Proceedings Paper:

French, R., Marin-Reyes, H. orcid.org/0000-0002-2919-5388 and Benakis, M. (2018) Transfer Analysis of Human Engineering Skills for Adaptive Robotic Additive Manufacturing in the Aerospace Repair and Overhaul Industry. In: Advances in Manufacturing, Production Management and Process Control. International Conference on Applied Human Factors and Ergonomics, 21-25 Jul 2018, Springer. Advances in Intelligent Systems and Computing book series (793). Springer International Publishing , pp. 3-12. ISBN 978-3-319-94196-7

https://doi.org/10.1007/978-3-319-94196-7_1

Transfer Analysis of Human Engineering Skills for Adaptive Robotic Additive Manufacturing in the Aerospace Repair and Overhaul Industry

Richard French, Hector Marin-Reyes, and Michalis Benakis

Physics and Astronomy, The University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, UK
{R.S.French,H.Marin-Reyes,M.Benakis}@Sheffield.ac.uk

Abstract. The desire for smart "lights out factories" which can autonomously produce components for high value manufacturing industries is described by the Industry 4.0 solution. This manufacturing methodology is appropriate for newly designed components, which take advantage of modern materials, robotic and automation processes, but not necessarily applicable to overhaul and repair. The aerospace overhaul and repair industry remains heavily dependent on human engineering skills to develop repair and re-manufacturing techniques for complex components of high value.

Development of any advanced, intelligent multi-agent robotic additive re-manufacturing system requires correct interrogation of metallic materials thermal properties, system control and output. Advanced programming of robots, data interpretation from associated sensory and feedback systems are required to mirror human input. Using process analysis to determine stimuli, replacement of human sensory receptors with electronic sensors, vision systems and high-speed data acquisition and control systems allows for the intelligent fine tuning of multiple heat input parameters to deposit the additive material at any one time. The interaction of these key components combined with novel robotic technology and experienced welding engineers has made possible the construction of a disruptive robotic re-manufacturing technology.

This paper demonstrates the design process and analyses the outputs sourced from observation and the recording of highly skilled human engineers when conducting manual remanufacturing and repair techniques. This data is then mined for the transferable control input parameters required to replicate and improve human performance.

This industry-academia research intensive collaboration between VBC Instrument Engineering Limited (UK) and The University of Sheffield has received project funding from the Engineering and Physical Sciences Research Council (EPSRC, 2006–2010), the Science and Facilities Technology Council (STFC, 2011–2013) and Innovate-UK with the Aerospace Technology Institute (2014–2018).

This work is supported by Innovate-UK.

1 Introduction

1.1 Aerospace Repair and Overhaul Industry

Aircraft turbofan or jet engines are highly complex structures, composed of approximately 30,000 individual components [1]. Component design materials selection and both manufacturing and in-service tolerances of each component drives optimum performance of the engine. However, harsh environmental and prolonged operational conditions result in physical wear of engine components, introducing a variety of defects. Operating in a high pressure/temperature environment, in combination with foreign object impact, leads to wear, distortion, dents and cracks on blades, vanes, blade-integrated disks (Blisks) and such other components [2]. Introduction of such defects can lead to catastrophic events, resulting in huge costs, both societal and economic. In order to prevent such failure, the turbofan engines are required to be removed from the aircraft and overhauled after $\sim$30,000 h of operation [3], a limited number of take-off/landings, the greatest contributor to wear.

Maintenance, repair and overhaul (MRO) is defined as the process of ensuring that a system or equipment, continually performs its intended functions, reliably and safely under acceptable constrains [4, 5]. MRO operations required by complex products in the aerospace industry result in high MRO costs. Many manufacturing companies have altered their business strategy to support the servicing of their products through the entire lifecycle. The main reason behind this shift is to allow long, intensive operational periods of high cost engines to quickly yield a profit for the customer. To guarantee the lifespan of the engine, repairs on worn components and manufacturing spare parts is essential to ensure long term reliability [6].

Engine components of particular interest to the aerospace engine overhaul companies are vanes, turbine blades and compressor blades. Their high value increases the need of repair instead of replacement. The blades of a turbofan engine are the most critical part, used in different stages of the engine with different sizes and roles. Their performance is based on their aerodynamic body, where even a small change in the geometry of the blade can result in a large change on the engine's performance and efficiency. It is therefore of major importance to maintain the original shape of the engine blades, while the repaired component conforms to and acceptable dimensional tolerance as defined by the original manufacturer. The traditional process for engine blade regeneration is mainly separated in four stages: pre-treatment, material deposition, re-contouring and post-treatment. Stages of pre-inspection and post-inspection are also included before, in-between and after the aforementioned stages, to identify defects, select appropriate restoration procedures and ensure the quality of the restored component.

1.2 Additive Manufacturing

The work presented on this paper is focusing on the second stage of the blade regeneration, which refers to the material deposition process. The techniques currently used for material deposition vary according to the material and the damage of the blade. For patch-repairs plasma arc welding is used to weld the patch joint without additive material. Crack-repair on the blade's body is carried out through brazing or welding depending on the size of the crack. Tip-repair is done via additive arc welding with filler material or via material cladding using laser welding, due to low heat input requirements. The tip-repair, due to blades "sulfidisation" and crack formations during operation, occupies the majority of the volume repaired in aeroengine components [7]. This paper follows the current developments of a robotic welding system for tip-repair of compressor blades, by means of Additive Manufacturing (AM) using Pulsed-Arc Tungsten Inert Gas (TIG) welding.

The thin tip of the compressor blades requires low heat input during repair, to ensure the mechanical properties of the material. In order to achieve acceptable control of the heat input, an advanced TIG welding power source, the Heat Management System (HMS) provides a high frequency pulsed weld current [8, 9]. An industry-academia collaboration between the University of Sheffield (UoS) and VBC Instrument Engineering Ltd (VBCie), described in Sect. 1.3 below, has developed the advanced HMS system.

The majority of aerospace component repairs are performed manually, by highly skilled welding engineers. The reasons behind the lack of automation is a combination of the complex geometries of the workpieces, individual repair requirements per blade type and the high purchase price of automated systems.

Traditionally, a human engineer will inspect the component to assess its level of damage. Should the repair criteria be met, the component is sent to the pre-treatment stage to undergo de-coating and surface grinding. Following this process, a welding engineer will apply the additive material to the manufacturer's predefined dimensions and welding procedure (WPS).

In order to automate the AM process, adaptive machining techniques are needed. Machine vision systems work in conjunction with advanced sensory systems, to generate data for a robotic or CNC welding platform. Generically these platforms use a robotic arm equipped with a welding torch to follow the component shape using measurement data. This adapts with the changing, complex requirements of the component's geometry and mimics the hand-eye coordination of a human welding engineer.

To monitor the transfer of human engineering skills to a robotic welding system, UoS performed a series of welding trials with the Nuclear Advanced Manufacturing Research Center (NAMRC). The aim of the trials was to firstly monitor the welding process in real-time, to be able to predict the quality of a manual weld, detecting errors and defects as they occur. The results of this research were presented [10] and this current research follows the transfer of the data collected during the trials to advance the robotic welding systems adaptability and performance.

1.3 The Academia Industry Collaboration

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, this research has increased in TRL substantially up to present day. As part of the UK High Value Manufacturing CATAPULT the NAMRC is part of UoS. The NAMRC enables its industrial partner network companies, based in the nuclear industry manufacturing supply chain, to develop new and improved manufacturing capabilities as part of the "Fit for Nuclear" programme. The UoS groups have collaborated on a number of projects aligned with fusion welding for high value manufacturing.

2 Human Skills Extraction and Implementation

2.1 TIG Manual Welding – NAMRC Welding Trails

Figure 1a shows the welding voltage and current obtained while welding two stainless steel plates with 152 mm length at 1.25 mm/s welding speed. The filler wire used is the same type as the SS plates. No visual defects or significant variations on the measurements were detected so it was determined it was a good weld.

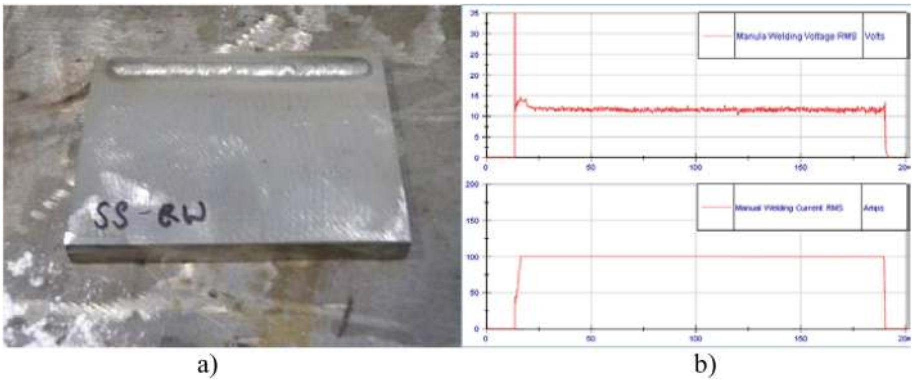


Fig. 1. (a) Manual TIG welding on a SS plate at the Nuclear AMRC, (b) Electric measurements of the arc welding from an experienced welding engineer

The build-up of the weld pool has been found to be closely related to the oscillation of the human hand while travelling alongside the welded joint and this oscillation is different under different WPS. Figure 1b. shows that the human hand oscillates from up to down at a frequency of 1.5 Hz. The extraction of the human hand oscillation frequency can be obtained in real-time using a prototype high speed data acquisition system (DAQ) developed by the UoS ESIM group.

3 Towards Industry 4.0

At the beginning of the fourth industrial revolution, the traditional aerospace remanufacturing factory transforms into a futuristic intelligent entity able to interoperably perform tasks with limited human interaction, driven by data and decentralized decisions. Beneath the term Industry 4.0, underlie four basic design principles: interconnection, information transparency, decentralized decisions and technical assistance. The adoption of these four design principles from manufacturing systems results in a controlled environment where quality assurance is achieved in parallel with cost and waste reduction.

The robotic welding system under development was designed to implement Industry 4.0 principles and reshape the aerospace remanufacturing industry. Initial experimental results presented [11] demonstrate modular design and interconnection of physical subsystems, to transparent data management and intelligent sensing. The individual subsystems are under constant development, adapting and advancing in a concurrent engineering ecosystem. Advances currently under evaluation are presented aligning with the Industry 4.0 concept adaption.

3.1 Weld Evaluation and Fault Detection

Real-time weld process monitoring, using high-speed intelligent sensing is essential as part of the Quality Assurance (QA) and Quality Control (QC) requirements of the advanced robotic welding system. Traditionally a finished component used in the aerospace industry undergoes evaluation through a series of inspection and non-destructive testing (NDT) techniques. These techniques, range from ultrasonic to x-ray inspection, have major drawbacks of high cost and duration of time. The greater flaw is post-manufacturing inspection, results in a high volume of scraped products when defects are detected. Performing non-destructive evaluation in real-time, provides the benefit of adjustable input parameters and process conditions which give a highly optimised finished component.

An example applicable to the regeneration of compressor blades is illustrated in Fig. 2. During the welding process where additive material is deposited on the tip of the blade, a variation occurs in the power supply, resulting in lower heat input to the material, Fig. 2a. The result of this variation shows lack of fusion in the weld (red colour). In this case the welding engineer completes the operation as normal, and post weld inspection detects the defect effectively scrapping of the part under regeneration. Conversely, presented Fig. 2b a real-time weld monitoring system detects the slight variation of the power supply as it occurs (green area). This triggers a signal that highlights the need for a change in the process parameters, and another subsystem adjusts the power to its new level. As a result the process continues with the corrected parameters, preventing the defect from lack of fusion to occur.

The high-speed DAQ has been proven to detect anomalies resulting in poor weld quality [11]. By monitoring the welding process with the DAQ system, implementation of data-processing techniques allows feedback to the robotic welder via a newly developed Arc Voltage Control (AVC). When combined DAQ and AVC data allows

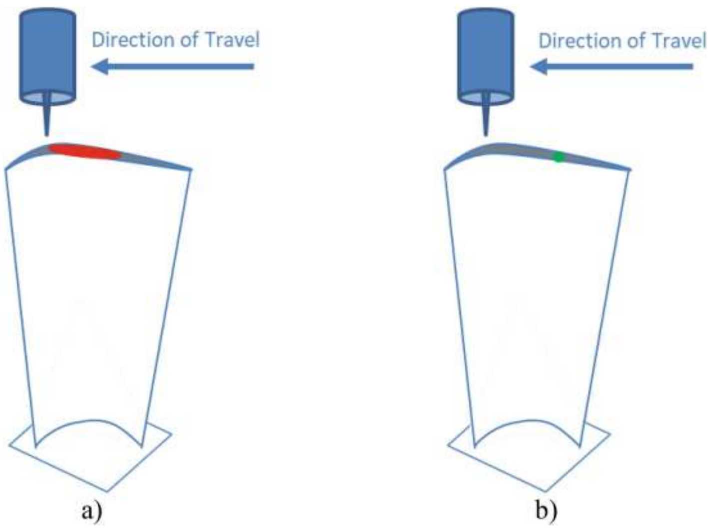


Fig. 2. A compressor tip-repair process. (a) a slight alteration on the power supply occurs in lack of fusion in a part of the weld (red), (b) the alteration is detected and a signal is triggering corrections, avoiding the formation of the defect.

for the adaptive development of partial human intelligence drawn from experienced welding engineers.

3.2 Automatic Voltage Control (AVC)

During the manual welding process, the human engineer uses their natural senses to monitor the welding process, adjusting their movements to control the heat input to the workpiece. These adjustments include, changes of direction and travel speed of the welding torch, electrode and workpiece distance. Variation in the distance between the electrode and the workpiece (arc gap), corresponds to changes in the voltage of the arc. The application of an electromechanical subsystem to maintain a preset arc gap (Fig. 3), achieves consistent voltage control. The AVC receives data from the DAQ monitoring system and reacts by positioning the electrode accordingly. By providing greater control of the system, achieves better control of the amount of heat delivered to the workpiece (heat input) and a stable process.

4 Welding Trials and Discussions

Analysis of GTAW welding machines to improve welding performance involves the monitoring of signals and generation of commands over an interface. Response to GTAW technique variation requires intelligence which has proven exceptionally challenging to develop for the complex profile (curved) and super alloy materials (heat input and distortion) now utilized by aerospace engine manufacturers. Experienced

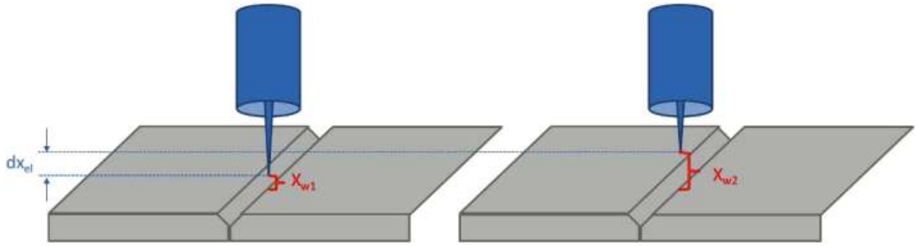


Fig. 3. Automatic Voltage Control (AVC) by altering the distance between the electrode and the workpiece. A change in the electrode position *(dx_{el})*, corresponds to a change in the voltage, which is proportional to the workpiece distance ratio X_{w1}:X_{w2}.

welding engineers dynamic inputs alter the weld deposition or AM characteristics (size, shape, depth and micro-structure) by varying parameters termed CLAMS (current, length, angle, manipulation and speed) [3, 10]. They use their knowledge and apply their skills almost automatically by subtly fine tuning CLAMS to achieve the required result. Automated repetition of CLAMS data enables production of the correct weld deposition with high repeatability but with the inability to respond to a change in dynamics or conditions.

Figure 4 shows the arc welding voltage and current measurements performed on the edge of a flat stainless steel plate of 1.5 mm width thickness, using a WPS created with the CLAMS tuned by experienced welding engineers from VBCie.

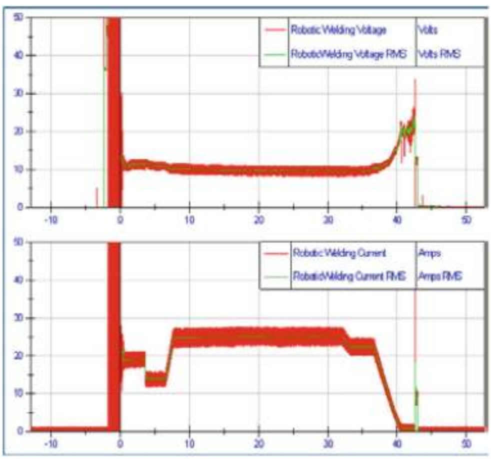
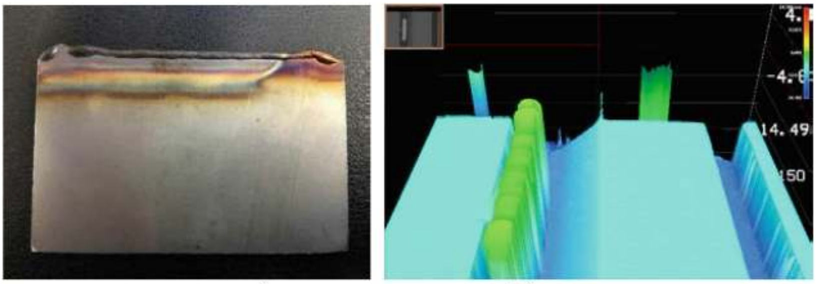


Fig. 4. Arc welding voltage (top) and current (bottom) of the IP-50 welding machine from VBC Ltd.

Measurements were performed using bespoke high speed sensors [10, 12]. The measurement signals have been filtered in real-time with a low-pass filter and cutoff frequency of 10 Hz. Different current levels were tuned to allow the weld pool to settle at the start and end of the WPS. The total travel distance of the welding torch over the test piece was 60 mm.

While Fig. 5 shows the 3D scan of the outcome of the robotic welding when the AVC is not active, Fig. 6 shows the 3D scan outcome of the adaptive robotic welding when the AVC is active.



a) b)

Fig. 5. Robotic welding with AVC OFF (a) Flat SS plate, (b) 3D image

Figure 7 compares the heights of test samples shown in Figs. 5 and 6. A downslope due to the melting of material at the end of the test sample can be seen when the AVC is active (graph in green). This effect is expected because more additive material needs to be deposited at the end of the outer edges to allow for the grinding process. However, when is the AVC is not active (AVC OFF, graph in red), the melting temperature of the material is too cool, even though the corresponding welding current in the WPS is suitably to achieve the correct melting point or fusion. Therefore, the AVC allows additive filler material to be fed in to the plate for the build-up or AM to occur by compensating the distance between the electrode tip and the turbine blade tip.

5 Conclusions

The repair or regeneration of high value aeroengine components is heavily dependent on large elements of manual welding. Because of the complex geometries and the large variety of non-uniform wear and deformation found on individual pieces, the automation of the remanufacturing process is extremely challenging. In order to achieve advances in this automation, human engineering skills need to be observed and recorded during the process, analysed and transferred to robotic welding systems.

A series of experimental welding trials were performed by the ESIM Group of University of Sheffield and its industrial partners, NAMRC and VBCie, providing the data used for training a robotic aerospace welding system. By applying design principles shaped by the Industry 4.0 concept, the robotic system adapts to changes in the repair process, resulting in better QC and increased success rates.

An AVC module has been developed, in order to achieve machine control of the arc welding voltage. The module receives data provided by a high-speed real-time process

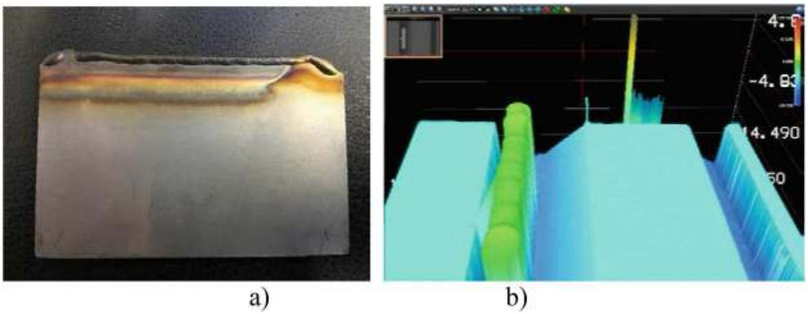


Fig. 6. Adaptive robotic welding with AVC ON (a) Flat SS plate, (b) 3D image

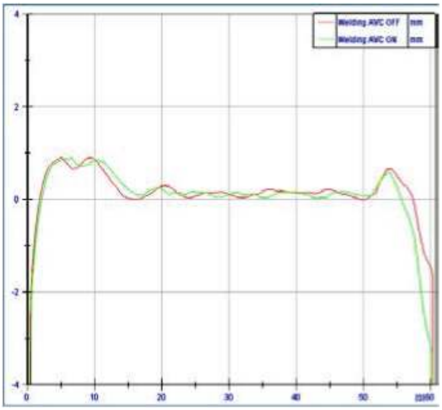


Fig. 7. SS plate heights with AVC ON (green) and without AVC (red). Very similar but at the end of the torch falls over the edge when AVC ON.

monitoring system and controls the voltage by altering the distance between the electrode and the workpiece.

The interoperability required by Industry 4.0 in a smart factory allows modular subsystems to perform such decentralized decisions, increasing production speed and assuring quality.

Acknowledgments. The authors would like to thank Mr Andrew Rendell-Read (VBCie Ltd). We are very grateful to the Nuclear AMRC *SIMPLE Phase I* project team of Professor Keith Bridger, especially Samantha Biddleston for their input to the manual welding trials.

References

1. Denkena, B., et al.: Engine blade regeneration: a literature review on common technologies in terms of machining. Int. J. Adv. Manuf. Technol. **81**, 917–924 (2015)
2. Yilmaz, O., et al.: A repair and overhaul methodology for aeroengine components. Robot. Comput.-Integr. Manuf. **26**, 190–201 (2010)
3. French, R., Marin-Reyes, H.: High value intelligent aerospace turbofan jet engine blade re-manufacturing system. In: Schlick, C., Trzcieliński, S. (eds) AHFE Advances in Intelligent Systems and Computing, vol. 490. Springer, Cham (2016)
4. Geng, J., et al.: A design method for three-dimensional maintenance, repair and overhaul job card of complex products. Comput. Ind. **65**, 200–209 (2014)
5. Zhang, Z., et al.: A cloud-based framework for lean maintenance, repair, and overhaul of complex equipment. J. Manuf. Sci. Eng. **137**, 11 (2015)
6. Ulhmann, E., et al.: MRO – challenge and chance for sustainable enterprises. In: 2nd International Through-life Engineering Services Conference (2013)
7. Compressor blades repair and overhaul. Rolls-Royce Plc Internal Report (2002)
8. French, R., Marin-Reyes, H.: Welding performance evaluation of the VBCie IP50 TIG orbital heat management system. In: IIW International Conference, High-Strength Materials - Challenges and Applications, Helsinki, Finland, July 2015
9. French, R., et al.: Real-time welding evaluation system assessment using the TIG orbital welding process on ultra-thin wall tube joints in titanium and stainless steel. In: IIW International Conference, Green Welding Technologies for Effective and Reliable Manufacturing, Shanghai, China, June 2017
10. French, R., et al.: 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) AHFE 2017, Advances in Intelligent Systems and Computing, vol. 606. Springer, Cham
11. French, R., et al.: Intelligent sensing for robotic re-manufacturing in aerospace — An industry 4.0 design based prototype. In: IEEE International Symposium on Robotics and Intelligent Sensors (IRIS), Ottawa, ON, pp. 272–277 (2017)
12. French, R., et al.: A Robotic re-manufacturing system for high-value aerospace repair and overhaul. In: Chen, S., Zhang, Y., Feng, Z. (eds.) Transactions on Intelligent Welding Manufacturing. Springer, Singapore (2017)