	86.2	34.1	44	28

Metallography

Samples from the longitudinal and transverse sections of the disc were prepared for metallography. Polished samples were immersion etched in the nital's reagent (5 percent nitric acid + alcohol) until grain boundaries appeared. In structural review, by considering the comparison of longitudinal and transverse sections, the morphology of grains shows that they are coaxial and have the same dimensions in different directions; therefore, mechanical strength of this part is nearly equal in different directions.

Also (as can be seen in Figure 5), there are macrocracks on grain boundaries. They are the resultant of creep mechanisms. First, isolated cavities are formed on boundaries; then, the quantity of them increases and oriented cavities are made. Next, these cavities join together and form microcracks and macrocracks, respectively.

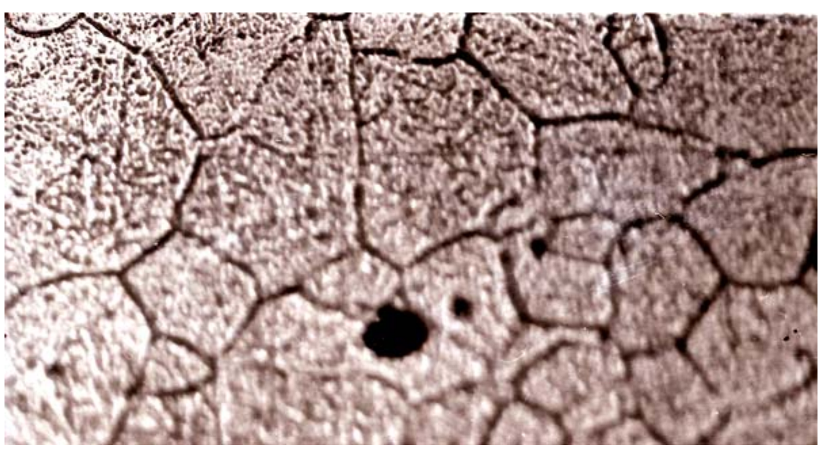

Figure 5: Macrocracks Have Formed on Grain Boundaries (200×)

Fractography

The fatigue fracture surface of the impeller was cut to be observed by SEM. As shown in Figure 6, the fracture surface created by the fatigue crack is smooth, but the initial crack looks coarse [7]. Figure 7 shows a part of cover coating that was removed due to fatigue. Figure 8 displays cracks on the fracture surface. Figure 9 shows fatigue striations, and in Figure 10, the detachment of grains due to the creep mechanism is clear.

Microscopic striations on fatigue fracture surfaces were first observed by Zapffe and Worden [8] in 1950 using optical microscopy. Forsyth and Ryder [9] subsequently showed that each striation was produced by one cycle of stress of examining fracture surfaces of specimens subjected to simple program loading. These observations showed that striations often have a saw tooth profile [10].

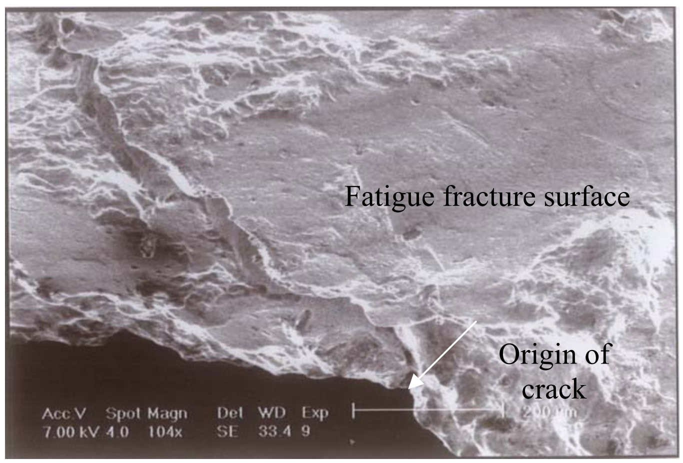

Figure 6: Fatigue Fracture Surface

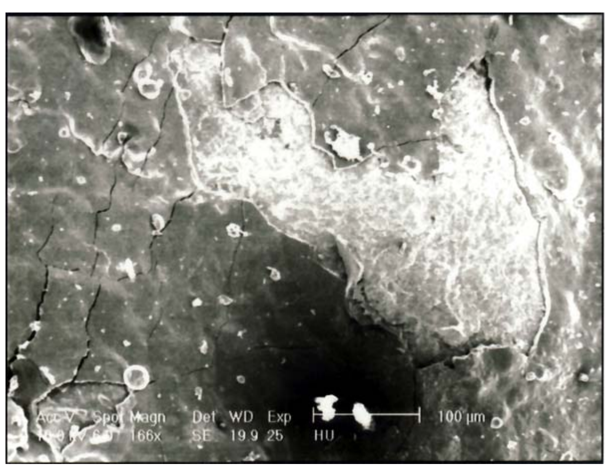

Figure 7: Fatigue Cracks on Cover Coating

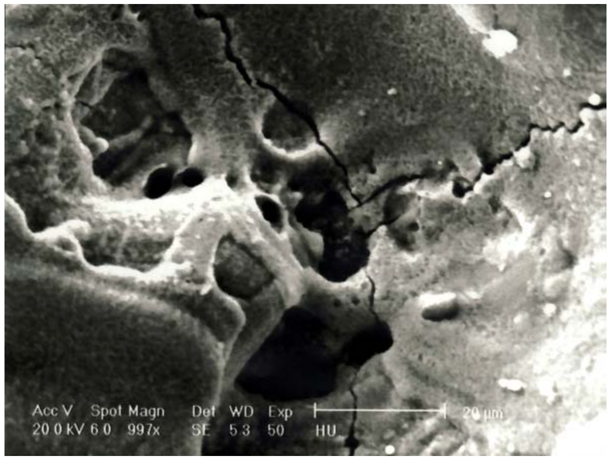

Figure 8: Cracks on Fracture Surface

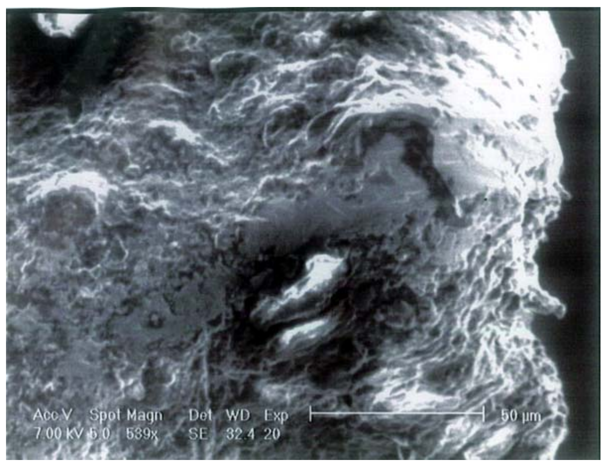

Figure 9: Fatigue Striations

Figure 10: Detachment of Grains Due to Creep Mechanisms

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Mechanical Section

In this section, we modeled the impeller and flow of gas with Mechanical Desktop (MDT) modeling software. Here, element of fluid (flow of gas) is called core. Figures 11 and 12 show the mechanical model of the impeller and its core, respectively. As can be seen from the series of figures below, pressure and temperature distributions and streamlines and velocity vectors of flow were analyzed by using advanced CFD (Figures 13–17).

From Figure 13, it is clear that pressure values vary from 134 bars at inlet to 140 bars at outlet. These changes were made layer-by-layer in gas flow. Temperature variations are similar to pressure, too. Temperature magnitude has changed from 326 to 328.5 K (Figure 14).

Apparently, velocity values change from 90 m/s at inlet to 137 m/s at outlet. In Figures 15 and 16, velocity streamlines are observed. By making a comparison between Figures 16, 18, and 19, we found that there is a positive agreement between practical and analytical results. In practice, it was observed that critical points were put at the junction of the disc and blade. On the other hand, we analyzed the impeller using software, and the resultant was similar. Because of the high flow velocity (approximately 169 m/s) at these points and mechanical design (vertical connection) between the blade and disc, the result is a zone of stress concentration. The stress contour is shown in Figure 19, and the position of maximum stress is clear in Figure 20. By considering pressure and temperature contributions, we understand that these parameters increase along the flow path. Also, observing velocity magnitude shows us that its magnitude increases at outlet. These results have a good agreement with real conditions.

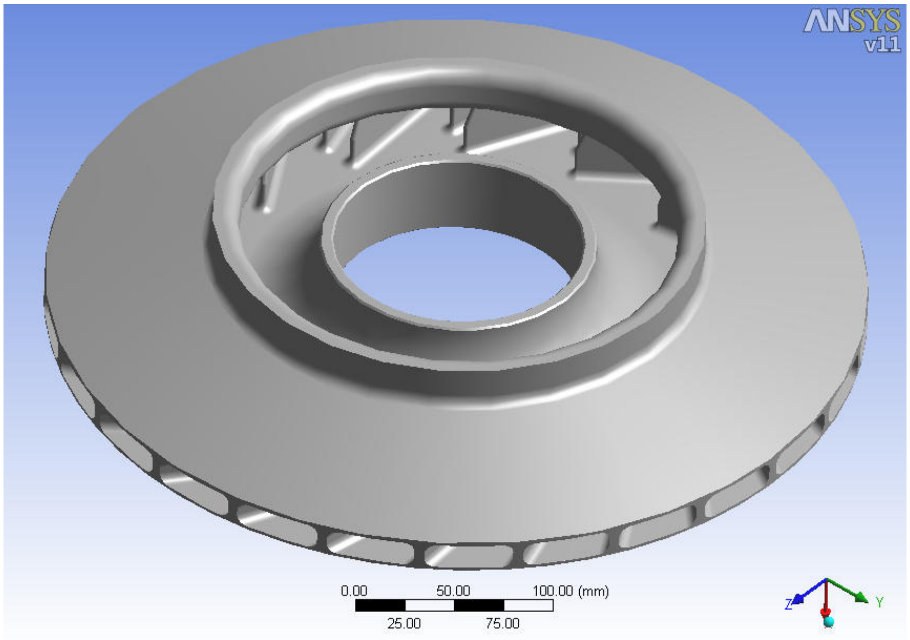

Figure 11: Mechanical Model of the Impeller

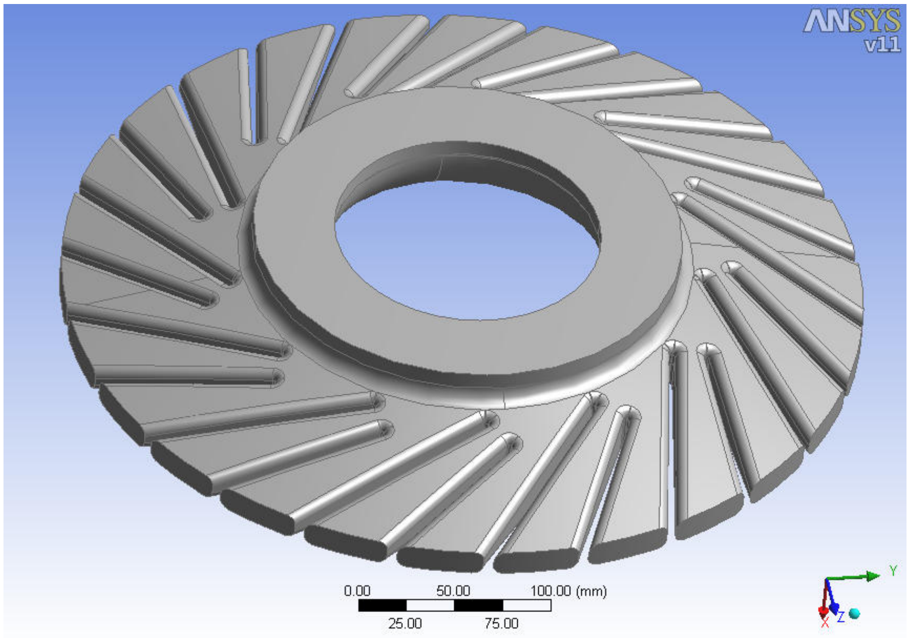

Figure 12: Mechanical Model of the Core

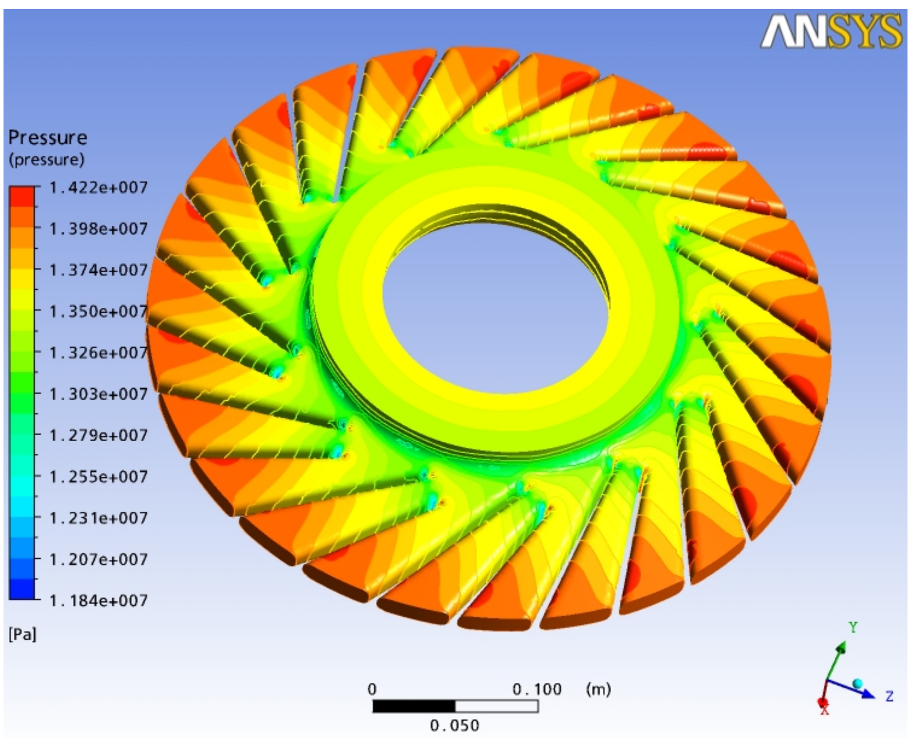

Figure 13: Flow Pressure Contour

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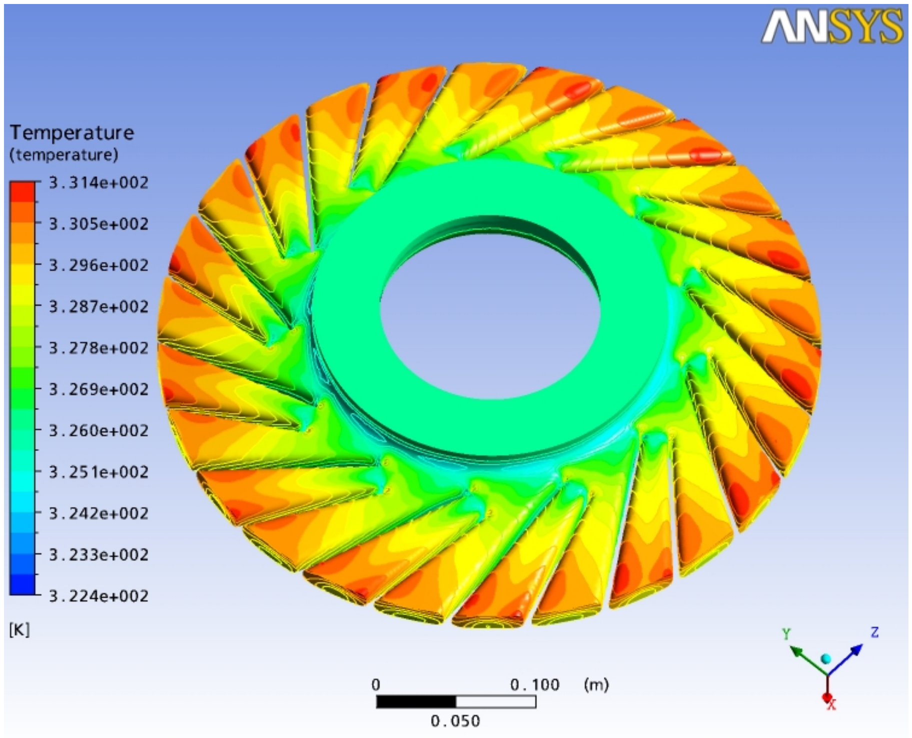

Figure 14: Flow Temperature Contour

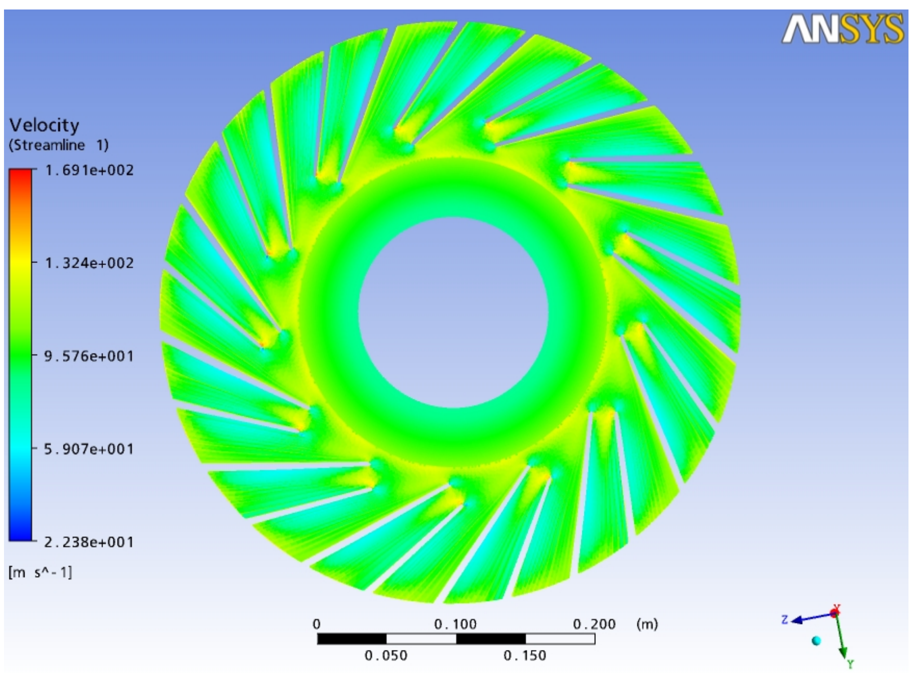

Figure 15: Velocity Streamline (Top View)

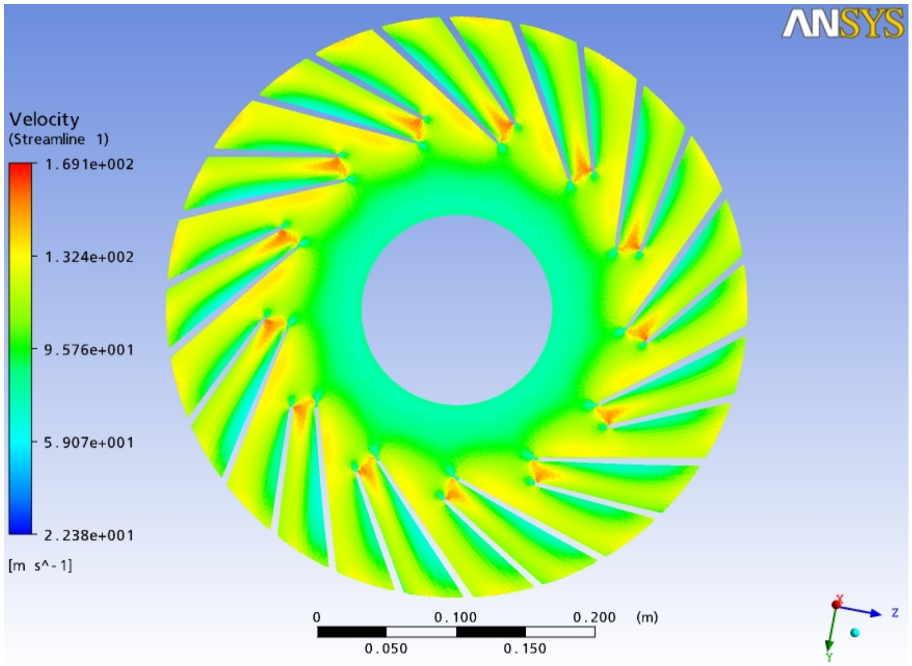

Figure 16: Velocity Streamline (Bottom View)

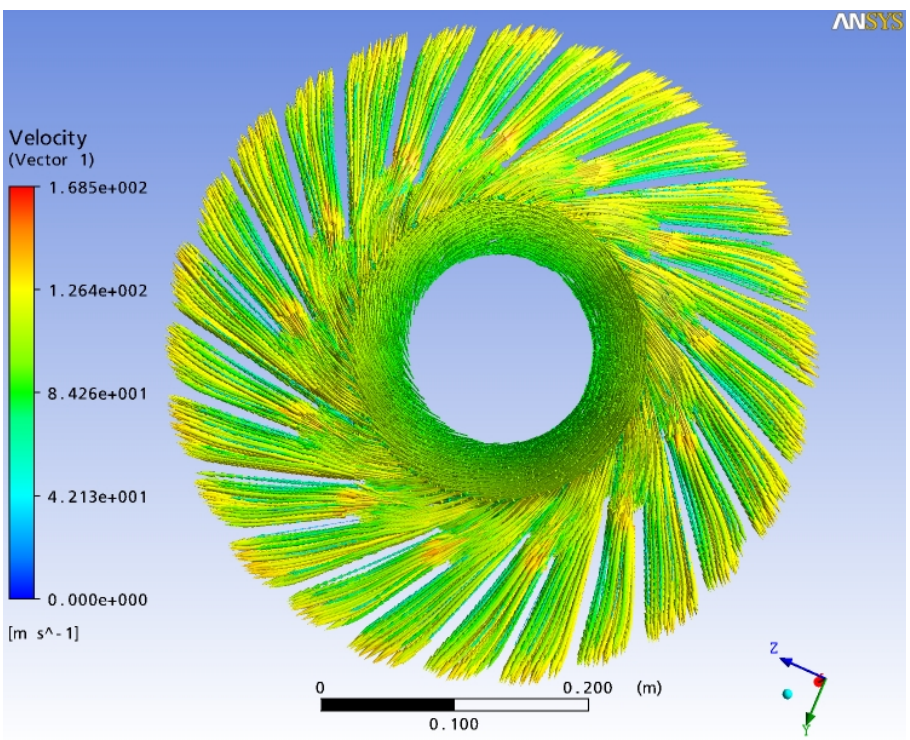

Figure 17: Velocity Vector

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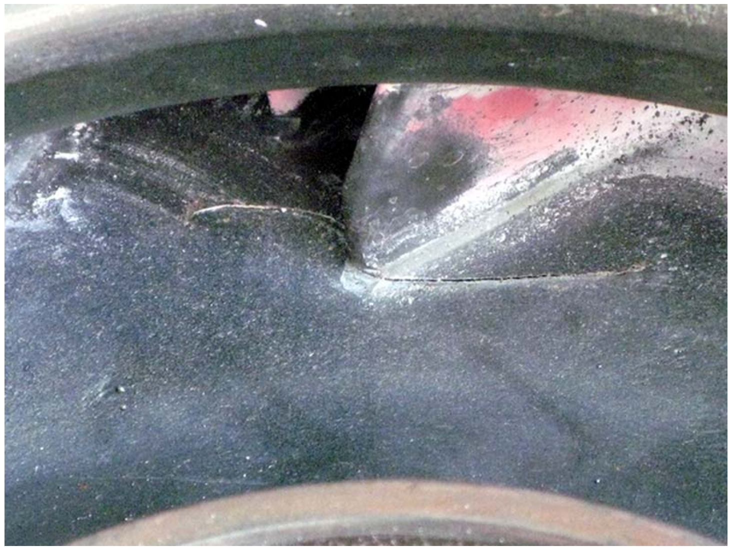

Figure 18: Crack at the Junction of Blade and Disc

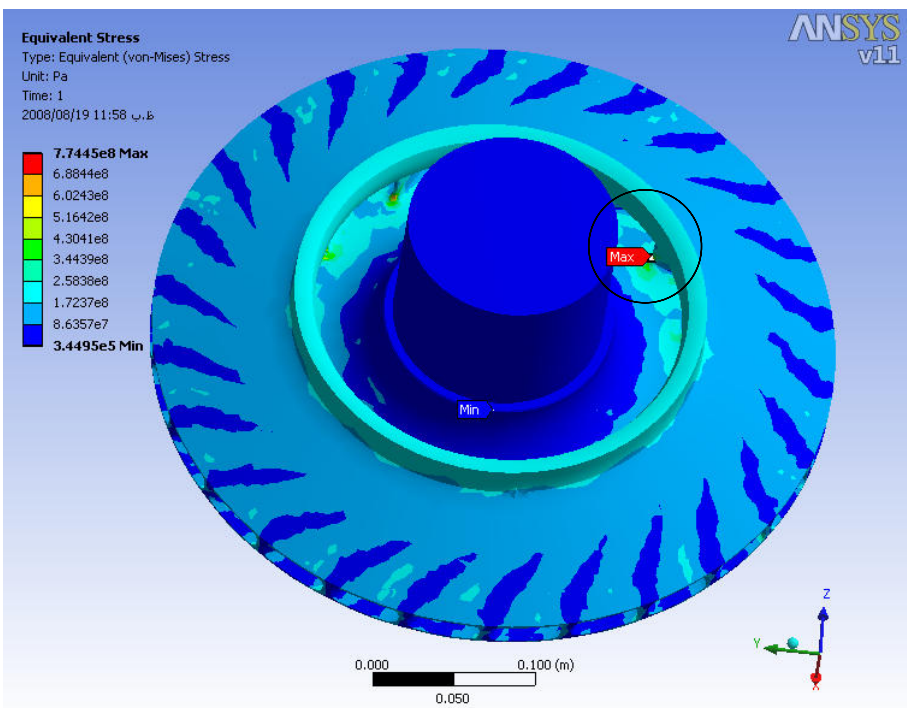

Figure 19: Stress Distribution

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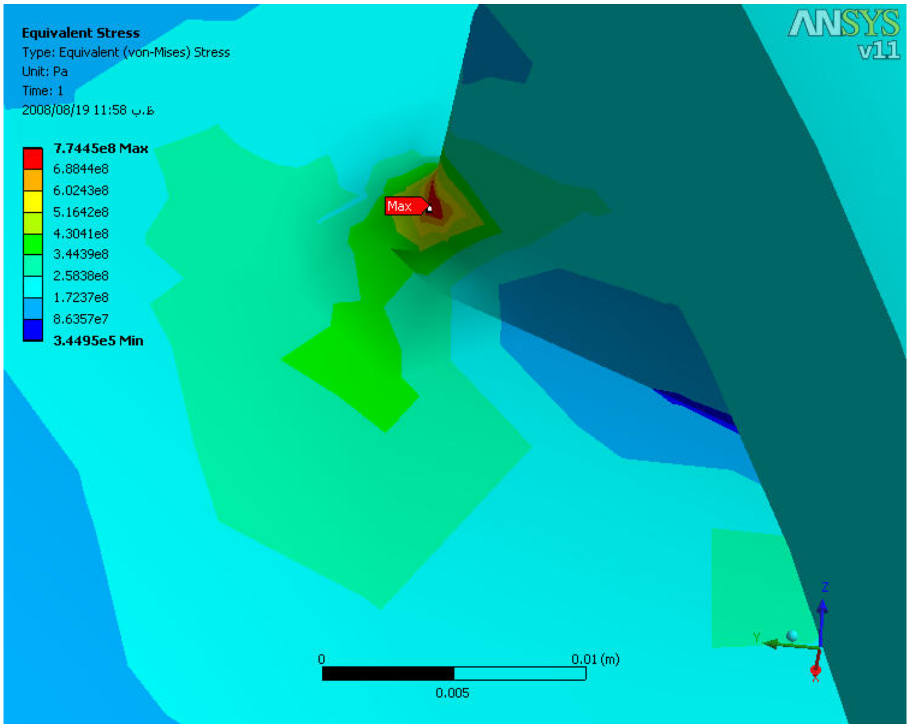

Figure 20: Stress Concentration

Conclusion

The failure analysis of the second stage impeller of a two stage centrifugal compressor after 81,000 hours of an operation period is carried out. Visual examination, photographic documentation, and non destructive testing (NDT) revealed the presence of many cracks on both the disc and cover and different sets of chevron markings.

After microstructural investigation by optical microscopy, it is found that there were some macrocracks on grain boundaries, which were the resultant of creep mechanism. Also, fractography by SEM showed fatigue striations. Furthermore, some fatigue cracks were found on fracture surfaces.

It is assumed that the accident happened from a fatigue crack through continued operation and changes in operational conditions.

Also, these observations were confirmed by mechanical analysis that carried out with Ansys Workbench. Therefore, there is a good agreement between practical and analytical results. These observations illustrate that the failure of this impeller has occurred on the basis of a creep-fatigue mechanism.

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Biography

NESA REZAMAHDI is currently a postgraduate student at K. N. Toosi University of Technology. She joined the university in the Department of Mechanical Engineering in September 2005. She is currently working on her thesis.

ISBN 978-1-60643-379-9