Institution: The Open University		
Unit of Assessment: B12 Engineering		
Title of case study: Manufacturing new components used in satellites, antiviral (Covid-19) sterilisation systems, and developing novel technologies for the manufacturers of microelectronics, jet engines, material processing and F1 racing cars		
Period when the underpinning research was undertaken: 2013-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Dr Amir Shirzadi	Senior Lecturer in Materials Engineering	2009-present
Period when the claimed impact occurred: 2013-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Novel technologies developed by The Open University have enabled high-precision and atomic level joining of advanced alloys that cannot be welded using conventional methods. Exemplary applications included:

- reducing faults in power transistors fitted in millions of electric cars for Mitsubishi;
- developing and fabricating new key components for X-ray sterilisers of the COVID-19 vaccines in the USA;
- manufacturing ultra-high-speed turbine and compressor rotors for the latest generation of satellites of the UK/European Space Agency;
- developed the world's first Auto Ejection Melt Spinner which is now on the market in Germany;
- development of new technologies for the manufacturers of aeroengine heat exchangers and F1 racing cars in the UK.

2. Underpinning research

In the last two decades, the development of advanced alloys and composites with superior mechanical properties (e.g. Titanium and Aluminium) has underpinned the rapid progress of engineered and new manufactured products particularly for the aerospace, transport and electronic industries. However, advanced engineering components require not only better materials but also new joining or welding processes. Traditional fusion welding processes are unsuitable for joining dissimilar and high precision components due to the high temperatures. In such cases, the components may be joined below their melting point by Diffusion Bonding.

Dr Amir **Shirzadi**, a Senior Lecturer at the Open University, established the Open University's Diffusion Bonding Lab in 2013, which is the only one among all UK universities. The following research underpins the impact described.

2.1 Gallium-Assisted Diffusing Bonding – **[O1 - O5]**

The main barrier to successful solid-state diffusion bonding is the presence of a stable surface oxide. Hence, developing new approaches to disrupt the oxide layer would lead to significant improvements in bond integrity. *Gallium-Assisted Diffusing Bonding* is a solid-state process, based on removing and/or modifying the nanometre thick surface oxides prior to the bonding cycle. The development of a suitable brazing technique essentially incorporates an in-depth understanding of the interfacial chemical reactions and identifying the mechanisms of these reactions, which can be used to optimize the bonding conditions, and hence achieve desirable properties of the joints.

Shirzadi's work has investigated methods for bonding high-performance materials such as titanium and aluminium alloys to a variety of other materials, and to themselves and these bonds were then evaluated by microstructural examinations and severe mechanical testing of the samples.

Research to investigate bonding stainless steel and titanium resulted in bonded samples at 92% the tensile strength of the original titanium **[O1]**. An experiment to bond titanium alloy (Ti-64) with Ti-64 metal matrix composite was successfully achieved using diffusion bonding.

Metallographic and Electron backscatter diffraction (EBSD) studies, as well as bending and microhardness tests across the bonds demonstrated joint integrity and the lack of microstructure alteration in the vicinity of the joint showed there was no degradation **[O2]**.

Similarly, a new method for liquid-phase bonding of copper plates to an aluminium nitride (AlN) substrate was developed for Mitsubishi, using a newly developed proprietary interlayer composed of titanium and silver powders. The microstructures of samples were analysed by scanning electron microscopy and energy-dispersive X-ray spectroscopy, and an ultrasonic flaw detector was used to assess joint integrity. The optimum composition of the Ti–Ag brazing alloy for producing defect-free joints was determined **[O3]**.

In collaboration with India’s Department of Atomic Energy (DAE) stainless steel and titanium were bonded using vacuum brazing and gallium-assisted diffusion bonding processes for an undisclosed application **[O1, O4]**.

Fuel/Oil Heat Exchangers (FOHE) are critical components of modern jet engines. Their primary function is to cool the hot engine lubrication oil while heating the cold fuel coming from the fuel tank before it enters the combustion chamber. The fuel heating increases the engine efficiency substantially by recuperating the waste heat from the oil into the fuel. The fuel/oil pressures and temperatures required are increasing with the development of more efficient jet engines. *Gallium-Assisted Diffusion Bonding* is used to join stacks of aluminium plates containing fluid flow channels; without the weaknesses and limitations inherent in traditional brazing. **Shirzadi’s** research identified a new technology for manufacturing more efficient and lighter Fuel/Oil Heat Exchangers than conventional shell and tube ones with tensile strength comparable to the parent alloy **[O5]**.

2.2 Invention of Auto Ejection Melt Spinning (AEMS) **[O6]**

Melt spinning is a method used for rapid solidification of certain alloys mainly to obtain completely non-crystalline ribbons, *i.e.* amorphous or so-called “metallic glasses”, that cannot be fabricated using conventional continuous casting processes. Depending on the spinning conditions extremely high cooling rates, sufficient to obtain amorphous structures, can be achieved (*e.g.* tens of thousands of centigrade per second). In this process, first an alloy is melted inside a crucible and then an inert gas is used to flush out the melt through a nozzle, located in the bottom of the crucible, straight onto a rotating copper wheel where it solidifies instantaneously. In the course of developing a new process to manufacture ultra-thin cobalt-based ribbons, Dr **Shirzadi** identified Melt Spinning as the only viable option. One drawback of conventional laboratory melt spinning processes is the need for a skilled operator to monitor the melt temperature and/or manually release the ejection gas at the right moment. Failure or error results in expensive waste. **Shirzadi’s** 3-year long project led to a new variant of Melt Spinning process which does not require a skilled operator; hence it substantially reduced the uncertainties associated with temperature measurement and human error **[O6]**. This work underpinned the commercial development of the world’s first Auto Ejection Melt Spinner by a German company in less than 12 months.

3. References to the research

O1. **Shirzadi, A.A**., Laik, A., Tewari, R., Orsborn, J., and Dey G.K. (2018) ‘Gallium-assisted diffusion bonding of stainless steel to titanium; microstructural evolution and bond strength’ *Materialia*, 4, pp. 115-126. https://doi.org/10.1016/j.mtla.2018.09.009. Blind peer reviewed.

O2. Prikhodko, S.V., Savvakin, D.G., Markovsky, P.E., Stasuk, O.O., Penney, J., **Shirzadi**, **A.A**., Davies, P.D., and Davies, H.M. (2020) ‘Diffusion bonding of TiC or TiB reinforced Ti–6Al–4V matrix composites to conventional Ti–6Al–4V alloy’, (2020) *Science and Technology of Welding and Joining***,** 25 (6), pp, 518-524. https://doi.org/10.1080/13621718.2020.1751403. Blind peer reviewed.

O3. Terasaki, N., Ohashi, T., Nagatomo, Y., Kuromitsu, Y., and **Shirzadi A.A.** (2019) ‘A new method for liquid-phase bonding of copper plates to aluminum nitride (AlN) substrates used in high power modules’ *Journal of Materials Science: Materials in Electronics*, Volume 30, Issue 7, pp 6552–6555. https://doi.org/10.1007/s10854-019-00961-6. Blind peer reviewed.

O4. Laik A., **Shirzadi A.A.**, Sharma G., Tewari R., Jayakumar T., and Dey G.K. (2015) **'**Microstructure and interfacial reactions during vacuum brazing of stainless steel to titanium using Ag-28%Cu Alloy, Metallurgical and Materials Transactions A', Vol. 46, No. 2, pp. 771-782. https://doi.org/10.1007/s11661-014-2671-9. Blind peer reviewed.

O5. **Shirzadi A.A**. (2019) 'Ultra-High Pressure Laminated Aluminium Heat Exchangers for Jet Engines'**,** International Congress *Aluminium Heat Exchanger Technologies* Düsseldorf, May 2019, DVS 352, pp. 16-18. Available from Semantic Scholar. Blind peer reviewed.

O6. **Shirzadi A.A.**, Kozieł T., Cios G., & Bała P. (2019) 'Development of Auto Ejection Melt Spinning (AEMS) and its application in fabrication of cobalt-based ribbons', *Journal of Materials Processing Technology*. Vol. 264, pp. 377-381. https://doi.org/10.1016/j.jmatprotec.2018.09.028. Blind peer reviewed.

This research programme was supported by funding from Welding Alloys Group, Innovate UK, EPSRC, Technology Strategy Board, Mitsubishi Corporation and the new techniques described in these publications have had significant impact on manufacturing processes.

4. Details of the impact

OU research described in this impact case study contributed to the productivity and performance of seven international businesses in the UK, Germany, France, Japan and USA. The vehicles for achieving these impacts have been through collaborations based on Dr **Shirzadi's** work on joining high strength materials, such as titanium alloys and nickel superalloys, as well as functional materials. He has also developed novel methods for materials and component processes. Examples of impact on manufacturing underpinned by the OU research are as follows:

4.1 Mitsubishi Materials (Japan) has collaborated on various projects with Dr **Shirzadi** including building on research that investigates the manufacture and performance of diffusion bonded products mainly so-called *Direct Bonded Aluminium* (DBA) substrates **[O1, O3]**.

The work included investigating and improving performance of specific Mitsubishi components. Although they operated at high reliability, this was not considered adequate for functionality under the specific conditions. **Dr Shirzadi's** research methods and Diffusion Bonding techniques were applied to the DBA-based components supplied by Mitsubishi Materials to eclectic car and train manufacturers. The work showed formation of a continuous and defect-free layer at the copper/aluminium nitride interface was essential for achieving high integrity joints. By applying the new techniques **Shirzadi** was able to identify the problems in construction, reduce susceptibility to cracks and increase reliability **[C1, O3]**. Mitsubishi noted that this is "*helping us to improve our manufacturing process"* and promotes the component by identifying the robust joins examined in the research **[C1]**. The DBA is a key component in every electric car or train with an annual market worth USD500,000,000. Mitsubishi [text removed for publication] Materials has a substantial percentage [text removed for publication] of the DBA global market **[C1]**.

4.2 Atlas Technologies (USA) makes enhanced vacuum technology products for energy, space, medicine, physics, quantum computing, and commodity preservation. A long-term collaboration with Atlas Technologies has led to development of new technologies and products. In July 2020, The Open University was approached by Atlas Technologies which had an urgent need of diffusion bonded bi-metal adapters for their high-power X-ray tubes. Such X-ray tubes are needed for sterilising blood products and vaccines. Demand had increased exponentially as the adapters are used in the development of COVID-19 vaccines **[C2]**. The fabrication of high vacuum adapters is a challenging task which was done by explosive welding with a lead time of 6-12 months. In addition to the lengthy leading time, the explosive welded adapters frequently suffer from vacuum leak.

Work in **Shirzadi's** Diffusion Bonding lab led to fabrication of new adapters at the required standards, which only took five months to develop. A set of six full-size adapters were manufactured by Dr **Shirzadi** and sent to Atlas Technologies on 26 November 2020 for installation and final testing on X-ray tubes. By 31 December 2020, Atlas committed to deploying the new adapters for sterilisation of transfused blood from virus pathogens and vaccine production, which would not have been possible before. The Vice President of Atlas Technologies noted that "*Dr **Shirzadi** has successfully produced full-size aluminium/stainless steel metal adaptors based on one of his inventions on joining un-weldable alloys. The helium leak tests as well as the sub-zero and high temperature endurance tests carried out on these adaptors have exceeded our expectation limits"* **[C2]**.

4.3 OFTTECH (UK/ESA): The European Space Agency (ESA) has commissioned OFTTECH to design and build ultra-high-speed rotors (250,000 RPM) operating at minus 233 °C in the latest generation of satellites. The UK company identified the OU's Diffusion Bonding research and facilities as the only option to fabricate the rotors. Four full-size sets, each set comprising one turbine and one compressor, were made by Dr **Shirzadi** at the OU's Lab, building on research investigating the bonding of titanium **[O1, O2]**. All four sets were tested by OFTTECH and passed on to the manufacturer of satellite cryogenic heat exchangers. Manager of OFTTech confirms the impact on the company: "*The ability to manufacture miniature components has given us a major advantage over all other European competitors, as well as enabling us to keep the entire manufacture inhouse […] such enhanced components enhances the UK's global position in the space sector"* **[C3]**.

4.4 Meggitt Co. (UK) with GBP2.2 billion turnover is one of the main manufacturers of the heat exchangers for jet engines and aircraft braking systems. Dr **Shirzadi** developed a method for diffusion bonding aluminium plates (containing cooling channels) for Meggitt as a part of a ~GBP1,000,000 project co-funded by Innovate UK. The OU was the only academic partner and in charge of diffusion bonding the heat exchangers. The outcome of the project, in which the OU played a seminal role, has led to GBP7,460,000 project on diffusion-bonded thermal systems for the next generation of Ultra High Bypass Ratio (UHBR) jet engines, co-funded by Meggitt and Innovate UK **[C4**, pp.1-6; **C5]**.

4.5 Edmund Buehler GmbH (Germany): Dr **Shirzadi's** invention of Auto Ejection Melt Spinning **[O6]** provided a novel solution for a long-lasting problem associated with melt-spinning process. As a result of the new process the repeatability of the process is improved due to reduced human error **[C8]**. The new method was independently checked, and its capability was verified in 2019 by a renown German manufacturer of melt spinners, Edmund Buehler GmbH. Since then Edmund Buehler developed and marketed the world's first Auto Ejection Melt Spinner branded as PA 500 **[C6, C7,** p.2**]**.

4.6 Red Bull F1 Technology (UK): THE OU's advanced joining and manufacturing technologies have been applied in developing racing car. Dr **Shirzadi** worked with the F1 racing car manufacturer on two different projects helping the company develop novel processes for fabrication of the [text removed for publication] parts [text removed for publication] **[C8]**.

5. Sources to corroborate the impact

C1. Testimonial from Assistant Director of Technology Division, Mitsubishi Material Corporation and Mitsubishi's website on the jointly developed technology.
C2. Testimonial from Vice President, Atlas Technologies & picture of component.
C3. Testimonial from Manager, OFTTech Ltd.
C4. Project summary and impacts- Aerospace Technology Institute.
C5. Testimonial letter from Meggitt Control Systems.
C6. Testimonial from General Manager, Edmund Buhler GmbH.
C7. Edmund Buhler brochure of the first Auto Ejection Melt Spinner.
C8. Testimonial letters from Red Bull F1 Technology's Thermal Management Engineer (p. 1) and Group Leader -R&D Projects Mechanical Development (p.2).