Institution: University of Wolverhampton (UoW)

Unit of Assessment: UoA12

Title of case study: Affordable Diffusion Bonding (ADB) of laminate sheet to produce micro-cellular structures relevant for ultra-lightweighting and high efficiency thermal and chemical devices for the aerospace, automotive, medical, chemical manufacturing sectors.

1. Summary of the impact (indicative maximum 100 words)

Diffusion bonding (DB) is well-known for producing structured materials with fine scale features and is a critical technology for high efficiency reactors, e.g. heat exchangers and fuel cells, but currently equipment is slow and expensive (and there are size limitations to the 'assemblies' that can be built). The University has researched and developed, with industry partners, a rapid affordable diffusion bonding (ADB) process involving direct heating to provide appropriate temperature and stress states and utilising flexible ultra-insulation (vacuum) for pressing titanium (and now aluminium) sheets together. The process operates at low stresses thus avoiding 'channel' collapse. Investment is taking place in the partner companies to exploit the technology. A breakthrough has been achieved in the chemical machining of three dimensional structures for laminar flow technology assemblies in aluminium and titanium, that can be built by ADB.

2. Underpinning research (indicative maximum 500 words)

The basis for ADB stemmed from initial needs to reduce the high cost of machinery and the long hours required to achieve diffusion bonds. Our research proved that it was possible to eliminate the large expensive pressure vessels, necessary in the conventional DB process, and, by using local heating; good bonds could be achieved in less than a minute [1]. The principal researchers associated with the case study are Professor F.R.Hall (joined the University 1998, left 31/07/2013) and P.J.Spence (joined the University 2002). Co-investigator is N Emekwuru (joined the University 2009).

The research led to work on a lower capital equipment cost process and a test rig demonstrator for the bonding process with Ajax Tocco Ltd (Birmingham), UNIPART (Coventry), Rolls-Royce, BAe and UTC HS Marston (Wolverhampton) (2007 to date) which shows its applicability to other areas of manufacture, apart from aerospace components [2]. The Department of Trade and Industry (DTI) through the Advanced Technology Exploitation Programme (ATEP) provided funding for the work [3]. A patent for the process is pending (detail is given in part 4 of this case study). The University research input was the simulation analysis and test validation of the thermo-mechanical parameters and their application to bonding titanium. The University also devised the closed loop feedback control, and the development of a high temperature vacuum insulation environment, which (being very thin) enabled efficient coupling of the induction heating equipment from outside the vacuum region (no contact heating is required thus eliminating contamination issues).

Research through a KTP with Advanced Chemical Etching (ACE) Ltd. [4], has led to the development and introduction of new etching chemistries for the chemical machining of three dimensional structures for laminar flow technology assemblies in aluminium and titanium used in the Aerospace, Automotive and Oil industries for fuel cell and heat exchanger type products. These complex plates are joined together using brazing or diffusion bonds. The intricate plates once bonded form fine complex channel arrays to carry both fluids and or gasses. The University, ACE and Ajax Tocco are collaborating to match ADB to the precision laminates. This will be particularly advantageous for larger structures (a limitation with conventional technology).

Linked to this is work on a MoD Shrivenham contract: Development of Innovative Energy Absorbing Light Weight Armour (Confidential) with BAE Systems. The University was responsible for the numerical simulation; new laminate designs were evaluated using the University supercomputer of high speed penetration by projectiles, up to 2 km/s speeds, from a gas gun. [5]. A range of cell structure designs were analysed, this included stability of impact behaviours against off-axis perturbation and effects. The work is concerned with development of new armour systems for lightweight agile vehicles. Promising results were obtained with multi-material laminate

structures to defeat high speed projectiles. These structures would be suitable for manufacture using the ADB technique to be successful commercially.
The research undertaken has involved extensive use of numerical modelling and more recent simulations have shown that the knowledge gained in the ADB research, i.e. utilising localised heating of the workpiece, can be extended to superplastic forming (SPF), to offer a more cost-effective approach to SPF especially when combined with ADB. The research offers a unique approach in SPF by applying selective heating whilst keeping dies at a lower temperature (contact friction is reduced) [6].

3. References to the research (indicative maximum of six references)

1. Peter J. Spence, Frank R. Hall , Nwabueze Emekwuru, "Preliminary study of improving the speed and cost of diffusion bonding of metal sheets", Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Published online before print September 2, 2013, doi: 10.1177/0954405413498584 **(Output 1 for Spence)**
2. Richard Hall, Julian Spence, Chris Kenward, Dave Scott, Dave Townsend, Midlands Aerospace Alliance presentation, June 2008. http://www.lightweighting.net/data1/PROJECTS/21/REFS/5Jun08ReportPresentation.ppt
3. ATEP 1 *Aerospace Technology Exploitation Programme*) funded (*internal project number C5136), Oct 2006 to Apr 2008)"Affordable Diffusion Bonding*.
4. KTP Advanced Chemical Etching Ltd (no. 8230).
5. IN CONFIDENCE COMPETITION OF IDEAS "Innovative Lightweight Energy Absorbing Armour" Contract No: RT/COM/5/006 Project Progress Report.
6. Michal Mis, Richard Hall, Julian Spence, Nwabueze Emekwuru, Kevin Kibble, (2013), Numerical study of radiation and temperature phenomena for improved super-plastic sheet metal forming, Materials Science Forum, Vol. 735, pp. 170-179. **(Output 2 for Spence)**

4. Details of the impact (indicative maximum 750 words)

Key step 1 was the **ATEP I project: (laminate technology R&D).** Core income of £64k (ATEP1+2), with match funding from the partners (total ~£300k) by the "Midlands Aerospace Alliance" and involving UTC HS Marstons, BAe, Rolls-Royce, AJAX Tocco and UEES**:** Development of the affordable diffusion bonding process. This ATEP project demonstrated for the first time localised induction heating can create a high speed diffusion bond (for Ti-6Al-4V), within 30 seconds; traditional methods take at least 8 hours) utilising an innovative new technique, involving vacuum insulation [1]. A patent is pending for detailing the technology developed in the ATEP [2].

BURCAS (KTP): "Improving the brazing process at Burcas knives division". The University supervised this KTP and collaborated with the original ATEP (DB) partner AJAX Tocco in developing the brazing process, defining and proposing machinery for improved and faster (and cheaper) brazing of large (5 m) industrial knives as well as for improved heat treatment of cutting edges, through localised induction heating technology. This KTP extended the research knowledge of selected localised heating necessary for the ADB process [3].

Key step 2 concerned the reputation gained by the University in ATEP 1 and led to further work in the development, design and manufacture of materials based on laminated layered manufacture, i.e. the **MoD funded project "Competition of Ideas"** in collaboration with BAe. This project involved the design of cellular materials, by numerical simulation, for impact energy absorption and based upon DB/SPF. This included the development of different geometries and topologies for the cellular structure and their behaviour under conditions of high speed impact [4].

Key step 3 was a second **ATEP 2 project TASC:** Advanced Surface Cooler technology development with HS Marston, Rolls-Royce, and ACE Ltd. (Feb 2009 to Apr 2011) [5]. In particular the collaboration with ACE Ltd resulted in a KTP project (no. 8230). **Advanced Chemical Etching** (**ACE) Ltd (laminate technology work):** To use advanced chemical etching linked to the affordable diffusion bonding process to manufacture highly intricate structures for various applications, aerospace, automotive, and other high value manufacturing.

ACE Ltd (KTP): The aim of the project was to improve the existing chemical etching process for aluminium and titanium components used in aerospace applications. This derived from working

with H S Marston (UTC) on developing shim plates for compact heat exchanger units requiring micro channels. The result of the project is new chemical etching processes capable of consistent and repeatable high quality component product. The new technology has proved to be 4 to 5 times quicker and capable of extending the life of chemicals used tenfold from the existing process. With significant confidence in the new processes, ACE has invested extensively both in buildings and new machinery, supported by increased sales and marketing activity, as well as increased investment in R&D. The value of KTP to ACE has been in changing the mentality within the company to use 'Science' in their everyday business dealings [6]

The work undertaken has significantly enhanced the capability of ACE for the processing of new technology components in titanium and aluminium alloys which had previously been out of reach. Laminar Plate Technology is in increasing demand for new generation developments of miniature heat exchangers for cooling electronic devices to light-weight aero engine fluid heat exchanger assemblies not available before. This development has had a significant impact on the continuing success of ACE's business both in the UK and internationally to give the company the confidence to undertake a recent substantial expansion of the business [6].

Linked to this research and development has been the need to investigate alternative methods of bonding leading to a further collaboration using the selective DB technology, developed by Ajax Tocco and the University, in identifying a significant practical application for the oil industry to use these new chemical etching processes [6, 7]. .

Further investments have been obtained and work is on-going to complete the development of the ADB process, with AJAX TOCCO, ACE and The University (HEIF-Fellow, Senior Research Fellow, and Research Fellow-in MidSim to support this R&D). Ajax TOCCO International Ltd are still actively involved with developing the diffusion bonding process, in collaboration with the University of Wolverhampton, and doing this with equipment located at the Saltley site of Ajax TOCCO International Ltd. Currently this includes the investigation of a titanium bond for a part to be used in the oil and gas industry. In addition they are considering how to do bonding on somewhat larger parts but in an aluminium alloy [8].

5. Sources to corroborate the impact (indicative maximum of 10 references)

1. ATEP I (*Aerospace Technology Exploitation Programme*) funded (*internal project number) C5136, Oct 2006 to Apr 2008)"Affordable Diffusion Bonding http://www.lightweighting.net/data1/PROJECTS/21/REFS/5Jun08ReportPresentation.ppt - to Midlands Aerospace Alliance (who organised the ATEP)*
2. Filing of World patent for DB process http://patentscope.wipo.int/search/en/WO2011012906 full Status copied to http://www.lightweighting.net/data1/JULIAN/REF_Review/WIPO_Status_Sep2012_iasr.pdf .
3 Burcas KTP 7503, "To investigate the existing metal bonding manual process, devise an automated replacement, and embed technologies to improve productivity." July 2009 to October 2011. Final Report: http://www.lightweighting.net/data1/JULIAN/REF_Review/BURCAS_KTP_Project%20Report%20Draft%201.doc
4. http://www.lightweighting.net/data1/JULIAN/REF_Review/COI_REPORT.doc COMPETITION OF IDEAS "Innovative Lightweight Energy Absorbing Armour" Contract No: RT/COM/5/006 Project Progress Report. Confidential.
5. ATEP2 TASC: *Advanced Surface Cooler technology development with HS Marston, Rolls-Royce, and ACE Ltd.* Funded by RDA, Midlands Aerospace Alliance.
6. October 2012 Personal communication Alan Rollason Chairman ACE, Telford, wants to invest further in laminate technology with the University as partner.
6. Letter of support providing details from Alan Rollason Chairman, Advanced Chemical Etching, Unit 31-34 Hortonwood 33, Telford, TF1 7EX, Tel: 01952416666, October 2013.
7. Letter of support, providing details, Chris Kenward, Process Engineering Manager, Ajax Tocco International Ltd, Saltley, Birmingham, B8 1BGL, Tel. 0121 - 322 – 8028.
8. Philip Hyland, Director of Operations, Ajax Tocco International Ltd, Saltley, Birmingham, B8 1BGL, email correspondence to J Spence 15-10-2013.