

Case study on the failure analysis of turbojet compressor blades

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Abstract

With a turbojet compressor that had its blades fractured during laboratory tests, this work carried out a failure analysis aiming at characterizing the problem, identifying the fracture mechanism and proposing a potential post-manufacturing improvement. Typical steps of a failure analysis were performed, including visual and fractographic analyzes via stereomicroscopy and scanning electron microscopy. The evidence indicated that the component failed due to fatigue, with the presence of very evident striations on the fracture surface, due to a high surface roughness. Therefore, it was considered suitable to propose a shot peening treatment on the product as a way of inducing residual compressive stresses and hindering the process of nucleation of a fatigue crack.

Keywords: Failure; Fatigue; Roughness; Machining.

1 Introduction

The part considered as the object of analysis in the present study is a turbojet compressor used in the aeronautical field. The compressor makes up an aeronautical engine that has a growing market in the Brazilian economy, especially with regard to turbojets intended to equip cruise missiles, target drones and unmanned aerial vehicles [1]. It is illustrated in Figure 1. Due to industrial secrecy, the alloy and the manufacturing process of the component are not disclosed, as is the case of the present work, but it is known from market knowledge that this component is made from aluminum alloys and manufactured through casting and machining processes [3].

As with the turbojet compressor, metallic engineering components subjected to mechanical stress can fail. A failure can be defined and understood at different levels within an industry and in the engineering field. At its most basic, failure is represented by the operational deficits of an element/equipment that operates, but does not reach its levels of excellence. At an intermediate level, the failure of an element/equipment can lead to the loss of its lifespan, that is, it can operate, however in a shorter period than stipulated, with the need for maintenance and even possible exchanges. At the advanced level, the failure can cause risks to the environment in which the element/equipment is located and it becomes inoperative, as it fractures [4]. Failure analysis comes precisely to investigate the mode and processes involved in the propagation of the failure and determine its root cause to mitigate future occurrences of fractures.

One of the most common fracture modes is fatigue. Fatigue occurs due to the infinitesimal propagation of cracks

from the surface to the interior of the component as a result of the stress state fluctuation of the material that composes it, given by the cyclic or dynamic loading, which varies over time [5]. In general, cracks are nucleated due to the presence of stress concentration surface defects, such as notches or irregularities in the roughness profile, or by the appearance of small discontinuities (steps) on the surface of the mechanically loaded material, called intrusions and extrusions, which are generated by the interpolation of different crystalline lattice slip systems as the plastic deformation progresses. As the component is stressed and the number of cycles gradually increases, the crack propagates perpendicularly to the direction of stress application, from the surface to the interior of the material, leaving striations on the fracture surface able to be seen with an electron microscope.

Finally, the cross-sectional area of the material is reduced and when the crack reaches a critical size, it propagates in an uncontrollable way, generating permanent damage to the component, the fracture, making it unfeasible. It is worth mentioning that the fracture occurs by overload at a stress of $\frac{1}{4}$ to $\frac{1}{2}$ of the ultimate tensile strength of the material [6-9].

In this scenario, this work aimed to determine the root cause of the fracture of the blades that made up an aeronautical metallic compressor that failed when submitted to the mechanical tests required before its application, and to propose a way to improve its processing in order to avoid failure and enable the safe application of the component.

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2 Materials and methods

The turbojet compressor consisted of a 7xxx series Al alloy (Al-Zn-Mg-Cu) and had four rows of blades and was provided already fractured. Initially, a visual inspection was carried out with proper lighting. Discontinuity sites such as cracks, pores, differences in shade, scratches, process burrs and other possible evidence of failure were looked for on the surface. Such discontinuities were photographed by a 12 Mp camera with a resolution of 4608 x 2592 pixels, coupled to an iPhone 8 cell phone. Samples from the base of the blade, corresponding to the region where the fracture occurred, were cut with a hand saw and subsequently cleaned for analysis of the fracture surface. Cleaning was performed by submitting the samples to an ultrasonic bath in ALTSonic Clean equipment with acetone solution during the time necessary for complete cleaning of the surface.

With the sample properly cleaned, the fracture surface was analyzed macroscopically and microscopically, using a Feldmann Wild Leitz stereomicroscope (model FWL SMZ 7.5) with 16 and 20 times magnification and a FEI scanning electron microscope (SEM) (model INSPECT S50), considering image formation by secondary electrons and magnifications of 19, 124 and 1200 times. For analysis in the stereomicroscope, the sample was positioned below the set of lenses of the equipment and in a suitable support. The luminosity was corrected in order to aid the visualization of the evidence of the fracture mechanism, and images were recorded. The fracture surface of the samples was also analyzed with higher magnification by SEM. Working conditions were 15 kV and 20 kV with working distance ranging from 11.8 mm to 39.66 mm. Finally, the surface roughness was evaluated by using an optical profiler Veeco Wyko NT1100 equipped with a 20x objective lens.

3 Results and discussion

The component is composed of a metallic cylindrical body with blades along its entire radial extension, which were all fractured (on all four rows of blades) during mechanical laboratory tests. The piece has average dimensions of 200 mm in diameter and 220 mm in height, and the blades of the upper row, two of which were extracted for fractographic analysis, are 43 mm long. Figure 2 shows some surface discontinuities of the part. The square highlights the surface roughness on the part derived from the machining process to which the part is subjected during its manufacture. The arrow shows a crack at the base of the fractured blade, which is parallel to the fracture surface plane. It is worth mentioning that the surface presents a difference in the topographic profile, with peaks and valleys.

In Figure 3, the set of arrows number 1 again highlights the existing roughness along the surface of the part, which even extends to the region of the surface of the blades. Another discontinuity observed is highlighted



Figure 1. Example of a turbojet compressor similar to the one in the present study [2].

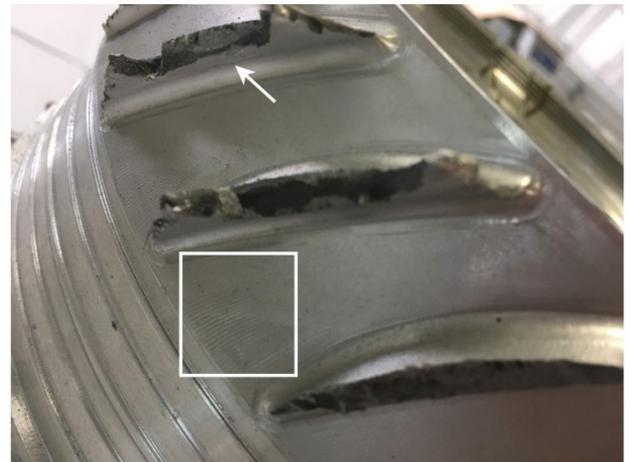


Figure 2. Photographic record of the fractured component with emphasis on surface discontinuities.

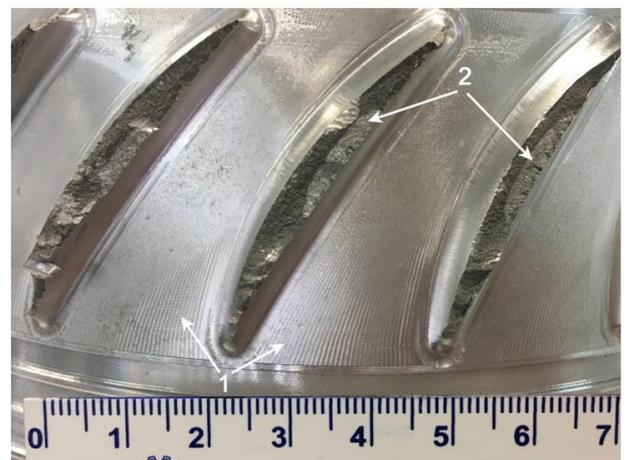


Figure 3. Photographic record of the fractured component, highlighting, in addition to the discontinuities, the fracture surface.

by the set of arrows number 2, where it is possible to identify a difference in shade on the fracture surface of the blades, which has a lighter region in an elliptical shape and the remaining area with a darker shade. Regarding the former, the surface finishing with high roughness is

likely to produce stress concentrators and facilitators of crack nucleation on the surface. Although the surface finishing was visually rough over the entire surface of the compressor, the regions near the exit of the radius of curvature between the blades and the compressor body had a slightly worse finishing. This difference can be noted in Figure 4(a), where a rougher surface is seen above the black dotted line towards the radius. This might be ascribed to some instability during the machining process. The roughness measurements obtained on the surface of a fractured blade and on a surface close to the radius of curvature are shown in Table 1. The mean values of both Ra and Rz are actually higher on the surface close to the radius, although the standard deviation values statistically minimize this difference.

Regarding the difference in shade in the region of the fracture surface, two samples of fractured blades were analyzed in stereomicroscope and SEM to complement the evidence of the fracture mechanism. Figure 4(b) illustrates the fracture surface of one of the samples, which was obtained with a stereomicroscope record and presents highlights to be discussed in the sequence. Again, as shown by arrow 1, it is possible to see the difference in shade between one region of the surface and another. Arrow 2 indicates the possible crack nucleation point. In this region, it is reasonable that the cracks were nucleated by the presence of surface defects which acted as stress concentrators and preferred crack nucleation sites. From this point, the cracks propagate towards the center of the blade until the resistance section no longer supports the mechanical stress, fracturing the component. Finally, in arrow 3, it is possible to see how the outer surface of the blade is finished, which is machined similarly to the metallic body of the turbojet compressor.

Table 1. Roughness measurements on two different positions

Sample	Ra (μm)	Rz (μm)
Blade surface	2.93 ± 1.43	23.02 ± 7.86
Near the radius	4.25 ± 0.01	29.76 ± 4.82

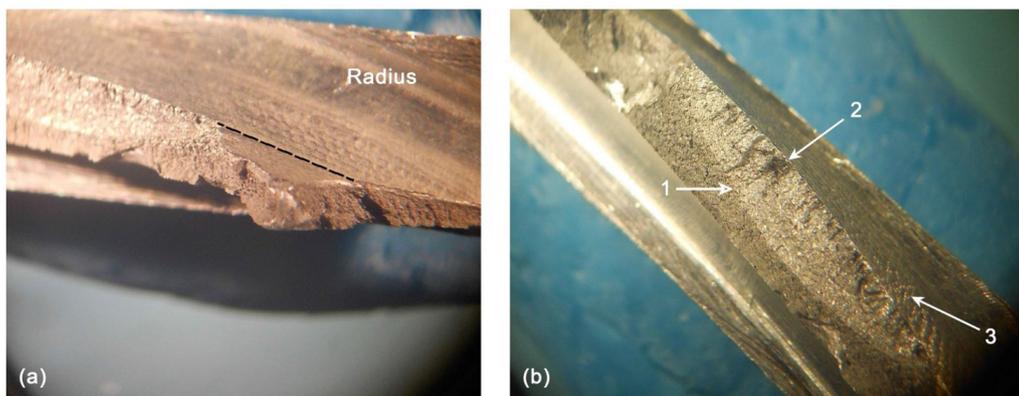


Figure 4. Micrographs obtained in stereomicroscope at 16x magnification: (a) fracture surface of a blade and (b) detail of the surface of a fractured blade.

Figure 5 shows SEM images in different positions of a fractured blade. It is evident in Figures 5(a) and 5(b) that the machined surface presents a periodic wavy irregularity that is likely to be the root cause of the failure. The roughness induces the process of crack nucleation and propagation since there is no need for the material to plastically deform and form intrusions and extrusions on the surface of the material so that a crack can then be nucleated and propagated [10]. Furthermore, during the mechanical stress of the material, the loading of forces presents an intensity profile that has a maximum on the surface of the component. Thus, the surface region is subject to greater stresses and any defect and irregularity acts as a stress concentrator and preferential site for crack nucleation and propagation [11]. Something that stands out in Figure 5(a) is that, observing the lateral surface of the fractured blade, the beginning of the crack matches with the region of higher roughness close to the radius of curvature between the blade and the compressor body. This is also clear in Figure 4(a), suggesting again that the crack nucleated in the region of higher roughness. In addition, in Figure 5(b), the arrow points out a microcrack below the fracture surface, also in the region with a rougher surface.

The failure mechanism that led to the fracture of the blades was fatigue, since there is evidence of beach marks and striations. It is worth mentioning that the difference in shade macroscopically visible on the fracture surface of the material is given by the beach marks and a consequence of the different rates of crack propagation, which varies during mechanical stress. This evidence of fatigue fracture was observed in all blades in the first row of the compressor. The nucleation region in most of these blades took place in the soffit side, which corresponds to the high pressure zone. The analysis of the fracture of the blades in the other rows of the compressor was impaired since the surfaces were dented, probably due to the collision with other fractured blades. Knowing the root cause of the failure, it is important to propose a solution to correct the surface finish defects of the machined part, and therefore, the prevention of similar failures.

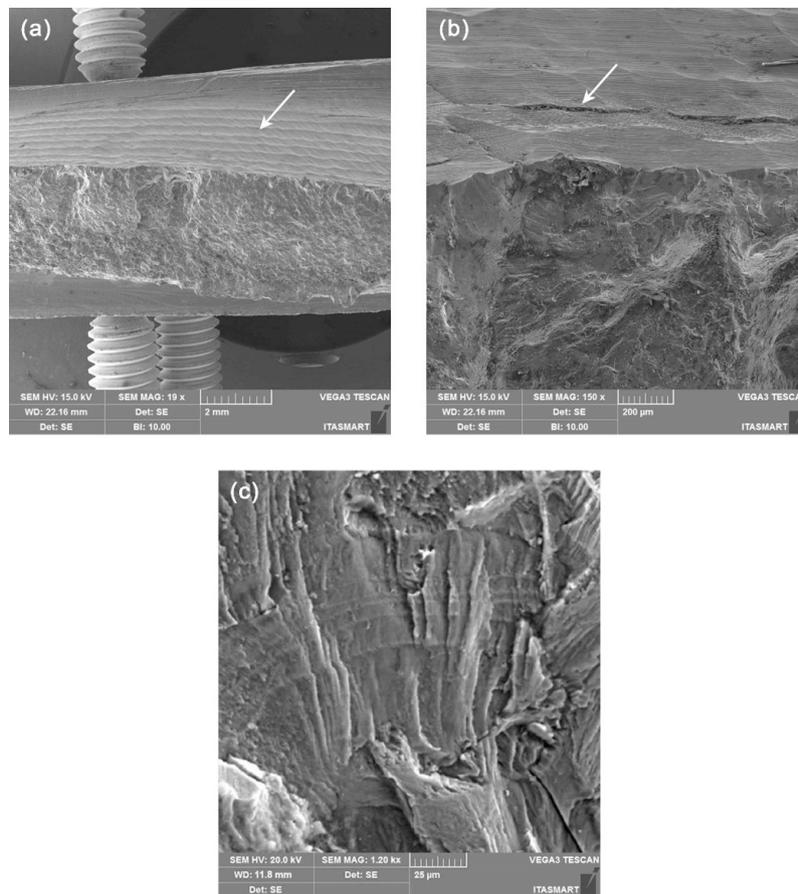


Figure 5. Micrographs obtained in SEM: (a) overview of the fracture surface of a blade, (b) higher magnification of the previous image and (c) highlight of the stable propagation zone on the fracture surface.

Although the method for manufacturing the compressor is confidential, similar engine components applied in the aeronautical sector are made of aluminum alloys manufactured with the casting and machining processes consolidated in the market. In machining, the part is “sculpted” from the metallic block, obtaining the “blisk”, derived from “bladed disk” that means “disk of blades”, and has the advantage of obtaining a single part, without the need to join the parts by welding or riveting processes that are critical for applications with high mechanical demands, as in the case of engines [3,12,13].

However, in the compressor studied in the present work, the machining of the radius region between the blade and the compressor body proved to be complex, leading to a critical roughness. In view of this difficulty of the machining process inherent to the geometry of the compressor, the “shot peening” process of the machined part stands out as a subsequent step to the machining process and obtaining the “blisk” that can contribute to increase the fatigue life of the part.

Shot peening is one of the cost-effective sandblasting methodologies defined as a cold mechanical surface treatment and consists of subjecting the metallic part to a jet of particles with a high degree of sphericity (S geometry), which promote



Figure 6. Schematic illustration of the surface after shot peening [16].

the surface hardening of the metal in addition to generating compressive residual stresses of uniform distribution along the region that vary between 70 to 80% of the yield strength of the material. Such factors tend to increase fatigue life as they make the process of surface crack nucleation difficult [14,15]. As shown in Figure 6, with the collision of the particles, the metallic surface is plastically deformed in a stretching trend, which is responsible for hardening the metal and inducing an internal reaction force that promotes the formation of compressive residual stresses [17].

It is worth noting that there are process parameters that can interfere with the effectiveness of the surface treatment,

such as: composition, granulometry and degree of sphericity of the particles; jet angle, distance, pressure and speed; exposure time. Such parameters can be varied depending on the geometry of the part, its composition, among others. However, the jet intensity parameter has been standardized since 1943, when J. O. Almen developed the Almen gage, which is the most effective instrument for controlling shot peening in industrial production. Thus, the technique began to be used in a standardized way and on a large scale in the industry [17]. In the aerospace field, since the 1970s, shot peening has been known to improve material performance in such a way that it justifies a possible additional manufacturing cost [18]. Improvements in the process towards its automation have been made until the present day [19].

4 Conclusion

It is concluded that the turbojet compressor failed due to fatigue as a consequence of the surface roughness, especially in the transition from the body to the blades, which acted as a stress concentrator facilitating the nucleation of cracks

on the surface of the blades. With mechanical loading, such cracks propagated into the material, plastically deforming it and reducing its resistant section, until the final fracture. The surface defect was originated during the manufacture of the component, in the machining process.

As an alternative to prevent the occurrence of failure and with minor impact to the traditional manufacturing process of aeronautical metallic parts, the application of the shot peening technique after the machining process was proposed to be efficient since it acts to increase the surface strength of the part by work hardening and induces residual compression stresses that make the process of nucleation and propagation of fatigue cracks difficult.

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