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Intelligent Sensing for Robotic Re-Manufacturing in Aerospace - An Industry 4.0 Design Based Prototype*

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***Abstract*—Emerging through an industry-academia collaboration between the University of Sheffield and VBC Instrument Engineering Ltd, a proposed robotic solution for re-manufacturing of jet engine compressor blades is under ongoing development, producing the first tangible results for evaluation. Having successfully overcome concept adaptation, funding mechanisms, design processes, with research and development trials, the stage of concept optimization and end-user application has commenced. A variety of new challenges is emerging, with multiple parameters requiring control and intelligence. An interlinked collaboration between operational controllers, Quality Assurance (QA) and Quality Control (QC) systems, databases, safety and monitoring systems, is creating a complex network, transforming the traditional manual re-manufacturing method to an advanced intelligent modern smart-factory. Incorporating machine vision systems for characterization, inspection and fault detection, alongside advanced real-time sensor data acquisition for monitoring and evaluating the welding process, a huge amount of valuable industrial data is produced. Information regarding each individual blade is combined with data acquired from the system, embedding data analytics and the concept of "Internet of Things" (IoT) into the aerospace re-manufacturing industry. The aim of this paper is to give a first insight into the challenges of the development of an Industry 4.0 prototype system and an evaluation of first results of the operational prototype.**

Keywords—Robot sensing systems; Non-Destructive Testing; Manufacturing automation; Additive Manufacturing; Welding

I. INTRODUCTION

One key point in the operation of aerospace turbofan jet engines is the compression of atmospheric air using high value compressor blades. Extreme operational temperatures and friction, result in wear and deformation, requiring engine overhaul every 30,000 hours of operation. The alloy blades need to be removed from the engines for inspection and then repaired where possible. The re-manufacturing of the blades is currently done using manual weld deposition and is carried out by highly skilled welders. While 80% of compressor blades recovered from serviced engines are repairable, only 45% of them are successfully repaired. This failure to achieve a high recovery yield is mainly attributed to errors in the process that originate from human input. A proposed autonomous robotic system for the re-manufacturing of turbofan jet engine blades is currently under development, aiming to eliminate human error and increase the successful repair yield up to 100% [1].

The proposed smart disruptive industrial solution is characterized as high-value, for its strong potential for high economic value and its aim in advancing re-manufacturing for the aerospace industry. The cost of a gas turbine blade repair ranges from £250 to £7000, depending on size and material. As an example, a Rolls-Royce Trent 1000 turbofan engine has approximately 600 blades. With the aim of repairing up to 100% of the repairable yield of blades, the advanced robotic system is extending the blade life, generating large savings on the operational costs with material re-use.

Apart from economic and environmental benefits, the robotic solution provides valuable social gains in health and safety. The process of turbofan blade re-manufacturing incorporates the Gas Tungsten Arc Welding technique (GTAW). Ergonomic studies revealed a number of existing hazards in the manual GTAW process, which include among others, prolonged sitting periods, manual handling, wrist fatigue, cutaneous burns and eye damage [2]. The advanced robotic system was designed with those hazards in mind, aiming in eliminating them from the aerospace re-manufacturing industry.

The robotic re-manufacturing system has a modular design, incorporating a variety of subsystems. These subsystems include a collaborative robot working with the peripheral systems used for characterization, inspection, monitoring and evaluation. The systems recruit, among others, machine vision systems with advanced scanning and optical imaging capability combined with novel real-time monitoring sensors. Advanced non-destructive testing (NDT) prototype systems assure repairs meet the acceptable mechanical properties of the product, which are defined by aerospace turbine manufacturers QA and QC process and inspection standards. For successful automation of the system, numerous detailed databases are under development, assisting in operation, safety monitoring, life cycle monitoring and logging. The welding system operating alongside the collaborative robot is composed of an advanced Heat Management System (HMS) with automatic filler material deposition, developed by VBC Instrument Engineering Ltd (VBCie).

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The robotic system is the result of an industry-academia collaboration between the University of Sheffield and VBCie. What started in 2006 as a concept of automation for a bespoke welding system has evolved in an innovative high-value aerospace re-manufacturing collaboration, advancing the compressor blade re-manufacturing process into an Industry 4.0 environment.

The fourth industrial revolution, named "Industry 4.0", is evolving around four basic design principles: interconnection, information transparency, decentralized decisions, and technical assistance [3]. These four principles are aiming to reshape the face of industry, advancing traditional manufacturing to futuristic smart factories. The autonomous re-manufacturing robotic solution is designed based on these principles, and its development is occurring guided by the advances in them.

All the elements that comprise the robotic system and its operational peripherals are interconnected, forming this way an "Internet of Things" (IoT). The human factor that is required for involving the human operator is connected via the "Internet of People" (IoP). Both together form the "Internet of Everything", where the actual human-machine collaboration is archived. The robotic system that performs all the mechanical operations is connected with a variety of essential peripherals, creating the network of the robotic solution that is presented in Fig. 1.

In the following text, the process management of the autonomous re-manufacturing system is presented (Section II), confined by non-disclosure agreements on intellectual property. Further analysis and emphasis is given on the conceptual development benefited by the Industry 4.0 principles (Section III). Evaluation on the operation and performance of the system and its peripheral sensors is also presented (Section IV), providing a glance on the first results.

II. System Process Management

The robotic concept is aiming to reduce the human impact on the re-manufacturing of gas compressor blades, targeting 100% success of the repairable yield. Based on these two goals the system was designed to receive used blades, characterize and intelligently inspect them, perform the necessary repairs and deliver a quality-finished product. The flow of the automated process, which is graphically presented on Fig. 2, is explained next.

1. Blade Detection

During the blade detection process the system checks for the presence of incoming blades and defines their position and orientation for pick-and-place operation.

2. Blade Identification/Blade Properties

Once the position and orientation are defined, the process of characterization of the blade takes place. This includes blade manufacturers' code recognition and shape definition. The type of the blade, the material and the original dimensions will be loaded from databases corresponding to either their embedded code or pattern recognition.

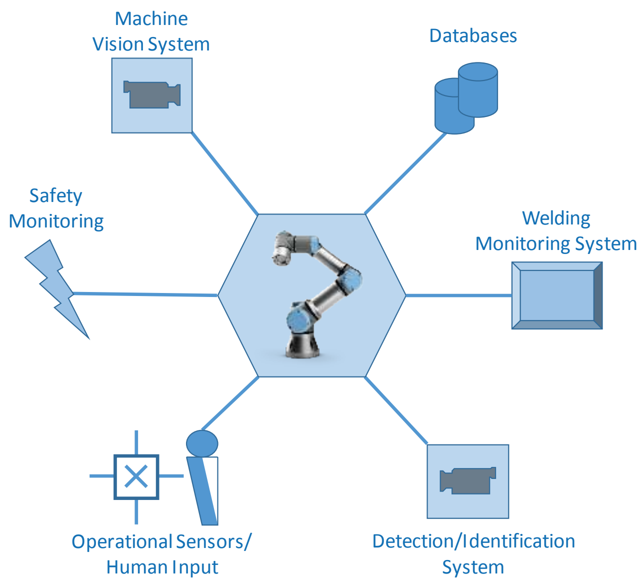

Fig. 1. Representation of the network formed between the robot and its peripheral systems.

3. Loading for Inspection

After the characterization of the blade the robot uses the information acquired from both scanning and databases to pick and place the blade, correctly attaching it to the tip-blade inspection site.

4. Inspection Vision System

4.1 Pre-Weld Evaluation & 4.2 Welding Parameters Determination

The machine vision system inspects the loaded sample defining its wear and damage. The system provides a pre-weld evaluation, defining if the blade is able to be repaired by the system or not. If the blade is repairable, then the welding parameters are calculated and set up in the welding system. If the blade is not repairable by the system it is rejected (e.g. excessive damage or non-re-manufactured edge, defects similar to Fig. 5, etc.).

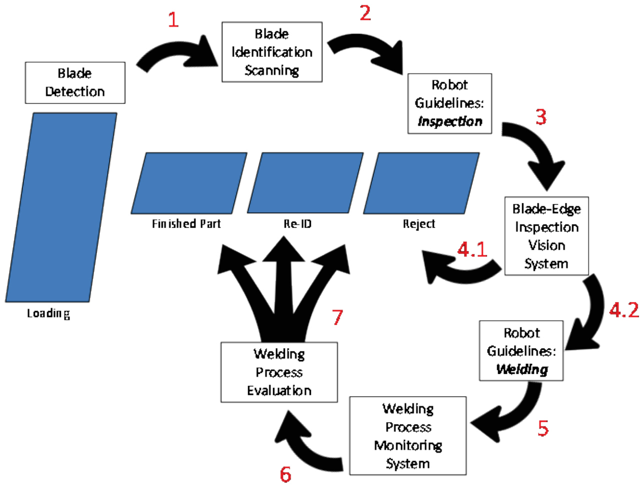

Fig. 2. The concept's process flow for re-manufacturing

5. *Welding Process*

Based on the welding parameters provided by the inspection vision system, the robot's guidelines are created and the robotic system performs the operations for the blade edge welding.

6. *Welding Process Monitoring*

During the welding process, a unique high-speed data acquisition System (DAQ) performs measurements that will be used to create a database for weld evaluation. A welding monitoring system transfers real-time image feed, along with electric measurements acquired by the DAQ and other operational parameters to the Graphic User Interface.

7. *Weld Evaluation*

Once the welding is completed, the welded piece is evaluated based on the data acquired by the welding process monitoring system and the blade inspection system. Based on the evaluation the robot transfers the blade to the corresponding stage of acceptance or rejection.

III. Implementation of Industry 4.0 Design Principles

While the network in Fig. 1 reminds an old-fashioned representation of a centralized production line, the following expanded overview of the individual advances, illustrates the evolution in robotics applied in the aerospace industry. Each concept presented was designed accordingly in order to match the requirements set by the Industry 4.0 principles.

A. Modularity/Flexibility:

Under the scope of the IoT in a smart industrial environment, each product is able to present its history and find its way on a production and re-manufacturing supply chain. This concept is being adapted in the aerospace industry, resulting in compressor blades with embedded codes and serial numbers. However, not all of the blades that are currently in use in operational gas turbines carry machine readable codes, and those who do have, carry them in a variety of ways: barcodes, embedded serial numbers, embedded script codes. With modularity and flexibility in mind the Detection-Identification system is being developed with the ability to detect and identify any kind of blade. Therefore, all the scanning, lighting and optical recognition elements are designed and developed to achieve this flexibility.

B. Sensor Fusion in Monitoring:

Advanced sensors that perform electric measurements on the welding equipment are transferring real-time data on a Graphic User Interface (GUI). Live video feed is also presented on the remote GUI, acquired by the vision system. This way direct visual contact with the bright welding light is avoided, eliminating eye-hazards during human-machine interaction and providing technical assistance. Remote monitoring through sensor fusion on one monitoring platform improves interoperability by ensuring the ability to use a variety of devices and sensors.

C. Sensor Fusion and Machine Vision in Inspection:

A machine vision system that combines advanced scanning and optical imaging equipment is under development. The system is aiming to detect the position and wear of each individual blade, characterizing imperfections and calculating the level of repairs in need. The system is designed to reject blades beyond the system's ability for re-manufacturing and calculate the layers of linear weld required based on manufacturers' and new machine-created referencing databases. This decentralized decision aids in the QA and QC and avoids waste of materials on both faulty products and manual working.

D. Sensor Fusion in Final Product Evaluation and Fault Detection:

An advanced High-Speed Data Acquisition System (DAQ) monitors the welding process, delivering real-time data regarding the quality of the weld. The system was developed by the University of Sheffield and has been proven able to detect malfunctions and flaws during a welding process (Section IV). QA on the final product increases the product lifecycle since faults detected will lead to re-re-manufactured products instead of unrepairable waste.

E. Sensor Fusion in Safety:

A cluster of peripheral sensors are utilized for monitoring the whole process, ensuring human and equipment safety. The robot itself is designed to stop operation when an obstacle is opposing its actions, and the use of proximity sensors for collision avoidance is under evaluation. The safety features for the operation of the robot are also being evaluated, aiming to personalize clearance in order to ensure that usage of untrained personnel is avoided. These Industry 4.0 adaptions aid not only in machine and human safety, but also Information Technology (IT) security since corporate intelligence will be available only on personnel with corresponding clearance.

F. Data Management:

Since information is the power that drives the modern industrial revolution, a number of databases are required for a smart factory to operate. The following databases are core elements in the developing system, providing information transparency and ensuring QC, QA, and IT safety, in parallel with the ability for further data analytics.

1) Database for blade-log: The complexity of the solution raises the need for flexible databases able to expand and adapt as the system progress. Existing data that are acquired by the blade manufacturers have to be combined by the data acquired by the system to create files corresponding to each blade. Apart from their type and origin the database must include a history of each blade when available, especially previous re-manufacturing history. If no data are available then a new data log has to be created.

2) Database for blade-type: Provided by the manufacturers the technical specifications for each type of blade has to be present in the system. These data are cross-referenced by the system on each blade for correct attachment and vision system positioning configuration. The size and shape of each blade will be used as a reference for evaluation during inspection. Alongside, the vision acquired data will be used to define the robotic welding-path coordinates.

3) Database for weld evaluation and fault detection: Data from the Hi-Speed DAQ system revealed that errors and malfunctions that occur during a welding process create variations in arc voltage measurements. These variations present as repeatable patterns based on their nature and origin, giving the ability to detect errors in real-time. As the categorization and identification of each error in real-time is currently under further commercial development, plans of a software based system for this application are underway. The system will incorporate a database of known malfunctions and their electrical fingerprints and using pattern recognition in real-time data analytics will be able to distinguish and clarify the error as it occurs.

4) Database for ID Clearance: In order to avoid untrained personnel use of the advanced remanufacturing system, and to protect classified commercial high-value information, access to the robot is limited. A security feature operator attached to the system, limits access to only persons that have the skills to interact with it. This platform can include simple security measures such as password protection, more advanced fingerprint sensors and facial recognition software. While the first one implemented for the prototype is an easy build, the others will require a safety database with the details required for login (facial recognition data, fingerprint data, etc.)

With all peripheral systems analyzed, the simple interconnection diagram on Fig. 1 is evolving in a more complex network, that is presented on Fig. 3.

IV. Evaluation of the First Results

Traversing through concept adaption and design phases, the milestone of the development of an operational robotic prototype has been reached. With its successful operation, the first welding results are being produced, allowing evaluation and assessment, in line with end-user requirements.

During the re-manufacturing process, additive material (AM) is deposited on the compressor blade. Monitoring of the process is achieved through the inspection and monitoring systems. A compressor blade is scanned before and after the additive deposition process, resulting in a series of different 3D models which forms part of the QA and QC process. An example of such series is presented in Fig. 4. Flat Compressor Blade-Models (CBMs) are initially scanned before the welding. The smooth surface of the refinished edge is identified with no variations on the height or the width of the edge (Fig. 4a). After additive deposition is preformed by means of welding, changes on the welded surface are detected on the scanned object. In Fig. 4b the result of welding without AM is represented whereas in Fig. 4c welding was performed using AM deposited on the surface. The increase in the height of the blade, due to material deposition, is notable with different coloring according to the scale.

The inspection system can also be used for detecting flaws on compressor blades that have been incorrectly remanufactured, or faults introduced by unknown factors. In order to simulate malfunctions and evaluate sensor fault detection performance, a series of faults were intentionally introduced on CBMs. CBMs with structural defects and contamination were initially scanned with the inspection system, to test the detection mechanisms. As presented on Fig.

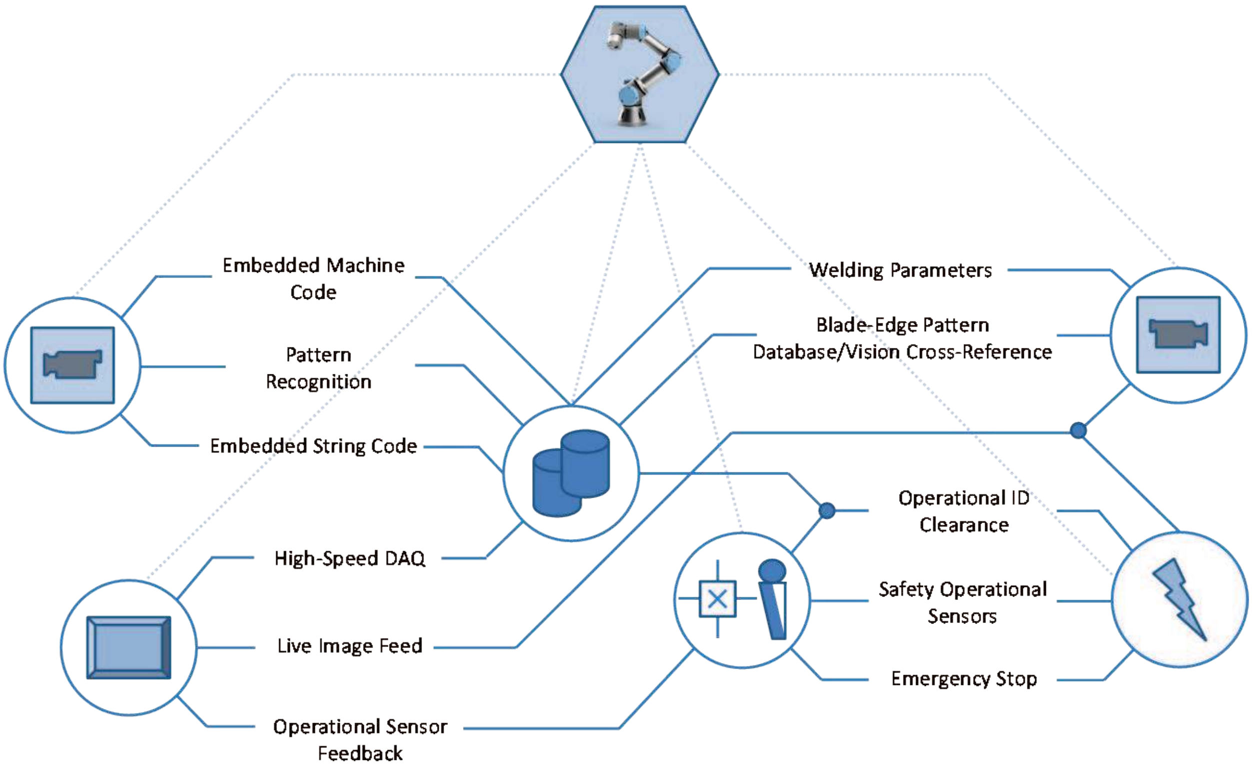

Fig. 3. Schematic representation of the interconnections between the robot's peripheral systems, after the Industie 4.0 design principles are applied

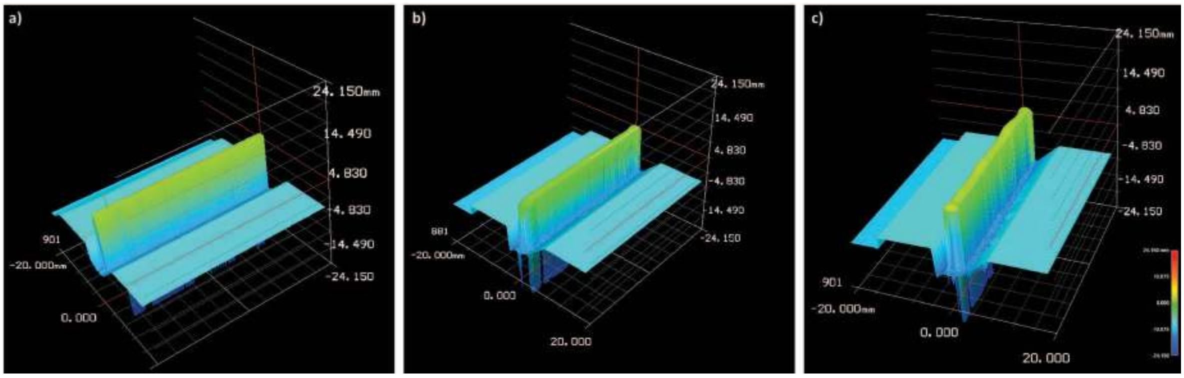

Fig. 4. 3D scanning modelling of a flat CBM: a) before welding, b) after welding without AM, c) after welding with AM

5a, blades that were not re-manufactured correctly are indicated by electrical noise, represented as spikes on the 3D scan image. A large v-shaped cut (Fig. 5a), a small notch (Fig. 5b) and grease contamination (Fig. 5c) altered the 3D model of the scanner, from a baseline profile, allowing the successful detection of the faults.

The evaluation of a finished re-manufactured product is performed using real-time monitoring of the welding or additive manufacturing process. The High-Speed DAQ system (Section III-D) has been used to evaluate welding operations in real-time for the ATLAS Experiment in CERN [4], [5], [6], and for nuclear applications at Nuclear AMRC [7]. The DAQ system is not only able to successfully detect welding process flaws, but can also detect subtle deviation in flaws originating from different events. When comparing imperfections on welds caused by different factors (e.g. mechanical imperfections, contamination, equipment malfunctions, etc.) the electromagnetic graphs or electro-fingerprint on the DAQ system differs.

After introducing the structural defects (small notch) and contamination (grease) on the CBMs described above, monitoring data of the welding process were compared to those of welding of normal CBMs. While under optical inspection the welded blades appeared normal without any defects, the acquired data revealed successful detection of disturbances on the power demands. These fluctuations occurring on the

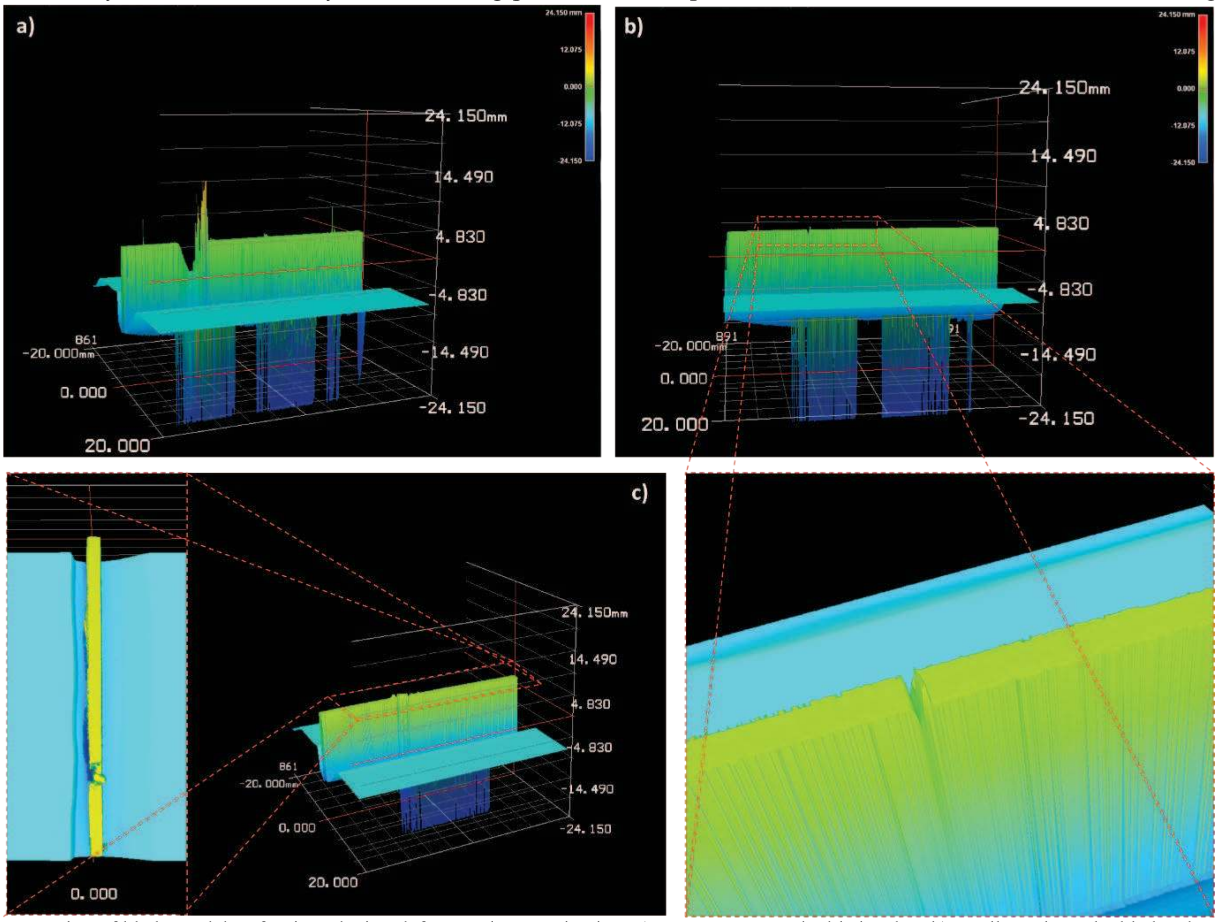

Fig. 5. 3D scanning of blade models, after introducing defects and contamination: a) Large V-cut on the blade edge, b) small notch on the blade edge, c) grease contamination.

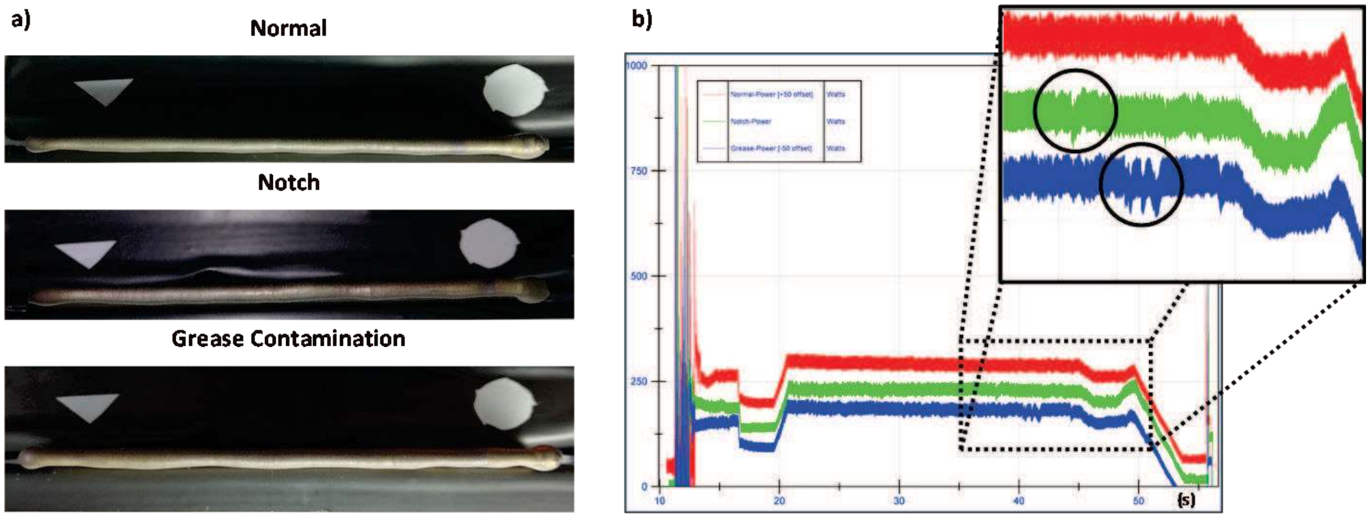

Fig. 6. a) Welded edge of turbine blade models on normal blade (top), blade with small notch (center) and blade with grease contamination (bottom). b) Power demand analysis from data received from the DAQ system during the welding process of the blades. Normal welding (red) and grease contamination (green) have +50 and -50 Watts offset respectively, in order to separate the graphs. Circles in the zoom-in section show the fluctuations of the power demand caused by the notch (green) and grease contamination (blue).

voltage measurements represent faults that are changing the power demands of the arc, in order to maintain a stable pre-set value on the current. These results highlight the importance of the DAQ system in maintaining the QA and QC of the welding process, since an object that would normally pass the optical welding inspection criteria, is being rejected by the welding monitoring data. These two sensory elements when combined form an intelligent QA/QC process, which removes the need for extensive post manufacture inspection increasing operator confidence. On Fig. 6a the welding final products on the CBMs show no variations, which will normally led to approved welding. In contrast, the acquired data during the welding process in Fig. 6b reveal the notch fault and contamination on the blades respectively.

Using this novel real-time system of NDT, the evaluation that was performed on the first outputs of the robotic prototype, shows successful initial operation and additive material deposition. This initiates the optimization and welding trial phase, where further advances on the welding are experimentally determined for the aerospace concept.

V. Conclusion

The automation of an aerospace re-manufacturing process, based on the design principles of the forth industrial revolution, is challenging. Smart factories under the Industry 4.0 concept are comprised of complex networks that incorporate robots and advanced sensors. The valuable industrial data that are created, are further analyzed and used for evaluation of the final product. The product itself, being part of the IoT, is able to tell its own characteristics and manufacturing history.

With all these in mind, a robotic solution for re-manufacturing of high-value aerospace blades was proposed. Aiming in repairing 100% of the repairable yield of used turbine blades and in eliminating hazardous to human effects, the proposed robotic solution emerged from an industry-academia collaboration between VBCie and the University of Sheffield. After years of research and development, an operational prototype is producing its initial results. The successful evaluation of the results, justifies the vision of the collaboration and provides market entry to autonomous re-manufacturing in the aerospace industry. The combination of independent inspection mechanisms that incorporate advanced sensor fusion will assure the quality of the process and eliminates faulty products reaching circulation.

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