BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 72(2), 2024, Article number: e147920
DOI: 10.24425/bpasts.2023.147920

MECHANICAL AND AERONAUTICAL ENGINEERING, THERMODYNAMICS

Development and implementation of robotized wire arc additive repair of a gas turbine diaphragm

Piotr STECKOWICZ[1,2]*, **Paweł PYRZANOWSKI**[2], and **Efe BULUT**[3]

[1] GE Power Sp. z o.o. – Oddział Engineering Innovation Center w Warszawie, Al. Krakowska 110/114, 02-256 Warsaw, Poland
[2] Warsaw University of Technology, Institute of Aeronautics and Applied Mechanics, ul. Nowowiejska 24, 00-665 Warsaw, Poland
[3] GE Marmara Technology Center Müh. Hiz. Ltd. Sti. Tubitak-Mam Teknoloji Serbest Bolgesi, 41400, Gebze/Kocaeli, Turkey

Abstract. The current practice of reconstruction of oxidized turbine parts (due to hot corrosion) using arc welding methods facilitates restoration of the nominal shapes and dimensions, as well as other attributes and features. Intense development of 3D additive methods and techniques contributes to the repair/modification of different parts including gas turbine (GT) hardware. The article proves the viability of the concept of using a robotized additive arc welding metal active gas (MAG) process to repair and modify gas turbine diaphragms using different filler materials from the substrate. The industrialized robotic additive process (hybrid repair) shows that very good results were achieved if the diaphragm is cast of nickel-iron and the filler material for welding the passes is austenitic stainless steel (for instance 308 LSi). This is one of the novelties introduced to the repair process that was granted a patent (US11148235B2) and is already implemented in General Electric Service Centers.

Keywords: WAAM; diaphragm; gas turbines; CMT; robotic additive repair; arc welding; Ni-Resist.

1. INTRODUCTION

Laser additive techniques usually offer accurate, high-quality printouts. In the selective laser melting (SLM) method a laser beam traverses the surface of the powder layer along a predefined profile [1]. This is a low deposit process used for instance on turbine blades for blade tip restoration. However, it relies on extremely expensive equipment and consumables [2]. This is often paid for by a long time to build out the parts. On the other hand, for many years repair/modification of turbine components has been performed by using cost-competitive methods, including arc welding sources with a gas-shielded consumable electrode MIG/MAG (metal inert gas/metal active gas) or gas tungsten arc welding (GTAW). Weld build-up is the process of applying weld metal to a metal surface that comes from a fusible electrode, mixed with a melted top layer of the substrate material. Metallurgical bonding of the surfaced layer with the substrate ensures high utility values of preformed layers. A layer of weld metal is applied to the surfaces to restore their nominal dimensions and shape while ensuring the appropriate quality, dimensional accuracy, and serviceable requirements [3]. The additive weld build-up process can be used to repair damaged and degraded areas on flat, rotating, and complex-shaped surfaces.

Key factors for the wide application and popularity of additive regeneration by MIG/MAG methods are as follows: availability of the welding equipment and consumables, variety of consumables (fillers and powders), high process efficiency, high deposit rate, and low cost. Mentioned advantages can be augmented by automation, including robotization [4]. Multi-layer arc surfacing for regeneration purposes shows some similarity to incremental 3D printing. Application of arc surfacing MIG/MAG may be driven by the following properties [5, 6]:

- High deposition rate, which may be translated into a short time of repair.
- Availability and low cost of welding sources and consumables. This includes low-energy methods limiting the amount of heat and sustaining better process control and stability, CMT (cold metal transfer by Fronius).
- Ease of robotization.
- Easy to control the process like welding MIG/MAG – inverter sources with synergic control.
- Universal use for repairs.

On the other hand, there are numerous concerns and limitations concerning the MIG/MAG weld build-up process, which can negatively influence the additive repairs [6]:

- A significant amount of heat, increasing as the process progresses, which may require several dozen or more layers, special tooling, and additional stops interrupting the process in between for partial cooling and/or location to assess the actual increment of overlapping layers.
- Deformation and incomplete fusion of the welding beads caused by the heat introduced into the subsequent layers.
- Low accuracy and irregular surface.
- Unfavorable structure and mechanical properties as a result of a multiple and long-term thermal cycle.
- Poor quality of start/end weld.

Despite the number of advantages of the arc wire additive process and the broader availability of more and more cutting-edge

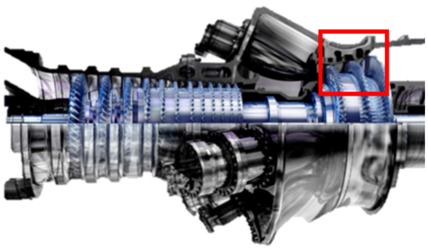
*e-mail: piotr.steckowicz.dokt@pw.edu.pl

Manuscript submitted 2023-04-14, revised 2023-09-21, initially accepted for publication 2023-10-07, published in March 2024.

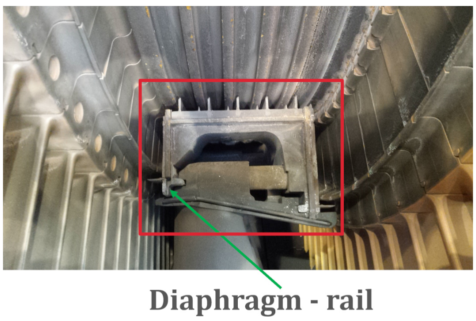
devices, there are only a few published proofs of additive repairs of gas turbine hardware. In scientific publications, readers can find reviews of the WAAM (wire arc additive manufacturing) process. In fact, it is a multi-layer, precisely controlled arc surfacing MIG/MAG and TIG methods (introducing hot-wire). WAAM methods are mainly aimed at building models made of titanium, nickel, cobalt, steel, or aluminum alloys for industrial purposes [7, 8]. It is still a process that reduces the process time and it is relatively easy to be robotized [9]. The additive process can be also leveraged to services to repair, modify, and enhance the durability of the hardware as WAAR (wire arc additive repairs).

2. GAS TURBINE DIAPHRAGM – OVERVIEW

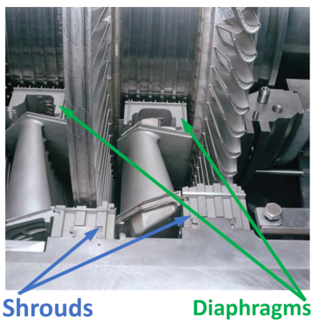
Gas turbines are designed in such a way that components operating in the most demanding conditions can be replaced or repaired at strictly defined intervals. Repairs performed in hot sections of gas turbines mainly include the reconstruction of the shapes and surfaces of worn parts, the rebuilding of protective coatings, and the repair of cracks [10]. One of the components that undergo such periodic repair is the diaphragm (Fig. 1). Diaphragms in the gas turbine are arranged in a ring around the entire circumference between the power nozzles and the turbine rotor (Fig. 1). The main task of the diaphragm is to provide sealing between the bottom of the power nozzle and the turbine rotor. It is extremely important because any leakage caused by the gap between the nozzle and the rotor may lead to a loss of power and reduced efficiency of the turbine [11]. A gas turbine diaphragm is comprised of stages, where the number and size of the stages and segments depend on the power of the turbine. The diaphragm forms a ring, which apart from serving several purposes, holds the power nozzles (stator vanes) in its annular area (Fig. 1). In each stage, a diaphragm consists of upper and lower segments. Those segments are assembled into the respective halves of the casing. This design makes the assembly/disassembly of the diaphragms feasible. Additionally, as there is a significant pressure drop across a turbine stage, the diaphragm also acts as a partition between the pressure stages [12]. This is another use of the diaphragm. By design of the gas turbine, the gas flows through the power nozzle causing a pressure drop across the stage. A radial clearance is necessary between the diaphragms and the rotor to facilitate the free rotation of the shaft. The gas that may bleed across the tips of the diaphragm contributes to a loss of performance known as tip-leakage loss. To minimize the leakage loss, the diaphragm often holds a labyrinth seal that mates with a shaft sealing surface [13, 14]. During the operation of the turbine, the diaphragms are exposed to several factors causing their oxidation. These gas turbine components operate in a high-temperature environment that in many cases exceeds substrate thermal properties. The diaphragm is attached radially to the power nozzle vanes of the nozzle segment and forms an air seal around the rotor. Since the diaphragm is not directly exposed to the hot turbine gas, they are typically manufactured from a material such as a cast nickel-iron, the so-called Ni-Resist. It is cast iron that is often used for heat and corrosion-resistant applications. The excessive temperature causes oxidation and erosion of the rail section where the diaphragm is attached to the nozzle [15]. One of the processes used to rebuild the shape of the worn/eroded diaphragm is the manual process of wire arc welding with the use of a metal inert gas (MIG)/metal active gas (MAG) process. Those processes are time-consuming and generate a significant quantity of rework due to the reduced weldability of the degraded material. This work demonstrates a robotized method of repair of 9FA & 7FA diaphragm rails. In this case, a novelty is a process of high deposit rate cladding (additive) to restore the affected rail section and the usage of different welding fillers (stainless austenitic steel 308 LSi) for the mentioned cladding/additive process (hybrid repair). This process is also enhanced by a specially developed sequence/program for the welding robot along with an application of the MAG pulse method. An additional advantage of the process is to perform it without pre-heat treatment [16].



(a)



(b)



(c)

Fig. 1. Cross overview of the gas turbine (a); Cross-section through turbine shell (b); Power nozzle assembly with marked diaphragm (c)

2.1. Materials used for diaphragms

The turbine diaphragms are made of creep-resistant and hot corrosion-resistant materials. The second stage diaphragm, which is the subject of the tests, is an element made of Ni-Resist with the chemical composition given in Table 1. The

Table 1
Chemical composition of Ni-Resist alloys [%] [18]

[% weight]	Ni	Cr	Si	Cu	Mn	C max	Other
NiResist D2	18.0–22.0	1.75–2.75	1.0–3.0	0.5 max	0.7–1.25	3.0	–
NiResist D-2W	18.0–22.0	1.50–2.20	1.5–2.2	0.5 max	0.5–1.5	3.0	12–20 Nb
NiResist D-2B	18.0–22.0	2.75–4.00	1.5–3.0	0.5 max	0.7–1.25	3.0	-

main application for Ni-Resist is in the gas turbine, automotive exhaust, and turbocharger systems, where the temperature fluctuates between 500 and 1050°C. Ni-Resist is suitable in these applications up to the temperature of 925°C due to its ductility, hot strength, and low coefficient of thermal expansion. This results in the best resistance to such severe thermal shock [17]. Ni-Resist is a hard weldable material because of a high amount of carbon alloying element. The repaired diaphragm is made of Ni-Resist D-2B, which has higher chromium content resulting in better corrosion and corrosion-erosion resistance than Ni-Resist D-2 [18].

2.2. Welding materials used for diaphragm repair

The welding materials used for the repair of Ni-Resist diaphragms are Ni-rod 55 and Ni-rod 44 (AWS A5.15). These fillers have low hot corrosion resistance. Using them in repair processes results in the degradation of the parts. Thus, the hardware needs to be refurbished once the interval of the turbine is completed. Manual (without pre-heat) cladding with cracks induced in those fillers (prone to hot cracking) results in a fusion zone that breaks out onto the surface. The conducted test proves that very good results are achieved if the diaphragm is cast of nickel-iron and the filler material for welding the passes is austenitic stainless steel (for instance 308 LSi). Numerous trials were performed that determined 308 LSI to be the recommended weld wire based on hot oxidation resistance. 308 LSI is a suitable alloy for heavy weld build-up, more durable than Ni-55 for oxidation resistance at high temperatures (Fig. 2) and it is cost-competitive from a serviceable standpoint. This is one of the novelties introduced to the repair process. It should be underlined that it is a challenge to find fillers with similar thermal coefficient to Ni-resist base metal. Still some cracks may occur in the fusion zone. However, they are inside the substrate and are acceptable from the serviceability standpoint. Chemical properties of the mentioned fillers are in Table 2.

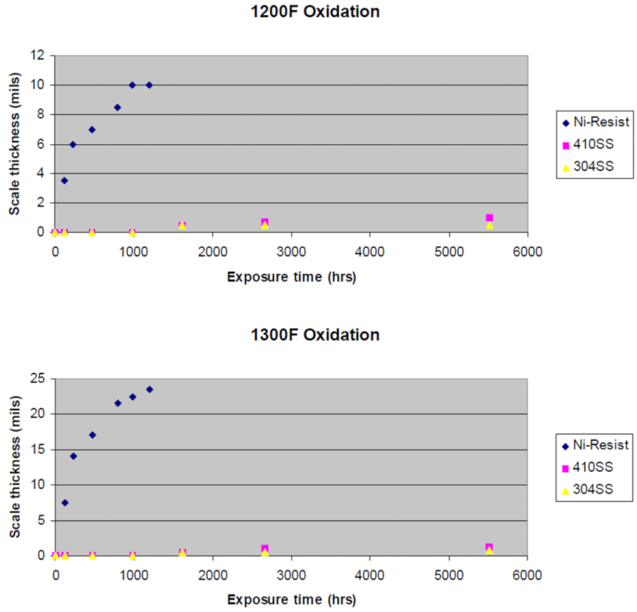


Fig. 2. Oxidation curves for 304SS, 410SS, Ni-Resist

3. TECHNICAL AND TECHNOLOGICAL ASSUMPTIONS OF THE DIAPHRAGM REPAIR

The diaphragm repair described herein is a fully developed and implemented process used to repair affected hardware. It shows the possibility of 3D additive wire arc welding using MAG Pulse cladding.

The following technological assumptions were made [9, 20, 21]:

- Robotization of the process with manual trajectory programming, mainly by repeating the set point several times.
- Multi-pass cladding – multiple applications of layers of molten metal with an increase in the vertical direction and horizontal).

Table 2
Chemical composition of Ni-rod 44, Ni-rod 55, 308 LSi welding fillers [19]

[% weight]	C	Mn	Si	Ni	Fe	Cr	Mo
Ni-rod 55	0.1	0.1	0.8	55.0	Balance	–	–
Ni-rod 44	1.5	1.1	–	44.0	45.0	–	–
308 LSi	0.03 max	1.0–2.5	0.65–1	9–11	–	19.5–22.0	0.75 max

- Single-pass cladding – a feature made of a single, multi-layer weld bead.
- Movement of the robot (straight contours) or simultaneous movement of the robot and rotary positioner table (continuous rotation with tilt).
- Cladding with the MAG pulse method using a CMT welding source (Fronius).
- Use of advanced control of the cladding parameters (gradual rise or drop of the current at the beginning and the end of the weld bid).
- Periodic stops of the process for cooling of the workpiece to control inter-pass temperature (pyrometric control). The workpiece temperature during cladding cannot go under 250 degrees Celsius to avoid hot cracks in the fusion zone breaking out onto the surface of the part. Thus, tooling that accommodates three diaphragms was designed and introduced. During additive repair, the robot switches from part to part so as not to overheat the parts.
- Dimensional inspection of the part by manual measuring devices.

Communication welding source – the robot was carried out via DeviceNet (development)/Ethernet (implementation) digital interface supported by built-in welding procedure of the FANUC ARC Mate 120i robot and a remote controller RCU 5000i (Fronius) (Fig. 3). Temperature control between welding layers was performed by the Infrared thermometer DX.T10 (Facom) coupled with a K-type thermocouple. The programming covered both the movement of the robot and the positioner, as well as the operation of the welding source, including setting parameters in the form of programmed "Jobs", supplemented with welding source settings TPS 5000 CMT. The initial steps involved creating simple geometric forms – vertical walls to be able to set the initial technological parameters and general settings of the programmed robot and welding source [9, 22]. During the initial trials, the CMT mode was rejected (due to the concave shape (lowering the profile) of the cladded layers) in favor of MAG pulse mode (Fig. 4). It was characterized by higher arc stability (no short circuit), almost no spattering and good flow of the welding beads (wide bead). Moreover, it has become possible to perform cladding with wide layers where the wall thickness goes up to 10 mm. When performing flat layers, every weld bead was overlayed on each other approximately 200 mm long by the corrective lifting of the welding torch in the vertical direction. The cladding was performed in a flat position with a vertical orientation of the electrode holder (torch). Additional fillet weld beads were performed along the corners. Simultaneously, welding parameters were adjusted such as starting current (125%), end current (45%), and slope function (flat weld beads 0.1 s). During the trials on a real part, large shrinkage stress was observed. Cladded layers bend in an upward direction causing nonacceptable indications. This was resolved by introducing run-in/run-out plates. The plates are welded onto the side walls and are 10 mm thick and at least 60 mm long. They allow the process to be stable (arc stability) before cladding the workpiece and prevent the seal slot from opening. It was also observed that when cladding the first layers (the diaphragm is "cold") welding beads were too wide. To minimize this and have an equal size of the cladding layers, Left-Right, and Right-Left welding movements were successfully validated and applied.

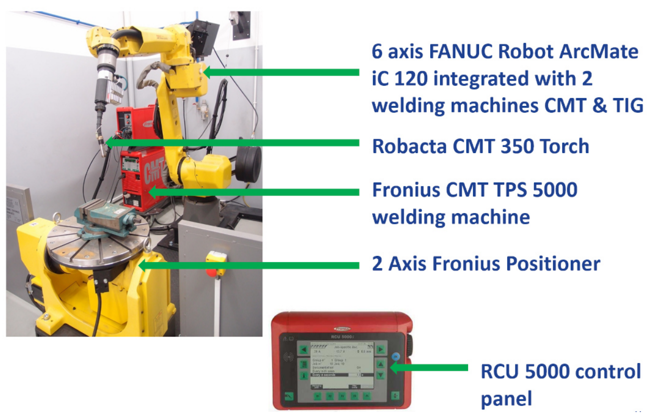


Fig. 3. Workstation with an Industrial robot FANUC ArcMate120iC, 2 axial positioner (Fanuc) and TPS 5000 CMT welding source (Fronius)

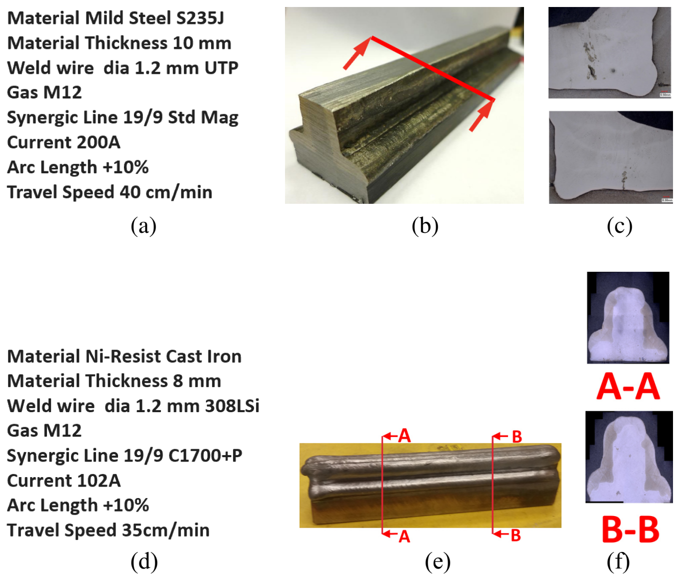


Fig. 4. Development of process parameters for diaphragm additive repair, welding parameters used in the development phase (a), additive mockup using (a) parameters (b), cut ups of (b) printout (c), welding parameters used in the development phase (d), additive mockup using (d) parameters (e), cut ups of (e) printout (f)

3.1. Robot programming

Repair parts have dimensional and positional variations due to three main reasons:

- Service deformations.
- Pre-weld machining tolerances.
- Ru-in/run-out coupon preparation.
- Fixturing tolerances.

These variations create low accuracy and irregular surfaces affecting weld quality in robotic welding. In order to eliminate these variations and get high fusion with accurate positioning robotic welding system requires an adaptive creation of specific welding tool paths for each part. Multi-layer welding creates heat that needs control and stops during the process. To control the heat input and optimize the process cycle time, development work shows the optimal solution of loading three parts in the system so that the robot can weld the next part while the previously welded part cools down to certain limits.

With the adaptive tool path generation and cycle time optimization targets mentioned above, a robotic welding system was created using the main components listed below:

- 6-axis robot manipulator with welding software and hardware options,
- 2-axis robot positioner,
- Welding fixture with three-part slots,
- CMT/PULSE MIG/MAG capable welding power supply & wire feed system,
- Torch service station,
- Torch center point (TCP) update station with camera,
- Robotic system with safety & automation equipment.

The additive repair process starts with the operator loading parts (three diaphragms) into the robotic cell and starting the system. The robot initially cleans the welding torch, cuts weld wire, and updates TCP using a camera system. Automated torch service and TCP updates are critical to get accurate positional data with weld wire probing. The robot initially touches the sides of the run-in/run-out coupons to calculate rail length and start/end positions. The robot then touches five edges of prepared rail to get positional data of reference points A, B, C, D. This is defined as a "slice search" (Fig. 5). The robot repeats slice search five times along the rail with equal separation between each slice to create radial arc tool path along the rail (Fig. 6). Three parts are probed, and data is stored for all parts before starting to weld. The robot probes all parts in positioner 0 tilt position. Each cladding pass has a specific tilt position and specific offsets from a certain reference corner. Data for all passes is stored in a recipe program. For each pass, the robot reads the recipe program and tilts the positioner to a defined angle. Coordinate system and weld position update automatically for each part and the robot welds specific passes with certain offsets from specific reference points.

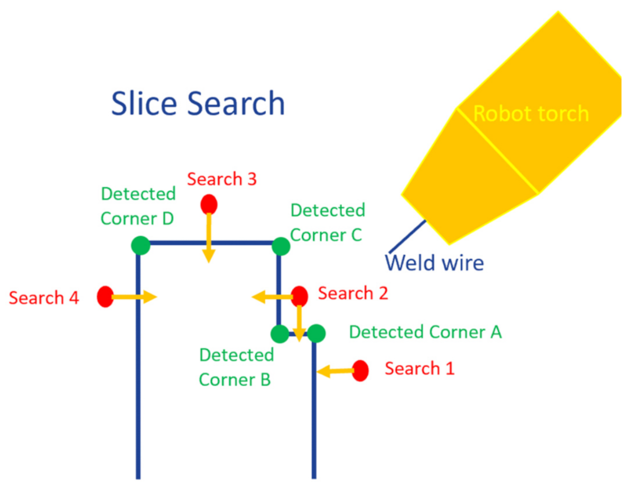


Fig. 5. Identification of positional data of reference points

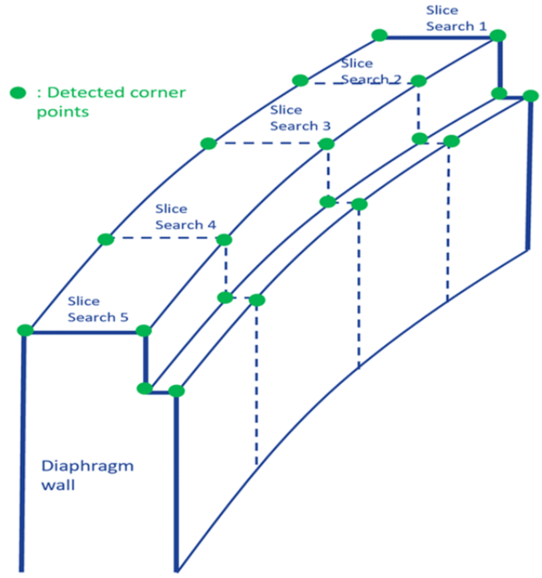


Fig. 6. Process of creating radial arc tool path along the diaphragm rail

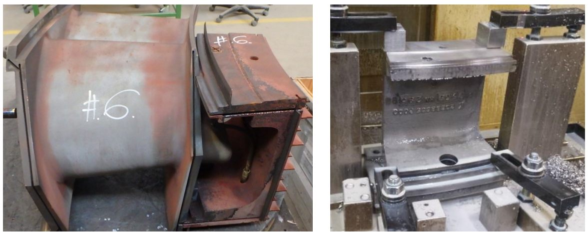
4. DIAPHRAGM REPAIR – PROCESS DEVELOPMENT

During the periodic outage of the turbine all the affected diaphragms assemblies are evaluated and disassembled if they do not meet serviceable limits. As previously written, due to excessive operating temperature that causes oxidation and erosion, the most common state is that the diaphragm rails are degraded and worn. The affected parts are sent out to specialized repair service centers (SC) where they undergo the repair. Once parts have gone through incoming processes upon arrival at an SC (dimensional inspection, power nozzle disassembly, cleaning, side seal removal, etc.). They are classified as light, medium, heavy, or super heavy additive repair. The described process is for the heavy repair of the 7FA diaphragm. It is also applicable to 9FA parts with some slight changes (scaled-up parts).

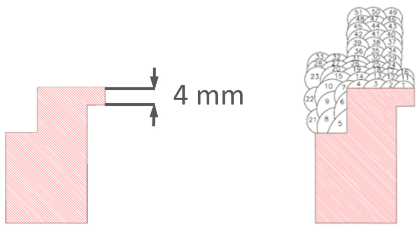
The first step of the repair is to mark up all the areas to be machined off during welding prep. Parts are machined by multi-axis CNC machine by using special tooling where the parts are mounted and datums are constrained (Fig. 7). This is followed by NDT inspection to verify if the part is ready for wire arc additive repair.

Before mounting diaphragms in the welding fixture, run-in and run-out plates are TIG welded, and previously developed welding parameters are set up (flat and fillet weld beads).

When the additive process starts, parts (three diaphragms) are measured by welding wire using touch sense mode. As it was mentioned before there only two synergic lines and two welding positions to repair the hardware. During the additive repair, the welding torch mounted on the robot arm changes the workpiece after weld build-up of some of the layers to have the part cooled down (to avoid trespass/decrease the inter-pass temperature of the hardware). The rotating table is synchronized with the robot and changes its tilt and position to allow weld build-up in flat and fillet positions. This ensures that the welded layers have the right geometry and minimizes the welding nonconformities. The process is completed when the hook/rail is fully restored.



(a)

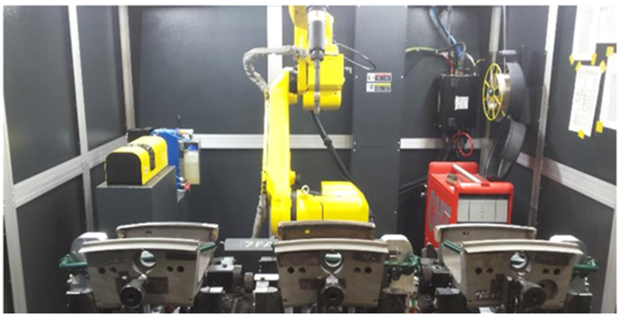


(b)

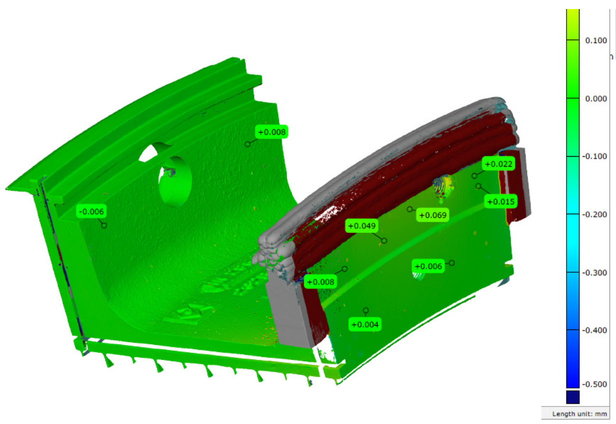
Fig. 7. Diaphragm assembly as received by Service Center (a) part after initial machining (a), cross section of the diaphragm after initial machining and different stages of cladding a worn diaphragm rail (b)

For the developed process it takes more than 50 welding beads to restore the hook (Figs. 7 and 8).

After welding, the diaphragms go through a post-machining process on a CNC machine. The designed repair process considers an additional material allowance. Thus, some of the material is machined off to bring the part to the drawing limits. This step is followed by the red dye inspection. If there are any deviations, they are repaired by a manual TIG welding touch-up process.



(a)

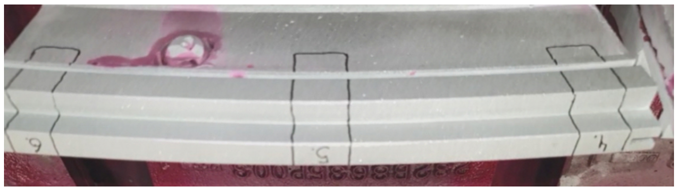


(b)

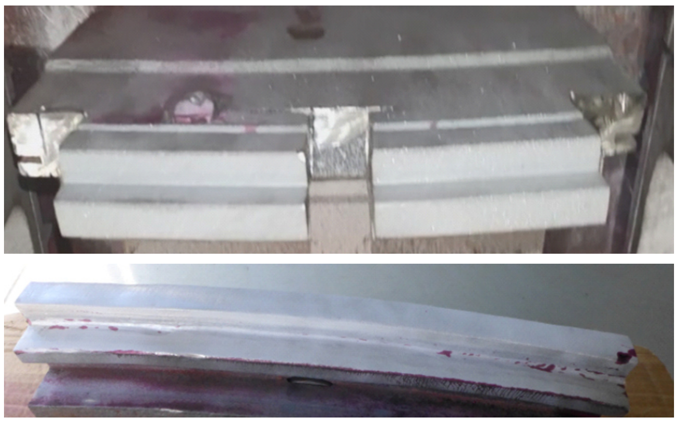
Fig. 8. Parts in the designated welding fixture (a), Blue Light Scanning comparison of the part before/after the wire arc additive repair (super heavy scenario) (b)

5. RESULTS AND VERIFICATION

During the setting up of the repair parameters, the first parts were evaluated by destructive tests. Cut-ups were done in specified areas to evaluate the quality of the additive process (Fig. 9) and approved. The developed technique was effectively implemented to repair a diaphragm cast made of nickel, with the



(a)



(b)

(c)

(d)

Fig. 9. Cut ups after final machining and Red Dye inspection (a), (b), (c) – Material evaluation results of the first batch of diaphragms – cut up no. 4 shown (d)

cladding comprising a weld filler made of austenitic stainless steel, like 308LSi stainless steel. This repair technique is flexible as only the worn-out sections of the diaphragm rail component are machined and clad. The rail sections that are not worn or eroded do not require cladding. Therefore, only the damaged areas of the diaphragm are repaired, reducing the cost of machining and cladding. If the distance between the machined surfaces and the nominal dimension of the part is greater than the thickness of one layer of cladding, several layers (up to ten or more) can be cladded to the machined surface of the diaphragm. After the welding process, the cladding surface exceeds the nominal dimensions of a new diaphragm. Therefore, the final step of the repair involves machining the cladded overlay to the nominal dimensions of a new component according to the manufacturer's specifications. Machining can be done using a milling process or any other suitable method.

The developed process can be enhanced further by adjusting the core welding parameters, such as voltage, current, and other parameters. These parameters can be adjusted for each pass of a layer, each layer, or only once for welding a complete cladding.

To prevent or at least minimize mechanical stress due to the cladding process, it is recommended that if the machined surfaces have a symmetric cross-sectional area, the passes should be welded alternately on each side of the axis of symmetry.

6. DISCUSSION AND CONCLUSIONS

The combination of the MAG process with a precisely programmed working movement of the robot and positioner as well as a complex cycle of the welding arc power supply shows that an additive wire arc repair process is feasible on GT components. It is proved that the wire arc multi-layer additive repair reduces the "repair time" of the hardware (around 80%) and provides high-performance parameters for the modified parts. Compared to other 3D methods, it is considered a low-cost and easily available method of repairing turbine parts. The described process is beyond laboratory and research scope, it was fully implemented in one of the GE Repair Service Centers and still has a lot of potential to be leveraged to repair other components. Nowadays the developed process is used for light, medium, heavy, and super-heavy repairs. For each of these variants, there is a unique combination of welding parameters and robot/positioner movement. In addition to that, the introduction of different fillers in specific areas of the modified parts optimizes their durability through the whole life cycle. The combination of the substrate and chosen filler was analyzed, tested, and verified against antioxidation resistance and showed a more robust condition of the diaphragm after a control interval. The process is easy to scale and adjust to other stages and gas turbine frames.

ACKNOWLEDGEMENTS

The research described in this article was conducted and published thanks to the courtesy of General Electric Company Polska Sp. z o.o.

REFERENCES

[1] L. Jyothish Kumar, P.M. Pandey, and D.I. Wimpenny, *3D Printing and Additive Manufacturing Technologies*, Springer Singapore, 2019, pp. 1–13, doi: 10.1007/978-981-13-0305-0.

[2] Y. Wang, X. Chen, and S.V. Konovalov, "Additive Manufacturing Based on Welding Arc: A low-Cost Method," *J. Surf. Investig.*, vol. 11, pp. 1317–1328, 2017, doi: 10.1134/S1027451017060210.

[3] D.H. Phillips, *Welding Engineering: An Introduction*, John Wiley & Sons, Ltd., 2016, pp. 177–186, (2016), doi: 10.1002/9781119191407.

[4] T. Chmielewski and D. Golański, "The role of welding in the remanufacturing process," *Weld. Int.*, vol. 29, no. 11, 2015, doi: 10.1080/09507116.2014.937604.

[5] Y. Nilsiam, P.G. Sanders, and M.J. Pearce, "Applications of Open Source GMAW-Based Metal 3-D Printing," *J. Manuf. Mater. Process.*, vol. 2, no 1, p. 18, 2018, doi: 10.3390/jmmp2010018.

[6] P. Cegielski, M. Ostrysz, W. Łacisz, M. Panas, and P. Kowalski, "New work on the use of MIG/MAG arc welding for 3D printing", *Weld. Tech. Rev.*, vol. 90, no. 1, pp. 43-47, 2018, doi: 10.26628/wtr.v90i1.851 (in Polish).

[7] N. Knezović and A. Topić, "Wire and arc additive manufacturing (WAAM) – a new advance in manufacturing," in *New Technologies, Development and Application. NT 2018. Lecture Notes in Networks and Systems*, 2018, vol 42, pp 65–71, doi: 10.1007/978-3-319-90893-9_7.

[8] J. Liu, Y. Xu, Y. Ge, Yu, Z. Hou, and S. Chen, "Wire and arc additive manufacturing of metal components: a review of recent research developments," *Int. J. Adv. Manuf. Technol.*, vol.111, no. 1-2, pp. 149–198, 2020, doi: 10.1007/s00170-020-05966-8.

[9] P. Cegielski, A. Skublewska, P. Gawroński, M. Ostrysz, M. Dylewski, and M. Gajowniczek, "Robotized 3D printing of the machines parts with welding methods," *Weld. Tech. Rev.*, vol. 89, no. 1, pp. 39–42, 2017, doi: 10.26628/wtr.v89i1.724.

[10] C. Soares, *Gas Turbines: A Handbook of Air, Land and Sea Applications*, Oxford: Butterworth-Heinemann, 2014, pp. 670–708.

[11] P.M. Boyce, *Gas Turbine Engineering Handbook*. Butterworth-Heinemann, 2011, pp. 827–833.

[12] A.S Rangwala, *Theory and Practice in Gas Turbines*, New Academic Science, 2013, pp. 447–450.

[13] "Steam-turbine diaphragm repair strategies," *Combined Cycle Journal*. [Online] Available: https://www.ccj-online.com/steam-turbine-diaphragm-repair-strategies/ (Accessed: 15. Dec. 2022)

[14] T. Ginter and O. Crabos, "Uprate Options for the MS6001 Heavy-Duty Gas Turbine GER-4217B (06/2010)," *General Electric Company*, 2010. [Online] Available: https://www.ge.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/resources/reference/ger-4217b-uprate-options-ms6001-heavy-duty-gas-turbine.pdf

[15] B.L. Henderson *et al.*, "Treated turbine diaphragm and method for treating a turbine diaphragm," U.S. Patent US10828732, Nov 10, 2020.

[16] A.M. Ostrowski *et al.*, "Repair of gas turbine diaphragm," U.S, Patent US11813708, Nov 14, 2023.

[17] "Ni-Resist Iron", *Castings PLC*. [Online] Available: https://castings.plc.uk/company/materials/ni-resist-iron/ (Accessed: 6. Apr. 2021)

[18] *Properties and Applications of Ni-Resist and Ductile Ni-Resist Alloys.* Nickel Institute, 1998.

[19] AWS A5.15:1990 – Specification for Welding Electrodes and Rods for Cast Iron (2016), An American National Standard.

[20] J. Liu, Y. Xu, Y. Ge, Z. Hou, and S. Chen, "Wire and arc additive manufacturing of metal components: A review of recent research developments," *Int. J. Adv. Manuf. Technol.*, vol. 111, pp. 149–198, 2020, doi: 10.1007/s00170-020-05966-8.

[21] Z. Wang, S. Zimmer-Chevret, F. Leonard, and G. Abba, "Improvement strategy for the geometric accuracy of bead's beginning and end parts in wire-arc additive manufacturing (WAAM)," *Int. J. Adv. Manuf. Technol.*, vol. 118, no. 7-8, 118, pp. 2139–2151, 2022, doi: 10.1007/s00170-021-08037-8.

[22] M. Cai, Ch. Wu, and X. Gao, "The Influence of Arc Length Correction on Welding in CMT Welding," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 170 p. 042106, 2018, doi: 10.1088/1755-1315/170/4/042106.