Assembly Fit-up Issue: Investigation of a First Stage High Pressure Gas Turbine Rotor

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Abstract — *A Gas Turbine engine generates mechanical energy from a combustible fuel. This mechanical energy could be converted into electrical power by means of a rotating shaft as opposed to the pressurized thrust generated on a gas turbine jet engine. Within the different variations of gas turbine engines, the Turbofan is the one configuration that is most commonly used across the commercial and military aviation industry because it provides high thrust and good fuel efficiency. These characteristics have been made possible in part by the development of new materials that are capable of sustaining higher temperatures, which is more evident on the hot section of the engine: the turbine. A gas turbine engine can be broken down onto five main modules: a) inlet/fan, b) compressor (high pressure and/or low pressure), c) combustor chamber, d) turbine (high pressure and/or low pressure), and e) outlet/nozzle. This is shown on Figure 1 [1]. This article will focus on the high-pressure turbine (HPT) module of a Turbofan engine, more specifically, the assembly between a high-pressure turbine Disk and Blades. The blades are installed into a disk as shown on figure 2. These blades incorporate a dovetail design with a total of 4 pressure faces. Pressure faces are called those surfaces that transition tangent from the adjacent radii. The pressure faces on the blades will load against parallel surfaces on the disk during engine operation to distribute loads due to the centrifugal force. The intent of this Disk and Blade sub-assembly is to extract energy coming from the burner.*

Key Terms *– Fit-up, Blades, Disk, High Pressure Turbine.*

PROBLEM STATEMENT

This article will summarize the findings from an investigation that is focused on the rotor sub-assembly of a first stage high-pressure module of a turbofan engine.

During the rotor sub-assembly, that is made up of blades and disk, the customer reported fit-up issues that affected the assembly line normal flow which then affected the total cycle time.

The blade dovetail configuration incorporates 4 total pressure faces. These blades will slide in into the disk which will incorporate a similar dovetail design. The assembly fit-up issues occur during the installation process of the high-pressure turbine blades and disk.

Each component is manufacture by different manufacturing sources. The blades are produced by casting and grinding processes. The dovetails are cast to a near shape form and its final form is controlled by creep feed grind process which is capable to attain tighter tolerances on a more consistent basis. The dovetail slots on the disks are created by broach manufacturing process. Finally, the final assembly is performed by the customer, all steps that adds up to variables and potential factors influencing the fit-up issues.

Research Description

A set of engine blades composed by 92pcs and the Disk exhibiting the fit-up issue was made available by the customer to support this investigation. The affected hardware was segregated for detailed inspection and analyses. Fielded blades originally installed into the fielded disk with no fit-up issues were disposed and detailed inspection was therefore not available.

Different inspection techniques were applied to each component to gather the required data. Correlation between techniques was demonstrated.

Affected blades were shipped by the customer to the original manufacturing source for inspection.

Inspection of disk was performed at the customer facility.

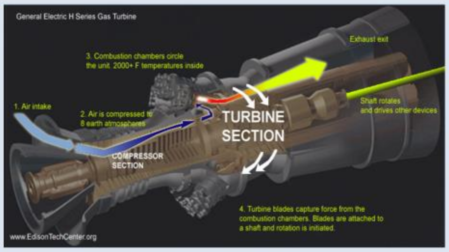


Figure 1
Gas Turbine Modules [1]

Research Objectives

The intent of this investigation is to identify all root causes and implement every corrective action necessary to mitigate the current and any potential future fit-up issues encountered during the assembly of a high-pressure turbine rotor between high pressure turbine blades and disk as reported by the customer.

The final goal is to satisfy the customer and demonstrate that a thoughtful fix to eliminate future issues was implemented.

Research Contribution

The corrective actions implemented as a result of this investigation will improve the overall quality of the affected components (high pressure turbine blades and disks) and will reduce waste in the form of added cycle time during the assembly process which represents cost savings for the customer.

Results and lessons learned from this investigation could also be leveraged across multiple legacy engine lines to prevent similar issues.

Figure 2
Turbofan HPT Rotor Sub-Assembly

BACKGROUND

During the 3rd quarter of 2018 a customer of a commercial airline reported fit-up issues between High Pressure Turbine Blades and Disk of a Turbofan Engine. The estate of each hardware was as follows: New Make Blades and Fielded Disk.
Highlights:

- Fielded Disk operated successfully before overhaul. This means that the engine was due for regular maintenance and there were no reported issues that required an un-scheduled engine inspection.
- No fit-up issues were encountered between the fielded Disks and the fielded/disposed Blades.
- New make Blades were manufactured at a source different to the fielded-disposed Blades.

METHODOLOGY/INSPECTION APPROACH

Preliminary engineering visual review of parts at the customer assembly facility indicated high risk of interference located along the MIN Neck region interface (see Figure 3).

This meant that either the high-pressure turbine blades were at or beyond max material condition (MMC) and/or disk were at least material condition (LMC). Inspections were therefore focused on the MIN neck area.

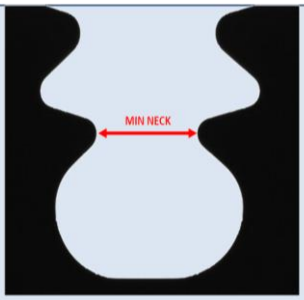


Figure 3
Disk Dovetail Sketch – MIN Neck

Historical inspection techniques were reviewed to determine the best approach to inspect the affected hardware.

At new make, the dovetail of both the disk and blades were inspected using optical comparator. An optical comparator inspection consists of placing the applicable hardware in between a light source and a screen. The shape of the hardware will then be reflected on the screen. This screen will contain what is often referred as a “glassine” that will include a trace of the drawing definition for the inspected hardware. This is, traces that are aligned with the drawing minimum and maximum definition. This inspection technique is ideal to inspect the complete form of the dovetail but was determined that different inspections would suffice for this investigation.

Since it was only the MIN neck region that was intended to be inspected, calibrated pins were selected to measure the maximum width of the MIN neck opening on the disk at all 92plc (see figure 4). The calibrated pins are precise to the third significant figure and provide accurate measures for the disk. In addition, these are set to the plus side of the applicable tolerance meaning that a 0.192in pin diameter could be offset to the max side by up to 0.0002in (e.g 0.1922in). Correlation between pin checks and inspection technique selected for the blades was proven with a 0.00001 delta difference.

For the blades, coordinate measurement machine (CMM) inspection was concluded to be the best method to inspect the blade thickness at the MIN neck region.

The CMM probe would scan the dovetail profile of the blade at two axial sections located at the forward and aft ends of the blade. CMM code will include calculation to establish the minimum circumferential length at either section. This measurement will correspond to the blade minimum MIN neck.

Figure 4
Disk Inspection – Calibrated Pin Checks

INSPECTION RESULTS

Inspection results for the high-pressure turbine disk are summarized on Chart 1. From this chart it can be seen that the MIN neck circumferential width met the drawing requirements but results are consistently running towards the lower end of the drawing tolerance band.

This data excludes the disk as the root cause for the fit-up issues given that measurements fall within the drawing specification limits (0.162-0.165). However, measurements run consistently on the lower side which closes to a minimum the amount of circumferential room to install the high-pressure turbine blades.

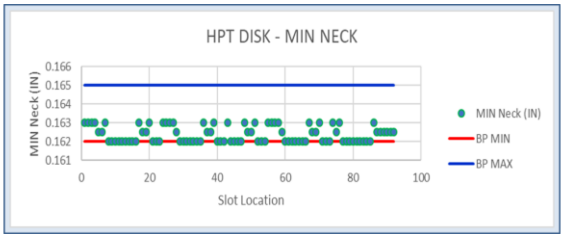


Chart 1
Disk MIN Neck Measurements (Data collected using Calibrated Pins)

It is important to note the condition of the disk prior to inspection. Disk was not what is considered a new make component, meaning that it operated for a specific number of cycles and was determined to be usable after inspection. Per the engine manual requirements, disk also had to go through a set of cleaning procedures that are performed by the customer.

For the blades, results summarized on Chart 2 shows that the MIN neck circumferential thickness met the drawing requirements but was running on the higher end of the drawing tolerance band. This data excludes the blades as the root cause for the fit-up issues given that measurements fall within the drawing specification limits (0.158-0.162). However, measurements run consistently on the higher side which closes to a minimum the amount of circumferential room for installation. Opposite to the disk, the blades were new make.

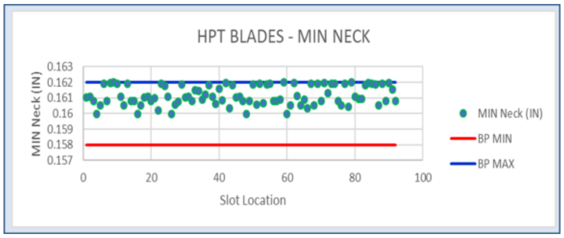


Chart 2
Blades MIN Neck Measurements (Data collected using CMM)

Chart 3 shows the resultant circumferential clearance at the MIN neck region between the disk and blades (92pcs) based on the individual data collected for each component and summarized on Charts 1 and 2. Results demonstrate that the circumferential clearance between blades and disk at the MIN neck region on several slot locations is negligible.

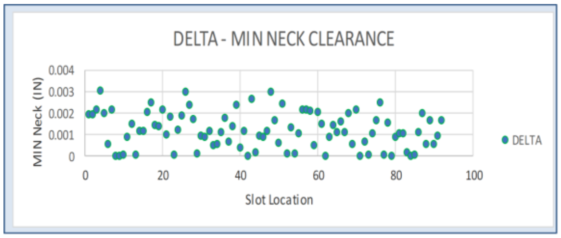


Chart 3
MIN Neck Resultant Circumferential Clearance at the MIN Neck Region between Blades and Disk

Even when the fielded blades were disposed (since these were going to be replaced by the new make blades), it was found out that those blades were manufactured by a different source. Feedback from the applicable manufacturing source confirmed that those blades ran close to nominal when they were shipped. This represents a MIN neck that was 0.0020in smaller in average than those exhibiting the fit-up issue. That is, the fielded blades were at 0.160in compared to 0.162in for the current. This additional clearance would likely provide enough additional room to install blades and compensate for any other factors influencing the interference fit.

ANALYSIS OF RESULTS

Inspection results indicated that both components, the HPT disk and blades, met the drawing requirements and should assembled together. Furthermore, the disk already ran successfully for thousands of cycles with blades and no fit-up issues were detected back then. So, what's causing the fit-up issue?

Looking back at the inspection results it can be seen that the fielded disk and new make blades ran at the low and high side of the tolerance band respectively. As a result, some slot locations would provide an almost line on line fit during the disk/blades sub- assembly. In summary, conforming blades and disk provide line to line fit at the MIN neck region and any other variations factors that may occur during the assembly process might influence this interface.

One important factor that was highlighted during the visit to the customer assembly line was that during the inspection of the fielded disk, the pin checks exhibited a tight fit. That meant that inspector had to exert some force and rotation on the pins at some slot locations to fit it in. But this statement didn't add up to latest inspections which showed that pins fit in with no force.

CLEANING, OR LACK OF. As noted above, the engine manual applicable to the fielded disk require cleaning of the disk. Customer shared this process with a different fielded disk. No detailed cleaning was performed on the MIN Neck. Dirt at this location in addition to the line to line MIN neck allowance would influence fit. Furthermore, the engine manual instructions prevent the use of any force to install blades that are slide in manually into the disk. This means that if there is any sign friction during the installation process these are not acceptable for use and would need to be called unacceptable. And this is precisely what drove the fit-up issue.

The sample fielded disk was inspected before and after a more robust cleaning process that included detailed cleaning of the MIN neck. All blades successfully fit in.

Root Causes and Corrective Actions

CLEANING: A short-term solution for potential future fit-up events will be to incorporate a detailed cleaning of the MIN neck area of the disk.

However, performing this detailed cleaning process require additional time that will translate into cost-in for the customer. The current cleaning process allows for a module level cleaning that do not require disassembly to a per piece level. On the contrary, the optional detailed cleaning process requires disassembly to a per piece level that increases cycle time. This was determined to be acceptable on the short term.

DRAWING TOLERANCE STACKUP: The final fix to eliminate any future fit-up events is to reduce the MIN neck thickness of the blades by 0.002in. This change will increase the current worst-case minimum clearance from line on line (0.000 clearance) to 0.002in. This minimum limit will provide adequate clearance to prevent future fit-up events.

During the investigation process it was determined that the current line on line minimum allowable fit between disk and blades at the MIN Neck area is not practical and represents a risk regardless of cleaning process on the disk given that inspection techniques utilized on both the blades and disk manufacturing sources combined with the level of stack up tolerances provide room for deviations that could cause interference.

EVALUATION

The additional circumferential room between HPT blades and disk at the MIN Neck region will be achieved by reducing the MIN Neck radius on the blades as shown by figure 5. The current radius will be reduced by 0.0020in. This change will increase the minimum clearance from line on line (0.000 clearance) to 0.0020in. The tolerance band will be kept unchanged.

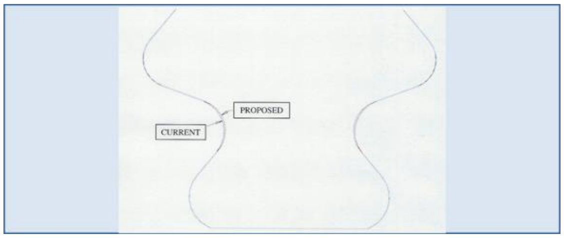


Figure 5
Disk Dovetail Sketch – MIN Neck

Calculations

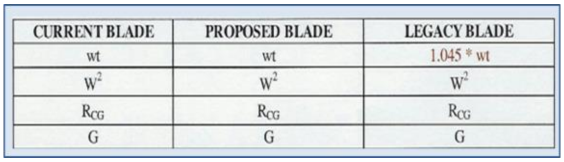
The smaller MIN Neck radius on the blades will impact stresses driven by the centrifugal force that the blades are subjected to during engine operation. Analysis were completed following a comparative approach. The current, proposed and successful designs were compared to validate the change.

Results summarized on Tables 1 and 2 shows that the proposed design will exhibit P/A stresses 0.2% higher than the current design but 4.4% below legacy experience.

List of Assumptions:

- Estimated crush Stresses calculated assuming 50/50 load split. There are slight differences compared to the ANSYS model that were concluded negligible.
- Pull load between the current and proposed geometries are assumed identical due to the negligible impact to weight due to the proposed change. Weight variations due to coating differences were also considered negligible.

Table 1
Centrifugal Force Variables



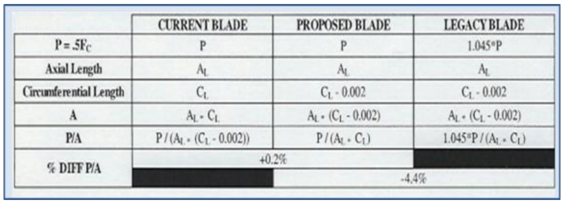
CURRENT BLADE	PROPOSED BLADE	LEGACY BLADE
wt	wt	1.045 * wt
W^2	W^2	W^2
R_{CG}	R_{CG}	R_{CG}
G	G	G

Centrifugal Force: Fc

$$F_c = \frac{W_t * w^2 * RCG}{G} \quad (1)$$

Where:
RCG - Radius @ Center of Gravity
w - Rotational Speed
W_t - weight
G - Gravity

Table 2
P/A Comparison



	CURRENT BLADE	PROPOSED BLADE	LEGACY BLADE
$P = .5F_C$	P	P	1.045*P
Axial Length	A_L	A_L	A_L
Circumferential Length	C_L	$C_L - 0.002$	$C_L - 0.002$
A	$A_L * C_L$	$A_L * (C_L - 0.002)$	$A_L * (C_L - 0.002)$
P/A	$P / (A_L * (C_L - 0.002))$	$P / (A_L * C_L)$	$1.045{*}P / (A_L * C_L)$
% DIFF P/A	+0.2%		■
	■	-4.4%	

Shear and Crush Stresses

Crush stresses are those that experience the blade at the pressure faces (4 locations) and is dependent upon the following variables: a) centrifugal force, b) load split, c) pressure face contact area and d) flank angle. None of the listed variables will be affected by the proposed radius change. Therefore, there is no impact to crush stresses.

In addition, the proposed radius change does not affect the transition from the MIN neck radius to the lower tangs, therefore, there is no impact to Shear through the Lower or Upper Tangs, therefore, there is no impact to Shear Stresses. This is shown on Figure 6.

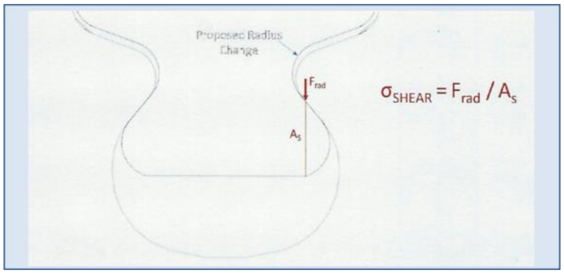


Figure 6
Shear Stress

CONCLUSIONS

The intent of this article was to document results of an investigation related to fit-up issues encountered during the sub-assembly of blades and disk of a High-Pressure Gas Turbine. At the end of this extensive investigation, all objectives were successfully satisfied. It was concluded that both blades and disk met the drawing requirements and it was the lack of cleaning on the fielded disk that drove the interference fit. In addition, it was also determined that the tolerance circumferential stack up also contributed to the fit-up issue with a worst-case scenario that creates a line to line contact.

Short term corrective actions were implemented consisting of detailed cleaning of the MIN neck area of the disk. The long term and final fix for the fit-up issues consisted of redefining the blades MIN neck area to provide additional circumferential room on a worst-case tolerance stack up.

Changes were validated by comparative analyses. The smaller radius translated into a smaller MIN neck cross sectional area that will carry the same centrifugal load. This constitute a stress increment. Three different blades geometries were compared: a) Current Design, b) Proposed Design and c) Legacy Design. In summary, stress on the proposed blade configuration is 0.2% higher than the current but still 4.40% below legacy. Successful experience of the legacy blade operating on the same disk under a harsher environment validated the proposed change.

Final change to the blade MIN neck design will provide adequate circumferential clearance at the MIN neck region and will mitigate future fit-up issues.

REFERENCES

[1] Edison Tech Center. (2014). *Gas Turbines. Learn about the history and development of the gas turbine* [Online]. Available: http://edisontechcenter.org/gasturbines.html