ENERGY SECURITY VIA BEARING & BLADE REMANUFACTURING OPTIMIZED BY HYBRID MANUFACTURING WITH IN SITU VOLUMETRIC INSPECTION

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Abstract

As the world races towards adopting Artificial Intelligence "AI" at scale, the demand for electricity for data centers grows with it. Nearly all mainstream energy generation infrastructure relies on using rotating machinery to drive the generators that produce the electricity.

Providing adequate electricity relies on the uptime of electricity-generating infrastructure and proactive maintenance, repair, and overhaul "MRO" of this equipment. MRO includes the disassembly, inspection, and repair of all worn and damaged parts. Turbine bearings and blades are examples of common and crucial equipment components assessed during MRO. A review of the manufacturing techniques employed for these parts shows a lengthy workflow involving many steps and a large amount of metal waste, including metals that are increasingly difficult to obtain due to evolving geopolitics. A key reason for the metal waste is the lack of insight into the quality of the metal condition before and in between typical repair steps.

The growth of the "hybrid manufacturing" market, which combines metal additive and subtractive steps together has made this type of repair easier over the last decade. Recently, hybrid machine capability has expanded to use subsurface inspection technologies as shown in Figure 1. This enables interrogation of the metal condition before and immediately after each repair operation. This work highlights the use of hybrid manufacturing with novel in situ use of water-coupled ultrasound. To the author's awareness, this is a world-first providing a practical means of inspecting metal bond quality in the same setup as the repair operation.

This work reviews results achieved by this newest generation of hybrid manufacturing capabilities, now including volumetric inspection, and the market response achieved thus far. It includes specific case study data using hybrid manufacturing to repair critical bearing pad surfaces for energy generation equipment consuming less than 25% of the white metal currently consumed and with ~10x faster turnaround time. These advantages compared to the conventional repair workflow are identified.

This work also highlights how the efficiencies demonstrated can help make related repairs of additional classes of metal parts practical for the first time.

Figure 1 – Hybrid machines co-locate digitally driven tools for adding, finishing, and now volumetric inspection

1 Introduction and Motivation

As our reliance and demand for electricity continue to grow, the need to maintain generators and turbogenerators in prime condition and improve their efficiency becomes an ever more strategic need. This article explores emerging trends to help generate electricity more reliably and cost-effectively by updating the manufacturing methods used to produce and repair the bearings and blades on power generation equipment/turbomachinery.

Electricity demand is rising in proportion to the megatrend of Large Language Models “LLMs” adoption that are powered by calculations at data centers. The global energy consumption of data centers is geographically clustered as of 2024 in the US (~45%), China (25%), and Europe (15%) (T. Spencer and Singh 2025; Shehabi et al. 2024).

Except for solar panels, nearly all electricity generation (~96% in the US) relies on rotating equipment to mechanically turn a generator to produce electricity ("Electric Power Monthly" 2024). Over time, the rotating machinery and generators require maintenance, repair, and overhaul “MRO,” which involves disassembling the equipment, inspecting it, and repairing or replacing damaged components. Increased operation results in increased MRO demand for this critical infrastructure (Manowitz 2020; Martinos and Spencer 2025). Examples of parts repaired during MRO operations include tilt pad thrust bearings (Figure 2) and turbine blades (Figure 3).

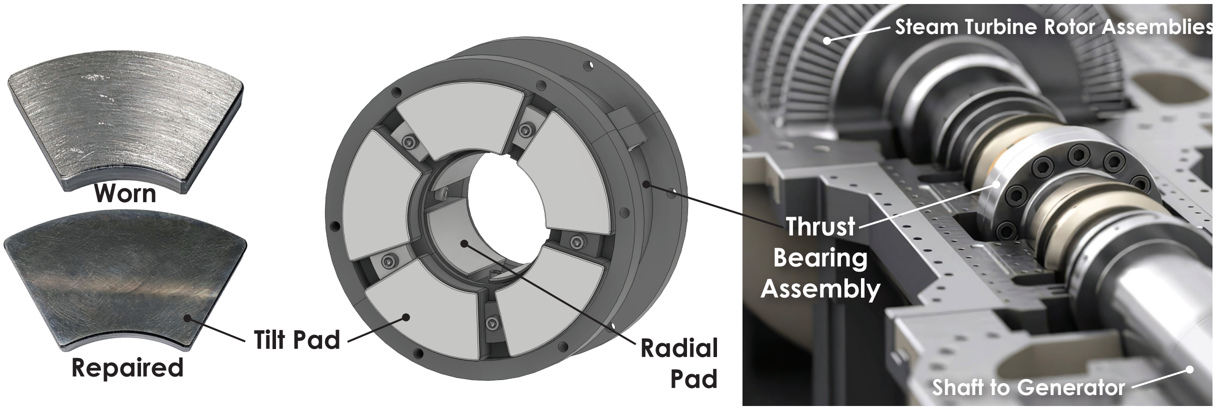


Figure 2 – Worn and repaired tilting pads for thrust bearings (left), their location within a carrier ring thrust bearing assembly (middle), and bearing installed in a steam turbine (right)

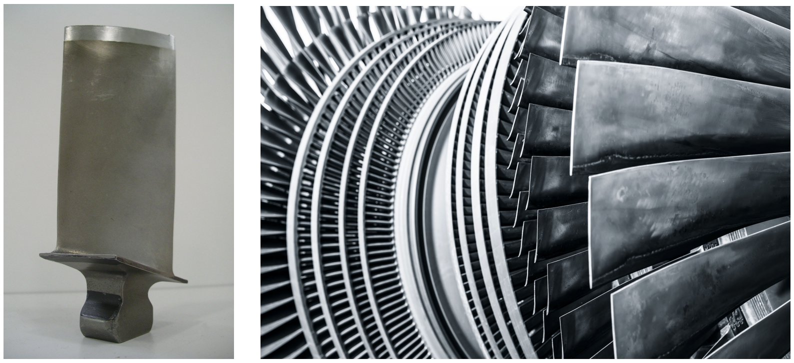


Figure 3 – A single metal blade (left) and blades installed on steam turbine (right)

The wear parts for thrust bearings (Figure 2) include bi-metallic tilting and radial pads where a soft metal layer absorbs abuse and wears away, requiring remanufacturing. Due to the nearly universal use of tilt pad thrust bearings in power generation, the current process for repairing worn tilting pads is the primary example reviewed in this work.

The repair of blades can also be benefited by the principles discussed herein but will not be illustrated. The reader is referred to existing repair literature on the topic (Jones, McNutt, et al. 2012; Nowotny et al. 2007; Yilmaz et al. 2005).

2 Current State of Bearing Repair Technology

2.1 Bearing Surfaces for Turbine Shafts

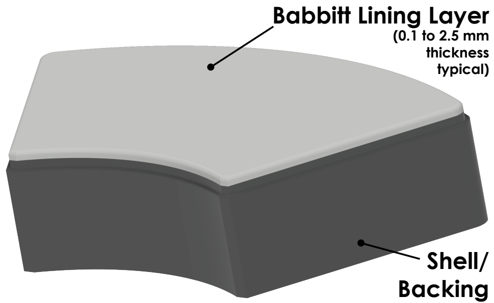


Figure 4 – Hybrid machines co-locate digitally driven tools for adding, finishing, and inspecting metal parts

As identified in §0, one of the most widely leveraged mechanisms in power generation is the tilt pad thrust bearing, ideally suited to support mechanical rotation with high axial loads. The function of the bearing pads (see Figure 2 and Figure 4) is to provide a smooth high-precision surface with a continuous oil film on it, upon which the large shafts, typically from ~150 to 355 mm (~6 to 14+ inches) in diameter, rotate at very high speeds with minimal friction (Wasilczuk 2015). While these hydrodynamic oil film bearings provide almost zero friction under optimal operating conditions, during equipment failure, circulation of contaminated lubrication, and startup/shutdown, the shaft comes into direct mechanical contact with the bearing surfaces (Wu 2015). The strength required in these bearings obliges them to be made of metal; however, to avoid damage to the precise, balanced turbine/generator shafts, a soft, tin-based metal often called "white metal" (typically Babbitt or a similar alloy) is applied as a lining layer for use as the bearing surface onto a stronger metal shell or backing normally made of steel, copper-chromium, or bronze. The sacrificial soft metal liner wears away in normal use and absorbs impacts during equipment failure to avoid damaging the main shaft.

Bearing pads are made by machining a steel or copper billet with extra space for a white metal layer. After a surface preparation step, a layer of the soft tin-based alloy is then cast on top, creating a bimetallic part, which is subsequently machined to its final shape and tolerances. It is critical that the two metals fuse together with a defect-free bond to avoid possible separation, peeling, or shearing under pressure. The natural wear on these bearing surfaces makes routine MRO necessary to refurbish or replace the soft metal layer/lining.

2.2 Remanufacturing Steps for Plain Bearings Used in Turbogenerators

The traditional MRO workflow—which involves moving parts between multiple setups for removing damaged areas, preparing the substrate where damage was removed, and then casting a new soft metal layer to restore the bearing—is laborious, complicated, and requires iterative quality checks as shown in Figure 5. This multi-step workflow is optimized to prevent a defective part from consuming precious manufacturing time unless it is certain to have quality bonding between the soft layer and its backing.

Ultrasound inspection is used to assess the bond integrity. To achieve adequate signal-to-noise ratio for reliable inspection results, it is necessary to machine the surface smooth prior to every ultrasound inspection step. As a result, parts alternate between machining and ultrasound at least three to four times during a typical repair cycle resulting in at least double that many setups.

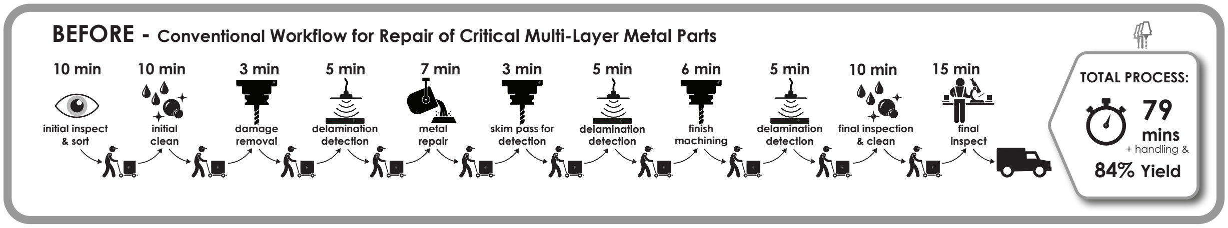


Figure 5 – Traditional workflow for turbine bearing remanufacturing steps to restore the white metal bearing face

From left to right, Figure 5 starts with an incoming inspection to assess if repair is viable, and if it is, then the next step is some cleaning. Next the parts get machined smooth and then go to a first ultrasound inspection. This assesses if the remaining soft metal layer is still well bonded to the substrate.

The results of the ultrasound test determine whether additional Babbitt metal can be added directly onto the existing layer or whether the entire soft metal layer needs to be replaced. If full replacement is needed, then the entire soft metal layer is removed, however, if full replacement is not needed, then it proceeds directly to the next step. A set of forms is placed around the bearing surface of the part in preparation for open-mold casting of the Babbitt onto the part to partially (or if needed fully) rebuild up the soft lining layer.

When the soft metal lining is added, the resulting as-cast state of the part must be oversized compared to the final "net shape." The extra material added during casting must exceed the "machining allowance" which is the excess metal thickness that is needed to reliably cut the part to its final shape. However, the state-of-the-art relies on casting whereby a skilled person manually pours the molten tin alloy from a ladle onto the part. The thickness is difficult to control precisely, so a *liberal amount of metal* is typically added to avoid costly re-routing for rework. Typically, the required thickness of the added soft metal alloy is exceeded by 5 times or more.

Once additional soft metal has been cast onto the part, it then needs to be returned to the inspection station; however, the as-cast surface texture is not normally smooth enough to reliably transmit the ultrasound signal. As a result, the part returns to a CNC machine where the surface is skim cut just deep enough to achieve a smooth enough surface for reliable inspection. (Note, although the part will need to return to the CNC for finishing to the final size and shape, it is not worth the risk of spending the CNC time to finish the part until the bond is tested). Then it returns to the inspection station for its second round of ultrasound testing. If the bond between the newly cast material and the underlying material is sound, then the part is approved to return to the CNC machine to be finished to its final shape and tolerances. If the material has not bonded well, then the added soft metal alloy must be removed and the preparation for and casting repeated. To limit the length of this text, the shortest possible workflow is described, which assumes successful inspection results at each inspection check shown in Figure 5.

For publication purposes a part with an 84% first pass yield (before any rework) is illustrated, however, please bear in mind that the yield on the above workflow is part dependent and may vary widely. Therefore, the opportunity for process improvement described herein is biased towards being understated because the parts that need rework typically requires a disproportionately high amount of resources due to the special skills, attention, and handling needed for rework. Once parts have been finish machined to their final shape they are returned once again to the ultrasound inspection station to ensure that the final machining did not introduce delamination or related defects at the bond interface to the underlying bond between metal layers. If the part passes its final ultrasonic inspection, then additional tests are undertaken, followed by final cleanup and preparation for return shipping and reinstallation at the maintenance location.

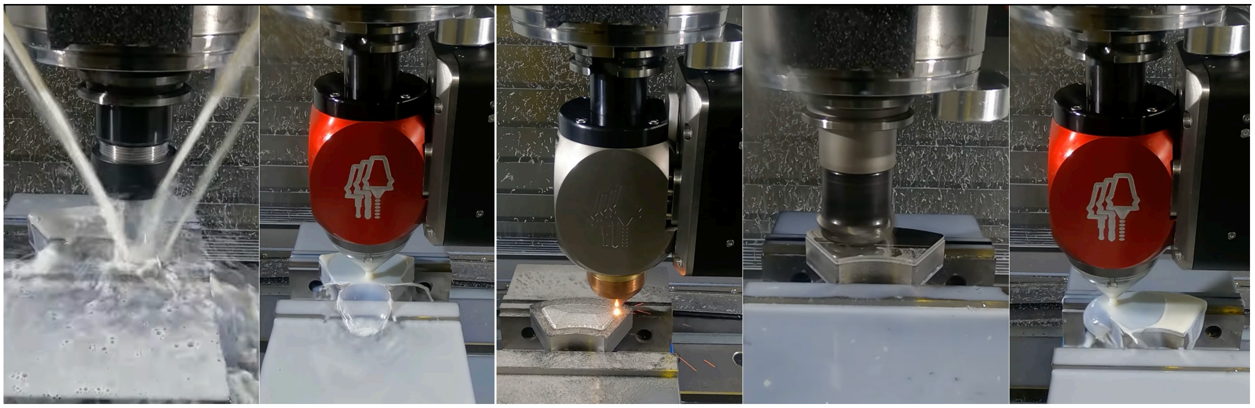
2.3 Opportunities to Improve the Remanufacturing of Bearings

Material usage and repair time are two key areas targeted for improvement in this study. Given the historical limitations of the process control, the excess amount of metal used for each pour is justifiable; however, it dramatically adds to the volume of metal in circulation which has a compound negative effect on resource utilization. The multiplied volume of metal in use drives the need to maintain a correspondingly larger volume of metal in a continuously molten state for on-demand casting availability. This consumes a substantial amount of energy just to be at the ready for casting. Additionally, all excess material deposited must be machined off which increases the machining cycle times at the corresponding machine burden rate and energy consumption. This also increases the volume of machined chips that need managing. Even though the white metal alloy in chip form can theoretically be remelted and recast, once it is machined these chips are typically mixed with chips of the backing material (steel or copper) and often are not recovered. Even if they are recovered and remelted, it further adds to the inefficiency of the process and raises the risk for cross-contamination.

In addition to reducing the metal usage, reducing turnaround time for repair is also a primary focus. Due to the many setups required to iteratively check the bonding quality of the parts, progress through the repair workflow is dominated by waiting time with only intermittent value add operations. Simplifying and smoothing out the remanufacturing process steps can improve energy infrastructure resilience and security.

3 Technology Approach and Results

In this study, a hybrid manufacturing machine combining a laser-based metal 3D printing technique called *directed energy deposition*, (a type of additive manufacturing per ISO/ASTM 52900(ISO/ASTM 2021)), subtractive CNC machining, and ultrasonic testing in the same setup has been utilized as shown in Figure 6. This type of system combining complementary techniques had a long history of anticipated synergy in the academic community since the 1990's when metal AM research began (J. Spencer, Dickens, and Wykes 1998; Weiss, Prinz, and Siewiork 1991; Greul, Pintat, and Greulich 1995) and a relatively lengthy incubation period to achieve practicality for use in industry (Nowotny et al. 2010). This combination allows for nearly end-to-end processing of these critical components streamlining the entire repair workflow, provided that the material combinations needed are amenable to deposition into the same monolithic part (with or without transition layers) (Jones, Cooper, et al. 2012). The system used for work reported herein was a hybridized 2024 Haas VF-4SS milling machine equipped with a 2025 AMBIT™ FLEX deployer system (SN13216) using an AMBIT™ LMD 21 head (laser metal deposition head with 2 mm spot size) and AMBIT™ WAVE head (for liquid-coupled ultrasound) made by Hybrid Manufacturing Technologies (McKinney, TX, USA). The single setup repair sequence is illustrated in Figure 6. Machining steps shown in Figure 6 steps a and d used conventional speeds and feeds for soft metals. Ultrasound inspection (steps b & e) was undertaken at a frequency of 15 MHz and voltage of 100V and feed rate of 1 m/s. The inspection time for the entire part was 1:19 each time it was repeated. Metal deposition (step c) was undertaken at 700W and feed rates varying between 0.7 and 1.4 m/s with metal addition averaging about 15 grams per minute. Maximum deposition time (for total Babbitt layer replacement) was 4:45. Total processing time varies with the amount of new Babbitt deposition required. When the entire Babbitt is added/replaced, the total process time for automated steps shown below is 15 minutes and 11 seconds.



a) Damage removal of existing Babbitt metal layer to leave a smooth surface for inspection

b) Ultrasound inspection of the bond between remaining Babbitt and the steel backing

c) Laser metal deposition of Babbitt onto the remaining Babbitt liner

d) Finish machining to the final size of the Babbitt layer (composed of newly deposited and remaining Babbitt)

e) Final ultrasound inspection to ensure no delamination is detected between any of the layers

Figure 6 – Consolidated workflow for plain bearing remanufacturing using an AMBIT™ multi-tasking system on a Haas CNC

With the ability to automatically transition between milling, ultrasound inspection, and metal deposition hybrid manufacturing machines present the opportunity to drastically reduce the setups needed as shown in the lower half of Figure 7. After the first and second steps of initial inspection and cleaning, the part then enters a setup in the CNC machine where steps 3 through 10 are undertaken without further operator intervention. Once the automated steps are completed final inspection and preparation for shipping occur outside of the machine.

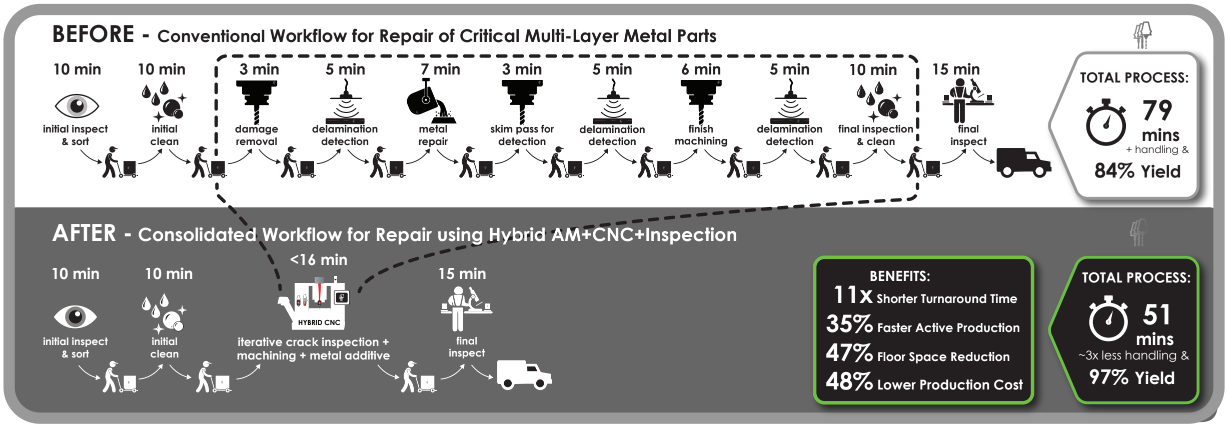


Figure 7 – Consolidated workflow for plain bearing remanufacturing compared to traditional workflow

As shown at the bottom right of Figure 7, the total active processing time is only moderately reduced (by about 35%); however, the part handling is dramatically reduced (by ~3 times) and the part yield is improved to 97%. The consolidated repair steps enable an eleven times shorter turnaround time, which is often the basis for competitive advantage in the remanufacturing industry. The shortened turnaround time is due to the "done-in-one" setup replacing the need to move the part between machines and the inspection station. Furthermore, the cost of repair is reduced by nearly 50% and the floor space required for the repair equipment is also reduced by nearly half. Energy savings using a hybrid machine are reduced by a factor of 10 to 12x compared to traditional approaches for reasons described in §4.

A financial analysis based on the material and time savings indicated by the pads illustrated, indicated a payback period of approximately 6-8 months assuming a smooth production ramp up and a sufficient volume of parts needing repairs to fully saturate the hybrid machine available hours.

4 Discussion

The introduction of hybrid manufacturing machines to the bearing repair process provides an automation solution for steps that otherwise require extensive multi-setup routing, with re-routing contingencies, as already discussed. The hybrid machine reduces the complexity of part routing and line balancing by bringing immediate validation of high-quality bonding between the soft and hard metal layers interleaved with the machining needed to produce the optimal surface conditions for inspection and the correctly toleranced finished parts. This approach provides advantages at the individual step level as well as in the aggregate.

In contrast to the manual ultrasound inspection that is standard practice, the automation of ultrasound on computer-controlled machines provides a uniformity, speed, and documentation advantage. First, automated inspection path planning unifies the nature of inspection by eliminating differences due to tendencies of individuals during manual inspection. Next, the inherent speed of the CNC machine coupled with the ability for algorithms to detect ultrasound reflection patterns at very high rates, allows for fast scanning of entire parts. Initial detection algorithms were used in this work to inspect the entire part inscribed within the perimeter of the part looking at the bond interface with a "go" or "no go" threshold set based on the thickness of Babbitt deposited. While this approach is viable in its current form for exactly learned parts, it lacks the sophistication and the flexibility of a human. It is not reasonable for simple algorithms to entirely replace the human for cases that are not exact or may have unanticipated results. Appropriate caution is advised to balance expectations against the variability of parts processed and allow for a manual inspection path to run in parallel or as a final sign-off until statistical certainty is demonstrated.

Lastly, the state-of-the-art is to provide a certificate of conformance that simply lists testing parameters signed off by the person doing the manual inspection but does not provide any actual documentation of the inspection signals during scanning. In contrast, inspection signals in an automated hybrid machine can be tracked and saved with the position of the probe relative to the part. This data package can be saved by the remanufacturer and/or provided in a report to the end customer to provide an added layer of confidence than is available using standard practice.

The laser-based metal deposition method is controlled to a much higher fidelity than manual molten metal casting and only melts the material as needed. This reduction of metal deposition is favorable in multiple ways. First, the use of feedstock material that does not require being kept in a molten state to be ready for use significantly reduces the energy consumption of this process. Additionally, the amount of metal consumed during the process is much less. The as-printed shape is built up just oversized enough to provide adequate allowance for machining, which typically only exceeds the minimum required deposition by 1.25 to 1.5 times. This significantly reduces the amount of soft metal alloy in circulation as both feedstock material and as machined chips. By printing much nearer to the final part's net shape the machining required for each part is significantly reduced, saving time and energy.

The automated processing in the machine also reduces the amount of cleaning between steps and at the end of processing, such as ultrasonic gel removal.

Collectively these operations undertaken in combination reduce the work-in-process that naturally accumulates in between the steps of a workflow involving multiple pieces of capital equipment (used to ensure high utilization of the equipment). This elimination of time and parts between each setup allows for a far more responsive turnaround timeline for repair.

By digitally controlling all major remanufacturing steps, the system inherently maintains high integrity "lossless" data sets about each of the manufacturing steps. Additionally, since processing is often achieved in a single setup, there are minimal gaps in the data compared to manually moving parts between setups. Thus, a hybrid manufacturing system provides an unparalleled comprehensive dataset which can be leveraged for analysis including by AI to help optimize the workflows to achieve higher efficiencies. In fact, it is the expectation that as AI continues to mature, all digital workflow planning, and any rework required will be actively planned, monitored, and adapted by human-in-the-loop AI enabling intelligent oversight of supervisory guidance and handling of what is hoped to become an ever-shrinking pool of unanticipated anomalies. By so doing, the very electricity and energy that is saved via adopting this process can figuratively and literally be reinvested to continue to enhance the efficiency further in a virtuous circle.

A key advantage of this automated process is that operator safety and working conditions are significantly enhanced by not needing to handle and manually pour molten metal with its accompanying risks. This automated solution can change the nature of human roles within bearing remanufacturing practices**.**

The adoption of this approach so far has focused on parts that are in the lower 50th percentile of size for turbogenerators. Although the advantages documented so far provide strong impetus for continued adoption, examination of larger parts is yet to be undertaken.

5 Conclusions and Recommendations

The hybrid additive, subtractive, and inspection system presented herein provides strong evidence that it has the potential to rewrite the bearing and blade remanufacturing workflow that has been used for more than a century. Furthermore, the data from hybrid systems is highly amenable to direct analysis and decision making by machine learning and other AI methods enabling a ripe ecosystem for rapid additional optimization and a pathway towards autonomous control.

The interest and flexibility of existing workers to be retrained and support this new approach will have a strong impact on the adoption rate, even with its inherent benefits. Although it leverages a known skill set for operation, it adds additional capacity demands and new learning for a finite pool of trained CNC machine operators.

The breadth of parts that can be effectively processed using this approach will also determine how quickly it can be invested in. Along this theme, an additional area for evaluation is to characterize how well these beneficial results will scale up as the size of the bearings increases above the 50th percentile. As the size of parts increases so does the volume of soft metal that needs deposition, which scales according to the square-cube law. This may introduce a ceiling to the cost-effectiveness of this approach as the repair focus increases to larger parts.

While the results of this approach are a strong reason to view it with great promise, a wide variety of improvements will be needed to help it become the de facto standard for this type of repair. Improved robustness in inspection algorithms, possibly leveraging AI, are bound to help feed the process with critical insight with minimum human intervention. Also, improved data compression and reporting methods will enable pedigreed part data to more readily be shared, interrogated, and archived.

The ultimate acceptance or rejection of this new hybrid manufacturing technology approach will be measured by market acceptance from both remanufacturers and end use energy generation users. Given that the increasing energy demands provide a unique set of market conditions (increasing the pressure to add capacity and upkeep current capacity) investment in automated hybrid machines can help ensure energy security going forward.

6 Acknowledgements

This work has been undertaken largely by internal R&D and applications teams at Hybrid Manufacturing Technologies Global Inc. (USA) and Hybrid Manufacturing Technologies Ltd (United Kingdom). Appreciation is expressed to Peter-Jon Solomon, Peter Coates, Mike Duffin, Dylan Jones, and Steve Berdote, who have been instrumental in achieving the results provided in this paper. Members of the REMADE funded project: Development of Hybrid Repair and Non-destructive Evaluation Technologies for Aerospace Components have also helped validate the applications opportunity for blade repair with specifics to be reported elsewhere.

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8 About the Author

Dr. Jason Jones is an award-winning inventor, entrepreneur, and the Co-founder and CEO of Hybrid Manufacturing Technologies. As the pioneer and world's leading authority on "hybrid manufacturing," he transforms machines into flexible smart factories. Dr. Jones has a PhD in 3D printing and holds dozens of patents. He was a founding member of the ASTM F42 standards and serves with the AMT board & SME.