Materials Systems for Extreme Environments, XMat, EP/K008749/2

**Period of Grant: 01.02.2013 – 31.01.2018**

### Final Report

1. **Executive Summary**

This Programme Grant was undertaken by four academics in three different universities, viz. Prof Jon Binner (Birmingham – originally Loughborough), Prof Mike Reece (Queen Mary) and Profs Bill Lee and Mike Finnis (Imperial College). The research programme focused throughout on the original vision, viz. *the development of the required understanding of how the processing, microstructures and properties of materials systems operating in extreme environments interact to the point where materials with the required performance can be designed and then manufactured*. The research has involved 17 major projects, 13 postdoctoral and 4 PhD, and there were also a total of 13 different Visiting Researchers.

The team has undertaken research that is of direct relevance to the strategies of all three universities involved in the programme. Each is interested in engineering novel solutions via high quality research that leads to internationally leading publications, recruitment of outstanding PhD students and results that will not only have a significant impact on the field being pursued but also, in some cases, commercial potential. We believe that we have achieved all of these goals and that, as a result of the work done to date, the UK has been propelled to the forefront of research in the field of developing materials for applications involving extreme environments. Evidence for this includes, amongst many other parameters, the number of papers published; 91 to date with others in press and being written; two patents published; 12 keynote lectures, 5 plenary lectures and 54 invited lectures, 29 other lectures plus 32 invitations to visit UK and overseas laboratories. One major international conference was hosted in Windsor UK in November 2017 by XMat, 14 other international conferences have had organisational input from the XMat team and Jon Binner appeared on the One Show on BBC 1. Exploitation of some of the research has started, and, possibly most importantly, we have created a completely new field of ultrahigh temperature ceramic matrix composites and have changed the way in which research is done in this field, not only in the UK but also overseas. For example:

* Our work at the University of Birmingham, UoB, and Imperial College, ICL, has resulted in ultra-high temperature ceramic matrix composites, UHTCMCs, and controlled porosity ceramics respectively that are both able to cope far better with thermo-mechanically demanding environments. This has led to many invitations to give Keynote, Plenary and Invited talks at international conferences and changed the way that UHT ceramics & composites, UHTCs, are perceived. As a result, many of the internationally leading groups are adopting similar approaches, e.g. for composites in the USA and Italy and controlled porosity ceramics in first Australia and now the USA. The ultra-high temperature composites developed at UoB have also been explored for a specific end-application by the Anglo-French defence company MBDA in joint research and a prototype component produced taking the work to approximately TRL4. It passed both mechanical and oxy-ablative testing. In addition, two of our publications have received international recognition; one paper was recognised as the best paper to be published by the Journal of the European Ceramic Society 2015 whilst a different paper won the IOM3 Pfeil Award in 2017.
* The work at Queen Mary University, QMUL, has resulted in a genuinely world-leading facility that combines the relatively new spark plasma sintering, SPS, process with the even newer flash sintering, FS, to yield the completely novel Flash SPS. This work has led to the ability to develop a range of novel materials that simply could not be fabricated otherwise. They have filed a UK patent application and have been awarded £40k to support Proof of Concept to commercialize / license the technology. They are in discussion with 3 industrial partners to verify the applicability of the novel sintering method to their industrial needs.
* The work at Imperial College London, ICL, on the irradiation and thermal damage of WC in hard radiation environments led to a patent that was subsequently licensed by Tokamak Energy Ltd, who contributed financially to the development through XMat.
* On the theoretical modelling front, the research at ICL has led to the development of an improved approach (called TU-TILD) to achieve fully anharmonic DFT calculations, providing at least an order of magnitude improvement in efficiency compared to the former approach (UP-TILD), which proved simply too slow for the calculation of thermophysical properties of UHTCs. This will enable *ab initio* calculations of more complex UHTCs and to higher temperatures than hitherto possible.

The ability to use the money flexibly has helped to draw in new partners and stimulated new research activity in timely areas, such as composites, Flash SPS and MAX phase ceramics. Existing partnerships have been extended, e.g. with DSTL, AFRL and ISTEC, and new partnerships created, e.g. with MBDA, Element Six, Tokamak Energy and the Max-Planck-Institut für Eisenforschung in Düsseldorf, Germany. Approximately £750k of additional projects resulted with another £7.92M attracted in projects that XMat helped to ensure came to the partners, but which were not formally part of XMat. each case, company funding has been leveraged with funding from Xme involving one postdoc at UoBogramme involving one postdoc

Funding has been used to attract Visiting Researchers; these have included Prof Michel Barsoum from Drexel University, Prof Bill Fahrenholtz of the University of Missouri Science & Technology (MS&T), Prof Takao Mori of NIMS in Japan and Prof Guo-Jun Zhang of the Shanghai Institute of Ceramics in China. Funding has also been used to send XMat researchers to work in laboratories outside of the consortium. For example, Davey (PhD) spent time at ICAMS in Bochum learning CALPHAD techniques, D’Angio (PhD) had a period at MS&T and Porter (PhD) spent time at his sponsor, the US Air Force Research Labs, AFRL, and at Worcester Polytechnic Institute in the USA learning how to model gas flow in porosity. Finnis (Investigator) spent time collaborating at both ICAMS and MPIE Düsseldorf, partially funded by his Alexander von Humboldt award.

The original management structure was simplified when the original approach was found to be too clumsy; the result was greater efficiency. Further changes included a refresh of the composition of both the Management Board and International Advisory Panel, IAP, after 3 years of the programme. The IAP is complemented for its tremendous support with members travelling from overseas to attend all meetings. Progress on each individual project was monitored via quarterly presentations made to the entire consortium by the researchers concerned; this provided an update, allowed an opportunity for searching questions to be asked and the direction of travel to be revised and ensured that all of the researchers knew what all of the others are doing. In addition, the researchers themselves developed their own quarterly network meetings, which led to significant interaction and cross-fertilisation of ideas. Two Industry Days were held in 2015 and 2017, a workshop on *Theory and Simulation of Materials for Extreme Environments* was held in Abingdon, UK, in 2016 and the fourth in the series of prestigious, international UHTC workshops, *UHTC IV*, was hosted in Nov 2017 in Windsor, UK. All events were regarded as successes.

In terms of taking relevant results through to commercialisation, QMUL are working closely with Kennametal to commercialise the Flash-SPS process. The knowledge and know-how in XMAT are also being applied to other classes of materials in other projects, including thermoelectrics and hard magnetic materials. The award of:

* An €8M Horizon2020 grant, led by ISTEC in Italy, by the European Commission to a consortium including UoB, Airbus, DLR and others;
* The EPSRC *Carbides for Future Fission Environments (CAFFE)* grant to Cambridge, Manchester and ICL, and
* ICL’s participation in the Westinghouse-led Collaboration for *Advanced Research on Accident Tolerant Fuel (CARAT)* network

are all provide funding and collaborations to develop the work of XMat further. UoB have worked with MBDA, DSTL and DGA in France to evaluate UHTC-based composites for commercial application. As mentioned earlier, a prototype part has been made and tested successfully.

Information on the research programme remains available via a website, see <http://www.xmat.ac.uk/>, which has both secure and open areas.

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**Abbreviations**

|  |  |
| --- | --- |
| ACerS | American Ceramic Society |
| ADMACOM | Advanced Manufacturing routes for metal/Composite components for aerospace |
| AFRL | Air Force Research Laboratory, USA |
| ANSTO | Australian Nuclear Science & Technology Organisation |
| ATFs | Accident tolerant fuels |
| C/HVN | Carbon fibre / HVN composites developed by Onera in France |
| CAFFE | Carbides for Future Fission Environments grant (an EPSRC-funded research programme) |
| CALPHAD | Calculation of Phase Diagrams |
| CARAT | Collaboration for Advanced Research on Accident Tolerant Fuel |
| CASC | Centre for Advanced Structural Ceramics, Imperial College London |
| CIMTEC | International Conference on Modern Materials and Technologies held in Italy |
| CMC | Ceramic Matrix Composites |
| CNR | Consiglio Nazionale Delle Ricerche, Genoa, Italy |
| CVI | Chemical Vapour Infiltration |
| DFT | Density Functional Theory |
| DISTINCTIVE | Decommissioning Immobilisation and storage soluTIons for NuClear wasTe InVEntories) |
| DSTL | Defence Science & Technology Laboratory, UK |
| DTP | Doctoral Training Partnership (funded by EPSRC) |
| EC | European Commission |
| ECAS | Electric Current Assisted Sintering |
| ECerS | European Ceramic Society |
| EPSRC | Engineering & Physical Sciences Research Council, UK |
| ERC | European Research Council |
| DGA | Directorate General of Armaments (French equivalent of the British Ministry of Defence) |
| FS | Flash Sintering |
| FSPS | Flash Spark Plasma Sintering |
| HP | Hot Pressing |
| ICACC | International Conference and Expo on Advanced Ceramics and Composites (US conference series) |
| ICAMS | Interdisciplinary Centre for Advanced Materials Simulation (Germany) |
| ICL | Imperial College London |
| IP | Intellectual Property |
| JECS | Journal of the European Ceramics Society |
| LU | Loughborough University |
| MCM-ITP | Missiles Innovation and Technology Partnership |
| MOD | Ministry of Defence (UK) |
| MPIE | Max Planck Institute for Iron Research GmbH (Düsseldorf, Germany) |
| MTC | Manufacturing Technology Centre (Ansty, UK) |
| NIRAB | Nuclear Innovation and Research Advisory Board |
| NNL | National Nuclear Laboratory, UK |
| OAT | Oxyacetylene Torch |
| PACRIM | Pacific Rim Conference of Ceramic Societies |
| PDRA | Post doctorate research assistant |
| QMUL | Queen Mary University, London |
| RF | Radio Frequency |
| SEM | Scanning Electron Microscope |
| SMEs | Small & Medium Size Enterprises |
| SPS | Spark Plasma Sintering |
| TEM | Transmission Electron Microscopy |
| TFL | Transport for London |
| TRL | Technology Readiness Level |
| TU-TILD | A modelling package to be used with DFT |
| UHTC | Ultra-High Temperature Ceramics |
| UHTCMCs | Ultra-High Temperature Ceramic Matrix Composites |
| UoB | University of Birmingham |
| UP-TILD | A modelling package to be used with DFT |
| WDS | Wavelength Dispersive Spectroscopy (used with SEM and TEM) |
| WPAFB | Wright-Patterson Air Force Base |
| XRD | X-Ray Diffraction |

**Main Body of Report**

**3.1 Introduction**

The conditions in which materials are being required to operate are becoming ever more challenging with increasing temperatures and pressures being required in their manufacture and applications such as energy generation, transport and environmental clean-up. Often these extreme temperatures are combined with severe chemical environments and, in the nuclear industry, exposure to high energy ionising radiation. The result is that new and significantly enhanced materials are needed that can operate under these conditions.

To achieve this involves the development of materials with new compositions and microstructures, and these will often require completely new processing routes. In addition, the need for long-term reliability in many components means that defects will need to be kept to an absolute minimum or defect-tolerant systems developed. Furthermore, the materials will often not function in isolation but as part of a system and it is the behaviour of the latter that is crucial. So interactions between different materials, the joining processes, the behaviour of the different parts under extreme conditions and how they can be made to work together must all be understood.

The key to speeding up the application of these next-generation materials is the development and use of modelling techniques that link different lengths and time scales, allowing the materials chemistry, microstructure, processing strategy and component design to be defined. Experimental work is required that can validate the models and develop the necessary understanding, not just in specific materials systems but more broadly across different materials, particularly those based on high melting point materials.

The vision for the Programme Grant was *the development of the required understanding of how the processing, microstructures and properties of materials systems operating in extreme environments interact to the point where materials with the required performance can be designed and then manufactured.* The primary goals of the programme did not change during the five year period in which XMat was in existence, though, as expected, there were modifications to some milestones and deliverables.

The Programme Grant has propelled the UK to the forefront of research in the field of developing materials for applications involving extreme environments. Evidence for this includes (details may be found later in this report):

* The 9 senior colleagues from overseas organisations who are willing to give up their time to fly to the UK for 2 days each year to sit on our International Advisory Board at our Annual Meetings in October and give us their advice, Annex 2. Clearly they feel that what they are gaining in return makes it worth it;
* The 12 keynote lectures, 5 plenary lectures, 54 invited lectures and 29 other lectures that members of our team have given to date at international conferences plus 32 invitations to visit UK and overseas laboratories, Annex 3;
* The 91 publications and 2 patent applications that have been made to date by the team, Annex 4;
* We hosted in the UK the fourth in the series of prestigious, international UHTC workshops, UHTC IV, in 2017;
* The 22 UK and overseas institutions who became involved with XMat research programmes, Annex 2;
* The fact that we changed the way in which research is done in this field, not only in the UK but also overseas, and created a new research field, UHTCMCs.

The last point merits further expansion, particularly since several changes have been driven by XMat research.

1. Historically, research into UHTCs has focused on producing monolithic ceramics. Whilst these offer excellent hardness and stiffness combined with good strength and oxidation and ablation resistance, their toughness is far too low for applications where very severe thermal shock combined with vibratory mechanical stresses occurs. Work within XMat has resulted in both fibre-reinforced composites (UoB) and controlled porosity ceramics (ICL) that exhibit far superior toughness and, for the composites, materials that can withstand even the most demanding of thermal shock environments (e.g. temperature changes of up to 1000oC s-1). Joint work by UoB, QMUL and ICL on joining UHTCs is also changing the way people think. All this has led to changes in the way that UHTCs are perceived, with greater work being undertaken on composites, controlled porosity systems and combinations of monolithics and composites.

* AFRL in the USA (Dr Allan Katz, International Advisory Board member) have largely stopped working on monolithic UHTCs, focusing instead on composites;
* the University of Melbourne in Australia (Prof George Franks) began working on controlled porosity UHTCs, though this work has now also started at Virginia Tech in the USA (Dr Carolina Tallon); and
* ISTEC in Italy (Dr Diletta Sciti, International Advisory Board member) has also initiated work on the concept of UHTCMCs by leading an €8M H2020 grant that also involves UoB. This new class of composite combines all of the benefits of fibre-reinforced ceramic matrix composites with the temperature capability of UHTCs for applications in erosion resistant rocket nozzles and thermal protection systems.

1. The combination of the concepts of spark plasma sintering, SPS, with those of flash sintering, FS, at QMUL has resulted in a world-leading facility, table 1, and hence a world-leading position, being achieved. They have filed a UK patent application and have been awarded £40k to support Proof of Concept to commercialize / license the technology. They are in discussion with 3 industrial partners to verify the applicability of the approach to their industrial needs.

Table 1: Capability of the combined SPS/FS facility at QMUL

|  |  |  |
| --- | --- | --- |
| **Capability** | **QMUL** | **Rest of the world** |
| Maximum temperature / oC | 2500 | 2200 |
| Maximum pressure / GPa | 1 | 0.1 |
| Maximum heating rate / oC min-1 | 105 | 102 |

This work has led to the ability to develop novel materials that simply could not be fabricated otherwise, e.g.:

* Flash sintered ZrB2 and SiC have been densified in a few tens of seconds leading to 99% time and energy savings compared to conventional SPS;
* Even the highest melting temperature ceramics (>4,000oC) can now be sintered to near theoretical density by using sintering temperatures approaching 2500oC;
* The use of 0.5 GPa with carbon composite dies up to 1800oC and 1 GPa using SiC dies up to 1600oC has allowed UHTCs to be densified to near theoretical density, thus preserving the fine/nano microstructure of the starting powders;
* A much better understanding of electric field effects has been gained, including addressing the question of whether a plasma is formed during SPS;
* Along with the ICL research team, strategies have been developed to achieve UHTCs with superior oxidation resistance based on the formation of a continuous network of protective SiC phase.
* Development of MAX and other carbide phase nuclear fuel cladding systems with sufficient refractoriness and oxidation resistance to survive the conditions which occurred in the Fukushima Daiichi reactors.

Existing partnerships have been extended and new partnerships created as a result of XMat, Annex 5, some being leveraged by XMat funding. DSTL extended their pre-existing relationship with both UoB and ICL via separate funded research programmes; the Anglo-French defence company MBDA funded a programme at UoB, Tokamak Energy funded a programme at ICL that led to a patent and AFRL funded a PhD student. On the theoretical side, we established strong collaborative links with the Max-Planck-Institut für Eisenforschung in Düsseldorf, who are doing pioneering work on the modelling of high-temperature thermophysical properties. each case, company funding has been leveraged with funding from Xme involving one postdoc at UoBogramme involving one postdocA range of other related projects have also been initiated, Annex 5, with XMat helping to ensure that they were attracted.

We are making excellent progress towards our vision of understanding of how the processing, microstructures and properties of materials systems operating in extreme environments interact to the point where materials with the required performance can be designed and then manufactured. Challenges remain, however, not least the ability to use modelling effectively to not only support the experimental work but to lead it. Work performed within XMat has led to the development of an improved approach (called TU-TILD) to achieve fully anharmonic DFT calculations, providing at least an order of magnitude improvement in efficiency compared to the former approach (UP-TILD), which proved simply too slow for the calculation of thermo physical properties of UHTCs. This has enabled *ab initio* calculations of more complex UHTCs and to higher temperatures than hitherto possible. As one example, the approach has been used to calculate the thermodynamic properties of ZrC up to its melting point. In related work, a systematic review has been carried out of the existing UHTC phase diagrams, involving experimental investigations and theoretical calculations. Weaknesses and inconsistencies in the existing thermodynamic descriptions have been identified and, based on these, the CALPHAD approach has been used to provide a complete description of the B-C-Hf-Zr system. This has suggested entirely new compositions, based on quaternaries, ternaries & solid solutions, for experimental investigation; systems that have the potential to operate in even more severe environments than the end-member phases examined to date.

Finally, a Research Data Management system (BEAR Datashare) was utilised at UoB for all the work undertaken in line with Open Access and Open Data requirements. This has acted as a “Knowledge Management” tool.

**3.2 Vision, Ambition and Research Programme**

As indicated in Section 2.1, the fundamental aim of the programme did not change throughout, though it underwent a degree of refinement over the course of the 5 years as a result of successes achieved and consequent new challenges that arose.

A total of 16 different projects were initiated within the XMat consortium. These can be roughly broken down across the 5 topics illustrated in figure 1, although there were a number of projects that were deliberately at the interfaces between them. Each project is summarised via the templates in Annex 1.

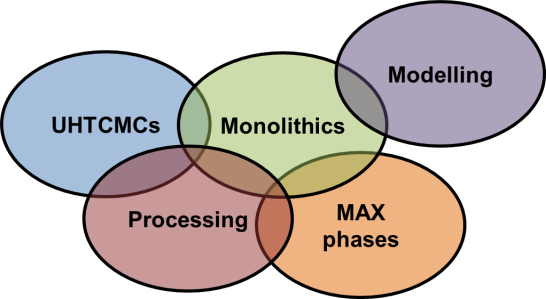


Fig 1: The relationship between XMat projects undertaken to date.

Approximately £750k in new projects directly related to XMat have been attracted and, in addition, another £7.92M has been attracted in projects that XMat helped to ensure came to the partners, even though they are not formally part of XMat. Details may be found in Annex 5. The ability to use the money in this way has helped to draw in new partners and stimulate new research activity in timely areas, specific new directions include:

* The development of flash-SPS (QMUL)
* Closer collaboration on new systems such as Hf-Ta-C and MAX phases (ICL & QMUL)
* Increased emphasis on nuclear applications (ICL), including accideATnt tolerant fuels (ATFs) and new materials for a fusion reactor diverter.
* The development of UHTCMCs (UoB)
* The joining of UHTCs (UoB, QMUL & ICL)

Funding has also been used to attract 13 Visiting Researchers, see Annex 6. We have attracted Prof Michel Barsoum from Drexel University (the world’s leading authority on MAX phases) to the UK from Sep to Dec 2015, acquiring funding from the Leverhulme Trust. He supported our MAX phase work and gave a post graduate course on structural ceramics at ICL as well as lectures/research visits at the NNL, Rolls-Royce and Birmingham, Cambridge, Liverpool, Manchester, Oxford and Sheffield universities. Earlier in 2015, from May to Jun, Prof Bill Fahrenholtz of the University of Missouri Science & Technology (a world leading authority on the mechanical and thermal properties of UHTCs) visited UoB and, as well as spending time working with the research team there and initiating new projects, he also gave a seminar at ICL. During July 2015, both Prof Takao Mori, the Group Leader of the Atomic Network Materials Group at NIMS in Japan and Prof Guo-Jun Zhang, the Deputy director of the State Key Laboratory of High Performance Ceramics and Superfine Microstructure at the Shanghai Institute of Ceramics in China, visited QMUL. They also took the opportunity to visit other universities and institutions across the UK. Funded by the Chinese Government, Dr Jie Xu, a postdoc at Tsinghua University in China, came to UoB for 6 months, from Sep 2015 to Mar 2016, to work on ‘Colloidal processing and properties of HfB2 ceramics’.

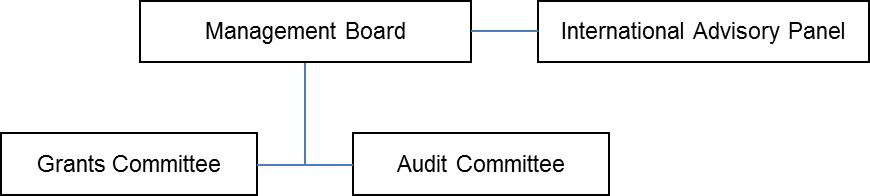
Funding has also been used to send XMat researchers to work in laboratories outside of the consortium. For example, Davey spent time at ICAMS in Bochum learning CALPHAD techniques and Finnis spent time collaborating at both ICAMS and MPIE Düsseldorf, partially funded by his Alexander von Humboldt award. Daniel visited the Nuclear Reactor Research Labs, Tokyo Institute of Technology from Nov 9-15, 2014 to collaborate on MAX phase research for ATF applications.

The strategy of having all of the researchers present their work to all the consortium every quarter worked very well, ensuring that all of the researchers knew what all of the others were doing. Not only did it lead to significant interaction and cross-fertilisation of ideas, as outlined in section 2.3, but it also kept everyone abreast of the latest developments and focused on the programme challenges. The team also regularly kept the list of milestones updated, proposing new milestones with every project undertaken, discussing modifying them when it was felt necessary at the quarterly management meetings and ticking them off when they were completed.

**3.3 Leadership and Management**

The management structure evolved over the 5 years of the programme; the original structure is shown in figure 2. It was found, however, that having separate Grants and Audit Committees was simply not necessary and by the beginning of the second year these activities were being handled by the Management Board. Further changes included the composition of both the Management Board and International Advisory Panel, which were reviewed and refreshed with new members being invited to join and existing members who had poor attendance records no longer being invited (a small number). Progress on each individual project was monitored via the quarterly presentations to the entire consortium by the researchers concerned; this provided an update, allowed an opportunity for searching questions to be asked and ongoing or potential future risks to be discussed by the entire team. Fortunately, throughout the programme there were no major problems to overcome; if there had been, they would have been handled in a professional manner, first by the specific project supervisor and then, if required, by the Management Board. Minutes of all of the meetings, together with copies of the presentations, were kept in a repository. Dissemination and exploitation was positively encouraged; there was significant dissemination, see Annex 3, and exploitation was initiated for some of the projects. In terms of the ‘people pipeline’, Annex 7 shows the destination of all of the key players involved in XMat.

Fig 2: The original XMat management structure



**3.4 Impact and Advocacy**

Two Industry Day meetings were held to date, on the 13th February 2015 at the University of Birmingham and the 16th November 2017 at the Institute of Materials, Minerals and Mining Headquarters in London. Excellent attendance was achieved at both events. A workshop was also held on *Theory and Simulation of Materials for Extreme Environments* in Abingdon from the 25th – 29th September, 2016 and the fourth in the series of prestigious, international UHTC workshops, *UHTC IV*, was hosted at Windsor, UK, from the 17th – 20th September, 2017. The latter was particularly well attended with nearly 100 attendees. XMat was well represented on the Centre for Advanced Structural Ceramics (CASC) stand at the Imperial College Festival Spring 2015 and Theresa Davey and Andrea D’Angio (PhD researchers) represented the UK on the American Ceramic Society President’s Council of Students Advisors during 2014-2016 (Theresa becoming the first international person to become Chair). Matt Porter (PhD researcher) also joined this prestigious group and currently chairs an outreach committee.

Annex 3 shows a reasonably complete list of talks given and visits made by the key players in the XMat team; it is a fairly lengthy list and represents excellent publicity for XMat and EPSRC – the latter was acknowledged in every presentation given.

Some of the investigators have roles outside of their universities that allow them to interact with policy makers and engage with the public; full advantage is taken of such opportunities to promote the R&D undertaken by XMat and, of course, the funding provided by EPSRC. Examples of these additional roles include:

**Jon Binner** was the President of the Institute of Materials, Minerals and Mining from Jan 2013 to Dec 2014 and Past President from Jan 2015 through to Dec 2016. He was also the Chair of the UK’s Ceramic Society from Sep 2012 – Sep 2016. Jon is also the UK’s representative on the Council of the European Ceramic Society, ECerS, sits on its Permanent Executive Committee and became the President Elect in July 2017. He will become President from July 2019 – July 2021. He has represented the UK on the International Ceramic Federation, ICF, since 2011 and in 2017 he was voted to become an AMPERE Fellow, one of only five worldwide over the 24 years that AMPERE (the Association for Microwave Power in Europe for Research and Education) has existed. In 2016 he won an MBDA UK Innovation Award with Dr Virtudes Rubio and the rest of the team working on the development of a prototype jet vane that withstood ~2500oC, a heat flux of ~6 MW m-2 and a gas velocity of ~Mach 0.6.

**Bill Lee** acted as Special Nuclear Advisor to the House of Lords Science and Technology Committee in 2013, is currently a member of the Government advisory Nuclear Innovation and Research Advisory Board (NIRAB) and a member of the National Nuclear Laboratory Technical Advisory Board. In July 2014 he won the Lee Hsun Lecture Award from the Institute of Metal Research, Chinese Academy of Sciences. He was President of the American Ceramic Society, ACerS, from Oct 2017 - Oct 2018 and elected a Foreign Fellow of the Indian National Academy of Engineering in 2017. In the same year, he also became a member of the US National Academies of Sciences, Engineering and Medicine committee for Independent Assessment of Science & Technology for the Department of Energy’s Defense Environmental Cleanup Programme and became Editor of Elsevier book series on Advanced Ceramics.

**Mike Reece** was appointed a Visitinig Professor at the Shanghai Institute of Ceramics from 2013 – 16 and an Adjunct Professor at the Northwestern Polytechnical University, Xian, from 2017 to current. In 2018, he was given the International Award of the Slovak Academy of Sciences. He was a board member of the EPSRC Thermoelectrics Network from 2013 – 2018.

**Mike Finnis** was invited by the Wissenschaftsrat (Advisory Board to the German Government) on 12/11/2013 to be a witness from the UK perspective to inform their development of recommendations for the way in which computational science should be included in the higher education curricula in German Universities.

**Annex 1**

**Project Information**

**UHTCMCs**

|  |  |
| --- | --- |
| **Title** | ***Ultra high temperature composites materials / Improvement of C/HVN low cost CMC*** (2 separate but related projects) |
| **Relationship to other projects/themes** | Funded by MBDA, an Anglo-French defence company, under the Anglo-French MCM Innovation and Technology Partnership (ITP) initiative with leverage provided by XMat. The work involved producing ultra-high temperature composites and was related to a similar project funded by DSTL, also with leverage from XMat. Note that the UK MOD and French DGA MCM ITP programme brings together industry, academia and SMEs to develop innovative technologies for defence applications. |
| **Project timing** | Formally, Jan 2014 –Dec 2015 but due to the appointment process, the actual dates were Apr 2014 –Mar 2016 |
| **Investigators** | Prof Jon Binner, UoB Email: [j.binner@bham.ac.uk](mailto:j.binner@bham.ac.uk) |
| **Staff Employed** | Dr Virtudes Rubio Diaz, UoB, 100% FTE |
| **Project Partners** | MBDA and Onera |
| **Aims** | The aim for the Ultra High Temperature Composites Material project was to investigate UHTC composites consisting of C fibre preforms impregnated with HfB2 powders and characterizing their mechanical and thermal performance with specific, but confidential, end applications in mind.  The aim for the Improvement of C/HVN Low Cost CMC project was to extend the high temperature performance and durability of a C/HVN composite material developed by Onera in partnership with MBDA without significantly increasing the cost of manufacturing process. |
| **Results** | **Ultra High Temperature Composites Materials**  Carbon fibre-HfB2 composites were prepared by vacuum impregnation and densified by carbon CVI. Then, the composites were machined to final shape to make shear, compression, flexural and tensile mechanical tests.  The impregnation of the samples was not as uniform as desired and this led to variability in the data obtained and lower values than expected. In general, samples with higher densities, i.e. more HfB2 inside, showed higher mechanical strengths. A new route was therefore developed to introduce more HfB2 powder into the preforms whilst simultaneously achieving more homogeneous samples.  A new batch of shear, flexural, compression 0/90, compression Z, tensile and demonstrator components were produced using the new route and far superior results were achieved. The new process could not be patented (confirmed by the patent agents at both UoB and MBDA) and so was considered ‘know how’. Although this did detrimentally affect the publications (which are still under consideration by MBDA, DSTL and DGA in France), it did lead to a PhD student being funded by MBDA to progress the IP further. The student started in October 2017.  A prototype jet vaneA prototype jet vane was constructed, see image left, and thoroughly tested both mechanically and thermoablatively. It met the mechanical requirements and no ablation was found on the surface after testing at 2500°C by oxypropane torch for 20 s.  **Improvement of Onera Low Cost CMC**  C/HVN composites provided by Onera were impregnated with powder slurries containing HfB2, ZrB2 or SiC. The composition of the slurries was modified and the rheology was studied to achieve the best impregnation possible. Impregnation efficiency was characterized by micro-CT.  Oxidation and ablation resistance was determined using an oxyacetylene torch, OAT, and the best results were obtained with HfB2 and ZrB2. The latter was selected for future research on the basis of its much lower cost.  Flexural strength and oxidation resistance were measured in different C/HVN process stage preforms impregnated with ZrB2 improving the oxidation resistance compared to original material by >500oC (from ~1100oC to at least 1600 – 1650oC). |
| **Publications** | ‘Ultra-high temperature ceramic composite materials’, Binner J, Rubio V, Ackerman T, Sousinet S, Bertrand X and Pommepuy N, Proceedings of the 4th MCM ITP Conference, Brighton, UK, Oct 2015.  ‘High temperature material improvement of C/HVN low cost CMD: Part 2’, Binner J, Rubio V, Ackerman T, Parlier M and Laguionie M, Proceedings of the 4th MCM ITP Conference, Brighton, UK, Oct 2015.  ‘Thermal ablation performance of Cf-HfB2 composites with and without a C matrix deposited by CVI’, Rubio V, Ramanujam P, Ramachandran DK, D’Angio’ A and Binner JGP, Proceedings of the 9th International Conference on High Temperature Ceramic Matrix Composites and Global Forum on Advanced Materials and Technologies for Sustainable Development 2016, HTCMC-9 & GFMAT 2016. |
| **Impact** | An **MBDA One Star Innovation Award, 2016** was awarded to the team that developed the prototype jet vane made of a carbon fibre / hafnium diboride powder composite that was shown to survive ~2500oC, a heat flux of ~6 MWm-2 and a gas velocity of ~Mach 0.6.  For the work involving Onera, the temperature capability of their material was extended by ~500oC.  A PhD studentship was funded by MBDA to pursue some of the ideas developed. The studentship started Oct 2017 and will run to Sept 2020. |

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| **Title** | ***Processing of UHTC composites for hypersonic applications*** |
| **Relationship to other projects/themes** | This project is funded by DSTL with leverage provided by XMat. The work involves processing of ultra-high temperature composites and is related to a similar project funded by MBDA, also with leverage from XMat. |
| **Project timing** | Jul 2014 – Jun 2016 |
| **Investigators** | Prof Jon Binner, UoB Email: [j.binner@bham.ac.uk](mailto:j.binner@bham.ac.uk) |
| **Staff Employed** | Dr. Prabhu Ramanujam, UoB, 100% FTE |
| **Project Partners** | DSTL, UK |
| **Aims** | To scale up the manufacturing process of ultra-high temperature composites based on carbon fibres and HfB2 powders, Cf-HfB2, and also to evaluate the high temperature mechanical and ablation properties.  To learn how to join Cf-HfB2 composites with themselves and subsequently with HfB2 monolithics and characterise the thermal and mechanical properties of the joined parts.  To investigate the synthesis of complex oxide UHTCs such as Ba(Mg1/3Ta2/3)O3 and characterise the material’s properties. |
| **Results** | Work had shown that when scaling up the size of the Cf-HfB2 composites, there was a tendency for the HfB2 powder to impregnate in a non-uniform manner. Thus a process to improve the homogenous distribution of the HfB2 powder in the carbon preforms was developed in conjunction with Dr Rubio, who was working on the MBDA project. This approach was further developed by being automated and 7 large test panels, 4 measuring 230 x 115 x 18 mm and 3 measuring 330 x 330 x 18 mm were produced successfully.  A new approach for joining of UHTC composites was also initiated in conjunction with Dr Laura Larimbe of ICL. Whilst the work was not completed, sufficient progress was made to allow consideration of a patent to protect the IP. This will be the subject of a meeting between Ploughshare Innovations (the MoD’s technology transfer company) and the two universities. Further optimisation of the process is required.  The oxyacetylene torch (OAT) testing facility that used to be at Loughborough University was installed at UoB and used to evaluate a range of different UHTC composites and monolithics. This includes a second round of samples under the AFRL-led ‘Round Robin’ that is driving the development of OAT testing standards. An oxypropane torch (OPT) was also constructed, again jointly between Drs Rubio Diaz and Ramanujam.  An oxide UHTC, barium magnesium tantalate, was synthesised using a solvothermal approach. The TEM results showed that the particles were ~15 nm in size, whilst the XRD suggested that the degree of crystallinity was too low to achieve the required thermo-physical properties above 2800°C. It is believed that longer reaction times are required to obtain phase pure BMT powders. |
| **Publications** | ‘Thermal ablation performance of Cf-HfB2 composites with and without a C matrix deposited by CVI’, Rubio V, Ramanujam P, Ramachandran DK, D’Angio’ A and Binner JGP, Proceedings of the 9th International Conference on High Temperature Ceramic Matrix Composites and Global Forum on Advanced Materials and Technologies for Sustainable Development 2016, HTCMC-9 & GFMAT 2016. |
| **Impact** | It was demonstrated possible to produce large plates of these composites and the manufacturing process was partially automated. |

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| **Title** | ***Fibre-reinforced UHTC ceramic matrix composites fabricated by RF-heated chemical vapour infiltration (RF-CVI)*** |
| **Relationship to other projects/themes** | Funded by XMat, the work involved creating a new RF-CVI facility and producing Cf reinforced UHTC composites. It is related to a PhD project funded by UoB on SiCf/SiC composites. |
| **Project timing** | Feb 2013 – Oct 2016 |
| **Investigators** | Prof Jon Binner, UoB Email: [j.binner@bham.ac.uk](mailto:j.binner@bham.ac.uk) |
| **Staff Employed** | Dr Anish Paul (Feb 2013 to Dec 2014) and Dr Dhavanesan Ramachandran (Jul 2015 to Oct 2016), UoB, 100% FTE each |
| **Project Partners** | None |
| **Aims** | The work involved producing C fibre / UHTC powder / UHTC matrix composites by RF-chemical vapour infiltration. The twin aims were to i) develop a process route capable of overcoming the problem with conventional CVI of very long processing times (6 - 8 weeks) and ii) to produce a new range of UHTCMCs showing properties that combine those of CMCs (high toughness) with those of UHTCs (high thermal and ablation resistance). Chemical, microstructural and thermo-mechanical characterization were undertaken. |
| **Results** | An RF-CVI facility was created and a methane gas line was introduced to allow the production of C fibre, UHTC powder, C matrix composites. In addition, an in-line chlorinator was developed that allowed refractory metal chlorides to be generated in a gaseous form so that they could be used for the chemical vapour infiltration of fibrous preforms to deposit refractory metal carbides. A BCl3 gas line was also introduced; this allowed the deposition of ZrB2. Preliminary tests Cf preforms loaded with a range of UHTC powders were undertaken and it became clear that the presence of UHTC powders improve the absorbtion of RF energy compared to the straight C fibre preforms. The equipment was subsequently used extensively in the subsequent C3Harme programme. |
| **Publications** | ‘Thermal ablation performance of Cf-HfB2 composites with and without a C matrix deposited by CVI’, Rubio V, Ramanujam P, Ramachandran DK, D’Angio’ A and Binner JGP, Proceedings of the 9th International Conference on High Temperature Ceramic Matrix Composites and Global Forum on Advanced Materials and Technologies for Sustainable Development 2016, HTCMC-9 & GFMAT 2016. |
| **Impact** | A new RF-CVI facility was created. |

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| **Title** | ***SiCf-SiC composites fabricated by microwave heated chemical vapour infiltration (MW-CVI)*** |
| **Relationship to other projects/themes** | This project was funded by the Univ of Birmingham in support of XMat. The work involved producing SiC/SiC composites using microwave CVI and is related to a similar project funded by the XMat grant on UHTCMCs. |
| **Project timing** | Jan 2014 – Jul 2017 |
| **Investigators** | Prof Jon Binner, UoB Email: [j.binner@bham.ac.uk](mailto:j.binner@bham.ac.uk) |
| **Staff Employed** | Andrea D’Angio’, UoB, 100% FTE (PhD student) – funded by UoB |
| **Project Partners** | None |
| **Aims** | The work was a basic science study of the production of silicon carbide fibre / silicon carbide powder / silicon carbide matrix composites (SiCf/SiCp/SiC) by microwave chemical vapour infiltration. The aim was to understand the effect of a wide range of process variables on the nature and location of the SiC matrix deposition within a SiC fibre preform. |
| **Results** | An investigation into the fundamentals of the deposition of silicon carbide within porous silicon carbide fibre preforms using microwave-enhanced chemical vapour infiltration has been undertaken. The study of the kinetics of deposition revealed an Arrhenius behaviour of the matrix growth rate against the temperature in the range 800-1000°C and a linear dependence on the pressure in the range 20 - 70 kPa. This is typical of a surface-reaction limited regime. The morphology of the SiC deposited changed with both temperature and pressure. Increases in both lead to a transition from a smooth, globular deposit morphology to something that was rougher and more angular; this corresponded to the transition from a nucleation to a growth regime. Stoichiometric SiC was predominantly found in the central region of the samples infiltrated at 1000°C, but the deposit became more silicon-rich (up to 2.6 at %) the farther from the initial deposit. Dielectric properties showed that ZMI Tyranno silicon carbide fibres readily absorbed microwave energy. In specific conditions of temperatures and pressures, 900-950°C and 50 kPa, an inside-out deposition pattern was observed indicating a temperature profile across the preform. Deposition of silicon carbide and silicon caused the gradual flattening of the temperature gradient. |
| **Publications** | ‘Mechanical properties and grain orientation evolution of zirconium diboride-zirconium carbide ceramics’, A. D’Angio’, J. Zou, J. Binner, Hai-Bin Ma, G.E. Hilmas, W.G. Fahrenholtz, *J. Eur. Ceram. Soc.* **38** 391-402 (2018).  ‘Thermal ablation performance of Cf-HfB2 composites with and without a C matrix deposited by CVI’, Rubio V, Ramanujam P, Ramachandran DK, D’Angio’ A and Binner JGP, Proceedings of the 9th International Conference on High Temperature Ceramic Matrix Composites and Global Forum on Advanced Materials and Technologies for Sustainable Development 2016, HTCMC-9 & GFMAT 2016.  ‘SiCf-SiC composites for energy applications’, Binner J and D’Angio A, MatiSSE Workshop, Joint Research Centre – Institute for Energy and Transport, Petten, the Netherlands, November 2015. |
| **Impact** | AFRL funded a 2nd PhD student to extend the work further in terms of the engineering involved. |

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| **Title** | ***SiCf-SiC composites fabricated by microwave heated chemical vapour infiltration (MW-CVI)*** |
| **Relationship to other projects/themes** | This project is ongoing and is being funded by the US Air Force Research Labs (AFRL) with a Univ of Birmingham scholarship in support of XMat. The work involved producing SiC/SiC composites using microwave CVI and is related to the project above. |
| **Project timing** | Feb 2016 – Jan 2019 |
| **Investigators** | Prof Jon Binner, UoB Email: [j.binner@bham.ac.uk](mailto:j.binner@bham.ac.uk) |
| **Staff Employed** | Matt Porter, UoB, 100% FTE (PhD student) – funded by AFRL & UoB |
| **Project Partners** | AFRL |
| **Aims** | The work is a science and engineering study of the production of silicon carbide fibre / silicon carbide powder / silicon carbide matrix composites (SiCf/SiCp/SiC) by microwave chemical vapour infiltration. The aim is to enhance the understanding of the effect of a wide range of process variables on the nature and location of the SiC matrix deposition within a SiC fibre preform. |
| **Results** | Work on the infiltration of SiC fibre preforms with an aqueous SiC slurry to fill porosity is now largely complete and the development of a SiC matrix inside the preform using microwave enhanced chemical vapour infiltration (MECVI) is underway. The work has concluded that slurry can be successfully added, consolidated and dried using vacuum bagging. Important parameters that have been considered include the impregnation technique, the resultant porosity distribution and size, the dielectric properties of the constituents and the consequential permeability of the preforms for chemical vapour infiltration. The results have shown that the addition of a powder reduced the average pore size by more than 50% and decreased the porosity significantly. A high degree of permeability could be maintained, however, within one deviation of the non-impregnated sample with a 10% decrease in porosity when the powder was added thus the amount of time required for MECVI to fill the remaining macro porosity was reduced without compromising the gases mean free path significantly.  With regards to the matrix formation stage using MECVI, kinetics, compositions, densification profiles, morphology and mechanism of growth of the SiC matrix have all been observed and analysed using a suite of characterisation techniques to see the effect of changing the processing variables. Transmission electron microscopy (TEM) and high resolution scanning electron microscopy (SEM) have been used to observe the degree of crystallinity of the resulting ß-SiC and more specifically the grain growth mechanism and thus the resulting morphology. Wave dispersive spectroscopy (WDS) and Raman has been used to determine the (consistently near stoichiometric) Si to C ratio with an accuracy of ±2% due to a small contribution from traces of oxygen present, the results corroborate with the data obtained using the TEM. Raman analysis identified the deposit as ß-SiC and a number of common polytopes have been found including 3C, 6H/15R and 4H. Results suggest MECVI is a viable method of producing SiC composites that are potentially suitable for the next generation of aerospace material, though a better understanding of the extent to which full densification can be achieved is still required.  Efforts are also ongoing to develop both a mathematical model of the pore closure in CVI process and an electromagnetic simulation of the microwave heating of the SiC fibre preforms. From this processing parameters will be backed out accordingly and verified using experimental methods and a thermal model will also be derived from the simulation respectively. |
| **Publications** | None to date, though a number of conference and other presentations have been made.  Poster – ‘Enhanced chemical vapour infiltration of high-temperature ceramic matrix composites’, 3GCMEA, July 2016, Cartagena, Spain  Poster – ‘Microwave enhanced chemical vapour infiltration of ceramic matrix composites’ MST ’16, October 2016, Salt Lake City, USA  Poster – ‘High-temperature ceramic matrix composites using microwave enhanced chemical vapour infiltration’, Ceramic matrix composites, November 2017 Engineering conferences international, Santa Fe, USA  Poster – ‘Optimisation of SiCf/SiCp Preform Prior to Matrix Consolidation Using Microwave Enhanced Chemical Vapour Infiltration’ 42nd ICACC, January 2018, Daytona beach, USA  Lecture – ‘Optimisation of SiCf/SiCp/SiC preforms prior to Microwave Enhanced Chemical Vapour Infiltration’ ECerS XIV, July 2017, Budapest, Hungary  Lecture– ‘High-temperature ceramic matrix composites using microwave enhanced chemical vapour infiltration’ 42nd ICACC, January 2018, Daytona beach, USA  Lecture – AFSOR Program review - ‘High-temperature ceramic matrix composites using microwave enhanced chemical vapour infiltration’ Fort Walton, May 2018, USA  Lecture – ‘High and Ultra-High Temperature Ceramic Matrix Composites’ Knowledge transfer network, June 2018, London |
| **Impact** | Ongoing. |

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| **Title** | **UHTC monoliths for supersonic applications** |
| **Relationship to other projects/themes** | This project was part of an integrated project that also involved UoB (Processing of UHTC composites for hypersonic applications) and, via the work on joining, also interacted with work at UoB within XMat with support from MBDA and the ADMACOM project at QMUL. |
| **Project timing** | June 2014 – October 2016 |
| **Investigators** | Dr Luc Vandeperre. Email: [l.vandeperre@imperial.ac.uk](mailto:l.vandeperre@imperial.ac.uk) |
| **Staff Employed** | Dr Laura Larrimbe, 100% FTE |
| **Project Partners** | DSTL, UK |
| **Aims** | To continue research into material development for the outer layer of a UHTC based protection system for space re-entry at very high heat flux, to find solutions to join this with UHTC based composites and to test and model performance in extreme environments. |
| **Results** | One of the key questions to be resolved in the material development area is the microstructure that allows components to survive both the high heat deposited into them as well as the thermal shock associated with rapid heating. A range of microstructures were produced and thermal shock results from laser heating established that a highly successful microstructure was achieved.  A second question was to develop a better understanding of the degradation of the material under very high heat flux. This built on work carried out in phase II, where it was shown that damage mechanisms were not geometry independent. Further work to develop a model allowed the prediction of both oxidation and melting during testing and good agreement between experimental observations and predictions was achieved. It was found that for extremely high heat fluxes (>50 MWm-2), performance was limited by direct melting of the material, whilst at lower but still significant heat fluxes (25-50 MWm-2), the shape remained stable for relatively short exposures (<1-2 minutes), but the progress of oxidation induces further melting and shape instability. At moderate heat fluxes, oxidation will occur, but this is much less of a problem.  In the area of up-scaling, large samples (Ø 30 mm x 55 mm, with hemispherical end) were successfully produced and delivered for arc jet testing. The modelling developed for laser heating was also capable of predicting that conditions set for arc-jet testing were unrealistic, as confirmed experimentally. New sample designs were made in collaboration with DSTL and allowed successful testing of the samples under arc-jet conditions.  Joining of the composites to the composites was also accomplished but this is the subject of a patent application so details cannot be revealed.  Tests to use a similar approach to bond a composite to a monolith were successful in as much that a bond between the two materials clearly formed. However, the large difference in coefficient of thermal expansion lead to a network of cracks in the monolith and these cracks penetrated into the composite and lead to detachment of the monolith by delamination within the composite. |
| **Publications** | ‘High Heat Flux Laser Testing of HfB2 Cylinders’, Larrimbe L, Pettina M, Nikbin K, Jones EL, Katz AP, Hawkins CJ, De Cerbo J, Brown PM,  Vandeperre LJ, *J. Eur. Ceram. Soc.* **100** [1] 293-303 (2017). |
| **Impact** | Critical defence data collected   * Arc jet testing of these materials added crucial new information into the defence material database of Dstl for their missile programme   Invited lectures at conferences   * Beyond Nickel Based Superalloys II, July 2016, Cambridge UK * 9th International Conference on High-Performance Ceramics, CICC-9, Guilin,China, 4th - 7th November 2015   Successful follow on funding   * EPSRC Programme grant : Transpiration Cooling Systems for Jet Engine Turbines and Hypersonic Flight, EP/P000878/1 |

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| **Title** | ***Structural reinforcement of HfB2 by HfC for hypersonic applications*** |
| **Relationship to other projects/themes** | Updating and extending creep data obtained by Dr Eugenio Zapata-Solvas on HfB2-based UHTCs. The results were obtained at ICL during 2017 as part of a masters project by ChenChen Liu supervised by Eugenio. |
| **Project timing** | May 2017 – September 2017 |
| **Investigators** | Prof. Bill Lee, ICL Email: [w.e.lee@imperial.ac.uk](mailto:w.e.lee@imperial.ac.uk)  Dr Eugenio Zapata-Solvas, ICL |
| **Staff Employed** | None |
| **Project Partners** | Prof. Mike Reece & Dr. Salvatore Grasso (QMUL)  Dr. Daniel Glymond (ICL)  Dr Ji Zou (UoB) |
| **Aims** | This project developed HfB2 composites by incorporating a second phase of precipitated particles within HfB2 grains, which was considered to be capable of delivering composites with higher flow stress than monolithic HfB2. These precipitates would act as obstacles for dislocation sliding at high temperatures producing an effective hardening of the HfB2 matrix. In order to maximize the hardening effect, a second phase which was incoherent with the h.c.p lattice as well as having a similar or higher refractoriness was desired. HfC was an ideal candidate as it has an f.c.c lattice and a melting point of ~3900°C. The desired microstructure in dense materials was obtained by hot pressing starting from nanostructured powders synthesized by Dr Ji Zou (University of Birmingham). |
| **Results** | Ideally nano-sized powders would have been used to fabricate HfB2 with microstructures containing HfC precipitates, however, due to deadlines and technical problems the project was developed using micron-sized HfB2 and HfC. The resulting creep resistance of the HfB2-HfC ceramic proved to be slightly lower than that of monolithic HfB2, which was attributed to the fact that the second phase was not acting as a precipitate because most of the particles were at the grain boundaries. Nonetheless, the creep resistance was higher than that observed in HfB2-SiC, which suggests that B diffusion through HfC is slower than through SiC. However, TEM studies are needed to confirm this. |
| **Publications** | None to date; a high-impact factor publication could be expected after the TEM studies are completed (JACerS or JECerS). |
| **Impact** | Project thesis on the MSc for Advanced Materials programme at ICL.  2 invited talks given:  *Creep of HfB2-based UHTCs up to 2000oC*; Ultra-High Temperature Ceramics: Materials For Extreme Environment Applications IV, 17-20 September 2017 Windsor, UK.  *Creep of HfB2-based UHTCs up to 2000oC* *or how important structural / dimensional stability could be on hypersonic applications*; ICC7, 7th International Congress on Ceramics, 17-21 June 2018, Fox de Iguazu, Brazil. |

**Monolithics**

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| **Title** | ***Processing and characterisation of ternary carbides and UHTCs for extreme environments*** |
| **Relationship to other projects/themes** | The project is funded by XMat and is related to development of UHTCs and MAX phases for aerospace and nuclear applications. |
| **Project timing** | Feb 2013 – Feb 2015 |
| **Investigators** | Prof Bill Lee, ICL Email: [w.e.lee@imperial.ac.uk](mailto:w.e.lee@imperial.ac.uk)  Prof Mike Reece, QMUL Email: [m.j.reece@qmul.ac.uk](mailto:m.j.reece@qmul.ac.uk) |
| **Staff Employed** | Dr Doni Daniel, ICL, 95% FTE  Dr Salvatore Grasso, QMUL, 3% FTE  Garry Stakalls, ICL, 3% FTE |
| **Project Partners** | **QMUL** as part of the XMAT programme (use of the SPS facility for fabricating Hf-Al-C and rare earth doped ZrB2 and HfB2 compounds).  **Tokyo Institute of Technology** (Dr Katsumi Yoshida)  **Japan Aerospace Exploration Agency** (Drs Takuya Aoki, Masaki Kotani and Toshio Ogasawara):Collaboration established to conduct tensile tests at 300°C / 250 bar water and water vapour corrosion tests at high temperature for up to 100 h.  **CARAT consortium** (led by Westinghouse): Working on ATF development based on MAX phase materials. |
| **Aims** | To develop: (i) single-phase ternary carbides, characterise them for the ATF and other applications in extreme environments and (ii) rare earth doped borides for improved oxidation behaviour. |
| **Results** | Ternary carbides including Hf2Al4C, Hf3Al4C6 and Hf2AlC have been fabricated by spark plasma sintering (SPS) and hot pressing (HP). Due to shorter holding time, HP seems to be the more appropriate method for the complete reaction for some compounds. The work was very successful in terms of fabricating Hf2Al4C5as *ICL were the first group to do so*. Evaluation of thermal, mechanical and oxidation behaviour was carried out. *Project Completed*  Commercially available Ti3SiC2 and Ti2AlC were evaluated for their tensile strength under the normal operating condition of a nuclear reactor (250 bar water at 300°C); results are yet to be obtained from the collaborators (TIT and JAXA, JAPAN). *Ongoing*  A full characterisation of rare earth doped ZrB2/HfB2 to improve the oxidation resistance of the composites has been carried out in collaboration with Dstl. *Project completed* |
| **Publications** | Microstructural evolution of HfB2–based ceramics during oxidation at 1600oC to 2000oC, DD Jayaseelan, E Zapata-Solvas, CM Carney, A Katz, P Brown, WE Lee, *Adv. in Applied Ceramics* **114** [5] 277-295, 2015.  Development of multi-layered thermal protection system (TPS) for aerospace applications, DD Jayaseelan, X Yanda, L Vandeperre, P Brown, WE Lee, *Composite, Part B***79** 392-405, 2015.  Structural and compositional analyses of oxidized layers of ZrB2-based ceramics, DD Jayaseelan, E Zapata-Solvas, R Chater, WE Lee, *J. Eur. Ceram. Soc*. **35** [15] 4059–4071, 2015. |
| **Impact** | Ongoing |

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| **Title** | ***Powder synthesis, green forming and densification (flash sintering and spark plasma sintering) of UHTCs*** |
| **Relationship to other projects/themes** | Produce and scale up fine UHTCs powders for use in a range of XMat projects; better understand the densification behaviour of UHTCs under a strong electric field; with DSTL: produce UHTCs with complex geometries for joining with UHTC-based composites |
| **Project timing** | Oct 2014 – Oct 2016 |
| **Investigators** | Prof Jon Binner, UoB. Email: [j.binner@bham.ac.uk](https://mail.bham.ac.uk/owa/redir.aspx?C=XWlaxMi86Eosg-1EEsILpLsnZTdpNE0-xGbz6qtF0BwIDR-QmvXVCA..&URL=mailto%3aj.binner%40bham.ac.uk)  Prof Mike Reece, QMUL. Email: [m.j.reece@qmul.ac.uk](https://mail.bham.ac.uk/owa/redir.aspx?C=uBCIdfHnSoMct07urm7Y0UtO3tCTdgJigDUt3XJFp9kIDR-QmvXVCA..&URL=mailto%3am.j.reece%40qmul.ac.uk) |
| **Staff Employed** | Dr Ji Zou, UoB, 100% FTE  Dr Salvatore Grasso, QMUL, 3% FTE |
| **Project Partners** | Prof William G. Fahrenholtz, Missouri University of Science and Technology, USA – pressureless sintering of UHTCs.  Dr T A Parthasarathy, UES, Inc., on-site contractor at AFRL, WPAFB, USA – modelling of oxidation behaviour of doped HfB2  Dr Prabhu Ramanujam, UoB – Joining of monolithic and composite UHTCs  Dr Salvatore Grasso, QMUL – SPS densification of monolithic UHTCs |
| **Aims** | 1.   Produce fine UHTC powders since these are not commercially available currently and make them available to a range of XMat-related projects.  2.   Develop advanced green forming methods for producing UHTCs with complex geometries;  3.   Develop an understanding of how the presence of an electric and/or electromagnetic field can enhance the sintering of ceramic materials. |
| **Results** | High purity, nanosized HfB2 and Ta doped HfB2 powders have been obtained starting from HfCl4 and B4C.  Stable HfB2 slurries with solid loadings up to 50 vol% have been prepared by adding PEI and adjusting the pH values of the slurry.  Crack-free HfB2 green bodies with complex geometry have been shaped via a gel casting approach assisted by bio-macromolecules.  Dense HfB2 and 5, 10 atm%TaB2 doped HfB2 ceramics have been obtained using spark plasma sintering.  Gel cast HfB2 samples have been successfully densified by presureless sintering at 2200oC with relative density over 95% and their mechanical and physical properties analysed.  High purity ZrC precursor with Hf content lower than 500 ppm has been prepared.  The ablation and crack healing behaviour of ZrB2-SiC-WC composites under oxyacetylene test have been investigated at different heat fluxes.  The volatility diagrams of α-WB at different temperatures have been calculated and compared with experiments.  Strong HfB2 powder green bodies with compressive strengths exceeding 20 MPa have been produced by two simple approaches..  Starting from the green body after debinding in argon, non-textured HfB2 ceramics (diameter ~20 mm and height ~4 mm) with a relative density of 95.1% were achieved using flash spark plasma sintering (FSPS) with a discharge time of 20 s, peak power of 19 kW and applied pressure of ~16 MPa. The lack of a need for a pre-sintering step resulted in energy savings compared to the densification of HfB2 ceramics by FSPS. |
| **Publications** | Ultra-low temperature reactive spark plasma sintering of ZrB2-hBN ceramics, J Zou, G-J Zhang, Z-J Shen & J Binner, *J .Euro. Ceram. Soc*., **36** 3637-3645 (2016).  *Invited Review:* Synthesis of ultra-refractory transition metal diboride compounds, WG Fahrenholtz, J Binner & Ji Zou, *Journal of Materials Research* **31** 2757-2772 (2016).  Thermoablative Resistance of ZrB2-SiC-WC Ceramics at 2400oC, J Zou, VR Diaz & J Binner, *Acta Materialia* **133** 293-302 (2017).  Flash spark plasma sintering of HfB2 ceramics without pre-sintering, J Zou, S Grasso, LF Liu, HB Ma, M Reece & J Binner, *Scripta Materialia* **156** 115-119 (2018).  Tungsten carbide: A versatile additive to get trace alkaline-earth oxide impurities out of ZrB2 based ceramics, J Zou, H Ma, A D'Angiò & Guo-Jun Zhang, *Scripta Materialia* **147** 40-44 (2018).  Mechanical properties and grain orientation evolution of zirconium diboride-zirconium carbide ceramics, A D'Angiò, J Zou, J Binner, H Ma, GE Hilmas, WG Fahrenholtz, *J. Euro. Ceram. Soc.,* **38** 391-402 (2018). |
| **Impact** | Further research was supported by EPSRC (MISE) focusing on analysing the interface of ultra-high temperature ceramics and composites.  A project was funded by BAe Systems involving HfB2 at UoB.  Two invited presentations at prestigious international conferences (ECERS and CICC).  Serving as organizing Committee member for the International Conference on High Performance Ceramics (CICC) series from 2019. |

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| **Title** | ***Irradiation and thermal damage of WC in hard radiation environments*** |
| **Relationship to other projects/themes** | This project was co-funded by Tokamak Energy Ltd and XMat. |
| **Project timing** | Sep 2014 – Sep 2016 |
| **Investigators** | Prof. Bill Lee, ICL. Email: [w.e.lee@imperial.ac.uk](mailto:w.e.lee@imperial.ac.uk) |
| **Staff Employed** | Dr Sam Humphry-Baker, ICL, 100% FTE |
| **Project Partners** | Tokamak Energy Ltd. co-funded this project and contributed with periodic update meetings and feedback.  Sandvik Hard Materials Ltd. contributed commercially available materials to be investigated.  Huddersfield University collaborated and performed ion-irradiations. |
| **Aims** | The primary aim of the project was to investigate the performance of tungsten carbide composites in hard irradiation environments. This involved (i) processing new material compositions, (ii) characterising their thermal and mechanical properties, and (iii) investigating degradation mechanisms under oxidation and irradiation damage. |
| **Results** | Tungsten carbide composites with iron-based binders were fabricated by liquid phase sintering and hot pressing, after which their microstructures were characterised by XRD and electron microscopy. Mechanical properties were measured by Vickers indentation, from which the hardness and fracture toughness were determined, and interpreted in terms of microstructural variables.  Oxidation behaviour was investigated using thermo gravimetric analysis, followed by post-mortem cross sectioning and x-ray diffraction – as well as oxyacetylene torch (OAT) testing at UoB. To improve oxidation resistance, a highly successful coating method was developed using pack cementation.  Finally, composites were irradiated by He-ions up to 500oC, using the in-situ electron microscopy facility, MIAMI. |
| **Publications** | ‘In-situ He+ irradiation of a fusion candidate WC-FeCr composite’, SA Humphry-Baker, R Harrison, G Greaves, A Knowles, GDW Smith, WE Lee and SE Donnelly, *Scripta Materialia* **155** 129-130 (2018). [doi.org/10.1016/j.scriptamat.2018.06.027](https://doi.org/10.1016/j.scriptamat.2018.06.027)  ‘Oxidation resistant tungsten carbide hardmetals’, SA Humphry-Baker, K Peng and WE Lee. *Int. J. Refract. Met. Hard Mater.* **66** 135-143 (2017). [doi:10.1016/j.ijrmhm.2017.03.009](http://www.sciencedirect.com/science/article/pii/S0263436816306199)  ‘Tungsten carbide is more oxidation resistant than tungsten when processed to full density’, SA Humphry-Baker and WE Lee, *Scripta Materialia* **116** 67-70 (2016)*.* [doi.org/10.1016/j.scriptamat.2016.01.007](http://dx.doi.org/10.1016/j.scriptamat.2016.01.007)  ‘Thermophysical properties of Co-free WC-FeCr hardmetals’, SA Humphry-Baker, JD Marshall, GDW Smith and WE Lee, *19th Plansee Seminar Proceedings* (2017). |
| **Impact** | Patent, licensed by Tokamak Energy Ltd.  ‘Oxidation resistant coating and methods of manufacturing thereof’, SA Humphry-Baker and WE Lee, filed to IPO on 30 March 2016 (GB201605361A). Issued on 11 May 2016 (GB201605361D0)  Patent was covered in an article on the Imperial Innovations website:  <https://www.imperialinnovations.co.uk/impact/case-studies/accelerating-nuclear-fusion-tokamak-energy/> |

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| **Title** | ***"High Entropy" Ultra-High Temperature Ceramic (UHTCs)*** |
| **Relationship to other projects/themes** | The “High Entropy” materials concept was first applied to metals in 2004 (High Entropy Alloys) and has received a lot of attention since. Its application to ceramics, however, is new and the fundamental science behind the link between the high entropy structure and physical / mechanical properties is not yet understood. The investigation of High Entropy UHTCs has shed light on some of these unknowns, which are applicable to any form of high entropy ceramic compound, not just UHTCs. |
| **Project timing** | Nov 2016 – Jan 2018 |
| **Investigators** | Prof. Mike Reece, ICL Email: [m.j.reece@qmul.ac.uk](mailto:m.j.reece@qmul.ac.uk) |
| **Staff Employed** | Dr Ellie Castle, QMUL, 100% FTE (Post Doctoral Research Assistant) |
| **Project Partners** | None |
| **Aims** | To investigate the feasibility to fabricate a single phase, high purity, high density High Entropy Carbide UHTC and investigate its mechanical properties. |
| **Results** | The precursor materials and ball milling + SPS process was optimised to produce a well-characterised, high purity, high density, single phase High Entropy (Hf-Ta-Zr-Nb)C material. The nanohardness and modulus of the material were evaluated and it was shown that the High Entropy Carbide has a 30% higher hardness and 8% higher modulus than that predicted from a rule of mixtures approximation based on the system’s monocarbide components. |
| **Publications** | ‘Processing and properties of high-entropy ultra-high temperature carbides’ EG Castle, T Csanadi, S Grasso, J Dusza & MJ Reece, *Scientific Reports*8:8609 (2018)  ‘Microstructure of (Hf-Ta-Zr-Nb)C high-entropy carbide at micro and nano/atomic level’, J Dusza, P Švec, V Girman, R Sedlák, EG Castle, T Csanádi, A Kovalčíková & MJ Reece, *J. Eur. Ceram. Soc.* **38** 4303-4307 (2018) |
| **Impact** | We are now working on an industrially funded project with a large company to produce components from the High Entropy Carbide material developed during the XMat project, which will take advantage of the materials electrical conductivity, resistance to high temperatures and improved mechanical properties. |

**MAX Phases**

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| **Title** | **Development of MAX phases materials (stabilized Zr2AlC and Cr-Ti-Al-C composites) for use in the nuclear industry** |
| **Relationship to other projects/themes** | A PDRA on this was partly funded by XMat for 14 months. |
| **Project timing** | Apr 2014 to June 2015 |
| **Investigators** | Prof. Bill Lee, ICL. Email: [w.e.lee@imperial.ac.uk](mailto:w.e.lee@imperial.ac.uk) |
| **Staff Employed** | Denis Horlait, ICL, 100% FTE  Salvatore Grasso, QMUL, 3% FTE  Doni Daniel, ICL, 1% FTE  Garry Stakalls, ICL, 3% FTE  Ben Milsom, QMUL, 3% FTE |
| **Project Partners** | **CARAT consortium** (led by Westinghouse): Consortium provides advice and collaboration with other partners. In-kind contributions through organizing and hosting meetings.  **NNL** (Dan Shepherd): Collaboration agreement initiated (results sharing; neutronic absorption calculations from NNL).  **University of Wisconsin** (K. Sridharan): In exchange for in-kind preparation and shipment of 2x ~500 g of Cr-Ti-Al-C composites powders, they tried cold-spraying on Zr tubes but results were unsatisfying.  **Drexel University** (Prof. M.W. Barsoum group): In-kind attempt at Zr2C MXene fabrication from Zr2(Bi0.58Al0.42)C powder provided.  **P. Burr** (ICL ~100 h), **S. Middleburgh** (ANSTO then Westinghouse ~50 h) + **A. Chroneos** (Coventry Univ ~50 h) contributed in-kind to the project through DFT calculations. |
| **Aims** | The project goal was to try to develop MAX phases or MAX phase-derived materials suitable for protecting nuclear fuel cladding made of a Zr alloy from severe (Fukushima-type) accidents, i.e. T >1200oC in humid air, but also able to withstand normal operating conditions over 4 years (250 bar water at 350oC). |
| **Results** | 3 systems were investigated:  *Ti3SiC2 with a preformed Si rich surface*: After the repeated absence of any promising results (oxidation resistance of treated and non-treated Ti3SiC2 equivalent) this system was abandoned.  *Stabilized Zr2AlC*: Zr2AlC, a then non-synthesisable but promising MAX phase (synthesis realised by a Belgian team recently) was tentatively stabilized by partial substitution of either Zr or Al. Successful samples were only obtained for Al partial substitution by Sn, Pb and Bi. For the latter, this represented the first synthesis ever of a Bi containing MAX phase. Although interesting from a fundamental point of view, the MAX phases produced were not suited for high-temperatures (the decomposition temperature was ~1300oC or lower). This might be fixed in the future using another substituting element.  *Composites in the Cr-Ti-Al-C quaternary system*: Due to the low mutual solubilities discovered for Cr2AlC + Ti2AlC or Ti3AlC2, the composites produced were usually composed of a MAX phase + TiC + Al-Cr alloys. Some of them were unexpectedly oxidation resistant at high-temperature (e.g. resistant 12 h at 1600oC in air). These composites therefore deserve further investigation and not just for the targeted application, since such performance is unusual for MAX phase-based materials. |
| **Publications** | **Journal papers:**  D. Horlait, S. Grasso, N. Al Nasiri, P.A. Burr, W.E. Lee, “Synthesis and oxidation testing of MAX phases in the Cr-Ti-Al-C quaternary system.”, *J. Am. Ceram. Soc.* **99** 682-690 (2016).  D. Horlait, S.C. Middleburgh, A. Chroneos, W.E. Lee, “Synthesis and DFT investigation of new bismuth containing MAX phases.”, *Sci. Reports*, **6** 18829 (2016).  D. Horlait, S. Grasso, A. Chroneos, W.E. Lee, “Attempts to synthesise quaternary MAX phases (Zr,M)2AlC and Zr2(Al,A)C as a way to approach Zr2AlC.”, *Mater. Res. Lett.* **4** 137-144 (2016).  P.A. Burr, D. Horlait, W.E. Lee, “Experimental and DFT investigations of (Cr,Ti)3AlC2 MAX phases stability.”, *Mater. Res. Lett.* **5** 144-157 (2017).  **Conferences oral talks:**  D. Horlait, A. Chroneos, S. C. Middleburgh, P.A. Burr, S. Grasso, W.E. Lee, “Development of MAX phases for high-temperature protection of nuclear fuel cladding in accident conditions.”, **Keynote Lecture** *14th* *Int. Conf. of the European Ceramic Society*, Toledo, 21-25 June 2015.  D. Horlait, D.D. Jayaseelan, S. Grasso, W.E. Lee, “Development of MAX phases for nuclear fuel cladding applications.”, 39th Int. Conf. and Expo on Advanced Ceramics and Composites, Daytona Beach, 25-30 Jan 2015. |
| **Impact** | **CAFFE Grant** “CArbides for Future Fission Environments”: EPSRC grant proposal partially prepared by D. Horlait and W.E Lee submitted August 2014 and awarded February 2015. Project is led by I. Farnan (Cambridge) and includes U. of Manchester and Imperial College (groups of M. Finnis and W.E. Lee, same as the ones participating in XMat). Total grant is ~£1.3M. A PDRA has been recruited and worked on Zr-C and Zr-Al-C systems, therefore continuing a part of the here-reported XMat project.  **Il Trovatore Grant** “Innovative cLadding maTeRials fOr adVAnced accidenT-tOlerant eneRgy systEms”: Project led by SCK-CEN, Belgium. 2017-21, with K Lambrinou, Katholic University Leuven and 20 others EC H2020 grant proposal partially prepared by D. Horlait, S. Grasso, M. Reece, M Finnis and W.E Lee. 4.5M euros (£150k to Imperial) Funded 1.5 years of post doc time at Imperial.  **Transpiration Cooling for Jet Engine Turbines and Hypersonic Flight** EPSRC Programme Grant 2016-21, Peter Ireland (Oxford, PI), with WE Lee, L Vandeperre, Jonathan Morrison (Imperial), Nick Green (Bham), Neil Sandham (Southampton) et al. £7.58M (£1.9M to Imperial). |

**Modelling**

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| **Title** | ***Ab initio thermodynamics of ultra-high temperature ceramics*** |
| **Relationship to other projects/themes** | The CALPHAD assessments are conducted using experimental data and ab initio calculations of thermodynamic and elastic properties of compounds produced by the XMat collaboration. Upon completion, the calculated descriptions and phase diagrams will be available to our collaborators and publicly for materials design. |
| **Project timing** | Aug 2013 – Jul 2016 (Duff)  Oct 2013 – Sep 2016 (Davey – PhD) |
| **Investigators** | Prof Mike Finnis, ICL |
| **Staff Employed** | Dr. Andrew Duff, ICL, 100% FTE  Ms. Theresa Davey, ICL, 100% FTE (PhD student) – funded by EPSRC DTA |
| **Project Partners** | *Ab initio* anharmonic method development in collaboration with Max Planck institute für Eisenforschung.  Collaboration with Suzana Fries at Ruhr-Universitat Bochum on CALPHAD assessments of the B-C-Hf-Zr system. |
| **Aims** | The thermodynamic properties and phase stabilities of UHTCs and MAX phases are poorly characterized due to the large experimental errors associated with measuring the onset of melting. To address this, the phase diagrams of the B-C-Hf-Zr system are being re-assessed using the CALPHAD approach, within which existing experimental data is being combined with new, fully *ab initio* density functional theory (DFT) calculations, performed up to the melting point. The latter posed a significant challenge, however, due to the strongly anharmonic lattice vibrations expected for such materials. This renders even recently developed schemes such as the UP-TILD approach too computationally inefficient for present purposes. To address this, new approaches are being developed that are significantly more efficient. |
| **Results** | An improved approach (called TU-TILD) to fully anharmonic DFT calculations has been developed, providing at least an order of magnitude improvement in efficiency compared to the former approach (UP-TILD). This will enable *ab initio* calculations for more UHTCs to higher temperatures than hitherto possible.  The approach has been used to calculate the thermodynamic properties of ZrC up to the melting point (recent publication DOI: 10.1103/PhysRevB.91.214311).  As a precursor to phase diagram assessment for the B-C-Hf-Zr system, a systematic review was carried out of the existing phase diagrams, experimental investigations and theoretical calculations. Weaknesses and inconsistencies in the existing thermodynamic descriptions were identified. Ab initio calculations of the vacancy formation energy in zirconium carbide demonstrated shortcomings in the existing thermodynamic description. Previously, such quantities have not been explicitly considered in thermodynamic assessments. A strategy was developed to directly include calculations of measurements of vacancy related quantities such as the vacancy formation energy in the optimisation of the thermodynamic description. As such, a reassessment of the carbon-zirconium system was conducted in the context of the B-C-Hf-Zr system, incorporating DFT calculations of the vacancy formation energy. |
| **Publications** | An improved method of calculating high-temperature thermodynamic properties ab initio with application to ZrC, Duff AI, Davey T, Korbmacher D, Glensk A, Grabowski B, Neugebauer J, Finnis MW, *Phys. Rev. B* **91** 214311-1-8 (2015).  A reference-free modified embedded atom method (RF-MEAM) energy and force-fitting code MEAMfit, Duff AI, Finnis MW, Maugis P, Thijsse BJ, Sluiter MHF, *Comp. Phys. Commun.* **196**439-445 (2015).  Density functional theory insights into ternary layered boride MoAlB, Bai Y, Qi X, Duff A, Li N, Kong F, He X, Wang R, Lee WE, *Acta Materialia* **132** 69-81 (2017) |
| **Impact** | The potential-fitting code (*Comp. Phys. Comm.* paper) used to provide the thermodynamic reference state in the TU-TILD algorithm (*Phys. Rev. B*) has been made publicly available. The code is versatile, easy-to-use and will provide a valuable service to the theoretical material science community. |

**Processing**

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| **Title** | **Densification and Texturing of Ceramics for Extreme Environments** |
| **Relationship to other projects/themes** | The densification of UHTCs was investigated using electric current assisted sintering techniques. Our work aimed to achieve precise microstructural design (in terms of grain size, texturing and morphology) of these materials by modulating the intensity of electro/magnetic field in combination with uniaxial pressing. |
| **Project timing** | Feb 2013 to Jan 2018. |
| **Investigators** | Prof Mike Reece, QMUL |
| **Staff Employed** | Dr Salvatore Grasso, QMUL, 100% FTE  Dr Elinor G. Castle, QMUL, 100% FTE  Dr Ben Milsom, QMUL, 50% FTE (technician)  Dr Theo Saunders, QMUL, 100% FTE (technician) |
| **Project Partners** | Dr. Andrew Duff and Dr Luc Vandeperre, ICL Experimental and modelling prediction of temperature dependence of elastic constants in ZrB2  Prof. Jan Dusza Institute of Materials Research, Slovakia Research collaboration for micro testing (nano hardness mapping and Micropillars testing) of ZrB2  Dr. Ji Zou, UoB, WDX determination of electrochemical reduction of ZrB2 during SPS processing  Dr Yuri Bogomol, National Technical University of Ukraine “KPI”,  melting of UHTCs for improved oxidation response  Prof Yoshio Sakka, NIMS Japan, Production of Textured UHTCs via Strong magnetic field alignment  Prof Nina Orlovskaya, University of Central Florida, Raman Mapping of UHTCs containing SiC particles to determine residual stresses |
| **Aims** | Ceramics that can operate in extreme environments tend to have strong covalent bonding, low diffusion rates and high melting points. This can make them extremely difficult to densify. To overcome this sintering techniques have been developed that involve pressure and electromagnetic fields. The use of SPS technique has been widely extended and improved with respect to operating temperatures (up to 2500 versus 2200oC for the state-of-the-art), pressure (1 GPa versus 0.1 GPa for the state-of-the-art) and heating rates (105 versus 102oC min-1 state-of-the-art). |
| **Results** | The unique developments in terms of the extension of SPS processing conditions (i.e. pressure, heating rate and maximum temperature) have allowed us to develop novel materials that could not be fabricated otherwise. There have been some notable achievements. Flash sintered ZrB2 and SiC materials were densified in a few tens of seconds leading to unprecedented time and energy saving, up to 99% compared to conventional SPS. The possibility of extending the SPS operating temperature (to as high as 2500oC) allowed us to reaction sinter solid solution carbides having the highest melting temperatures among all the materials. The use of high pressure up to 0.5-1 GPa, even at 1800oC, allowed us to densify UHTCs at unusually low temperatures thus preserving the fine/nano microstructure of the starting powder. We gained a better understanding of electric field effects on the high temperature electrochemical reactions occurring during the oxidation of ZrB2, we also defined the electric condition for plasma formation during sintering of UHTCs powder. More recently, along with the ICL research team, we developed strategies to develop UHTCs with superior oxidation resistance. |
| **Publications** | Processing and Properties of High-Entropy Ultra-High Temperature Carbides, Elinor G. Castle, Tamas Csanadi, Salvatore Grasso, Jan Dusza, Mike J. Reece, (2018) Scientific Reports 8:8609  Erratum: Corrigendum to “Mechanical properties and residual stresses in ZrB2–SiC spark plasma sintered ceramic composites” Stadelmann R, Lugovy M, Orlovskaya N, Mchaffey P, Radovic M, Sglavo VM, Grasso S and Reece MJ (J. Eur. Ceram. Soc. (2016) 36(7) (1527–1537)). Journal of The European Ceramic Society  vol. 36, (14) 3545-3545 (2016)  Growth of SiC platelets using contactless flash technique. Wang C, Wu D, Grasso S, Saunders T, Castle E, Yan H and Reece MJ (2016). Nippon Seramikkusu Kyokai Gakujutsu Ronbunshi/Journal of The Ceramic Society of Japan, vol. 124, (9) 845-847 (2016)  Ultrafast-Contactless Flash Sintering using Plasma Electrodes. Saunders T, Grasso S and Reece MJ. *Sci Rep*  vol. 6, article 27222, (2016)  Flash Spark Plasma Sintering (FSPS) of α and β SiC. Grasso S, Saunders T, Porwal H, Milsom B, Tudball A, Reece M and Chen IW. *Journal of The American Ceramic Society*  vol. 99, (5) 1534-1543 (2016)  Ultra-Rapid Crystal Growth of Textured SiC Using Flash Spark Plasma Sintering Route. Grasso S, Kim E-Y, Saunders T, Yu M, Tudball A, Choi S-H and Reece M. American Chemical Society  Crystal Growth and Design  vol. 16, (4) 2317-2321 (2016)  Sintering behaviour, solid solution formation and characterisation of TaC, HfC and TaC-HfC fabricated by spark plasma sintering. Cedillos-Barraza O, Grasso S, Nasiri NA, Jayaseelan DD, Reece MJ and Lee WE.  *Journal of The European Ceramic Society*  vol. 36, (7) 1539-1548 (2016)  Plasticity in ZrB2micropillars induced by anomalous slip activation. Csanádi T, Szommer P, Chinh NQ, Grasso S, Dusza J and Reece M.  Journal of The European Ceramic Society vol. 36, (3) 389-394 (2016)  Synthesis and Oxidation Testing of MAX Phase Composites in the Cr-Ti-Al-C Quaternary System. Horlait D, Grasso S, Al Nasiri N, Burr PA and Lee WE. Journal of The American Ceramic Society  vol. 99, (2) 682-690 (2016)  Nanohardness and elastic anisotropy of ZrB2crystals. Csanádi T, Grasso S, Koval¿íková A, Dusza J and Reece M. Journal of The European Ceramic Society vol. 36, (1) 239-242. (2016)  Limiting oxidation of ZrB2 by application of an electric field across its oxide scale. Saunders T, Grasso S and Reece MJ. Journal of Alloys and Compounds  vol. 653, 629-635 (2015)  2D Raman mapping and thermal residual stresses in SiC grains of ZrB2-SiC ceramic composites. Stadelmann R, Hughes B, Orlovskaya N, Grasso S and Reece MJ. Ceramics International  vol. 41, (10) 13630-13637. (2015)  The effect of spark plasma sintering on lithium disilicate glass-ceramics. Al Mansour F, Karpukhina N, Grasso S, Wilson RM, Reece MJ and Cattell MJ.  Dent Mater  vol. 31, (10) e226-e235. (2015)  Electric field in SPS: Geometry and pulsed current effects, Grasso, S, Sakka, Y, Journal of the Ceramic Society of Japan, 1414 [121] 524-526 (2013).  Flash Spark Plasma Sintering (FSPS) of Pure ZrB2 Powder, Grasso S, Saunders T, Porwal H, Cedillos-Barraza O, Jayaseelan DD, Lee WE and Reece M, (accepted) J. Am. Ceram. Soc. 97 [8] 2405-2408 (2014).  Ultra-high temperature spark plasma sintering of α-SiC, Grasso, S., Saunders, T., Porwal, H., Reece, M., Ceramics International, 41 (1), pp. 225-230 (2014).  Grasso, S., Saunders, T., Milsom, B, Porwal, H., Reece, M.J.  Flash Spark Plasma sintering of α and β Silicon Carbide, Journal of the American Ceramic Society (Jun 2015 submitted, under review). Related patent submitted to UK Patent Office.  2D Raman mapping and thermal residual stresses in SiC grains of ZrB2–SiC ceramic composites,  Stadelmann, B. Hughes, N. Orlovskaya, S. Grasso, and M. J. Reece, Ceramics International accepted  Observation of Curie transition during spark plasma sintering of ferromagnetic materials, Mani, M.K., Viola, G., Hall, J.P., Grasso, S., Reece, M.J., Journal of Magnetism and Magnetic Materials, 382, pp. 202-205 (2015).  Tailoring Ti3AlC2 ceramic with high anisotropic physical and mechanical properties Zhang, H.B., Hu, C.F., Sato, K., Grasso, S., Estili, M., Guo, S.Q., Morita, K., Yoshida, H., Nishimura, T., Suzuki, T.S., Barsoum, M.W., Kim, B.N., Sakka, Y.  Journal of the European Ceramic Society, 35 (1), pp. 393-397 (2015)  Tailoring Ti3AlC2 ceramic with high anisotropic physical and mechanical properties Zhang, H.B., Hu, C.F., Sato, K., Grasso, S., Estili, M., Guo, S.Q., Morita, K., Yoshida, H., Nishimura, T., Suzuki, T.S., Barsoum, M.W., Kim, B.N., Sakka, Y.  Journal of the European Ceramic Society, 35 (1), pp. 393-397 (2015)  Tough and dense boron carbide obtained by high-pressure (300 MPa) and low-temperature (1600°C) spark plasma sintering, Badica P, Grasso S, Borodianska Sky H, Xie S, Li P, Tatarko P, Reece MJ, Sakka Y and Vasylkiv O, Journal of the Ceramic Society of Japan 122 271-275 (2014)  Synthesis of High-Purity Ti3SiC2 by Microwave Sintering, Wang, Q, Hu, C, Cai, S, Sakka, Y, Grasso, S, Huang, Q, International Journal of Applied Ceramic Technology DOI: 10.1111/ijac.12065, (2013). |
| **Impact** | Their work on flash sintering has attracted significant attention from the industrial and scientific community. They have filed a UK patent application and have been awarded £40k to support Proof of Concept to commercialize / license the technology. They are in discussion with 3 industrial partners to verify the applicability of the approach to their industrial needs.  To support the research activities they received funding from:  National Oilwell Varco (USA), £20k (cash), Feb 2013-Feb 2014, Development of Innovative diamond joining  techniques  London Underground  (TFL), £10k (cash), July 2013, Development of materials for electric relay  Harbin Institute of technology (China), £15k (cash), August 14, Development of WC moulding  Kennametal UK, £10k (in kind), September 14, Use of Industrial SPS machine and fabrication of novel tooling to upscale Flash-SPS  Element Six, £40k (cash), May 2015, c-BN Ceramic composites by SPS routes  Kennametal UK, £10k (Cash), September 15, Scaling up development of High pressure SPS sintering. |

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| **Title** | ***Unconventional electric field assisted ceramics processing*** |
| **Relationship to other projects/themes** | The work aims to identify the intrinsic (i.e. non thermal) electric field effects in ceramics processing. This work is fundamental and it aims to contribute to the general knowledge of poorly understood multi-physical phenomena, such as, electro-migration, electro-plasticity, electrochemical reduction, electro-wetting etc. |
| **Project timing** | Sep 2013 to Aug 2016 |
| **Investigators** | Prof Reece, QMUL  Dr Ben Milsom, QMUL |
| **Staff Employed** | Theo Saunders, QMUL, 100% FTE (PhD student) – funded by QMUL & the EC |
| **Project Partners** | None |
| **Aims** | The work aims to understand/clarify the electric field contribution in electric current assisted sintering technique. For this purpose, a wide range of processing techniques assisted by an electromagnetic field are being considered / developed. |
| **Results** | The work has been focused on use of optical emission spectroscopy to identify the formation of plasma occurring during sintering in presence of al electric field. Under the supervision of Dr. Grasso and Prof Reece, we have been developing novel sintering techniques based on contactless flash sintering method. More recently we have been focusing our attention on methods to arrest oxidation in UHTCs based on oxygen ions diffusion through its oxide scale. The latter has been proven particularly effective, in fact, by application of an electric filed (~1 V) we were able to reduce the oxide scale growth by 800%. |
| **Publications** | Plasma formation during electric discharge (50V) through conductive powder compacts, Saunders, T., Grasso, S., Reece, M.J. Journal of the European Ceramic Society, Volume 35, Issue 3, March 2015, Pages 871–877, (2014)  Limiting oxidation of ZrB2 by application of an electric field across its oxide scale, Saunders, T., Grasso, S., Reece, M.J. Journal of Alloys and Compounds (2015) accepted.  Conference: Field effects and plasma formation in Electric Current Assisted Sintering (ECAS) techniques’, T Saunders, Workshop on Spark Plasma Sintering, Toulouse, France, 18th July 2014 |
| **Impact** | Our work on flash sintering and contactless flash sintering (still in the initial development stage) has attracted significant attention from the industrial and scientific community. We are in discussion with a UK company to scale up the contactless flash sintering technology. |

**Annex 2**

**Management Board Membership**

|  |  |
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| Prof Jon Binner | Deputy Head of College and Professor of Ceramic Science and Engineering, University of Birmingham |
| Prof Bill Lee | Professor of Ceramic Engineering and Director of the Centre for Nuclear Engineering, Imperial College London |
| Prof Mike Finnis | Professor of Materials Theory and Simulation, Imperial College London |
| Prof Mike Reece | Professor of Functional Ceramics and Director of Nanoforce Technology Ltd, Queen Mary University, London |
| Mr Daniel Shepherd | Technical Lead, Fuel & Radioisotope technology, NNL Fuel Technology, UK |
| Dr Jonathan Phillips | New Horizons Leader - Global Materials Centre of Excellence at Morgan Advanced Materials, UK |
| Dr Roger Morrell | Emeritus Fellow, NPL, UK |
| Prof Peter Brown | Senior Principal Scientist - Materials, Platform Systems Division. DSTL, UK |
| Dr Azad Hussain | Lead Technologist and Domain Lead, MBDA |
| Dr Ken Young | Technology Director, MTC, UK |
| Dr Adam Tudball | Senior Engineer, Materials Science (SPS), Kennametal, UK |
| Sinead Balgobin | Research Portfolio Manager – Engineering, EPSRC  (previously Luke Davis, Engineering Manager, EPSRC) |

The Management Board is also attended by Dr Alba Matas-Adams, Technical Manager in the Department of Materials, ICL, and Ms Allie Hardwick, Research Administrator, College of Engineering & Physical Sciences, UoB.

**International Advisory Board Membership**

|  |  |
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| Prof Paolo Colombo | Professor of Materials Science and Technology, University of Padova, Italy and Adjunct Professor of Materials Science and Engineering, Penn State University, USA |
| Prof Bill Fahrenholtz | Curators' Professor of Ceramic Engineering, University of Missouri S&T, USA |
| Dr Allan P. Katz | Senior Program Manager, Composites Branch, Air Force Research Laboratory’s Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, USA |
| Prof David Marshall | Principal Scientist, Materials Division, Teledyne Scientific and Adjunct Professor, University of California Santa Barbara, USA |
| Dr Diletta Sciti | Research manager (national and international research projects), ISTEC, Italy |
| Prof David Smith | Professor Ecole Nationale Supérieure de Céramique Industrielle, Groupe d'Etude des Matériaux Hétérogènes, Limoges, France |
| Prof Peter Brown | Senior Principal Scientist - Materials, Platform Systems Division. DSTL, UK |
| Dr Peng Xu | Principle Engineer, Methods and Technology, Westinghouse Electric Company, Hopkins, SC 29061 |
| Dr Dietmar Koch | Vice Director and Head of Department, Institute of Structures and Design, Ceramic Composites and Structures, DLR, Germany |
| Sinead Balgobin | Research Portfolio Manager – Engineering, EPSRC  (previously Luke Davis, Engineering Manager, EPSRC) |

The International Advisory Board is also attended by Profs Binner, Lee, Finnis and Reece and Dr Alba Matas-Adams and Ms Allie Hardwick.

**Organisational Membership**

AFRL, USA (Air Force Research Labs)

Atomic Weapons Establishment (AWE), UK

DSTL, UK

European Centre of Ceramics (Centre Européen de la Céramique)

ISTEC, Italy

Kennametal, UK

Kerneos, France

Lucideon, UK

Materials KTN

MBDA, UK & France

Missouri University of Science and Technology

Morgan Ceramics, UK

NASA, USA

National Nuclear Laboratory (NNL), UK

National Physical Laboratory (NPL), UK

Teledyne Scientific & Imaging, US

Tokamak Solutions, UK

The Welding Instutute, UK

University of Limoges, France

University of Missouri S&T, US

Westinghouse plc

Vesuvius, UK

**Annex 3**

**Lectures, Visits, Conference Organisation and Related**

**Jon Binner**

* ***Visits*** to AFRL, Dayton, OH, USA, every January from 2013 to 2018 inclusive as well as May 2017 – each time updates were given on XMat and the research undertaken.
* ***Invited Lecture*** ‘High-Temperature Strength Measurements of Cf-HfB2 UHTC Composites’, Paul A, Binner J, Vaidhyanthan B, Heaton A and Brown P. 37th Int Conf and Expo on Advanced Ceramics and Composites, Daytona Beach, FL, USA, 27th Jan to 1st Feb 2013.
* ***Lecture*** ‘Nano HfB2 Powders, Mini-composites and Impregnated Carbon Fibre Preforms’, Venugopal S, Paul A, Zheng P, Vaidhyanathan B, Binner J, Brown P. 37th Int Conf and Expo on Advanced Ceramics and Composites, Daytona Beach, FL, USA, 27th Jan to 1st Feb 2013.
* ***Lecture*** ‘Synthesis of HfB2 Powders for Aerospace Applications’, Zheng P, Venugopal S, Paul A, Binner J and Vaidhyanathan B. 37th Int Conf and Expo on Advanced Ceramics and Composites, Daytona Beach, FL, USA, 27th Jan to 1st Feb 2013.
* ***Visit*** to MBDA, Stevenage, UK: Tues 26th Feb 2013 – presentation given on XMat; led to a contract to work with us on the programme.
* ***Keynote Lecture*** ‘High-Temperature Strength Measurements and Arc-Jet Testing of Cf-HfB2 UHTC Composites’, Binner JGP, Paul A, Venugopal S, Vaidhyanathan B, Brown P and Heaton A. 13th Int Conf of the European Ceramic Society, Limoges, France, June 2013.
* ***Visit*** to Alstom, Baden, Switzerland: Fri 13th Sept 2013 – presentation given on XMat.
* ***Media appearance****, The One Show* (talking about cubic boron nitride, the hardest man-made metal), 2013.
* ***Award*** *‘UHTC-carbon fibre composites: Preparation, oxyacetylene torch testing and characterisation’*, Paul A, Venugopal S, Binner JGP, Vaidhyanathan B, Heaton ACJ and Brown PM. *J. Eur. Cer. Soc.* **33** 423-432 (2013)won the **JECS Best Paper Award**.
* ***Invited Lecture*** ‘Processing and Properties of UHTC Composites’, Binner JGP. 13th Int Ceramics Congress, Montecatini Terme, Tuscany, Italy, June 2014.
* ***Member of the International Advisor Board***, 13th International Ceramics Congress, Montecatini Terme, Italy, June 2014.
* ***Keynote Lecture*** ‘Processing and Characterisation of Advanced Ceramics for Demanding Applications’, Binner JGP, 11th Conf on Solid State Chemistry, Trenčianske Teplice, Slovakia, July 2014.
* ***Keynote Lecture*** ‘UHTC Composites: From powder synthesis to arc-jet testing’, Binner J, Paul A, Vaidhyanathan B, Venugopal S, Zheng P and Brown P, 5th Int Congress on Ceramics, Beijing, China, August 2014.
* ***Plenary Lecture*** ‘Processing and Characterisation of Advanced Ceramics for Demanding Applications’, Binner J, PSA 2014 Conf and Exhibition, Manchester, UK, September 2014.
* ***Plenary Lecture*** ‘Ultra-High Temperature Ceramics: Processing, Properties and Applications’, Binner J, 90th DKG Annual Conference, Bayreuth, Germany, March 2015.
* ***Member of the International Advisory Board***, German Ceramic Society (DKG) Annual Meeting, Bayreuth, Germany, March 2015.
* ***Keynote Lecture*** ‘Ultra-High Temperature Composites’, Binner J, Ultra-High Temperature Ceramics: Materials for Extreme Environment Applications III, Gold Coast, Australia, April 2015.
* ***Member of the Scientific Committee***, Ultra High Temperature Ceramics: Materials For Extreme Environment Applications III, Gold Coast, Australia, April 2015.
* ***Keynote Lecture*** ‘Ultra-High Temperature Composites: Processing, Performance and Future’, Binner J, Anish Paul, Prabhu Ramanujam, Virtudes Rubio, Bala Vaidhyanathan, Saranya Venugopal, Penxiang Zheng, Ji Zou, 14th International Conference of the European Ceramic Society, Toledo, Spain, June 2015.
* ***Chair, Theme 1 – Innovative processing and synthesis***, 14th European Ceramics Society, Toledo, Spain, June 2015.
* ***Member of the Technical Programme Committee***, 2015 International Conference on Ceramic Science and Technology (CST 2015), Shanghai, China, July 2015.
* ***Invited Lecture*** ‘Ultra-High Temperature Ceramics: Processing, Properties and Applications’, at the UK-USA Dynamic Materials Symposium, Defence Academy, Shrivenham, UK, September / October 2015.
* ***Invited Lecture***‘SiCf-SiC composites for energy applications’, MatiSSE Workshop, Joint Research Centre – Institute for Energy and Transport, Petten, the Netherlands, November 2015.
* ***Invited lecture*** ‘Creating Ultra-High Temperature Ceramic Matrix Composites’ Binner J, 40th International Conference & Exposition on Advanced Ceramics & Composites (ICACC), Daytona Beach, Florida, USA, January 2016.
* ***Symposium Organiser, Symposium 12 - Materials for Extreme Environments: Ultra-High Temperature Ceramics (UHTCs) and Nano-Laminated Ternary Carbides and Nitrides (MAX Phases)***, 40th International Conference and Expo on Advanced Ceramics and Composites (ICACC’16) Daytona Beach, Florida USA, January 2016.
* ***Member International Organization Committee***, International Conference on Ceramic Processing Science (ICCPS-13), Nara, Japan, May 2016.
* ***Award*** *‘Heat flux mapping of oxyacetylene flames and their use to characterise Cf-HfB2 composites’,* Paul A, Binner JGP, Vaidhyanathan B and Brown PM. *Adv. Appl. Ceram.* **115** [3] 158-165 (2016) won the **2017 IOM3 Pfeil Award**.
* ***Visit*** to Ansaldo Energia, Baden, Switzerland: 22nd May 2017 – presentation given on XMat.
* ***Member of the Organisation Committee,*** *Materials for extreme environments: Ultrahigh-temperature ceramics and nano-laminated ternary carbides and nitrides (MAX phases)* at the 9th International Conference on High Temperature Ceramic Matrix Composites and Global Forum on Advanced Materials and Technologies for Sustainable Development, Toronto, Canada, June 2016.
* ***Invited lecture*** ‘Thermoablative Resistance of ZrB2-SiC-WC Ceramics at 2400oC’ 15th European Ceramics Society conference, Budapest, July 2017.
* ***Invited lecture*** ‘Progress in Manufacturing High and Ultra-High Temperature Ceramic Matrix Composites’, 15th European Ceramics Society conference, Budapest, July 2017.
* ***Invited lecture* ‘**Ultra High Temperature Ceramic Matrix Composites Based On Carbon Fibres’, 15th European Ceramics Society conference, Budapest, July 2017.
* ***Session organiser,*** *High Temperature Processes and Advanced Sintering,*15th European Ceramics Society conference, Budapest, July 2017.
* ***Plenary lecture*** ‘Designing Advanced Ceramics and Composites’, CERMODEL, Int. Congress on Modelling & Simulation in Ceramics Technology, Trento, Italy, Jul 2017.
* ***Member Technical Programme Committee,*** 3rd International Conference on Ceramic Science and Technology (CST 2017), Jeju Island, South Korea, July 2017.
* ***Conference Chair,*** Ultra High Temperature Ceramics: Materials For Extreme Environment Applications IV, Windsor, UK, September 2017.
* ***Invited lecture*** ‘Processing and properties of ultra-high temperature ceramic matrix composites’, CICC-10, Int. Conf. on High-Performance Ceramics, Nanchang, China, Nov 2017.
* ***Invited lecture*** ‘Designing the processing of advanced ceramics and composites to yield the required properties’, in “Advancing Frontiers of Ceramics for Sustainable Societal Development - International Symposium in Honor of Dr. Mrityunjay Singh” –held during the 42nd International Conference on Advanced Ceramics & Composites (ICACC 2018), Daytona Beach, Florida, January 2018.
* ***Invited lecture*** ‘Ultra-high temperature ceramic composite materials’, 42nd International Conference on Advanced Ceramics & Composites (ICACC 2018), Daytona Beach, Florida, January 2018.
* ***Symposium organiser,*** *Advanced MAX/mxene phases and UHTC materials for extreme and high temperature environments*, 42nd International Conference And Exposition On Advanced Ceramics And Composites, ICACC2018, Daytona Beach, Florida, USA, January 2018.
* ***Invited lecture*** ‘Thermal ablation performance of Cf-HfB2 composites with and without a C matrix deposited by CVI’, Rubio V, Ramanujam P, Ramachandran DK, D’Angio’ A and Binner JGP, Proceedings of the 9th International Conference on High Temperature Ceramic Matrix Composites and Global Forum on Advanced Materials and Technologies for Sustainable Development 2016, HTCMC-9 & GFMAT 2016.
* ***Invited lecture*** ‘Creating Ultra-High Temperature Ceramic Matrix Composites By Microwave Or RF Assisted Chemical Vapour Infiltration’, 3rd Global Congress on Microwave Energy Applications (3GCMEA), Cartegena, Spain, July 2016.
* ***Invited lecture*** ‘UHTCMCs: Importance of the oxide’, 41st International Conference & Exposition on Advanced Ceramics & Composites (ICACC), Daytona Beach, Florida, USA, January 2017.
* ***Invited lecture*** ‘Ultra-high temperature ceramic composite materials’, 42nd International Conference on Advanced Ceramics & Composites (ICACC 2018), Daytona Beach, Florida, January 2018.
* ***Conference organiser*** UHTC-IV, Jon Binner was the Chair and Bill Lee was the Co-Chair of the international conference Ultra-High Temperature Ceramics IV, which was held in Windsor, UK, in Sept 2017 and attracted almost all of the top people in the field.
* ***Keynote lecture*** ‘Developing high and ultra-high temperature ceramic matrix composites’, 6th International Conference & Exhibition on Materials Science & Chemistry, Rome, May 2018.
* ***Symposium co-organiser*** Symposium N – High and Ultra High Temperature Ceramics, International Congress on Ceramics, ICC7, Iguassu Falls, Brazil, June 2018.
* ***Symposium co-organiser*** Integration Technologies for Energy and Environmental Applications, 12th International Conference on Ceramic Materials and Components for Energy and Environmental Applications (CMCEE-12), Singapore, July 2018.

**Bill Lee**

* ***Plenary Lecture*** ‘Fabrication, Microstructural Characterisation, Oxidation and Laser Testing of Ultra High Temperature Non-oxide Ceramics’, 6th Intl. Conf. on Advanced Materials and Nanotechnology (AMN6), Auckland, New Zealand, 12th Feb 2013.
* ***Invited Lecture*** ‘Fabrication, Microstructural Characterisation, Oxidation and Laser Testing of Ultra High Temperature Non-oxide Ceramics’, Industrial Research Ltd., Wellington, New Zealand 18th Feb 2013.
* ***Invited Lecture*** ‘Working with DSTL: The Good, The Bad and The Summary’, DSTL National PhD Scheme Conference, Kassam Stadium, Oxford, 27th Feb 2013.
* ***Invited Lecture*** ‘Fabrication, Microstructural Characterisation, Oxidation and Laser Testing of Ultra High Temperature Ceramics (UHTCs)’, Dept. of Materials, Oxford University 9th May 2013.
* ***Invited Lecture*** ‘Current and Future Ultra-high Temperature Ceramics Research at Imperial College’, Materials Research Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio, USA 7th June 2013.
* ***Invited Lecture*** ‘Imperial’s Fuel Cycle Research’, IChemE Nuclear Research Seminar, Magdalene College, Cambridge, 24th Sept. 2013.
* ***Invited Lecture*** ‘The UKs Radioactive Waste Management Programme’, Materials Science and Technology, Montreal, Canada, 28th Oct 2013
* ***Invited Lecture*** ‘Materials Research for Inertial Fusion Energy and Magnetic Confinement Fusion’, UK Inertial Fusion Energy Network Kick-off Meeting, Royal Society, London, 26th Nov 2013
* ***Invited Lecture*** ‘Understanding Wasteforms from Thermal Treatment Methods’, Thermal Treatment of Radioactive Wastes meeting, Risley, 12th Dec 2013
* ***Invited Lecture*** UK Trade and Investment UK-China Civil Nuclear Mission – Industry Days, London, Nuclear R&D in UK Universities, 24th Jan 2014.
* ***Invited Lecture*** EPSRC DISTINCTIVE (Decommissioning, Immobilisation and Storage Solutions for Nuclear Waste Inventories) Consortium Kick-off Meeting, Leeds, Work Package on UK Legacy Ponds and Silos Wastes 29th April 2014.
* ***Invited Lecture*** ‘Current US/UK Nuclear R&D Collaborations’, US/UK Technical Experts Workshop, Bilateral Civil Nuclear Energy R&D Cooperation, Institute of Mechanical Engineering, London, 13th May 2014.
* ***Invited Lecture*** ‘Materials Needs in the UK’s Nuclear Programme’, The Armourers and Brasiers Cambridge Forum, Gordon Seminar, 17th June 2014.
* ***International Advisory Cttee*** 13th Int. Ceramics Congress (CIMTEC 14), Montecatini Terme, Italy, June 8th – 13th, 2014.
* ***Invited Lecture*** ‘Microstructural Characterisation, Oxidation and Laser Testing of Ultra High temperature Ceramics’, China University of Geosciences, Beijing, China, Fabrication, 14th July 2014
* ***Invited Lecture*** ‘Fabrication, Microstructural Characterisation, Oxidation and Laser Testing of Ultra High temperature Ceramics’, Beihang University, Beijing University of Aeronautics and Astronautics, Beijing, China, 16th July 2014.
* ***Lee Hsun Award Lecture*** ‘Structural Ceramics for Extreme Environments’, Institute of Metals Research, Chinese Academy of Sciences, Shenyang, China, 17th July 2014.
* ***Invited Lecture*** National Nuclear Laboratory Lunchtime Seminar (Risley, Harwell, Springfields, Sellafield), “Challenges and Opportunities for Advanced Ceramics and Composites in the Nuclear Sector”, 17th Sept. 2014
* ***Plenary Lecture*** ‘Structural Ceramics for Extreme Environments’, Serbian Ceramic Society Conference Advanced Ceramics and Applications III, Serbian Academy of Sciences and Arts, Belgrade, Serbia, 29th Sept 2014.
* **Lecture** ‘Low Temperature Synthesis of Organometallic Hybrid Precursor-derived Nanosized HfC’, Materials Science and Technology 2014, Pittsburgh, PA, USA, 14th Oct 2014.
* ***Invited Lecture*** ‘Structural Ceramics for Extreme Environments’, Dept. of Materials, Katholic University of Leuven, Belgium, 12th Nov 2014.
* ***Keynote Lecture*** ‘Structural Ceramics for Extreme Environments’, Intl. Symp. on Ceramics Nanotune Technology, ISCeNT 4, Nagoya Institute of Technology, Nagoya, Japan, 3rd Mar 2015.
* ***Invited Lecture*** ‘Nuclear Ceramics: Key Materials in Waste Management and Advanced Reactors’, Tokyo Institute of Technology, Tokyo, Japan, 5th Mar 2015.
* ***Invited Lecture*** ‘Processing and Characterisation of (Ta,Hf)C Ultra-High Temperature Ceramics’, Ultra-high Temperature Ceramics: Materials for Extreme Environment Applications III, Gold Coast Australia, 13th Apr 2015.
* ***Invited Lecture*** ‘Nuclear Ceramics for Fuel and Wasteforms’, Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights, Sydney, Australia, 22nd Apr 2015.
* ***International Advisory Cttee*** 5 Int. Congress on Ceramics (ICC5), Beijing, China, Aug 17th – 21st, 2015.
* ***International Advisory Cttee*** 11th Int. Ceramics Conference of Pacific Rim countries (PACRIM 11), Jeju Island, Korea, Aug 30th – Sep 4th, 2015.
* ***Lecture*** NSF Workshop on Emerging Opportunities in Ceramics and Glass Science, Arlington, VA, USA, ‘Structural Ceramics for Extreme Environments’, Sept 13th 2016.
* ***Lecture*** American Ceramic Society New England Section meeting, Boxborough, New Hampshire, USA, ‘Structural Ceramics for Extreme Environments: Accident Tolerant Fuels and the Highest Melting Material on the Planet’, Nov 1st 2016.
* ***International Advisory Cttee*** 2nd Int. Conf. on Alumina and other Functional Ceramics (AOFC 2017), Kolkata, India, Feb, 2017.
* ***Lecture*** Dept. of Materials Science and Engineering, Lehigh University, Bethleham, PA USA, ‘Structural Ceramics for Extreme Environments: Wasteforms for Fukushima and the Highest Melting Material on the Planet’, March 28th 2017.
* ***Lecture*** Advances in Solid State Chemistry and its Applications: ARW70, Glasgow, UK, ‘Ceramics for Extreme Environments: From Refractories at Sheffield to UHTCs at Imperial’, Jul 22nd 2017.
* ***International Advisory Cttee*** 10th Int. Conf. on High Performance Ceramics (CICC10), Nanchang, China, Nov 4th – 8th, 2017.
* ***Book*** DW Richerson and WE Lee, “Modern Ceramic Engineering”, 4th Edition (CRC Press 2018) pp. 800.
* ***International Advisory Cttee*** 14th Int. Ceramics Congress (CIMTEC 18), Salsomaggiore Terme, Italy, Jun 4th – 8th, 2018.
* ***Technical Panels*** *for Symposia**on ‘New Trends in Silicate and Clay-Based Ceramics’ and ‘High and Ultra-High Temperature Ceramics’, 7th Int. Congress on Ceramics (ICC7), Foz do Iguacu, Brazil, Jun 17th – 21st, 2018.*

**Mike Reece**

* ***Visit*** to Shanghai Institute of Ceramics. Purpose: to meet Prof. Guo-Jun Zhang and develop collaboration on development of textured ZrB2, HfB2 ceramics, April 2013. Followed up by EPSRC-supported visit of Prof Zhang to UK in summer 2015.
* ***Visit*** to Prof D.K. Kim, KAIST, South Korea, to discuss common interests in UHTC, August, 2013.
* ***Visit*** to NNL (with Salvatore Grasso). Purpose: to establish research collaboration between NNL and QMUL. NNL is planning to install an SPS machine for processing nuclear fuel pellets, 9th December 2013.
* ***Visit*** to IFAM, Dresden, Germany (with Salvatore Grasso). Purpose: to get an update on the SPS research trends in Germany. During the same trip, visited SPS manufacturer FCT Systeme GmbH Rauenstein. Purpose: to discuss possible improvements and modifications of the existing SPS furnace at QMUL, April 2014.
* ***Invited lecture*** ‘Densification of UHTCs by Electric Current/Field Assisted Sintering’, 13th CIMTEC Tuscany, Italy, June 2014.
* ***Visit*** to Kenametal, Newport. Purpose: To discuss collaboration on scaling up of SPS and Flash-SPS. 2nd March 2015.
* **Visit** Gave presentations on XMAT research at ISTEC and CNR-Genoa, April, 2015.
* ***Visit*** to the European Space Agency to disseminate results from XMAT and explore areas for future collaboration, 5th June 2015.
* ***Keynote lecture*** ‘Densification and Microstructural Design of Ceramics Assisted by Electric Current/Field’, 14th International Conference of the European Ceramic Society, Toledo, Spain, June 2015.
* ***Invited lecture*** ‘Developments in SPS processing’, PACRIM11, Korea, August-September, 2015.

**Mike Finnis**

* **Lecture** Unary Workshop at Schloss Ringberg, 24th – 29th March 2013, one of a CALPHAD series, organised by Tilman Hickel (MPI Düsseldorf) and Suzana Fries (ICAMS, Bochum).
* ***Invited Lecture***, ‘Progress in the theory of oxide scale growth’, ICAMS2 Symposium, RUB Bochum, 6-7th May 2013.
* **Lecture** CCP9 Conference, Clare College Cambridge, 1st – 2nd April 2014.
* **Lecture** UKCP Meeting, Kings College London, 8th April, 2014.
* ***Invited Lecture***, ‘Modelling Oxide Scale Growth: Insights, Progress, Limitations’, Possibilities and Limitations of Characterization and Modeling of Defects, Interfaces and Phase transformations, Bernkastel-Kues, Germany, 26th – 28th May 2014.
* ***Invited Lecture*** ICMR Summer Workshop on Ab initio description of charged systems and solid/liquid interfaces for semiconductors and electrochemistry, Santa Barbara, 6th – 11th July 2014.
* ***Invited visitor*** to Interdisciplinary Centre for Advanced Materials Simulation (ICAMS), Ruhr-Universität Bochum, August – October 2014, developing contacts there and with other visitors from the MPIE in Düsseldorf, The Centre for Advanced Ceramics at TU Hamburg and the Materials Department at UCSB, USA.
* ***Invited Lecture***, ‘High temperature thermodynamic properties of ceramics’, A\*STAR, Singapore, 2nd Dec 2014.
* ***Invited Lecture***, ‘High Temperature Thermodynamic Properties of Ceramics’, RMIT Melbourne, Ian Snook Conference on Chemical Physics, 4th – 5th Dec 2014.
* ***Invited Lecture***, “Calculations of high-temperature thermodynamic properties of ceramic materials”, ICAMS, RUB Bochum, 8th Jan 2015.
* ***Invited Lecture***, ‘Alumina Interfaces – structure and transport’, PICS Workshop, Luminy, France, 27th – 29th May 2015.
* **Invited Lecture**, ‘Calculated thermodynamic properties of ceramics’, Possibilities and Limitations of Characterization and Modeling of Defects, Interfaces and Phase transformations, Bernkastel-Kues, Germany, 31st May – 3rd June 2015.
* ***Invited Lecture***, ‘Modelling Grain-Boundary Structure and Processes’, Gordon Conference on High Temperature Corrosion, 27th – 30th July 2015.

**Ellie Castle**

* ***Attendance*** 1 Day Research Meeting on Advanced Ceramics (1DRAC), 5th December 2016 Kingston University London, UK
* ***Attendance*** 1st Meeting UK International Chapter of ACerS, 15th March 2017, Imperial College London, UK
* ***Attendance*** High Temperature Uses of Light Alloys, 29th November 2016, Institute of Materials, Minerals and Mining, London, UK
* ***Lecture*** ‘High Entropy Transition Metal Carbides’ at UHTC IV, 17th-20th September 2017, Windsor, UK
* ***Lecture*** ‘High Entropy Transition Metal Carbides’ at XMat Industrial Showcase, 17th November 2017
* ***Visit*** to Element Six on 24.11.17 for a tour of their high pressure and diamond synthesis facilities and to discuss potential collaboration on the High Entropy Carbides
* ***Lecture*** ‘High Entropy Transition Metal Carbides’ at ICACC’18 20-26th January 2018, Daytona Beach, Florida, USA.
* ***Visit*** To MS&T university to begin a collaboration on the High Entropy Carbides with Dr Greg Hilmas and Prof. Bill Fahrenholtz. 26 January 2018 – 23rd February 2018

**Andrea D’Angio**

* ***Poster*** ‘Microwave heated chemical vapour infiltration of ultra-high temperature ceramics’, Poster MST '14, October 2014, Pittsburgh, PA, USA.
* ***Leadership*** PCSA delegate meeting, MST '14, October 2014, Pittsburgh, PA, USA.
* ***Lecture*** ‘Microwave heated chemical vapour infiltration of ceramic matrix composites’, ECERS XIV, Toledo, Spain, June 21-25, 2015
* ***Lecture*** ‘Microwave enhanced chemical vapour infiltration of ceramic matrix composites’, ICC6, Dresden, Germany, August 21-25, 2016
* ***Lecture* ‘**Preparation and characterisation of Cf-ZrCp-ZrCm composites’, ICC6, Dresden, Germany, August 21-25, 2016

**Doni Daniel Jayaseelan**

* ***Invited Lecture***, ‘Development of ultra-high temperature ceramics (UHTCs) for hypersonic applications’, D.D. Jayaseelan, P. Brown and W.E. Lee, AMPC 2013, Chennai, India, 6th – 8th Feb, 2013.
* ***Keynote lecture***, ‘Materials for extreme environments’, D.D. Jayaseelan, The Indian Ceramic Society – Chennai Chapter, India, 5th Feb, 2013.
* **Lecture** ‘Materials for extreme environments’, D.D. Jayaseelan and W.E. Lee, CASC Industrial Day, 25th May, 2013.
* **Lecture** ‘Process development and microstructural characterization of (Ta,Hf)C ultra-high temperature ceramics’, O. Cedillos, D.D. Jayaseelan and W.E. Lee, ECERS XIII, Limoges, France, 23rd – 27th, June 2013.
* ***Invited lecture*** ‘Joining ultra-high temperature ceramics, D.D. Jayaseelan, L. Vandeperre, P. Brown and W.E. Lee, AWE Joining Symposium, Surrey, UK, 24th July, 2013.
* ***Invited Lecture*** ‘Development of multilayered UHTCs for thermal protection systems’, D.D. Jayaseelan, P. Brown, C. Allen and W.E. Lee, HT-CMC8, Xi’an, China, 22nd – 26th Sept 2013.
* ***Visit*** to the US Air Force Research Lab (AFRL), Daytona, Doni Daniel and Bill Lee, and gave presentations on ‘UHTC research at Imperial College’ and ‘Development of multi-layered UHTC composites’, Ohio, 6th – 7th June 2013.
* **Lecture** ‘Zr-Al-C and water vapour corrosion resistance at high temperature’ in CARAT 2nd conf on MAX phase collaboration at Dalton Nuclear Institute, D.D. Jayaseelan, The University of Manchester, 16th June, 2014.
* **Lecture** ‘Development of multi-layered UHTCs for aerospace applications’, D.D. Jayaseelan, Review of the NHSC Program and Future of High Temperature Structural Ceramics, Boulder, Colorado, US, 28th – 31st July, 2014.
* **Lecture** ‘Carbothermal synthesis and characterization of zirconium diboride by facile one-pot reaction’, N. Patra, D.D. Jayaseelan, W.E. Lee, International Workshop in Advanced Ceramics (IWAC-06) 28th – 30th Sep 2014, Erlangen, Germany.
* **Lecture** ‘Low temperature synthesis of organometallic hybrid precursor-derived nanosized HfC’, N. Patra, D.D. Jayaseelan, W.E. Lee, Materials Science & Technology 2014 (MS&T 2014), 12th – 16th Oct 2014, Pittsburgh, PA, USA.
* ***Visit*** to Nuclear Reactor Research Labs, Tokyo Institute of Technology, to collaborate on MAX phase research for ATF applications, 9th – 15th Nov 2014
* ***Invited Lecture***, ‘Ultra High Temperature Ceramics research at Imperial College London’, Japan Aerospace Exploration Agency, 11th Nov. 2014.
* **Lecture** ‘In situ synthesis of ZrB2/SiC composites for hypersonic applications’, N. Patra, D.D. Jayaseelan, W. E. Lee, 39th Int Conf on Advanced Ceramics and Composites (ICACC-2015), 25th – 30th Jan 2015, Daytona Beach, Florida, USA.
* **Lecture** ‘An ultra-high-temperature organometallic hybrid precursor infiltrate carbon fiber mat and its characterization’, N. Patra, D.D. Jayaseelan, W.E. Lee, 14th Int Conf of the European Ceramics Society 2015 (ECerS-2015), Toledo, Spain, 21st – 25th June 2015.

**Theresa Davey**

* **Poster** ‘Revisiting Boron-Carbon-Hafnium-Zirconium Thermodynamics’, Poster TMS 2015, February 2015, Orlando, Florida, USA.
* **Lecture** ‘Phase Diagrams in the system boron-carbon-hafnium-zirconium’, UHTC III, April 2015, Gold Coast, Australia.
* **Lecture** ‘Fully anharmonic first principles data in the assessment of the B-C-Hf-Zr system’ CALPHAD 2015, June 2015, Loano, Italy.
* **Visit** to ICAMS at the Ruhr-Universität Bochum in Germany a lot to work with Suzana Fries.
* **Leadership** Became the first international to Chair the ACerS Presidents Council of Student Advisors (PCSA) in 2016.

**Andrew Duff**

* ***Visit*** to the Max Planck Institut fuer Eisenforschung to collaborate with them on calculations of high-temperature free energy, 23rd Aug – 1st Sep 2013.
* ***Invited Lecture***, ‘Bringing Modelling to UHTCs’, AI Duff, T Davies, Wl Lee and M Finnis, 13th CIMTEC Tuscany, Italy, June 2014.
* ***Lecture****,* ‘*Ab initio* description of the Ti bcc to omega transition at finite temperature’, D Korbmacher, A Glensk, T Hickel, J Neugebauer, AI Duff, M. W. Finnis, DPG-Fruhjahrstagung 2015
* ***Lecture***, ‘Thermodynamic properties of zirconium carbide: *ab initio* accuracy up to the melting point’, TYC Seminar, 30th Nov 2015, Imperial College London
* ***Workshop****,*co-hosted the “International Workshop on Theory and Modelling of Materials in Extreme Environments” (Oxfordshire, 2016)

**Salvatore Grasso**

* ***Invited Lecture***, ‘Electric Current Activated/Assisted Sintering (ECAS): 20 years impact on science and technology’, 10th Pacific Rim Conference on Ceramic and Glass Technology (PACRIM 10), Coronado, USA, June 2013.
* ***Visit*** to Loughborough University. Purpose: to develop joint effort between QMUL, ICL and LU in order to achieve a more complete understanding of the Flash Sintering technique. July 2013.
  + ***Visit*** to National Institute for Material Science NIMS, Tsukuba Japan (with Mike Reece). Purpose: to develop the existing the collaboration between NIMS and QMUL. July 2013.
  + ***Visit*** to Geni Core Ltd, Poland (with Theo Saunders). The company has developed high energy electric pulse discharge with peak power of the order of several GW – aim was to discuss the possibility of using PPS for sintering UHTCs. 8th – 9th May 2014.
  + **Poster** China-Russia Expo, Harbin, China, 28th June 28 – 3rd July 2014. Presented a poster and discussed possible collaboration on WC binderless materials for superplastic forming of titanium alloys. An MOU was signed between QMUL and Harbin Institute of Technology.
* **Lecture** ‘Field effects and plasma formation in Electric Current Assisted Sintering (ECAS) techniques’, S Grasso & T Saunders, Workshop on Spark Plasma Sintering, Toulouse, France, 18th July 2014.
  + ***Keynote Lecture***, ‘Field effects in Electric Current Assisted Sintering (ECAS) techniques’, Sintering 2014, Dresden, Germany, 31st August 2014.
  + ***3 visits*** to Kennametal Sintec, New Port, Wales, (with Ben Milsom). Purpose: to develop Flash Sintering of large SiC parts, Jan 2015.
  + ***Multiple visits*** to Element Six Ltd, Global Innovation Centre, Didcot, Oxfordshire (with Mike Reece & Ben Milsom). Purpose: to develop composites containing hard phases operating under extreme drilling conditions.
  + **Leadership** Became research representative inside the XMat Consortium, May 2015. Meets the researcher once a month to discuss possibilities for linking and extending the research undertaken.
  + ***Invited Lecture***, ‘Flash Sintering of SiC based ceramics’, Institute of Material Research, Kosice, Slovakia, 8th August 2015. Also discussed with Prof Frank Lofaj about ongoing research related to micro mechanical testing (e.g. micro-pillars and nano-hardness mapping).

**Denis Horlait**

* ***Lecture*** ‘MAX phases for ATF cladding: Projects at Imperial College’ in CARAT 2nd conf on MAX phase collaboration at Dalton Nuclear Institute, The University of Manchester, 16th June, 2014.
* ***Lecture*** ‘MAX phases for ATF cladding: Projects at Imperial College’ Presentation for the Nuclear Advisory Committee meeting, Imperial College London, 09th July, 2014.
* ***Keynote*** ‘Development of MAX phases for high-temperature protection of nuclear fuel cladding in accident conditions’ ECERS XIV, Toledo, Spain, June 21-25, 2015.
* ***Keynote*** ‘Synthesis, characterization and oxidation testing of MAX phases in the Cr-Ti-Al-C system and of Zr2AlC based compounds’, ICACC39, January 2015, Daytona Beach, FL, USA.
* ***Visit*** to NNL Central Laboratory, Sellafield, 2nd June 2015, to discuss possibilities of Imperial-NNL collaborations.

**Sam Humphry Baker**

* ***Lecture*** ‘Microstructural evolution in helium implanted cermets’, S. A. Humphry-Baker, G. Greaves, J Hinks, S. E. Donnelly, G. D. W. Smith and W. E. Lee in Symposium: Characterisation and modelling of radiation effects across classes of materials: Tungsten, AMPT Annual meeting 2015, Madrid, Spain 14th December 2015
* ***Poster* ‘Irradiation and thermal damage of tungsten carbide cermets’,** S. A. Humphry-Baker,K. Peng, B. Tavaya, G. Greaves, J. A. Hinks, S. E. Donnelly, G. D. W. Smith and W. E. Lee, in Symposium: Irradiation effects in materials. MFFP September Workshop, Oxford, UK 23rd September 2015
* ***Poster* ‘Helium ion irradiation of tungsten carbide neutron shields’,** S. A. Humphry-Baker,K. Peng, G. Greaves, J. A. Hinks, S. E. Donnelly, G. D. W. Smith and W. E. Lee**,** in session P3.107 of the 29th Symposium on Fusion Technology, Prague, CZ ,5th September 2016
* ***Lecture* ‘Update on** tungsten carbide cermets’, at the IEA Tungsten Workshop, in conjunction with SOFT 2016, Prague. 6th September 2016
* ***Lecture* ‘**Engineering composite materials for next-generation nuclear reactors’, at the Tech-foresight 2036, Imperial College London, 24th June 2016.
* ***Conference talk* ‘Oxidation resistant tungsten carbide cermets’,** S.A. Humphry-Baker, K. Peng, and W. E. Lee**,** in Symposium: Multiscale behaviour of materials in extreme environments, MRS Spring meeting 2016, Phoenix, Spain 28th May 2016.
* ***Lecture* ‘**Oxidation and corrosion of hardmetals with FeCr binders’, at theBritish Hardmetal Research Group Meeting, National Physical Laboratory, Teddington, 16th March 2016
* ***Lecture* ‘**Irradiation of tungsten carbide hardmetals for fusion applications’, S.A. Humphry-Baker, G. Greaves, J.A. Hinks, S.E. Donnelly, D. Kingham, G.D.W. Smith and W.E. Lee**,** 19th Plansee Seminar, Reutte, Austria 29th May 2017
* ***Lecture* ‘**Advanced ceramics for fusion applications’, at the 1-DRAC Spring meeting, Imperial College London. 7th April 2017
* ***Lecture* ‘**WC cermets for fusion’, at University of Oxford, Materials for Fusion and Fission Powder seminar. 13th January 2017
* ***Poster* ‘**Oxidation resistant hardmetal coatings by Si-impregnation’, S. A. Humphry-Baker, K. Peng, G.D.W. Smith and W.E. Lee**,** 19th Plansee Seminar, Reutte, Austria 29th May 2017
* ***Poster* ‘**In-situ irradiation of metal-ceramic composite neutron shielding materials’, S.A. Humphry-Baker, G. Greaves, J.A. Hinks, S.E. Donnelly, D. Kingham, G.D.W. Smith and W.E. Lee**,** 16th International Conference on Plasma-Facing Materials and Components for Fusion Applications, Neuss/Dusseldorf, Germany 16th May 2017
* ***Poster* ‘**Coating of tungsten carbide composites for accident tolerance’, S. A. Humphry-Baker, K. Peng, G.D.W. Smith and W.E. Lee**,** 16th International Conference on Plasma-Facing Materials and Components for Fusion Applications, Neuss/Dusseldorf, Germany 16th May 2017
* ***Lecture* ‘**Thermophysical properties of Co-free WC-FeCr hardmetals’, S. A. Humphry-Baker, J.D. Marshall, G.D.W. Smith and W.E. Lee,in session HM 19 of the 19th Plansee Seminar, Reutte, Austria 29th May 2017
* ***Invited talk* ‘**Tungsten-based ceramic composites in extreme fusion reactor environments’, S. A. Humphry-Baker, L. Vandeperre, G. D. W. Smith and W. E. Lee,in Symposium N: High and Ultra High Temperature Ceramics, 7th International Congress on Ceramics, Foz de Iguacu, Brazil 17th Mar 2018

**Niranjan Patra**

* ***Lecture*** ‘Carbothermal synthesis and characterization of zirconium diboride by facile one-pot reaction’, N. Patra, D.D. Jayaseelan, W.E. Lee, International Workshop in Advanced Ceramics (IWAC-06) 28th – 30th Sep 2014, Erlangen, Germany.
* ***Lecture*** ‘Low temperature synthesis of organometallic hybrid precursor-derived nanosized HfC’, N. Patra, D.D. Jayaseelan, W.E. Lee, Materials Science & Technology 2014 (MS&T 2014), 12th - 16th Oct 2014, Pittsburgh, PA, USA.
* ***Lecture*** ‘In situ synthesis of ZrB2/SiC composites for hypersonic applications’, N. Patra, D.D. Jayaseelan, W. E. Lee, 39th Int Conf on Advanced Ceramics and Composites (ICACC-2015), 25th – 30th Jan 2015, Daytona Beach, Florida, USA.
* ***Lecture*** ‘An ultra-high-temperature organometallic hybrid precursor infiltrate carbon fiber mat and its characterization’, N. Patra, D.D. Jayaseelan, W.E. Lee, 14th Int Conf of the European Ceramics Society 2015 (ECerS-2015), Toledo, Spain, 21st – 25th June 2015.
* ***Lecture*** ‘Solution-based synthesis of HfB2/SiC composite powder from an organic-inorganic hybrid precursor’ N. Patra, D. D. Jayaseelan, W. E. Lee, European Congress and Exhibition on Advanced Materials and Processes” (Euromat-2015), Warshaw, Poland, September 20-24, 2015.

**Anish Paul**

* ***Lecture*** ‘Preparation of HfB2 powder and HfB2/carbon composites for ultra-high temperature applications’, P. Zheng, S. Venugopal, A. Paul, J. Binner and B. Vaidhyanathan, 8th International Conference on High Performance Ceramics (CICC-8), Chongqing, China, November 2013.
* ***Keynote*** ‘High-temperature strength measurements and arc-jet testing of Cf-HfB2 UHTC composites’, A. Paul, S. Venugopal, J. Binner, B. Vaidhyanathan, A. Heaton and P. Brown, ECERS XIII, Limoges, France, June 2013.
* ***Lecture*** ‘Ultra-high temperature ceramic – HfB2’, S. Venugopal, A. Paul, J. Binner, B. Vaidhyanathan, A. Heaton and P. Brown, ECERS XIII, Limoges, France, June 2013.
* ***Award*** *‘UHTC-carbon fibre composites: Preparation, oxyacetylene torch testing and characterisation’*, Paul A, Venugopal S, Binner JGP, Vaidhyanathan B, Heaton ACJ and Brown PM. *J. Eur. Cer. Soc.* **33** 423-432 (2013)won the **JECS Best Paper Award**.
* ***Award*** *‘Heat flux mapping of oxyacetylene flames and their use to characterise Cf-HfB2 composites’,* Paul A, Binner JGP, Vaidhyanathan B and Brown PM. *Adv. Appl. Ceram.* **115** [3] 158-165 (2016) won the **2017 IOM3 Pfeil Award**.

**Matt Porter**

* ***Poster*** – ‘Enhanced chemical vapour infiltration of high-temperature ceramic matrix composites’, 3GCMEA, July 2016, Cartagena, Spain
* ***Poster*** – ‘Microwave enhanced chemical vapour infiltration of ceramic matrix composites’ MST ’16, October 2016, Salt Lake City, USA
* ***Poster*** – ‘High-temperature ceramic matrix composites using microwave enhanced chemical vapour infiltration’, Ceramic matrix composites, November 2017 Engineering conferences international, Santa Fe, USA
* ***Poster*** – ‘Optimisation of SiCf/SiCp Preform Prior to Matrix Consolidation Using Microwave Enhanced Chemical Vapour Infiltration’ 42nd ICACC, January 2018, Daytona beach, USA
* ***Lecture*** – ‘Optimisation of SiCf/SiCp/SiC preforms prior to Microwave Enhanced Chemical Vapour Infiltration’ ECerS XIV, July 2017, Budapest, Hungary
* ***Lecture*** – ‘High-temperature ceramic matrix composites using microwave enhanced chemical vapour infiltration’ 42nd ICACC, January 2018, Daytona beach, USA
* ***Lecture*** – AFSOR Program review - ‘High-temperature ceramic matrix composites using microwave enhanced chemical vapour infiltration’ Fort Walton, May 2018, USA
* ***Lecture***– ‘High and Ultra-High Temperature Ceramic Matrix Composites’ Knowledge transfer network, June 2018, London
* ***Visit***to carry out TEM analysis and high temperature treatment of SiC fibre at Wright Patterson Air Force Base, Dayton, Ohio
* ***Visit*** to learn the fundamentals of the mathematical modelling of the chemical vapour infiltration process in parallel to the development of an electromagnetic and thermal simulation of the process at Worcester Polytechnic institute, Massachusetts
* ***Leadership*** Became a PCSA delegate in 2016 and then became a Committee Chair of the outreach programme in 2017, looking to try and get ceramics into schools (mainly in the US). Have produced 8 educational posters for schools and are in the process of producing demonstrational videos, as well as promoting materials science kits that schools can purchase.

**Dhava Ramachandran**

* ***Invited Lecture*** ‘Creating ultra-high temperature ceramic matrix composites’ at 9th Intern. Conf. on High Temperature Ceramic Matrix Composites, June 36- July 1, 2016, Toronto, Canada.
* ***Lecture*** ‘Preparation and characterization of carbon reinforced ZrC composites via combined slurry impregnation and volumetrically heated RF-CVI processing’ at 9th Intern. Conf. on High Temperature Ceramic Matrix Composites, June 36- July 1, 2016, Toronto, Canada
* ***Poster*** ‘Thermal ablation effects on carbon CVI-densified Cf-HfB2 composites’ at 9th Intern. Conf. on High Temperature Ceramic Matrix Composites, June 36- July 1, 2016, Toronto, Canada.
* ***Poster*** ‘Microwave Heated Chemical Vapour Infiltration of ceramic matrix composites’ at 9th Intern. Conf. on High Temperature Ceramic Matrix Composites, June 36- July 1, 2016, Toronto, Canada.

**Prabhu Ramanujam**

* **Training** Attended ECERS/JECS Trust SEM-FIB-AFM training program in Istanbul, Turkey Sept 2014.
* **Lecture** ‘Processing of UHTC composites for hypersonic applications, P Ramanujam, A Paul, S Venugopal, V Rubio, JGP Binner and P Brown, ECERS XIV, Toledo, Spain, June 21-25, 2015.
* **Poster** ‘Modelling and experimental validation of the ablation of Cf-HfB2 composites via oxyacetylene torch testing’, AZ Bahramian, N Nirmalkar, A D’Angio’, P Ramanujam, V Rubio and JGP Binner, ECERS XIV, Toledo, Spain, June 21-25, 2015.
* **Poster,** ‘Evaluating UHTC monolithics, UHTC composites and graphite by oxyacetylene testing’, V Rubio, P Ramanujam, A Paul, JGP Binner and A Katz, ECERS XIV, Toledo, Spain, June 21-25, 2015.
* **Poster,** ‘Strong ZrB2-SiC-WC composites for hypersonic applications’, J Zhou, V Rubio, P Ramanujam, JGP Binner, J Vleugels and O van der Biest, ECERS XIV, Toledo, Spain, June 21-25, 2015.
* **Poster** ‘Oxyacetylene vs oxypropane torch testing of uhtc composites’, V Rubio, P Ramanujam, L Cormack, JGP Binner, HTCMC 9, Toronto.

**Virtudes Rubio**

* **Lecture** ‘UHTC Monolithics, UHTC composites and graphite by oxyacetylene testing’, V.Rubio, A.Paul, P.Ramanujam and J.G.P. Binner, ECERS XIV, Toledo, Spain, June 21-25, 2015.

**Theo Saunders**

* **Lecture** Contributed to dissemination by presenting results of plasma formation while sintering ZrB2 at the 3rd International Workshop on SPS in Toulouse in June 2014.
* **Visit** Has a keen interest in any technical advancements that might help in processing of UHTCs and related materials, having visited FCT (SPS machine manufacturer) Dresden in 2014 to examine their recent hybrid induction heating SPS, which was employed for flash sintering.
* **Visit** Toured the prototype GeniCore pulse capacitor sintering machine in Krakow May 2014.
* **Visit** Has maintained a good collaboration with academics from CNR Genoa having visited their labs in April 2015.
* Has recently developed a wetting test inside an SPS machine operating at a heating rate of 1000ᵒC/min that was employed for wetting of UHTC's and other high temperature ceramics.

**Eugenio Zapata-Solvas**

* **Lecture** ‘Creep of HfB2-based UHTCs up to 2000oC’; Ultra-High Temperature Ceramics: Materials For Extreme Environment Applications IV, 17-20 September 2017 Windsor, UK.
* **Lecture** ‘Creep of HfB2-based UHTCs up to 2000oC or how important structural / dimensional stability could be on hypersonic applications’; ICC7, 7th International Congress on Ceramics, 17-21 June 2018, Fox de Iguazu, Brazil.

**Ji Zou**

* ***Lecture***‘A top-down approach to densify UHTCs by exchange reactions among borides, carbides and nitrides’, 1 DRAC meeting, Imperial College London on 24th April 2015.
* ***Poster*** ‘Strong ZrB2-SiC-WC Composites for Hypersonic Applications’ European Ceramic Society conference’, Poster ECERS XIV, Toledo, Spain, June 21-25, 2015.
* Discussion and cooperation with Prof Bill Fahrenholtz from Missouri University of Science and Technology on ZrC ceramics during his stay in Birmingham. May, 2015, Birmingham.
* ***Two visits*** to Queen Mary University of London. Purpose: to develop joint effort between QMUL and UOB in order to achieve a more complete understanding of the Flash Sintering technique. Mar-June 2016.
* ***Invited Lecture*** ‘Thermoablative Resistance of ZrB2-SiC-WC Ceramics at 2400oC’, 15th conference and exhibition of the European Ceramic Society (ECERS XV), Budapest, Hungary, July 9-13, 2017.
* UK representative on the assessment panel for the [Student Speech Contest](https://ecers2017.akcongress.com/index.php/satellite-events/event-six) during ECERS XV, Budapest, Hungary, July 9-13, 2017.
* ***Invited Lecture*** ‘Flash sintering of difficult-to-densify ceramics for nuclear applications’, 10th International Conference on High-Performance Ceramics (CICC10), Nan Chang, China. Nov 4-7, 2017.
* Committee Member for the [Student Speech Contest](https://ecers2017.akcongress.com/index.php/satellite-events/event-six)during CICC 10, Nan Chang, China, Nov 4-7, 2017.
* ***Organizing Committee Member*** The International Conference on High-Performance Ceramics (CICC11), Kunming, China, May 2019.
* ***Committee member and Point of Contact***, Symposium of Borides and Boron Related Materials, The International Conference on High-Performance Ceramics (CICC11), Kunming, China, May 2019.

**Annex 4**

**Publications**

Published

1. E Zapata-Solvas, DD Jayaseelan, PM Brown and WE Lee, **Thermal Properties of La2O3-doped ZrB2– and HfB2-based Ultra-high Temperature Ceramics**, *J. Euro. Ceram. Soc*., 33 [15-16] 3467-3472, 2013.
2. J Ye, RP Thackray, S Zhang and WE Lee, **Microstructure and Rheological Properties of Titanium Carbide Coated Carbon Black Particles Synthesized from Molten Salt**, *J. Mater. Sci.*, 48 [18] 6269-75, 2013.
3. ***Winner of JECS Best Paper Award*** A Paul, S Venugopal, JGP Binner, B Vaidhyanathan, ACJ Heaton and PM Brown, **UHTC–carbon fibre composites: Preparation, Oxyacetylene Torch Testing and Characterisation**, *J. Euro. Ceram. Soc.,* 33 [2] 423-432 (2013).
4. JGP Binner, B Vaidhyanathan and D Jaglin, **Microwave Heated Chemical Vapour Infiltration of SiC Powder Impregnated SiC Fibre Preforms**, *Adv. Appl. Ceram.,* 112 [4] 235-241, 2013.
5. A Paul, JGP Binner, ACJ Heaton, B Vaidhyanathan, and PM Brown, **Oxyacetylene Torch Testing and Microstructural Characterisation of Tantalum Carbide**, *Journal of Microscopy*, 250 [2] 122-129, 2013.
6. B Cui, E Zapata-Solvas, MJ Reece, C Wang and WE Lee, **Microstructure and High-Temperature Oxidation Behaviour of Ti3AlC2/W Composites**, *J. Am. Ceram. Soc*., 96 [2] 584-591, 2013.
7. E Zapata-Solvas, DD Jayaseelan, P Brown and WE Lee, **Mechanical Properties of ZrB2– and HfB2-based Ultra-High Temperature Ceramics Fabricated by Spark Plasma Sintering**, *J. Eur. Ceram. Soc.*, 33 1373-1386, 2013.
8. S Grasso, J Poetschke, V Richter, G Maizza, Y Sakka and MJ Reece, **Low-Temperature Spark Plasma Sintering of Pure Nano WC Powder**, *J. Am. Ceram. Soc.,* 96 [6] 1702-1705, 2013.
9. S Grasso, H Yoshida, H Porwal, Y Sakka and MJ Reece, **Highly Transparent α-Alumina Obtained By Low Cost High Pressure SPS**, *Ceramics International*, 39 [3] 3243-3248, 2013.
10. D Manara, HF Jackson, C Perinetti-Casoni, K Boboridis, MJ Welland, L Luzzi and WE Lee, **The ZrC-C Eutectic Structure and Melting Behaviour: A High-temperature Radiance Spectroscopy Study**, *J. Eur. Ceram. Soc*., 33 1349-61, 2013.
11. WE Lee, MI Ojovan and CM Jantzen (Editors), **Radioactive Waste Management and Contaminated Site Clean-up: Processes, Technologies and International Experience**, (Woodhead, 2013).
12. B Cui and WE Lee, **High-temperature Oxidation Behaviour of MAX-Phase Ceramics**, Refractories World forum, WINNER of 3rd place in Gustav Eirich Award 2012, 5 [1] 105-112, 2013.
13. WE Lee, M Gilbert, S Murphy and RW Grimes, **Opportunities for Advanced Ceramics and Composites in the Nuclear Secto**r, *J. Am. Ceram. Soc.*, 96 [7] 2005-30, 2013.
14. S Grasso, Y Sakka, **Electric field in SPS: Geometry and Pulsed Current Effects**, *J. Ceram. Soc., Japan*, 1414 [121] 524-526, 2013.
15. J Ye, S Zhang and WE Lee, **Molten Salt Synthesis and Characterization of SiC Coated Carbon Black Particles for Refractory Castables Applications**, *J. Euro. Ceram. Soc.*, 33 [29] 2023-29, 2013.
16. JGP Binner, B Vaidhyanathan, D Jaglin and S Needham, **Use of Electrophoretic Impregnation And Vacuum Bagging to Impregnate Sic Powder into Sic Fibre Preforms**, Int. J. Appl. Ceram. Techn., 1-11 DOI:10.1111/ijac.12143 (2013).
17. S Venugopal, A Paul, B Vaidhyanathan, JGP Binner, A Heaton, PM Brown, **Synthesis and Spark Plasma Sintering of Sub-micron HfB2: Effect of Various Carbon Sources**, *J. Eur. Ceram. Soc*., 34 [6] 1471–1479, 2014.
18. WE Lee, R Harrison, E Giorgi, A Maitre and O Rapaud, WG Fahrenholtz, EJ Wuchina, **Nuclear Applications for Ultra-High Temperature Ceramics and MAX Phases, in Ultra-High Temperature Ceramics: Materials for Extreme Environment Application**, Lee WE and Zhou Y (Eds.), Wiley (2014).
19. WG Fahrenholtz, EJ Wuchina, WE Lee and Y Zhou (Editors), **Ultra-High Temperature Ceramics: Materials for Extreme Environment Applications**, Wiley, (2014).
20. C Carney, A Paul, A Venugopal, T Parthasarathy, JGP Binner, A Katz and P Brown, **Qualitative Analysis of Hafnium Diboride Based Ultra-High Temperature Ceramics under Oxyacetylene Torch Testing at Temperatures above 2100oC**, *J. Eur. Ceram. Soc.,* 34 [5] 1045–1051, 2014.
21. Q Wang, C Hu, S Cai, Y Sakka, S Grasso and Q Huang, **Synthesis of High-Purity Ti3SiC2 by Microwave Sintering**, *Int. J. App. Ceram. Tech*.,11 [5] 911-918, 2014.
22. A Paul, JGP Binner and B Vaidhyanathan, **UHTC Composites for Hypersonic Applications**, Chapter 7, in *Ultra-High Temperature Ceramics: Materials for Extreme Environment Applications*, First Edition. Edited by William G. Fahrenholtz, Eric J. Wuchina, William E. Lee and Yanchun Zhou. The American Ceramic Society. Published by John Wiley & Sons, Inc, 144-166, 2014.
23. JD Rogal, MW Finnis, A Glensk, J Neugebauer, JH Perepezko, S Schuwalow, MHF Sluiter, B Sundman, **Perspectives on Point Defect Thermodynamics**, *Physica Status Solidi B*, [251] 97-129, 2014.
24. S Grasso, T Saunders, H Porwal, O Cedillos-Barraza, DD Jayaseelan, WE Lee and MJ Reece, **Flash Spark Plasma Sintering (FSPS) of Pure ZrB2 Powder**, *J. Am. Ceram. Soc*., 97 [8] 2405-2408, 2014.
25. E Zapata-Solvas, DD Jayaseelan, PM Brown and WE Lee, **Effect of La2O3 Addition on Long-term Oxidation Kinetics of ZrB2-SiC and HfB2-SiC Ultra-high Temperature Ceramics**,*J. Euro. Ceram. Soc.*, 34 [5] 3535-3548, 2014.
26. P Badica, S Grasso, H Borodianska Sky, S Xie, P Li, P Tatarko, MJ Reece, Y Sakka and O Vasylkiv, **Tough and Dense Boron Carbide Obtained By High-Pressure (300 MPa) and Low-Temperature (1600°C) Spark Plasma Sintering**, *J. Ceram.Soc., of Japan*, 122 271-275, 2014.
27. S Venugopal, EE Boakye, A Paul, K Keller, P Mogilevsky, B Vaidhyanathan, JGP Binner, A Katz and PM Brown, **Sol Gel Synthesis and Formation Mechanism of Ultra High Temperature Ceramic: HfB2**, *J. Am. Ceram. Soc.*, 97 [1] 92–99, 2014.
28. MI Ojovan and WE Lee, (2nd Edition, Elsevier) **An Introduction to Nuclear Waste Immobilisation**, 362 2014.
29. H Zhang, C Hu, J Lv, S Grasso, M Mishra, M Estili, Y Yamauchi, B Kim, Y Sakka, **Microstructure and Adsorption Property of Nano Carbide-derived Carbon (CDC) Synthesized at Ambient Temperature**, *Materials Letters,* 130 188-191, 2014.
30. S Grasso, T Saunders, H Porwal and MJ Reece, **Ultra-High Temperature Spark Plasma Sintering of α-SiC**, *Ceramics International*, 41 [1] 225-230, 2014.
31. R Harrison, O Ridd, DD Jayaseelan and WE Lee, **Thermophysical Characterisation Of ZrCxNy Ceramics Fabricated Via Carbothermal Reduction-Nitridation**, *J. Nuclear Mats.*,454,46-53 , 2014.
32. J Gonzalez-Julian, O Cedillos, S Doring, S Nolte, O Guillon and WE Lee, **Enhanced Oxidation Resistance of ZrB2/SiC Composites Through *In Situ* Reaction of Gadolinium Oxide in Patterned Surface Cavities**, *J. Euro. Ceram. Soc.*, 34,4157-4166, 2014.
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34. R Harrison, O Ridd, DD Jayaseelan and WE Lee, **Synthesis and Characterisation of ZrCxNy Ceramics via Carbothermic Reduction-Nitridation**, *J. Nuclear Mats.*
35. T Saunders, S Grasso,  MJ Reece, **Plasma Formation during Electric Discharge (50V) through Conductive Powder Compacts**,*J.Eur. Ceram. Soc.*, 35 [3] 871–877, 2015.
36. DD Jayaseelan, E Zapata-Solvas, CM Carney, A Katz, P Brown, WE Lee, **Microstructural Evolution of HfB2–based Ceramics during Oxidation at 1600oC to 2000oC**, *Adv. in Applied Ceramics*. 114 [5] 277-295, 2015.
37. JGP Binner, B Vaidhyanathan, D Jaglin, S Needham, **Use of Electrophoretic Impregnation And Vacuum Bagging To Impregnate Sic Powder Into Sic Fibre Preforms**, *S. Int. J. Appl. Ceram. Tech*., 12 [1] 212–222, 2015.
38. S Venugopal, DD Jayaseelan, A Paul, B Vaidhyanathan, JGP Binner,PM Brown,**Screw Dislocation Assisted Spontaneous Growth of HfB2 Tubes and Rods**, *J. Am. Ceram. Soc.,* 98 [7] 2060-2064, 2015.
39. DD Jayaseelan, X Yanda, L Vandeperre, P Brown, WE Lee, **Development of Multi-Layered Thermal Protection System (TPS) For Aerospace Applications**, *Composite, Part B,*[79] 392-405, 2015.
40. N Patra, DD Jayaseelan, WE Lee, **Synthesis of Biopolymer-Derived Zirconium Carbide Powder By Facile One-Pot Reaction**,*J. Am. Ceram. Soc.*, 98 [1] 71-77, 2015.
41. HB Zhang, CF Hu, SK Sato, S Grasso, M Estili, SQ Guo, K Morita, H Yoshida, T Nishimura, TS Suzuki, MW Barsoum, BN Kim, Y Sakka, **Tailoring Ti3AlC2 Ceramic With High Anisotropic Physical And Mechanical Properties**,*J.Eur. Ceram. Soc.*, 35 [1] 393-397, 2015
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**Patents**

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**Annex 5**

**XMat Research Collaborations**

|  |  |  |  |
| --- | --- | --- | --- |
| **Partner** | **Contribution** | **Period** | **Value** |
| National Oilwell Varco, USA | Development of innovative diamond joining techniques | Feb 2013 – Feb 2014 | £20k |
| London Underground (TFL), UK | Funding for the development of materials for electric relays | Jul 2013 | £10k |
| Max Planck Institut For Eisenforschung, Dusseldorf, Germany | Assisted with the development of the TU-TILD method for achieving fully anharmonic DFT calculations with at least an order of magnitude improvement in efficiency over the existing method. | Aug 2013 |  |
| ICAMS, Ruhr-Universität Bochum, Germany | Assisted with applications of ThermoCalc | Ongoing since 2013 |  |
| NOV | Development of novel joining techniques for diamond cutting materials | Sep 2013 |  |
| Harbin Institute of Technology, China | Dr Yuelei Bai academic visitor to ICL. Investigated a wide range of ternary compounds in the Hf-Al-C system using First-Principle simulation. | Feb 2014 – Jan 2015 |  |
| ICAMS, Ruhr-Universität Bochum, Germany | Assisted with the development of the TU-TILD method for achieving fully anharmonic DFT calculations with at least an order of magnitude improvement in efficiency over the existing method. | May 2014 |  |
| MBDA, UK | Funded two related programmes, viz.: i) determining the potential of Cf-UHTC powder composites for specific applications and ii) improving an existing, low cost CMC by incorporating UHTCs. | Apr 2014 – Mar 2016 | £250k |
| A 3rd programme, a PhD studentship, has also been funded by MBDA. | Oct 2017 – Sept 2020 | £75k |
| DSTL, UK | Funded a programme on Cf-UHTC powder composites primarily aimed at determining whether the processing can be scaled up to allow the production of full size components. | Jul 2014 – Jun 2016 | £150k |
| Harbin Institute of technology, China | Development of WC moulding | Aug 2014 | £15k |
| Kennametal, UK | Use of Industrial SPS machine and fabrication of novel tooling to upscale Flash-SPS. | Sep 2014 | £10k |
| Huddersfield, UK | Provided ion irradiation for the Humphrey-Baker project. | Sep 2014 – Aug 2016 |  |
| Tokamak, UK | Funded a programme on investigating the performance of WC composites in hard irradiation environments. | Sep 2014 – Aug 2016 | £68k |
| Institute of Materials Research, Slovakia | Research collaboration for micro testing (nano hardness mapping and micropillars testing) of ZrB2 | Feb 15 – Jun 2015 |  |
| Element Six, UK | c-BN ceramic composites by SPS routes | May 2015 | £40k |
| Missouri S&T, USA | Visit by Prof Bill Fahrenholtz; worked with the research team at UoB, initiated new projects and gave a seminar at ICL. | May – Jun 2015 | - |
| Kennametal, UK | Scaling up development of high pressure SPS sintering. | Sept 2015 | £10k |
| AFRL, USA | High temperature composites using microwave enhanced chemical vapour infiltration | 2016 – 19 | £102k |
| **TOTAL** | | | **£750k** |

**Projects obtained because of XMat but not formally part of it**

|  |  |  |  |
| --- | --- | --- | --- |
| **Partner** | **Contribution** | **Period** | **Value** |
| Harbin Institute of Technology (China) | Development of WC moulding | Aug 2013 | £15k |
| ONRG | Processing of carbon fibre UHTC ceramic composites | 2013 – 15 | £196k |
| Element Six | C-BN ceramic composites | Sep 2014 | £40k |
| DSTL & ONRG | Scaling up of transparent nano alumina for armour protection | 2014 – 15 | £67k |
| Rolls-Royce | Improving oxidation resistance of SiC/SiC | 2014 – 15 | £265k |
| Lloyds Register | Support for Chair in Nuclear Regulation | 2014 – 17 | £150k |
| University of New South Wales, Australia | Synroc durability PhD | 2014 – 18 | £180k |
| EPSRC Nuclear Decommissioning Authority Industrial CASE | Oxidation of uranium carbide nuclear fuel | 2014 – 18 | £150k |
| EPSRC, Sellafield, NNL, NDA | Distinctive (Decommissioning Immobilisation and storage soluTIons for NuClear wasTe InVEntories) consortium | 2014 – 19 | £450k |
| EPSRC | Nuclear Energy Centre for Doctoral Training, with Cambridge and The Open University | 2014 – 19 | £4M |
| Leverhulme Trust | Visiting Fellow Michel Barsoum | Sept – Dec 2015 | £16k |
| EPSRC | Carbides for Future Fission Environments (CAFFE), with Cambridge (leader) and Manchester | 2015 – 18 | £555k |
| EPSRC | Strategic Equipment – MagMat – Synthesis and processing of materials in a strong magnetic field | 2015 – 20 | £328k |
| EU Horizon 2020 | Next generation ceramic composites for combustion harsh environments and space (D Sciti, CNR-ISTEC, Italy, PI) | 2016 – 20 | £611k |
| MBDA | Rheological processing of UHT ceramics and composites | 2016 – 18 | £75k |
| Rolls-Royce | CMCs | 2018 – 19 | £137k |
| EU Horizon 2020 | Effect of rare-earth doping elements on the mechanical and oxidation resistance performance of SiC coated C fibre / ZrC composites for high temperature applications | 2018 – 20 | £176k |
| ATI / Rolls-Royce | Ox/Ox CMC – Ultrafan Heat Shield | 2018 – 20 | £269k |
| DSTL / BAE Systems | Low observable composites | 2019 – 22 | £97k |
| **TOTAL** | | | **£7.92M** |

**Annex 6**

**Visiting Researchers**

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Institution** | **Dates** | **Visiting** |
| Dr Katsumi Yoshida, | Tokyo Institute of Technology, Japan | Nov – Dec 2013 | ICL |
| Dr Jesus Gonzalez, | Friedrich-Schiller University Jena, Institute of Materials Science and Technology (IMT), Jena Germany | 2013 to 2014 | ICL |
| Dr Yuelei Bai, | Centre for Composite Materials and Structures, Harbin Institute of Technology, China. | 2014 to 2015 | ICL |
| Ms Christin Pietsch | TU Bergakademie Freiberg, Germany | Oct 2014 – Mar 2015 | UoB  (Erasmus scheme) |
| Dr Ke Peng | State Key Laboratory for Powder Metallurgy in Central South University, Changsha, China | Jan – Dec 2015 | ICL |
| Dr Eugenio Solvas-Zapata, | University of Seville, Spain | March – April 2015 | ICL |
| Prof. Ted Besmann | University of South Carolina and Oak Ridge National Laboratory | May 2015 | Primarily ICL, but visited 2 other universities |
| Prof Bill Fahrenholtz | University of Missouri S&T | May – Jun 2015 | Primarily UoB, but also ICL |
| Prof Takao Mori | NIMS, Japan | July 2015 | QMUL, but visited 3 other universities |
| Prof Guo-Jun Zhang | SICCAS, China | July 2015 | QMUL, but visited other universities |
| Prof Michel Barsoum | Drexel University, USA | Sept – Dec 2015 | ICL/QMUL/UoB |
| Ms Selina Presser | TU Bergakademie Freiberg, Germany | Oct 2015 – Mar 2016 | UoB  (Erasmus scheme) |
| Ms Phylis Makurunje | University of Witwatersrand | Oct 2017 | UoB |

**Annex 7**

**People Pipeline**

**Next destination for researchers:**

|  |  |  |
| --- | --- | --- |
| **XMat Researcher** | **Current role** | **Current destination** |
| Dr Ellie Castle, PhD student, QMUL | Ceramics Research & Industrial Liaison Manager | School of Engineering & Materials Science, Queen Mary University of London |
| Dr Andrea D’Angio, PhD student, UoB | Research Engineer | National Composites Centre, Bristol, UK |
| Dr Doni Daniel, postdoc, ICL | Senior lecturer | School of Mechanical and Aerospace Engineering, Kingston University, Roehampton Vale, UK |
| Dr Theresa Davey, PhD student, ICL | Assistant Professor | Tohoku University, Sendai, Miyagi, Japan |
| Dr Andrew Duff, postdoc, ICL | Researcher | Scientific Computing Department, Daresbury Lab, STFC |
| Dr Salvatore Grasso, postdoc, QMUL | Research Fellow and Professor | Research Fellow, QMUL and Prof in Ceramics at Southwest Jiaotong University, Chengdu, China |
| Dr Denis Horlait, postdoc, ICL | Researcher | Centre d'Etudes Nucléaires de Bordeaux-Gradignan (CENBG), French National Centre for Scientific Research, Paris, France |
| Dr Sam Humphrey-Baker, postdoc, ICL | ICL Research Fellow | Department of Materials, Imperial College, London, UK |
| Dr Niranjan Patra, postdoc, ICL | Postdoc | Department of Mechanical Engineering, University of Wyoming, Laramie, USA |
| Dr Anish Paul, postdoc, UoB | Materials Engineer | Ansaldo Energia, Baden, Canton of Aargau, Switzerland |
| Mr Matt Porter, PhD student, UoB | PhD student | Completing the final year of his PhD in the School of Metallurgy & Materials, University of Birmingham |
| Dr Dhavanesan Ramachandran, postdoc, UoB | Consultant | Dhavaa Technical Ceramics & Consultancy, Coimbatore, Tamil Nadu, India |
| Dr Prabhu Ramanujam, postdoc, UoB | Research Specialist (AGM) | Research and Development, Wendt India Ltd, Hosur,  Chennai, Tamil Nadu, India |
| Dr Virtu Rubio Diaz, postdoc, UoB | Advanced Research Engineer | National Composites Centre, Bristol, UK |
| Mr Theo Saunders, PhD student, QMUL | PhD student | Completing the final year of his PhD in the School of Engineering & Materials Science, Queen Mary University of London |
| Dr Eugenio Zapata-Solvas, postdoc, ICL | BEAMS Strategic Research Facilitator | University College London, UK |
| Dr Ji Zou, postdoc, UoB | Postdoc, UoB | School of Metallurgy & Materials, University of Birmingham, UK |