Institution: The University of Manchester

Unit of Assessment: UoA 12b Mechanical, Aerospace and Manufacturing Engineering

Title of case study: Laser Cleaning for Aerospace Manufacturing

1. Summary of the impact

Research at the University of Manchester on laser cleaning of Ti alloys has resulted in practical implementation of the technology at Rolls-Royce for the automatic preparation of surfaces prior to electron beam welding. This has been applied to 24 different aero-engine component types including compressor drums across most current engine families. This has resulted in close to 100% ‘first time right’ aero-engine component welds. The technology is also being adopted by BAE Systems to replace chemical cleaning during airframe manufacture. The elimination of manual and chemical cleaning processes results in savings of several million pounds per annum.

2. Underpinning research

The impacts are based on research that took place in the Laser Processing Research Centre at The University of Manchester from 2003-2013. The key researchers involved in the research were:

- Professor Lin Li (2003-2013), PI and laser cleaning project leader.
- Dr Mark Turner (2003-2007), PhD student at The University of Manchester.
- Dr. David Whitehead (2003 – 2013). Senior Experimental Officer – laser processing.
- Dr Philip Crouse (2005-2007), Postdoctoral Research Associate, laser cleaning and modelling
- Dr. Wei Wuo (2010 – 2013, postdoctoral researcher, laser cleaning and in-process monitoring, instrumentation.
- Dr. Sundar Marimuthu (2009-2011), postdoctoral researcher, laser cleaning process development, and modelling.
- Dr. Zhu Liu (2003 – 2013), Senior Lecturer, Material Science.

As many contaminants, such as metal oxides, have vaporisation temperatures much higher than the substrate alloy and Ti-alloy is highly reactive to N_2 and O_2 at elevated temperatures (from 600^oC upwards), it is critical to demonstrate the total removal of contaminants without damaging the substrate. Through our research, laser beam interactions with various industrial contaminants and specific aerospace alloys have been understood, and a new laser cleaning process has been demonstrated and subsequently adopted by the aerospace industry.

In this research, three different lasers: CO_2, Nd:YAG and excimer were investigated to identify the basic process characteristics in laser removal of a variety of contaminants including synthetic oil, silicon grease and machining coolant, applied on Ti-6Al-4V, Ti-6Al-2Sn-4Zr-6Mo and IMI834 alloys, without damaging the substrates. Fundamental studies on how the lasers interact with these materials were carried out through both experimental investigations and theoretical modelling. We have shown that:

- The continuous wave CO_2 laser at 10.64 µm wavelength and nanosecond pulsed Nd:YAG laser at 1.06 µm wavelength were not suitable for cleaning aerospace components with the specific type of contaminants, for E-beam welding or diffusion bonding applications, because of their specific beam absorption characteristics (e.g. Nd:YAG laser is transparent to silicon grease) and thermal history (leading to excessive heat input to the substrate material if the contaminants are to be removed) [1,2,4].
- The excimer laser at 248 nm wavelength at 8-20 nm pulse lengths was the most suitable tool for the cleaning the contaminants without damaging the substrate alloys under specific operating parameters [3].
- The excimer laser removes organic contaminants mainly by photo-chemical ablation

mechanisms while oxide particle removal is by photo-thermal ablation [3].

- Electron beam welded components following excimer laser cleaning were shown to be defect free after excimer laser cleaning [3].
- We found the emission spectroscopy and probe beam reflection techniques can be applied to monitoring the laser cleaning process [5]. This has been further developed by the same research team using an acoustic monitoring technique in collaboration with Rolls-Royce and BAE System.

3. References to the research

At least five publications (on laser cleaning for electron beam welding) are in the leading journals, e.g. Applied Surface Science, several invited/keynote international conference presentations were made and a patent was generated from the research.

Key Publications

[1] M.Turner, M.J.J.Schmidt and L.Li, "Preliminary study into the effects of YAG laser processing of Titanium 6Al-4V alloy for potential aerospace component cleaning application", Applied Surface Science, 247, (2005), 623-630.. DOI 10.1016/j.apsusc.2005.01.097

[2] M.W.Turner, P.L.Crouse, L.Li and A.J.E.Smith, "Investigation into CO_2 laser cleaning of titanium alloys for gas-turbine component manufacture", *Applied Surface Science*, 252, (2006), 4798-4802. DOI 10.1016/j.apsusc.2005.06.061

[3] M.W. Turner, P.L.Crouse and L.Li, "Comparative interaction mechanisms for different laser systems with selected materials on titanium alloys", *Applied Surface Science*, 253, No.19, (2007), 7992-7997. DOI 10.1016/j.apsusc.2007.02.173

Other relevant publications

[4] M.W.Turner, P.L.Crouse and L.Li, "Comparison of mechanisms and effects of Nd:YAG and CO_2 laser cleaning of titanium alloys", *Applied Surface Science*, 252,No.13, (2006), 4792-4797. DOI 10.1016/j.apsusc.2005.06.050

[5] D.Whitehead, P.Crouse, M.Schmidt, L.Li, MW.Turner, A.J.E.Smith "Monitoring laser cleaning of titanium alloys by probe beam reflection and emission spectroscopy", *Applied Physics A-Material Science & Processing*, 93, Issue 1, (2008),123-127. DOI 10.1007/s00339-008-4643-7

4. Details of the impact

Context

Electron beam welding and diffusion bonding are typical joining processes (in the final stages of aero-engine assembly) used in the aerospace industries for a variety of components and structures. Insufficient bonding and defects such as porosity can occur if the surfaces are not perfectly clean from dirt, particles, oil/grease and machine coolants. The resultant cracking and porosity leads to quality assurance failure of these very expensive parts in this final stage of aero-engine manufacture.

Prior to our research, the practice in use for E-beam welding of aero-engine components was either manual cleaning (up to 10 different steps) using chemicals and abrasives or dipping the components into a bath of concentrated HF (hydrofluoric acid) that is highly corrosive and hazardous, with chemical residuals sometimes becoming trapped (e.g. HF) in the material [A] .

Our research has shown that laser cleaning offers great advantages eliminating the use of chemicals and allowing the process to be fully automated and over 20 times faster [A]. The new technology allows precise control of the process, so that all contaminants are removed, without damage to the substrate surface.

Pathways to Impact

The research work was carried out in collaboration with Rolls-Royce (since 2003) and later (since 2009) with BAE Systems. The companies participated in all stages of the R&D (monthly review meetings), provided the test materials, process requirements, welding and diffusion bonding of laser cleaned components, and testing of laser cleaned specimens and components to industrial standards [A,B]. Rolls-Royce subsequently certified and implemented the technology. BAE Systems is also taking up the technology for diffusion bonding surface preparation.

This work was originally funded by Rolls-Royce (CASE studentship) and the Northwest Science Council (N0003200) with over £1m. Following the successful application of the technique at Rolls-Royce since 2008, major funding from industry (Rolls-Royce, BAE Systems) and EPSRC and TSB of around £2m was granted (SAMULET project) to further develop the laser cleaning process for diffusion bonding applications (2009-2013).

Reach and Significance of the Impact

The impact of our research is demonstrated by its adoption and use by the leading UK aerospace company Rolls-Royce – globally the second largest manufacturer of aero-engines. In addition BAE Systems is also now adopting the technology.

Rolls-Royce began introducing the laser cleaning technology, developed through our research, for E-beam welding of aero engine components in 2008. By May 2013, Rolls-Royce had approved 24 different aero-engine components such as compressor drums in almost all the current engine families such as Trent 700, using the laser cleaning technology in the manufacture of commercial aero-engines [A]. The technology has shown improved productivity and reduced failure rate. The first time right rate using chemical methods was 82-90% and has improved significantly utilising our new laser cleaning method. In his statement [A] the global process owner for laser processes at Rolls-Royce confirms *"This automatic laser cleaning process has replaced previous manual chemical cleaning of parts for electron beam welding with significant improvements in productivity and first time right*."

The economic impacts are multiple including cost savings in reducing scraps at this final stage of the aero engine assembly, estimated at several millions of £ per year and elimination of the use of harmful chemicals and their disposal, estimated at a few £ million per year. In 2013, a new in-process monitoring system, developed at the University of Manchester, was installed at Rolls-Royce for the monitoring of the laser cleaning process [A].

Following the successful use of laser cleaning of Ti alloys in welding, the research has been further developed (2009-2013) for diffusion bonding of a wide variety of aerospace products. The diffusion bonding of Trent 900 fan blades at Rolls-Royce, after laser cleaning, has passed the quality criteria. A modelling tool has been delivered to Rolls-Royce and BAE Systems for laser cleaning process evaluations. This tool has been successfully utilised by BAE Systems to aid their decision-making with regards to the installation of a laser cleaning system in the company [B]. As a result the laser cleaning technology is now being commissioned by BAE Systems for military aircraft manufacture, with the diffusion process replacing chemical cleaning [B].

5. Sources to corroborate the impact

[A] Letter from Global Process Owner – Laser Processes, Rolls-Royce plc corroborating deployment of laser cleaning process by Rolls Royce, replacing previous manual cleaning process, and procurement of patented monitoring techniques.

[B] Letter from SAMULET Project Manager, BAE Systems corroborating transitioning of laser cleaning process by BAE Systems and use of modelling tool for evaluation of performance.