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High Value Intelligent Aerospace Turbofan Jet Engine Blade Re-manufacturing System*

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Abstract. Development of any advanced, intelligent robotic welding system requires correct interrogation of welding parameters 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 welding parameters at any one time.
This paper demonstrates the design process, highlighting interaction between robotics and experienced welding engineers, towards construction of an autonomous aerospace turbofan jet engine blade re-manufacturing system. This is a joint collaborative research and development project carried out by VBC Instrument Engineering Ltd (UK) and The University of Sheffield (UK) who are funded by the UK governments' innovation agency, Innovate-UK and the Aerospace Technology Institute (UK).

Keywords: Robot · Ergonomic · Machine Vision · GTAW Welding · Re-manufacturing System

1 Introduction

High value aerospace gas turbine blades are subjected to extreme temperatures during operation, resulting in wear, deformation & distortion over time. After ~30,000 hours of operation, turbofan jet engines are entirely overhauled. The compressor blades are removed then inspected and where possible repaired using manual weld deposition. Investigations into the intelligent automation of the GTAW (Gas Tungsten Arc Welding) process for turbofan blade re-manufacturing has demonstrated that highly skilled welding engineers are required to carry out what is perceived to be a simple task.

Existing standard practice for the re-manufacturing of high value compressor blades is predominantly performed manually, on-site under extreme environmental constraints (noise, heat and restricted spaces). However with such high value components, a high yield of re-manufacturing is required, but not achievable with current manual processes providing less than 50% yield.

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Experienced welding engineers use their knowledge and apply their skills almost automatically by subtly fine tuning multiple welding control parameters to achieve the required results. Their dynamic inputs alter the weld deposition characteristics such as; size, shape, depth & micro-structure. The variable parameter changes are termed CLAMS (current, length, angle, manipulation and speed). CLAMS detailed in a welding procedure schedule or document is used to provide numerical input for the manual operator to achieve correct results with high yield.

A prototype system will be built in this study which will be interfaced to a robotic welding arm to prove that the system can operate in a representative environment. The system has great potential to be developed not only in robotic welding but also for other automated robotic systems that require locational and structural information to determine the appropriate procedure required and optimize control. A route map of commercialization will be produced to develop commercial products in different industries.

2 Reducing human labour in re-manufacturing Aerospace Turbo Fan Compressor Blades

Aero engine gas turbine compressor blades are subjected to extreme temperatures during operation, resulting in wear, deformation and distortion over time (Fig. 1 shows a Rolls-Royce Trent1000 turbofan engine). The overhaul process is predominantly undertaken manually. In this instance we discuss the high value compressor blades which are stripped from their mountings, removed and repaired using manual weld deposition then refinished.

Fig. 1. Cross sectional rendering of Rolls-Royce Trent1000 turbofan engine detailing the removable compressor blades in the central section

The aviation industry, driven by tight profit margins, strict safety profit margins and safety regulations, has become an extremely well developed remanufacturing industry. Half of all overhauled compressor blades are reclaimable through the re-manufacturing process (Fig. 2 shows the re-manufacturing industry life cycle). However, there is a problem because current re-manufacturing yield of compressor blades is only around 80 per cent of that half owing to high heat input during welding and poor practice.

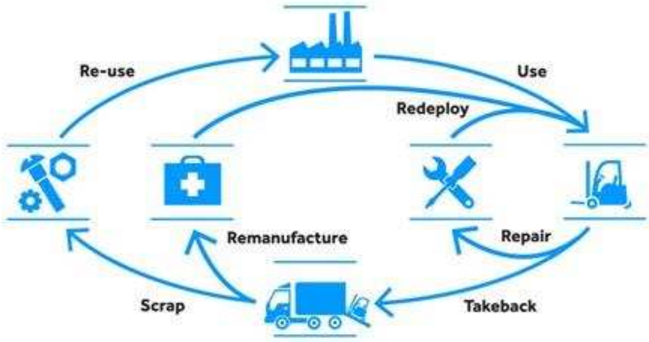

Fig. 2. Diagram of re-manufacturing industry life cycle asset management process.

Major problems have been identified through errors in the manual weld build-up process and it is desirable to assist the human operators with robotic solutions. With air travel set to increase, there will be even more demand for remanufactured components and systems. With new materials and technologies being incorporated into aircraft, it is important that science keeps pace with technology to repair these parts and detect faults before they fail.

Turbine compressor blades experience dimensional and metallurgical degradation during engine operation. Dimensional degradation derives from wear, nicks, dents and hot corrosion. The current solution is to grind back the blade tip to a predetermined globally approved specification which results in non-defective sectors being reworked unnecessarily which significantly reduces the lifespan of the part (Fig. 3 shows the manual weld build up process).

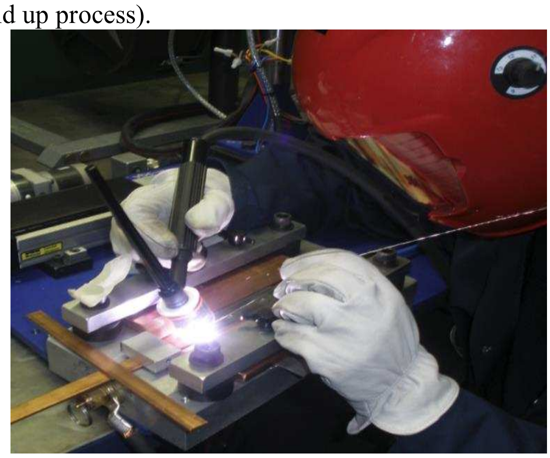

Fig. 3. Photograph of welding engineer carrying out the manual weld build up process.

This current practice evolved from the need to build in low tolerance manual welding and hand grinding of very high tolerance components. Manual processes are still widely used because there is very limited amounts recorded welding knowledge or data available. The remanufacturing industry relies instead on highly skilled welding staff to "feel" their way through a blade repair (Fig. 4 shows compressor blades after manual weld deposition).

Fig. 4. Photograph of compressor blades after manual weld deposition

Combined with existing manufacturers' inability to utilise accurate component wear identification with good welding power supplies and non-destructive testing (NDT) weld monitoring systems provides an ideal opportunity to reduce human labour in this process.

Automated solutions to address this area of concern have been attempted before. Existing solutions do not offer anywhere near the proposed level of intuition simply through the lack of correct use, or development of sub-systems to aid the welding and inspection processes.

By providing a high fidelity process for a high tolerance component the system relieves dependency on the dwindling supply of highly skilled welding engineers through automation. Data captured from the welding and inspection process can then be fed back to the manufacturers both as further fine tuning of the welding system but more importantly providing hyper-accurate wear data for each identified part.

3 Ergonomic considerations in existing manual GTAW processes for re-manufacturing

If robots are to share the same environment, cooperate and assist in manufacturing tasks by substituting humans, then designing robots based on knowledge of human cognitive processes offers a good starting point. Use of robotics will significantly enhance the product by providing their complementary capabilities dexterity and repetition in an ergonomically efficient and more user-friendly working environment. To begin to understand the environmental constraints, we must first examine the background of the existing hazards in manual GTAW processes. We must then apply these findings to the robotic solution for the re-manufacturing and discuss how these parameters and constraints can be challenged.

3.1 Manual GTAW Welding

Hazard: Manual GTAW welding of aero engine compressor blades can expose workers to prolonged periods sitting down (Fig. 5 shows the manual weld deposition operation). Research has suggested that remaining seated for too long is detrimental to your health, regardless of how much exercise you do. Studies have linked excessive sitting with being overweight and obese, type-2 diabetes, some types of cancer, and premature death. Prolonged periods of sitting are thought to slow the metabolism, which affects the body's ability to regulate blood sugar, blood pressure and break down body fat [1].

Solution: The use of robotic systems for welding operations, removes the necessity for workers to endure prolonged periods sitting down. Furthermore robotic systems are more productive because they can operate in a continuous manner for long periods of time without stopping.

Fig. 5. Photograph of a skilled welding engineer performing a manual weld deposition operation on a compressor blade

3.2 Manual handling of wire welding units

Hazard: Heavy wire welding units or drums must be either transported or carried to the work location by each worker. The wire unit must then be manually loaded into the machine wire feed or manually mounted onto a spool feed. Electrical cables and welding leads (power, cooling and electrical earth) can become tripping hazards.

Solution: Automatic wire welding and loading units can be attached to the autonomous system eliminating the need for workers to carry and load the wire units. Elimination of tripping hazards is simply achieved by system design. Through enclosing the welding operations in a closed chamber or cell, hazardous trailing electrical cables are eliminated.

3.3 Wrist fatigue during welding

Hazard: Manual wire welding is a primary element in the re-manufacturing of high value compressor blades. The use of standard right or left handed welding techniques and conventional welding torch design, forces the worker to flex the wrist towards and load the little finger. CTS (Carpal tunnel syndrome) may also be associated with the use of straight welding whips for long periods [2].

Solution: Through use of a 6 DOF articulated robot which is capable of automatic wire feeding and welding allows for autonomous aerospace turbofan compressor blade re-manufacturing. In this manner, the robotic end effector, not the welder's wrist is bent.

3.4 Contact burns

Hazard: Welding engineers involved in the re-manufacturing processes can be subject to sparks and hot metal spatter generated by either a human error or defect in the weld bead. The severity of a burn injury is related to the power of the arc, the distance from the arc, and the duration of exposure.

Solution: The use of a robot arm will remove the welder from risk of burns by eliminating contact with the hot metal and sparks.

3.5 Eye damage (Arc eye)

Hazard: The use of high frequency constricted arc welding power supplies to deposit weld beads on aerospace turbofan compressor blades is hazards to human welding engineers. This is because the pulsed & constrained electrical arc technology creates a very intense electrical arc faster than the protective photosensitive (auto dimming) welding lenses or masks used for eye protection can react to the change in brightness.

Solution: Machine vision can operate as stand-alone system feeding information back to the system of a successful or failed output dependent on the criteria specified by the welding engineer throughout a program.

4 Robotics in re-manufacturing

The remanufacturing industry differs from the Original Equipment (OE) sector. It is primarily a 'service sector' and is subject to different market dynamics and regulatory environment. Across the globe, airlines, armed forces, corporations, cargo and charter operators combined, operate over 110,000 aircraft. So whilst in any one year, the world's aircraft manufacturer's build about 4,500 new airframes, there is a dynamic, operational and service-demanding supply chain keeping 110,000 aircraft flying safely and reliably, wherever they are. Engine overhaul is a huge area of remanufacturing (Fig. 6 shows an overhauled engine), currently work is outsourced to competitive third party bases e.g. Lufthansa Technik and independents like MTU and Vector Aerospace but also includes OEMS such as Rolls-Royce, GE and Pratt & Whitney [3].

Robots have traditionally been used and are well established within manufacturing environments. Generally they are confined to simple pick and place tasks with little decision making autonomy. However, the current trend with newly emerging lightweight and flexible robots is to develop fully autonomous capabilities. Thus, efforts are directed towards the mechanical design of such robots, control and automation techniques, locomotion techniques, intelligence and autonomy. A more specialized market is the operation of robotics. By closing of the loop between the vision system and the robotic welding arm this allows information from the vision system to be used by the robotic arm enabling autonomous operation. For re-manufacturing applications, this represents a significant advancement, as the robotic system can make decisions based on the information received from the vision system eliminating the need for a human to be involved in the process.

The aim of this specific prototype system will be to detect the incoming parts, assess the shape, profile and type, inspect the condition then move the robotic arm ensuring correct position for the weld to be conducted. This is of critical importance to the aerospace re-manufacturing industry as many parts consist of unique shapes, profiles and sizes. Not only will the automated process result in direct cost savings for industry, when combined with advanced real-time weld monitoring systems it will also allow non-destructive testing and component evaluation for system control during the welding process.

Fig. 6. Manual maintenance, repair and overhaul for aircraft engines.

The primary aim of the study is to produce a dynamic, high resolution stereo camera system with area matching software and autofocus capabilities for integration with automated welders. This system will enable real-time monitoring, inspection and repair of high-value aerospace components. Survival of the harsh environment will be a key factor. The system will have adjustable focus through the use of liquid lenses allowing it to be used on different types of materials and be capable of automatically working on different shaped components at different working distances, taking the technology beyond current commercially available systems.

The automated process will result in direct cost savings for industry and it will also allow a non-destructive test of component evaluation for system control during the welding process. The feasibility of this approach carries a high risk with a number of unknowns, including factors such as achieving the required speed in the stereo vision matching algorithm and if the automatic calibration techniques proposed will operate in practice with sufficient accuracy.

5 Modules of the autonomous re-manufacturing system to mirror human cognition

The automated system is to be constructed in modules to mirror human cognition which will allow operation of the autonomous re-manufacturing system. Each unit has its own modular capability. The inspection module dictates the automatic loading and unloading of blades, the automatic part recognition, selection of the weld program, weld torch with wire feed and work piece tooling block. The system automatically loads the part into the correct set of tooling, thus different types of blades can be continuously loaded and unloaded via the robot whilst the repair welds are undertaken. Three robust universal weld chill fixtures accommodate different parts to be welded (Fig. 7 shows an early system design). These will require resources including: supporting camera identification system, a profile camera system via imaging software, 3D weld monitoring system and dimensional scan equipment to monitor the weld process. This is later interfaced with the welding machine. A real-time weld evaluation data acquisition (DAQ) system has been developed to measure the HMS Inter-Pulse welding system [4], [5], this FPGA based DAQ system performs both power analysis and arc measurements. This module interfaces with the camera systems and weld controller to provide operator with visual confirmation of faults. Interfacing of the modules with software and development of GUI provides overall system control throughout.

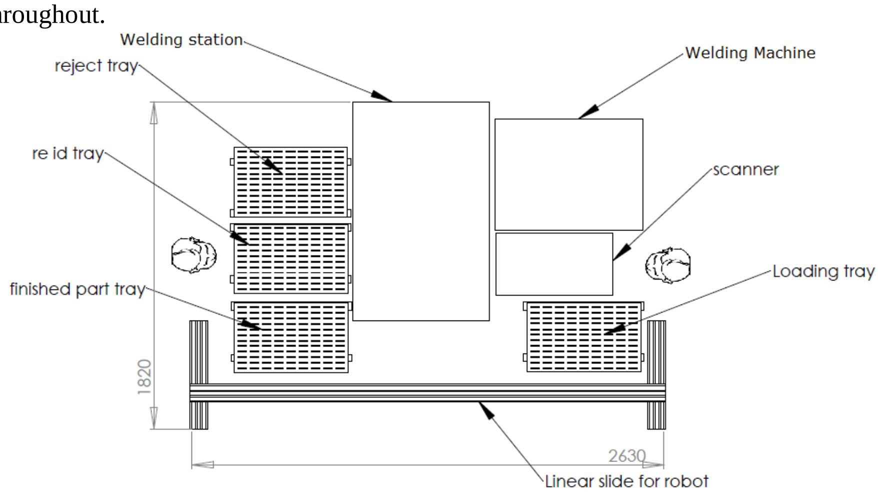

Fig. 7. Modules of the aerospace turbofan engine blade re-manufacturing system.

In the following section the main unit modules will be explained. Further adjustments are needed to fully incorporate the ergonomic considerations in existing manual GTAW processes for re-manufacturing, discussed in section 3.

5.1 6 DOF Articulated Robot

A 6 DOF robotic arm with rotating wrist will be use to move parts through the system to the main chassis (welding station) to carry out the welding operations. Modern lightweight and flexible robots carry out automated, repetitive and dangerous tasks with payloads of up to 5 kg. Processes for payloads less than 5Kg, such as picking, placing and testing, lend themselves well to modern lightweight robotic arm design.

With a working radius of up to 850mm, places everything within reach, freeing up operators' time to add value to other stages of the production. Modern lightweight robots are easy to program, fast to set up, collaborative and safe. Like other similar collaborative robots, they quickly achieve rapid industrial investment payback [6].

5.2 The Machine Vision Sensor

In order to guide the robotic arm a machine vision system with a very high frame rate and analogue camera configuration was considered. The analogue camera captures an image and stores it in its buffer. A signal is issued to the DAQ hardware which reads out the image. The DAQ converts and processes the data, then delivers it to the host PCI bus. The host can then analyse the image. The acquisition can be triggered externally or via the DAQ. High frame rates demand a high speed GPU computing based DAQ in order to process the video information in real-time. First tests performed showed that using single camera stereo was good enough because the pattern was simple and well defined which gives precise and fast measurements despite the use of a low resolution camera.

The use of a laser and optical filters tuned to the specific spectra of the welding power supply's electrical arc was used to reduce the intensity of light allowing image capture under any light conditions.

Key technology developments for engine overhaul are to maximize the productivity of this service network. A machine vision system which is interfaced with a robot effectively provides the "eyes" and cognition for the robot. The machine vision system equipped with the latest 3D algorithms and is able to detect weld defects and cracks and obtain depth information for objects.

5.3 GTAW Welding System.

Use of new welding processes and increased use of automation and robotics will take place slowly and gradually, only justified where the introduction creates significant gains in productivity or cost reduction. As such, these changes can be expected particularly in situations where skilled labour is short, where welding cells can be kept fully occupied or when customized, made to order components are needed [7].

Automated repetition of CLAMS data enables production of the correct weld deposition with high repeat ability but with the inability to respond to a change in dynamics or conditions. True response requires intelligence which has proven exceptionally challenging to develop when welding complex profiles (curves) and super alloy materials (heat input & distortion) now utilized by aerospace engine manufacturers with the GTAW technique.

The GTAW welding machine operation involves monitoring signals and generating commands over an interface; these signals are protected against welding current interference by galvanic isolation. Arc current measurements were performed at 46.875 KHz using a bespoke high speed phase current shunt sensor. Signal filtering is performed in real-time and the filter method selected was low-pass.

6 Conclusions

Advanced programming of robots, data interpretation from associated sensory and feedback systems required to mirror human input were considered for the development of a high value intelligent aerospace turbofan jet engine blade re-manufacturing system. Ergonomic considerations in existing manual GTAW processes for re-manufacturing were introduced in the design process, highlighting interaction between robotics and experienced welding engineers, towards construction of an autonomous aerospace turbofan jet engine blade re-manufacturing system.

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