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generation syngas steam turbine was
modified after catastrophic damage.

cover STORY

A HYBRID approach

An operator of an ageing turbine is faced with difficult decisions with regards to repair. In-kind replacement of damaged parts may be unavailable or expensive, but has almost certainly become obsolete by modern technology, which affords greater reliability. Replacement of an entire unit is usually cost-prohibitive, and still requires maintenance of the ageing machine during the manufacturing of the new unit. A third option is a hybrid approach where the modification of existing equipment can enhance the reliability of the machine for decades to come. However, this approach has its own challenges.

This article will explore the challenges facing the hybrid approach, supported by a case study where Mitsubishi Heavy Industries Compressor International (MCO-I) repaired three turbine stages of a syngas turbine by applying its blade design

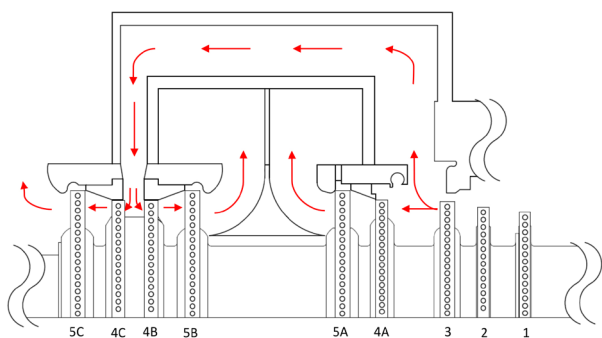


Figure 1. Configuration of the subject turbine.



Figure 2. Missing shroud band (left) and tenon (right) found after shutdown.



Figure 3. Tenon UT inspection of the subject rotor.

standards to provide a modern, robust repair that eliminates the possibility of a recurring failure.

In this case, the subject rotor was a split-flow steam turbine operating at 11 230 RPM, which is above second critical. To accommodate the centrifugal forces associated with this type of operating speed, the rotor was configured with a single disc for stages 1 – 3, and triple discs for stages 4 and 5, which minimises the maximum outside diameter (OD) of the latter stages. This reduces thrust loads and was done due to manufacturing and technological limitations relating to the blade height when the turbine was manufactured. An illustration of the turbine is shown in Figure 1. In February 2017, the unit began experiencing vibration issues, which continued until

a full shutdown in June 2017. At this time, several tenons on stage 5A were found to have failed, as shown in Figure 2.

Peened tenons

Peened tenons are potentially problematic. First, in order to effectively couple the blades, tenons must have a high degree of contact with the inner wall of the shroud orifice, which is achieved by upsetting the tenon prior to peening. This critical fit is difficult if not impossible to verify after assembly. Next, when tenons are plastically deformed in the peening process, cracks or stress risers can occur which may lead to fatigue failure. Finally, non-destructive testing (NDT) of tenons at maintenance intervals requires advanced technology that is not widely available, so cracks are unlikely to be detected after initiation. Magnetic particle (MT) and liquid penetrant (PT) inspections can only detect cracks within line of sight, and normal ultrasonic (UT) practices have inherent dead zone and geometry requirements have previously prevented successful inspection of this critical area.

UT inspection of tenons is shown in Figure 3. In this case, using a proprietary UT inspection method, MCO-I detected over 12 additional cracks that would have led to additional damage. A root cause failure investigation showed the failure was due to improper peening in a previous repair. The customer's decision to improve the rotor was driven by the desire to have a reliable and safely operating turbine for years to come. MCO-I was consequently tasked with the redesign of stages 5A – 5C.

Blade design

The difficulties associated with peened tenons for this highly stressed rotor resulted in the blade design being changed to an integrally-shrouded type, which eliminates tenons. Additionally, the fifth stages operate in the Wilson Zone, which is the region of the turbine that is most susceptible to corrosive element accumulation due to the transient conditions of wet and dry steam. Therefore, stress corrosion cracking (SCC) in the blade roots is a major consideration that can be mitigated through the use of axial entry roots. MCO-I proposed these changes using MHI design with integrally-shrouded, twist-lock shrouds and axial entry roots, as shown in Figure 4.

To prevent the harmonic excitation of blades, particularly the excitation of the first tangential mode (bending of the rotor blade as a cantilever beam), multiple blades are often connected by designers using a shroud band or similar means. This rotor used a shroud band attached to the blade by peened tenons, and the blades were grouped in 'packets' of 10 and 11 blades. Moving to a twist-lock shroud design eliminated the peened tenons (and their associated failure modes), creating an endless grouping. In order to achieve this, the original 2D blade profile was replaced with a 3D twisted profile. As the rotor spins, each blade tries to 'untwist' due to centrifugal forces. This twisting motion causes opposing contact forces between each blade, linking them together, as shown in Figure 5. The continuous ring formed by the

A diagram showing three identical, vertically oriented, three-lobed structures arranged horizontally. Each structure has a central vertical axis and three lobes extending outwards. Green arrows point to the lobes of each structure. The structures are connected by a horizontal line passing through their centers.

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Axial entry roots offer several advantages to their radial entry counterparts. Radial entry blades do not present a surface to react tangential loads, so a twist-lock style blade cannot be used. They also rely on pack compression to lock the blades in position. The design is also not open to steam flow, which allows for localised accumulation of corrosive contaminants. Finally, the 'closed' nature of the design makes inspection difficult if not impossible. Axial entry roots provide an answer to each of these design difficulties. Additionally, axial entry root designs reduce radial stresses by 15 – 30% over the conventional design.

Creating a sound weld with material of this type requires preheating to high levels to avoid cold cracking. However, with increased preheat, strength is sacrificed. Therefore, post-weld heat treatment must be carefully considered to ensure adequate strength, hardness, and toughness properties are achieved. A full scale mock up test piece was created from a forging with similar chemistry (AISI 4350) and mechanical properties as the actual rotor. Welding parameters were chosen based on previous work, and the test piece was welded with a similar weld buildup profile as the actual rotor would receive. The resulting test piece was approximately 14 in. dia. with 3 in. of weld thickness per side, as shown in Figure 6.

Seven 1 in. thick coupons were created through the fusion line, and were subjected to a three hour PWHT at various temperatures. The resulting pieces were then hardness tested in the base material, heat affected zone (HAZ), and weld material. Figure 7 shows the effect of PWHT in these regions plotted against the Larson-Miller parameter – a dimensionless factor that combines the effects of time and temperature. Based on the hardness results and required strength, a target Larson-Miller parameter for the actual weld was chosen, and test results for the procedure qualification record (PQR) piece showed acceptable yield strength, toughness, and hardness through the weld. Additionally, UT inspection and macroetch samples showed zero unacceptable defects in the test piece.

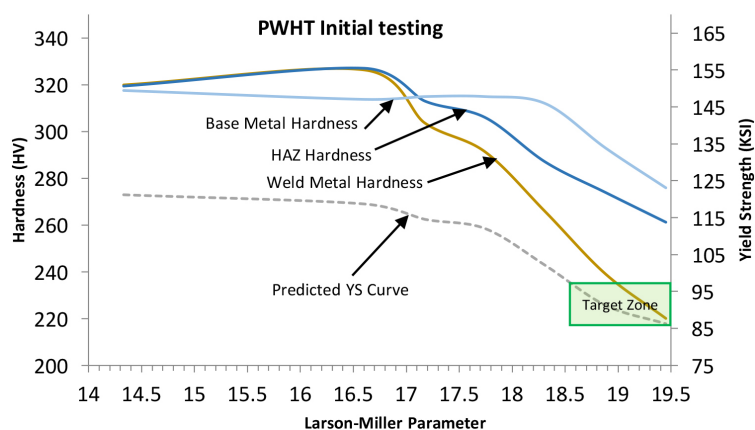


Figure 7. PWHT testing.

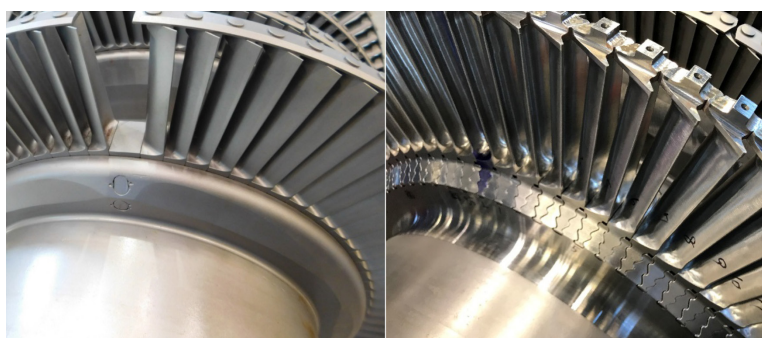


Figure 8. Stage 5b before the modification (left) and after modification (right).

Having successfully qualified the procedure, the rotor was prepared for welding by machining off the existing discs and creating a joint profile that removed welding starts and stops from high stressed locations. Care was taken to

establish reference radial bands to ensure that no significant distortion or bowing occurred during welding or stress relief heat treatments.

After welding, the discs were rough-machined and thoroughly inspected for cracks and other flaws by UT and MT inspection. The rotor was post-weld heat treated to relieve welding stresses and temper the material in the same manner as the test piece and inspected again by MT and UT. Finally, the new discs were machined into their new shape, axial entry roots were cut, and the new discs were inspected again by MT. New blades were installed, as shown in Figure 8, and the rotor was at-speed balanced.

Conclusion

Modification of older equipment presents a challenge when determining the design envelope and constraints that must be met with extensive research and sound engineering practice. When repairing ageing equipment, operators have cost-effective options to upgrade existing equipment to improve reliability using modern design. In this case, MCO-I applied a new blade design to increase reliability of a 50+ year-old turbine by applying a new blade design with axial entry roots and integral shroud bands to mitigate a previous failure. This modification presented its own challenges due to the rotor chemistry, which required careful consideration of

welding parameters to achieve the desired properties. These challenges were met, and the customer has a robust repair that can be used without any additional modification of its existing assets. 