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Process monitoring and industrial informatics for on-line optimization of Welding Procedure Specifications (WPS) in Gas Tungsten Arc Welding (GTAW) – Industry 4.0 for robotic additive re-manufacturing of aeroengine components*

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Abstract— **Industry 4.0, the scheme that drives the fourth industrial revolution, has been, since its conception, reshaping the manufacturing industry. To advance current industrial chains into the smart factories of the future, cyber-physical systems are monitored and communicate with each other to ensure transparent interoperability, giving birth to the emerging field of industrial informatics. To enable the repair and recycling of high value jet engine compressor blades, additive manufacturing is utilized. The complex geometries and asymmetrical wear of the blades require robotic welding systems to be trained by experienced human welding engineers in order to be able to adapt to differing components. Demonstrated in this paper, process monitoring and industrial informatics are introduced to the adaption of Welding Procedure Specifications (WPS) utilized by a developing robotic system for the additive re-manufacturing of aeroengine components. Using a novel variant of Gas Tungsten Arc Welding (GTAW), the robotic welding system under development is a product of an industry-academia collaboration between the Enabling Sciences for Intelligent Manufacturing Group (ESIM) of the University of Sheffield and VBC Instrument Engineering Ltd.**

Keywords—additive manufacturing, blade regeneration, industrial informatics, process monitoring, welding

I. INTRODUCTION

Components used in the aerospace industry are characterized by their high value, due to their manufacturing and evaluation processes combined with the use of lightweight materials which results in high production costs. Components of this nature can be found in compressor blades used in the hot and cold stages of aircraft turbofan or jet engines. Compressor blade wear and defects induced by extreme and prolonged operational conditions lower the engine's performance, reducing fuel consumption and power output. To mitigate operational safety risks, requires the need of maintenance, repair and overhaul (MRO) of the engine to a predetermined schedule. In order to decrease the MRO costs, engine manufacturers and MRO service providers minimize the replacement of high value components by undertaking their repair where applicable.

The regeneration or recycling process of engine compressor blades is traditionally comprised of four individual processes: pre-treatment of each individual blade, repair via material deposition, re-contouring and post-treatment. The process of material deposition is carried out in a variety of ways, depending on the material of the blade and the repair required by each individual piece. Normally cracks presented on the blade's body are repaired via brazing or welding, depending on the defect's size. Plasma arc welding is employed for repairs where a patch-joint is required without additive material. Tip-repair represents the significant majority of high volume repairs in aerospace engine components which is carried out either via material cladding by laser welding, or via additive arc welding with filler material [1-6].

The tip-repair process, due to complex geometries and different repair requirements by each individual blade, is heavily dependent on manual welding performed by experienced, highly skilled welding engineers. However, while 80% of the recovered blades are repairable, the percentage that is successfully repaired attributes to only 45%. The reason behind this failure is mainly identified as errors originating from human input. To improve and increase the repair yield volume, the avoidance of human error is achieved by automation of the repair process.

In order to automate the compressor blade regeneration process, The University of Sheffield (UoS) teamed up with VBC Instrument Engineering Ltd in an industry-academia collaboration, to develop a robotic additive manufacturing system.

A. *Additive manufacturing in Aerospace*

Three-dimensional (3D) metal parts printed using additive manufacturing (AM) technologies are revolutionizing the

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aerospace manufacture industry. AM has already been established in the industry. Boeing has installed more than 200 3D printed components across 10 different models of commercial and military jets since 2013 [7].

The reason behind this increasing adoption of AM technology by the aerospace industry is the ability of AM to produce parts with complex shapes and geometric features, an ability previously limited by traditional manufacturing processes. This geometrical freedom of design results in lightweight construction, allowing two, three, and even up to 10 parts that were traditionally manufactured separately to be fused into a single part design. This flexibility provides the ability to define the force distribution within a component while keeping the component density under control and determining the microstructure quality. Additionally, the ability to print any part on-demand on decentralized locations eliminates the need for warehousing of spare parts that are rarely needed all over the world. AM has also been proven to shorten the time and cost of production up to 75%, by eliminating the need of specific construction tools [8 - 10].

An additional benefit of using AM in aerospace manufacturing is the reduction of waste. Conventional milling processes can produce recyclable waste up to 75% of the plate material, whereas the 3D printed parts have near-final contours, with only about 5% of waste. Furthermore, the capability of producing calculated hollow and bionic (porous) structures increases the material savings and decreases the structural weight without compromising its mechanical properties.

B. GTAW-based AM

There is a variety of systems used to perform AM on metals. The AM systems are usually classified in three major categories based on the way they provide the additive material: “bed” systems, “fed” systems and “hybrid” systems. In bed systems the additive material in the form of powder or liquid lies in a bed of raw material, whereas in fed systems the additive material is fed in the process via a variety of methods, usually as a filament (wire), filament tape and powder spray. A hybrid system can be either a bed or a fed system, combined with a milling machine. In bed and fed systems the additive material is being printed layer by layer to form the final part, which is then moved outside the system and down the production line for post-treatment, including milling and heat-treatment. In hybrid systems the milling process occurs within the system, resulting in a finished part that meets the size requirements. While bed systems are the most prevalent in aerospace they are limited to small applications since larger manufactured parts will require larger bed of material, increasing cost in case of contamination. Weight and exposure to hazardous conditions are also increased, raising safety concerns. Additionally, fed systems provide much higher material usage efficiency (up to 100%) compared to bed systems [11, 12].

In order to fuse the additive metal material to the base material, welding techniques are recruited. The techniques most commonly used in AM are laser and electron beam (EB). Laser and EB present good dimensional properties in the shaping of parts, as a result of their very high energy density. On the downside, their material deposition rate is very low and their cost of equipment is very high. Apart from electron beam and laser, there is also another group of welding techniques recruited for AM, classified under the name Wire and Arc Additive Manufacturing (WAAM). The group comprises of widely used arc welding techniques such as Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW). The main benefits of using WAAM over laser and EB, apart from the low cost, are the high material deposition rate and shape deposition efficiency [13, 14]. These points in favor, along with the limitations of bed systems, make the use of WAAM in the manufacturing of aerospace components very promising, benefiting in aspects of cost, productivity and energy efficiency.

In the following sections the work done for the automation and optimization of the robotic system for the build-up process of additive material is presented. In Chapter III the regeneration of the compressor blade through additive manufacturing is presented, followed by Chapter IV with details on the Welding Process Specifications. The welding process monitoring and its implementation in Industry 4.0 is presented in Chapter V.

II. INDUSTRY-ACADEMIA

UK Small Manufacturing Enterprise (SME), VBCie have been in partnership with the Enabling Sciences for Intelligent Manufacturing Group (ESIM) based at UoS since 2006. Multiple innovative low Technology Readiness Level (TRL) projects have been developed based around novel fusion welding and additive manufacturing systems for high value manufacturing. The development of this research has substantially increased TRL up to present day. The UoS group have collaborated on a number of projects aligned with developing robotic additive manufacturing systems targeted at aerospace repair and overhaul and high power, low heat damage, adaptive welding systems for high value manufacturing.

III. COMPRESSOR BLADES REGENERATION

As previously discussed, the regeneration process of the compressor blades is divided into four stages: pre-treatment, material deposition, re-contouring and post-treatment. The robotic welding system under development is focusing on the automation of the second stage, the material deposition. Compressor blades used to be produced by steel alloys in early jet engine designs. Steel has now been replaced by titanium, due to its high ratio of strength to density. Even with its high initial cost, titanium is the preferred material since the lightest possible rotor assembly reduces the forces on the engine structure, which in turn enables a further deduction in weight. Titanium’s high initial price justifies further the adoption of AM for the repair, as it is a promising alternative of fabricating components made of expensive material in the aerospace industry where such components often suffer an extremely high buy-to-fly ratio [12].

For the purpose of this research, compressor blade models made of 316L stainless steel are used in the welding trials for reduced cost, aiming for transition to titanium blade models for process optimization. The robotic welding system uses Pulsed GTAW-based AM, depositing layers of additive material in a blade tip-repair process which is further described (Fig. 1).

When receiving the blades for material deposition, it is expected that the stage of pre-treatment has been completed; a pre-ground surface on the tip of the blade, without any defects or contamination. To ensure the surface quality meets the requirements for repair and to calculate in parallel the AM deposition path of the system, an intelligent 3D scanning system is used (Fig. 2: Scanning Phase). Previous work [15] demonstrated the successful detection of surface defects due to either imperfections of the surface treatment or contamination on compressor blade models. The scanning phase is also used for inline metrology purposes, identifying the tip-wear of the blade (Fig. 2c).

After the scanning of the blade, the additive repair process is initiated. The first stage in material deposition process is called root pass. During the root pass, the first layer of the additive material is deposited and fused with the blade's based material. The heat generated from the arc and transferred to the blade plays a critical role in the success of the fusion. If the heat is insufficient, the additive material will not fuse with the base material, resulting in failure of the weld due to lack of fusion. If the heat is very high, the thin tip of the blade will melt in a high rate, making very challenging the control of material's build-up. As illustrated in Fig. 2, the corners of the tip during scanning phase are sharp. Once the arc strikes, the distribution of the heat is limited due to the corner, which results in higher melting rate compared to the inner sections of the blade. This higher melting rate results in curved corners highlighted in Fig. 2d. To fix this problem, the rate of feeding of the additive material (wire feed) is accelerated at the two corners of the blade. This results in excess of material at the beginning and the end of each pass, creating the "bumps" shown in the figure.

Once the root pass is completed, 3D scanning is confirming the material deposition and the path of the second root is calculated. Similar with the root pass, the corners melt faster than the tip interior, therefore the feed rate is readjusted to fill the generated gaps by creating the bumps. The stages of scanning and deposition are repeated again until the deposited material exceeds the requirements for regaining the original shape (Fig. 2e).

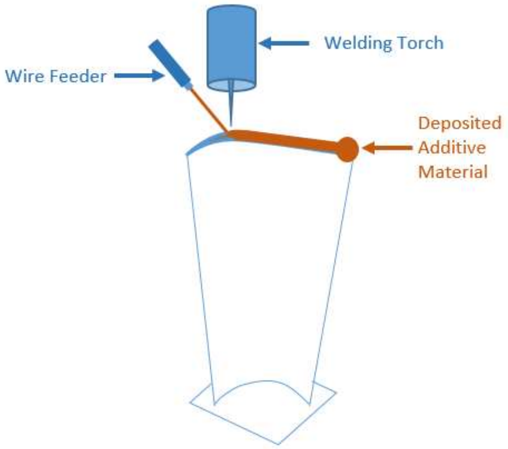

Fig. 1. Blade tip-repair using GTAW-based additive manufacturing. The additive material is fed on the workpiece in the form of a wire.

IV. WELDING PROCEDURE SPECIFICATIONS

In order to achieve and maintain repeatable quality standards in a welding process, a welding engineer needs to generate a standard guideline to be followed. These guidelines, called welding procedure specifications, (WPS), contain a number of variables that affect, directly or indirectly, the quality of a weld. Fixed variables like the type of welding process, the type of the shielding gas and the shape of the electrode are maintained the same in all the individual welds following the specific WPS. Variables like current, voltage, travel speed and heat input are given values in a range, allowing some tolerance as long as the outcome is experimentally proven not to affect the quality of the weld [16].

For the blade regeneration process, the WPS variables are adjusted on each individual blade, providing control of the quality outcome. This adaptive ability is achievable by the

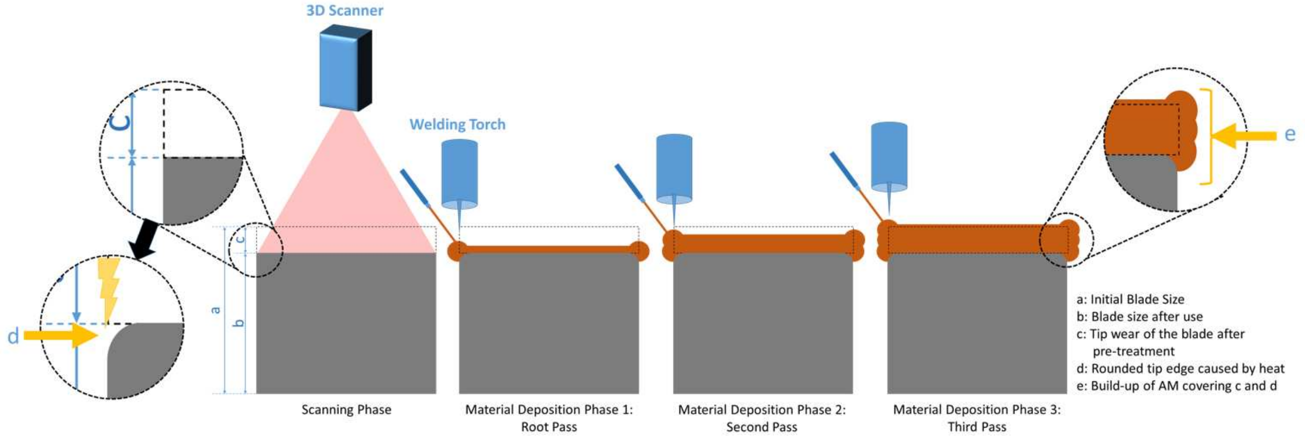

Fig. 2. Schematic representation of the AM build-up process for the regeneration of a compressor blade

recruitment of process monitoring techniques and industrial informatics presented in Chapter V.

A. Travel speed and torch positioning adaptation to temperature

As highlighted in Chapter III, the temperature of the blade should be in a specific range in order to have a successful weld. To achieve the desired temperature, the welding travel speed is adjusted. At the beginning of the material deposition process, the blade temperature is in low levels, prohibiting the melting of the base material given the preselected current-voltage range limitations. To deal with this, the arc is used to heat the base material before the additive material is fed (Fig. 3). Additionally, during the welding process the heat accumulated by the blade is increasing its temperature, resulting in faster rate of melting of the base material. To deal with this, the system is adjusting by increasing the travel speed as the temperature increases.

B. Wire feed adaptation to temperature

Similar with the travel speed, the wire feeding also needs to be adapted to the temperature of the blade. The feed rate at the beginning of the weld is slower than the speed at the end, since the additive material needs to fill more area in a shorter amount of time. To achieve these alterations in the wire feed speeds a Wire Feed Controller module was developed and attached on the system.

C. Voltage adaption to power variations

Variations occurred in the distance between the electrode and the workpiece (arc gap), correspond to changes in the voltage of the arc. By applying an electromechanical subsystem to maintain a preset arc, consistent voltage control is achieved. The Arc Voltage Controller (AVC) receives data from the process monitoring system (Chapter V), and positions electrode accordingly. By gaining greater control over the voltage, the amount of heat delivered to the workpiece (heat input) is controlled providing a more stable welding process.

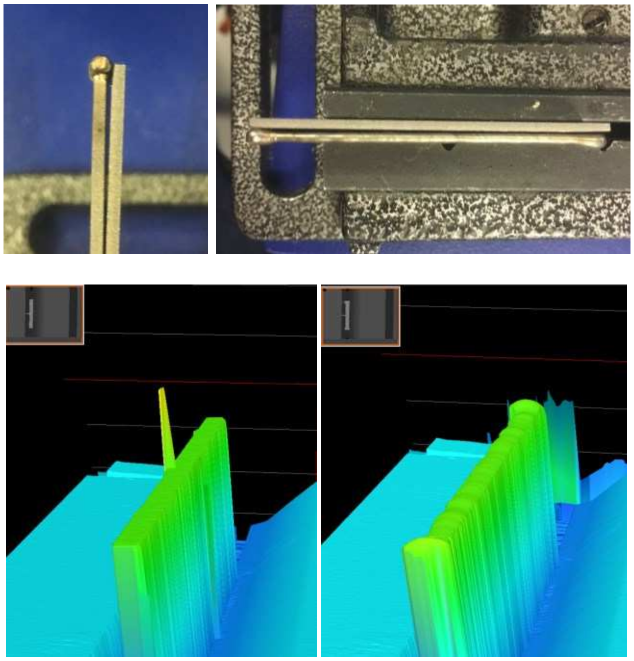

Fig. 4. Successful material deposition on the root pass of a blade model tip-repair. Top: edge comparison with a non-welded blade model. Bottom: 3D scanning image.

D. Welding current adaptation for build-up

As the successful build-up of additive material increases, adaptions on the welding current need to be made. By gathering data from the scanning system between the different layers, the current output changes throughout the process. This adaption occurs from experience of human welders, added on the WPS though experimental trials and aiming to be adjusted based on the type and shape of blades.

The aforementioned adaptions of the WPS result in increased control of the welding process, allowing successful material deposition for the tip-repair process. The experimental

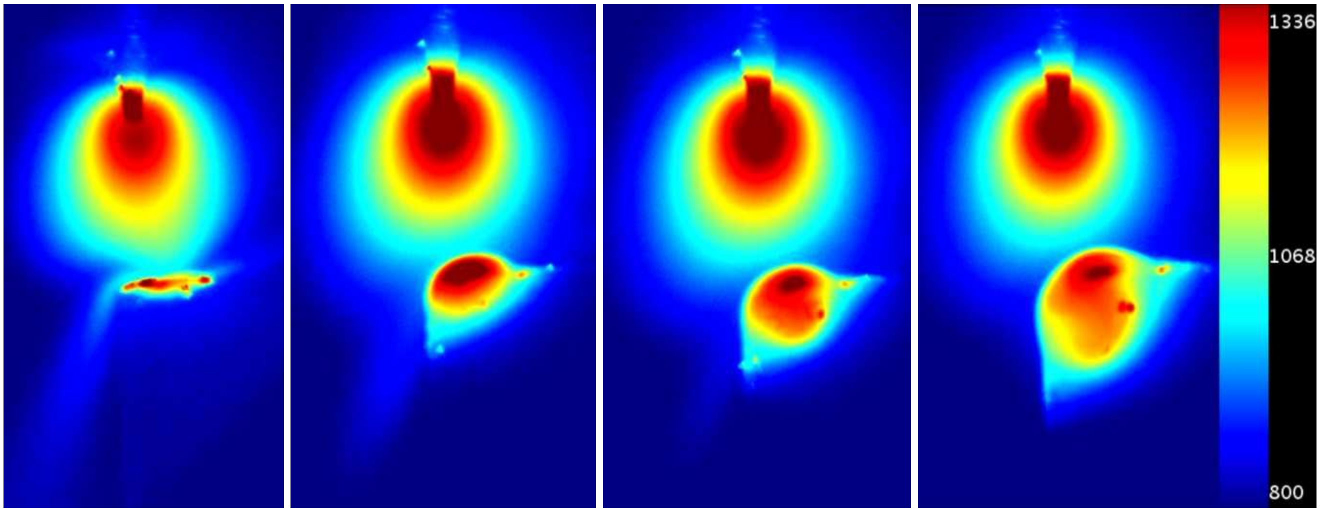

Fig. 3. Thermal Camera Images illustrating the gradual accumulation of the arc heat before the additive material deposition

trials with AVC and Wire-feed adaption have let to the successful material deposition during root pass on compressor blade models. In Fig. 4 one example of root pass is shown, in comparison with an non-welded blade model.

V. WELDING PROCESS MONITORING AND INDUSTRY 4.0

The fourth industrial revolution is characterized by four basic design principles: interconnection, information transparency, decentralized decisions and technical assistance [17]. On previous work [15] the modularity and interconnectivity of the robotic system was presented. Each step in the system process management involves advanced intelligent sensory for its interoperability, allowing decentralized decisions without the requirement of constant human input. While the system process monitoring consists of different stages, such as parts loading monitoring and identification, pre-weld evaluation and general safety monitoring, this present report focuses on the welding process monitoring

A. Welding Process Monitoring

During manual welding, the human welder uses his senses to monitor the process and readjust specific parameters to optimize the outcome of the process. Similarly, in automatic welding, a variety of sensors is used to monitor the process. These sensors are based in technologies divided in four categories: arc sensors, optical sensors, infrared sensors, and acoustic and ultrasonic sensors. Each technology has its benefits and drawbacks when recruited for welding process monitoring. Fragile components in industrial environments, instrumentation susceptible to arc plasma emissions, high costs and size limitations are some of the reasons that act as inhibitors in the acquisition of the respective technology by the industry.

With these limitations in mind University of Sheffield developed a variant of their high-speed data acquisition system based on arc sensing, for real-time monitoring of the welding process. By measuring current and voltage at a very high sampling rate, the system has been experimentally proven to be able to detect variations in GTAW processes that correspond to defects and poor quality of welds [18, 19].

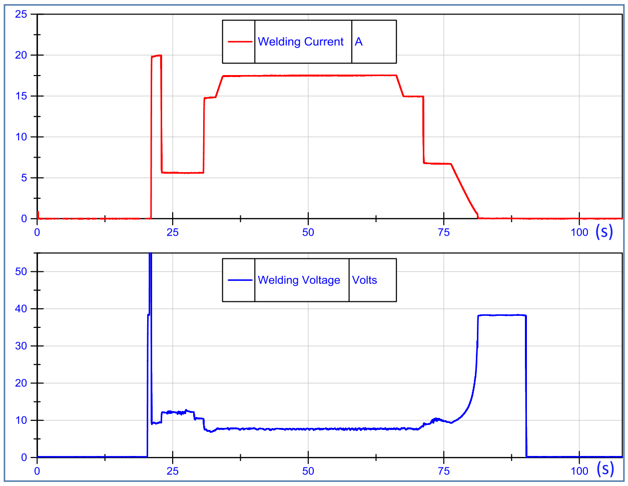

Fig. 5. Electric measurements during root pass welding

To ensure the high quality of the welds required by the aerospace industrial standards, the WPS undergo a series of adaptive control. To achieve this control the system gathers data from the welding process monitoring equipment, including the high-speed DAQ. As shown in Fig. 5, real-time measurements of voltage and current are fed back to the system during the welding process. These measurements are then used by the peripheral systems accordingly. Measurements within expected limits represent good welds, in contrast with abnormal disturbances which are detected in the presence of defects and malfunctions. This can act as a good build-up indicator, so the additive process can be further evaluated and corrected. Variations detected are used to adapt the voltage via changes in the distance between the electrode and the workpiece.

B. Towards the era of industrial informatics

The concept of Industry 4.0, and especially the principle of information transparency is not only applicable within the premises of the smart factory, but also in the communication between suppliers, manufacturers and customers. When it comes to aerospace components, where quality assurance is of outermost importance in order to avoid critical malfunctions that result in high social and economic costs, each component is required to have a "ledger", recording its history since manufacturing. This can be achieved by unique identification numbers provided for each component during initial manufacturing and used by service providers and operators, turning it into a cyber-physical entity (Fig. 6).

The robotic system is developed with this working principle in its core. Its architecture ensures its ability to handle the information already provided and enrich the log of each component with extensive data regarding its condition. By implementing the high-speed DAQ system on the robotic

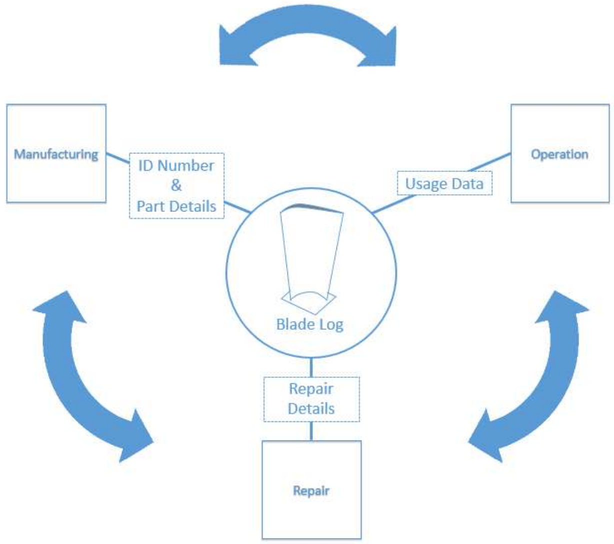

Fig. 6. Information transparency between manufacturers, customers and service providers

welding system, a huge amount of valuable industrial information for each component is made available. Details of the system parameters and conditions present during the repair process are recorded in parallel with the DAQ measurements. Images from the 3D scanner prior and post material deposition are also available providing detailed product characteristics. Additionally, data from system condition monitoring and peripheral safety monitoring are fused with operational details to ensure increased security and effective production management.

All produced data require secure storage in a number of suitable databases, following specific network protocols. Classification of access to the respected databases is then required to be set within the company, taking into consideration matters of privacy and confidentiality. Upon request by the customers, the owner of the robotic system will be able to provide detailed reports of each individual manufactured component. Having the ability to prove that a part was manufactured and/or repaired properly under pre-requisite conditions and within standards, the manufacturer/re-manufacturer is able to increase his credibility. At the same time, monitoring the process increases intra-organizational management, giving the ability to pinpoint occurrences of errors and initiate correction actions, reducing wastes of both material and time.

VI. CONCLUSION

The high value of aerospace components raises the need for effective ways in their repair and regeneration. Additive manufacturing has been proven beneficial for use in the aerospace industry due to the geometrical freedom it provides. A robotic GTAW-based re-manufacturing system is under development following Industry 4.0 design principles. By introducing online process monitoring and the concept of industrial informatics the component regeneration process transforms into a cyber-physical system able to adjust accordingly in order to assure optimum weld quality. Using a high-speed data acquisition system the Welding Procedure Specifications, used for the build-up of additive material for tip-repair on compressor blades, are automatically controlled. The first tangible results of the robotic system show successful build-up of the additive material on compressor blade models, allowing the development to proceed further, increasing the layers and testing the system on real components.

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REFERENCES

[1] O. Yilmaz, N. Gindy and J. Gao, “A repair and overhaul methodology for aeroengine components”, Robotics and Computer-Integrated Manufacturing, 26 (2010), 190–201.

[2] B. Denkena, V. Boess, D. Nespor, F. Floeter and F. Rust., “Engine blade regeneration: a literature review on common technologies in terms of machining”, Int J Adv Manuf Technol (2015) 81:917–924.

[3] Z. Zhang, G. Liu, Z. Jiang and Y. Chen, “A Cloud-Based Framework for Lean Maintenance, Repair, and Overhaul of Complex Equipment”, J Manuf Sci Eng, Vol 137, August 2015.

[4] E. Ulhmann, M. Bilz and J. Baumgarten “MRO – Challenge and Chance for Sustainable Enterprises”, 2nd International Through-life Engineering Services Conference, 2013.

[5] J. Geng, X. Tian, M. Bai, X. Jia and X. Liu, “A design method for three-dimensional maintenance, repair and overhaul job card of complex products”, Computers in Industry, 65 (2014), 200–209.

[6] “Compressor blades repair and overhaul”, Rolls-Royce Plc Internal Report, 2002.

[7] Richard E. Crandall, “Where Will Additive Manufacturing Take Us?”, APICS Magazine, 2013.

[8] Liz Nickels, “AM and aerospace: an ideal combination”, Metal Powder Report, Volume 70, Issue 6, 2015, Pages 300-303, ISSN 0026-0657, doi: 10.1016/j.mprp.2015.06.005.

[9] Mohsen Attaran, “The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing”, Business Horizons, Volume 60, Issue 5, 2017, Pages 677-688, ISSN 0007-6813, doi: 10.1016/j.bushor.2017.05.011.

[10] Terry Wohlers, “Making Products By Using Additive Manufacturing”, Manufacturing Engineering, April 2011, (www.sme.org).

[11] G.J. Schiller, "Additive manufacturing for Aerospace," 2015 IEEE Aerospace Conference, Big Sky, MT, 2015, pp. 1-8, doi: 10.1109/AERO.2015.7118958.

[12] D. Ding, Z. Pan, D. Cuiuri and H. Li, “A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM)”, Robotics and Computer-Integrated Manufacturing, Volume 31, 2015, Pages 101-110, ISSN 0736-5845, doi: 10.1016/j.rcim.2014.08.008.

[13] J.L. Prado-Cerqueira, J.L. Dieguez and A.M. Camacho, “Preliminary development of a Wire and Arc Additive Manufacturing system (WAAM)”, Procedia Manufacturing, Volume 13, 2017, Pages 895-902, ISSN 2351-9789, doi:10.1016/j.promfg.2017.09.154.

[14] H. Geng, J. Li, J. Xiong, X. Lin and F. Zhang, “Optimization of wire feed for GTAW based additive manufacturing”, Journal of Materials Processing Technology, Volume 243, 2017, Pages 40-47, ISSN 0924-0136, doi:10.1016/j.jmatprotec.2016.11.027.

[15] R. French, M. Benakis and H. Marin-Reyes "Intelligent sensing for robotic re-manufacturing in aerospace — An industry 4.0 design based prototype", 2017 IEEE International Symposium on Robotics and Intelligent Sensors (IRIS), Ottawa, ON, 2017, pp. 272-277. doi: 10.1109/IRIS.2017.8250134.

[16] H. Qazi, “Study of verification and validation of standard welding procedure specifications guidelines for API 5L X-70 grade line pipe welding”, Žurnal Inženernih Nauk, 2017, 4(2):B11-B14, doi: 10.21272/jes.2017.4(2).b11

[17] M. Hermann, T. Pentek and B. Otto, "Design Principles for Industrie 4.0 Scenarios", 2016 49th Hawaii International Conference on System Sciences (HICSS), Koloa, HI, 2016, pp. 3928-3937, doi: 10.1109/HICSS.2016.488.

[18] R. French, H. Marin-Reyes, M. Benakis, “Advanced Real-Time Weld Monitoring Evaluation Demonstrated with Comparisons of Manual and Robotic TIG Welding Used in Critical Nuclear Industry Fabrication”, In: Trzcielinski S. (eds) Advances in Ergonomics of Manufacturing: Managing the Enterprise of the Future. AHFE 2017. Advances in Intelligent Systems and Computing, vol 606, 2018. Springer, Cham, doi: 10.1007/978-3-319-60474-9_1.

[19] R. French, H. Marin-Reyes, M. Benakis, “Real-time welding evaluation system assessment using the TIG orbital welding process on ultra-thin wall tube joints in titanium & stainless steel”, in The 70th IIW Annual Assembly and International Conference, Shanghai, China, 2017.