EPSRC Centre for Innovative Manufacturing in
LASER-BASED PRODUCTION PROCESSES

ANNUAL REPORT 2014 2015

Centre

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Introduction

Laser-based manufacturing is a global multi-billion dollar industry with significant business opportunities. The past 25 years have seen industrial lasers replace conventional tools in many diverse areas of manufacture, enabling increased productivity, functionality and quality.

The EPSRC Innovative Manufacturing Centre in Laser-based Production Processes is working to increase the uptake of laser-based manufacturing through a wide-ranging programme of coordinated research and network building activities, enabling significant business growth opportunities, stimulating the broader UK community, providing leadership in the development of UK public policy, providing access to infrastructure for SMEs, and education and training for industry.

Executive Summary

Our second Annual Report provides an overview of the research, innovation and outreach happening in the EPSRC Centre for Innovative Manufacturing in Laser-based Production Processes. In this report we are proud to highlight activities and achievements from the first two years of operation, and outline our plans for future years.

Our vision is to *exploit the unique features of laser light and the experience of our world-leading team, to unlock manufacturing innovation and deliver ground-breaking industrial impact in key areas of the UK economy.* To realise this vision we are focusing on science-based research, drawing on our considerable depth and breadth in physics, materials science, and mechanical/electrical/photonics engineering at the five partner universities to deliver innovative laser process and hardware solutions, thereby enabling the creation of high-impact laser-based production process and machine technologies.

The academic team consists of 16 academic staff, 15 RAs and 8 PhD students supplemented by the excellent support and important advice we have received from both our industrial advisory group and our independent steering group, which between them provide input from a total of 44 different companies and other independent organisations.

To date we have co-funded, with our industrial collaborators, a total of 21 projects, led by 13 different Principal Investigators across the 5 universities. Seeking to implement our strategy of combining laser material interaction fundamentals with advanced materials science to underpin the development and optimisation of laser-based manufacturing processes,

we have initiated projects across a wide range of laser interaction timescales (from picosecond pulsed to continuous lasers) that seek to characterise basic laser-material interactions at a fundamental level, whilst solving specific manufacturing challenges. A key aim is to enable robust transfer of optimised process conditions between different machines, a capability that is essential for implementing highly-automated, reliable, high yield component manufacture.

Key research highlights this year include the development of a miniaturised GHz frame rate holographic imaging system and testing of this with ultra-short pulsed laser processes including the welding of glass to metal; the manufacture of well-controlled high friction surfaces onto marine engine components; the development of a phenomenological model for laser powder bed processes, essential to understand and compensate machine-to-machine variability with powder bed additive manufacturing; and the demonstration of improved strength dissimilar welding (steel to aluminium) by pre-processing with a pulsed laser.

Our geographic spread brings its own challenges but we maintain good communication by frequent visits between sites, supplemented by the use of video and teleconferencing. In particular we have recognised the importance of providing the RAs employed by the Centre with appropriate networking opportunities by creating a series of events for Research Associates from across the Centre to come together for 1-2 days at a time, to discuss their research, and interact with each other and industrial collaborators. These networking opportunities have delivered two seedcorn projects, initiated and led by the Centre's RAs working across the University partners. These projects are already delivering exciting results, with key publications and larger projects likely in the next year.

Our Outreach Activity is focused on building links to the overall UK industrial and academic communities beyond the cohort of our collaborators and working with them to develop a National Strategy for Laser-based Manufacturing. Building on the work producing the UK Roadmap last year we are now (jointly with AILU, Association of Industrial Laser Users) constituting a National Strategy Working group to develop recommendations that will provide a framework for researchers, industry and funding agencies to increase the exploitation of laser processes and support UK manufacturing.

Our future plans include projects on:

- applying the holographic imaging system to investigate the dynamics of a range of processes
- welding, including of ultra-thin materials - and of nonlinear crystals to create novel nonlinear optical devices
- laser beam shaping – applications to welding; hybrid welding; cutting
- high precision machining of fibre-end components for medical applications
- laser development – 2 μm short pulsed; high brightness laser diodes
- development of laser-based techniques for optical systems fabrication – to replace manual construction and alignment approaches for lasers and other complex optical components

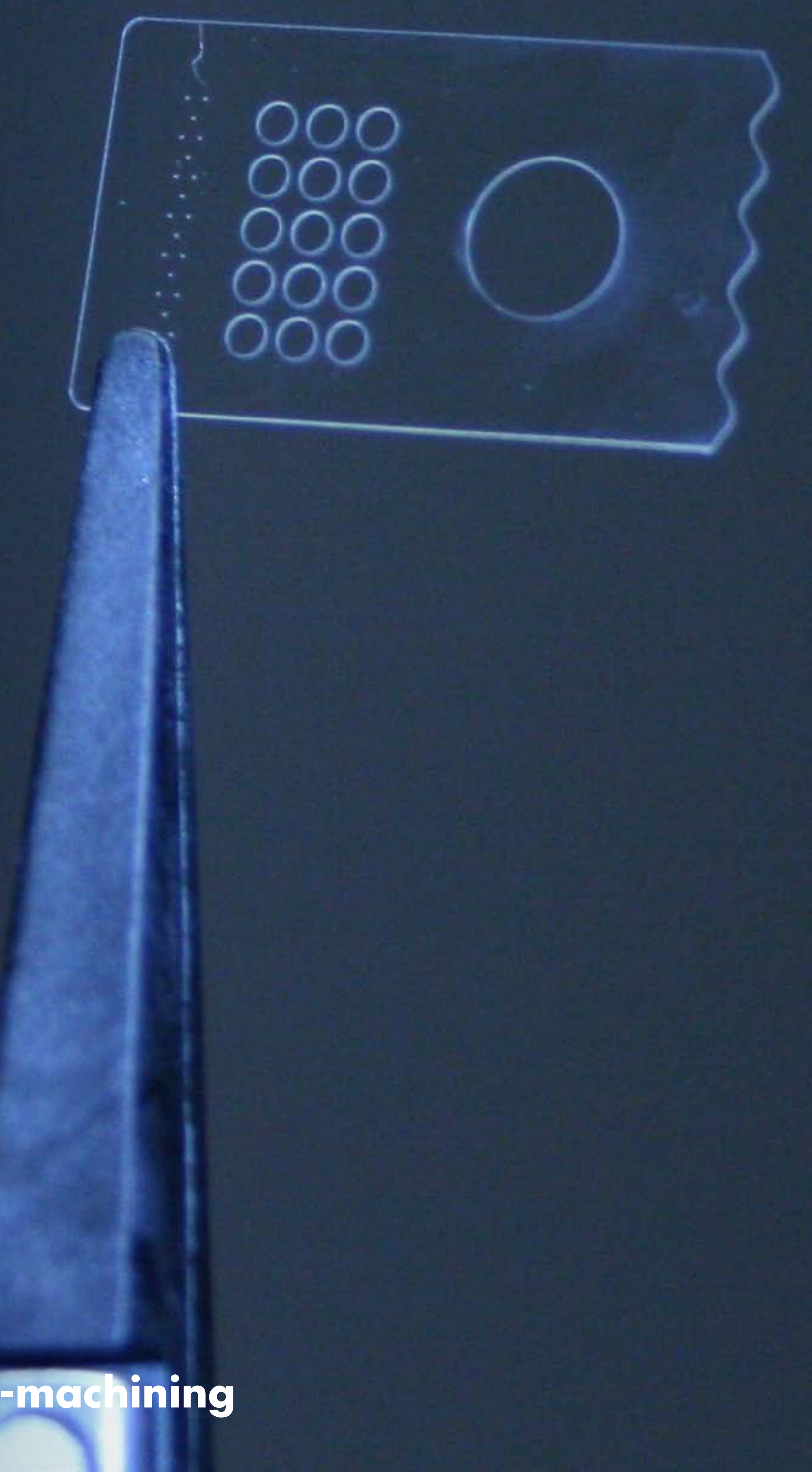
We gratefully acknowledge the support of all those engaged with the Centre, both the dedicated academic team and our highly supportive (and challenging!) industrial partners.

Professor Duncan Hand
Centre irector

Professor Len Cooke
Chair of the Independent Steering Group

Micro-Machining

There are increasing manufacturing applications for laser processing at micron-scale resolution, including material removal, surface and bulk structuring, joining and surface texturing, smoothing and polishing. Our research in this area covers the fundamentals of laser ablation and melt flow on the micro scale on a range of different materials using pulse lengths from the nanosecond to femtosecond regime.



cim-laser.ac.uk/micro-machining

HIGH SPEED, LARGE AREA SURFACE STRUCTURING

Ultra fast (UF) lasers have particular advantages with brittle materials such as glass, avoiding the thermally-induced cracking problems observed with longer pulsed lasers. Initial research in this area has concentrated on the development of UF laser processes to generate controlled scattering features on glass surfaces, at a high speed and hence low cost, and comparisons made with more established and lower cost CO2 laser systems. Directly patterning the glass using a suitable laser provides the prospect of a simpler solution. Promising initial results were obtained for applications in Organic LED materials for example, a CO2 laser can be effectively used for the fabrication of scattering textures (i.e. hemispheres arranged in a hexagonal pattern) directly on glass used in OLED devices. However for commercial reasons the project is now focusing on more general applications of processing of thin flex glass (including through cutting). This glass provides the opportunity to create flexible packages without the hermeticity issues associated with polymer packaging. It has been demonstrated, for example, that picosecond laser pulses of 515nm wavelength can be used for drilling small (60µm diameter) holes in a 100µm thin glass sheet at a speed of 20 holes per second.

ULTRASHORT PULSED LASER WELDING OF OPTICAL MATERIALS

This work focuses on the development of industrially-relevant advanced laser bonding techniques for direct bonding of optical materials, including glass and crystalline materials to other optical materials and metallic components. Ultrashort laser pulses can provide a highly localised heat source, due to their nonlinear material interaction, and so are highly suited to such applications. This research is required in order to transform bonding demonstrations into robust high-yield manufacturing processes, including the development of strategies to avoid material cracking. Considerable progress has been made in developing the necessary expertise and experience in a range of skills necessary to take the project forward including: In the surface preparation of non-glass (e.g. metal) components, techniques for holding materials together during the laser welding process, building up knowledge of the parameter space necessary for successful welding and proof-of-principle examples in a range of industrially relevant materials. At the same time our outreach efforts have isolated a number of suitable industrial processes to be investigated as the project continues.

LASER MICRO-SCUPLTING OF SECURITY MARKINGS ON METAL COMPONENTS

This project will investigate a novel laser marking process based on the laser-micro-sculpting approach, known as *'YAGboss'*. This process was developed by Heriot-Watt University and Renishaw plc initially for the generation of sinusoidal gratings (scales) on metals for high-accurate positioning encoders and recently for the generation of holographic structures directly embossed onto the surface of 304-grade stainless steel. The current downsides of this process are: (a) a lack of established laser processing parameters for the generation of holographic structures on high-value metals , (b) very low speed , and (c) a low diffraction efficiency and wavelength-insensitivity of the laser-generated holographic structures. In this project, we want to investigate the feasibility of using the *'YAGboss'* process for the generation of optically-smooth holographic security markings directly on high-value metals, such as nickel-chromium Inconel® alloys and cobalt-chromium, which are used for manufacturing, e.g.aero-engine parts and medical implants.
To significantly improve the generation time of holographic structures we propose to combine a laser source with a galvo-scan system equipped with a short focal length telecentric lens.

FUNDAMENTALS OF LASER SHOCK PEENING

Laser shock peening is a metal surface processing tool which can improve integrity of structures used in critical service conditions by creating near surface compressive residual stress state. Currently the application of this technique is limited to high value applications such as aero engine turbine blades. Although there is a significant amount of data showing the benefit in life improvement in components subjected to fatigue, there is limited understanding of the laser metal interaction and the resulting residual stress. Currently the process is used with an ablative layer which avoids thermal damage of the substrate and a laser transparent confinement layer which resists expansion of the plasma and enhances the creation of a shock wave. These features make the process difficult and expensive to apply. Furthermore the laser used for the commercial process is a very high pulse energy system developed for laser fusion applications, the consequence of this highly specialised equipment, is that it makes the process even more expensive to apply in practice. By obtaining a fundamental understanding of the process it will be possible to identify optimum performance for a laser for this process in various applications.

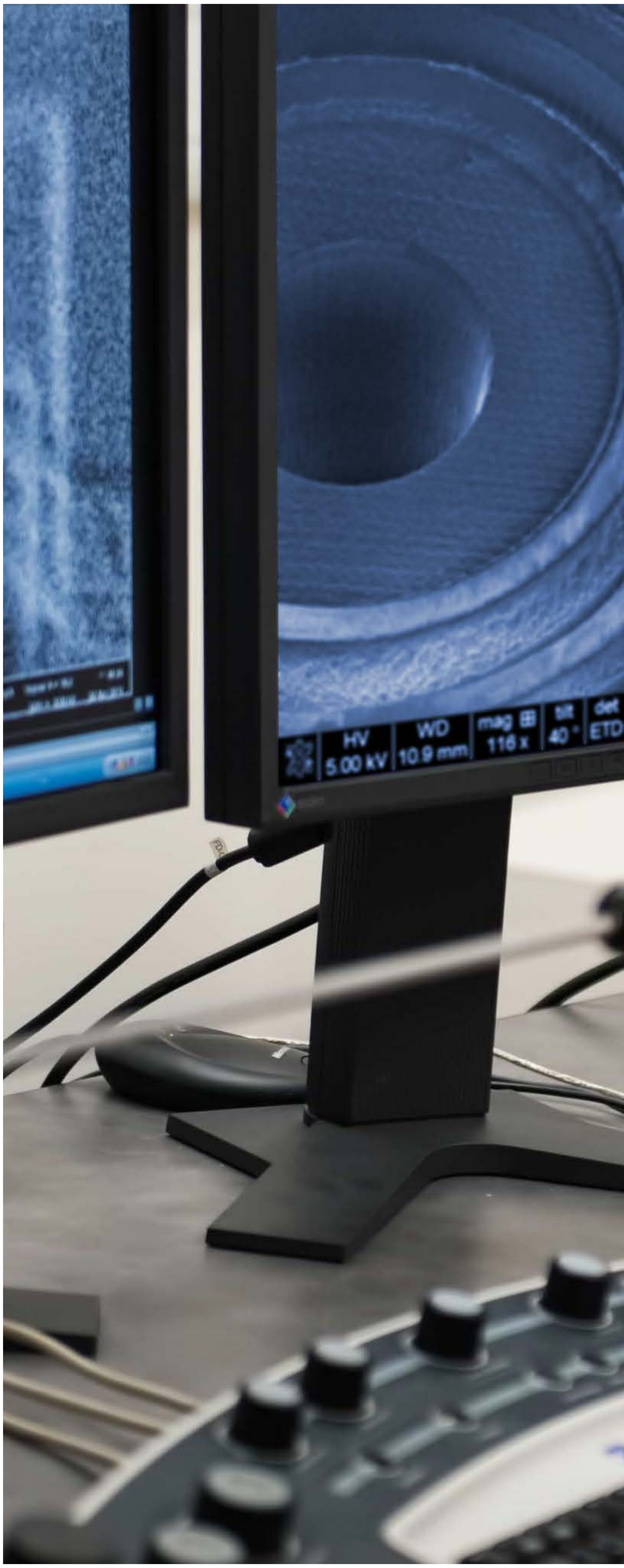
This project aims to develop fundamental understanding of the mechanism of shock wave generation by laser metal interaction which along with the material hardening behaviour, physical and constitutive properties would help in direct correlation of laser-metal interaction and stress and hardening behaviour of structural alloys.

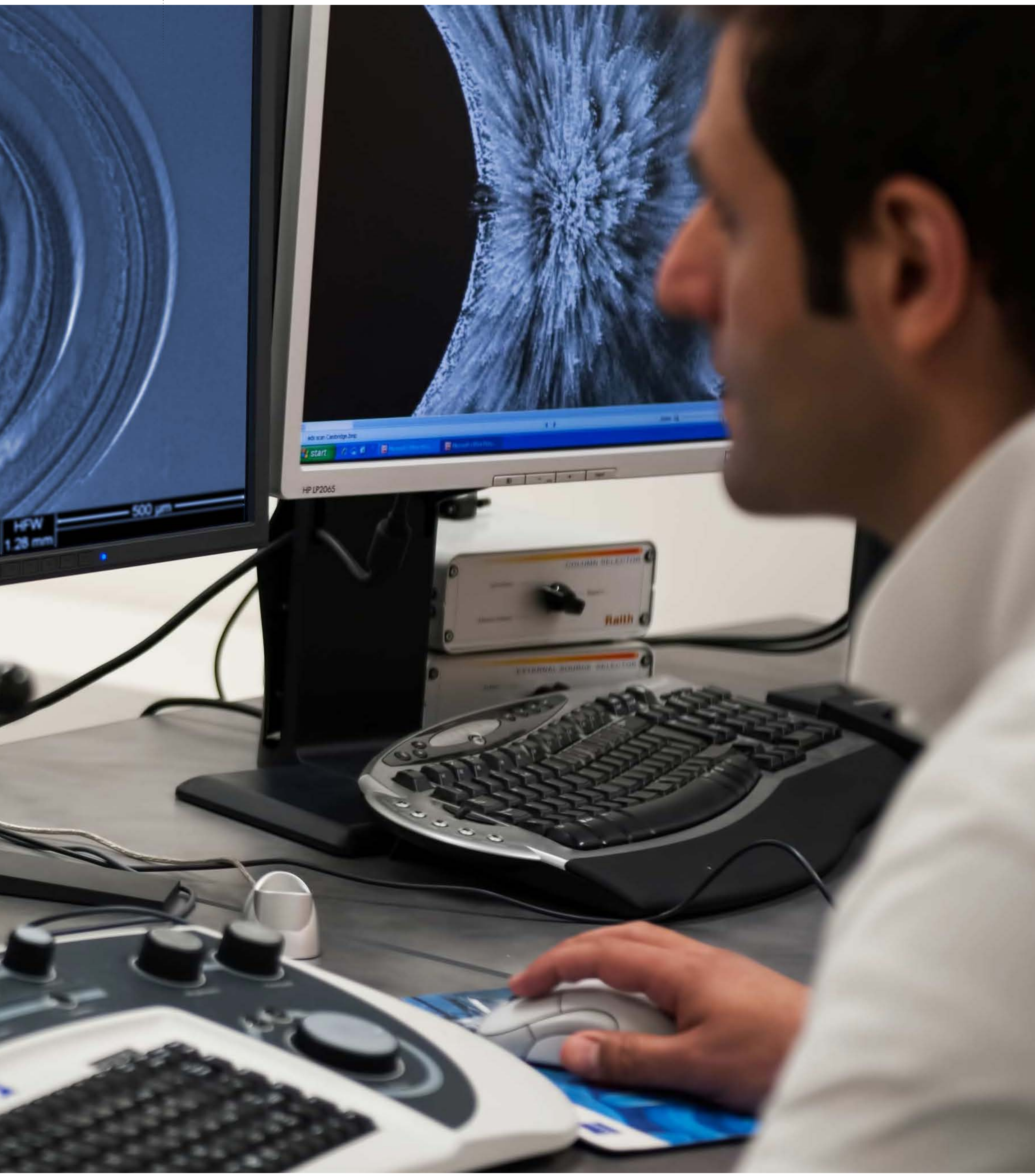
LASER FINISHING

The Centre investigated the feasibility of using laser processing for post-machining of parts manufactured by powder bed and wire based additive manufacturing processes. A range of different laser ablation and smoothing approaches were tested, including stainless steel, cobalt-chrome alloy, aluminium and titanium. Many applications e.g. medical, require a reasonably polished surface finish (i.e. good micro-roughness), so there was a particular focus on laser polishing processes, the results of this work have led to research in 'Laser Polishing of Complex AM Structures' and the generation of IP in the form of process parameters.

LASER POLISHING OF COMPLEX AM STRUCTURES

Following on from the successful Centre feasibility project 'Laser finishing', research in this area seeks to take the basic process developed to date on flat additively manufactured (AM) parts, and to apply this to complex 3D structures. A particular focus is dental applications, chosen because AM is well-established as a manufacturing process for dental implant applications, and the complex 3D shapes required provide a case study for the practical implementation of the laser polishing process. Only selected areas of the surface of dental implants should be polished – hence the highly selective nature of the laser polishing process is particularly interesting.

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Laser Development & Engineering

Our ongoing research in this theme underpins the development of technologies and components crucial to the hardware supply chain for laser-based machine manufacture. Our research efforts concentrate on new laser device technologies, including solid state lasers pumped by diode laser arrays, with particular focus on the development of laser systems producing trains of ultrashort pulse pulses to enable significant expansion in novel laser processing applications.

HIGH ENERGY AMPLIFIERS FOR ULTRAFAST LASERS

Research in this area will further develop UK-based amplifier technology for ultrashortpulse laser systems with pulse durations in the 0.5 to 10 ps range. Work is on-going to develop new amplifier device architectures to scale to kW average powers, with design goals of high efficiency and minimising the cost of system production. New concepts that may prove instrumental in future high-power amplifier systems are being critically evaluated together with an industry partner. A system design has been proposed that incorporates new laser amplifier device architectures (thin fibre-crystal rod pre-amplifier and thin-slab power/energy amplifier) and a multi-stage amplifier strategy.

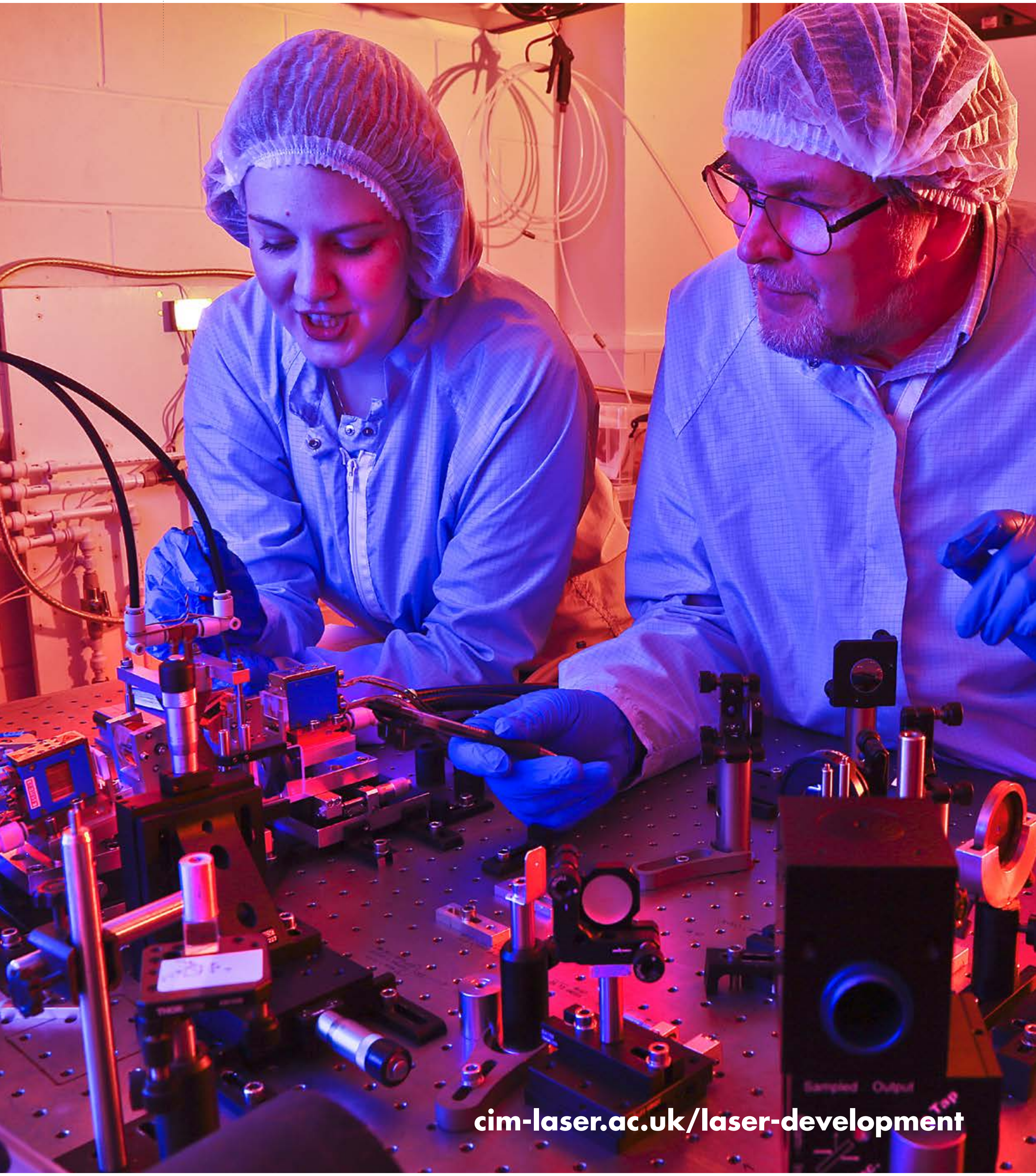
FEASIBILITY & DESIGN: 2μm LASERS FOR INDUSTRIAL APPLICATIONS

Laser-based production processes are dominated by solid-state lasers in the UV, visible and near-infrared wavelength ranges, and by CO_2 lasers in the far-infrared. However, there is an emergence of industrial applications where traditional laser sources are not necessarily the preferred option, but rather lasers operating in the spectral region in-between the near- and far-infrared should be utilised. Er-doped lasers operating at 1.5 μm are already finding industrial applications, while Tm-doped lasers at 1.9-2.0 μm are now becoming a particular topic of interest.

This project aims to collate all the relevant information on modern 2 μm lasers, as well as critically evaluate the emerging laser processes which will benefit from the industrialisation of these lasers. Based on this information, a concept design will be delivered for a 2 μm laser processing system which would be able to address specific industrial applications.

LASER WELDING OF OPTICAL COMPONENTS TO METAL ALLOYS

Electro-optic systems, including lasers, incorporate a range of optical components that need to be adjusted and mounted into a mechanical supporting structure, usually made from machined metal. Mounting of these optical components uses various adhesives and/or mechanical clamping arrangements. Adhesives suffer from long term stability issues, including creep and degradation; as well as outgassing if used in a hermetically sealed or vacuum application. We have been developing a direct laser bonding process using an ultrashort pulsed picosecond laser, and have demonstrated its feasibility for the welding of glass to metal, in addition to glass-to-glass bonding. Having proven this feasibility, this project aims to deliver detailed development of the process for the bonding of standard optical components to metal parts, based around the requirements of the industrial partner. This will include investigation of the metal surface finish and preparation requirements; together with extensive mechanical, thermal and vibrational testing of joined parts. The impact of any stress induced by the bonding process will also be analysed, using polarimetric techniques to analyse induced birefringence in the optical parts.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cim-laser.ac.uk/laser-development

Fusion Based Processes

Our research in this area is focused on additive manufacture applications where there is an urgent need to solve the unreliability and low efficiency of the laser-based process, concentrating on laser-powder and laser shaped wire interaction and fundamentals. Our research will feed into improved powder bed technology and a new laser-based additive manufacture process combining a very high power laser with wire strip.

**cim-laser.ac.uk/
fusion-processes**

FUNDAMENTAL LASER MATERIAL INTERACTION PARAMETERS IN POWDER MELTING

Work to define a set of interaction parameters that controls the fusion characteristics and profile of build layers in powder bed systems is ongoing. The aim of this research is to make the selective laser melting process more robust and transferable between different powder bed systems. These fundamental parameters can also be used for optimisation of the laser powder bed system in terms of process efficiency and scale-up to higher powers and build rates. The first phase will develop the relationship between the fundamental laser material interaction parameters and powder melting characteristics.

SMART LASER TECHNOLOGY FOR WELDING AND CUTTING

Laser processing is currently highly dependent on user knowledge and experience to choose correct or optimum parameters to obtain a reliable high quality process. Alternatively for every new application or different laser system expensive process development is required. Furthermore continuous human monitoring is often required to ensure smooth defect free production. The combination of these two factors is greatly limiting the potential exploitation of laser based production process in industry. To tackle this we are proposing two approaches: The development of an Expert Laser System (ELS) which aims to greatly simplify the selection of laser welding parameters. The user only needs to set the requirements for the laser process (i.e. productivity, fit-up tolerance, penetration depth etc.); and Back reflected light (BRL) which is ideal for process monitoring and control of laser processes being entirely non-intrusive. The Centre is investigating the use of analysed BRL as a laser process monitoring tool for cutting. Initial results show BRL can distinguish three distinct regions: laser start; material pierced; and laser cutting providing the opportunity to develop software to monitor the cutting process.

MULTI-LASER SELECTIVE LASER MELTING

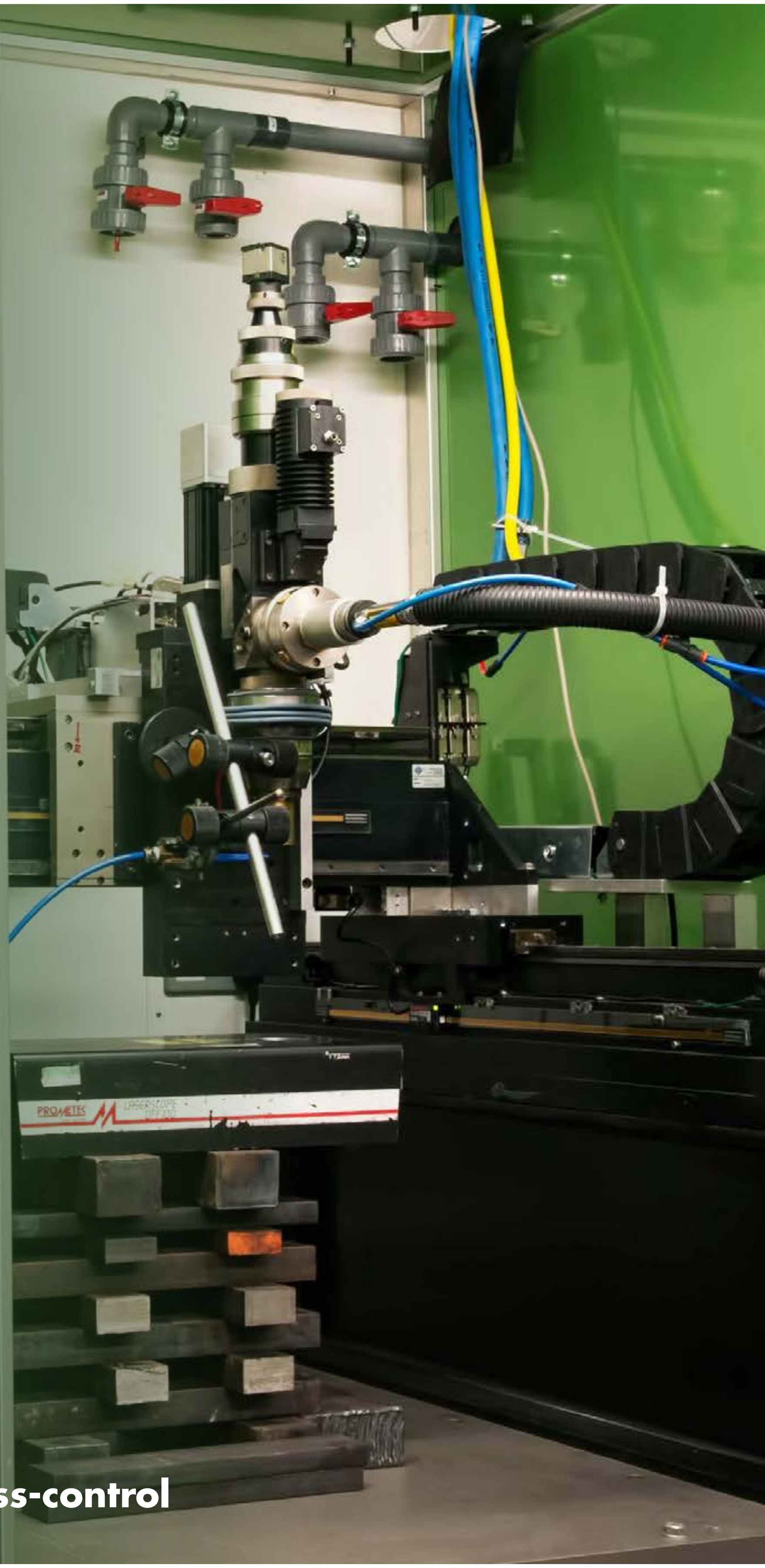
Additive Manufacturing methodologies are beginning to achieve commercial uptake due to the advantages they bring in terms of part complexity, design freedom and material economy. Selective Laser Melting is one such technology which utilises a scanning galvanometer system to divert a process laser across a metallic powder bed in order to create complex 3D components. In order for the uptake of this technology to continue improvements in build speed and material microstructure coupled with reduction in part defects and process uncertainties must be achieved. As affordable high power fibre lasers become available their integration into such systems should allow for some of the stated issues to be resolved. However the current optical configuration utilised will not readily accommodate increases in optical energy. The Centre is developing a proof-of-concept high power multiple laser scanning Selective Laser Melting system to allow for increased build rates and novel scanning strategies aimed at improving surface finish and reducing component residual stresses.

PROCESSING OF REFRACTORY METALS BY SELECTIVE LASER MELTING

There are currently no commercially available Selective Laser Melting (SLM) systems able to process refractory metals reliably. Refractory metals have high strength, are able to function at high temperature and have excellent corrosion resistance making them applicable to high strength medical devices, rocket nozzles and support hardware in the nuclear industry, while their ability to absorb radiation is useful in medical imaging devices. There are a number of challenges associated with processing refractory metals, including the high temperatures and strengths at temperature. Work in this area will develop processing parameters for a minimum of three refractory metals, identify any barriers that may limit the effectiveness of SLM processing and evaluate the performance. An initial study is being conducted that will evaluate the impact of cellular refractory metal structures for industrial applications. The results of this work will give UK industry an advantage in this high value manufacturing sector.

Sensing & Process Control

Real time control of laser-based processes is a key laser system goal, and techniques for sensing and monitoring of such laser-material interaction processes is a basic requirement to achieve reliable, flexible laser-based production processes. Our research addresses important aspects of the system design for specific laser machines will be addressed (e.g. for additive manufacture, UV laser processing, joining, peening) to achieve cost effective manufacture and high-level performance.



cim-laser.ac.uk/process-control

CONTROLLED LASER MILLING

Research in this area is developing laser based methods for the specific removal of thin metallic protective layers from a metallic substrate material with integrated process monitoring. Laser Induced Breakdown Spectroscopy is an established tool for the identification of metals in laser plasmas and the Centre is developing the use of the spectral emission as a process monitoring tool to detect complete removal of the protective layer material.

PROCESS CONTROL FOR LASER-HYBRID ADDITIVE MANUFACTURE OF METALS

Additive manufacture of metals can produce fully-dense, near-net shape, free-form components directly from a CAD model. Wire feedstock (compared to powder) provides higher deposition rates, higher efficiency of material use, lower porosity, cheaper feed material, simpler feed mechanism and less surface roughness. Centre work in this area is investigating the laser-hybrid AM process in order to introduce build-height control for the first time, thus reducing the aggregation of height errors between layers. We will also introduce simultaneous height and temperature control, and investigate whether this approach enables control of the height-to-width ratio of the deposited bead, again for the first time. Both control approaches will reduce process variation: the serial production of parts in the future will require these assurances of process reliability and output material quality, particularly for aerospace applications.

ADD, REMOVE, MEASURE OR REPAIR

Development of a novel 3D freeform fabrication laser based manufacturing platform will provide a flexible platform combining the ability to construct, build and add material to freeform shapes with metrology of the created part and the ability to remove material to achieve a high level of form fit and low tolerances in excess of that achievable in freeform manufacture on its own. By integrating fibre delivered laser sources into a parallel robot device we will produce a flexible system capable of a number of concurrent engineering processes. This combines new product development and/or fabrication steps for novel customised parts or repair of damaged high value components with the ability to monitor the process and measure the component. Research is ongoing but recent developments include: power control of novel fibres during manipulation, important for the 'remove' part of the project; the novel software interface between the laser source and parallel robot platform has been implemented; and a coaxial powder nozzle that enable additional control parameters for laser metal deposition has been developed.

GHZ-RATE HOLOGRAPHIC OBSERVATION & OPTIMISATION OF LASER PROCESSING

Industrial laser users have access to an immense parameter space consisting of nearly infinite combinations of wavelength, pulse duration, temporal pulse shape, spatial profile and polarisation (not to mention processing parameters such as processing speed, pulse overlap etc). Centre work in this area aims to develop a system that will be the first of its kind, enabling detailed observations of high-speed laser processing events that will empower laser designers and laser users to optimise their technologies for laser materials processing applications.

This will be accomplished through direct observation of process dynamics using an image capture technique through an ultra-high speed Pulsed Digital Holographic system. The objective is to develop a system that can measure 3D spatial information such as plasma and shockwave induced refractive index gradients, and particulate ejecta with the ability to resolve temporal events down to 500ps and frame rates in the GHz time domain. The imaging system has been tested with our industrial partner who responded very positively and have commissioned us to provide them with a system to form an integral part of their laser applications laboratory. We have jumped ahead of our original development plan and have delivered the TrueGHz capability for the ultrafast imaging system. The system is now capable of up to 1 GHz frame rate, although for most applications we are operating at 40 MHz, or in certain cases 10 MHz.

Researcher Seedcorn Projects

The centre has a cohort of talented and enthusiastic researchers, this year they have been encouraged to develop and lead their own 4-6 month projects.

LASER TEXTURING OF STEEL TO IMPROVE LASER WELDING PERFORMANCE

One of the challenges in the automotive industry is to reduce the carbon emission of manufactured vehicles. This can be done by incorporating lightweight metallic alloys (e.g. aluminium alloys) with more generic automotive modulus (often made of uncoated mild steel) in order to reduce the total mass of a vehicle. Joining these two dissimilar metals together is a difficult task because chemical reactions between aluminium alloy and uncoated low carbon steel lead to the formation of intermetallic compounds at the metals interface during a welding process and thus the mechanical properties of the welds are deteriorated.

This project aims to investigate a nanosecond laser texturing process for improving the laser spot welding performance of two dissimilar metals, i.e. aluminium alloy to uncoated low carbon steel, which are used in the automotive industry, in order to reduce the total mass of a vehicle.

MEET THE TEAM

Researchers: Dr Krysitan Wlodarczyk, Dr Sonia Meco Martins & Dr Goncalo Rodrigues Pardal

How is the project developing? Any exciting results so far?

The project is at its final stages and showing encouraging results. By using a nanosecond pulsed laser to texture the steel surface it is possible to increase the tensile shear load of dissimilar metal spot welded joints between Al and steel by about 25%, compared with non-textured samples joined in the same conditions.

What is the main benefit of access to seedcorn funding?

Seedcorn projects allow researchers to start their own projects with their own ideas, giving us the freedom to carve our own niche in the centre. The funding allows us to develop more speculative ideas and generate initial results that can then be developed into larger projects with our industry partners. This particular seedcorn project between Heriot-Watt and Cranfield has further developed researcher links inside the Centre.

What are the next steps for this research?

We will be developing this seedcorn project into a standard CIM project, using the results to approach our industry partners for joint funding. The preliminary results obtained with the seedcorn project are the perfect tool to persuade companies to fund a bigger project with higher aims and a possible commercial application.

DIAGNOSTICS AND PROCESS IMPROVEMENT FOR ULTRAFAST PS LASER WELDING

Ultra-fast ps welding is in principle a simple procedure. Two materials are brought into close proximity and a laser is focused onto the interface. Absorption at the interface produces a plasma that, when cooled, forms the weld. In practice laser-material interactions and particularly the absorption of the radiation are complex; this leads to a process which is hard to predict and difficult to optimise. At present we are researching the capability of ps welding to bridge gaps in both similar and dissimilar materials. Direct observation of this bridging behaviour would lead to a better understanding of the process and allow for the welding of more industrially relevant components.

This project aims to create a portable imaging system to allow non-portable breadboard and brass board lasers and processing systems to be tested across the centre.

MEET THE TEAM

Researchers: Richard Carter & Krste Pangovski

How is the project developing? Any exciting results so far?

The project has produced the world's fastest industrially viable holographic camera. This system is capable of taking 16 consecutive frames at up to 1,000,000,000 frames per second. The system has been applied to study the effect of light-in-flight using picosecond lasers. The objectives of this project are two-fold. Firstly, for glass-metal welding, it is to identify how the plasma filaments are formed, how long do they last and what are their geometries are throughout the process. This will allow us to better understand when, where and how to deposit laser energy, in real world applications. One of the most surprising results thus far are the timescales: structural modifications occur typically in a few nanoseconds (or less) but for glass to revert to its original state, assuming that we have not damaged it, is on the order of milliseconds! This brings us to the second objective: knowing the relaxation times of different glasses allows us to understand how often we can pass laser pulses through an optical element, given a particular energy density, without damaging the optic. In turn, this will allows us to design optical systems with additional insights into material damage thresholds constraints.

What is the main benefit of access to seedcorn funding?

Access to seed corn funding allows us to undertake some fundamental studies which would perhaps, be otherwise overlooked in an industrially-focused project. This project is likely to make a significant impact on how we think about laser process design, particularly in a novel application area such as dissimilar materials joining, namely glasses to metals.

What are the next steps for this research?

Our initial work has concentrated on static processing of cubes to flat surfaces; we deposit energy in a single location where the work piece and laser beam are fixed. This has allowed us to probe the interaction timescales for our chosen energies. Over the next quarter, we would like to start observing the welding process as it might work in an industrial setting. Further, we will look to study more complex geometries to understand those influences of light propagation in glasses and the formation of welds.

SME Seedcorn Projects

In order to demonstrate the potential value of laser-based manufacturing to industry the Centre is offering 2 weeks of researcher time to companies via our Seedcorn projects.

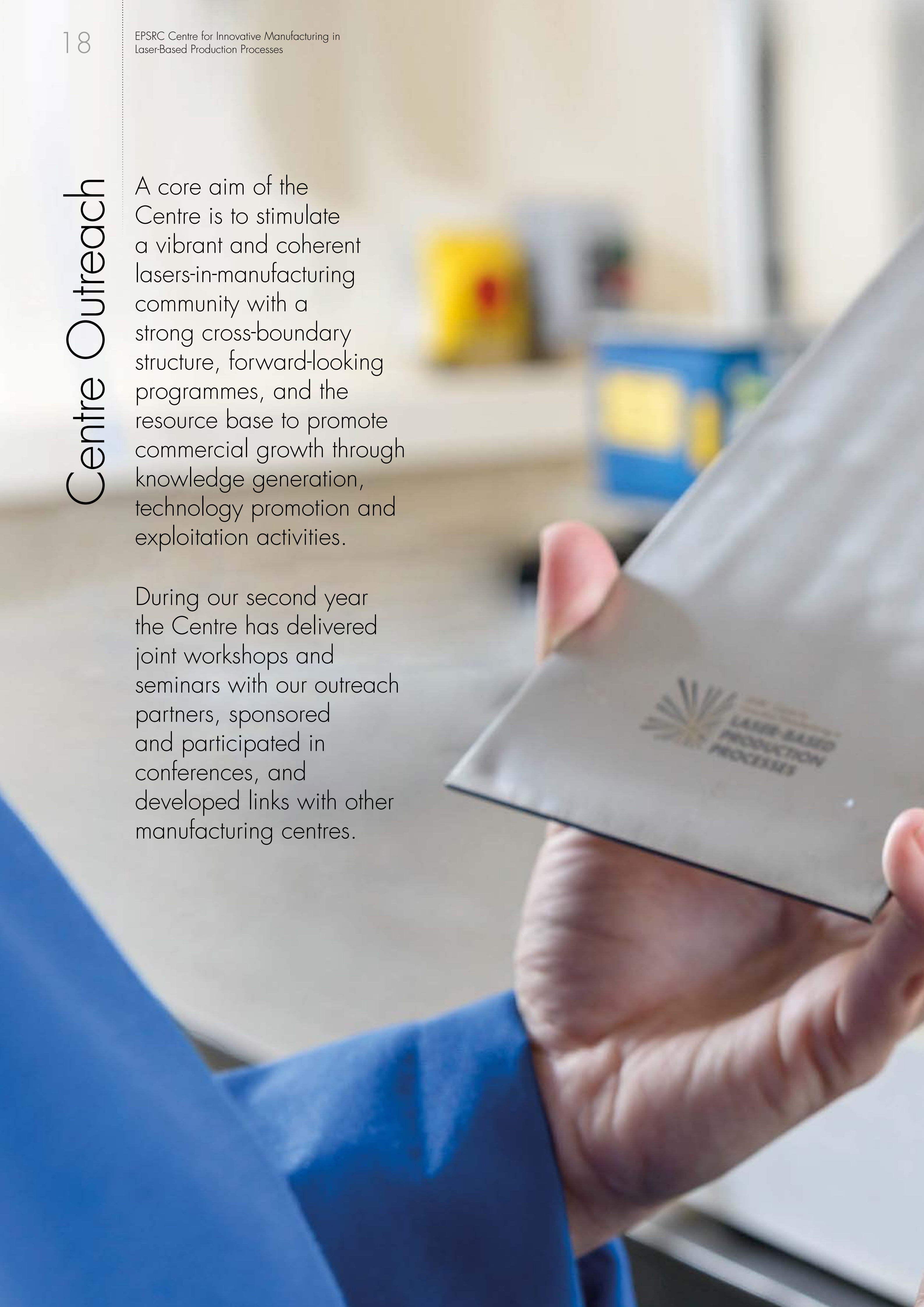
Seedcorn projects allow SMEs to work with the Centre on 2 week feasibility studies or pump-priming projects at no cost to themselves. A project will be awarded up to 2 weeks researcher time with input from members of the Centre academic team to develop or test laser-based production processes that could benefit the SME involved.

How to apply:
For more information on this scheme and details of how to apply please email *LbPP@hw.ac.uk.*

Centre Outreach

A core aim of the Centre is to stimulate a vibrant and coherent lasers-in-manufacturing community with a strong cross-boundary structure, forward-looking programmes, and the resource base to promote commercial growth through knowledge generation, technology promotion and exploitation activities.

During our second year the Centre has delivered joint workshops and seminars with our outreach partners, sponsored and participated in conferences, and developed links with other manufacturing centres.



Selected Outreach Activities

INDUSTRIAL LASER APPLICATIONS SYMPOSIUM - MARCH 2015

Organised by the Association of Industrial Laser Users, ILAS is the biennial 2-day laser event that provides a unique opportunity for users, suppliers and researchers to explore recent advances in applications and processes and opportunities presented by laser materials processing.

LASER WORLD OF PHOTONICS - JUNE 2015

The international trade fair for the laser and photonics industry. Together with the World of Photonics Congress, the fair unites research and industry and promotes the use and on-going development of optical technologies. The trade fair presents technology in direct combination with industrial application sectors for the widest variety of industries and uses.

VISIT TO THE MANUFACTURING TECHNOLOGY CENTRE - AUGUST 2015

The Centre organised a visit to the MTC to discuss and foster future collaboration – particularly with respect to micro-machining with Lasers. Also in attendance were representatives from some of our key partner companies with a research interest in this area – M-Solv, SPI Lasers, Oxford Lasers, and Micrometric.

National Strategy for laser-based manufacturing

There is some evidence that UK manufacturing companies have been slow to engage with, invest in and to utilise flexible laser-based production technologies, with consequent adverse effects. A key aim of the Centre and its partners is to generate a coherent strategy document and technical roadmap for the UK that will be used to influence UK policymakers, trainers, educators and industry. This industry-led effort will aid in driving economic growth in key high value-added industry sectors - helping stimulate an expansion in the industrial exploitation of laser-enabled manufacturing processes in such industries.

The Initiative aims to:

- encourage the implementation of laser-based manufacturing processes across a much broader range of UK manufacturing.
- increase the coherence and effectiveness of links between UK manufacturing companies, between such companies and the academic Research and Development sector and with government agencies to influence investment policy and to draw development funding into the sector.
- stimulate growth in the laser UK industrial laser system and photonic component manufacturing sector both by expanding the use of laser processes across a much broader range of UK manufacturing, and through growth in laser-related exports.

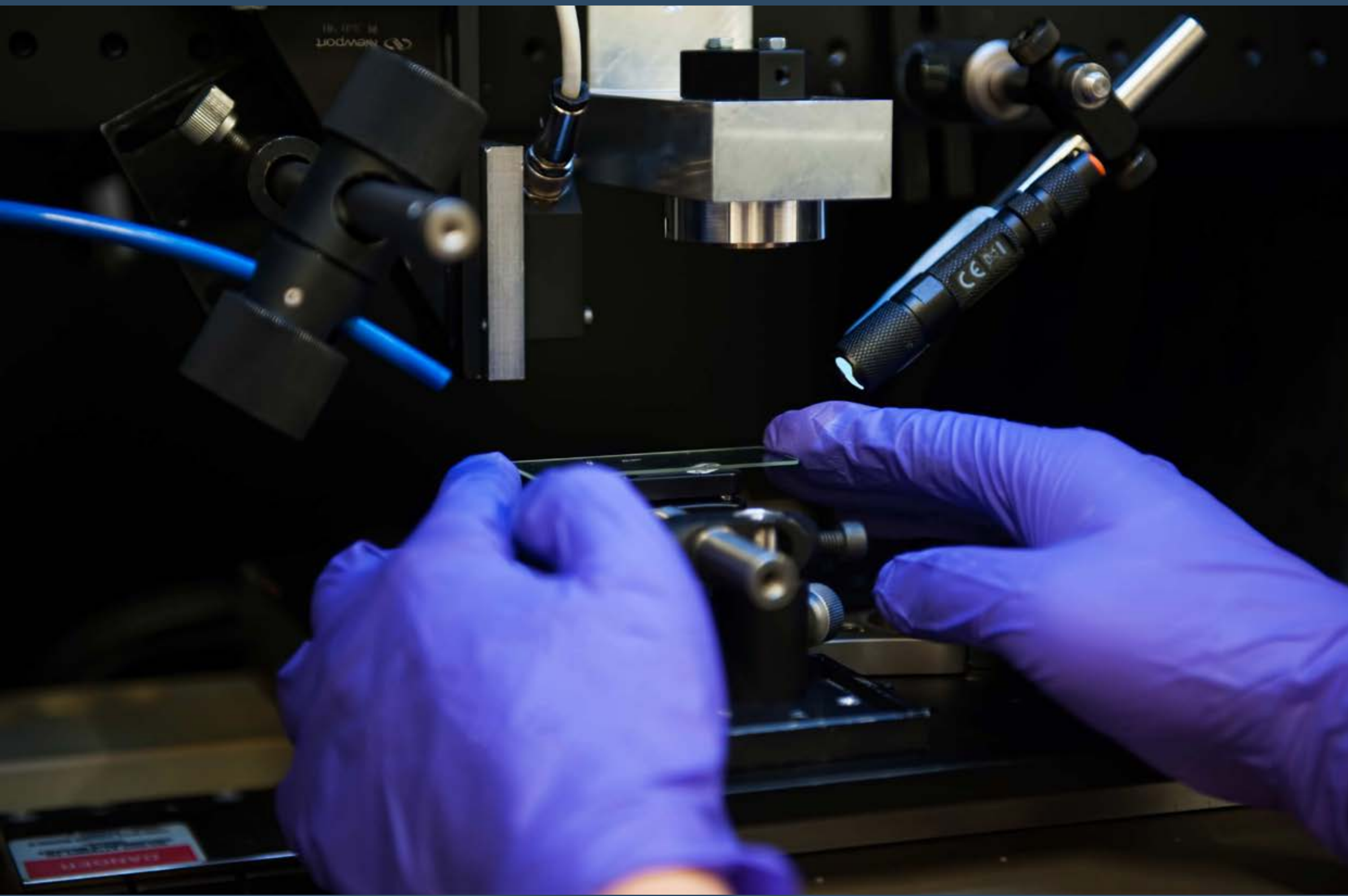
A Strategic Working Group is being assembled with predominantly industrial membership and with strong representation from UK manufacturing companies that are currently users - or likely future users - of laser-enabled manufacturing technologies. Delegates are being sought from UK companies who are active in the industrial laser-system hardware supply chain, and also from academics with significant industry/research-group collaborative development experience. Also represented will be trade bodies, industry independent research organisations, funding agencies, and universities.

This working group will draw both on their own wide range of experience and knowledge, and on a broad evidence-base. The Working Group aims to deliver the National Strategy Document in spring 2016.

Renishaw Plc

"Renishaw has worked with Heriot-Watt University for over a decade. Over the years the collaboration has become deeper and wider with projects in subject areas such as laser processing, metrology, micro-manufacturing. With the advent of the EPSRC Centre for Laser-Based Production Processes the talent pool of potential collaborators has become even richer, with the complementary skills of world leading academic partners, as well as commercial partners which represent some of the most innovative companies operating in the UK. These par tners represent whole value chains in terms of system design, build, deployment and use of laser-based production. The Centre's match making skills mean we now have four programmes under-way or due to commence which involve more than one commercial or academic partner. The facilities, organisation and skills deployed make me very optimistic that significant positive impact to Renishaw's business will result from this work."

Nick Weston
General Manager
Renishaw Edinburgh.



Publications

Richard M. Carter, Jianyong Chen, Jonathan D. Shephard, Robert Thomson and Duncan P. Hand (2014)*"Picosecond Laser Welding of Similar and Dissimilar Materials"*, Applied Optics **doi: 10.1364/AO.53.004233**

Meco S, Ganguly S, Williams S & McPherson N (2014) «*Effect of laser processing parameters on the formation of intermetallic compounds in Fe-Al dissimilar welding"*, Journal of Materials Engineering and Performance, 23 (9) 3361-3370 **doi: 10.1007/s11665-014-1106-5**

Pardal G, Meco S, Ganguly S, Williams S & Prangnell P (2014) I, *"Dissimilar metal laser spot joining of steel to aluminium in conduction mode"* International Journal of Advanced Manufacturing Technology, 73 (1-4) 365-373 **doi: 10.1007/s00170-014-5802-y**

Usani Ofem, Supriyo Ganguly and Stewart Williams, *"Evaluation of Laser-assisted Gas Metal Arc Welding for Deep Water Hyperbaric Application"*, (2014), International Journal of Offshore and Polar Engineering (ISSN 1053-5381), 24(1), 61-67 **web: www.isope.org/publications/journals/ijope-24-1/abst-24-1-p061-oa02-Ofem.pdf**

Ofem U, Ganguly S, Woodward N & Williams S (2014) "*Investigation of Thermal Cycle and Metallurgical Characteristics of Hyperbaric Gas Metal Arc Welding*", International Journal of Offshore and Polar Engineering, 24 (1) 61-67 **web: www.isope.org/publications/journals/ijope-24-3/abst-24-3-p206-oa07-Ofem.pdf**

Ganguly S, Wescott A, Nagy T, Colegrove P & Williams S (2014) "*Characterisation of residual stress state and distortion in welded plates stress engineered by local mechanical tensioning*" Materials Science Forum, 772 187-191 **doi: 10.4028/www.scientific.net/MSF.772.187**

M. Ardron, N Weston, D Hand (2014) "*A practical technique for the generation of highly uniform LIPSS*", Applied Surface Science, 313, 123–131 **doi: 10.1016/j.apsusc.2014.05.154**

A. Dunn, J. V. Carstensen, K. L. Wlodarczyk, E. B. Hansen, J. Gabzdyl, P. M. Harrison, J. D. Shephard, D. P. Hand (2014) "*Nanosecond Laser Texturing for High Friction Applications*" Optics and Lasers in Engineering, 62, 9-16 **doi: 10.1016/j.optlaseng.2014.05.003**

L. Wang, Y. Wang, C. Zhang, L. Xu, J.D. Robson, P.B. Prangnell (2014) "*Controlling Interfacial Reaction During Dissimilar Metal Welding of Aluminium Alloy*"s, ICAA14, Mater Sci Forum, 794-796, pp 416-421 **doi: 10.4028/www.scientific.net/MSF.794-796.416**

G. Pardal & S. Meco & S. Ganguly & S. Williams and P. Prangnell (2014) *"Dissimilar metal laser spot joining of steel to aluminium in conduction mode"*, International Journal of Advanced Manufacturing Technology, 73, pp. 365–37 **doi: 10.1007/s00170-014-5802-y**

S. Tammas-Williams, H. Zhao, F. Leonard, F. Derguti, I. Todd, P. B. Prangnell (2015) *"XCT Analysis of the Influence of Process Parameters on Defect Population in Ti-6Al-4V Components Manufactured by Selective Electron Beam Melting"*, Material Characterisation 102, 47–61 **doi: 10.1016/j.matchar.2015.02.008**

Krystian L. Wlodarczyk, A. Brunton, P. Rumsby, and D.P. Hand *"Picosecond laser cutting and drilling of thin flex glass"* submitted to the Journal of Optics and Lasers in Engineering.

K.L. Wlodarczyk, M. Ardron, A.J. Waddie, A. Dunn, M.D. Kidd, N.J. Weston, and D.P. Hand (2015) *"Laser microsculpting for the generation of robust diffractive security markings on the surface of metals,"* Journal of Materials Processing Technology 222, 206-218 **doi: 10.1016/j.jmatprotec.2015.03.001**

Jianyong Chen, Richard Carter, Robert Thomson and Duncan Hand (2015) *"Avoiding the Requirement for Pre-existing Optical Contact during Picosecond Laser Glass-to-Glass Welding"*, Optics Express **doi: 10.1364/OE.23.018645**

L Wang, Y Wang, PB Prangnell, JD Robson (2015) *"Modelling of intermetallic compounds growth between dissimilar metals"*, Metal and Mater Trans A **doi: 10.1007/s11661-015-3037-7**

Jianyong Chen, Richard M. Carter, Robert R. Thomson, and Duncan P. Hand (2015) *"Avoiding the requirement for pre-existing optical contact during picosecond laser glass-to-glass welding"*, Optics Express 23(14)18645-18657 **doi: 10.1364/OE.23.018645**

Meco S, Pardal G, Ganguly S, Williams S & McPherson N (2015) *"Application of laser in seam welding of dissimilar steel to aluminium joints for thick structural components"*, Optics and Lasers in Engineering, 67, pp. 22-30 **doi: 10.1016/j.optlaseng.2014.10.006**

Sule J, Ganguly S, Coules H & Pirling T (2015) *"Comparative study of evolution of residual stress state by local mechanical tensioning and laser processing of ferritic and austenitic structural steel welds"*, , Journal of Mechanical Engineering and Automation, 5 (1) 33-42 **doi: 10.5923/j.jmea.20150501.05**

Sule J, Ganguly S, Coules H & Pirling T (2015) *"Application of local mechanical tensioning and laser processing to refine microstructure and modify residual stress state of a multi-pass 304L austenitic steels welds"*, Journal of Manufacturing Processes, 18 141-150 **doi: 10.1016/j.jmapro.2015.03.003**

Sule, J. and Ganguly, S. (2015) *"Application of Local Mechanical Tensioning and Laser Processing to Modify the Residual Stress State and Microstructural Features of Multi-Pass HSLA Steel"* SAE Int. J. Mater. Manf. 8(2):494-502 **doi: 10.4271/2015-01-0604**

N. K. Metzger, C.-R. Su, T. J. Edwards, and C. T. A. Brown, (2015) *"Algorithm based comparison between the integral method and harmonic analysis of the timing jitter of diode-based and solid-state pulsed laser sources,"* Optics Communications, vol. 341, pp. 7–14 **doi: 10.1016/j.optcom.2014.11.088**

Invited talks

Electron Backscatter Diffraction Meeting, March 2014, London. Keynote opening address. *EBSD Analysis to Understand Additive Manufacturing (3D Printing) in Titanium: RMS*	**P.B. Prangnell**, J. Donoghue, A. Gholinia, O. Ciuca A.A. Antonysamy	01 March 2014
AILU Metal additive Manufacturing: Opportunities in applications and improvements in process technologies	Denis Hall, Duncan Hand, Stewart Williams	01 April 2014
EMRS-Spring 2014, Lille, *"Astrophotonic Applications of Ultrafast Laser Inscription,"*	R. R. Thomson	26 - 30 May 2014
15th International Symposium on Laser Precision Microfabrication, Vilnius, Lithuania, D. P. Hand, K. L. Wlodarczyk, F. Albri, J. Li, M. Ardron, R. M. Carter, J. D. Shephard: *"Precision laser processing for optical device manufacture"*	Duncan Hand	01 June 2014
AILU: Innovations for economic growth: The UK uptake of Laser Materials Processing Presentation First steps in producing a UK Roadmap	Duncan Hand	08 July 2014
Fibre Optics in Astronomy, Cambridge, MA USA, *"Pioneering the development of planar and 3D waveguide structures in Astronomy,"*	R. R. Thomson	19 - 21 August 2014
Congress of the International Commission for Optics (ICO23), Santiago de Compostela, *"Optical metrology for additive manufacture of metals"*	Andrew Moore	26 - 29 August 2014
ICALEO 2014, *"Laser Texturing for High Friction Applications"*	Andrew Dunn, Krystian L Wlodarczyk, Jonathan D Shephard, Duncan P Hand	19-23 October 2014
CAPE: Manufacturing Research and its Applications in the 21st Century, Keynote. *"Laser device technology for laser-based manufacturing"*	M J Daniel Esser	03-04 November 2015
On the cusp of the new industrial revolution, Additive Manufacture for Defense & Aerospace, London,	Stewart Williams	18 - 19 February 2015

On the cusp of the new industrial revolution, Additive Manufacture for Defense & Aerospace, London *'An introduction to additive manufacture'*	Bill O'Neill	18 - 19 February 2015
On the cusp of the new industrial revolution, Additive Manufacture for Defense & Aerospace, London, *'The Development of Additive Manufacturing Techniques'*	Chris Sutcliffe	18 - 19 February 2015
Applied Optics and Photonics China 2015, *"Ultrafast laser inscription of 3D "photonic dicers" for astrophotonic applications,"*	R. R. Thomson	5 - 7 May 2015
4th Workshop on Specialty Optical Fibers (WSOF 2015), Hong Kong, *"Ultrafast laser inscription of 3D components for multicore fibre coupling,"*	R. R. Thomson	4 - 6 November 2015
Photonics West 2016, *"Ultrafast laser inscription of 3D components for spatial multiplexing,"*	R. R. Thomson	16 - 18 February 2016

Facilities & Equipment

The Centre has a range of state of the art facilities and equipment available across all University partners that enable comprehensive manufacturing research programmes. Our academics and researchers work across all sites and with industry partners to ensure the Centre produces cutting edge, industrially relevant research.

HIGH POWER LASER APPLICATION LABORATORIES

The High Power Laser Application laboratories at Heriot-Watt are well-equipped, including various high average/peak power lasers across a wide range of pulse lengths (millisecond, nanosecond, picosecond and femtosecond plus continuous wave) and wavelengths from the UV through to the infrared (355nm, 532nm, 1.06μm, 2.94μm, 10.6μm). These laser systems are coupled with high precision motion systems, including high speed galvo scanners and high precision air bearing and cross bearing stages. The laser processes that can be provided encompass micromachining, optical modification, polishing, cutting, joining, and microwelding.

WELDING AND LASER PROCESSING LABORATORY

The Cranfield laboratory is an industrial scale facility dedicated to the study and development of joining, laser processing and large scale metal additive manufacture. Lasers available include an 8 kW IPG fibre laser, 200 W Synrad CO2 laser, SPI pulsed fibre laser, TEA CO2 laser and a JK 300 W average power pulsed Nd-YAG system. The lasers are supported by an extensive range of manipulators include robots, a 3m linear slide and traditional precision XYZ linear slides. For very large scale parts we have the 5m x 3m x 1m Hi Value Engineering system which is equipped for welding, machining and rolling. There are three environmental chambers for operating in controlled at atmosphere including vacuum and up to 250 bar pressure for hyperbaric studies. For hybrid processing there is a host of state of the art fusion arc welding power sources with the latest variants both in gas metal arc (e.g. surface tension controlled metal transfer) and gas tungsten arc welding (e.g. TOPTIG). The laboratory is equipped with 20 tonne cranes for management of large parts.

For process analysis we have a range of cameras (IR and high speed), beam diagnostics and thermal/electrical measuring systems. For material characterisation there are electron microscopes (with EBSD and EDS) and mechanical testing with Digital Image Correlation.

ADDITIVE MANUFACTURING

Additive manufacturing facilities at Liverpool consist of three MCP Realizer Selective Laser Melting machines, used for the development of new optical systems, powder handling systems and general building work. These machines are highly modified and can be reconfigured with reasonable ease allowing rapid development of optical, mechanical and materials systems. They are also able to produce solid, porous and combinations of solid and porous structures, suitable for the orthopaedic industry. There are also two Renishaw AM (Laser Melting Additive Manufacturing) machines, which are being developed to incorporate new technologies. An E-beam additive manufacturing machine will be installed soon. These machines all use metal powders and full safe powder handling systems are incorporated. Other work in the area is on Laser Cladding and Direct Fabrication using wire feed systems that give compositional control and in the use of technologies normally associated with semi-conductor manufacture to improve the ink jet printing of metals. The University also has a full range of analytical techniques that can be used to analyse and quantify the experiments carried out. These include optical and electron beam microscopy (SEM, TEM, STEM), X-ray based techniques (EDS,XRD) and mechanical testing facilities.

Additional equipment is available at Heriot-Watt (Realizer 250) for 3D printing of stainless steel components from metal powders. An extensive suite of testing and measuring instrumentation and facilities for fibre optic sensing and fibre optic handling. Cu-vapour laser for basic fibre Bragg grating writing.

LASER DEVICE PHYSICS AND ENGINEERING

Heriot-Watt University hosts the laboratories and facilities that support the research of new laser technology. We focus on developing, characterising and applying novel ultrafast lasers, near- and mid-infrared solid-state laser devices, as well as semiconductor diode laser systems. We have a track record of developing a wide range of laser systems, many of which are available for application testing. These include 1 μm wavelength ultrafast oscillators (Yb:YAG, Yb:KYW and mode-locked semiconductor lasers), ultra-fast amplifiers (Yb:fibre and Yb:YAG slab architectures), 1350-4000-nm optical parametric oscillators, 1530-nm femtosecond fibre lasers and 450–1500-nm supercontinuum sources. The Centre has the capability to develop bespoke laser systems, and as such we have the expertise, equipment and capability to fully characterise laser systems (e.g. beam profiling of high power laser beams up to kW-level; precision ultrafast pulse characterisation; as well as laser wavelength measurement in the visible, near-, mid- and far-infrared).

CENTRE FOR INDUSTRIAL PHOTONICS LABORATORIES

The laboratories at Cambridge encompass a range of both high average power lasers (including fibre lasers up to 4kW) and ultrashort (femtosecond) pulsed lasers, together with a suite of analysis equipment, such as beam analysers and a FLIR thermal camera.

ANALYTICAL FACILITIES

Based at the University of Manchester we have a suite of 20 electron microscopes, comprising 12 scanning electron microscopes (SEMs), two dual beam Focused Ion Beam (FIB) microscopes, and five transmission electron microscopes (TEMs). This includes the recently installed state-of-the-art FEI Titan G2 80-200 scanning transmission electron microscope (S/TEM) with ChemiSTEM™ technology, the first of its kind in the UK. TEM preparation of complex specimens and serial sectioning is possible with the two dual beam Focused Ion Beam (FIB) microscopes: an FEI Nova 600i, equipped with an HKL electron backscattered diffraction (EBSD) system, and an FEI Quanta 3D FIB. In addition to our dual beam FIBs, we also have an FEI Quanta 250 FEG SEM dedicated to 3D imaging at the nano-scale using a Gatan x-ray tomography and ultramicrotome capability (Gatan 3View and XuM). The FEI Magellan FEG-SEM has a resolution of 0.8 nm, and is equipped with Oxford Instruments Xmax80 SDD system, EBSD detector and an AZTEC integrated analysis system. We have 5 FEG-SEMs equipped with EBSD analysis systems. In addition to the Manchester facilities there is high quality analysis equipment (SEMs, optical microscopes, Raman microscope, mechanical testing) available at the other institutions.


EDWARDS
EDWARDS

Leadership Team

Professor Duncan Hand

Centre Director, Precision Laser Processes

Duncan Hand, Centre Director, has been a member of staff at Heriot-Watt University for over 20 years, following a PhD in fibre optics at the University of Southampton. Duncan's work on lasers in manufacturing includes laser precision machining; the use of adaptive optics in laser manufacturing processes; and laser micro-joining processes. In this work he collaborates with a range of companies including SPI Lasers, AWE, Renishaw and M-Solv. He has further research activity, in collaboration with the University of Bath, on the delivery of high peak power laser light through novel microstructured optical fibres, with applications in manufacturing and medicine.

Professor Len Cooke

Chair of the Independent Steering Committee

Professor Cooke graduated in Physics from Queen's University Belfast. Following completion of a PhD in Laser Plasma interaction he joined the laser group at AWE Aldermaston where he worked on the development of X-ray diagnostic equipment and the commissioning of the HELEN high Power Laser. He joined the Optics and Laser technology Department of BAe Systems in 1984, becoming Department Head in 1989. The dept comprised ~35 research scientists and was responsible for the development of Photonics and Laser Technology for defence and Aerospace applications. He retired in November 2010.
He was a cofounder of the AILU and is also chairman of the Steering group of the CIM in Photonics at Southampton University.

Professor Stewart Williams

Fusion Based Processes

Stewart Williams has nearly thirty years' experience in research of laser material processing for manufacturing applications. This has been both in industry and more recently in academia. Topics have covered welding, cutting, drilling, micromachining and surface treatments. The main focus for his current research is elimination of black art in laser processes. This is being tackled by understanding scientific fundamentals in processes and then working how to apply them. The objective is to increase the industrial use of laser based production processes. This has approach has already been proven in laser keyhole welding and is being extended further.

Professor Bill O'Neill

Process Monitoring & Control

Bill O'Neill is Professor of Laser Engineering within the Cambridge University Engineering Department and Director of the Centre of Industrial Photonics. He has written over 170 research publications and scientific papers on the subject of laser-matter interactions, optical engineering, laser based manufacturing technologies, and micro/nano fabrication techniques. He is a member of the international advisory panel of the National Laser Centre of South Africa, a Director of the Laser Institute of America, and advises industry on a number of laser based manufacturing technologies.

Professor Daniel Esser

Laser Engineering

Daniel Esser is a professor in Laser Device Physics & Engineering at Heriot-Watt University, focussing on diode-pumped solid-state lasers and devices in the near and mid-infrared spectral range. His research background include key demonstrations of Nd-doped systems for 1 μm operation, Tm-doped systems at 1.9 μm and Ho-doped lasers and amplifiers for high energy 2 μm operation. His research interests include power and energy scaling modern lasers, as well as the myriad applications where these lasers are used. Daniel has a relentless passion to see new technological developments in diode-pumped solid-state lasers to be adopted by industry.

Dr Chris Sutcliffe

Powder Bed Additive Manufacturing

Dr Chris Sutcliffe has worked in a range of fields including laser processing using short pulse duration lasers, cold gas dynamic manufacturing, stereolithography of anatomical phantoms, selective laser sintering of medical devices, the production of controlled release oral dosages and selective laser melting. He is now recognised as an expert in the field of selective laser melting; in particular in the design of production manufacturing equipment and the development of next generation orthopaedic, trauma, spine and CMF implants for which he holds base technology and device design patents which have been licensed internationally. He has extensive industrial experience including being R&D Director at MTT Technologies.

Professor Phil Prangnell

Material Characterisation

Phil Prangnell's research activities are focused on studying advanced thermomechanical processing and joining techniques for light alloys (mainly aluminium and titanium). In particular, he is interested in understanding and modelling interactions between phase transformations, deformation microstructures, and industrial processes. He has worked extensively with the aerospace industry on developing welding techniques for aerospace alloys. In recent years his welding research had focused on joining dissimilar metals and friction welding, as well as variations on the friction stir welding process (e.g. FSSW, static shoulder FSW, USW etc.). He is also actively engaged in understanding relationships between microstructure and properties in additive manufacturing.

Professor Denis Hall

Outreach Co-ordinator

Denis Hall is the Centre's outreach co-ordinator. As Professor of Photonics at Heriot-Watt University he conducted research on laser device physics and applications his group pioneered ultra-compact high power planar waveguide lasers, exploiting concurrent research in RF discharge physics and optical waveguides to develop new laser concepts based on 2-D laser power scaling and novel laser resonators. Such lasers are now successful industrial products for several global companies. His work, part of a general industrial orientation involving partnership in many industry/university collaborative research projects, has produced a series of commercial laser products and industrial laser-based systems. He has co-founded three successful start-up companies producing lasers and photonic systems.

Andrew Rutherford

Outreach Officer

Andy Rutherford is the Centre's Industrial Outreach Officer. His experience has been in the development of partnerships between industry and the Higher Education sector, creation of communication materials in a range of on and offline media, and events organisation.

Key People

Professor Howard Baker

Laser Engineering

Professor Andrew Moore

AWE William Penney Fellow, Optical Diagnostics

Dr Peter Fox

Lecturer in Additive Manufacture

Dr Supriyo Ganguly

Lecturer in Welding Science

Professor Derryck Reid

Ultrafast Optics & Director of EPSRC CDT in Applied Photonics

Alex Peden

Centre Co-ordinator

Dr William MacPherson

Lecturer in Applied Optics & Photonics

Dr Jonathan Shephard

Reader in Applied Optics & Photonics

Dr Robert Maier

Research Fellow in Sensor & High Power Laser Applications

Dr Robert Thomson

Reader in Applied Optics & Photonics

Researchers

- Dr Ian Ashton
- Dr Rainer Beck
- Dr Antoine Berrou
- Dr Richard Carter
- Dr Christine Crombie
- Dr Tavi Ciuca
- Wojciech Gora
- Dr Filomeno Martina
- Dr Sonia Meco Martins
- Dr Jinesh Mathew
- Dr Krste Pangovski
- Dr Goncalo Rodrigues Pardal
- Dr Peter Schemmel
- Dr Wojciech Suder
- Dr Usani Unoh Ofem
- Dr Krystian Wlodarczyk

EPSRC Centres for doctoral Training

The Centre for Laser-based Production Processes has links to several EPSRC Centres for Doctoral Training that compliment and augment the research effort of the Centre. These centres offer 4 year PhD or EngD programmes in areas related to the work of the centre, providing more opportunities for collaboration between industrial and academic partners.

EPSRC CENTRE FOR DOCTORAL TRAINING IN APPLIED PHOTONICS

The Centre can fund up to 10 new Research Engineers each year, including a stipend of £20,100 for 2010/11 intake plus fees paid. The Centre currently has 45 Research Engineers ranging from those in their 1st year to those who are in the final stages of writing-up their thesis. Projects range from fundamental research aimed at developing company technical capabilities to applied research and development of product prototypes.

www.idcphotonics.hw.ac.uk

EPSRC CENTRE FOR DOCTORAL TRAINING IN ADVANCED METALLIC SYSTEMS

The Centre was set up to address the critical shortage of doctoral level metallic material specialists in the UK. Graduates from physical science and engineering disciplines over a 4 year period are trained in fundamental metallurgical science and engineering as well as undertaking an industry sponsored multi-disciplinary cutting-edge doctoral project.

www.metallicscdt.co.uk

EPSRC CENTRE FOR DOCTORAL TRAINING IN ULTRA PRECISION

Many emerging sectors and next generation products will demand large scale ultra precision (nanometre level tolerance) complex components. Such products include: next generation displays, plastic electronic devices, low cost photovoltaic cells, energy management and energy harvesting devices and logistics, defence and security technologies. Their product performance is set to advance and the innovative manufacturing based on ultra precision technologies for these products defines the scope for the EPSRC Centre.

www.cdt-up.eng.cam.ac.uk

EPSRC CENTRE FOR DOCTORAL TRAINING IN RENEWABLE ENERGY MARINE STRUCTURES

The Centre of Renewable Energy Marine Structures (REMS) will train fifty Engineering Doctorate (EngD) students over an eight-year period, admitting ten new students each year for five years starting in October 2014. This is a collaborative partnership between Cranfield University and the Department of Engineering Science at the University of Oxford in which the Centre for Laser-based Production Processes is a partner.

www.rems-cdt.ac.uk

EPSRC CENTRE FOR DOCTORAL TRAINING IN ADDITIVE MANUFACTURE

The primary objective of the Centre for Doctoral Training in Additive Manufacturing and 3D Printing is to produce research leaders to tackle the major scientific and engineering challenges over the next 10-15 years in enabling Additive Manufacturing and 3D Printing to play a prominent role in manufacturing, providing the people and talent to fuel this new industrial revolution.

www.nottingham.ac.uk/additivemanufacturing

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