

ADVANCED MATERIALS: MATERIALS FOR EXTENDED USE AND RE-USE

UPCYCLING OF LIGHT ALLOYS BY RHEOFORMING SCRAP

TSB Project No: TP/6/MAT/6/S/K1046J

COMMERCIAL RESTRICTED

May 2011


Project Leader

Circulation: All Project Partners
Project Monitoring Officer

This plan is a living document and will be updated during the project. The aim of the plan is to confirm the business case for the project and describe the partner activities towards exploitation of the results of the project so that 1) changes in the commercial environment can be monitored and accounted for, 2) adequate resources are committed to exploitation and 3) so that exploitation can be monitored by the stakeholders.

Business Case

Partners' capability to develop and exploit the technology

Summarise the Technical Approach to be taken

One of the main barriers to the increased use of recycled light alloy scrap (both process scrap (new) and post-consumer scrap (old)) is the existence of excessive levels of inclusions and impurity elements, which usually leads to downgrading into materials with poorer mechanical properties and reduced corrosion resistance. This project aims to break down this barrier and current market failure through the application of the step-change melt conditioning technology to allow the re-use of aluminium and magnesium alloy scrap in high-level automotive and other value-added applications.

The technical approach was to condition melts of recycled light alloy scrap using a twin screw melt processor and to feed the conditioned melt into a high pressure diecaster for near net shape components. This was then to be followed by similar studies using a twin roll caster for strip production or to directly cast billets, rolling blocks or forging stock. The long term aim was to enable extensive materials re-use by producing castings and semi-fabricated products of aluminium and magnesium alloys from selected combinations of post-consumer scrap (PCS) supplied by Norton Aluminium and magnesium diecasting process scrap supplied by Meridian. The mechanical performance and corrosion properties of the melt conditioned products was to be assessed against current production aluminium and magnesium castings and wrought products made from conventional primary metal based melts. For magnesium the emphasis of the project was on production of high pressure diecastings with a much smaller activity on wrought products, whilst for aluminium the emphasis was on high performance castings and then on wrought products. One specific aspect of the project was the manufacture of a high temperature melt conditioner for aluminium alloys. The project aimed to develop a unique UK partnership of material producers, recyclers, technology providers and product manufacturers to develop a novel process route for increasing the re-use and recycled content of light alloy materials by upcycling into higher-value products. Such a collaborative development would enable rapid UK commercial exploitation and will reduce dependency on imported products.

Historically, the light alloys industry has been divided artificially into cast and wrought sectors. Cast alloys are net shape components, which are usually non-heat-treatable due to the existence of high levels of porosity and other cast defects that are used in less demanding applications. Wrought alloys are usually cast into billets or slabs with a highly non-uniform structure and chemistry that then undergo extensive solid state deformation processing to enhance their mechanical performance that results in a substantial loss of material, intensive energy consumption and a negative environmental impact. The major scientific and engineering challenge has been to develop solidification processing technologies which will provide a fine and uniform microstructure, a uniform chemistry and a reduction/elimination of cast defects in the as-cast condition, so that cast components can be heat treated, and feedstock billet and slabs can be processed with minimal solid state deformation processing.

A major barrier to the reuse of light alloys is the existence of substantial amounts of inclusions and impurity elements in the scrap (both new and old). Such inclusions cause severe losses in ductility and strength and certain impurity elements significantly reduce corrosion resistance. The major challenges for reprocessing light alloy scrap were therefore to deal with the increased inclusions and impurity elements. Conventional wisdom states that the amounts of such inclusions and impurities must be reduced by a chemical refinement approach, a high cost and low efficiency process. This project aimed to develop recycling technologies to process light alloy scrap using a physical approach to eliminate the detrimental effects of both the inclusions and impurities, so that higher grade light alloy products can be produced from their scrap.

The technical approach was to use melt conditioning to reprocess light alloy scrap into either cast engineering components or semi-fabricated feedstock materials, both with improved qualities

compared to currently available primary alloys. This approach was termed upcycling which is in contrast to the current concept of recycling where the scrap is converted into an existing grade of alloy often with inferior quality compared to the corresponding primary alloy grade.

Melt conditioning is a step-change metal processing technology for producing high quality and low cost metallic components or feedstock materials directly from liquid alloys. The key processing technology was based on the twin-screw melt conditioner, which has a pair of co-rotating, fully intermeshing and self-wiping screws rotating inside a barrel. The screws have specially designed profiles to achieve a high shear rate and a high intensity of turbulence. As a consequence of such fluid flow characteristics, the conditioned melt has uniform temperature, uniform chemistry, well-dispersed nucleation agents and fast heat extraction. Solidification after melt conditioning results in a fine and uniform microstructure, a uniform chemical composition throughout the entire casting (either components, strip, blocks or billets), and a much reduced (or even eliminated) presence of cast defects, resulting in a substantial improvement in mechanical properties. Melt conditioning provides an effective solution to surmount the barriers to the reuse of light alloy scrap. The high shear rate and high degree of turbulence inside the melt conditioner brings the following extra benefits:

(1) Through enhanced nucleation the primary intermetallic compounds, such as iron aluminides, have a much finer particle size and a more compact morphology instead of conventional coarse needles or plates. This results in improved ductility and corrosion resistance. Intensive melt shearing increases the tolerance of light alloys to iron impurities. Also, the addition of appropriate alloying elements like manganese can enhance the melt shearing effects on size and morphology characteristics of the intermetallic compounds

(2) Inclusions, such as oxide particles and oxide films, are dispersed uniformly throughout the alloy matrix and become dispersion strengthening or nucleating phases rather than detrimental features, leading to a significant improvement in mechanical properties by the elimination of stress concentrations and precursor cracks.

(3) Due to the chemical uniformity and the fine and uniform microstructure provided melt conditioning, the amount of solid state deformation processing can be significantly reduced, or even eliminated.

The full technological significance can be summarised as follows:

(1) Scientifically, the project pushes the boundaries of solidification science from the current static conditions to a controlled dynamic condition and brings in a new branch of solidification science: with effective nucleation and nucleation-controlled microstructural formation.

(2) Potentially it merges the current division between cast and wrought alloy sectors, allowing for a strategic restructuring of the metallurgical industry in terms of resource distribution, energy consumption, waste management and sustainability.

(3) Economically, upcycling of light alloy scrap to produce high performance engineering components represents a major opportunity for wealth creation. It could bring to the UK economy billions of pounds in the next decades. The economic benefits will be even larger if the concept of upcycling is implemented within other metals industries, such as in steel and copper.

(4) Environmentally, this project delivers an innovative solution as the upcycling of light alloy scrap will conserve natural resources, increase energy efficiency, and reduce waste generation and greenhouse gas emissions. All of these attributes will contribute greatly to a more sustainable global economy.

The technical approach combines the skills and experience of the consortium partners to maximise the potential for success in upcycling of light alloy scrap. The approach is unique to this consortium as it is derived from a UK-based novel technology at Brunel University that is combined with the skills, experience and capabilities in scrap sourcing, recycling, component production, alloy development and process development offered by the UK-based partner engineering companies.

The project was lead by Innoval Technology as they have extensive experience of the leadership and management of this type of project.

Ten milestones have been identified and timed to provide critical review and decision points. Three milestones specifically relate to the provision of alloy data sheets that will define the extended impurity

and inclusion tolerance limits provided by melt conditioning of light alloy scrap. These data sheets are key to successful technology exploitation and to more properly determine the potential commercial value. It is critical for project success that the aluminium melt conditioner is constructed and commissioned in the first 18 months so that it is available for WP 4 to start in month 16. This will also coincide with the availability of the magnesium melt conditioner from a sister EPSRC project. In the first year the emphasis will be on characterisation of the scrap feedstock and melt processing at Brunel using equipment available from earlier TSB projects. Work packages 3 and 5 are the critical heart of the project as this is where the melt processing equipment is directly used in an industrial rather than a research environment. The cost modelling work package (WP6) will be carried out using information generated as the project develops. Project management and reporting will be led by Innoval as they are fully familiar with TSB reporting requirements, multi-partner project management based on quarterly reviews and the achievement of defined objectives, and the use of milestones as decision points. Risk management will use the principles developed by the OGC, modified for application in a technology-dominated project. Each partner will lead at least one work package and will be active across several work packages to maximise information flow and cross fertilisation. Each partner within each work package reports to the work package leader. The work package leader reports to the project leader and the project steering group, and the project leader interacts directly with the monitoring officer as a single point of contact. The exploitation plan will be developed over the full span of the project and will be reviewed at each quarterly project review. The quarterly review will include the steering group, the project leader, the relevant work package leaders and the project monitoring officer.

The project plan contains seven work packages with tasks detailed within each work package and defines the work package leaders. Zyomax will lead the work to design and construct the aluminium melt conditioner as they have the most appropriate experience. Innoval will lead WP2, 6 and 7 as they have the most experience in material characterisation (WP2), process cost modelling (WP6) and the management and reporting of TSB Innovation projects. Norton and Meridian will lead the aluminium scrap (WP3) and magnesium scrap (WP5) processing work packages as these coincide with their major technical and business interests. Brunel will lead the melt conditioning work package as the equipment will be sited at the university.

The results for exploitation will be: (1) novel melt conditioning technologies for the upcycling light alloy scrap; (2) a new generation of scrap-based aluminium and magnesium alloys and; (3) high performance light alloy products based on high content of recycled scrap. The alloys produced will be impurity tolerant versions of existing alloy compositions or new specifications developed to allow higher impurity contents. Initially, melt conditioned scrap based alloys will find applications in general engineering as both high performance castings and as semi-fabricated profiles and rolled strip. The magnesium high pressure die-castings will find specific applications in products like automotive interior components, wheelchairs, housings for power tools, and electronics casings. With time the melt conditioned alloy products will compete directly with their primary metal counterparts for the full range of automotive applications, having the considerable advantages of the low cost metal source and the simplified production process. Commercial exploitation will be through licensing agreements of the type established within the two existing consortia. The potential benefits to each partner are governed by a formal Consortium Agreement. The major items in the Agreement include that Brunel University, as the IPR owner, will grant a royalty-free license to the consortium partners for use of the melt conditioning technologies for the duration of the project. Meridian (UK), as a component supplier, and Norton, as an alloy and component supplier, will be granted a royalty-free license for unlimited supply of upcycled products for 5 years starting from the completion of the project. Any new IPR will be owned by its generator(s) and will be made available to other partners for royalty-free use. Consortium workshops will be held to disseminate the scrap reprocessing technology to other recyclers, materials suppliers and end users. The melt conditioning technologies will be readily integrated into the family of technologies used for light metal recycling. In the future, conventional chemical refining technologies may only be used to process the lowest quality scrap, whilst the melt conditioning technologies will upcycle the remaining higher quality scrap for more demanding applications. The conventional chemical refining techniques will persist in countries where energy and employment costs are low.

Summarise the innovative aspects of the project, are they still innovative?

This project is both timely in that the available tonnages of light alloy scrap for recycling are increasing and innovative in that it is based on a novel upcycling concept using novel melt conditioning technology combined with a wide range of casting processes enabling the direct production of cast and wrought aluminium and magnesium alloys from a mechanically processed melt of recycled scrap. This technology is a radical innovation, completely circumventing existing recycling technology boundaries with a sustainable, simpler, lower cost process for lower cost, high performance light alloy products.

The technology eliminates the UK need for energy intensive refining operations that are carried out where low cost labour and electricity are available to make high performance alloys by conventional melt processing and casting techniques as for example, in China for aluminium and in the Czech Republic for magnesium.

Academically, the specifically innovative steps of this project are: (1) Upcycling vs. recycling: the usual concept of recycling is to produce an equivalent or a lower grade material via chemical refining. In contrast, upcycling produces equivalent or better grades of material via a physical approach to reduce or eliminate the deleterious effect of inclusions and impurities. (2) High shear melt conditioning is a step-change technology providing both cast and wrought alloy materials with enhanced processability and improved mechanical properties with extended first use and re-use characteristics. (3) High shear melt conditioning pushes solidification boundaries from the current static conditions to controlled dynamic conditions. Under intensive forced convection, nucleation and growth mechanisms favour the formation of fine and uniform solidification microstructures throughout the entire cast component. (4) Melt conditioning has the potential to create a new category of light alloys with combined low cost and high performance based on recycled scrap. Such new alloys not only enlarge the metallic alloy family but provide major new opportunities for more diverse applications.

The high shear melt conditioning process is innovative for the UK and EU industry, producing materials from lower cost feedstocks with properties equivalent to or better than those from higher cost or primary feedstocks. This will reduce exports of scrap that can be used to produce higher value-added materials and components more competitively for incorporation into UK and worldwide manufactured end products. Melt conditioning in the UK will progressively displace exports of UK scrap with exports of higher value-added high performance components and assemblies. On a world scale the Chinese will continue to import scrap and make feedstock materials for conventional diecasting. It will take time for melt conditioned diecastings to displace conventionally produced diecast alloys, but this will accelerate when specifiers design new products that are smaller, thinner, etc and only melt conditioned products will meet the requirements. Obviously a large demand for the current quality of Al and Mg diecastings will continue for non-critical applications and many such castings will be imported from low cost labour regions of the world.

Explain the roles of each of the consortium members highlighting the necessary skills and experience

The consortium partners provide precisely the optimum blend of knowledge, skills and experience to carry out the proposed project and to commercially exploit the results. The solidification science and process casting technology are soundly based at BCAST and the project builds both on EPSRC funded projects and two successful TSB innovation projects already in place. Zyomax is an SME start-up company spun-out from BCAST to design and build the melt processing equipment. This combination of BCAST and Zyomax is a unique resource that has already designed and built the robust melt processing equipment that will be used for the project. Norton Aluminium is an SME with an exceptional, in depth knowledge of aluminium post-consumer scrap and its reuse. Norton provides ingots to diecasters and supplies aerospace quality aluminium sand castings. Meridian, as the largest magnesium diecaster in the UK, fully understands the recycling requirements for magnesium diecast process scrap. Both Norton and Meridian are forward-looking companies, pre-eminent in light alloy casting, committed to technology development and its commercialisation, and have track records of supporting UK university work. Both Norton and Meridian seek to generate new business opportunities based on the results of the project. Innoval Technology, also an SME, has developed a close relationship with BCAST to exploit the rheoforming family of technologies for the benefit of UK industry. Innoval are a globally-leading technology provider with extensive, in depth, experience of light alloy development, process and product innovations and interact with both the UK and EU university base. Innoval are already leading two TSB supported innovation projects. Zyomax will commercialise the

high shear melt conditioning equipment. Norton will commercially exploit melt conditioning to provide new feedstock alloys to supply to conventional diecasters and will supply both high performance billet and forging stock. The nature of the consortium will deliver substantial extra benefits, such as extensive knowledge transfer between partners, accelerated technology development and maximised social and environmental impact.

Norton has developed a close relationship with the casting research group at Birmingham University and Brunel has extended their links with Oxford University through the appointment of [REDACTED] as a Visiting Professor. This means that the project will serve to consolidate the links between the major UK centres for light alloy casting and will facilitate knowledge transfer. Both Norton and Innoval have strong links with the Aluminium Federation and Innoval has strong links with NAMTEC that will assist with dissemination of information. Magnesium Elektron are fully supportive of the aims of the project and both Ford and JLR have been involved in defining potential applications and property targets.

The market opportunity

Summary of Expected Deliverables From Project

The upcycled aluminium and magnesium products will be first to market as the technology is unique to Brunel University. In North America although the requirement to recycle scrap into high grade products has been recognised by the Aluminum Association in their industry roadmap, the focus of their interest is to develop a low cost process for metal purification or to develop new alloys that better match the composition of the available scrap and to increase the tolerance to impurities by the use of processes such as spray rolling or other rapid solidification based processing techniques.

The EU aluminium recycling industry employs more than 10,000 people and half the aluminium produced in the EU is recycled (4.5 million tonnes), as is about one third of world annual consumption. Worldwide, the automotive industry is the largest single sector for both producing and consuming recycled aluminium. In the UK, scrap recovery rates vary from sector to sector with more than 95% of aluminium recovered from transport and building applications but only 25% from packaging applications. The market for aluminium and magnesium recycling is very dynamic and it is anticipated to grow steadily over the next decade, being driven by weight reduction in the automotive industry and the increased need for high performance castings which are presently produced from primary metal. In the EU, the average use of aluminium in cars is predicted to reach 200 kg/car by 2015 from its present level of 140 kg/car. The added value for the UK by melt conditioning aluminium scrap can be estimated from the potential to increase the value of the scrap that is exported each year. UK exports of scrap outside the EU were 404kT in 2005 (source Eurostat). If 75% of this exported scrap (300 kT) was reprocessed by melt conditioning in the UK and turned into high quality cast or wrought products its value would increase to at least an average of the LME price for primary aluminium, representing an increase in value of £330 million. Over ten years this would be a £3.3 billion increase in potential revenue. In consideration of the increasing aluminium content in cars, the estimated potential revenue could be >£5 billion over the next 10 years. It is more difficult to estimate the current UK market for recycling magnesium scrap. The size of the Mg market opportunity is estimated to be less than 10% of the opportunity for melt conditioned aluminium scrap based on the analysis of the available data from Germany. There is considerable potential to extend the unique UK concept of upcycling light alloy scrap beyond the UK, across the EU and then globally. By 2015 it is estimated that in the EU 0.8 million tonnes of cast and 0.3 million tonnes of wrought aluminium scrap will be recovered from 9.5 million end of life vehicles. Upcycling of this 1.1 million tonne scrap stream into wrought products and high performance castings would result in revenues of more than a billion pounds/year.

The global aluminium flow is reasonably well understood and monitored on an annual basis. In 2003 it was estimated by International Aluminium Institute that there were 516.1 million tonnes (Mt) of aluminium in use or in storage from all the aluminium manufactured since 1888. In 2003 27.4Mt of primary aluminium and 28.7Mt of recycled aluminium were made into 56.2Mt of cast ingot that were fabricated into 33.1Mt of finished products. This resulted in a net increase of 19.0Mt of aluminium in use or in storage in 2003. The 14.1Mt difference comprising of 3.3Mt of aluminium lost to landfill, missing aluminium 3.1Mt (aluminium possibly reused, recycled or landfilled) and old scrap of 7.0Mt and 0.7Mt lost in applications where aluminium is consumed as powder paste or in the deoxidation of steel. The 28.7Mt of recycled aluminium was composed of 7.0Mt of old scrap and 23.1Mt of new scrap, the difference being 1.4Mt of melt losses. The global supply of old aluminium scrap will increase from 7.1Mt in 2003 to a predicted figure of 14Mt in 2020 and that the largest source of old scrap is from the automotive industry (5 Mt). The global magnesium flow is much less well defined.

Due to the increasing concerns for environmental protection and ever-tightening government regulations for sustainable economic development, there is an increasing pressure on automakers to improve fuel consumption to reduce greenhouse gas emissions. The automakers have studied the relationship between vehicle mass and fuel economy for decades. The majority of the studies to date conclude that for every 10% reduction in vehicle weight there will be a corresponding 6-8% decrease in fuel consumption. The importance of vehicle weight reduction has also been demonstrated in a recent North American automaker study; this indicated that vehicle usage over its typical lifetime (200,000km or 9-12 years) generates considerably more greenhouse gas emissions (816 GJ) than the sum of the energy (155 GJ) consumed by materials production, vehicle assembly, repair and maintenance, and

end-of life recycling. Aluminium and magnesium alloys provide a high-tech solution to weight reduction. One kg aluminium typically replaces 2 kg steel, resulting in dramatic weight savings without compromising safety. The resultant fuel savings can significantly lower the operating costs of the vehicle over its lifetime. To achieve weight reduction, the application of aluminium in the automotive industry has increased by more than 3.6% pa and magnesium by average of 15% in the last decade. Currently, an average Big 3 vehicle weights 1525kg, out of which 145kg is aluminium (9.5%) and 5kg is magnesium (0.3%). It is predicted that the usage of light alloys in cars will continue to rise at an even faster pace in the next decade.

Driven by the environmental legislations worldwide, the market for recycling of light alloys is very dynamic. In the US, the recycled aluminium has increased by 760% from 1960 to 2000, representing an average annual growth rate of 19%. In the EU, recycled aluminium was more than 3 times larger in 2003 (3.7Mt) than in 1980 (1.2Mt), representing an average annual growth rate of 9.1%. More than two thirds of aluminium used in automotive applications in the US is sourced from recycled aluminium; more than half of all the aluminium produced in the EU originates from recycled materials, and this trend is on the increase; worldwide, more than a third of the aluminium shipment is from recycled source.

The source of aluminium scrap can be divided into the automotive, other transport, building, packaging, engineering, consumer durables and others. Old aluminium scrap will be 2 times more in 2020 than it is today, increasing to 14 million tonnes. The automotive industry is the largest single sector both producing and consuming recycled aluminium. The total amount of aluminium stored in use (aluminium inventory) will reach 926 million tonnes in 2020, representing an average annual growth rate of 4.5%. The largest contribution to this growth is from the automotive aluminium stored in cars, which will reach 184 million tonnes in 2020, showing an average annual growth rate of 20%. The market for magnesium scrap recycling is even more dynamic. Although magnesium as an industry is still in its infancy and the global production of primary magnesium was only 525 kT in 2005, the annual growth rate for magnesium die-castings in the automotive industry is a staggering 15%, and this growth trend is predicted to continue in the next decade. It is clear that the major source of magnesium scrap is end-of-life vehicles. In Germany alone, the stored automotive magnesium will reach 51 kT, representing an average annual growth rate of 80%. The general picture of the dynamics of magnesium scrap market is expected to be similar in the developed countries, such as the US and the UK.

Recycling of light metals is an economically viable business even without the consideration of environmental benefits. Although aluminium only accounts for 5% of the car content, it represents 50% of the materials scrap value at the end of the car life because aluminium scrap is 10 times more valuable than steel and cast iron scrap. The value of magnesium scrap is similar to that of aluminium scrap. Based on the previous market analysis, upcycling light alloy scrap has a current market value of hundreds of million pounds. Recycling metals is not only economically viable, but also extremely beneficial for conservation of limited natural resources, reduction of energy consumption and waste generation; all contributing positively to a sustainable economy. For instance, in 2003 the EU recycled 4Mt of aluminium alloys, compared with primary alloy production, this conserved 53 Gkwh energy, 16.4Mt of bauxite, 0.2Mt of alloying elements (silicon, copper, iron, magnesium, manganese, zinc and others), 6.3 Glitres of water, and saved 1.5 million cubic meters of landfill space, 8 Mt of CO₂ emissions, and 0.044 Mt of SO₂ emissions.

Unlike other materials for engineering applications, metals, such as aluminium and magnesium, can be recycled repeatedly without loss of their inherent properties. Recycled light alloys from a scrap source only consume 5% of the energy required to produce the same amount of primary alloys. The application of recycled light alloys in cars can lead to a substantial reduction of greenhouse gas emissions. This has been exemplified in a recent study where the life cycle CO₂ equivalent emissions for the first life cycle of a magnesium cross car beam produced by high pressure die casting was 110 kg CO₂; the second life cycle equivalent emissions were 26 kg CO₂, and the fifth life cycle equivalent emissions were 34 kg CO₂.

The results for exploitation will be: (1) melt conditioning technologies for upcycling light alloy scrap; (2) a new generation of scrap-based aluminium and magnesium alloys and; (3) high performance light alloy products based on scrap. The alloys produced will be impurity tolerant versions of existing alloy compositions or new specifications developed to allow higher impurity contents. Initially, melt conditioning technologies and their aluminium products will find applications as semi-fabricated

products for a range of general engineering applications. The magnesium castings will initially find applications in products like automotive interior components, wheelchairs, housings for power tools, and electronics casings. With time the melt conditioned products will compete directly with their primary metal counterparts for the full range of automotive applications, having the considerable advantages of the low cost metal source and the simplified production process. Commercial exploitation will be through licensing agreements of the type established within the two existing consortia. The potential benefits to each partner are governed by a formal Consortium Agreement. The major items in the Agreement include that Brunel University, as the IPR owner, will grant a royalty-free license to the consortium partners for use of the melt conditioning technologies for the duration of the project. Meridian (UK), as a component supplier, and Norton, as an alloy and component supplier, will be granted a royalty-free license for unlimited supply of upcycled products for 5 years starting from the completion of the project. Any new IPR will be owned by its generator(s) and will be made available to other partners for royalty-free use. Consortium workshops will be held to disseminate the scrap reprocessing technology to other recyclers, materials suppliers and end users. The melt conditioning technologies will be readily integrated into the family of technologies used for light metal recycling. In the future, conventional chemical refining technologies may only be used to process the lowest quality scrap, whilst the melt conditioning technologies will upcycle the remaining higher quality scrap for more demanding applications. The conventional chemical refining techniques will persist in countries where energy and employment costs are low.

The upcycled aluminium and magnesium products will be first to market as the technology is unique to Brunel University. In North America although the requirement to recycle scrap into high grade products has been recognised by the Aluminum Association in their industry roadmap, the focus of their interest is to develop a low cost process for metal purification or to develop new alloys that better match the composition of the available scrap and to increase the tolerance to impurities by the use of processes such as spray rolling or other rapid solidification based processing techniques. The project can be partially successful as it is based on both magnesium and aluminium and three processing work packages (WP3, 4 and 5) that could be successful individually.

Commercial Opportunity

The ULARS project has confirmed that oxide films can be dispersed by physical melt conditioning and that this process can be used to develop improved cast microstructures. The ULARS project has directly resulted in the development of a novel dispersive mixing melt conditioning technology for which a patent application has been filed. The output of the ULARS project was a highly important for the establishment of an EPSRC Centre of Excellence in Liquid Metal Engineering at Brunel University. Upcycling of post consumer scrap is a major research and development theme within the LiME programme and its industrial programme will be the main opportunity for the commercial development of commercial opportunities from the ULARS project. The focus has changed from rheoforming of light alloy scrap to a more generic reprocessing of light alloy scrap. The LiME centre has been funded by Brunel university to install a new high pressure diecasting machine. This will be used to complete the melt conditioned scrap based HPDC studies that were not completed within the ULARS project. The commercial opportunities from the ULARS project have expanded within the LiME centre

The existing or emerging competitive offerings

Work within the LiME centre has been expanded to examine a wider range of physical and chemical melt conditioning techniques. Work on the use of ultrasound and melt cavitation as a melt conditioning technique has been assimilated into the LiME programme.

Quantify the commercial returns expected, together with the timescale.

The commercial returns from the ULARS project have now become part of the wider exploitation plans of the EPSRC LiME Centre of Excellence.

The primary impact of the EPSRC LiME Centre of Excellence will be on UK based businesses in the supply chain of metallic materials. This impact will be delivered in the following ways:

- Materials suppliers such as Sapa, LSM and MEL will benefit from an increased range of high quality metallic materials based on secondary metals with reduced cost and environmental impact;
- Materials processors such as Meridian, JVM and Aeromet will be able to offer an increased range of metallic components with improved quality but reduced cost;
- Equipment manufacturers such as Foseco and Rautomead who incorporate process innovations into their product portfolio and offer these to markets worldwide;
- Recyclers such as Norton and MEL who will provide high quality materials from recycled sources with reduced cost, but without expensive chemical conversion routes;
- Component end users such as JLR and Rolls-Royce who will benefit from the availability of cheaper, higher performance castings to meet their targets for lightweighting;
- The training and supply of the next generation of young researchers to work in this key area of the UK economy; and
- The wider metallurgical industry will be enabled to undergo a progressive reconfiguration from one that is profoundly dependent on primary metal supply to one that thrives on secondary metal sources.

The overall benefit to the UK supply chain will be enhanced economic competitiveness in the global market and improved sustainability through technological innovation. The overall accumulative contribution the UK economy could be in billions of pounds in the next 10-20 years.

The long-term goal is to create an optimised metallurgical industry based on full metal circulation. Achieving this not only requires advanced technologies, but also changes in government legislation and the attitudes in wider society. This may have a significant impact on policy makers such as international trade organisations (IAI, IMA), government departments (BIS), government funding bodies (EPSRC, TSB) and local authorities. Such policy makers need to direct research funding to the development of innovative technologies to achieve metal circulation, to increase the public awareness of the importance of metal circulation to achieve the environmental goals, and to reinforce metal circulation through legislation if necessary.

The long-term impact of EPSRC LiME Centre of Excellence research on the environment, and therefore, the general public, will be highly significant. Taking the aluminium industry as an example. Currently, 37 million tons of Al are produced each year. This uses 217 Mt bauxite and 1.67 trillion kWh electricity, and releases 444 Mt CO₂ into space. 20 years later, if we have achieved full circulation with only 25% primary metals, each year we would save 163 Mt bauxite and 1.25 trillion kWh electricity (equivalent to 3 times of the UK's annual electricity consumption), and reduce CO₂ emission by 333 Mt. The energy saving and CO₂ emission reduction could be much more significant if other metals also achieved full circulation.

The EPSRC LiME Centre of Excellence Management Group (LMG) will be responsible for the delivery of the above impact. As well as embedding exploiters of the research in specifying the LiME programme from the outset a number of additional specific initiatives to help ensure the delivery of the expected income, including:

- Partnerships with intermediate organisations who are already engaged with our target community and comprising industry trade bodies including (CMF, AlFed), learned society (ICME), knowledge transfer networks (Mat KTN (IOM)), etc so we draw on best-practice without duplication; and
- A Programme Manager has been appointed to deliver a programme of out-reach and dissemination seminars, workshops, publications, website, etc where gaps appear in the existing provision of partners.

The potential impact

Summary of wider benefits from the Project for those outside the consortium

This technology development will bring an economic benefit of hundreds of millions of pounds per year to UK industry. The potential benefits of the project are orders of magnitude larger than the project costs. The technology can be viewed as truly groundbreaking in providing economically attractive, high performing products from light metal scrap re-use. In terms of the consortium, Brunel will benefit as the key technology provider and owner of the processing IP. Norton Aluminium will find new, higher-value UK-based product markets for its scrap. Meridian and Norton will both benefit through sourcing lower cost raw materials to produce high value products. Innoval will benefit through having access to novel reprocessing technologies that can be applied to other market sectors. Within 5 years high performance products manufactured through this lower cost materials re-use route will provide significant commercial advantages and benefits to the initially targeted sectors and also to spillover market sectors. There will, ultimately, be substantial commercial benefits to all light metal producers, recyclers and high performance product manufacturers. The overall risks associated with the project are manageable due to the maturity of the technology and the exceptional level of expertise and experience within the consortium. The vision of the project is based on the sustainability and the development of a new generation of materials based on the upcycling of scrap. Scrap sources are the basic materials for the ecological and sustained production of light alloy components, particularly for the growing automotive market. On a global basis recycling aluminium already saves 84 M tonnes/year of greenhouse gases and reduces the world's need for mining and primary processing by one third. As aluminium and magnesium can be repeatedly recycled with an energy requirement that is only 5% of that for the primary refining operation, the cumulative potential contribution to sustainability is enormous. The sustainability benefits to the consortium partners are also considerable. Meridian will achieve up to 100% in-house scrap recycling rates, resulting in improved energy efficiency, a decreased scrap rate and a lower materials consumption for the same productivity. Norton will benefit from improved energy efficiency, reduced processing steps and an enlarged product range, all leading to more sustainable development.

The melt conditioning technology can be considered as more like a mechanical refinement or filtration process applicable to light alloys and metals in general. This also means that the potential commercial benefits are much, much larger than previously anticipated and could disrupt the present metals processing industry as the need for extensive thermomechanical processing by rolling or extrusion could decline significantly.

The economic and sustainable benefits will be realised by end users of light alloys in structural applications since they will be provided with lower cost and high performance products from an ecologically attractive resource. The potential spillover benefits from the initial, mainly automotive, applications could extend to both aerospace and military applications. This potential has to be balanced against the increased risk of not achieving the higher performance targets required for these aerospace and military applications with alloys directly processed from a scrap source. The project can enhance the sustainability of the UK light metals industry and significantly reduce its dependence on primary metal or metal that has been refined back to primary grade. There are also major opportunities for start-up companies and small business development as the upcycling process is not capital intensive and can be developed in modular fashion. There are opportunities for light alloy recyclers to extend their businesses by becoming suppliers of value-added cast components and/or semi-fabricated products. Vehicle manufacturers will be able to use more recycled light metals in the production of lightweight vehicle components. The social and environmental impacts of the project are overwhelmingly positive and are directly in line with governmental targets for recycling and greenhouse gas reduction. The goals of increasing materials re-use addresses the 2006/7 strategic sustainable consumption objectives identified by the Sustainable Development Commission (April 2006) and the strategic outcomes outlined by DEFRA in their 5 year strategy report (December 2004) on "Protection of human health and the environment by minimising amounts of waste produced and getting as much value as possible out of what is left by re-use or recycling....and the recovery of energy". Environmentally the key benefits will be achieved through significant materials re-use in manufacturing, increased product life, improved energy efficiency, reduced landfill and also a reduction in primary materials demand (with its concomitant higher energy, transport costs and carbon dioxide emissions).

For every application where either recycled aluminium or magnesium is used to replace the use of primary metal this will represent a 95% reduction in energy used. In addition, the energy used to provide a uniform fine grained microstructure by melt conditioning is less than 10% of that required for conventional mechanical processing of aluminium and less than 5% of that required for the complex processing of wrought magnesium alloys. Furthermore, waste is effectively eliminated as any process scrap becomes available for the next scrap casting event and scrap can be recycled indefinitely. Product lifetimes may also be significantly extended through the refinement of coarse intermetallics providing improved corrosion resistance.

Exploitation Plan

Business Plan

Detail the activities and timescales for exploitation activities, including the activities to develop the market buy-in and the activities to present the outcome to the market.

Indicate the joint activities between partners.

If further capital is required, consider the plans which will be carried out to raise it.

Dissemination Activities during the Project

The results have been disseminated through a series of papers and presentations

Refereed Journal papers

H. Men, B. Jiang, and Z. Fan, Mechanisms of grain refinement by intensive shearing of AZ91 alloy melt, *Acta Materialia* 58 (2010) 6526
S. Tzamtzis, H. Zhang, N. Hari-Babu, and Z. Fan, Microstructural refinement of AZ91D die-cast alloy by intensive shearing, *Materials Science and Engineering A* 527 (2010)
H. Kotadia, N. Hari-Babu, H. Zhang, and Z. Fan, Microstructural refinement of Al-10.2% Si alloy by intensive shearing, *Materials Letters* 64 (2010) 671
Y. Wang, M. Xia, X. Zhou and G.E. Thompson, The effect of Al₈Mn₅ intermetallic particles on grain size of as-cast Mg-Al-Zn AZ91D alloy, *Intermetallics* 18 (2010) 1683-1689
I. Stone, Casting is considered, *Materials World* 18 (2010) 27-28
Y. Zuo, H.T. Li, M. Xia, B. Jiang, G.M. Scamans, and Z. Fan, Refining grain structure and porosity of an aluminium alloy with intensive melt shearing, *Scripta Materialia* 64 (2011) 209-212
S. Tzamtzis, H. Zhang, M. Xia, N. Hari-Babu, and Z. Fan, Recycling of high grade die casting AM series magnesium scrap with the melt conditioned high pressure die casting (MC-HPDC) process, *Materials Science and Engineering A* 528 (2011) 2664
Y.B. Zuo, H. Li, M. Xia, G.M. Scamans, and Z. Fan
Refining grain structure and porosity of an aluminium alloy with intensive melt shearing, *Scripta Materialia* 65 (2011) 209-212
Y.B. Zuo, M. Xia, S.M. Liang, Y. Wang, G.M. Scamans and Z. Fan, Grain refinement of DC cast AZ91D Mg alloy by intensive melt shearing, *Materials Science and Technology* 27 (2011) 101-107
Y.B. Zuo, B. Jiang, P. Enright, G.M. Scamans and Z. Fan, Degassing of LM24 Al-alloy by intensive melt shearing, *Journal of Cast Metals Research* (2011)
H. Men and Z. Fan, Transition of amorphous to crystalline oxide film in initial oxide overgrowth on liquid metals, *Materials Science Technology* (2011) in press

Accepted Conference papers

Z. Fan, Y. Zuo, B. Jiang, A new technology for treating liquid metals with intensive melt shearing, *Proceedings of Light Metals Technology 2011*, 19-22 July 2011, Lüneburg, Germany.
Y. Zuo, B. Jiang, Z. Fan, DC casting of aluminium alloy with intensive melt shearing, *Proceedings of Light Metals Technology 2011*, 19-22 July 2011, Lüneburg, Germany.
Z. Fan, Y. Zuo, B. Jiang, Heterogeneous nucleation and nucleation control through liquid metal engineering, *Proceedings of 3rd International Conference on Advanced Solidification Processing (ICASP-3)*, Aachen, Germany, 7-10 June 2011.
T. Qin, Z. Fan, Molecular dynamic analysis of grain refining in aluminium with Ti-5Ti-1B, *Proceedings of 3rd International Conference on Advanced Solidification Processing (ICASP-3)*, Aachen, Germany, 7-10 June 2011.
H. Men, Z. Fan, Molecular dynamic simulations of heterogeneous nucleation in liquid aluminium, *Proceedings of 3rd International Conference on Advanced Solidification Processing (ICASP-3)*, Aachen, Germany, 7-10 June 2011.
Y. Zuo, B. Jiang, Z. Fan, Microstructure of DC cast light alloys under the influence of intensive melt shearing, *Proceedings of 3rd International Conference on Advanced Solidification Processing (ICASP-3)*, Aachen, Germany, 7-10 June 2011.
H.-T. Li, Z. Fan, Enhanced heterogeneous nucleation based on oxide in Al-alloys by intensive shearing, *Proceedings of 3rd International Conference on Advanced Solidification Processing (ICASP-3)*, Aachen, Germany, 7-10 June 2011.
F. Yan, B. McKay, Z. Fan, Effect of intensive melt shearing on microstructures and mechanical properties of Al-Mg based alloys, *Proceedings of 3rd International Conference on Advanced Solidification Processing (ICASP-3)*, Aachen, Germany, 7-10 June 2011.