Innovative Manufacturing Research Centre for Liquid Metal Engineering (IMRC-LiME)

Part I: Track record

1. Investigators

Professor Z. Fan (ZF): For track record of Professor Fan please see the attached 2-page CV.

Professor PS Grant (PG): Patrick has held the Cookson Chair of Materials at Oxford University since 2004. His research interests include developing fundamental understanding of the complex underlying physics during materials processing and detailed investigations of novel manufacturing routes based on solidification, using a combination of experimentation on a near industrial scale, on-line process diagnostics, numerical simulation, and close collaboration with industry. He has over 140 papers and 6 patents (3 licensed). From 1999 to 2004, he was Director of the Oxford Centre for Advanced Materials and Composites (OCAMAC) that helps to coordinate industrial materials related research across Oxford University, and was Director of Faraday Advance from 2000 until 2007 when he became Executive Director of the Materials KTN Transport Node. He was one of the founding academics that established the Begbroke Science Park at Oxford University, now a major regional and international hub for innovation and close industrial-university collaboration. Professor Grant was a member of the 2008 Research Assessment Exercise panel for Materials, is a member of the Materials & Structures National Technical Committee and EPSRC's Fusion Advisory Board, and consultant for a venture capital company.

Professor NR Green (NG): Nick holds the EPSRC-Rolls-Royce Star Chair in Casting Technology at Birmingham University. He leads the Casting Research Group, and is Director of the Casting Partnership with RR. His research interests include both light alloy and high temperature materials, principally aluminium, nickel superalloys and titanium aluminides. Recent publications encompass development of modelling methods for multi-phase centrifugal casting of complex components, free surface entrainment and defect tracking and objective functions for filling system optimisation, and the experimental investigation and development of solutions to defect formation in single crystal turbine blades. He has filed 2 patents related to casting technologies. In the last 2 years he has secured £1.3M private venture research funding. He worked as Technical Director of Cosworth Technology (2000-2005) and Technical Manager of VAW (1996-2000). During this time he directed and led the technical launch of a major green field joint venture in Mexico. In 2000 he received the Howard F Taylor Award from AMF for far-reaching contributions to the technical advancement of the worldwide foundry industry.

Professor GM Scamans (GS): Geoff is Professor of Metallurgy in BCAST at Brunel University. He earned both his BSc and PhD in Metallurgy from Imperial College. He started his research career in 1974 at Alcan International, initially as research scientist (1974-1982), senior research scientist (1982-1983) and later as principal scientist (1983-2003). More recently, he was the Chief Scientific Officer (2003-2007) at Innoval Technology. His expertise is in light metals and their applications in the automotive and aerospace industries, and in knowledge transfer from the research base to industry. Over the last 30 years he has initiated and managed a number of R&D programmes on both materials development and technological innovation, making substantial scientific and technological contributions to the light metals sector, described in over 130 publications. He is a Fellow and Vice President (LMD) of IOM^3. He has been invited to speak at numerous international conferences, and has organised many international conferences on light metals, earning an international reputation in the light metals community. He is currently leading 5 DTI/TSB funded projects all related to light metals research.

Dr N Hari-Babu (NH): Hari has been a Lecturer and RCUK Research Fellow in BCAST at Brunel University since 2006. Prior to that he was a Research Fellow (1999-2002), then a Senior Research Fellow (2002-2003) and, ultimately, Advanced Research Fellow (2003-2006) at the University of Cambridge. He has published over 120 papers in international peer reviewed journals and holds 3 international patents. He was awarded the "PASREG award of excellence" in 2007 for his outstanding contribution to the development and characterisation of bulk high temperatures superconductors. During his post-doctoral career, he received several best poster presentation awards. During his time at Cambridge, he worked in the Melt Processing Research Group at the IRC in Superconductivity, and was involved in the day-to-day management of collaborative projects with other research groups around the world. Since joined in BCAST, his research has been focused on understanding heterogeneous nucleation during solidification, processing of high performance MMCs using intensive melt shearing, twin roll casting Al-alloys from a recycled source for automotive application.

Dr KAQ O'Reilly (KO): Keyna is a Lecturer at Oxford University and has researched melt processing for over 20 years, specialising in Al alloys. Her work centres on controlling intermetallic phase formation in Al alloys by understanding the nucleation and growth mechanisms. She has developed a unique technique for measuring the nucleation potential of a melt and improving the melt cleanliness of alloys through intermetallic phase nucleation and sedimentation early in solidification processes. She has also developed a number of techniques for investigating nucleation and growth mechanisms and how they affected by impurity levels, grain refiner additions, thermal history and melt cleanliness. Her research work spans from small scale laboratory experiments where precise control of parameters is possible, through near-industrial scale casting in the laboratory, up to full scale industrial trials in industry where she has demonstrated that control of intermetallic phases during casting leads to increased productivity downstream and ultimately to cost savings.

Dr W D Griffiths (WG): Bill is Senior Lecturer at the University of Birmingham. He has over 20 years' experience in solidification and heat transfer research. The theme of his research is the identification and study of the mechanisms that control metallurgical processes, beginning with a PhD on thermal stress and strain during quenching, and continued during his employment in a commercial R&D company. He continued with postdoctoral research at Nottingham University, before moving to UMIST to study heat transfer during solidification and finally to the University of Birmingham. His current research covers: (1) interfacial heat transfer and particularly the enhancement of heat transfer by casting in a He atmosphere; (2) formation of oxide films and their effects on casting quality; (3) the Lost Foam casting process; and (4) positron Emission Particle Tracking (PEPT) and its application in studying the behaviour of oxide inclusions during casting processes. He has published 65 journal and conference papers.

Dr BJ McKay (BM): Brian is a newly appointed lecturer in BCAST at Brunel University. Prior to that he was a university assistant at the Institute of Casting Research (ICR), University of Leoben, Austria (2003-2009) and a research fellow at UMIST (2003). He obtained his DPhil from Oxford University, MSc from The Queen's University of Belfast and BEng from the University of Ulster. He has over 10 years' experience in solidification research and has published over 20 papers, mainly in internationally peer-reviewed journals. His research interests have been centred on understanding heterogeneous nucleation during solidification, which has included the characterisation of Al/TiB_2 interfaces by transmission electron microscopy and the development of ZrB_2 based grain refiners for Mg-Al based alloys. In the last 6 years, as a university assistant, he effectively ran the solidification research activities in ICR at Leoben, and developed many links with the metal casting industry. This has allowed him to obtain extensive knowledge of, and wider skills in, various casting processes.

2. Capability of the Research Team

The IMRC-LiME research team has assembled the key UK academic skills in solidification science and technology to form a critical mass for addressing the grand challenges now facing the metal casting industry and its customers. ***Brunel*** has expertise in nucleation modelling through analytical modelling, molecular dynamic simulation and phase field approaches, the dynamic study of the structure of liquid metals, nucleation control through both physical and chemical approaches, melt conditioning by intensive melt shearing, high pressure die casting, sand casting, gravity die casting, DC casting and twin roll casting; ***Oxford*** provides expertise in the nucleation of intermetallics, grain multiplication effects during solidification, spray forming, squeeze casting, low pressure casting and DC casting; ***Birmingham*** provides expertise in oxidation of liquid metals, numerical modelling of solidification processing, investment casting, precision sand casting and solidification of high temperature alloys, particularly nickel superalloys and titanium aluminides. The combined expertise and skills of the IMRC-LiME research team covers both the major research areas in solidification science and the mainstream solidification processing technologies. The team also provides a unique collection of ***state-of-the-art facilities*** for: (1) theoretical modelling and simulation from atomic scale phenomena at the solid/liquid interface, microstructural evolution at micro-scales, and complex mould design and process simulation at macro-scales; (2) advanced materials characterisation ranging from microstructural analysis to large scale testing of mechanical and physical properties; (3) solidification processing, such as high/low pressure die casting, gravity die casting, squeeze casting, investment casting, spray forming, sand casting, twin roll casting and DC casting, many of which are at near or full industrial scale. Inevitably, this expertise and infrastructure can never be complete, and we will strive to expand our partnership as the IMRC-LiME expands to include those facilities and expertise necessary for new research activities from organisations outside the current partnership.

The IMRC-LiME research team has a proven ***track record in attracting research grants*** from both public and private sectors. In the last 5 years, the team has secured over £5M in research grants from EPSRC, TSB, EU and other public funding bodies, all related to solidification research. The team also has a proven track record of working with a wide range of industrial sectors, involving the entire supply chain of metallic materials manufacturing. Our industrial partners in IMRC-LiME span materials suppliers (Sapa, MEL, LSM and Norton), materials processors (Aeromet, Meridian, JVM, NewPro Foundry, Grainger & Worrall), equipment manufacturers (Foseco and Rautomead), recycling companies (Norton and MEL), to end-users (JLR, RR, DSTL and Qinetiq). Many of them are existing partners convinced of our quality to deliver, and many are SMEs. A key feature of our industrial partners is that they are all forward-looking and have a strong track record of commitment to technological innovations and above all have the ambition to drive their businesses up the value chain in global markets. Our total industrial funding in the last 5 years has been more than £5M, over 25% of which was direct financial contribution. For the IMRC-LiME, we have industrial commitment of over £1.6M direct and over £3M in-kind.

3. University Support

Our Universities have been strongly supportive of solidification research. ***Brunel University*** created BCAST in 2002 as a Specialist Research Institute (SRI) to boost solidification research, and invested over £3M in BCAST in the last 7 years in terms of space, equipment and particularly academic staff. To support IMRC-LiME for the next 5 years, Brunel has committed a further £1.35M for large processing equipment including a new 400 ton high pressure die casting machine and sand casting facilities (£0.5M), 2 new University-funded lectureships (£0.6M), and a Departmental Manager to release Prof Fan (PI) to the management of IMRC-LiME (£0.25M), and an extra $300m^2$ of laboratory space for housing new research activities directly related to IMRC-LiME. ***Birmingham University*** has recently invested £2.5M in materials processing facilities, many of which are relevant to solidification research initiatives. To support IMRC-LiME, Birmingham will provide at least two fully University-funded PhD studentships per year accounting for an accumulative total of £0.5M. ***Oxford University*** built the "big shed" Advanced Processing Laboratory (APL, £800K, $400m^2$) in 2006 in connection with Prof Grant's appointment to the Cookson Chair of Materials Processing that aligns exactly with the theme and content of this proposal. Within the APL, $100m^2$ will be re-allocated to the IMRC, and Oxford will provide two fully University-funded PhD studentships (about £140k) in connection with the proposal. In addition, research at Oxford will be supported 100%FTE (for 2 years) by a senior modelling researcher arriving in Oxford in 2009 under a recently awarded, and highly competitive, RS/RAE Newton Fellowship. This gives a total cash contribution of £2M to the IMRC-LiME in the next 5 years from the host Universities.

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Part II: Case for Support

1. Overview

The UK metal casting industry is a key player in the global market. It adds £2.6bn/year to the UK economy, employs directly around 30,000 people and produces 1.14 billion tons of metal castings, of which 37% is for direct export [1]. It underpins the competitive position of every sector of UK manufacturing across automotive, aerospace, defence, energy and general engineering. However, its 500 companies are mainly SMEs, who are often not in a position to undertake the highest quality R&D necessary for them to remain competitive in global markets. The current EPSRC IMRC portfolio does not cover this important research area nor does it address this clear, compelling business need. We propose to establish IMRC-LiME, a 3-way centre of excellence for solidification research, to fill this distinctive and clear gap in the IMRC portfolio. IMRC-LiME will build on the strong metal casting centres already established at Brunel, Oxford and Birmingham Universities and their internationally leading capabilities and expertise to undertake both fundamental and applied solidification research in close collaborations with key industrial partners across the supply chain. It will support and provide opportunities for the UK metal casting industry and its customers to move up the value chain and to improve their business competitiveness.

The main research theme of the IMRC-LiME is liquid metal engineering, which is defined as the treatment of liquid metals by either chemical or physical means for the purpose of enhancing heterogeneous nucleation through manipulation of the chemical and physical nature of both endogenous (naturally occurring) and exogenous (externally added) nucleating particles prior to solidification processing. A prime aim of liquid metal engineering is to produce solidified metallic materials with fine and uniform microstructure, uniform composition, minimised casting defects and hence enhanced engineering performance. ***Our fundamental (platform) research theme*** will be centred on understanding the nucleation process and developing generic techniques for nucleation control; ***our user-led research theme*** will be focused on improving casting quality through liquid metal engineering prior to various casting processes. The initial focus will be mainly on light metals with expansion in the long term to a wide range of structural metals and alloys, to eventually include aluminium, magnesium, titanium, nickel, steel and copper.

In the long-term IMRC-LiME will deliver:

- ***A nucleation-centred solidification science***, that represents a fundamental move away from the traditional growth-focused science of solidification.
- ***A portfolio of innovative solidification processing technologies***, that are capable of providing high performance metallic materials with little need for solid state deformation processing, representing a paradigm shift from the current solid state deformation based materials processing to a solidification centred materials engineering.
- ***An optimised metallurgical industry***, in which the demand for metallic materials can be met by an efficient circulation of existing metallic materials through innovative technologies for reuse, remanufacture, direct recycling and chemical conversion with limited additions of primary metal to sustain the circulation loop. This will lead to a substantial conservation of natural resources, a reduction of energy consumption and CO_2 emissions while meeting the demand for metallic materials for economic growth and wealth creation.

We request £4.3M from EPSRC (£5.38M in FEC) to establish IMRC-LiME, with further support of £1.6M direct and £3M in-kind contribution from our industrial partners and by £2M cash contribution from the host Universities.

2. Background

2.1 Solidification science

Solidification research as a scientific discipline has a history of about 60 years marked by the publication of the classic nucleation theory by Turnbull in the early 1950's [2], though metal casting practices can be traced back for thousands of years. Although the solidification process comprises two distinctive stages: nucleation and growth, the majority of the research has been focused on understanding of crystal growth with the nucleation stage being largely neglected due to practical difficulties and lack of a basic scientific framework. In the early days of solidification research, the focus was on analysing the heat and solute balance at the moving solid/liquid (S/L) interface to predict solidification patterns and casting defects [3]. In the late 1960s and early 1970's, the focus moved to the stability of the S/L interface and chemical segregation at both macro and micro-levels [4], with most effort in the 1980's being on the study of microstructures as a pattern selection problem through a competition between heat and solute transport [5]. More recently, with enhanced computing power, more numerical approaches have been developed to accurately study pattern selection and defect formation [6].

Nucleation research has centred on the practical development of effective grain refiners for structural refinement. Today, addition of grain refiners (inoculation) in both continuous and shape casting is a common industrial practice [7]. For instance, Al-Ti-B or Al-Ti-C master alloys are added to Al-alloys, Zr or C to Mg-alloys, ferrosilicon to cast iron, Fe, Co or Zr to Cu-alloys, P to hypereutectic Al-Si alloys, and Ti to Zn-alloys. However, there is no consensus on the precise mechanisms responsible for grain refinement. Following the historical models, such as the carbide-boride, the peritectic reaction, the adsorption and the hyper-nucleation models (see review in [7]), two major theories of grain refinement have emerged: the free growth theory [8] and the constitutional undercooling theory [9]. A major contribution from the free growth theory is the recognition of the importance of particle size and size distribution in grain initiation. With appropriate experimental data as input, this approach can correctly predict the grain size of Al-alloys as a function of processing conditions. The constitutional undercooling theory emphasises the importance of solute elements and the potency of nucleating particles on the evolution of grain size, and can also be used to predict the grain size of Al- and Mg-alloys once critical model parameters have been determined by experiment. However, both theories fail to specify the exact nucleation mechanisms at nucleating particles, thus limiting their practical use in the development of more effective grain refiners.

The benefits of enhancing nucleation can be numerous. For continuous casting of wrought alloys, enhanced heterogeneous nucleation reduces the propensity for hot tearing and cracking allowing higher casting speeds. It also promotes the formation of fine and equiaxed grains and a more uniform microstructure with significantly reduced chemical segregation, resulting in improved down-stream processability and a reduced cost of subsequent thermo-mechanical processing. For shape casting, grain refinement promotes equiaxed solidification, which again results in better liquid feeding, a reduced tendency for hot tearing, reduced and/or better dispersed porosity and an improved surface finish, all leading to improved mechanical properties of the final cast components. Since shape cast components are usually used in their as-cast state with little (if any) further processing, grain refinement and the reduction of casting defects are more crucial than for continuously cast feedstock materials. ***The key challenge in solidification research*** is to understand nucleation and to develop techniques for nucleation control. This is the central research thrust of IMRC-LiME.

2.2 Casting technologies

Shape casting is one of the oldest known manufacturing methods and a very direct method of producing metal objects. Development has been continuous from bronze casting (Bronze Age) to iron casting (Iron Age) up to the present day, though more progress has been made since World War II than in the previous 3000 years [10]. Today, metal castings play a critical role in the economy of all industrialised countries, and are used in 90% or more of all the manufactured goods and in all manufacturing machinery [10]. World production of metal castings exceeded 100 million tonnes in 2007. Shape casting techniques, such as sand casting, gravity die-casting, high/low pressure die casting and investment casting, are used to provide shaped metallic components for direct engineering applications with little requirement for further processing. Shape casting is characterised by low energy consumption, high material yield, high efficiency and low cost. However, shape cast components usually have a coarse and non-uniform microstructure, severe chemical segregation and a substantial amount of casting defects, and consequently offer degraded mechanical performance which limits their use in demanding applications.

Continuous (or semi-continuous) casting processes, such as direct chill (DC) casting and twin roll casting (TRC), are used to produce ingots, billets or strips of wrought alloys for downstream thermo-mechanical processing for more demanding applications. Continuously cast wrought alloy feedstock is fed into a lengthy thermo-mechanical processing route, such as rolling and extrusion, to refine the microstructure, reduce chemical segregation, eliminate casting defects and achieve the appropriate dimensions for potential applications. However, thermo-mechanical processing is time consuming, energy intensive and high cost. A critical question is “can we directly produce components with a fine grain size, uniform chemistry and free from casting defects by solidification processing?” Our recent work on liquid metal engineering [11] has convincingly demonstrated that this is feasible. This forms the basis for the technological development in the IMRC-LiME research programme.

2.3 Metallurgical industry and sustainability

Metals start their life as minerals mined from the Earth’s crust. The mined minerals undergo extensive processing to produce oxide or other concentrates, which are then converted into primary metals through extractive metallurgy processes. The primary metals are alloyed with other elements either as cast alloys for shape casting or as wrought alloys for DC casting followed by thermo-mechanical processing. For this reason, the metallurgical industry has become segmented into distinct sectors, including mineral processing (mining), primary metal production (extractive metallurgy), shape casting (foundry), thermo-mechanical processing (metal forming), and secondary metal processing (recycling). A metallurgical company usually only deals with one sector, and is often in competition with other sectors. There is an emerging consensus for a more holistic approach to an optimised metallurgical industry in terms of preserving natural resources, promoting energy conservation, facilitating technological development and ensuring environmental protection.

The world produces 37 million tons of Al and over 2 billion tons of steel every year, accounting for around 8% of the total global CO_2 emission [12]. A recent life cycle assessment for the Al industry [13] showed that the production of 1kg of *primary* Al (including all electricity generation and transmission losses) requires 45kWh of energy and emits 12kg CO_2; 1 kg of *recycled* Al requires only 2.8kWh (5%) energy and emits 0.6kg (5%) CO_2. Energy consumption for processing 1 ton of Al product is 4kWh, 590kWh, 265kWh and 350kWh for shape casting, extrusion, hot rolling and cold rolling, respectively, meaning that thermo-mechanical processing uses about 100x more energy than shape-casting, emphasising the urgent need for more energy efficient processing technologies.

We have identified ***three major technological challenges*** facing the metallurgical industry; IMRC-LiME will address the latter two:

- Development of more energy efficient extractive metallurgical processes for converting minerals into metals.
- Development of effective solidification processing technologies that produce high quality components directly from liquid metals with little need for thermo-mechanical processing.
- Development of effective technologies for reuse, remanufacture and recycling of scrap metals so that there is only a limited need for primary metal production each year.

2.4 Business and Policy Needs and User Drivers for IMRC-LiME

Manufacturing adds £150bn/year to the UK economy (14-15% of GDP), accounts for over 50% of exports, and employs 3 million people [14]. The UK Government’s vision for the future is a mixed and balanced economy, where manufacturing activities complement services to deliver the widest possible range of economic and social benefits [14]. To achieve this vision, the TSB has identified four “pillars” for high value manufacturing: products, production processes, service systems and value systems. The key drivers identified by the TSB include resource efficient and sustainable processes and technologies for efficient disposal, recycling or re-manufacturing of materials at the end of their lives [15]. In addition, the recent EPSRC Strategic Advisory Teams Conference identified "understanding and designing of new materials for new applications" as a top priority for scientific and technological breakthroughs by 2050, since it underpins most other strategic challenges facing the UK over the next 50 years [16]. However, the recent International Materials Review conducted by EPSRC and the IOM^3 showed that the UK's research capacity and international visibility in this area has declined dramatically in the last decade, with the UK rapidly falling behind the other G8 countries [17]. Therefore, there is a compelling and independently identified need to strengthen metallurgical research in the UK, and IMRC-LiME will make a major contribution to meeting this need.

Low-carbon energy generation and reducing energy *use* are major targets for the UK's CO_2 emission policy [18]; vehicle lightweighting has been identified by "the King Review" as one of the key technologies with the greatest potential to contribute to this goal [19]. Accelerated deployment of light alloy castings and wrought components is crucial for vehicle lightweighting, where innovative solidification processing technologies are vital. A recent government report identified key opportunities for local procurement in the areas of Al and Fe castings but flagged up the poor performance of UK suppliers in investing in relevant new technologies [20]. BIS and the industry-led NAIGT [21] both seek to address these challenges for the supply chain. IMRC-LiME will offer a major contribution to meeting this objective through engaging end-users and their supply chains with a shared vision. In addition, castings will be important for energy generation, from (large) steel castings for nuclear applications, to (precision) investment castings for gas turbines. Since UK companies comprise 50% of Europe's and 10% of the world's investment casting capacity, it is crucial that technological advances continue to ensure the UK's leading position.

3. OVERALL VISION of IMRC-LiME

3.1 The Vision of IMRC-LiME

IMRC-LiME aims to be an international leader in liquid metal engineering to underpin solidification research, strategic technology developments and user-led industrial applications. We will conduct fundamental research to generate world-class knowledge in solidification science. We will develop and exploit innovative and sustainable technologies and enable the UK metal casting industry and its customers to improve their competitiveness in global markets.

This is deeply rooted in our vision for future solidification science, technological development and sustainability for the metallurgical industry:

- ***Solidification science***: *Effective microstructural control can be achieved by control of nucleation during solidification through better understanding of liquid metal engineering*. This represents a fundamental move away from the traditional growth-focused solidification research to a new nucleation-centred one. Nucleation largely controls the solidified microstructure, casting defects and performance of cast components, and if it can be enhanced to such an extent, crystal growth will become simpler and less important. Liquid metal engineering broadens the horizon of nucleation control through manipulation of the chemical and physical nature of both endogenous and exogenous nucleating particles prior to solidification processing. It promises in the long-term a new framework for solidification science, based on which advanced materials, highly efficient processing technologies and new products can be developed.
- ***Technological development***: *High performance metallic components and feed stock materials can be manufactured by innovative solidification processing through liquid metal engineering with little requirement for solid state processing, which is energy intensive, time consuming and inevitably high cost*. This represents a paradigm shift from the current solid state deformation based materials processing to a solidification centred materials engineering. This will profoundly change the configuration of the future metal processing industry, in which metal casting will deliver the required engineering properties with little or no contribution from thermo-mechanical processing and result in significant savings of energy and materials at all manufacturing stages.
- ***Sustainable metallurgical industry***: *The demand for metallic materials can be met by an efficient circulation of existing metallic materials with limited additions of primary metal to sustain the circulation loop*. After so many years of intensive mining and chemical extraction, billions of tons of metals have been produced, and primary metals production is still rising. The earth's resources have been extremely exploited; this trend has to be reversed. In say 20-30 years, all metallic materials will be effectively circulated (e.g., in a 20-year cycle) through innovative technologies for reuse, remanufacture, direct recycling and chemical conversion and only limited amount of primary metals will need to be produced each year to sustain the circulation and to allow for growth and circulation losses. This will transform the current primary metal based metallurgical industry into one that thrives on secondary metals, and will lead to significant conservation of natural resources and energy.

3.2 Objectives

We have set the following objectives in order to deliver the IMRC-LiME vision:

- To be an international leader in fundamental research, technology development and industrial applications in the field of liquid metal engineering.
- To provide a nucleation-centred framework for solidification science.
- To harness the impurities and inclusions in metallic materials for enhancing heterogeneous nucleation to allow a greater level of recycling of secondary metals.
- To conduct a coherent programme of user-led research based on liquid metal engineering.
- To be a key provider of innovative processes and products to the metal casting industry and its customers.
- To nurture both national and international collaborations in solidification research and industrial applications.
- To train the future leaders in the field and thus maintain a critical mass of solidification research in the UK.

- To maximise IMRC-LiME's impact by providing a network service to a wider academic/industrial community.
- To develop a growing number of academic and industrial collaborators and establish IMRC-LiME as the leading UK resource for solidification research and technological development.

3.3 Long-term Research Activities of IMRC-LiME

- ***Fundamental research***: Nucleation–based solidification research including the structure of liquid metal, mechanisms of heterogeneous nucleation and the generic approach for enhancing and controlling nucleation through both physical and chemical methods.
- ***Technology development***: Innovative generic technologies for nucleation control including techniques for liquid metal treatment, techniques for enhancing nucleation on both endogenous and exogenous solid particles through both physical and chemical methods, and applications of developed techniques for nucleation control to the existing shape casting and continuous casting processes.
- ***Industrial applications***: IMRC-LiME will undertake proprietary applied research with individual industrial partners to exploit fundamental research and generic technological development to support the UK metal casting industry in implementing innovative processing technologies and new products.
- ***Network service***: IMRC-LiME will provide a network service to support a wider academic and industrial community beyond the IMRC-LiME research partners. IMRC-LiME will also promote and organise workshops, seminars and conferences at both national and international levels to maximise the impact of its research.

4. Platform Research Theme: Nucleation and Nucleation Control through Liquid Metal Engineering

4.1 Overview

The long-term aim is to establish a nucleation-centred solidification science, based on which advanced materials, highly efficient processing technologies and new products can be developed with the widest possible impact.

The specific objectives for the first 5 years are:

- To understand the nucleation mechanisms at the particle/liquid (P/L) interface.
- To understand the behaviour of alloying elements at the P/L interface and their effects on nucleation.
- To understand the relative potency and efficiency of both endogenous and exogenous particles with varying morphology, size, size distribution and number density for heterogeneous nucleation.
- To develop generic techniques for enhancing nucleation through liquid metal engineering.
- To provide strong and effective support to user-led research activities.

The platform research activities fall into two broad categories: (1) understanding heterogeneous nucleation processes through both experimental and modelling approaches; and (2) development of generic techniques for enhancing heterogeneous nucleation through liquid metal engineering.

Table 1. Crystal structure, orientation relationship (OR) and lattice mismatch (δ) of various solid particles with aluminium.

Particle	Crystal system	Lattice (nm)	Orientation relationship (OR)	δ (%)*
Al	FCC	a=0.40494	---	---
Mg	HCP	a=0.32095 c=0.52105	---	---
γ-Al_2O_3	FCC	a=0.79240	$\{100\}\langle 001\rangle_{Al}//\{100\}\langle 001\rangle_p$ $\{111\}\langle 110\rangle_{Al}//\{111\}\langle 110\rangle_p$	3.38 3.38
$MgAl_2O_4$	FCC	a=0.80831	$\{100\}\langle 001\rangle_{Al}//\{100\}\langle 001\rangle_p$ $\{111\}\langle 110\rangle_{Al}//\{111\}\langle 110\rangle_p$	1.41 1.41
MgO	FCC	a=0.42112	$(0001)\langle 2\text{-}1\text{-}10_{Mg}//\{111\}\langle 011\rangle_p$ $\{111\}\langle 110\rangle_{Al}//\{111\}\langle 110\rangle_p$	6 59 2 98
TiB_2	HCP	a=0.30303 c=0.32295	$\{111\}\langle 110\rangle_{Al}//\{0001\}\langle\text{-}12\text{-}10\rangle_p$	4.05
TiC	FCC	a=0.43274	$\{100\}\langle 001\rangle_{Al}//\{100\}\langle 001\rangle_p$ $\{111\}\langle 110\rangle_{Al}//\{111\}\langle 110\rangle_p$	5 21 5 21

*δ is the lattice mismatch at the interface along the OR direction.

4.2 Scientific approach

Heterogeneous nucleation is a complex phenomenon, and so far, our scientific understanding is quite limited. In recognition of the breakdown of the classical nucleation theory for potent nucleating particles, Greer et al [8] developed a free growth model to describe grain initiation. The undercooling for free growth (ΔT_{fg}) was found to be inversely proportional to the particle diameter (d): $\Delta T_{fg}=4\sigma_{SL}/(\Delta S_v d)$, where σ_{SL} is the interfacial energy of the S/L interface and ΔS_v is the volume entropy change of fusion. Further work by Quested and Greer [22] examined the importance of size, size distribution and number density of nucleating particles, the level of alloying elements (through the growth restriction factor Q) and cooling rate on grain initiation. By combination with the front-blocking CET (columnar to equiaxed transition) model developed by Hunt [23], the free growth model was further extended to predict solidification microstructure under various conditions [24]. Although the free growth model is consistent with most experimental observations and contributed significantly to our understanding of grain initiation, it carries no information about exact nucleation mechanism. Nonetheless, it is generally accepted that the smaller the crystallographic mismatch between the nucleating particle and the nucleated solid phase, the smaller the energy barrier for nucleation, and consequently the more potent the particle is for heterogeneous nucleation, as described by the edge-to-edge matching approach [25].

We have proposed the following criteria for the selection of effective nucleating particles [26]. They need to be

- Stable crystalline solid particles at temperatures above the alloy liquidus.
- Fully wetted by the alloy melt.
- Available in sufficient numbers, with favourable particle size and with a narrow size distribution;
- A small crystallographic mismatch (<10%) with the nucleated solid phase.
- Insensitive to the processing conditions.

From these criteria and the crystallographic data in Table 1, we have predicted that oxide particles are *potentially* potent for heterogeneous nucleation. Work at Brunel has confirmed that MgO particles are potent for nucleation of α-Mg (Fig. 1a) and Al_8Mn_5 intermetallics in Mg-alloys [27], and that $MgAl_2O_4$ particles are potent for nucleation of α-Al (Fig. 1b), primary Si and Al-Fe-Si-Mn intermetallics in Al-alloys [28]. In addition, work at Oxford has identified oxide inclusions as nucleation sites for $TiAl_3$ intermetallics [29], and a research group in Japan reported enhanced nucleation of δ-ferrite by Al_2O_3 particles [30].

Oxide particles exist in nearly all liquid metals and alloys exposed to air, even under protective atmospheres. Oxide exists in liquid metals in the form of dross (lumps) formed during melting in the furnace, oxide films formed during melt handling and oxide skins incorporated from the original solid ingots [27]. Oxide particles are often considered as harmful inclusions since they reduce castability of the alloy melt, degradate ductility and fatigue strengths of castings and cause severe difficulties in downstream processing of continuously cast feedstock [31]. In current foundry practice, the norm is either to prevent oxide formation by using protective gas during melting and handling or to clean the melt by an expensive melt treatment process, such as filtering, fluxing and manual dedrossing. However, recent research work at Brunel has demonstrated that the oxide film is a liquid film containing a high volume fraction of fine solid oxide particles (Fig. 2a), and more importantly, that such oxide inclusions can be effectively dispersed into individual particles with a fine size and a narrow size distribution by intensive melt shearing provided by the MCAST (melt conditioning by advanced shear technology) process developed at Brunel (Fig. 2b) [27]. According to the free growth theory [8], such dispersed oxide particles will be more effective for enhancing heterogeneous nucleation. Such grain refining effects have been confirmed in many Al- and Mg-alloys by conditioning with intensive melt shearing (Fig. 3).

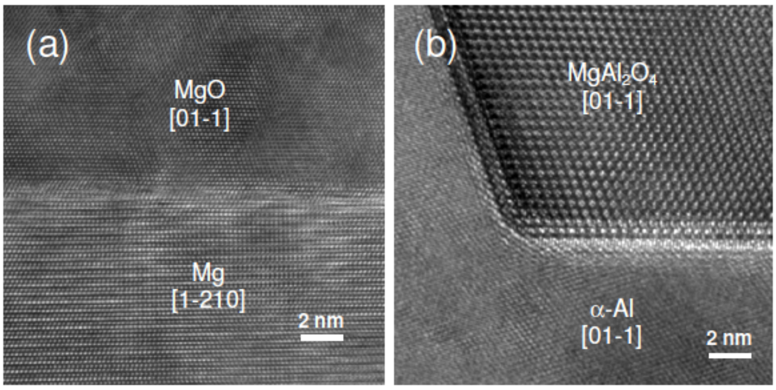

Fig. 1 HRTEM micrographs showing (a) MgO nucleating α-Mg in AZ91D Mg-alloy; and (b) $MgAl_2O_4$ nucleating α-Al in LM24 Al-alloy.

Our scientific approach to nucleation research is depicted in Fig. 4 and summarised below:

- ***Chemical approaches*** to increase nucleating potency by searching for suitable solid particles (both endogenous and exogenous) with small crystallographic misfit and adding trace elements to reduce the misfit.
- ***Physical approaches*** to increase the efficiency of a selected population of solid particles by manipulation of their physical nature (suitable size, narrow size distribution and adequate number density) and by improving their wettability by liquid alloys.

4.3 Initial platform research activities

Based on the above approach, the following **platform research activities** (**PRAs**, or tasks) have been set up as the starting point for the platform research theme.

PRA1: *Analytical modelling and molecular dynamic (MD) simulation of nucleation mechanisms at the P/L interface.* A MD simulation code developed at Brunel will be used to study nucleation behaviour at the P/L interfaces as a function of crystallographic mismatch and segregation of trace elements at the interface. Based on the MD simulation results, an analytical model will be developed to describe the heterogeneous nucleation process at the P/L interface. Particular reference will be made to the naturally occurring oxides in the alloy melt. PRA1 will be led by ZF and NH at Brunel and interact with KO at Oxford.

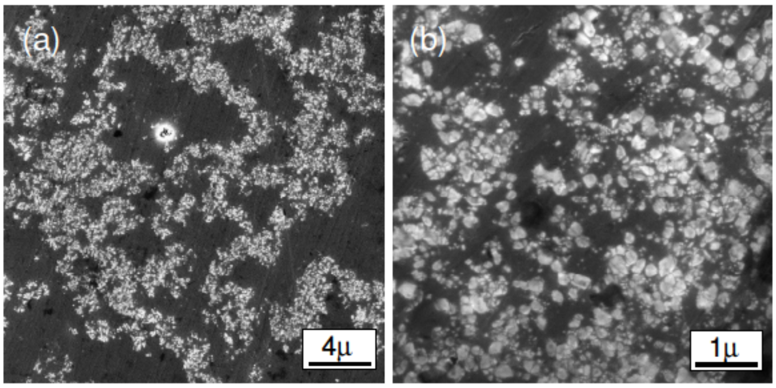

Fig. 2 SEM micrographs showing the detailed structure of oxides in AZ91D Mg-alloy collected by using a pressurised filtration technique. (a) heavily folded oxide films before shearing; and (b) dispersed oxide particles after intensive melt shearing.

PRA2: *Oxidation of liquid metals and alloys.* An experimental approach will be used to investigate via in-situ and post mortem the thermodynamics and kinetics of oxidation of molten alloys as a function of temperature, atmosphere and composition allowing the selection or design of suitable oxide particles for enhancing nucleation. Thermodynamic software (e.g., Thermo-Calc) will be used to model the chemical compositions of the oxides formed in different alloys with a view to tailoring δ to higher temperature alloy systems. PRA2 will interact with PRA1, PRA3 and PRA4, and will be led by NG and WG at Birmingham and in collaboration with ZF and NH at Brunel.

PRA3: *Manipulation of the chemical and physical nature of solid inclusions in metallic melts by intensive melt shearing.* [redacted]

PRA4: *Potency of oxide particles for heterogeneous nucleation of intermetallics.* [redacted]

[redacted]

PRA5: *Grain multiplication for microstructural refinement - modelling and experiment*. Previous work at Oxford has shown the potency of copious dendrite fragmentation as a mechanism for refining microstructures; this task will extend this work using non-contact external fields to dramatically enhance fragmentation, firstly in low melting point systems, progressing to high melting point alloys. The work will include: (1) modelling of grain multiplication by dendrite fragmentation process under dynamic conditions and (2) the design-build of a fragmentation station for experiments that is compact and portable for subsequent integration at the Joint Environmental, Engineering and Processing (JEEP) beamline at the Diamond Light Source to conduct *in situ* studies of grain fragmentation dynamics under external fields. PRA5 will be led by PG at Oxford, and interact strongly with NG at Birmingham.

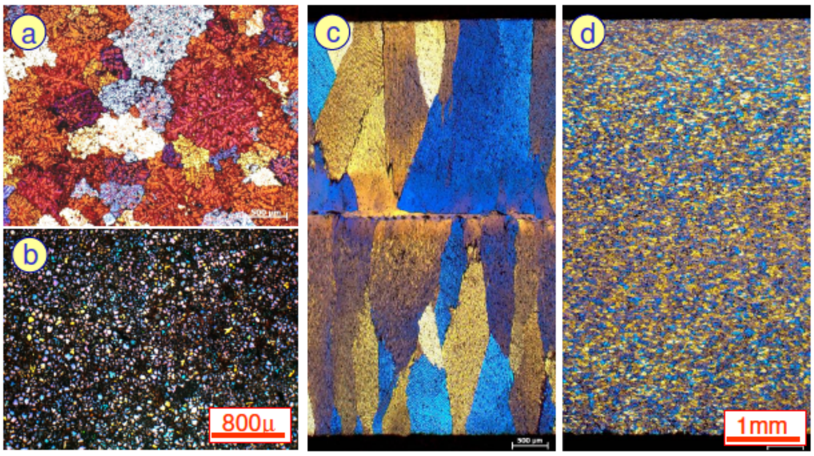

Fig. 3 Micrographs showing the structural refinement by intensive melt shearing. (a)&(b) for DC cast AZ91 billet (cooling rate=3.5K/sec); (c)&(d) for TRC AA5754 strip (4mm thick, cooling rate=350K/sec); (a)&(c) without shearing; (b)&(d) with shearing.

PRA6: *Enhancing the efficiency of Al-Ti-B grain refiner.* [redacted]

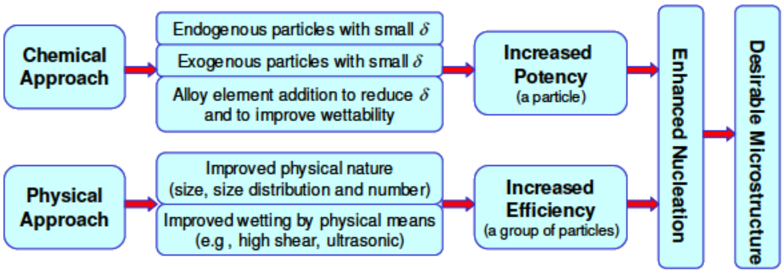

Fig. 4 Scientific approach to the fundamental research programme of the IMRC-LiME. δ is the crystallographic mismatch.

5. User-Led Research Theme: Enhancing Casting Quality through Liquid Metal Engineering

5.1 Overview

The user-led research theme is the enhancement of the quality of both shape cast components and continuously cast feedstock through liquid metal engineering. ***The primary aim*** is to produce as-cast materials with fine and uniform microstructure, uniform chemistry and minimised casting defects, and therefore improved mechanical properties. ***The generic approach*** is to enhance heterogeneous nucleation through appropriate liquid metal treatment prior to solidification processing with various casting technologies. The generic techniques developed in the platform research theme will be applied to specific casting processes to enhance the quality of castings. A key feature of this research theme is the emphasis on the use of secondary metals to reduce the energy consumption and cost of the final components whilst improving their performance. All the research activities are formulated with the relevant industrial partners, who have not only set the research objectives but also committed technical support and financial contributions (both cash and in-kind) to the specific research activities. A further important feature of this research theme is its dynamic nature. The specific research activities described below are only the starting point; further research activities will be developed with both existing and new partners over time.

5.2 Key challenges and technical approaches

In spite of tremendous efforts in R&D, the metal casting industry is still facing great challenges:

- To produce shape castings with fine and uniform microstructures and reduced/eliminated casting defects.
- To produce shape castings with increased content of secondary metals without degradation of mechanical performance.
- To produce feedstock materials with fine and uniform microstructures, uniform chemical compositions and closer to the required dimensions of their final applications reducing the requirement for extensive downstream processing.

Our technical approach to these challenges (Fig. 5) is to condition liquid metal prior to solidification processing. Research at Brunel has confirmed that intensive melt shearing can disperse oxide and other naturally occurring inclusion particles in liquid metals, and that such dispersed oxide particles not only reduce/eliminate the harmful effects of inclusions and impurities on both casting processes and mechanical properties, but also can be positively utilised to enhance heterogeneous nucleation of both intermetallics and the primary phases, and therefore promoting equiaxed solidification, preventing chemical segregation and reducing casting defects [27], and consequently providing a significant improvement on mechanical properties [11] and a substantial increase of the tolerance to inclusions and impurity elements [32, 33]. For instance, melt conditioning can increase the elongation of HPDC AZ91D alloy by over 200% (Fig. 6a), the Fe tolerance of HPDC LM24 alloy by 100% (Fig. 6b), the fatigue life of HPDC LM24 alloy by a factor of 10 (Fig. 6c) and the high temperature elongation of twin roll cast (TRC) AZ31 alloy strip by a factor of 3. Thus, melt conditioning by intensive melt shearing can be combined with various casting processes to produce as-cast materials (or components) with refined microstructure, uniform chemical composition, minimised casting defects and increased secondary metal contents. Intensive melt shearing has provided the impetus and demonstration for our approach, and other effective techniques will be developed for melt conditioning based on the same principle through the platform research theme, with exploration of other alternative techniques a long-term strategy of the IMRC-LiME.

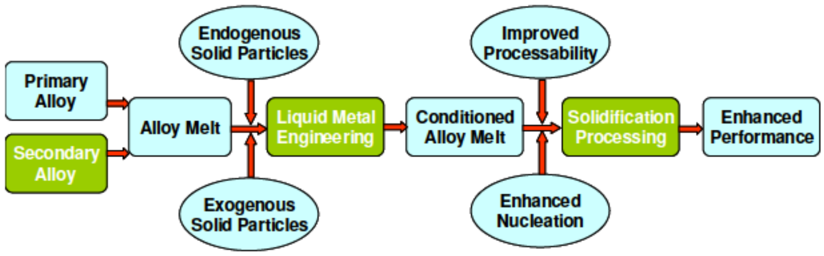

Fig. 5 Schematic illustration of the technical approach to the user-led research project.

5.3 Methodology and specific research activities

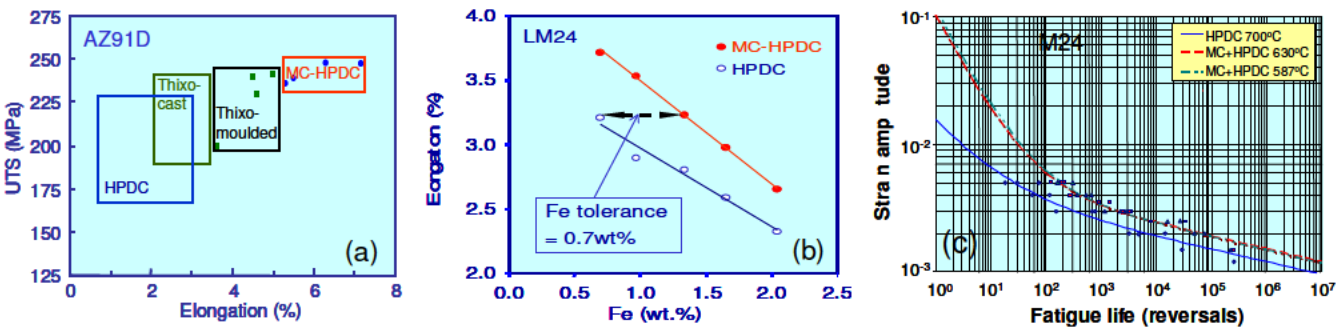

Fig. 6 (a) Mechanical properties of MC-HPDC AZ91D; (b) elongation of LM24 as a function of Fe contents illustrating the increased Fe tolerance by melt conditioning (MC); and (c) fatigue properties of MC-HPDC LM24.

Through intensive discussions with our industrial partners, we have identified the following specific user-led research activities (ULRAs, or tasks) as the starting point for longer-term collaboration.

ULRA1: *Melt conditioned high pressure die casting (MC-HPDC) of automotive components*: [redacted]

ULRA2: *Melt conditioned sand casting (MC-SC) of Al-alloys for automotive and aerospace applications*: [redacted]

ULRA3: *Melt conditioned twin roll casting (MC-TRC) of Al- and Mg-alloy strip*: [redacted]

ULRA4: *Elimination of macro-segregation in AA6xxx extrusion alloys by melt conditioning*: [redacted]

ULRA5: *Development of a rheo-extrusion process to produce extruded profiles directly from liquid alloys*: [redacted]

ULRA6: *Development of a multi-functional liquid metal treatment process for conditioning Al-melt*: [redacted]

ULRA7: *Grain refining of γ' reinforced superalloys by melt conditioning*: [redacted]

ULRA8: *Ductile Al MMCs produced by melt conditioned precision sand casting*: [redacted]

ULRA9: *Spray forming recycled spray cast alloys*: [redacted]

5.4 User engagement and impact on users

Our industrial partners are forward looking and fully committed to technological innovation and sustainable development. They share the vision of IMRC-LiME for fundamental research, technological development and sustainability of the metallurgical industry. Their full engagement with this research programme is evidenced by:

- strong participation in formulating our research agenda.
- specification of project objectives, detailed research activities and time scales.
- undertaking specific research activities with ULRAs.
- committing substantial cash and in-kind support as specified in the letters of support, with a total of £1M cash and £4M in-kind. We suggest that this level of financial support from the manufacturing sector in a time of economic recession demonstrates the strong endorsement for our proposal.

For more detailed description of user engagement and impact on users please refer to "Impact Summary" in the JeS form and the attached "Impact Plan".

5.5 Progression of user-led research activities

We envisage that the ULRAs will be dynamic. The ULRAs listed above have been chosen by the users as a starting point. With the emergence of new results from these ULRAs and new business needs from our industrial partners, such ULRAs may take a different course and new ULRAs may set up to reflect the new circumstances, while some of the activities with less promising outcomes will be replaced with potentially more rewarding ones. With the increased user engagement, further new ULRAs will be set up with new users. In addition, although the first phase ULRAs are mainly based on the technology for intensive melt conditioning, over time other techniques for melt conditioning will be developed under the platform research theme, and will be used to generate new ULRAs with potential users. Further information on progression of user-led research activities is given in Section 6.

6. Exploitation Strategy

The industrial partners engaged in the first phase of the ULRAs are mainly those who are already working with Brunel, Oxford and Birmingham Universities. These include JLR, Meridian, JVM and Norton who have directly experienced the rapid evolution of the melt conditioning technology at Brunel over the past five years from its original concept for processing semisolid Al- and Mg-alloys into a generic technology with the potential for processing all liquid metals. This has significantly broadened the academic and commercial interest in the technology and has already brought in new partners, for example Sapa, LSM, Foseco, Aeromet, and G&W who have a specific interest in melt conditioning. In addition, the first phase of the ULRAs are mainly based on Al- and Mg-alloys. This will change during the lifetime of the IMRC-LiME grant as melt conditioning is applied more widely to other metals and this has already been recognised by RR, Rautomead, Doncasters and Corus. Once it is established from the platform research activities that melt conditioning is generic across a wide range of metals then the spectrum of collaborative partners will widen and further projects and technological developments will result. In addition as melt conditioning offers a cost effective approach to impurity tolerance in recycled metals it is expected that this will generate significant interest from companies beyond the metal manufacturing base to other industrial sectors who wish to increase the recycled content of their product offerings. As for the family of melt conditioning technologies are established in the platform research theme this will bring in further users and result in new ULRAs.

Our exploitation strategy will address the three primary forms of output from the programmes of research, namely, *knowledge, people and technology*.

Knowledge transfer: this will be conducted via a new network for liquid metal engineering, **Net-LiME**. Net-LiME will reach out to parts of industry and academia that have direct and immediate interests in the work of IMRC-LiME, in partnership with professional bodies, trade associations, KTNs, learned societies and policy makers (see letters attached). A priority will be to engage SMEs with the IMRC-LiME programme and this will achieved by establishing thematic, supply-chain clusters to optimise the targeting of outputs and information. Net-LiME will deliver a number of products including newsletters, workshops, trade press articles as well as the provision of good practice guides, training and consultancy.

People transfer: IMRC-LiME recognises that one of the most effective means of exploiting and embedding the innovations from the research programmes is through the transfer of people. Industry to academia secondments for limited time periods will be established and supported by IMRC-LiME and its industrial partners. The secondments will facilitate the two-way transfer and exchange of expertise and skills for mutual benefit, will strengthen long term relationships between IMRC-LiME and its industrial stakeholders with a view to developing, sustaining and extending future collaborative opportunities.

Technology transfer: IMRC-LiME will be pro-active in seeking opportunities to mature its generic technologies to higher technology readiness levels (TRLs). The collaboration agreement will address IP ownership, management and exploitation rights and responsibilities as between all partners. The LiME Management Group will oversee IP issues and ensure best practice is adopted within the centre. Where new, potentially commercialisable technologies and processes are identified, the centre will work with the universities' commercial offices through a stage-gate process including: *market scoping* to identify the size of the market opportunity for the new IP; *proof of concept* work to verify the basic premise underlying the technology; *patent filing*, where appropriate; *prototype development* including building of a demonstrator that can be exposed to potential customers; and customer engagement with the aim of securing customer buy-in and uptake of the technology. Pre-arranged routes for marketing the research outcomes of IMRC-LiME include Rautomead's intent to market the rheo-extrusion equipment and process for a range of metallic materials in partnership with Brunel University, and Foseco's intent to market worldwide the multi-functional liquid metal treatment equipment and process with support from Brunel University. Such partners will take the specific technologies to higher TRLs following proof-of-concept at laboratory scale. Other partners will push relevant technologies to higher TRLs via industrial trials, volume production of engineering components and their final applications. Such R&D activities may be supported through collaborative mechanisms such as the TSB programme and the EU Framework Programme when TRL<7, or through direct industrial funding. We intend to engage users through the full spectrum of the TRLs, though with a gradually reduced role as TRL increases.

More information on exploitation of research outcome from IMRC-LiME is presented in the attached "Impact Plan".

7. Management

7.1 The overall management

The overall management of IMRC-LiME is depicted in Fig. 7. Prof Fan, as PI, will take overall responsibility for delivery of the aims and objectives of the IMRC-LiME programme. ***A LiME management group (LMG)***, chaired by Prof Fan, has been set up with members including Profs Grant, Green and Scamans and the LiME Programme Manager (TBA). The objective of LMG is to ensure the successful execution of the research programme through effective coordination of research activities and industrial partners. LMG will hold monthly meetings with a participant from each site. In each quarter, the first two monthly meetings will be internet meetings and the third face-to-face in turn at each site. The quarterly LMG management meeting will coincide with quarterly reviews of platform research activities. This will provide the opportunity to redirect resources as appropriate to areas where the most interesting and significant research findings are emerging, and to reduce or halt effort in areas that are not delivering against their research objectives. ***A LiME Programme Manager (LPM)*** will be a new appointment whose role will be to assist the PI to co-ordinate the research activities across the three academic sites and to manage the various interfaces between IMRC-LiME and its widest possible stakeholders (the responsibilities of the LPM are described in the attached JoR). ***An industrial steering panel (ISP)***, chaired by Mark White (Chief Technologist, JLR), has also been set up to ensure the industrial relevance of the IMRC-LiME research. ISP membership will be reviewed by the LMG annually to reflect the dynamic nature of the research programme. An overview of ULRAs will be presented to the ISP at the quarterly reviews by the LMG, accounting for confidentiality issues where appropriate. Each ULRA will have its own quarterly progress meeting with the project leader, the project team members (as required) and the industrial partners involved in the project. ***An international advisory board (IAB)*** chaired by Professor L. Ratke (DLR, Germany) has been set up to advise LMG on strategic scientific research directions and to benchmark the IMRC-LiME research activities from an international perspective. IAB memberships will be by invitation from the LMG, and will consist of leading international authorities in solidification research. The first phase of IAB members include Prof John Hunt (Oxford, UK), Prof Karl Kainer (GKSS, Germany), Prof David StJohn (Queensland, Australia), Prof Lindsay Greer (Cambridge, UK), Prof Hasse Fredrikson (KTH, Sweden) and Prof Lars Arnberg (NTNU, Norway). The IAB will meet annually to consider an annual report prepared in advance by the LMG and to give its feedback to the LMG, senior members of the ISP and the IMRC Programme Manager at EPSRC. The annual IAB meeting will be organised to coincide with a themed international workshop on solidification research. The IAB will be used to promote the widening of the academic base both within the UK and globally. There will also be regular informal contact between the IAB and LMG members.

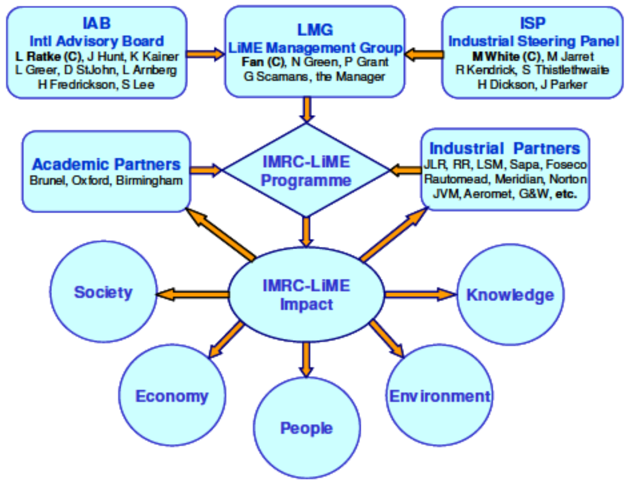

Fig. 7 Schematic of the management structure of IMRC-LiME.

7.2 Balancing user-led research and ambitious fundamental research

Balancing user-led research and ambitious fundamental research will be a key aspect of IMRC-LiME management. The intention is to maintain an approximate 50:50 balance of funding between PRAs and ULRAs supported by EPSRC funding. A key management goal is to develop new ULRAs from ideas and concepts in the platform research theme. This requires: (1) the platform research theme becomes an effective source of generic technologies; (2) ULRAs are completed on time; (3) technologies developed in the laboratory are pushed to higher TRLs with the assistance of TSB, industry and other support as appropriate; (4) more ULRAs will be developed through EU, TSB and full industrial funding as research activities progress and the economy gradually recovers; and (5) exciting results from platform research and feasibility studies will be transformed into further, separately funded EPSRC projects. All these will ensure that the overall funding of IMRC-LiME is steadily increased with time but maintaining the overall 50:50 balance between fundamental and user-led research activities.

7.3 Risk management and mitigation strategy

Risk management and mitigation will be embedded into the PRAs and ULRAs which will require a risk and mitigation plan to be formulated by the project leader and approved by the LMG before the project start date. It is expected that project leaders will be responsible for implementing the plan and that the LPM will take formal responsibility for monitoring the implementation of such plans. However, the overall risks associated with the platform and user-led activities are manageable and a preliminary risk analysis has already been carried out to evaluate the impact and probability of the risk and to develop the appropriate mitigation strategies. In summary, the main technical risks are mitigated as our work has already shown that melt conditioning can deliver both significantly improved mechanical properties and impurity tolerance for aluminium and magnesium alloys. The commercial and managerial risks are mainly low as preliminary economic evaluation shows that significant value-added opportunities will be created and the risk due to lack of coordination between partners will be reduced through the LMG and the ISP and the previous history of good collaboration between the partners involved in existing projects. In addition, the extensive experience within the ISP will be drawn on to help mitigate risks as part of the quarterly reporting and reviewing system.

7.4 Long-term sustainability of IMRC-LiME

The long-term sustainability of the IMRC-LiME derives from our vision to build a world-class centre of excellence to pioneer solidification science and solidification processing technologies to support a sustainable metallurgical industry. This will be achieved through the following approaches:

- The initial EPSRC funding will be invested in strategically important research activities that lay down a solid foundation for achieving our long-term vision. Some of the successful feasibility studies under the platform research theme will be developed into major, long-term research activities funded by the EPSRC. In addition, some of the ULRAs (TRL=3-4) will be successfully pushed to higher TRLs for industrial development (TRL=4-6), and funding for further development will be sought from EU Framework and TSB Technology Programmes. We are also prepared to carry out proprietary applied research with individual companies and such research activities will be funded either by the private sector or in combination with Government agencies.
- The first phase of PRAs and ULRAs are mainly focused on the MCAST technology for processing low temperature alloys (e.g., Al- and Mg-alloys). With time new technologies will be developed for high temperature alloys, such as Cu-alloys, Ni-alloys, cast iron and steels. This will create new research activities in both fundamental and user-led areas.
- Development of effective solidification processing technologies based on the principles of liquid metal engineering will break down the current division between cast alloys and wrought alloys. This opens the door for the development of a unified class of metallic alloys that take the full advantages of both cast and wrought alloys. IMRC-LiME is expected to lead this new research direction.
- To achieve full metal circulation requires step change technologies for re-use, re-manufacture and recycling of metallic components at the end of their service. This will provide IMRC-LiME with long-term opportunities for both fundamental and user-led research to generate a sustainable metallurgical industry.

8. Impact

The ultimate objective of IMRC-LiME is to maximise its impact by engaging with a widening community of end users and exploiters of science and engineering. The LMG will endeavour to ensure that the EPSRC funding is used effectively to maximise impact by both quantitative and qualitative measures. For more detailed description of the impact please see “Academic Beneficiaries”, “Impact Summary” and the attached “Impact Plan”.

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