Paper No: 03-IAGT-205

15TH SYMPOSIUM ON INDUSTRIAL APPLICATIONS OF GAS TURBINES

Degradation, Restoration & Maintenance Of Gas Turbine Compressor Efficiency

by

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Presented at the 15th Symposium on Industrial Application of Gas Turbines
Banff, Alberta, Canada - October 13 - 17, 2003
The IAGT Committee is sponsored by the Canadian Gas Association.

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ABSTRACT

Compressor efficiency is a design variable governed by the original manufacturer's requirements regarding compressor flow capacity and handling characteristics. The intended efficiency will degrade during service however, due to the decay of key elements related to this characteristic. These elements include airfoil geometry, blade length, tip clearance, protective coatings and surface finishes. It is therefore crucial to maintain these elements at original, or better condition to obtain maximum efficiency and returns from the overall gas turbine engine. This paper will discuss how degradation of these elements negatively affect compressor performance through reference to previous industry studies and actual cases observed at Standard Aero. Methods to return lost efficiency, including topics specific to repair/overhaul and on site maintenance will also be discussed.

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INTRODUCTION

The performance of a given compressor design is usually evaluated in terms of efficiency, flow capacity and handling characteristics; and these properties are largely governed by the original manufacturers design. This paper's goal is not to improve on that efficiency, but to focus on how it can degrade during service due to progressive alteration from design geometry, and the methods available to return the compressor to its originally designed performance.

❑ BACKGROUND

The importance of efficient compression for gas turbine operation was proven during initial development of the technology in the 1920's. At this time thermal efficiencies relative to specific work were extremely low, causing problems with engine self-sustainability. The lack of self-sustainability was attributed to low compressor efficiency. In other words, the compressor required nearly all the power the turbine could produce, with little excess power available for useful work. Much attention has therefore been given to the improvement and maintenance of compressor efficiency; today's gas turbine compressors utilize approximately 2/3 of the energy produced by the turbine. Figure 1 shows the progression in development of the PT6 compressor. The improvements experienced are due to extensive research and concept development, improved aerodynamic design, and analysis capability.

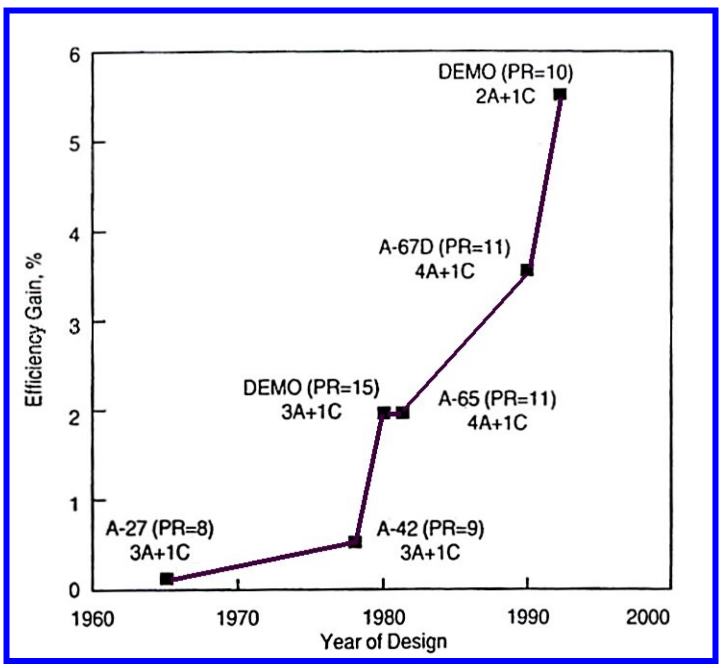

Figure 1: Improvement of PT6 compressor efficiency from inception to present day, obtained from Badger, Julien, LeBlanc, Moustapha, Prabhu and Smailys [1].

Compressor efficiency (i.e. isentropic efficiency) is critical to all gas turbines, regardless of application - flight, marine or industrial. It is the actual amount of work needed to produce a given pressure rise versus the theoretical work as defined in Equation (1).

$$(1) \qquad \text{Isentropic Efficiency} = \eta_c = \frac{W_{isentropic}}{W_{actual}} = \frac{\Delta T_{isentropic}}{\Delta T_{actual}} \quad \text{where}$$

$W_{isentropic}$ = Theoretical power required by the compressor for ideal isentropic compressoion

W_{actual} = Actual power required by the compressor

$\Delta T_{isentropic}$ = Theoretical change in temperature from inlet to outlet during isentropic compression

ΔT_{actual} = Actual change in temperture from inlet to outlet of compressor during opeartion

The theoretical temperature ratio is then tied to the pressure ratio through the isentropic relationships shown by:

$$\frac{T'_{outlet}}{T_{inlet}} = \left[\frac{\mathrm{P_{outlet}}}{\mathrm{P_{inlet}}}\right]^{(\gamma-1)/\gamma} \quad \text{where}$$

T'_{outlet} = Ideal isentropic outlet temperature

T_{inlet} = Temperature of inlet air to the compressor

$\mathrm{P_{outlet}}$ = Outlet pressure of the compressor

$\mathrm{P_{inlet}}$ = Inlet pressure of the compressor

γ = Specific heat ratio, typically 1.4 for air

Therefore compressor efficiency can be evaluated by Equation (2) based on measured temperature and pressure rise across the machine:

$$(2) \qquad \text{Pressure Ratio} = \frac{\mathrm{P_{outlet}}}{\mathrm{P_{inlet}}} = \left[1 + \frac{\eta_c \Delta T}{T_{inlet}}\right]^{\gamma/(\gamma-1)} \quad \text{where}$$

ΔT = Actual change in temperture from inlet to outlet of the compressor

The primary role of the compressor is efficient compression (ideal compression is isentropic) of large volumes of air to supply for combustion. This is accomplished by increasing the total pressure of an incoming fluid through stages of rotating blades and stationary vanes, as shown in Figure 2. Compressor blades impart kinetic pressure (one component of total pressure), through addition of velocity to the fluid. The stationary vanes, which are located aft of their respective stage blades, then convert the kinetic pressure to useful static pressure (the second component of total pressure), by reducing velocity and increasing pressure much like a diffuser. The cross-sectional area of the compressor gas path also becomes smaller with each successive stage as shown in Figure

3. This maintains a nearly constant axial fluid velocity as density changes along the flow path. Typical 501-K compressor characteristics are shown in Figure 4. An increase in total pressure, via increasing static pressure, is the end goal, as high kinetic, or dynamic pressure, is not desirable for efficient combustion. A good compressor accomplishes this with a minimum of stages, a minimum increase in temperature above ideal isentropic levels, high isentropic efficiency and good aerodynamic stability over the entire operating range. Aerodynamic stability is maintained at off-design points via bleed valves and variable-stator-vanes (VSV).

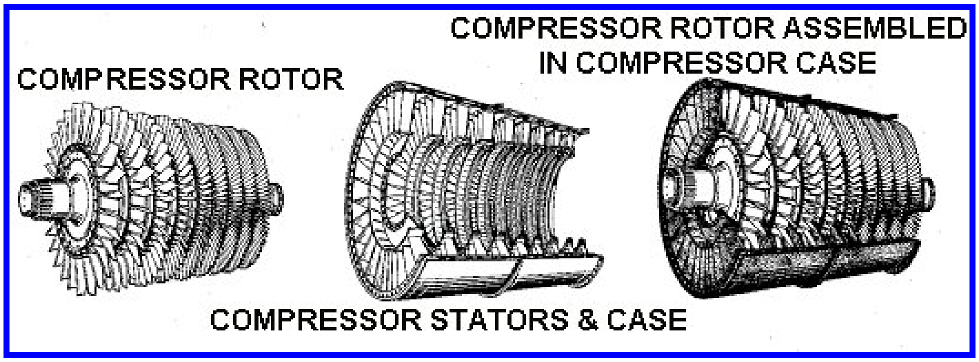

Figure 2: General configuration of an axial flow compressor.

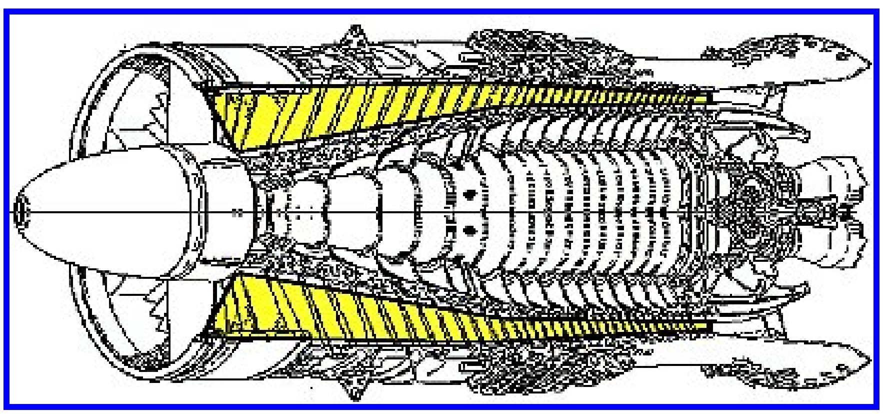

Figure 3: Shaded area shows the reduction in the cross-sectional area of the gas path of the compressor from inlet to outlet.

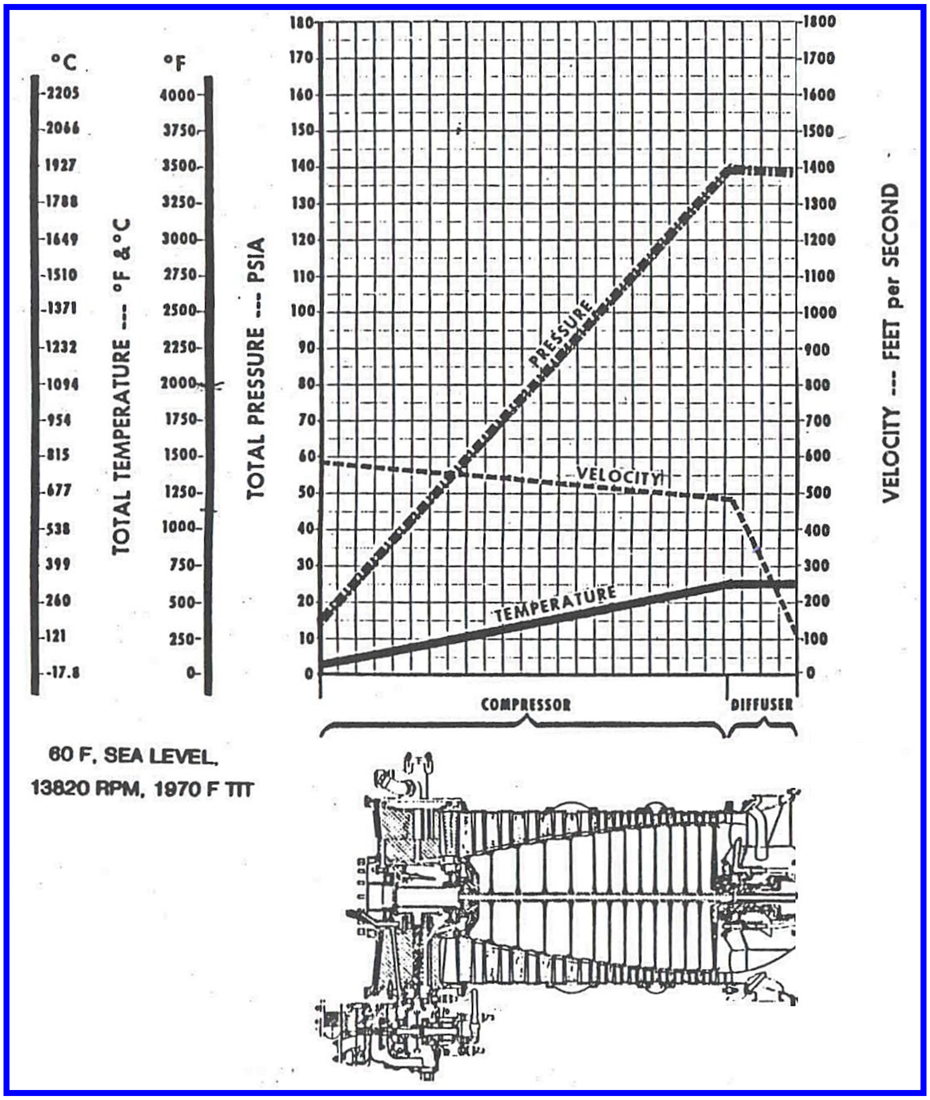

Figure 4: Estimated compressor performance characteristics obtained from Allison 501-KB/KB5/KB7 Training Manual GTP5437-12, pp. 7-19.

❑ Maintaining an Efficient Compressor

Compressor efficiency will degrade during service, as shown in Figure 5. This degradation is attributable to several key factors related to compressor performance including airfoil geometry, blade length, tip clearance, protective coatings and surface finishes (i.e. gas path surface roughness and fouling). These areas require monitoring and maintenance to ensure peak compressor efficiency is maintained, therefore maximizing returns from the engine. For example, a 1% decrease in compressor efficiency can cost 4.5% in engine power. Therefore if an operator is running a 3.5 MW (4695Hp) unit this results in a 158KW (212Hp) loss in power and depending on energy costs and engine use, can cost the user $66,000 (USD) per year[*].

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[*] Assuming $0.05 USD/KW.hr @ 8760 hrs/year @ 95% engine use

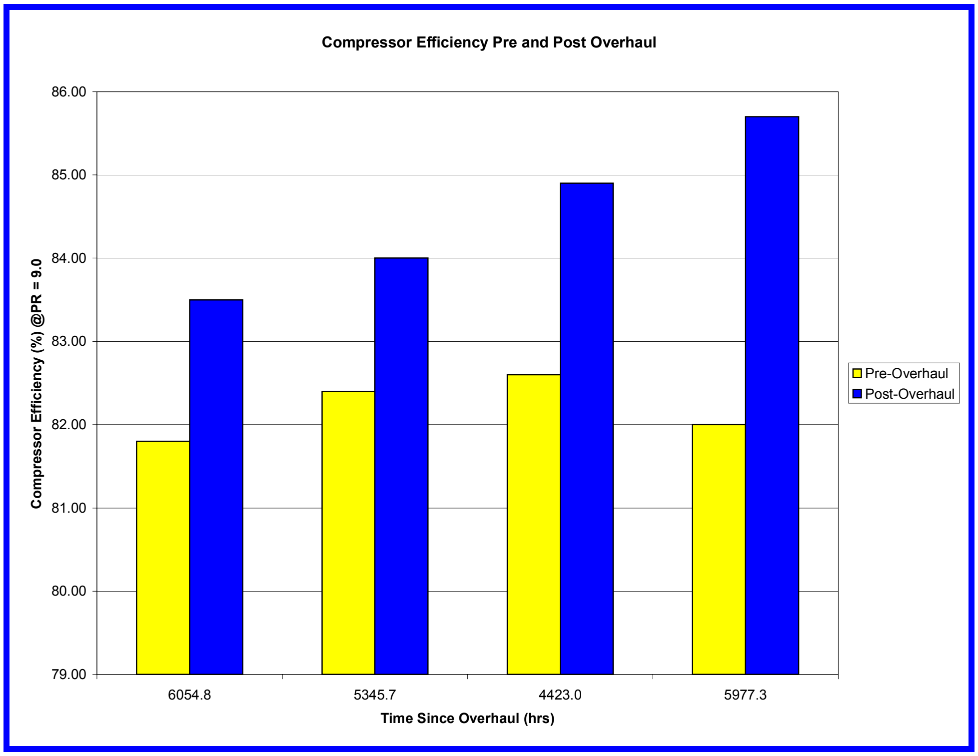

Figure 5: Compressor efficiency pre and post overhaul.

AIRFOIL GEOMETRY

Blade airfoil geometry is designed for effective/efficient input of velocity (kinetic pressure) into the fluid being compressed. An appropriate leading edge profile, trailing edge exit angle, chord length and blade twist angle will positively affect airfoil performance and compressor efficiency. The leading edge profile and chord length can degrade over a blade's operational life, while the trailing edge exit angle and blade twist angle are governed by the original design and do not typically change during service. If all these characteristics are not properly controlled at manufacture, or degrade during service, then compressor efficiency will suffer. As this paper's focus is on degradation and recovery of compressor efficiency, only leading edge and chord length erosion will be discussed.

Leading edge erosion is characterized by the increase of the leading edge radius relative to original design requirements, which is also referred to as "blunting". By changing the leading edge profile, the airflow over the airfoil is altered, and boundary layer phenomenon such as laminar separation and turbulent flow alter position relative to the leading edge. When this occurs, the ability of the blade to efficiently impart velocity to the incident air decreases. A case study accomplished on the JT8D indicated up to a 0.5% decrease ([2]) in compressor efficiency due to leading edge erosion. Eroded leading edge radii were 0.018 mm (0.007") to 0.025 mm (0.010"), while after restoration the leading edge radii were maintained within 0.010 mm (0.004”) to 0.015 mm (0.006”). Leading edge restoration can be labour intensive however, and may be uneconomical when compared with part replacement.

Chord length erosion is the second major contributor to airfoil geometry degradation. It reduces the axial surface area of the airfoil resulting in reduced performance. Determination of chord erosion and its severity must be accomplished through comparison methods, either with gauge blocks, or a new part. As shown in Figure 6, the blade on the left has been heavily eroded along the chord as compared with the new blade on the right. Once the level of degradation is determined, then the affect on compressor efficiency must be correlated. It has been suggested that a Blade Quality Factor (BQF) ([3]) be applied to compressor blades with degraded chords. This factor would describe the blade condition numerically with respect to chord length erosion. It would also weight particular wear zones according to the affect on compressor performance. A correlation could then be developed empirically based on BQF values given to known blades, installed in a known engine, with known test results. The importance of weighting is shown in Figure 6. The subject blade’s chord length, as defined by the overhaul manual, was within limits, however the affect of the chord erosion on this, and similar blades was sufficient to fail the engine during final test for low power. The failure was attributed to the loss in efficiency caused by the local chord length erosion. Current inspection methods provided by the original manufacturer were not able to address this issue, however a BQF with proper weighting would indicate such local erosion as detrimental to engine performance.

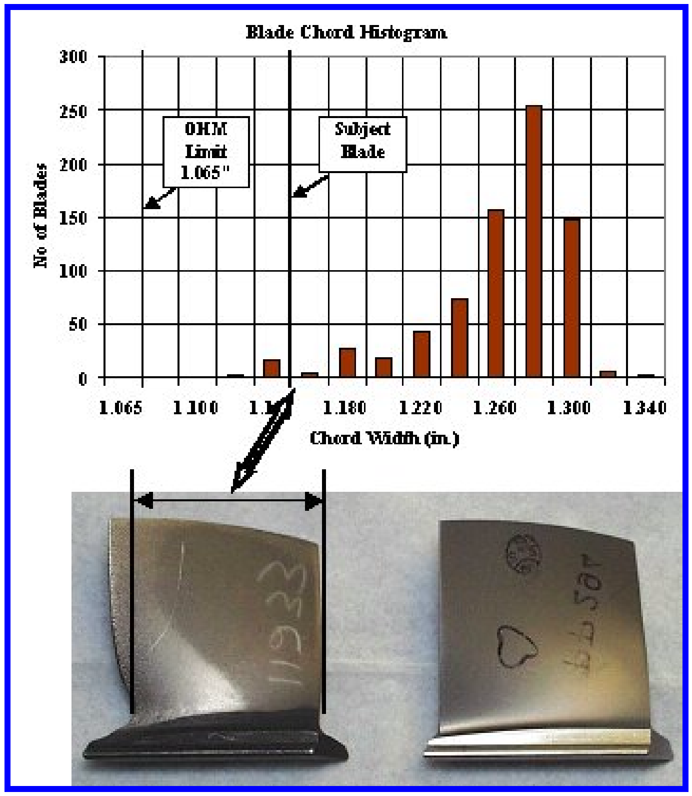

Figure 6: Eroded compressor blade as compared to a new compressor blade and overhaul manual limits for serviceability.

Another case of chord erosion involved an engine operating in a ceramic tile factory. This engine was exposed to fine ceramic tile dust for approximately 35,000 hours of its time-since-new of 82,000 hours prior to last removal. The tile dust had severely eroded the compressor blades, as shown in Figures 7 and 8. The blades shown on the right of the figures are from a serviceable compressor; the blades on the left are from the eroded engine. The thin trailing edges and rounded trailing edge corners are prevalent relative to the serviceable blades. Due to the reduction in chord width, and subsequent degradation in compressor characteristics, such as mass flow, pressure ratio and efficiency, 90% of the compressor blades required replacement.

Figure 7: Trailing edge eroded on left compressor blades from exposure to fine dust during operation.

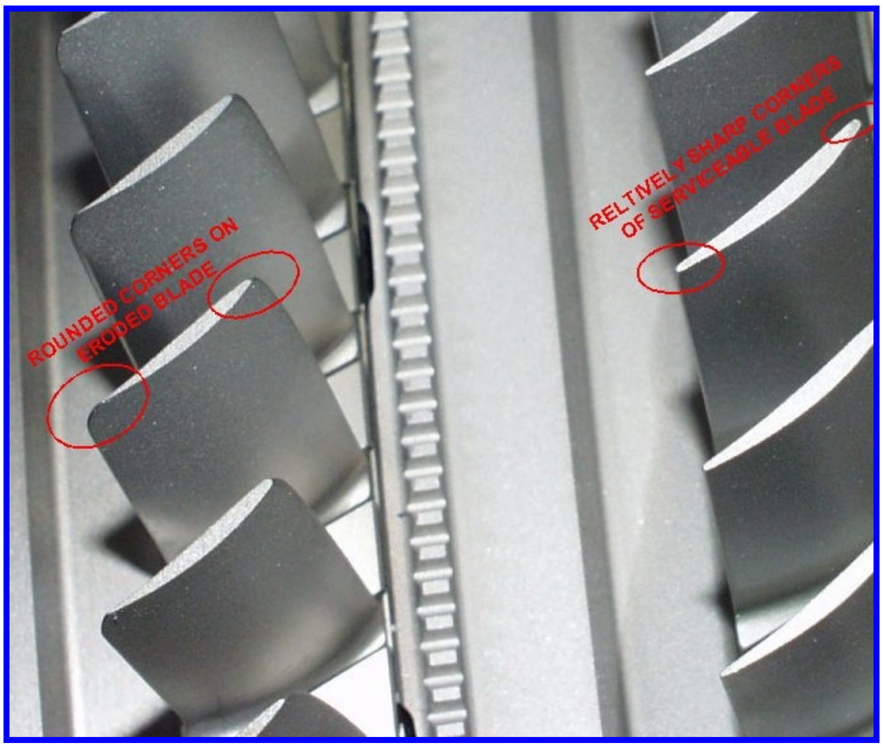

Figure 8: Trailing edge and blade-tip corners on left compressor blades eroded from exposure to fine dust during operation.

TIP CLEARANCE / BLADE LENGTH

- **BLADE TIP CLEARANCE**

Radial clearances between compressor blade tips and the mating blade paths are key to efficient compressor operation. A general rule of thumb quoted by Okiishi and Wellborn

([4]) states that for every 1%* increase in the blade tip-to-case clearance, a resultant decrease of approximately 1.5% in compressor efficiency can be expected. Furthermore, other studies have shown ([5]) that increasing tip clearances throughout the entire rotor a moderate amount has a more detrimental effect then increasing the clearance on a single stage by a large amount. The authors also show a non-linear relationship between increasing tip clearance and characteristic degradation; i.e. as clearances increase, there is less affect on performance. An ideal compressor would consist of zero clearance, however, due to differing operating characteristics and requirements of in-service, operational compressors, this is not practical. It is therefore paramount for manufacturers and repair facilities to maintain blade tip clearances at a minimum to ensure the maximum energy is imparted to the fluid during compression, while maintaining operability of the compressor. This is the reason blade tip clearance is one of the most studied and documented aspects of compressor efficiency/operation.

An increase in blade tip clearance allows the acting fluid to by-pass the blades without the required flow turning. This secondary flow then intermixes with the core flow downstream of the blades. The mixing causes complex fluid interactions, resulting in turbulence, flow separation and disruption of the flow entering the stator vanes. The result is a loss in efficiency in applying the kinetic energy to the fluid and converting the kinetic pressure to useful static pressure. All these factors combine to reduce the overall efficiency of the compressor, negatively affecting engine output power, fuel flow and air flow, with little to no affect on the exhaust gas temperature.

A case study accomplished on a helicopter engine by Brun and Kurz ([6]) utilized compressor blades cropped to simulate an increase of 3% tip clearance. This reduced the flow 4.6%, decreased the pressure ratio by 3% and compressor efficiency dropped by 2.5%. These compressor performance losses resulted in an overhaul gas turbine power loss of 8% and a drop in engine efficiency of 3.4%.

There are two main origins for excessive blade tip clearance; compressor build and compressor operation. During build the compressor rotor can be installed eccentric to the cases, resulting in non-uniform clearance around the circumference and yielding tighter-than-desired clearances at one polar point and larger clearances 180° opposite. The compressor cases can also be produced oval due to in-exact machining of the blade paths. This results in the same condition as an eccentric rotor. Compressor operation will also erode compressor blade tips due to particulates present in the inlet flow. Increasing clearances due to build problems are minimized by high speed grinding and sophisticated measuring devices, while operational wear can be addressed with proper filtration and abradable coatings on the blade paths.

Methods used to control tip clearances during build of compressors include abradable coatings and tip grinding. The abradable coating is typically an aluminide rich metal

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* A 1% increase in clearance on a 501-K series engine results in an approximate increase of 0.0003 mm (0.00012”) to the clearance.

powder that is applied through any number of metallizing processes. The coating is designed such that it resists erosion and maintains a high bond strength with the cases, but allows shearing, or cutting, by the compressor blades during operation. Cutting is facilitated by centrifugal forces experienced on the compressor blades at full operational speed. By cutting their own path, the blades seal themselves, yielding an optimum tip-to-case clearance specific to the compressor.

Tip grinding, and the resulting rotor diameter measurement, are key to ensure a uniform rotor is produced to the desired size. Final tip grinding is normally accomplished with the rotor in its fully assembled state to minimize the effect of tolerance stacking. Grinding prior to the 1980's was accomplished via low speed manual grinding processes, as shown in Figure 9. This method resulted in high turn times and less than desirable results as the blades were ground in an "unseated"* state due to the lack of centrifugal force. Furthermore, the final measurement of the blade length after grinding was accomplished using a dial fitted with a stylus, which is reliable only to the nearest 0.0025 mm (0.001"), with the blades again in an "unseated" state. High speed tip grinding was introduced in the 1980's and continues to be incorporated in overhaul facilities and to be specified for new engine manufacturing. This method spins the rotor up to 9000 RPM for smaller engines and 2000 to 3000 RPM for larger engines. The weight of the blades and resulting centrifugal force are then sufficient to "seat" the blades outward during grinding to obtain a true operational length. A typical high-speed tip grinder is shown in Figure 10.

* "unseated" refers to the loose fit of the compressor blade in the wheel dovetail. During low speed grinding the blades rest in the dovetail (unseated) and can tilt circumferencially resulting in erroneous grinding results.

Figure 9: Manual blade-tip grinder.

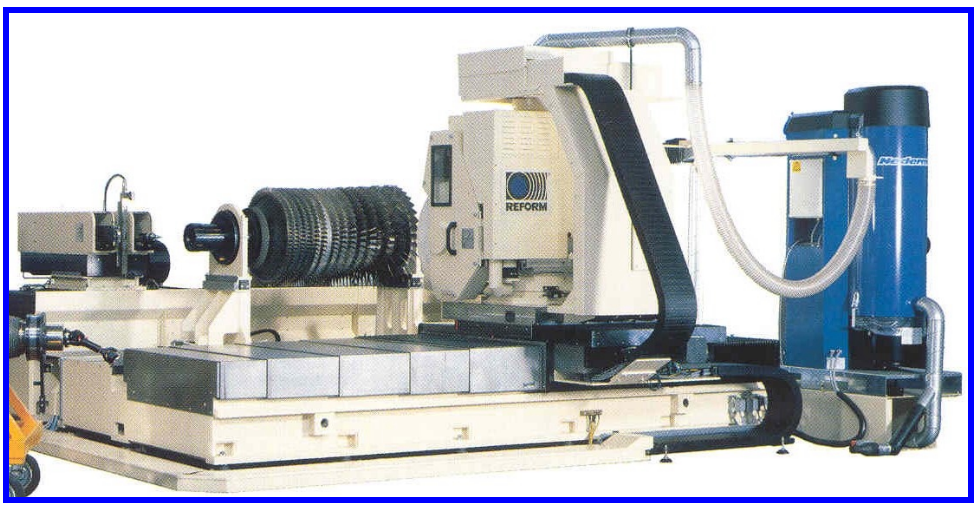

Figure 10: Image of a REFORM – Aero high-speed tip grinder.

New methods of measurement have also been developed concurrently with high speed tip grinding. Blade measurement is conducted as the rotor is being ground, yielding a more true to operation measurement. Lasers are widely utilized in the industry to accomplish this due to the precision tolerances.

An example of the advantage of laser measurement is shown in Figure 11. This compressor rotor was removed after a failed test for low power. Final grind measurements prior to build (using the OEM specified setup and gauges) were within limits, however when the rotor was re-measured using a laser system the baseline shown in the graph was created. The baseline shows a run-out of approximately 0.010 mm (0.004"). The rotor was therefore tip-ground to rectify the excessive run-out. The second set of data (Test #1 – PreGrind) was obtained prior to grinding. Note the excellent repeatability of the laser measurement from baseline to Test #1 – PreGrind. After grinding, the final set of data was produced (Test #1 – PostGrind), which shows the run-out reduced to 0.0013 mm (0.0005"). This example demonstrates the laser's ability to accurately measure blade length, and determine run-out where the manual method was not capable. Capacitance probes have also been suggested as an alternative to lasers and are in use in industry. This method has been stated by Fitzpatrick, Killeen, Sheard and Westerman ([7]) to be reliable to +/- 0.00005".

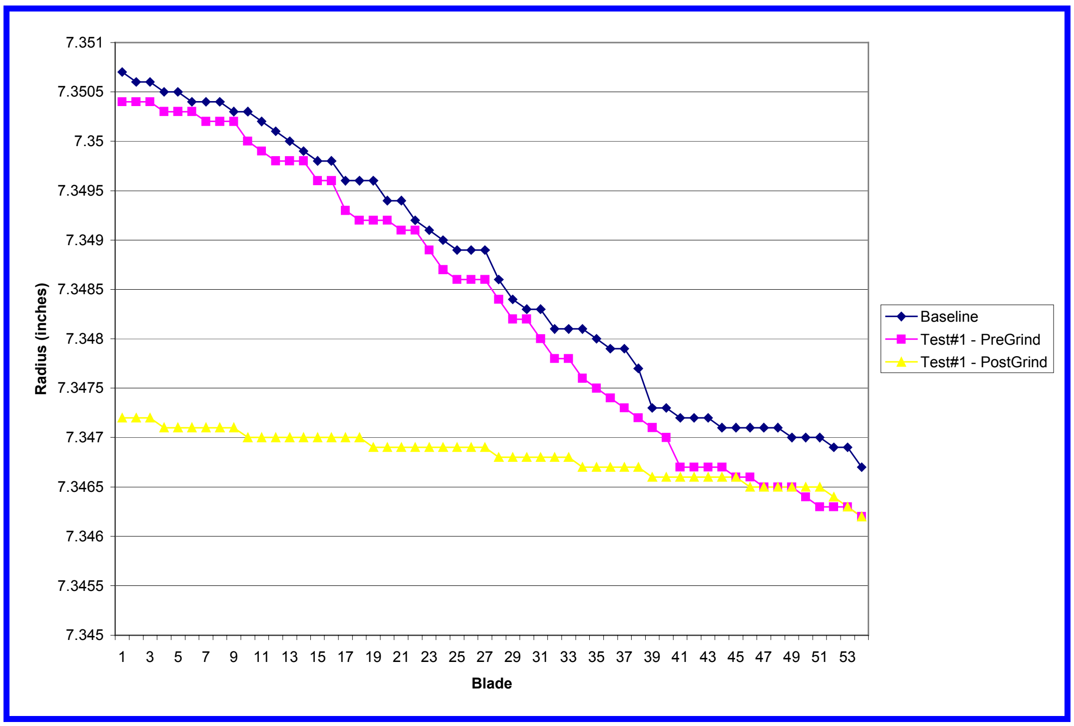

Figure 11: Laser measurement results prior to and after final blade tip grinding.

- **BLADE LENGTH**

Blade length can also become an issue as compressors age and undergo repair/overhaul. The overall blade length decreases due to the requirement to maintain proper tip clearances via grinding and tip-rub/erosion experienced during service. The decrease directly affects the mass flow through the compressor by reducing the effective flow area. The reduction in mass flow then upsets the velocity vectors within the compressor rotor, which negatively affects compressor efficiency. Therefore, although a compressor rotor may be cut uniformly, and to a length that maintains optimum tip clearance with a round compressor case, compressor efficiency will suffer if short blades appreciably affect mass flow.

PROTECTIVE COATING / SURFACE FINISH / FOULING

❑ PROTECTIVE COATINGS

Protective coatings do not enhance compressor performance; they prevent degradation. A new compressor with smooth new blades will perform identical to the same compressor with a protective coating applied, if the surface finish is not improved by the coating. This was shown by Laflamme and MacLeod ([8]) where a new T56 compressor was coated with Titanium Nitride using Plasma Vapour Deposition. The coated versus non-coated compressor performance was nearly identically in all parameters. Compressor efficiency degrades in service because of progressive roughening of the gas path surfaces caused by fouling and corrosion. There are several coating types that offer protection including ceramic-based and aluminum particle coatings. The aluminum acts as a sacrificial anode much like zinc plating on the outer hull of ships. Application of these coatings is generally accomplished by dipping or spraying; electroplating, electroless plating, and vapour processes are also available. Superior coatings are smooth, corrosion and erosion resistant, and maintain high bond strength. Top-coats can also be applied to coatings to enhance their operating characteristics. The key to protective coatings is two-fold. First it prevents corrosion, thereby maintaining efficient compressor operation throughout the compressor life cycle. Secondly, protective coatings may improve the surface finish of units with rough, in service, airfoils.

Most compressor components are fabricated from Stainless Steel, which has good corrosion properties, however this material is prone to corrosive pitting over time. Pitting then leads to two forms of compressor performance degradation; decreased quality of surface finishes and increased fouling rate, which ultimately cause a loss in compressor efficiency. Protective coatings therefore maintain efficiency by preventing pitting, which maintains surface finish and keeps fouling to a minimum.

Protective coatings can also *negatively* affect compressor performance. As shown by Chima, Roberts, Strazisar and Suder ([9]) where a protective coating was knowingly applied exessively thick to a test compressor. The coating thickness applied was approximately 0.001". The study found that the excessively thick coating resulted in a 3% decrease in compressor efficiency, even though the coating was smooth. The same thickness of coating applied in a rough state resulted in an efficiency decrease of 6-8%. The performance reduction seen relative to the thick, smooth, coating was attributed to the resulting blunting of the leading edge, which is known to decrease compressor performance from previous discussions regarding airfoil erosion.

❑ SURFACE FINISH

Surface finish is vital in obtaining efficient compressor operation, as proven by Chima, Roberts, Strazisar and Suder ([9]) where the efficiency of the rough-coated compressor decreased twice the amount as the smooth, but thick-coated, compressor. This is because rough surfaces impose drag/friction across the airfoil, which results in a pressure loss and reduces efficiency. Surface roughness and its effect on compressor efficiency is also linked to Reynolds number. It has been shown by Shaffler ([10]) that surface roughness effects increase with the increase of the effective Reynolds number. Moreover, this study shows that once a critical Reynolds number is reached, surface roughness becomes a dominant variable in compressor efficiency. Therefore engines operating at high blade Reynolds numbers will experience increased effects from surface roughness than those running at lower Reynolds numbers.

Surface finish is degraded in two ways - through corrosion/erosion and fouling. Protective coatings are used to hinder the corrosion and erosion of airfoil surfaces during operation. It is imperative however, that the coating is not applied too thick and has a smooth surface finish (as good or better then that of the original surface).

Fouling is also controlled through protective coatings, however these coatings usually have Teflon, Polytetrafluoroethylene (PTFE), or some similar compound added to the topcoat. This additive ensures the particulates responsible for fouling of compressor surfaces cannot bond to those surfaces. These anti-fouling coatings therefore aid in washing and its effectiveness in improving compressor performance. As discussed by Bouris, Hirata, Kubo and Nakata ([11]), fouling is most severe at the leading edge, and is orders of magnitude higher than the rest of the blades' surfaces for both the rotor and the stator. The mechanism governing the leading edge deposition rate is inertial impact, while the same mechanism dominates the stator pressure side. The particles that remain on these surfaces then increase surface roughness, and decrease compressor performance. The larger particle size impacting on these regions also leads to erosion, therefore having a two-fold affect on surface roughness. The second major mechanism of deposition is turbulent diffusion, also discussed by Bouris, Hirata, Kubo and Nakata ([11]). In the case of the stator, only the lighter particles are able to follow the highly curved suction side surface and therefore the deposits formed will contain mainly small particles. This is also true for both sides of the rotor. The presence of a high Mach region and possibly a shock wave causes an increase in the turbulent kinetic energy near the blades, which is the forcing function facilitating deposition on blade surfaces. The study by Bouris, Hirata, Kubo and Nakata ([11]) states that "different material properties is not as important as the affect of particle motion in the flow. This is due to the dominance of diffusion as the deposition mechanism so that whether the particle will reach the surface and how becomes more important than how hard or soft the particle is." This speaks to the importance of filtration systems and ensuring their elements are sufficient to trap/prevent particles of detrimental size from the inlet.

Degraded surface finishes can be restored via mechanical polishing, burnishing, or super-polishing. These methods are applied to coated and un-coated surfaces alike. Typical surface roughness values of new compressor blades range from 35-40 micro-inches (Ra), while in-service blades received can range from 120-180 Ra. Polished blades can reach Ra values as low as 9 Ra with averages around 10-15 Ra. The smoother the surface, the less drag imposed on the airflow over the surface, thus resulting in more efficient operation.

Roughness effects are shown by Chima, Roberts, Strazisar and Suder ([9]) where a special non-reflective paint was applied to a compressor rotor in order to suppress laser light reflection during a flow field investigation by Suder and Celestina (1994). The paint had silica deposits in the topcoat to diffuse the laser light. During the study, a 9% decrease in the pressure ratio, and a 6% decrease in compressor efficiency was noted after painting. When the roughness of the painted rotor was measured, it was found to be comparable to roughness experienced by compressor rotors after operation and prior to restoration. Once the paint was removed from the rotor, compressor performance returned to pre-painted levels.

Surface roughness will also affect compressor efficiency through indirect means - a rough surface will trap and bond with a larger number of contaminants. Therefore, fouling rates will increase as surface roughness increases, which further increases roughness and deteriorates compressor performance.

WASH / MAINTENANCE

Maintenance of an industrial gas turbine compressor is required to ensure efficient operation of the unit. This includes items such as the filter system (some installations have very expensive, elaborate filtration systems), ensuring all seals on the exterior of the compressor maintain pressure under operation and washing of the compressor at regular intervals.

- **FILTRATION**

Filtration systems require regular cleaning of filter elements to ensure the pressure drop experienced by the gas turbine is kept to a minimum. If the pressure drop across the filter rises, then the compressor is forced to work harder to output the same airflow, which decreases the efficiency of the compressor and entire engine. It also important that the filtration system is sufficient to remove damaging particles from the inlet air. This is to ensure that fouling, erosion and subsequent degradation of surface finishes doesn’t occur. High grade High Efficiency Particulate Air (HEPA) filters and waterfall systems are widely used for this. It should be noted however, that even these expensive filtration systems can be detrimental. Sudden impacts can dislodge particles trapped in a saturated filter. The particles can then be ingested into the engine, having a drastic affect on compressor performance.

- **EXTERNAL ENGINE SEALS**

Ensuring the compressor has no external leaks at bleed valves, cap nuts, splitlines, etc. ensures that all air taken into the compressor is compressed and used by the engine. Air that does escape from a leaking valve, nut or splitline cannot be used and negatively affects compressor performance.

- **COMPRESSOR WASHING**

All gas turbine OEM’s specify wash intervals, however different engine operating environments are unique and wash intervals must be scheduled according to specific requirements. These requirements must take into consideration air contaminants, filtration systems and engine duty cycle.

Washing is accomplished either with the engine cold (no combustion), which is known as crank, or motoring wash, and with the gas turbine hot (full operation), which is know as an on-line wash. Washing is accomplished with a mixture of water (de-ionized or potable depending on wash criteria) and detergent. The detergent will have some type of inhibitor to prevent degradation of internal components between wash cycles. It is also designed to effectively clean throughout the entire length of the compressor, as detergent is typically input through the inlet of the unit. Washing a compressor removes air-borne contaminants that have bonded to internal compressor components. These contaminants negatively affect compressor performance by increasing surface roughness, altering leading edge profiles and reducing effective flow areas.

An example ([6]) describes an engine that had operated for 3,500 hours without a compressor wash and in an environment with heavy salt spray and jet engine exhaust, much like an oil platform or ocean going vessel. The engine was also underfired due to the reduction in the critical turbine temperature ratio caused by environmental contaminants. Prior to the wash the compressor efficiency was down 2.1%, airflow and pressure ratio were down 5% and there was a reduction in turbine efficiency of 0.5%. The total power was therefore down by 8.6% and engine efficiency was down by 3.5%. After a detergent wash, the engine experienced an increase of 9.7% in output power and all other characteristics were in “like new” condition.

Compressor washing effects can also be enhanced through the use of anti-fouling coatings containing Teflon, or similar compounds. This allows the wash to remove more contaminants from the internal surfaces because the particulates are not able to bond well to the surfaces.

CONCLUSION

Compressor efficiency is paramount in obtaining good engine efficiency and is one of the least costly ways to improve engine operation and decrease operating costs. This is attributed to the low cost of compressor components relative to their turbine counterparts and the low costs associated with compressor maintenance events. Additionally, the processes required to repair and coat compressor parts are less sophisticated than what is required for turbine components. This means the compressor accounts for ¼ of the final cost to overhaul an engine, while a reduction of 1% in compressor efficiency can cost 4.5% in engine power. The relative cost of the lost performance versus efficient operation therefore makes investment in compressor efficiency economical.

Compressor efficiency is obtained two ways; through the maintenance organization responsible for repair/refurbishment, and the operator via maintenance events and proper monitoring. These two areas can compliment each other. An example is a compressor with some form of coating applied with some type of special surface treatment to reduce surface roughness. The unit will perform exceptionally well after overhaul due to the smooth surfaces on the gas path components. However, if maintenance is not performed by the operator during engine use (i.e. compressor washes), then the compressor will foul and efficiency will be lost due to the resulting degraded surface finish.

The two areas can also work independently. For instance, maintenance facilities can match compressor rotor blade lengths to the specific compressor-case blade-paths, ensuring the best possible blade tip clearance. They can also use the latest grinding techniques (i.e. high-speed tip grinding with laser aided measurement) to ensure the rotor is cut to the required size and is perfectly concentric/circular to maintain equal clearance with the CNC machined compressor-case blade-paths. The operator can ensure that package-filtering systems are maintained and filter elements are cleaned/changed regularly to avoid increasing the pressure drop across the filter and particles being released into the inlet from a saturated filter.

Ensuring compressor efficiency is at its peak requires capital expenditure. The capital required to increase compressor efficiency via part replacement, repair or coating is economical however, and less costly than turbine components. Areas that users can improve compressor efficiency during repair/refurbishment include:

- Upgraded coatings that inhibit erosion/corrosion to gas path components and decrease surface roughness, or reduce fouling.
- Specialized surface-finishing processes accomplished on un-coated, or coated, gas-path components and that drastically reduce surface roughness, such as super-polishing.
- Replacing blades that have worn during service life either on length, leading edge (i.e. blunting) or chord width.
- High-speed tip grinding of the rotor rather than classical manual grinding.
- Applying the latest compressor case metallizing to the blade paths to ensure good sealing/cutting of the blade paths during seal break-in.

Areas that users can improve on compressor efficiency on site include:

- Upgrading filtering systems to ensure harmful air borne particulates do not contaminate the compressor. These particulates can erode and foul compressors.
- Increased monitoring equipment so compressor health can be known, and maintained during operation.
- Determining and maintaining a schedule for maintenance events (i.e. washing, borescoping, filter maintenance, etc.) that is designed for the engine's specific operating environment.

Efficient engine operation has always meant lower operational costs and is becoming even more important as environmental requirements become more stringent, i.e. Kyoto protocol. Emissions requirements are typically met by controlling combustion processes through water injection, Dry Low-Emission (DLE) systems, etc. However, efficiency can also play an important role in meeting these requirements by reducing the total amount of emissions released. A more efficient engine will burn less fuel to produce the same power. Therefore, an efficient engine will cost less in fuel charges and produce fewer emissions. An efficient compressor is a relatively inexpensive way to improve on overall engine efficiency.

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