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SOLUTION FOR GAS TURBINE ROTOR END OF LIFE

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Abstract

EthosEnergy has developed a rotor solutions program to introduce to the marketplace. Integrity of rotor assembly is very critical for safe and reliable operation of a gas turbine. Rotor components have finite design life and consequently, planned maintenance involving inspection and replacement of life limiting components is critical for reliable operation. Rotor reliability issues can cause unit unavailability, increased maintenance costs and forced outages. Recently, OEM has released a technical information letter (TIL) to inform customers of end of life of rotor and consequence of rotor failure, if prescribed maintenances are not performed. To address rotor end of life issues, some independent service providers may offer inspections during a planned maintenance and rotor life time extension. Rotor life time interval extension needs to be based on engineering assessment of operating stresses/temperature, understanding of material failure modes, advanced NDE inspection techniques, OEM know-how, etc., which many of these independent service providers may not have. As a result, fidelity of a life time extension recommendation provided by an independent service provider should be carefully evaluated relative to risk associated with consequence of a rotor failure. Contrary to many other service providers including OEM, EthosEnergy has adopted a different approach by offering a cost-effective rotor solution. Using state-of-the-art engineering tools and advanced manufacturing techniques, EthosEnergy has designed replacement compressor and turbine wheels for frame 6 and frame 7 gas turbines. EthosEnergy wheels are interchangeable with OEM components and can be tailored to accept in-kind or improved blade root profile. EthosEnergy solution is to replace life limiting components of a rotor and thereby minimize overall project cost for a typical user. EthosEnergy rotor exchange program has been developed to reduce our customers risk profile at a cost substantially below a complete replacement of an OEM rotor. Details of EthosEnergy rotor solution will be discussed in this paper.

1. Introduction

EthosEnergy is a leading Independent Service Provider of rotating equipment services and solutions for clients in the power, oil & gas and clean energy markets. Worldwide, products and services include power plant engineering, procurement and construction; facility operations & maintenance; repair & overhaul, optimization and upgrade of gas, steam turbines, generators, pumps, compressors, transformers and other high-speed rotating equipment. A new rotor solution product has been developed to meet needs of the heavy duty gas turbine customers and is specifically targeted for aging fleet to address end of life and risk concerns.

Rotor components have finite design life and consequently, planned maintenance involving inspection and replacement of life limiting components is critical for reliable operation. GE Frame 7EA gas turbines have 17-stage compressor and compressor rotor is assembled from individual stage bladed-wheel assemblies held by through-bolts. Compressor blades are installed on broached slots and held in axial position by staking. In each stage, air is compressed by rotating blades and stationary blades (located in casings) direct compressed air to the next stage at proper angle. Similar rotor construction has been used by GE for other frame sizes (such as 7FA) and a typical 7FA compressor rotor has 18-stages. Required inspection for GE heavy duty gas turbine rotors is prescribed in GER 3620[1] and such inspection is defined as a complete disassembly of the rotor so that a thorough analysis of the rotor components in both the compressor and turbine sections can be performed. It should be expected that some rotor components will require replacement at this inspection point. Failure to perform these inspections leaves the gas turbine at greater risk for failure, as a rotor carries the highest energy in a turbine. High stress & high temperature environment (e.g. salt corrosion, erosion) may contribute to premature failure of some parts. Exceeding the serviceable life of the rotor system can lead to a wheel failure that causes extensive damage to the gas turbine. This event can also potentially lead to substantial damage to adjacent equipment and serious injury to any nearby personnel. Factors contributing to rotor failure involving wheel or disc burst have been discussed for common rotor designs and materials.[2-5]

Rotor reliability issues can cause unit unavailability, increased maintenance costs and forced outages. Recently, GE has released a technical information letter (TIL) to inform customers, the end of life of rotor and consequence of rotor failure, if prescribed maintenances are not performed. A rotor inspection should be performed at 200,000 Factored Fired Hour (FFH) or 5,000 Factored Fired Start (FFS) for a typical Frame 7EA gas turbine rotor as shown in GER 3620[1].

1.1. EthosEnergy Rotor Solution

The need for a rotor end of life solution is driven by the need for an alternate solution for the Frame 7EA gas turbine fleet that has been operating since 1970’s.

Many of these gas turbines are approaching rotor end of life and would need solutions for continued operation. For many GE gas turbine users a low-cost, low-risk, flexible solution tailored specifically for current operating profile is needed as an alternate to complete rotor replacement that may be offered by OEM and others. EthosEnergy has developed an alternate solution by re-designing life limiting components in GE gas turbine rotor train so that only components that do not meet inspection criteria can be replaced as oppose to complete rotor replacement. EthosEnergy rotor solution has been engineered to meet or exceed original equipment manufacturer (such as GE) recommended rotor end of life.

Some independent service providers may offer life time extension. Fidelity of a life time extension recommendation provided by an independent service provider should be carefully evaluated relative to risk associated with consequence of a rotor failure. Contrary to many other service providers including OEM, EthosEnergy has adopted a different approach by offering a rotor solution where by operating clock on a used rotor will be re-set by replacing life limiting components. Using state-of-the-art engineering tools and advanced manufacturing techniques, EthosEnergy has designed replacement compressor and turbine wheels for frame 7 gas turbine and these parts can be used for resetting the operating clock on a rotor. The rebuilt rotor is as good as new and would meet GER 3620[1] intervals for future operations. EthosEnergy designed compressor/turbine wheels are interchangeable with OEM components and can be tailored to accept in-kind or improved blade root profile. Program goal is to replace life limiting components of a rotor and thereby minimize overall project cost for a typical gas turbine user. Rotor exchange program has been developed to reduce our customers risk profile at a cost substantially below a complete replacement of an OEM rotor.

2. Rotor Product Development

EthosEnergy has rotor facility that is fully equipped to perform gas turbine compressor and turbine rotor overhauls for Frame 3, 5, 6B, 7B/EA, 7FA, 9B/EA, Fiat Avio TG series, GT11, GT13, and Westinghouse 101-191, 251, 501. All rotors are repaired to meet or exceed OEM standards with minimal turn-around time. New and refurbished components used to assemble turbine and compressor rotors for most gas turbines are kept in stock. This paper describes, EthosEnergy's reverse engineering efforts in development with new Frame 7EA rotor parts.

2.1. EthosEnergy Reverse/Re-Engineering Process

EthosEnergy has adopted a systematic and process-based approach for reverse engineering and re-engineering of new products[6] as summarized in Figure 1.

Our new product development team works closely with various other Engineering and Operational teams to gather initial reversal data. Reversal data may sometimes be collected when a gas turbine rotor is received at our facilities and sometimes, reversal data may be collected from a customer's outage when a unit is open for planned maintenance. Depending on geometrical features, part complexity, etc., different reverse data collection tools are used for data gathering as shown in Figure 2. Primary goal of these tools is to get accurate part definition that will be used for creating solid models needed for engineering analysis. An example reverse data collection for a typical Frame 7 rotor is shown in Figure 3. As illustrated in Figure 3, Frame 7 rotor was accessible during a typical planned outage and an engineering team visited the site for reverse data collection. Such necessary data was collected from the unit as opening clearances, casing dimensions, rotor assembly dimensions, unit operating conditions, rotor operating history (such as fired starts, fired hours, trips, etc.), etc. More detailed data characterization of individual rotor components such as wheels, blades, bolting etc. was performed when a typical gas turbine rotor is disassembled for overhaul. Individual stage data will be used for creating component solid models which are used as building blocks for complete rotor assembly.

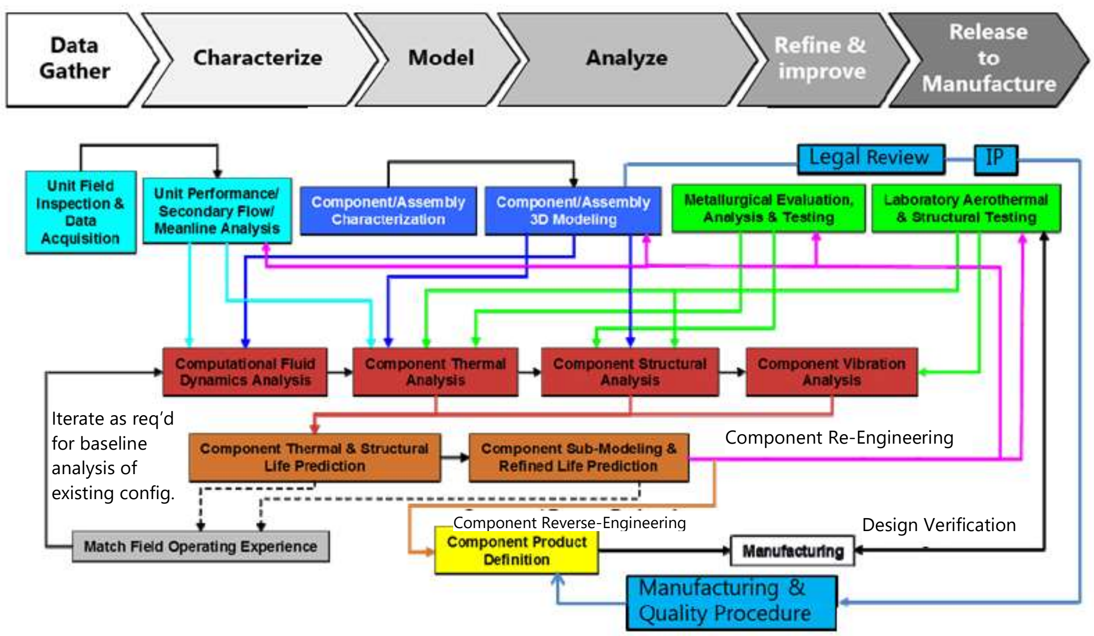


Figure 1: Reverse & Re-Engineering Process Map

Reverse Engineering Data Techniques

- ATOS II triple scan blue light 3-D analyzer showing scanning of nozzle
- FARO Laser Scan of bucket

FARO Laser

FARO arm ATOS II

Figure 2: Typical reverse data gathering tools used for parts characterization

Unit Outage

- Typical Reverse Engineering data includes sub-assemblies measurement, operational data, outage data, unit configuration, part numbers
- Data collected before and after rotor is removed from unit. Casings and other sub-assemblies scanned

Prior to rotor removal After rotor removal Casings Data

Rotor Overhaul

- Typically at on-site, EthosEnergy Location. Individual parts and sub-assembly characterization

Bladed Wheel Prior to blade removal Rotor Assembly

Figure 3: Reverse engineering data gathering of parts and sub-assemblies. Data collected during off-site outage and during on-site rotor overhaul.

2.2. Rotor Material Characterization

EthosEnergy has leveraged such IP access for characterization of gas turbine rotor materials used for rotors and Figure 4 shows typical materials used for an oOEM gas turbine rotor. Figure 5 shows typical materials used in OEM gas turbine rotors. Accurate material properties are very critical for engineering analysis and EthosEnergy has access to a large database of commonly used gas turbine materials that have been field validated. Additional mechanical and metallurgical tests may be conducted to validate a specific material property relative to known materials used in Siemens OEM material database. These mechanical properties requirements are used for design analysis as well as product specification development that will be used for first article qualification.

Typical GE (oOEM) Rotor Materials

Composition	Nominal Composition					
	CrMoV	NiCrMoV	M152	AISI 403 Cb	GTD-450	SS422
Carbon - C	0.3	0.24-0.3	0.12	0.15	0.03	0.23
Nickel - Ni	0.5	3.4	2.5		6.3	0.8
Chromium - Cr	1	2	12	12	15.5	11.5
Molybdenum - Mo	1.25	0.6	1.7		0.8	1
Vanadium - V	0.25	0.15	0.3			0.25
Aluminum - Al		0.015				
Iron - Fe	Balance	Bal	Balance	Balance	Balance	Balance
Titanium - Ti						
Cobalt - Co						
Columbium - Cb				0.2		
Manganese - Mn		0.06-0.´2				0.75
Phospherous - P		0.012				
Silicon - Si		0.1				0.35
Tungston - W		0.1				1

EthosEnergy Material Characterization Methodology

+ Chemistry determination using X-ray diffraction technique
+ Macro/ micro grain etching and hardness measurement
+ Mechanical properties testing, (e.g. LCF, tensile)

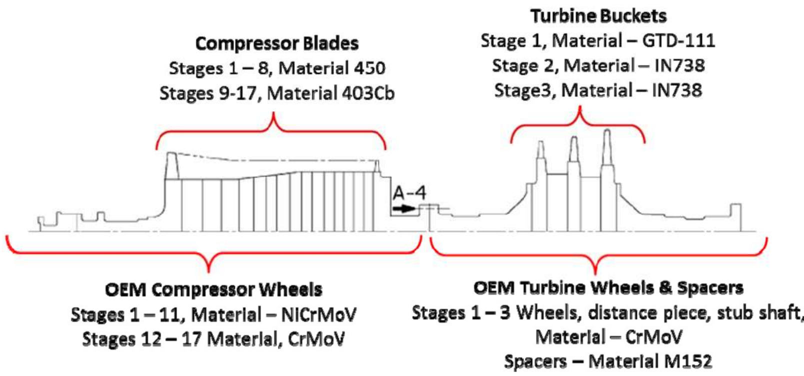


Figure 4: oOEM Gas Turbine Rotor Material Characterization

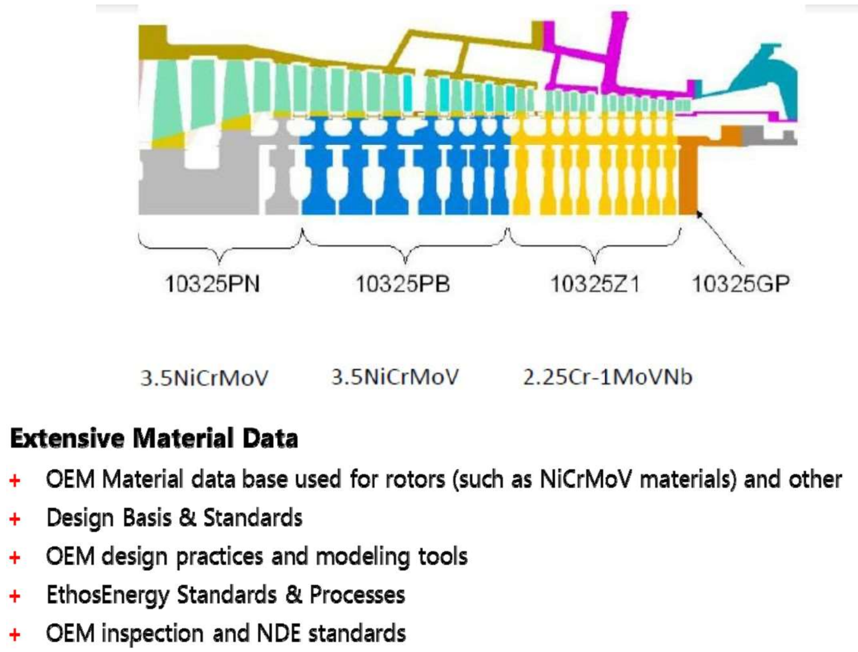


Figure 5: OEM Gas Turbine Rotor Materials used in typical rotor configurations (shown for W501D rotor)

2.3. Design Analysis Methodology

Significant effort has been focused around modeling and analyzing a gas turbine rotor as illustrated in Figure 6. As part of the design methodology, a baseline analysis of rotor has been performed using proprietary design practices, tools, material databases[8-10]. Primary focus of the baseline rotor analysis is to characterize and evaluate operating stresses and observed failure modes in the field. Specific unit operating data (such as firing temperature, ambient conditions, fuels, etc.) will be used to calibrate model predictions relative to observed failure modes. This serves as validation of rotor model as well as a baseline that will be further improved later on. Baseline analysis provides additional details such as temperature profiles, stress profiles, locations of high stresses, life-limiting locations, etc. which can be further analyzed by sub-modeling. Sub-modeling and refinement of such life limiting locations will be focus of re-designing efforts. Results of analysis are not discussed in public domain due to proprietary and confidentiality reasons.

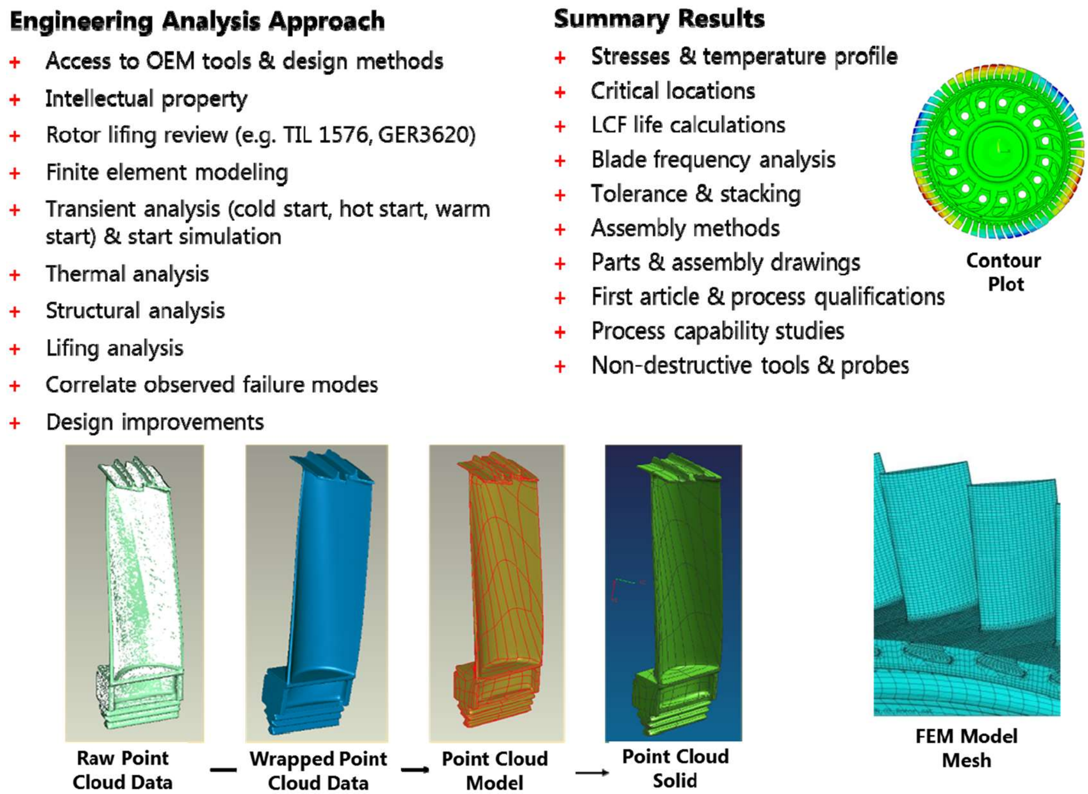


Figure 6: Summary of Gas Turbine Rotor Baseline Analysis showing scanning of parts, solid model generation and engineering analysis

2.4. Improvement and Re-Engineering

EthosEnergy has re-engineered GE Frame 7 gas turbine rotor blade slot profile as shown in Figure 7. Many GE gas turbine rotor wheels have flat bottom compressor blades which use flat bottom blade slots. Based on design analysis, it has been observed that flat bottom slots are susceptible to pre-mature cracking due to high operating stresses at these locations. Figure 7 shows location of field observed cracking and location of high stresses correlate with observed crack location. An optimized round bottom profile that has lower stresses and results in improved life as compared to OEM design has been developed. EthosEnergy also offers compressor blades that are reversed to be identical to OEM profile and are made spacer-less, eliminating need for spacers (Figure 8). EthosEnergy uses upgraded compressor disc material based on Siemens alloys that have been field validated in proven gas turbine rotors. Design incorporates improvements in the compressor blade root profile to improve cycling capability (patents pending solution). The combination of a change in material and reduced stresses increases cyclic capability.

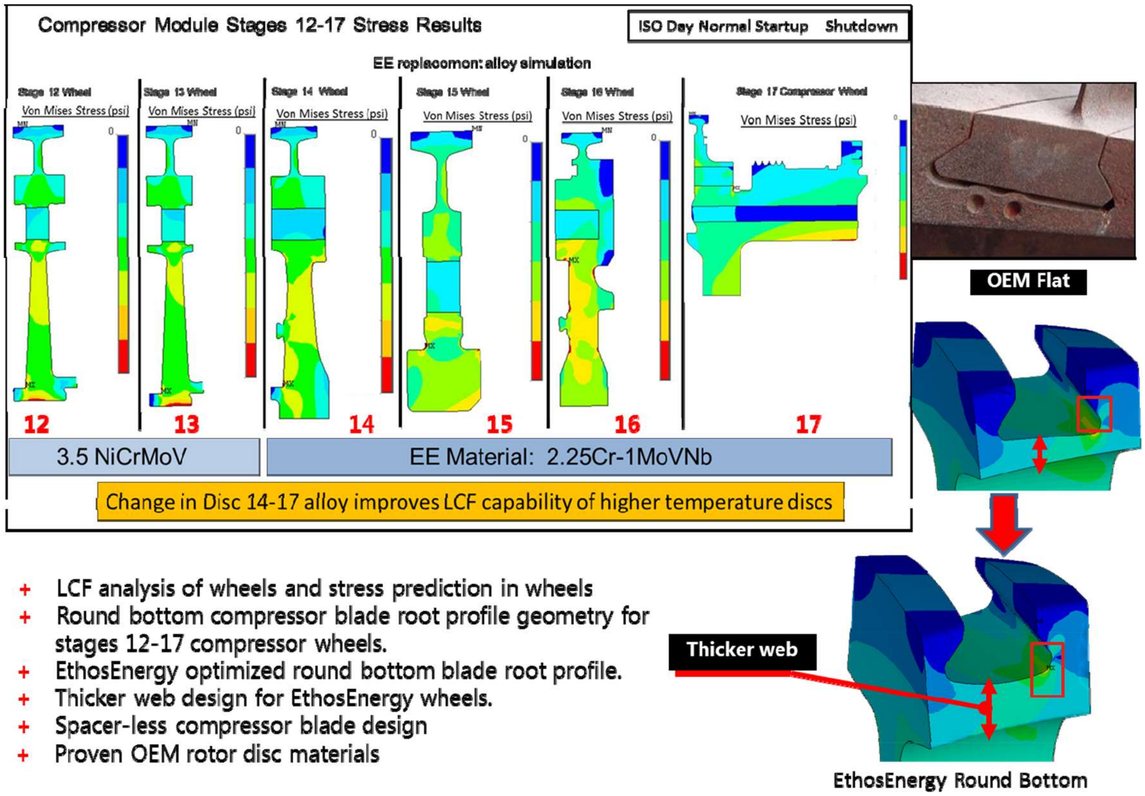


Figure 7: Re-engineered, enhanced blade root profile. Note that EthosEnergy optimized root profile to reduce stresses and minimize cracking

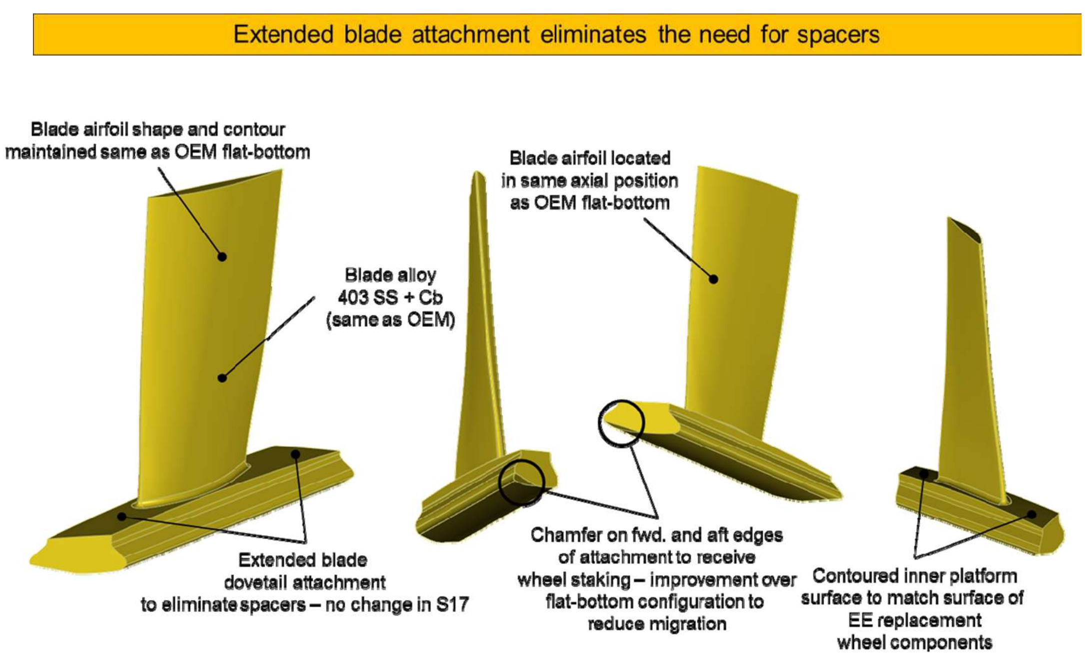


Figure 8: EthosEnergy Frame 7 compressor blades showing optimized root profile

3. Rotor Component Manufacturing

EthosEnergy has developed detailed product definition drawings and specification for first article manufacturing and production. Product definitions include such details as component definition at sub-assembly level, forging profile definition drawings, manufacturing processes details, key quality indicators, acceptable process variations, etc. Tolerances are applied based on design intent, characterization data distributions, and similar component producibility reviews.

3.1 Forging Qualification and Wheel Machining

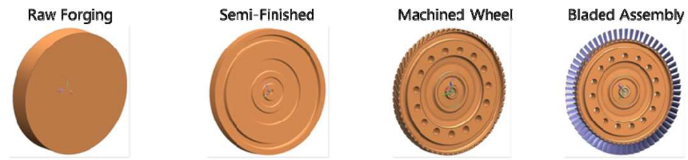
As illustrated in Figure 9, a schematic of how a typical stage sub-assembly is produced starting from a forging pancake. Forging pancakes are subjected to same OEM rigor in terms of quality requirements such as metallurgical, non-destructive tests. Those forgings that meet OEM requirement and approved by NDE inspection are used for subsequent wheel machining. Forging procurement is typically a long lead time in overall manufacturing cycle and multiple forging vendor(s) are qualified by to mitigate procurement and cycle time risks. Semi-finish machined forgings are procured ahead of time for critical stages and the Supply Chain team is tasked to maintain critical quantity of forgings to support on-going projects. Details of forging processes are considered company proprietary and are not disclosed. EthosEnergy has discussed these details with many customers once a proper non-disclosure agreement is signed. Manufacturing process specifications and NDE certifications are available for customers to review upon signing non-disclosure agreements.

Figure 10 shows machining of typical wheels. Finished wheels are shipped to EthosEnergy rotor facility in Houston, TX for sub-assembly and rotor re-assembly.

Production:

- Forging pancake and machining drawings
- First article qualification
- Tooling development
- Final, finished machining.
- Final wheel Assembly & balance

Typical Production Sequence



EthosEnergy Production Control Document

TYPE	CRITICAL APPLICABLE DOCUMENTS						NOTES
	CD-12	CD-13	CD-14	CD-15	CD-16	CD-17	
FAI	MSS-1455-71320-1201	MSS-1455-71420-1201	MSS-1455-71520-1201	MSS-1455-71620-1201	MSS-1455-71720-1201	MSS-1455-71820-1201	Part Specific Qualification Documents
Material	CP-1101-33202		CP-1101-33201				Superclean Steel Type By Stage
HT	FS-CP-1101-33202		FS-CP-1101-33201				Furnace Sheets / HT Instructions
FORG	SP-FORG-5010						Controlling Forging Documentation
UT	SP-IC-1000, SP-IC-1001, SP-IC-1009, SP-IC-2100, SP-IC-5000, SP-IC-5300, SP-IC-5311, SNT-TC-1A, ISO 9712						Controlling Ultrasonic Testing Doc's.
MT	SP-IC-1000, SP-IC-1001, SP-IC-1011, SP-IC-2100, SP-IC-5000, SP-IC-5500, SNT-TC-1A, ISO 9712						Controlling Mag. Particle Testing Doc's.
MACH	SP-MACH-2120, SP-MACH-2150						Controlling Machining Doc's.
TQA	ASTM A751, ASTM A788, ASTM A370, ASTM E112						Supporting Testing Doc's.
MARK	SP-MARK-1000, SP-MARK-1101, SP-MARK-1201						Controlling Marking Doc's.

Figure 9: First article production of turbine rotor wheel assemblies showing manufacturing cycle for a typical bladed wheel assembly

- Finish machining operation on individual wheels at EthosEnergy facility
- Manufacturing processes quality control & Service Excellence
- Final acceptance & sign-off of wheels
- Individual stage wheels shipped to Houston TX facility

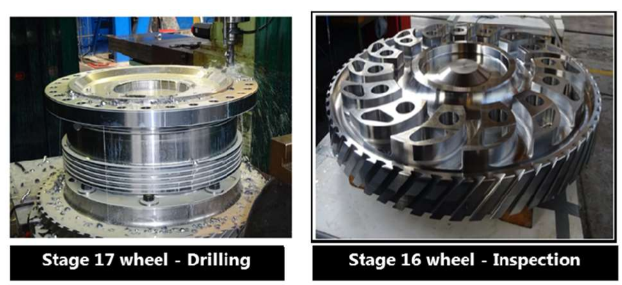


Figure 10: Compressor wheel machining at EthosEnergy facility

3.2 Compressor Blades

As illustrated in Figure 11, compressor blades are manufactured at EthosEnergy facility in Chicopee, MA. Blades are made from same materials (GTD450, 403Cb, etc.) as OEM. EthosEnergy also stocks typical compressor rotating and stationary blades to support emergent needs. EthosEnergy has also re-engineered several compressor blades – most of them on the shelf and ready to go. In addition to quick repairs, EthosEnergy offers important efficiency and reliability improvements with reversed/re-engineered compressor blade designs. Our advanced in-house coatings lead the industry in both resistances to erosion/corrosion and in efficiency gains. All blades are interchangeable with the OEM in form, fit and function.

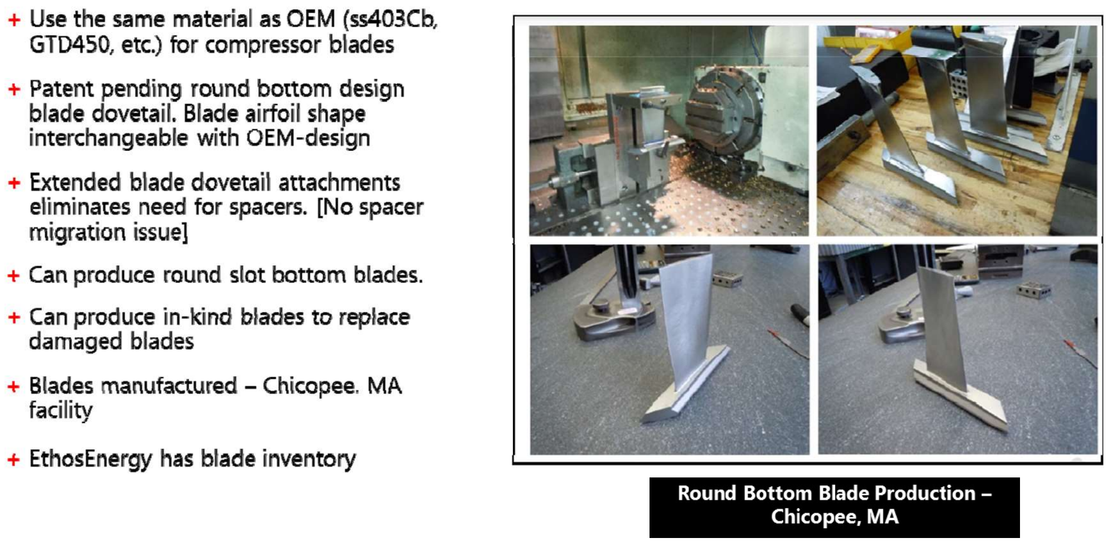


Figure 11: Compressor blade manufacturing at EthosEnergy facility

EthosEnergy Chicopee team can also reverse a compressor blade once a typical sample is available for scanning. Scanning data can be gathered in the field or at an EthosEnergy facility for quick reversal and manufacturing to assist customers during forced outage situations.

4. Rotor Overhaul Experience and Validation

EthosEnergy has performed non-OEM gas turbine rotor overhaul and recent rotor experience is high-lighted in Figure 12. Recently, a Frame 7 rotor solution for major US utilities customers was implemented. EthosEnergy fleet leader Frame 7 unit rotor is successfully operating since 2015 and has accumulate >150 starts. This Frame 7 rotor solution has been sold to a major utility customer. EthosEnergy is working with EPRI on rotor solution independent verification.

Frame 3	Frame 5	Frame 6	Frame 7	Frame 9
Gulf South Pipeline®	Savannah Power®	NAES® Bayonne	Progress Energy®	Rusail Oman
PTC	Hydro-Agri	Inland®	Tri-State® Generation and Transmission Association	
Georgia Gulf®	British Petroleum®	E.On®	Texas Gen Co	
	PCS Nitrogen	GLOW	Oceana State	
	Talisman Energy®	Vattenfal	Cinergy®	
	Valero®	Ineos®	Sunoco®	
	ZTEC	Sime Darby	Watson Cogen	
	Fertail Algeria	Berakas Power Management Company	Georgia Gulf®	
	Constellation®	PSE - Encogen	Formosa Plastics®	
	Astoria		British Petroleum®	
	NRG El Cajon		Golden Valley Electric Association	
			PREPA	
			GenOn®	
			Exelon®	
			DOW® Chemical	
			Air Products	
			Eagle Point	

Figure 12: EthosEnergy GE gas turbine rotor experience

Summary

EthosEnergy currently offers the following options[9-10] for Frame 7 customers:

Solution A – NDE inspections during typical outage duration. Unit-specific rotor life assessment can be performed either at site or at EthosEnergy facility. No parts replaced.

Solution B – Replace individual wheels. Rotor re-built during extended MI. parts to be ordered in advance.

Solution C – Replace life limiting rotor parts & Rotor Life Management. Rotor re-built during extended MI outage. Parts will be ordered in advance. Reverse engineering data on unit rotor for a customized solution.

Solution D – Exchange rotor option (low operation, overhauled rotor, ready to drop in the unit)

EthosEnergy currently offers a coupling to coupling 7EA rotor and 7FA compressor solution as a viable alternative to OEM and other independent service providers.[9-10] In addition to this offering EthosEnergy has the ability to scan a customer's rotor of a different technology to offer a similar solution. EthosEnergy operates a fully equipped rotor service facility in Houston to service gas turbine rotors. In addition to a full design capability, the group has complete portfolio of compressor blade and rotor component manufacturing capability for both OEM & oOEM units. EthosEnergy Rotor Solution is engineered to addresses specific life limiting issue in Frame 7 rotors and does not require a complete rotor parts replacement. The offer gives gas turbine users a solution at a fraction of the cost of a replacement rotor. In summary the EthosEnergy solution is quick and flexible so that customers may not have to adhere to the new rotor replacement option for an aging unit.

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