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ExoMet Project

"Physical Processing of Molten Light Alloys under the Influence of External Fields"

Collaborative Project

Thematic Priority – NMP

Final Report

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PART A Final Publishable Summary Report

A.1 Executive summary

The ExoMet project revolved around innovative liquid-metal engineering and the application of external physical fields in order to significantly influence the microstructures and properties of aluminium- and magnesium-based materials. Three types of external fields were explored: electromagnetic (EM), ultrasonic (US), and intensive liquid shearing (LS).

To meet the future European challenges of light-weighting and pollution reduction, especially relevant in transportation, it is necessary to improve the castability of these light alloys, to enhance grain and eutectic refinement in monolithic alloys, and to develop new high-strength composites (so-called metal-matrix nanocomposites, or MMNCs), using nanoparticles which have only recently become available. Significant mechanical-property improvements are foreseen, including 50% increases in tensile strength and ductility, as well as in creep resistance up to 300–350 °C (currently limited to about 200 °C). This applies to both shape castings and wrought products. Manufacturing scale-up was also tackled in ExoMet, using a variety of techniques. The application of external fields to these industrial techniques is novel and would bring about major savings in energy, scrap and processing cost. The final stage of the project was on prototyping and the assessment of industrial applications in (1) automotive powertrain and chassis, (2) aircraft and aero-engine structures, (3) space satellite and rockets, and (4) high-strength high-conductivity aluminium electrical cabling. Computer modelling, rig-testing, standardisation, life-cycle analysis and patenting were also undertaken.

A.2 Project context and objectives

Rationale

No other materials have contributed more to the technological development of humankind over the past 10,000 years than metals and alloys. In fact the study of metallurgy is one of the oldest branches of physical sciences and has evolved over millennia to become a highly sophisticated research field that influences almost all sectors of industry including energy, aeronautics, automotive, space, chemical, machinery, scientific equipment, construction, packaging, electrical, computing and health. Without metals and alloys the modern world would be inconceivable and could not function successfully.

As a result of the ubiquity of metals, the metal industry has become one of the largest sectors in the European Union economy. The combination of (1) primary metal production, (2) alloy manufacturing, (3) all downstream processing and integration of metal products and (4) metal recycling accounts for 46% of all EU manufacturing value and 11% of the EU's total gross domestic product, which equates with an added value of approximately 1.5 trillion € annually in the EU.[1] The key technical topic that underpins these four areas is "solidification". The fact that 97% of all metal products are manufactured using at least one solidification process gives an indication of how important it is to understand, influence and

[1] World Trade Organisation & International Metalworkers' Federation statistics

control the micro/nano-structures that emerge in solidifying metals, alloys and their composites.[2]

As is widely known, liquid-metal engineering – and in particular casting – has a very long history. However, this legacy has both positive and negative consequences. On the upside, casting has progressed over thousands of years of trials to become an extremely versatile, modern method for making complicated 3D net-shape components (such as aero-engine turbine blades, car-engine blocks, thin-walled structures and housings for spacecraft, aeroplanes, helicopters, road vehicles, industrial equipment, or biomedical orthopaedic devices). On the downside, however, this long history often creates two false impressions, namely that there are few innovations left to be discovered, and that the potential for process improvement in solidification has been completely exhausted.

The ExoMet project challenges this by presenting a number of innovative concepts in liquid-metal engineering that, when successfully industrialised, would be of major manufacturing and economic significance. To meet the challenges of the 21st century, new principles of liquid-metal engineering are required, including the application of external physical fields, enhanced grain refinement, eutectic modification and nano-sized reinforcement, which have only recently become available. This would allow European alloy developers, foundries and end-users to successfully claim patents on and take advantage of new solidification processes, light alloys and nanocomposites – thereby outpacing key companies in the US and Asia in this area.

In addition to technical and economic reasons, there is another critical factor that is emerging – namely the need to reduce emissions in relation to pollution and climate change. The importance of light-weighting in the transport sector, as an effective way of cutting greenhouse gas emissions, cannot be overstated. As an example of weight-saving potential, a 100 kg weight reduction for a long-haul aeroplane saves about 20,000 gigajoules of energy and 1,900,000 kg of CO_2 emission over its 30 year life-time; similarly, a 100 kg weight reduction for an average car saves about 25 gigajoules and 1,600 kg of CO_2 over its 10 year life-time.[3] These figures are very encouraging, especially when multiplied by the large number of cars and planes in service, now and also in the future. Furthermore, the *UN Intergovernmental Panel on Climate Change* has also stated that "material substitution and advanced design could reduce the weight of vehicles by 20–30%", with the use of lightweight aluminium and magnesium being explicitly mentioned in the report.[4]

Project concept

The core concept of the ExoMet project involves developing new liquid-metal processing techniques coupled with external fields. These techniques will revolutionise microstructure control in metallic alloys and their composites, and allow for properties not reachable by conventional processing routes and compositions. The metals of greatest interest in this project are light alloys of aluminium and magnesium, although it should be appreciated that the new methods will also be of high value to other alloy systems in the future (e.g., titanium, copper, steel, cobalt, nickel, zinc, inter-metallics, high-entropy alloys, bulk-metallic glasses).

The use of external fields to disperse novel grain refiners and reinforcing nanoparticles into melts and the subsequent solidification of light-alloy nanocomposites

[2] Kelton K., Greer A.L.; *Pergamon Materials Science*; 15 (2010)
[3] Helms H. *et al.*; *International Journal of Life Cycle Assessment*; (2007)
[4] N.N.; *Transport and Infrastructure*; 4th Assessment Report of the IPCC (2007)

have been key topics tackled in ExoMet. In terms of external fields, the team has investigated the influence of electromagnetic (EM), ultrasonic (US) and intensive liquid shearing (LS) on large volumes of alloy. Combinations of these different techniques (e.g., US and EM) have also be explored. This study logic is summarised in figure A.1.

Project objectives

The targeted goals of the ExoMet project are summarised as follows.

- **Scientific**: (1) to reveal a quantified understanding of the influence of external fields on liquid-metal processing, solidification and the structures formed in monolithic and nanocomposite light alloys, (2) to create the first-ever "process-structure-property map" in this field, capable of predicting mechanical, physical and chemical property trends of relevance to the industrial end-users, and (3) to develop and enhance multi-scale, multi-physics models describing the physical phenomena that occur during field-enabled particle dispersion, nucleation, solidification and microstructure formation – noting that these models are also of great value for many other alloy systems.
- **Technological**: (1) to develop three new field-enabled technologies, based on tailored electromagnetic fields, power ultrasound and intensive liquid shearing, that can be applied to light-alloy shape castings and wrought billets, (2) to industrially implement these knowledge-based methods for the purpose of making monolithic light-alloy components with 25% improvements in yield stress, ultimate tensile strength and ductility, (3) likewise, to produce recyclable light-alloy nanocomposites with up to 50% improvements in tensile properties, and operating temperatures of 300–350°C (e.g., based on aluminium alloy A357 and magnesium alloy Elektron21), (4) to obtain specific strengths in aluminium and magnesium nanocomposites four times higher than mild steel and with fatigue-life enhancements of 100%, (5) to produce prototype shape castings and wrought parts for real automotive, aerospace and electrical systems with a special focus on achieving thin-walled parts <2mm thick, this particular objective being aided and optimised by predictive numerical modelling, and (6) to produce a set of reference materials that can be used for the development of new ISO and ASTM standards, as well as the certification of components prior to in-service use.
- **Commercial**: (1) to demonstrate scalable field-enabled processing of light alloys and nanocomposites that adds no more than 20% to the cost of a conventionally-produced light-alloy component, which would represent a modest premium considering that all the expected performance increases are well above 20%, (2) to lower component cost by using a larger proportion of recycled feedstock than currently used by industry (>50%), (3) to encapsulate all the above knowledge into an integrated set of software solutions for industrial process optimisation, resulting in a 20% reduction in lead-time and scrap-rate in the foundry, (4) to apply for five or more patents during the course of the project, in order to protect the most commercially-viable process improvements and light-alloy compositions, and (5) to expand on the secondary utility of light alloys and their nanocomposites in new markets – likewise the field processing could later be extrapolated to other alloys (e.g., Fe, Cu, Ti, Co, Ni).

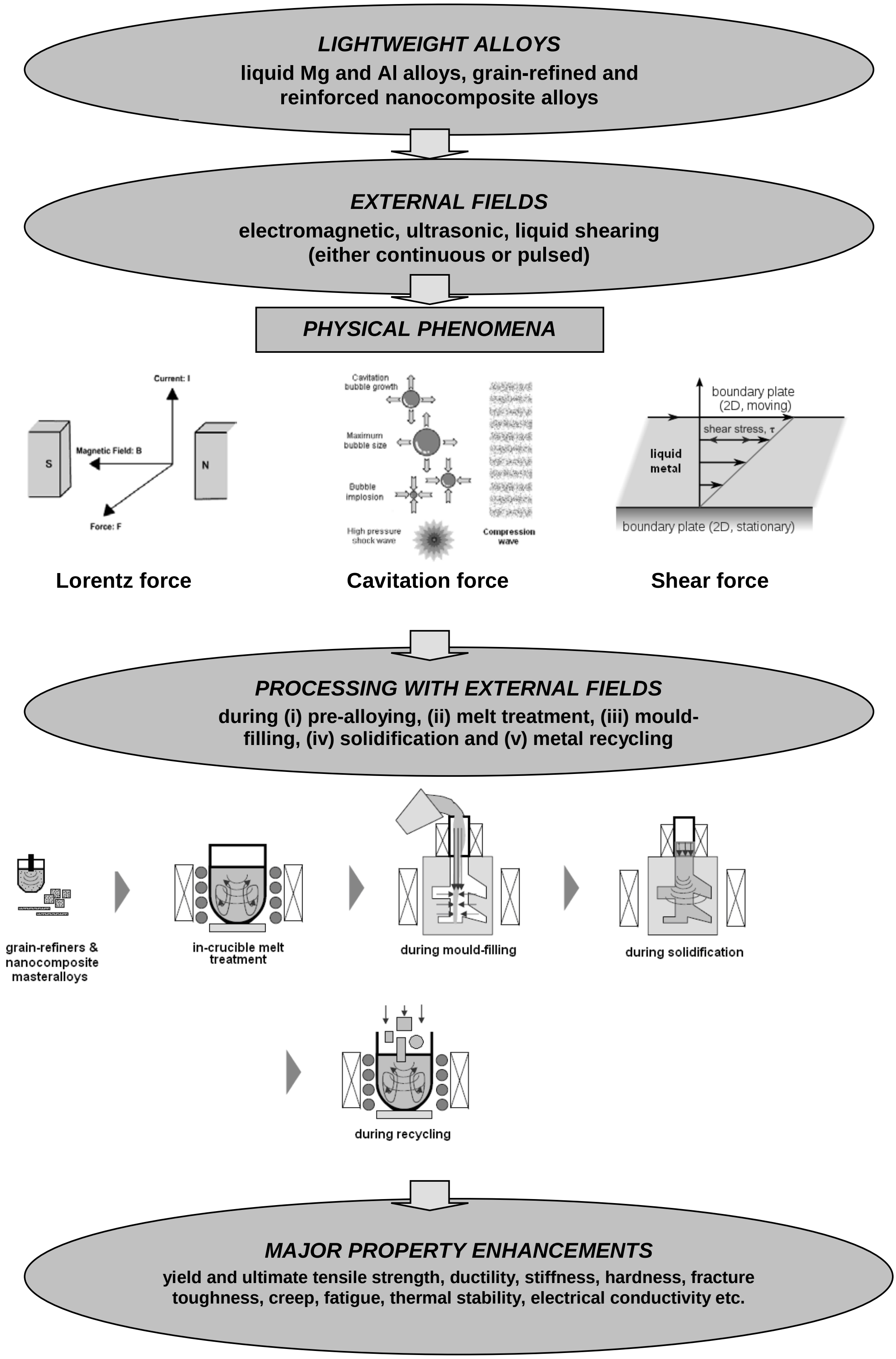


Figure A.1 *Schematic diagram showing the project's focal points*

- **Environmental**: (1) to complete a life-cycle analysis, closely following the guidelines of ISO14040-43 and the ILCD Handbook, that will quantify the environmental benefits of field-enabled melt processing of light-alloy components, (2) to demonstrate at least 30% weight saving in vehicle components when using novel light alloys, compared to steel, and estimate the CO_2 and other greenhouse-gas reductions during the life-time of a component/vehicle, (3) to investigate and promote the use of recycled aluminium and magnesium alloys and MMNCs, (4) to develop best practice, with respect to health, safety and environment, for the use of external fields, the handling of nanoparticles and the replacement of SF_6 cover gases.

A.3 Main scientific and technological results

Considering the variety of activities and the multi-disciplinarity of the approach, it is not really in order to pinpoint a few developments that proved crucial at the end, but it is rather the collection of results from these diverse activities that have advanced the field overall. In this sub-section, however, selected results will be highlighted as being exemplary of the achievements deriving from the project. Most of these examples are drawn from publications (as cited in the accompanying footnotes) and are as such of a non-confidential nature.

Scientific findings

As an example of modelling the fundamentals of particle interactions in a melt, figure A.2 shows Computational Fluid Dynamics / Discrete Element Method (CFD-DEM) simulation results on the break-up of particle clusters under the influence of external fields.[5] The numerical model incorporates different adhesion-force theories (Johnson, Kendall and Roberts – JKR, and Derjaguin, Müller and Toporov – DMT) in an effort to compare those with respect to the behaviour of a cluster of nanoparticles subjected to a shockwave originating in the centre of the cluster. This study on the particle-particle interaction forces under various conditions was to explore the mechanisms of de-agglomeration and is expected to help optimising the electromagnetic and ultrasonic treatment of metal melts with added nanoparticles.

[5] Manoylov A., Bojarevics V., Pericleous K.; "Modelling the formation and breakup of particle clusters in metal melt subjected to external fields"; *Proceedings of the 4th International Conference on Particle-based Methods – Fundamentals and Applications* (PARTICLES 2015): 1–12

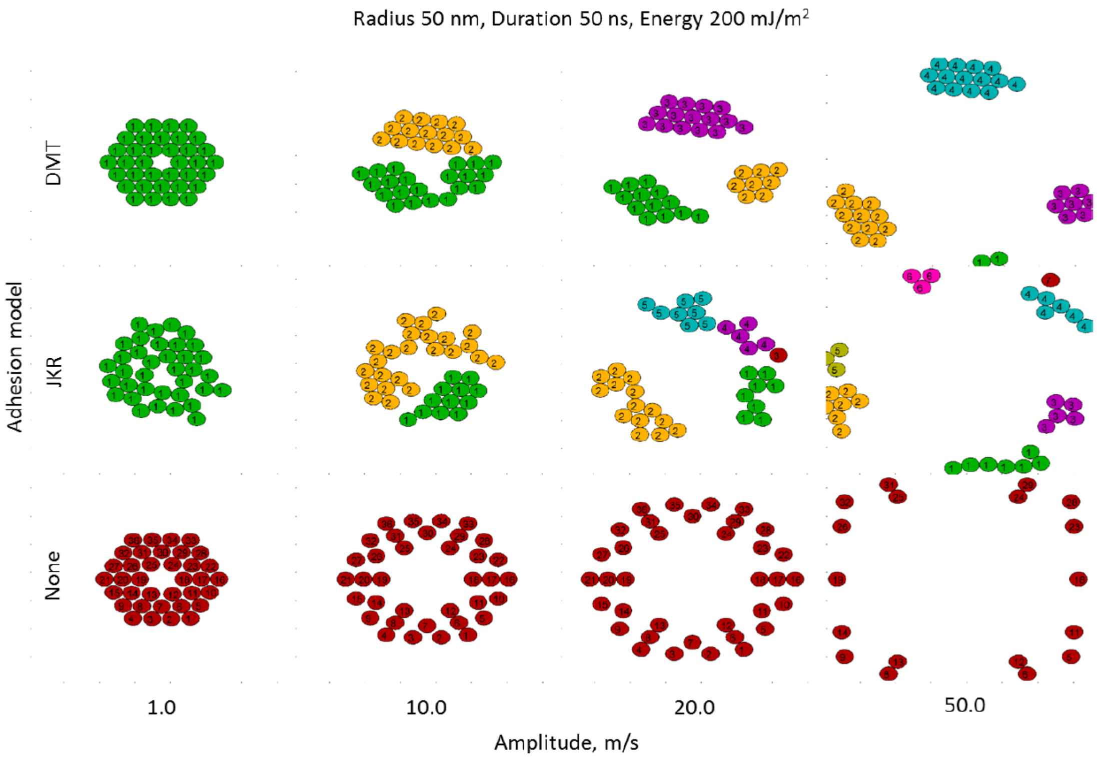
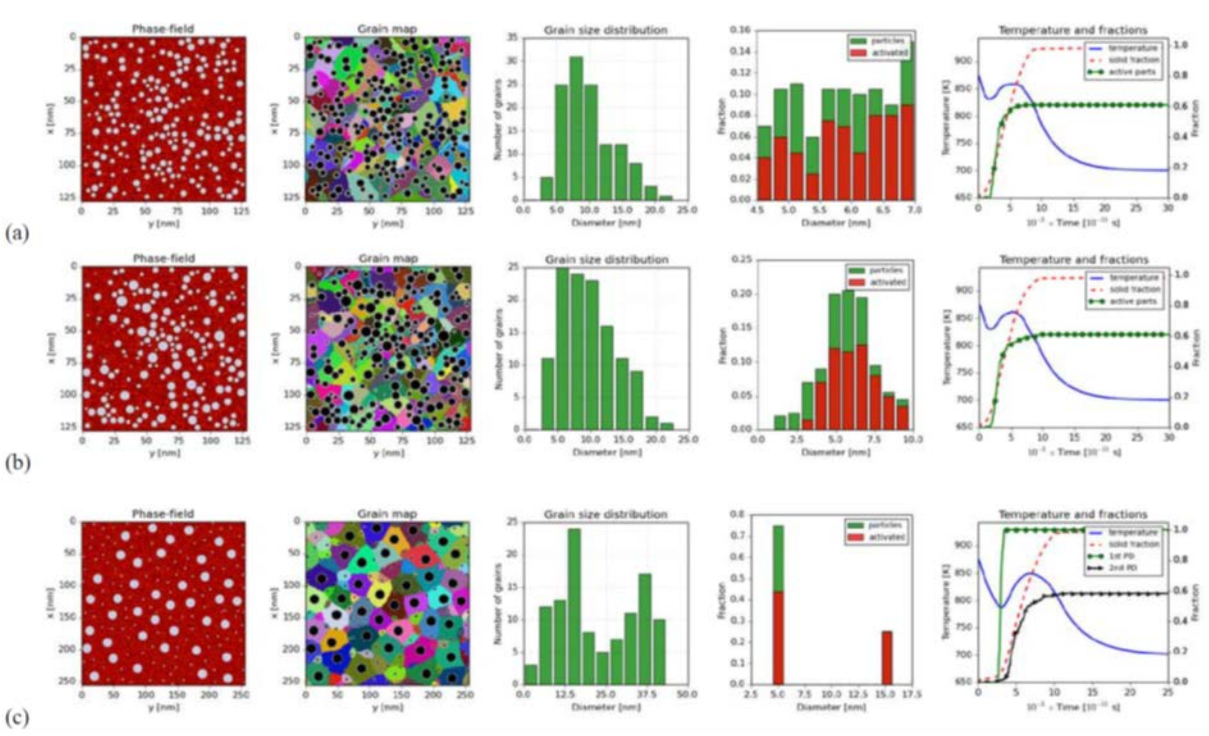


Figure A.2 *The effect of the adhesion model on breaking up nanoparticle clusters via spherical shockwave*

As an example of modelling the fundamentals of particle interactions with a melt, figure A.3 shows phase-field simulation results of the solidification of a particle-containing melt for different particle sizes and particle-size distributions.[6] This model addresses crystal nucleation and growth in the presence of foreign particles characterised by a size- and velocity-related mobility and a contact angle ϑ. Apparently, features of the size distribution of the foreign particles are reflected by the resulting grain-size distribution (e.g., a bimodal particle distribution of particles often leads to a bimodal grain-size distribution). A general observation is also that crystallisation starts in areas where the particle density is the highest. It has also been demonstrated that particle motion can be taken into account, and that this may influence the solidification microstructure considerably, especially if the contact angle of the particles is large. An issue with these models is that the values of material-property parameters, such as the contact angle, need often to be assumed or estimated in the absence of accurate (experimental) data under the conditions at hand.

[6] Pusztai T., Rátkai L., Szállás A., Gránásy L.; "Phase-field modeling of solidification in light-metal matrix nanocomposites"; *Magnesium Technology 2014*; Wiley–TMS, Hoboken NJ (2014): 455–459 (DOI 10.1002/9781118888179.ch83)



<u>Figure A.3</u> *Solidification in the presence of foreign particles of ϑ=10°: 200 particles of (a) uniform, (b) normal, and 160 particles of (c) bimodal size distribution (40 large, 120 small). The final (fully solidified) stage is shown. From left to right, the phase-field map, the grain map (different colours correspond to different grains), the size distribution of the crystalline grains, the size distribution of the foreign particles (red fraction participated in nucleation), and the time evolution for the temperature (solid), the crystalline fraction (dashed), and the fraction of activated foreign particles (circles and triangles for the two sizes) are shown. Grid sizes: (a), (b) 512×512 and (c) 1024×1024*

As a contribution to acquire such material-property data for the solid state, <u>figure A.4</u> presents Density Functional Theory (DFT) simulation results of interfacial free energies (that strongly influence many material properties, especially for nanomaterials that have very large interfacial areas per unit volume).[7] For the temperature range of 0–800 K, it is found that all free energies decrease almost linearly with temperature. It is also found that interfacial free energy increases with the decrease of particle size at a constant temperature and the excess free energy in the nanocomposites is increased ~10 times when the particle size is reduced from 100 to 10 nm.

[7] Xu W., Horsfield A.P., Wearing D., Lee P.D.; "First-principles calculation of Mg/MgO interfacial energies"; *Journal of Alloys and Compounds* <u>650</u> (2015): 228–238 (DOI 10.1016/j/jallcom.2015.07.289)

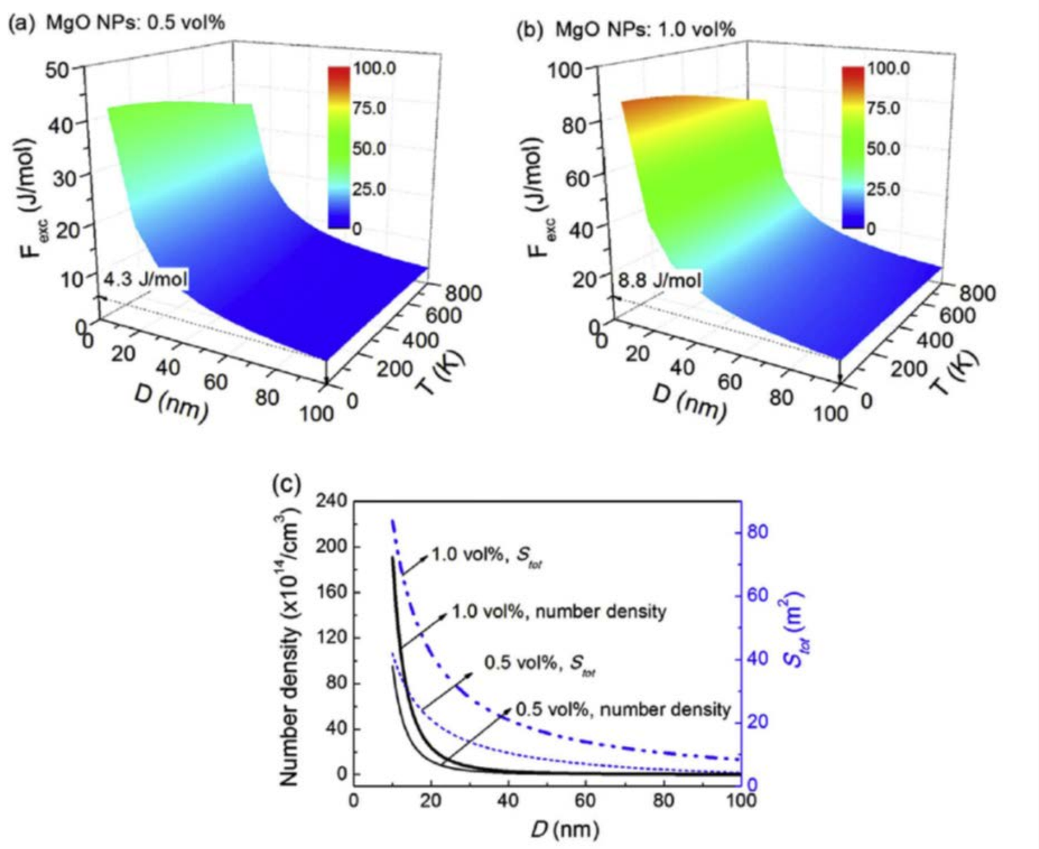


Figure A.4 *Excess free energy F_{exc} as a function of temperature and particle size: (a) 0.5 vol.% MgO, (b) 1.0 vol.% MgO; (c) number density of nanoparticles and total area of hetero-phase interfaces as a function of particle size for the system of metal Mg reinforced by MgO nanoparticles*

Numerical models have also been developed to study the flow of particle-containing solidifying metal melts under the influence of electromagnetic fields; an illustration of that is shown in figure A.5.[8] For this particular case, the calculations as well as the experiments demonstrate that the direction of the travelling magnetic field has an apparent effect on the dispersion of the particles and their final distribution in the casting.

[8] Garrido M., Bojarevics V., Rattoni B., Davoust L., Daudin R., Fautrelle Y.; "Dispersion of microparticles into magnesium materix using travelling magnetic field"; *Proceedings of the 10th PAMIR International Conference – Fundamental and Applied MHD (PAMIR10)*

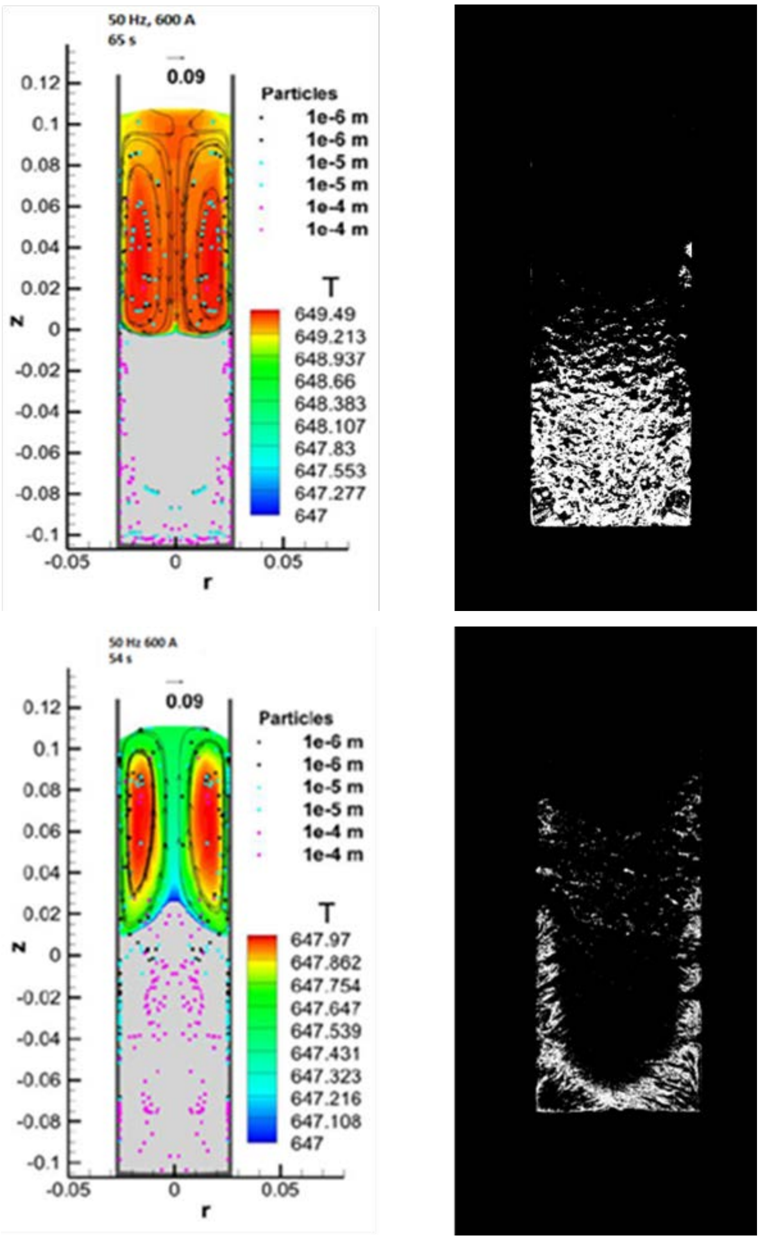


Figure A.5 *Simulated particle flow and temperature distribution versus experimental particle distribution in the as-cast Mg/SiC material, obtained under the influence of an upward (top) and downward (bottom) travelling electromagnetic field*

Advanced metallographical characterisation techniques have been used to study the microstructures of the developed metal-matrix nanocomposite materials; an example of a Transmission Electron Microscopy (TEM) investigation is shown in figure A.6.[9] The magnesium alloy Elektron21 displays a complex microstructure with a high density of rare-earth containing precipitates well-distributed in the magnesium crystals, contributing to its favourable mechanical properties. Regarding the addition of Al_2O_3(AlOOH) nanoparticles to

[9] Mounib M., Pavese M., Badini C., Lefebvre W., Dieringa H.; "Reactivity and microstructure of Al_2O_3-reinforced magnesium matrix nanocomposites"; *Advances in Materials Science and Engineering* (2014): ID 476079 (DOI 10.1155/2014/476079)

this alloy, the study learned that a chemical reaction of those particles with the melt occurs during the synthesis of the nanocomposite material, facilitated by the high surface area of the particles. Apart from the dissolution of Al in the melt (which eventually ends up in the eutectic regions of the solidified material), this leads to the *in-situ* formation of submicron-scale MgO particles that do conceivably contribute to the enhanced high-temperature properties of the composite material versus the monolithic alloy.

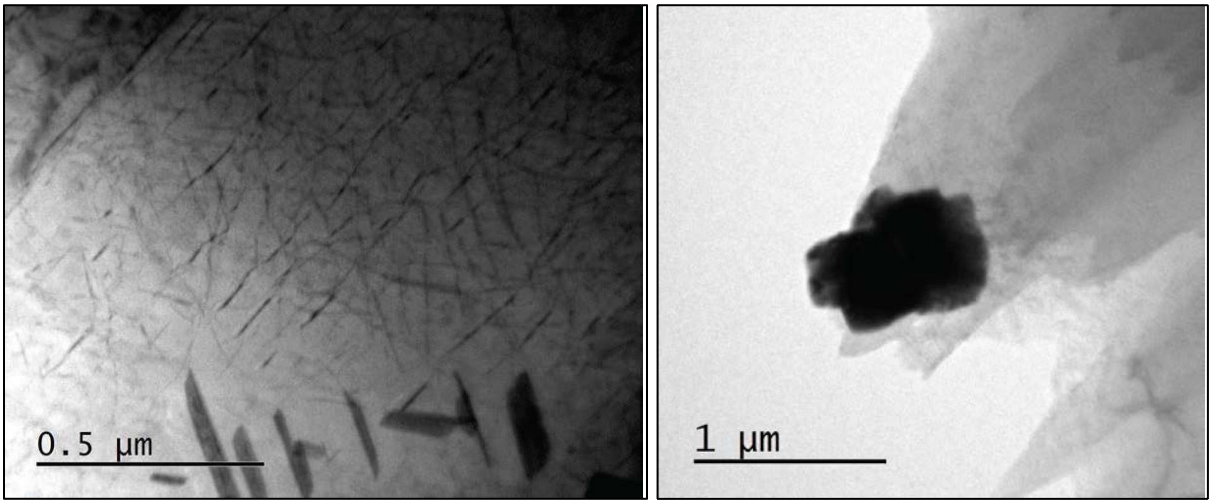


Figure A.6 *Bright-field TEM images of Elektron21/Al_2O_3(AlOOH) nanocomposite material (left) and of an MgO particle formed in this material during its synthesis (right)*

Advanced characterisation also involved the use of synchrotron facilities, as is illustrated by the result depicted in figure A.7.[10] This particular study focussed on the behaviour of submicron-sized Y_2O_3 particles incorporated in the aluminium alloy 6082 during re-melting and solidification, for which *in-situ* X-ray microtomography was used. The presence and spatial distribution of the particles in the alloy were revealed through the dissolution of the intermetallic phase upon re-melting. These particles were mostly found agglomerated at grain boundaries, suggesting that particle pushing has likely been the predominant mechanism in interfacial interactions during the sample's prior solidification. This trend was also confirmed by the direct observation of the solidification process from the fully re-molten state, showing clusters of yttria particles pushed by growing dendrites.

[10] Daudin R., Terzi S., Lhuissier P., Salvo L., Boller E.; "Remelting and solidification of a 6082 Al alloy containing submicron yttria particles: 4D experimental study by in situ X-ray microtomography"; *Materials and Design* 87 (2015): 313–317 (DOI 10.1016/j.matdes.2015.07.141)

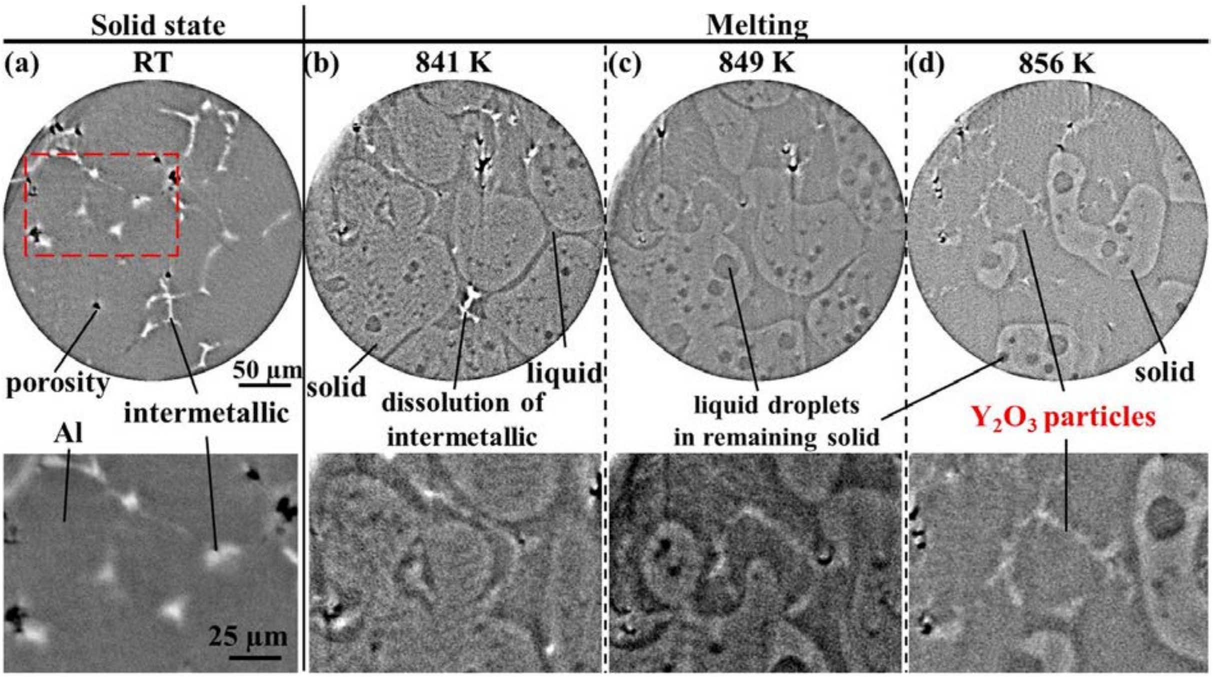


Figure A.7 *Sequence of 2D images extracted from the volume of the specimen showing the evolution of the microstructure during re-melting of a 6082/Y_2O_3 nanocomposite material: (a) room temperature where Y_2O_3 particles cannot be distinguished; (b) 841 K; (c) 849 K; (d) 856 K – the bottom part is a zoom of the region highlighted by the dashed box*

As yet another example of synchrotron studies, figure A.8 illustrates an investigation into the dynamic behaviour of ultrasonic cavitation gas bubbles in a molten Al10Cu alloy, using *in-situ* X-ray radiography.[11] Analysis of the captured images allowed for quantifying the formation and growth of the bubbles upon sonication, as well as their size distribution and number density. Knowledge of these kinetics is important for the control of casting defects such as porosity and dissolved hydrogen, but within the scope of of the project also for assessing the mechanisms behind the dispersion of particles and the de-agglomeration of particle clusters by ultrasound.

[11] Xu W.W., Tzanakis I., Srirangam P., Mirihanage W.U., Eskin D.G., Bodey A.J., Lee P.D.; "Synchrotron quantification of ultrasound cavitation and bubble dynamics in Al-10Cu melts"; *Ultrasonics Sonochemistry* 31 (2016): 355–361 (DOI 10.1016/j.ultsonch.2016.01.017)

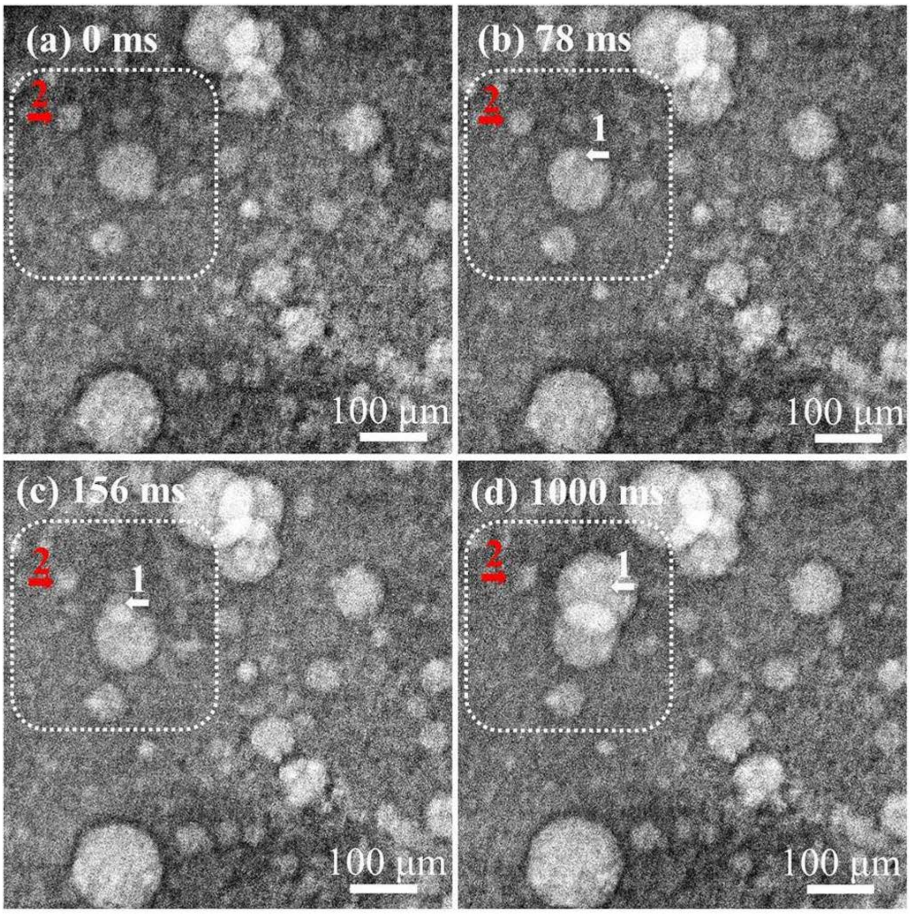


Figure A.8 *Nucleation and fast growth of a single cavitation gas bubble: (a) just before nucleation; (b) <78 ms after the nucleation process starts and is represented by the light dotted area on top left region of the bubble's periphery (white arrow); (c) in growth process; (d) the end of growing process at the end of cycle (1.0 s)*

X-ray radiography was also used in a laboratory setting by using a micro-focus X-ray source, of which some results on the *in-situ* solidification of a magnesium alloy are shown in figure A.9.[12] Apart from a visualisation of the actual nucleation and growth of the primary crystals in the melt, image analysis enables to derive and plot such fundamental information as dendrite-growth velocities and by that quantify the observed solidification phenomena. This can then be linked to complementary tools of analysis such as thermodynamic calculations and density functional theory simulations so as to unravel the mechanisms at play.

[12] Casari D., Mirihanage W.U., Falch K.V., Ringdalen I.G., Friis J., Schmid-Fetzer R., Zhao D., Li Y., Sillekens W.H., Mathiesen R.H.; "α-Mg primary phase formation and dendritic morphology transition in solidification of a Mg-Nd-Gd-Zn-Zr casting alloy"; *Acta Materialia* 116 (2016): 177–187 (DOI 10.1016/j.actamat.2016.06.035)

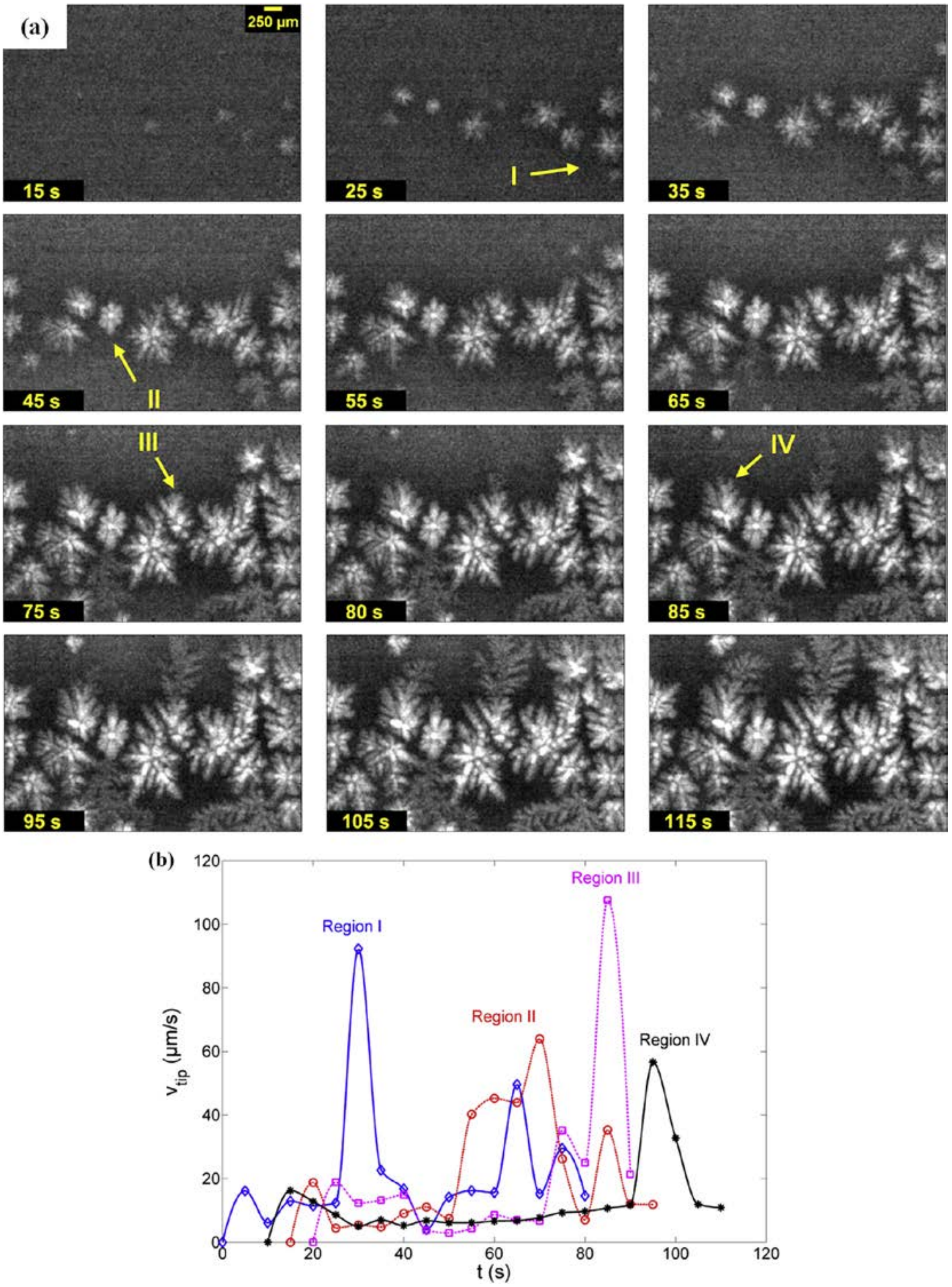


Figure A.9 *(a) Images taken from a sequence of X-ray radiograms showing the time evolution of the α-Mg primary phase in the Elektron21 alloy under nearly isothermal conditions at a cooling rate of 0.0125 K/s. The initial α-Mg dendrites appear as bright, while the secondary morphologies are distinctively darker. The grey levels in the liquid phase relate to its constitution, where enhanced solute concentration gives darker image pixels. The regions marked with I, II, III and IV represent the spatial locations where a morphologically different structure appeared. (b) Instantaneous interface velocities extracted for the dendrites that undergo the transition in regions I–IV*

Technological findings

In its most basic representation, the main technological results on the conducted material and process investigations are outlined in figure A.10. This top-level inventory contains the 3–4 most-notable favourable findings for each of the four sub-sets of developments – distinguishing between the two investigated light metals (aluminium and magnesium) and the two explored development tracks (grain refinement and MMNCs). It is to be noted that only the promising findings are highlighted here from the perspective that these are of direct concern in carrying the developments further. In general terms, the reached state-of-the-art (e.g., expressed as Technology Readiness Level) is the most advanced for aluminium grain refinement, followed by magnesium MMNCs, then magnesium grain refinement, and finally aluminium MMNCs.

	Grain refinement	Metal-matrix nanocomposites
Aluminium	+ New Al-Ti-Nb-B grain refiners are effective in Al-Si alloys (including A357, Al9SiMg and M174+) for microstructural refinement and RT tensile properties (notably ductility), and considerably more efficient vs standard commercial grain refiner (TRL 5–6) + New grain refiners based on $MgAl_2O_4$ (*in situ*) are effective in Al-Si alloys, but are not ready for scale-up yet (TRL 3–4) + There is a clear benefit in application of US processing in manufacturing of new master alloys and/or during their introduction into the melt (TRL 4–5)	+ Mechanical properties are improved only if uniform distribution of nanoparticles is achieved, with most promising particle additions being Al_2O_3, Y_2O_3 and AlN (TRL 2–3) + Various approaches of introducing nanoparticles to a melt were explored (TRL 2–3) + US processing has been shown to be an efficient way of introduction, de-agglomeration and dispersion of nanoparticles in a melt (TRL 2–3)
Magnesium	+ SiC acts as a strong grain refiner in Zn-free Al-bearing alloys upon US processing (TRL 3–4) + Al-B-C master alloy made with US processing is efficient as grain refiner in AZ91 (TRL 2–3) + Bi addition appears an effective grain refiner in pure Mg and AZ31 (TRL 2–3)	+ AlN and Al_2O_3(AlOOH) additions using US processing appear effective in enhancing creep resistance of Elektron 21 (TRL 4) + AlN acts as a strong grain refiner in Zn-free Al-bearing alloys upon US processing (TRL 3–4) + AlN containing AM60 shows good recyclability with only small loss in grain refinement and tensile strength (TRL 3–4) + SiC addition to AM30/CaO through melt shearing, twin-roll casting and rolling yields more isotropic mechanical response (TRL 4)

Figure A.10 The main favourable results from the material and process research

As for magnesium nanocomposites, figure A.11 summarises the results of initial screening tests for the alloy Elektron21 with some distinct (nano)-particle additions.[13] The images at the left-hand side reveal no substantial differences in the microstructures between the monolithic alloy (top) and the two composites (middle and bottom). Noting that the included particles are smaller than the resolution of these micrographs, it however also

[13] Sillekens W.H., Jarvis D.J., Vorozhtsov A., Bojarevics V., Badini C.F., Pavese M., Terzi S., Salvo L., Katsarou L., Dieringa H.; "The ExoMet project: EU/ESA research on high-performance light-metal alloys and nanocomposites"; *Metallurgical and Materials Transactions A* 45 (2014): 3349–3361 (DOI 10.1007/s11661-014-2321-2)

means that their influence on average grain size (AGS) in these cases is negligible. The graph at the right-hand side shows that the creep resistance of the composite materials has been improved over the monolithic alloy: based on the indicated average creep rates $\acute{\varepsilon}_s$ accompanying the curves, it has increased by a factor of roughly three. In this respect it needs to be remarked that the conditions as imposed during the creep tests – a temperature of 240 °C and a stress of 140 MPa – have been quite harsh; actually, the recommended maximum service temperature for the reference alloy is 200 °C. In subsequent investigations, creep response was further investigated and characterised as shown in figure A.12.[14] In this case, the Elektron21/AlN nanocomposite material shows a considerably lower creep rate as compared to the monolithic alloy for all imposed stresses, although the differences decrease with increasing stress.

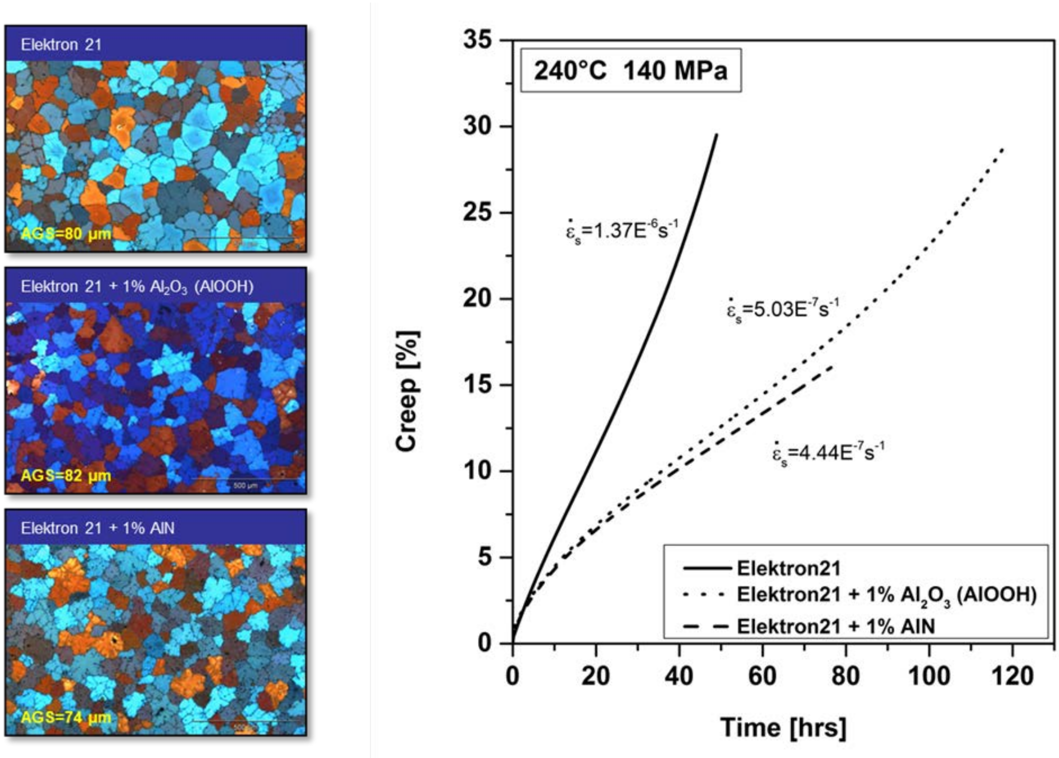


Figure A.11 *Light-optical microscopy images (left) and compression creep response (right) of magnesium alloy Elektron21 and its (nano)-composites including a nominal 1 wt.% aluminum nitride and aluminum oxide/hydroxide with 20–30 nm and 0.5–1.0 µm average particle size, respectively*

[14] Katsarou L., Mounib M., Lefebvre W., Dieringa H.; "Magnesium alloy Elektron21 reinforced with AlN: Processing, microstructure and compression creep response"; *20th International Conference on Composite Materials (ICCM20)*; July 19–24, 2015; Copenhagen (DK)

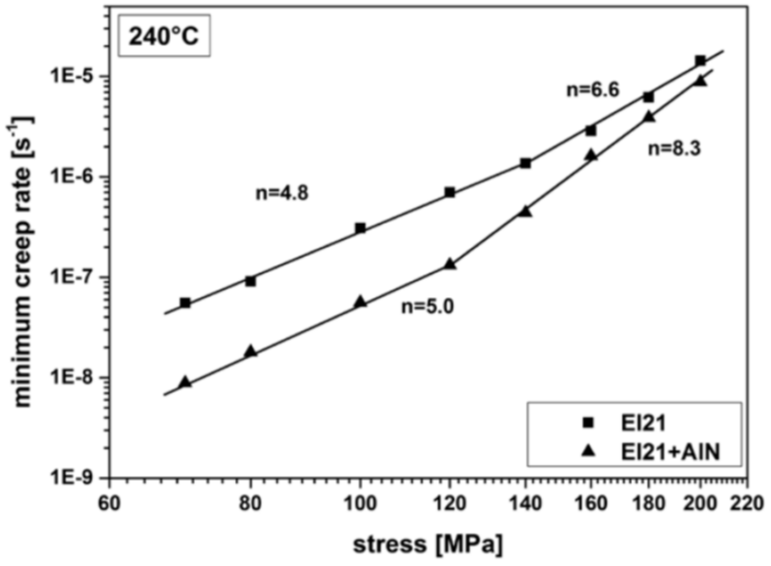


Figure A.12 *Double logarithmic plot of minimum compression creep rate versus applied stress for magnesium alloy Elektron21 and the Elektron21/AlN nanocomposite material*

As for magnesium grain refinement, figure A.13 shows some results for the alloy AM60 without and with a nominal 1 wt.% of SiC and AlN nanoparticles.[15] The casting procedure included an ultrasonic melt treatment for the de-agglomertaion and dispersion of the particles. Particle addition in both cases resulted in an exceptional grain refinement with an associated improvement in room-temperature mechanical properties. For the AM60/SiC composite material, increases of +60% for the yield stress, +87% for the ultimate tensile strength, and +79% for the elongation were noted versus the monolithic alloy. For the AM60/AlN composite material, these enhancements were even more pronounced: +103%, +115%, and +143%, respectively.

[15] Unpublished results

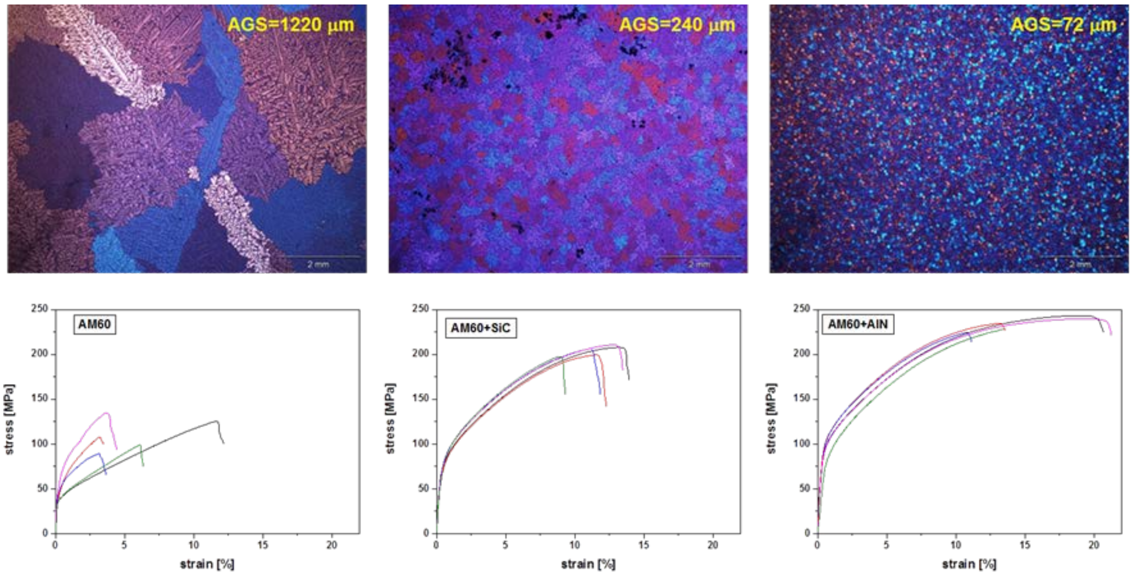


Figure A.13 *Microstructures and tensile-testing results of as-cast magnesium alloy AM60 (left) and its AM60/SiC (middle) and AM60/AlN (right) nanocomposites*

As for aluminium grain refinement, some initial works targeted a confirmation of the favourable effect of using an external field for particle de-agglomeration and dispersion. Figure A.14 illustrates the influence of applying mechanical stirring and ultrasonic treatment during master-alloy preparation using the classical grain-refining agent TiB_2.[16] This study amongst others demonstrated that ultrasonic treatment in particular enhances the uniform distribution of the particles and by that improves the grain-refining efficiency in the casting. That in turn implies that either lower grain-refiner addition levels are required, or that even finer microstructures (with their associated benefits) can be obtained by maintaining the same addition level.

On the same topic, figure A.15 shows a result for the explorative development of oxide-based (and more in particular for $MgAl_2O_4$- or spinel-based) grain-refiner master alloys.[17] The master alloy in this case in synthesised by the addition of SiO_2 to an Al2Mg alloy melt as a solid oxygen source for *in-situ* $MgAl_2O_4$ formation, with mechanical stirring and ultrasonication being applied to facilitate the reaction and the dispersion of the formed spinel particles. Adding the obtained master alloy in small quantities to pure aluminium, Al1Mg and Al4Cu as well as to the shown A357 alloy proved successful in substantially reducing the grain size in the obtained castings.

[16] Djan E., Vadakke Madam S., Hari Babu N., Tamayo-Ariztondo J., Eskin D.G., Fan Z.; "Processing of metal matrix composites under external fields and their application as grain refiner"; *Light Metals 2014*; Wiley–TMS, Hoboken NJ (2014): 1401–1404 (DOI 10.1002/9781118888438.ch234)

[17] Sreekumar V.M., Hari Babu N., Eskin D.G., Fan Z.; "Development of new oxide based master alloys and their grain refinement potency in aluminium alloys"; *Materials Science Forum* 828–829 (2015): 23–28 (DOI 10.4028/www.scientific.net/MSF.828-829.23)

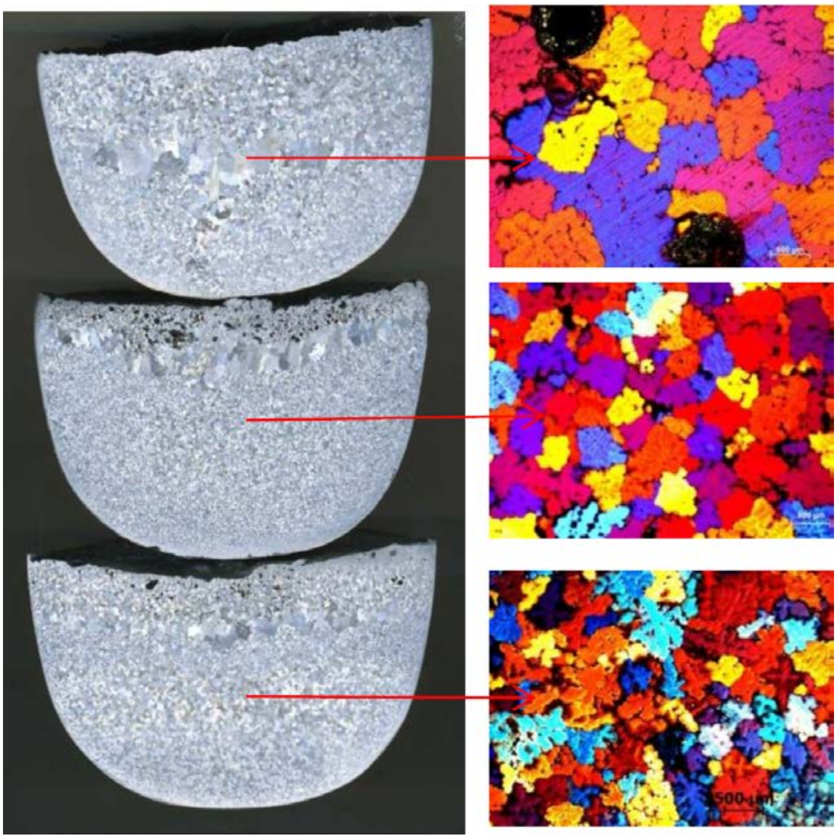


Figure A.14 *Grain-refinement effect of an Al-Mg-Ti/TiB_2 composite master alloy (1%) added to an Al-3% Mg-0.01% Ti alloy: no additions (top), addition of a master alloy made using mechanical stirring (middle), and addition of a master alloy made using ultrasonication (bottom)*

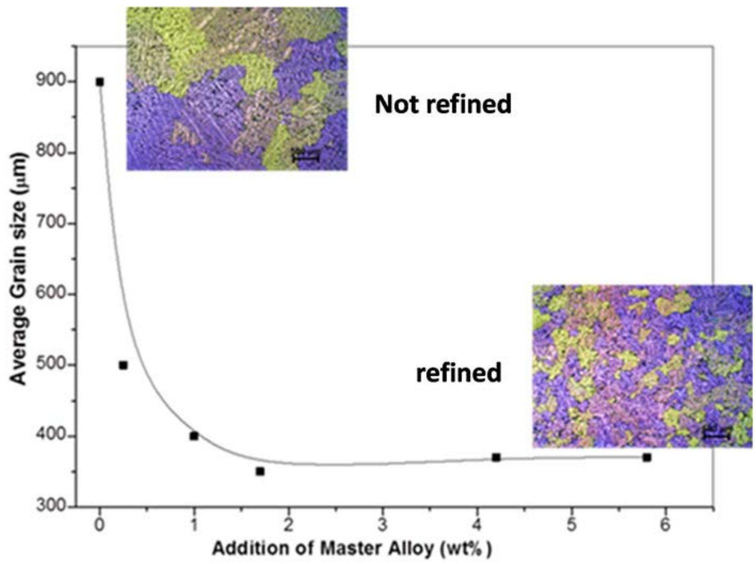


Figure A.15 *Average grain size versus addition of $MgAl_2O_4$ master alloy in aluminium alloy A357 (microstructures are in the same magnification, size bar: 500 μm)*

Another promising development appeared to be the manufacturing of dense and concentrated master alloys containing nano-sized Al_2O_3 by a technique called shockwave compaction. Figure A.16 summarises some of the results.[18] Shockwave compaction involves – as the name suggests – the consolidation of (in this case) Al and Al_2O_3 particles that are contained in a thin-walled aluminium tube by placing this tube in a blast chamber and then initiating a detonation that dynamically compresses the tube. Resulting Al/Al_2O_3 composite material (with 10 wt.% alumina contents) has full density and by that is convenient for metallurgical handling. It is found that the use of such a master alloy facilitates the introduction into an aluminium-alloy melt. An ultrasonic treatment performed during and after the introduction of the master alloy further leads to uniform distribution of the particles and eventually to a notable improvement in strength and ductility.

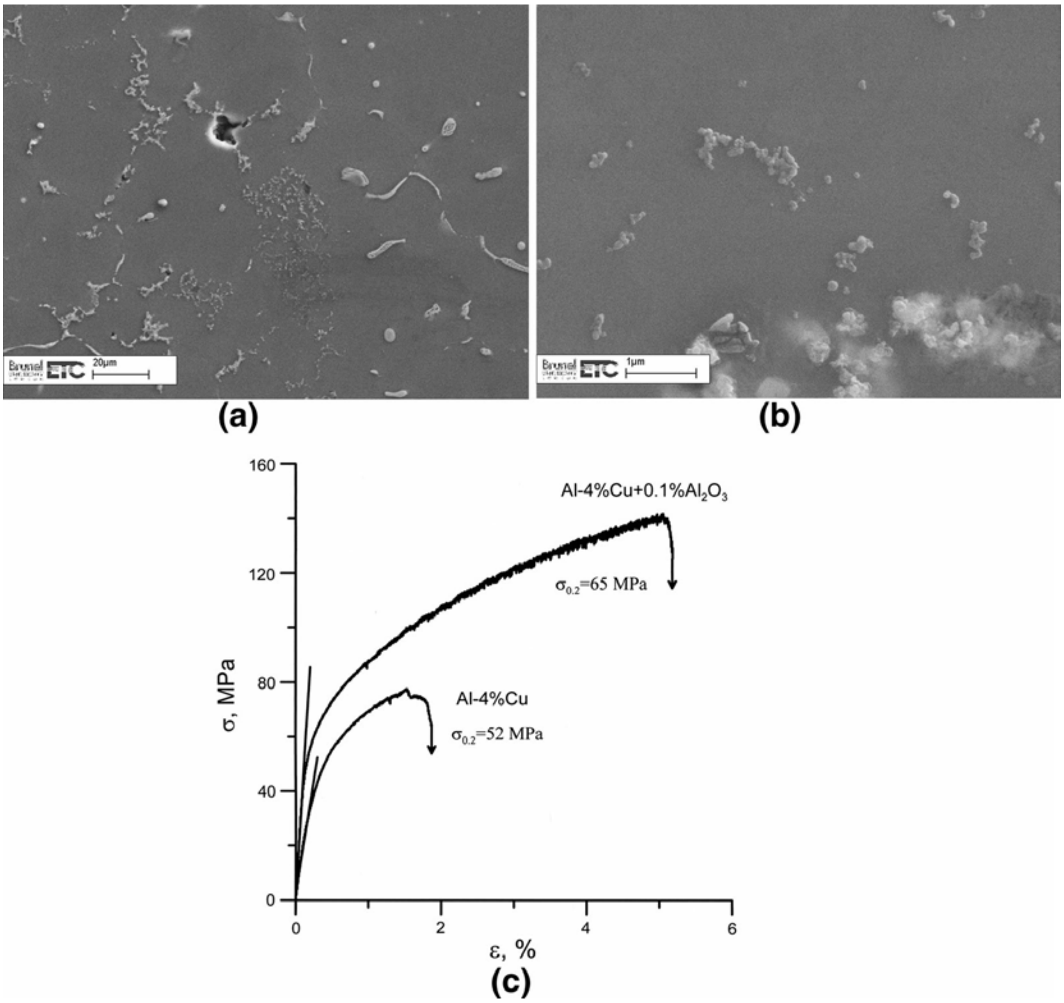


Figure A.16 *SEM images of the as-cast Al4Cu/0.1Al_2O_3 nanocomposite material (a, b), and stress-strain curves of this material in comparison with the matrix material (c)*

[18] Vorozhtsov S.A., Eskin D.G., Tamayo J., Vorozhtsov A.B., Promakhov V.V., Averin A.A., Khrustalyov A.P.; "The application of external fields to the manufacturing of novel dense composite master alloys and aluminum-based nanocomposites"; *Metallurgical and Materials Transactions A* 46 (2015): 2870–2875 (DOI 10.1007/s11661-015-2850-3)

As for grain-refiner and MMNC processing, a patent was granted on a device that enables contactless induction of high-frequency vibrations in a metal melt contained in a crucible.[19] Figure A.17 shows an embodiment. This equipment – which is descriptively called the "top-coil arrangement" or "contactless sonotrode" – involves the use of multiple electromagnetic coils that are designed in a sense that intense stirring of the melt and possibly cavitation in the melt can result, with the obvious purpose of effectively and efficiently de-agglomerating and dispersing particles in it.

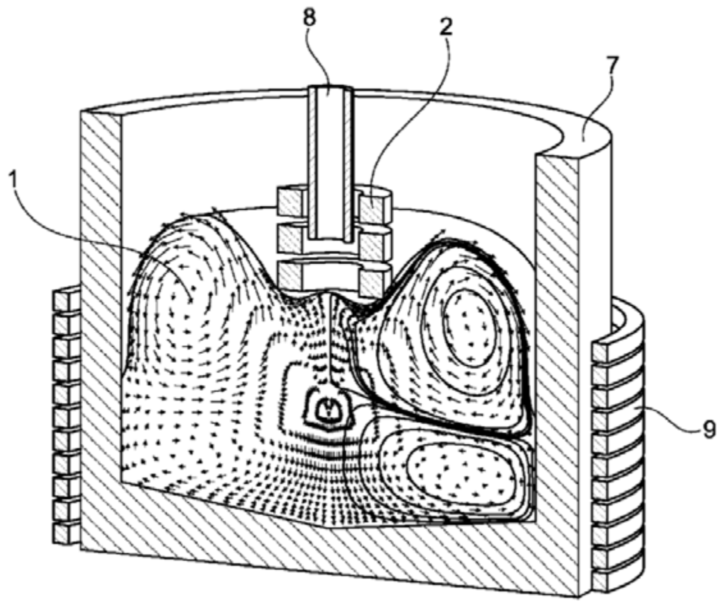


Figure A.17 *Schematic of the top-coil arrangement*

Simulation tools developed within the project were used to predict the flow and other physics in order to conceive and optimise such an arrangement; an example of that is reproduced in figure A.18.[20] In the presented concept, the top coil and the coil surrounding the crucible are tuned to induce high acoustic pressures in the melt and simultaneously provide for intense stirring so as to distribute the effect to treat larger volumes of material. The calculations of sound, flow, and electromagnetic fields suggest that large pressure amplitudes leading to cavitation may be achievable with this method, which would provide for a highly effective sonotrode. As noted this sonotrode concept is contactless, so that it could be used for reactive and high-temperature melts, avoids contamination of the melt and can fit in with existing induction-coil arrangements.

[19] Jarvis D.J., Pericleous K., Bojarevics V., Lehnert C.; "Manufacturing of a metal component or a metal matrix composite component involving contactless indusion of high-frequency vibrations"; patent WO 2015/028065 A1 (2015)

[20] Bojarevics V., Djambazov G.S., Pericleous K.A.; "Contactless ultrasound generation in a crucible"; *Metallurgical and Materials Transactions A* 46 (2015): 2884–2892 (DOI 10.1007/s11661-015-2824-5)

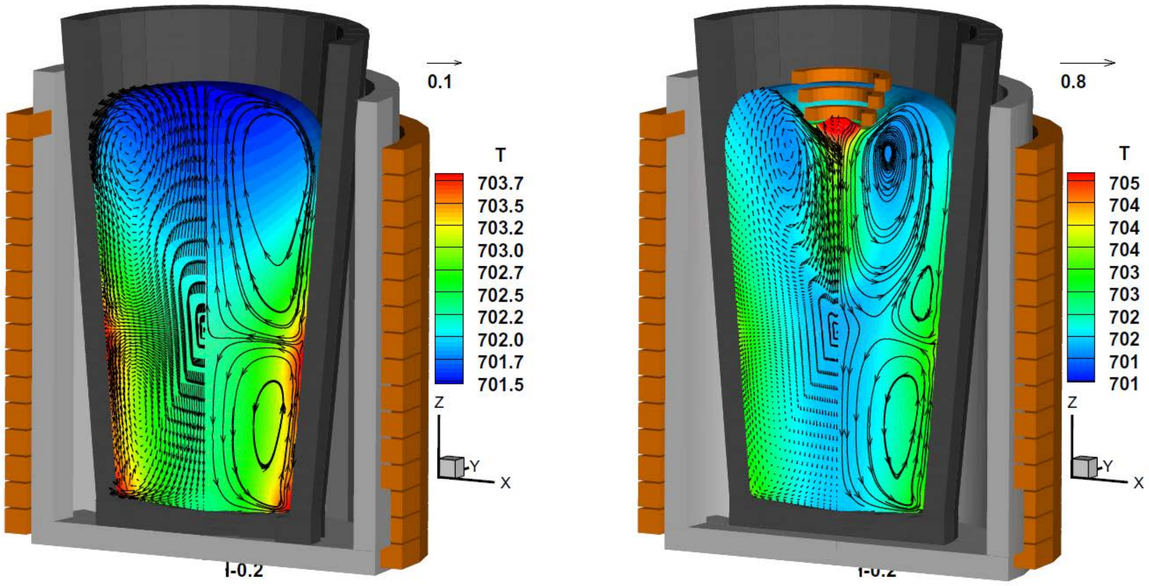
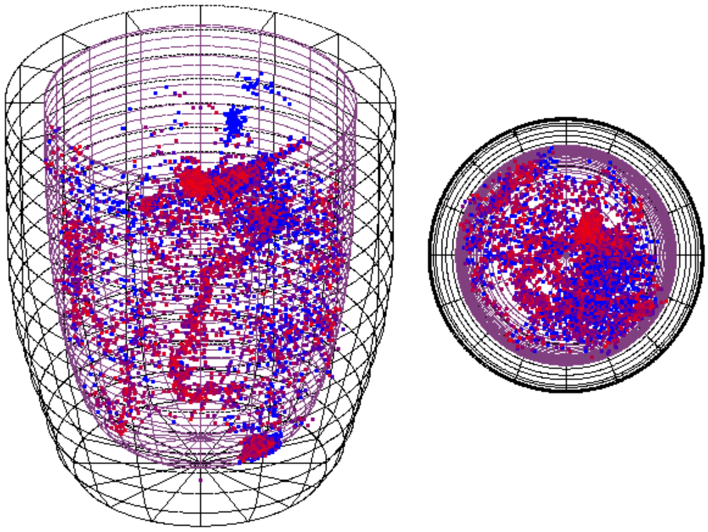


Figure A.18 *Two alternative arrangements for melt stirring and vibration of the melt, showing the computed velocity and temperature fields: traditional arrangement with a cylindrical coil, operating at 2 kHz and 1.6 kA (left), and the new concept of the immersed top coil, operating at 10 kHz (right)*

Based on such considerations, a pilot-scale experimental top-coil facility was realised and tested, the latter amongst others by using positron-emission particle tracking experiments to trace particles in the melt. An example of that is presented in figure A.19.[21] Such a particle-tracking experiment consists of adding a 200 μm radioactive alumina particle to an aluminium-alloy melt and then follow its location over time with bismuth-germanate detectors surrounding the crucible. The example shows that the particle travels through most of the melt's volume, although it seems that there are some favoured locations of residence as well.

[21] Bojarevics V., Djambazov G., Lebon G.S.B., Manoylov A., Pericleous K.A., Burnard D.J., Griffiths W.D., Shevchenko D.; "Dispersion of nano particles in melts using electromagnetic wave action"; *VII European Congress on Computational Methods in Applied Sciences and Engineering* (ECCOMAS Congress 2016); June 5–10, 2016; Crete (GR)



<u>*Figure A.19*</u> *Top-coil experiment: positions occupied by particles at different times (aluminium alloy A357, coil AC frequency 8.82 kHz)*

A.4 Impact, dissemination, exploitation

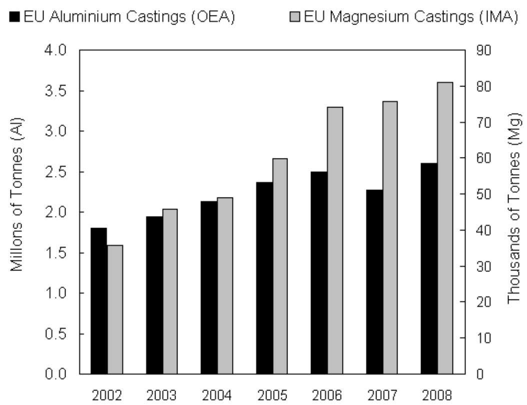
Potential impact

EC-policy areas where impact is expected from the project – as specified in the original call text – are addressed below.

- **Transforming traditional industry**. The European casting industry is already starting to transform itself from a traditional area of manufacturing towards high-tech processing with automation, high quality and novelty. All of this is aimed at controlling the microstructure and properties of new castings, as well as producing high-quality components quickly and affordably. Swiftly adopting the new field-enabled innovations from ExoMet would allow these casting companies and alloy producers to outperform American and Asian manufacturers, while of course benefitting end-user businesses across a range of EU commercial sectors – automotive, powertrain, aeronautic, space, electro-technical etc. One of the strengths of carrying out solidification-based research of this type is the added value it represents for the wrought-metallurgy sector that produces extruded profiles, wire and rolled products. Since wrought billet is initially produced via casting, the new thermally-stable micro- and nanostructures have important knock-on implications for final properties – thus helping shape an industrial transformation towards high-tech wrought processing. Trade figures show that the EU consumption of aluminium and magnesium castings remains high, see <u>figure A.20</u>, with very impressive growth rates especially for magnesium at 15% p.a. in recent years. In total, the light-alloy casting industry in the EU is worth >55 billion € p.a., and the wrought product market is of a similar order. The growth in aluminium wrought products over recent years has been particularly strong, and now amounts to over 8 million tonnes per year. In fact, Europe has recently become a net exporter of wrought aluminium and is also the leading recycler of light alloys.[22] Against this growing, multi-billion € market,

[22] Source: *European Aluminium Association*

there is considerable room for further growth by enhancing alloy products – for both domestic and export markets. The increased applicability of novel grain-refined light alloys and dispersion-strengthened nanocomposites is a key economic driver here. Thus, the economic impact is expected to be very high. A estimate of 10% market penetration for ExoMet alloys/MMNCs would represent over 10 billion € p.a., in the EU alone. The overall benefit to the supply chain and its end users will be enhanced economic competitiveness in the global marketplace. In turn, this will lead to increased stability in the manufacturing sector and EU job creation in the area of sustainable, net-shape production of high-value recyclable metal components.



<u>Figure A.20</u> *Trade figures for EU consumption of aluminium and magnesium cast products (left) and aluminium wrought products (right)*

- **Fostering scale-intensive and specialised suppliers industry**. ExoMet technologies are scalable from an industrial standpoint; in most cases, only minor adaptations to existing factory facilities are needed. The business associated with specialised suppliers of external-field equipment (electromagnetic, ultrasound, liquid shearing) will be strongly promoted. ALD Vacuum Technologies is one of the key industrial partners that will design, test, commission and commercialise such external-field equipment, in collaboration with the metallurgical companies and foundries. Being able to incorporate ExoMet innovations into their product portfolio would allow equipment makers to generate new global business. Furthermore, businesses like KBM supplying specialised grain-refiners, master alloys and/or nanoparticle powders have a lot to gain from such a research project. These commercial partners are eager to see new scalable developments in this area, as well as make a shift towards more nanotechnology- and knowledge-based metal products. The existing EU suppliers of nanoparticle powders may also benefit, in order to broaden the powder-supply chain that could eventually reach several 10,000s of tonnes p.a. Grain-refiner and MMNC master-alloy production is also an example of scale-intensive supply. It should be noted that software packages are also part of a specialised supplier industry and, in Europe, the key engineering-software group ESI is involved and will take on the task of integrating the various solidification-simulation tools into a commercial and sellable deliverable.
- **Promoting science-based industry**. There is no doubt that the competitiveness of the manufacturing sector is critical to the long-term economic prosperity and growth of developed countries. However, the competition among nations to create and maintain a

vibrant manufacturing sector is now fierce – especially due to the emergence of markets in Asia and South America. A study of global manufacturing has concluded that all European countries are generally considered less competitive than China, India, Korea, USA, Japan and Brazil; see also figure A.21.[23] As a result, it is imperative to focus attention on novel, sustainable and science-based forms of manufacturing that can provide a competitive edge and boost sales and exports in favour of European industry. To this end, ExoMet will be an excellent demonstration of science-based high-value business in Europe, by delivering new processing routes and improved properties in real components. Moreover, the scientific developments from the project will be the foundation for industrial advancement in this field in the coming years. The emphasis on systematic nucleation, solidification and recycling studies, process-structure-property maps, comprehensive property testing, *in-situ* dynamic imaging, advanced materials characterisation techniques, computational metallurgy and scientific reference samples will bring considerable benefit to the industrial partners – both manufacturing and end users. In terms of human resources, the recruitment and training of 25 PhDs and postdoctoral researchers in ExoMet has increased the EU pool of highly-competent metallurgists with the skills to become the next generation of academic and industrial R&D leaders. This will address today’s skills gap in metallurgy. In summary, the new science performed here will provide opportunities for the metals industry to remain competitive in existing markets and to allow new global markets to be developed, where the strength and weight advantages of light alloys and nanocomposite materials will be advantageous.

Current competitiveness

Rank	Country	Index score (10=High 1=Low)
1	China	10.00
2	India	8.15
3	Republic of Korea	6.79
4	United States of America	5.84
5	Brazil	5.41
6	Japan	5.11
7	Mexico	4.84
8	Germany	4.80
9	Singapore	4.69
10	Poland	4.49
11	Czech Republic	4.38
12	Thailand	4.17
13	Canada	4.11
14	Switzerland	3.07
15	Australia	3.07
16	Netherlands	2.90
17	United Kingdom	2.82
18	Ireland	2.78
19	Spain	2.67
20	Russia	2.58
21	Italy	2.42
22	South Africa	2.28
23	France	1.70

Competitiveness in 5 years

Rank	Country	Index score (10=High 1=Low)
1	China	10.00
2	India	9.01
3	Republic of Korea	6.53
4	Brazil	6.32
5	United States of America	5.38
6	Mexico	4.84
7	Japan	4.74
8	Germany	4.53
9	Poland	4.52
10	Thailand	4.35
11	Singapore	4.30
12	Czech Republic	3.95
13	Canada	3.71
14	Russia	3.47
15	Australia	3.40
16	Spain	2.63
17	Netherlands	2.63
18	Switzerland	2.62
19	South Africa	2.52
20	United Kingdom	2.51
21	Ireland	2.43
22	Italy	2.37
23	France	1.92

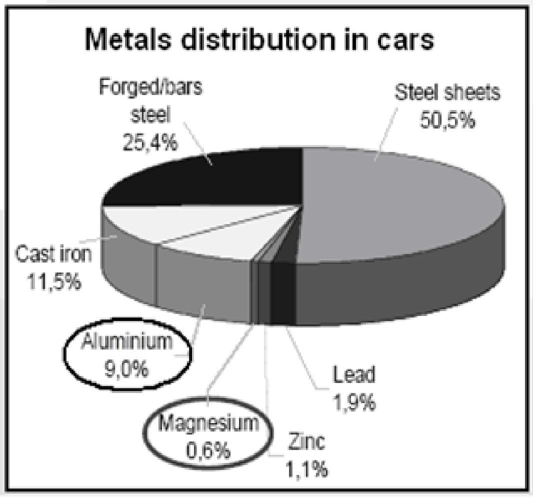
Figure A.21 *Manufacturing competitive index, by country*

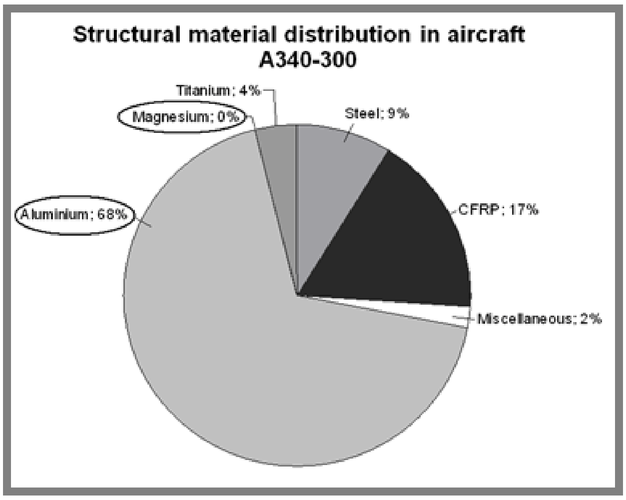
[23] *Global Manufacturing Competitiveness Index*; Deloitte (June 2010)

- **Towards a sustainable supply industry**. It is felt that the supply chain in ExoMet is comprehensively covered. Major alloy and equipment producers have been involved, including those companies making special grain-refining master alloys and nanoparticles. The casting companies will supply lightweight structural components with enhanced properties to the end users producing cars, trucks, buses, aeroplanes, helicopters, spacecraft and electrical sub-systems. The final part of the chain is metal recycling, which will also be addressed by a number of partners. The whole chain was supported by sophisticated modelling tools, integrated by ESI Group. The project's IPR strategy will help introduce long-term sustainability. By closely analysing international competition and developing their own IPR, the partners will be in a strong position to protect the most commercially-viable process improvements and light-alloy compositions for the next 20 years. Promoting standardisation of these new materials will also have a lasting impact on the industrial take-up of ExoMet technology. The sustainability of the supply chain will also be analysed and documented by a life-cycle analysis, which will help identify the most energy-saving and environmentally-friendly processes.
- **Substantial enhancement of material properties**. The expected improvements for light alloys and their nanocomposite materials are 25–50% increases in tensile strength and ductility, operating temperatures in the range 300–350 °C, as well as other benefits for other material properties, like fatigue, fracture toughness, tuneable coefficient of thermal expansion or specific electrical conductivity in aluminium composites. Producing lightweight materials with this range of enhancement will allow new design choices and new components to be made, with increased safety margins – hence offering better consumer safety than before. When analysing the material distribution in present-day vehicles, it is quite apparent that only a small fraction of aluminium and magnesium is used in European cars (9.6 wt.% combined), while in aircraft aluminium is widely used (68 wt.%) and magnesium not at all. The two pie-charts in figure A.22 depict these material distributions. ExoMet will therefore have a high impact in promoting novel melt processing and delivering a new class of light materials for numerous transport applications. The property enhancements, once correctly transferred to real components, will lead to further weight saving in vehicles in the coming years. This will directly support IPCC recommendations[24], and ACARE targets (of 50% less CO_2 from aircraft by 2020), as well as EC Regulation[25] (that has set a 130 g CO_2/km emission standard for new passenger car fleets made during 2012–2015). In the space sector, there are also strong reasons to reduce mass. This weight-saving strategy is very much motivated by techno-economic reasons. For instance, the commercial cost of entering a payload into low-earth orbit can be as high as 30,000 €/kg and even more expensive for scientific missions to the Moon, Mars and deep space. By reducing the mass of rocket structures, as well as the payload satellite structures themselves, it is possible to make large cost and efficiency savings. To put things into economic perspective, a payload-mass saving of about 600 kg in the space sector would represent the total value of the ExoMet project. Since public taxpayer funds are very often used for space missions, these mass and cost reductions are financially significant. Hence, for space, the development of ExoMet materials and processes are also of high impact. This supports the recent EU Space Strategy for the European Union[26], including the aim to "support

[24] *IPCC 4th Assessment Report* (2007)
[25] EC Regulation No.443/2009
[26] EC COM(2011) 152 (April 2011)

R&D to increase European technological non-dependence in space and ensure that innovation in this field will be of benefit to non-space sectors and citizens". As a final remark about property enhancements, it should be appreciated that there are often knock-on or secondary weight savings for automotive, aircraft and spacecraft that can be of the order 10–15%. This is because a weight saving for a given component (e.g., a lighter car engine) often confers a weight saving on to the structure holding that component (e.g., a lighter engine chassis). A downward spiral in weight is thus achievable, especially using MMNCs, while still preserving structural integrity and safety.





<u>*Figure A.22*</u> *Light alloys and their present usage in automotive (left) and aircraft structures (right)*

- **Modest implementation costs for production**. The costs of implementing external-field processing in the master-alloy and foundry sectors will be relatively modest. The estimated costs for adapting existing crucibles and casting equipment and installing external-field capabilities (i.e., electromagnetic, ultrasound or liquid shearing) would range from 50–200 k€. These costs are considered to be within the realms of commercial reality. All industrial manufacturing partners are prepared to make private company investments, during and after the project, to deliver new capabilities and end-user components. On the materials' side, the additional costs of adding novel grain-refiner particles or reinforcing nanoparticles are also considered reasonable, with the extra premiums lying somewhere between 10–20% on top of conventional alloy costs. Moreover, using endogenous oxide particles that are already present in the liquid melt and shearing them into finer particles is clearly a very cost-effective way of achieving better properties. Industrially, these strategies are fully acceptable since the performance advantages are expected to be 50% higher. Add to this, the potential for secondary weight-saving of 10–15%. In summary, the cost-benefit analysis is sound and this will ensure high impact.
- **Environmental sustainability assessment**. ExoMet placed a special emphasis on process solutions and new light alloys that are more sustainable than the present-day capabilities. This sustainable approach is of high strategic value and fits well with a

decade of European policy in this area.[27] As well as being better performing, the new processes and alloys should also have a reduced environmental impact. This implies that the external-field processes have relatively low energy levels (in kWh) and are efficient in their energy conversion. Raw material usage will need to be significantly reduced too, and this project aimed at 20% reduction in scrap-rate in the foundry. Meanwhile the light alloys and nanocomposite materials shall contain no toxic components and will need to be highly recyclable. Combining computer modelling of process, component performance and durability will be of great value here. An important consideration for the analysis of environmental sustainability is the recent EU ban on sulphur hexafluoride SF_6 (a very potent greenhouse gas used in the foundry sector as a cover gas) and the relative merits of other replacement gases. In addition, it is worth recalling that the lightweight alloys and nanocomposite materials being investigated here will have a major impact on weight saving in the transport sector. The environmental benefits of reducing a component's weight (e.g., by 30% when using light alloys cf. steel) are critically important, since they can help lower fuel consumption, oil dependency and CO_2 emissions, in line with international climate-change policy, as well as the EU's Strategic Energy Technology Plan[28]. In the context of environmental sustainability, it is believed that this material/manufacturing project could play a highly-enabling role in support of the Europe2020 Strategy, as announced by the EC on 3rd March 2010, namely: "to conserve natural resources and raw materials, support the shift towards a low-carbon economy, increase the use of renewable energy sources, modernise our transport sector and promote energy efficiency".

- **Support to European policy development**. The ExoMet project will make a strong and compelling link between advanced research, industrial capability and societal challenges. The project could thus have a direct and lasting impact on the following EU and international policies: (1) Europe2020 Strategy – towards a resource-efficient Europe, (2) European Innovation Union, for 2020, (3) Göteborg Sustainability Declaration, 2001, (4) UN Kyoto Protocol for Climate Change, 1997, plus successor policy in 2011, (5) EU Strategic Energy Technology (SET) Plan, 2009, (6) EU Sustainable Materials Management, 2010, (7) Critical Raw Materials for the EU, 2010, (8) EU Economic Recovery Plan, 2010–2011, and (9) individual policies of EU Technology Platforms, principally EUMAT, ManuFuture, ACARE, ESTP, EUCAR and NanoFuture.
- **European and multi-disciplinary dimension**. Considering the broad range of expertise and capabilities required to fulfil the objectives of ExoMet, the multi-national and multi-sectoral dimension of the team has evolved very naturally. In total, twelve countries were represented (CH, DE, ES, FR, HU, IT, NL, NO, SE, UK – plus RU, AU). This pan-continental team of R&D experts and world-leading end-user industries is a unique feature of ExoMet. Great efforts have been made to assemble a well-balanced and multi-disciplinary team of established R&D leaders. The team comprised many European experts in the field of physical metallurgy, external-field processing, casting, solidification, aluminium- and magnesium-alloy development, metal-matrix composites, computational fluid dynamics, magneto-hydrodynamics, powder production, advanced characterisation, modelling, property testing, metrology, standardisation, health and safety, recycling, as well as automotive, aerospace and electrical engineering. The convergence of all these research areas into one single project is truly unique – not only

[27] Göteborg Declaration 2001; Europe2020 Strategy (March 2010)
[28] EC COM(2009) 519 (October 2009)

in Europe, but also in the world. ExoMet will also capitalise on the extensive experience of ESA in the management of large-scale EC projects (e.g., IMPRESS Integrated Project in FP6).

- **External factors**. There are no specific factors outside the consortium that would seriously affect the expected impact. The initial patent search and knowledge of 'prior art' has revealed that there are no IPR 'show-stoppers'. Likewise, there are no future EU or international policies that would nullify the rationale of ExoMet – on the contrary the UN Climate Change Conference in Durban in 2011 will no doubt bring a considerable boost to the field of weight-saving and low-carbon technology.[29] The fact that the UN Intergovernmental Panel on Climate Change has already explicitly mentioned the need to use lightweight aluminium and magnesium in its 4th Assessment Report on Transport & Infrastructure in 2007 shows that there is a positive external factor in favour of such research. Furthermore, the new EC Strategic Energy Technologies Plan should also have a very positive effect within EU circles and will trigger considerable R&D investment in 2010–2020, particularly for new lightweight materials and processes that contribute to the decarbonisation of Europe. One thing to highlight here is the fact that this plan openly recognises the activities of ESA, namely: "the expertise of other sectors can also be harnessed to support EU energy policy, for instance the European Space Agency."
- **National and international research activities**. The research activities around the world have been properly taken into account in the formation of ExoMet. Within the EC R&D programmes very few metallurgy projects exist (and there are none on casting, solidification, light-alloy development, or MMNCs). At national level only a handful of large-scale activities are noteworthy. In the UK, a new EPRSC-funded centre called LiME has been established with a focus on nucleation solidification science. In Germany various DfG "Schwerpunkt" projects have previously tackled certain aspects of cast and wrought light alloys – one worth highlighting is *InnoMagTec* on magnesium alloys. However, the major competition is coming from US, Japanese and Chinese R&D programmes (the latter particularly dominating magnesium research and patenting in recent years). The world-leading research infrastructure in Europe, relating to material characterisation using neutron and X-ray sources, has also be exploited in the context of the EIROforum Charter. A specific trilateral Memorandum of Understanding (MoU) signed by the Directors of ESA, ESRF and ILL has encouraged the use of beam-lines for the purposes of projects such as ExoMet. Furthermore, dedicated beam-time for ExoMet has also been made available at the Diamond Light Source UK, via a special agreement with the University of Manchester. Overall, the pooling together of ESRF, ILL and Diamond resources plus ESA's microgravity toolbox, represented an outstanding European opportunity to characterise light alloys and nanocomposite materials.

Main dissemination activities

The track records of all public-relation and dissemination efforts for the ExoMet project includes more than 130 distinct entries on dissemination activities, a number that is expected to further increase somewhat still (with several publications in the pipeline yet). About a third of these are of an archival nature (theses, journal papers), representing an important part of the scientific findings. Another rough third relates to more interactive exchanges with the scientific world (specifically conference presentations, published in part

[29] UN/COP17/2011

also in their proceedings), while the final rough third relates to a variety of other activities including those for a wider audience (such as guest lectures for students, internet video lectures, and trade-fair participations). Figure A.23 shows the overall publications output upon closing the project.

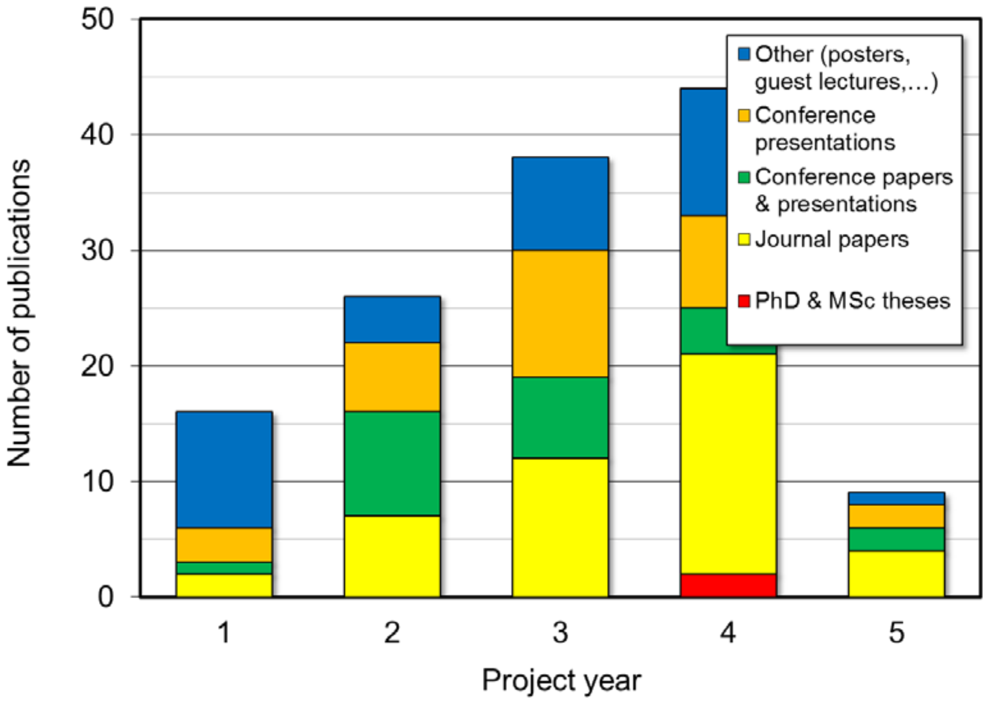


Figure A.23 *Publications output, distinguishing between different publication types*

One specific action to disseminate project contents and findings to the public in general, and to school and university students in particular, was to record science lectures given by early-career researchers from the project. Title, presenters and URLs of these online videos are as follows.

- **Metal-matrix composites and their electromagnetic processing** – Mariano Garrido; *Université Grenoble Alpes*, Grenoble, France (https://www.youtube.com/watch?v=EeZMuPTruXs).
- **Microwave heating technology** – Naiara Azurmendi Apalategui; *Tecnalia*, San Sebastián, Spain (https://www.youtube.com/watch?v=nNs_8ytydwU).
- **X-ray microscopy of metallic alloys** – Daniele Casari; *NTNU Norges Teknisk-Naturvitenskapelige Universitet*, Trondheim, Norway (https://www.youtube.com/watch?v=lvV_Uqx4znU).

Exploitation of results

In order to prepare for the future use of project results, some supporting analyses were done with respect to the implementation of the developed materials, processes and products in industrial practice. As the production, handling and processing of micro- and notably nano-sized particles may affect working procedures, a health and safety analysis was done early on during the project and complemented later on with actual particle-emission measurements during the casting of metal-matrix nanocomposites. A life-cycle analysis was done for selected prototyping components to assess environmental impact and compare this for the existing and novel product designs. Further, a cost-benefit analysis was done for some prototyping components to evaluate financial implications. Finally, an IPR and patent mapping analysis was done at the start of the project and repeated at the end of the project to include the more recent developments.

Towards the end of the project, the main project results with possible exploitation potential (so-called Key Exploitable Results or KERs) were identified as listed in table A.1.

Table A.1 Key Exploitable Results from the project

#	DESCRIPTION
1	Novel grain-refining master alloys for aluminium, produced by melt treatment with external fields (e.g., ultrasound)
2	Elektron21-based nanocomposite materials with enhanced creep resistance
3	AM50/AM60-based grain-refined materials with enhanced mechanical performance
4	Electro-magnetic top-coil arrangement in conjunction with an inductive melting furnace for (in-situ) synthesis of master alloys and (nano)-composite materials
5	Electro-magnetic flow-nozzle arrangement for in-line de-agglomeration and dispersion of grain-refining particles in aluminium master alloys
6	Theoretical/numerical tools for describing mixing, dispersion and de-agglomeration of particles in a metal melt under the influence of electro-magnetic fields
7	Numerical models, describing the mixing of micro- and nanoparticles in a metal melt
8	Theoretical/numerical tools for describing microstructure formation in magnesium-based composite materials
9	Aluminium- and magnesium-based cast components with enhanced performance
10	Scientific publications and other dissemination activities
11	Methodology for studying plasticity micromechanics of magnesium alloys and other anisotropic metals

Further to that, work was done to outline the perspectives for future research and developments on light alloys and liquid-metal engineering. The scope for this so-called "technology roadmap" is the implementation of the ExoMet outcome with a time horizon of 5–10 years. Distinguishing between the two investigated light metals (aluminium and magnesium) and the two explored development tracks (grain refinement and metal-matrix nanocomposites), this provides for four sub-sets of scenarios to project the way forward. Such scenario then starts with specifying market needs and identifying products that will contribute to meeting these needs, after which the required technology development to bring these products to the market, and finally the implied expertise to support these developments are itemised. Figure A.24 shows an example of such a sub-set of the roadmap.

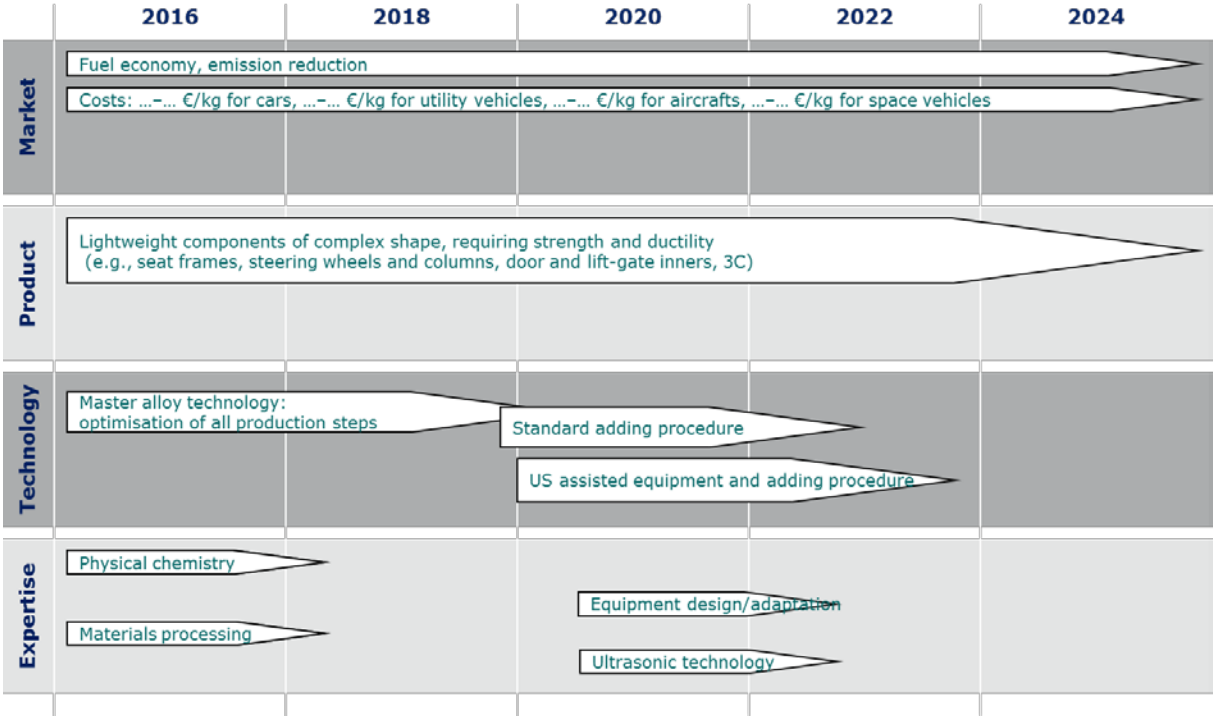


Figure A.24 *Future development of magnesium-based grain-refined materials, processes and products*

In view of exploitation, the protection of knowledge is also of concern. Table A.2 lists the patents stemming from the project.

Table A.2 *Intellectual Property Rights*

#	TYPE OF IP RIGHTS	APPLICATION REFERENCE(S)	SUBJECT OR TITLE OF APPLICATION	APPLICANT(S)
1	Patents	WO 2014/202130 A1	Method of manufacturing a metal matrix composite component by use of a reinforcement preform	European Space Agency
2	Patents	WO 2015/028065 A1	Manufacturing of a metal component or a metal matrix composite component involving contactless induction of high-frequency vibrations	European Space Agency

A.5 Project website and contacts

The URL of the project public website is www.exomet-project.eu.

Table A.3 lists the consortium, including the names of the primary contact persons at the involved organisations.

Table A.3 Consortium list

#	FULL NAME; LOCATION	CONTACT NAME(S)	REMARKS
1	European Space Agency – ESTEC; Noordwijk (NL)	SILLEKENS, Wim	Project coordinator
2	AVIO; Torino (IT)		Take-over by #29 as of August 1, 2013
3	Airbus Defence and Space; Münich/Ottobrunn (DE)	HOMBERGSMEIER, Elke	Before: EADS-G
4	Airbus Group; Paris/Suresnes (FR)	SCHUSTER, Dominique	Before: EADS-F
5	Centro Ricerche FIAT; Torino (IT)	PULLINI, Daniele	
6	Volvo Powertrain Corporation; Göthenburg (SE)	BERTILSSON, Ingemar	
7	Precer Group; Karlstad (SE)		Until April 22, 2015
8	Hydro Aluminium; Sunndalsøra (NO)		Until April 23, 2013
9	London & Scandinavian Metallurgical Company; Rotherham (UK)		Until December 10, 2013
10	Brabant Alucast; Oss (NL)	BROEK, Cees van de	
11	ALD Vacuum Technologies; Hanau (DE)	LEHNERT, Christian	
12	ESI Group; Paris (FR)	KÖSER, Ole	
13	Steinbeis Advanced Risk Technologies; Stuttgart (DE)	JOVANOVIĆ, Aleksandar	
14	TECNALIA Corporación Tecnológica; San Sebastián (ES)	AGOTE, Iñigo	
15	Helmholtz-Zentrum Geesthacht; Geesthacht (DE)	DIERINGA, Hajo	
16	Fundación IMDEA Materiales; Madrid (ES)	PÉREZ-PRADO, María Teresa MOLINA-ALDAREGUIA, Jon	
17	Wigner Fizikai Kutatóközpont; Budapest (HU)	GRÁNÁSY, László	
18	Institut Polytechnique de Grenoble; Grenoble (FR)	FAUTRELLE, Yves SALVO, Luc	
19	University of Manchester; Manchester/Harwell (UK)	LEE, Peter	
20	Norges Teknisk-Naturvitenskapelige Universitet; Trondheim (NO)	MATHIESEN, Ragnvald	
21	Université de Rouen; Rouen (FR)	LEFEBVRE, Williams	
22	Brunel University; London (UK)	ESKIN, Dmitry	
23	University of Greenwich; Greenwich (UK)	PERICLEOUS, Koulis	
24	Politecnico di Torino; Turin (IT)	BADINI, Claudio	
25	University of Birmingham; Birmingham (UK)	ADKINS, Nicholas GRIFFITHS, William	
26	Tomsk State University; Tomsk (RU)	VOROZHTSOV, Alexander	
27	The University of Queensland; Brisbane St Lucia (AU)	STJOHN, David	
28	KBM Master Alloys; Oss/Delfzijl (NL)	WIGGEN, Piet van	From April 1, 2014
29	General Electric AVIO		Successor of #2 as of August 1, 2013 Until May 8, 2015

Full contact details of the project scientific coordinator are as follows.

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PART B Use and Dissemination of Foreground

B.1 Dissemination measures

Table B.1 Scientific publications contributed by the consortium members

#	DATE	PUBL. TYPE	AUDIENCE TYPE	SIZE	PART.(S)	REFERENCE*	F/P**
1	11/2012	Journal paper	Computational physics community	N/A	WIGNER	Emmerich H., Löwen H., Wittkowski R., Gruhn T., Tóth G.I., Tegze G., Gránásy L.; "Phase-field crystal models for condensed matter dynamics on atomic length and diffusive time scales: An overview"; *Advances in Physics* 61/6 (2012): 665–743 (DOI 10.1080/00018732.2012.737555)	P
2	03/2013	Contributed presentation and paper	Scientific and industrial materials community	…	UBRUN	Hari Babu N., Fan Z., Eskin D.G.; "Application of external fields to technology of metal-matrix composite materials"; *TMS2013 Annual Meeting Supplemental Proceedings* (2013): 1037–1044 (DOI 10.1002/9781118663547.ch127)	F
3	03/2013	Journal paper	Scientific materials community	N/A	WIGNER	Pusztai T., Rátkai L., Szállás A., Gránásy L.; "Spiraling eutectic dendrites"; *Physical Review E* 87/3 032401 (2013): 1–4 (DOI 10.1103/PhysRevE.87.032401)	P
4	05/2013	Invited presentation	Scientific materials community	~100	ESA	Sillekens W.H., Jarvis D.; "The ExoMet project: EU/ESA research on high-performance light-metal alloys and nano-composites"; *Magnesium Workshop Madrid 2013*; May 21–24, 2013; IMDEA Materials Institute, Madrid (ES)	F
5	05/2013	Contributed presentation	Scientific materials community	~100	IMDEA	Sánchez R., Pérez-Prado T., Segurado J., Gutierrez I., Llorca J., Molina-Aldareguia J.M.; "Measuring the critical resolved shear stresses in Mg and its alloys by instrumented nanoindentation"; *Magnesium Workshop Madrid 2013*; May 21–24, 2013; IMDEA Materials Institute, Madrid (ES)	F
6	07/2013	Contributed presentation	Scientific materials community	…	UniQue, UniMan	Prasad A., Yuan L., Lee P., StJohn D.; "Improvement of the interdependence analytical model through selection of interfacial growth rates during the initial transient"; *Light Metals Technology 2013*; July 24–26, 2013; Old Windsor (UK)	P
7	07/2013	Journal paper	Scientific and industrial materials community	N/A	UniQue, UniMan	Prasad A., Yuan L., Lee P., StJohn D.; "Improvement of the interdependence analytical model through selection of interfacial growth rates during the initial transient"; *Materials Science Forum* 765 (2013): 77–81 (DOI 10.4028/www.scientific.net/MSF.765.77)	P
8	09/2013	Contributed presentation	Scientific materials community	…	UniMan	Zhang Y., Lee P.; "An analytic model for gas bubble oscillation during ultrasonic treatment of molten metal"; *European Congress and Exhibition on Advanced Materials and Processes* (EUROMAT2013); September 8–13, 2013; Sevilla (ES)	F
9	09/2013	Journal paper	Scientific materials community	N/A	UniQue, UniMan	Prasad A., Yuan L., Lee P.D., StJohn D.H.; "The interdependence model of grain nucleation: A numerical analysis of the nucleation-free zone"; *Acta Materialia* 61/16 (2013): 5914–5927 (DOI 10.1016/j.actamat.2013.06.015)	P

10	09/2013	Contributed presentation	Scientific and industrial materials community	~50	ESA	Sillekens W.H., Jarvis D.; "The ExoMet project: EU/ESA research on high-performance light-metal alloys and nano-composites"; *Euro LightMAT 2013 – International Congress on Light Materials*; September 3–5, 2013; DGM, Bremen (DE)	F
11	11/2013	Contributed presentation and paper	Scientific nanotechnology community	…	UniMan	Horsfield A.P., Wearing D., Xu W., Wang J., Lee P.D.; "Atomic scale simulation of growth of solid metal from the melt"; *Proceedings of the 4th International Workshop on Nanotechnology and Application* (2013): 20–23	P
12	01/2014	Journal paper	Scientific materials community	N/A	WIGNER	Podmaniczky F., Tóth G.I., Pusztai T., Gránásy L.; "Free energy of the bcc–liquid interface and the Wulff shape as predicted by the phase-field crystal model"; *Journal of Crystal Growth* 385 (2014): 148–153 (DOI 10.1016/j.jcrysgro.2013.01.036)	P
13	01/2014	Poster	Computational materials science community	…	UniMan	Xu W., Horsfield A.P., Zhang Y., Wearing D.J., Srirangam P., Lee P.D.; "*Ab initio* thermodynamics of the Mg/MgO interface"; *Conference on Multiscale Modelling of Condensed Phase and Biological Systems*; January 7–9, 2014; CCPBioSim; Manchester (UK)	F
14	02/2014	Journal paper	Computational physics community	N/A	WIGNER	Tóth G.I., Gránásy L., Tegze G.; "Nonlinear hydrodynamic theory of crystallization"; *Journal of Physics: Condensed Matter* 26/5 (2014): 1–10 (DOI 10.1088/0953-8984/26/5/055001)	P
15	02/2014	Contributed presentation and paper	Scientific and industrial materials community	…	TOMSK, UBRUN	Vorozhtsov S., Eskin D., Vorozhtsov A., Kulkov S.; "Physico-mechanical and electrical properties of aluminum-based composite materials with carbon nanoparticles"; *Light Metals 2014*; Wiley–TMS, Hoboken NJ (2014): 1373–1377 (DOI 10.1002/9781118888438.ch229)	F
16	02/2014	Contributed presentation and paper	Scientific and industrial materials community	…	UniGre	Djambazov G., Bojarevics V., Lebon B., Pericleous K.; "Contactless acoustic wave generation in a melt by electromagnetic induction"; *Light Metals 2014*; Wiley–TMS, Hoboken NJ (2014): 1379–1382 (DOI 10.1002/9781118888438.ch230)	F
17	02/2014	Contributed presentation and paper	Scientific and industrial materials community	…	ESA/ESRF, INPG, UniMan	Terzi S., Daudin R., Villanova J., Srirangam P., Lhuissier P., Salvo L., Boller E., Schweins R., Lindner P., Blandin J.-J., Lee P., Lemmel H.; "X-ray tomography and small-angle neutron scattering characterization of nano-composites: Static and in situ experiments"; *Light Metals 2014*; Wiley–TMS, Hoboken NJ (2014): 1389–1393 (DOI 10.1002/9781118888438.ch232)	F
18	02/2014	Contributed presentation and paper	Scientific and industrial materials community	…	UBRUN	Djan E., Vadakke Madam S., Hari Babu N., Tamayo-Ariztondo J., Eskin D.G., Fan Z.; "Processing of metal matrix composites under external fields and their application as grain refiner"; *Light Metals 2014*; Wiley–TMS, Hoboken NJ (2014): 1401–1404 (DOI 10.1002/9781118888438.ch234)	F
19	02/2014	Contributed presentation and paper	Scientific and industrial materials community	…	INPG, ESI, UniGre	Garrido M., Fautrelle Y., Davoust L., Bojarevics V., Pericleous K., Megahed M., Koeser O.; "Grain refinement and nanoparticle dispersion using traveling magnetic field"; *Light Metals 2014*; Wiley–TMS, Hoboken NJ (2014): 1405–1410 (DOI 10.1002/9781118888438.ch235)	F

20	02/2014	Contributed presentation and paper	Scientific and industrial materials community	…	UBRUN	Tamayo-Ariztondo J., Vadakke Madam S., Djan E., Eskin D.G., Hari Babu N., Fan Z.; "Nanoparticles distribution and mechanical properties of aluminum-matrix nano-composites treated with external fields"; *Light Metals 2014*; Wiley–TMS, Hoboken NJ (2014): 1411–1415 (DOI 10.1002/9781118888438.ch236)	F
21	02/2014	Invited presentation and paper	Scientific and industrial materials community	…	WIGNER	Pusztai T., Rátkai L., Szállás A., Gránásy L.; "Phase-field modeling of solidification in light-metal matrix nanocomposites"; *Magnesium Technology 2014*; Wiley–TMS, Hoboken NJ (2014): 455–459 (DOI 10.1002/9781118888179.ch83)	F
22	02/2014	Contributed presentation and paper	Scientific and industrial materials community	…	UniRou	Mounib M., Lefebvre W.; "Advanced characterization of metal matrix nano-composites"; *Magnesium Technology 2014*; Wiley–TMS, Hoboken NJ (2014): 461–464 (DOI 10.1002/9781118888179.ch84)	F
23	02/2014	Poster	Scientific and industrial materials community	…	ESA	Sillekens W.H., Jarvis D.J.; "The ExoMet project: EU/ESA research on high-performance light-metal alloys and nano-composites"; *TMS 143rd Annual Meeting & Exhibition*; February 16–20, 2014; San Diego, CA (USA)	F
24	02/2014	Contributed presentation	Scientific and industrial materials community	…	IMDEA	Molina-Aldareguia J., Sánchez R., Pérez-Prado M., Segurado J., Llorca J.; "Measuring the critical resolved shear stresses in Mg alloys by instrumented nanoindentation"; *TMS 143rd Annual Meeting & Exhibition – Multiscale Perspectives on Plasticity in HCP Metals*; February 16–20, 2014; San Diego, CA (USA)	P
25	04/2014	Journal paper	Scientific materials community	N/A	IMDEA	Sánchez-Martín R., Pérez-Prado M.T., Segurado J., Bohlen J., Gutiérrez-Urrutia I., Llorca J., Molina-Aldareguia J.M.; "Measuring the critical resolved shear stresses in Mg alloys by instrumented nanoindentation"; *Acta Materialia* 71 (2014): 283–292 (DOI 10.1016/j.actamat.2014.03.014)	P
26	04/2014	Journal paper	Scientific materials community	N/A	WIGNER	Gránásy L., Rátkai L., Szállás A., Korbuly B., Tóth G.I., Környei L., Pusztai T.; "Phase-field modeling of polycrystalline solidification: From needle crystals to spherulites – A review"; *Metallurgical and Materials Transactions A* 45 (2014): 1694–1719 (DOI 10.1007/s11661-013-1988-0)	P
27	04/2014	Journal paper	Scientific chemicals community	N/A	WIGNER	Gránásy L., Podmaniczky F., Tóth G.I., Tegze G., Pusztai T.; "Heterogeneous nucleation of/on nanoparticles: A density functional study using the phase-field crystal model"; *Chemical Society Reviews* 43 (2014): 2159–2173 (DOI 10.1039/c3cs60225g)	P
28	06/2014	Contributed presentation	Scientific aluminium community	~60	UBRUN	Sreekumar V.M.; "Grain refinement studies of oxide ($MgAl_2O_4$) containing master alloys in Al"; *14th International Conference on Aluminium Alloys (ICAA 2014)*; June 15–19, 2014; NTNU; Trondheim (NO)	F
29	06/2014	Journal paper	Scientific materials community	N/A	UBRUN	Sreekumar V.M., Hari Babu N., Eskin D.G., Fan Z.; "Grain refinement efficiency of a new oxide-containing master alloy for aluminium casting alloys"; *Materials Science Forum* 794–796 (2014): 155–160 (DOI 10.4028/www.scientific.net/MSF.794-796.155)	F

30	06/2014	Contributed presentation and paper	Scientific MHD community	80–100	UniGre, INPG	Bojarevics V., Pericleous K., Garrido M., Fautrelle Y., Davoust L.; "Travelling magnetic field mixing for particle dispersion in liquid metal"; *Proceedings of the 9th PAMIR International Conference on Fundamental and Applied MHD* (2014): 140–144	F
31	06/2014	Contributed presentation and paper	Scientific MHD community	80–100	UniGre	Pericleous K., Lebon B., Djambazov G., Bojarevics V.; "Induction-driven contactless acoustic wave generation in a crucible"; *Proceedings of the 9th PAMIR International Conference on Fundamental and Applied MHD* (2014): 385	F
32	06/2014	Contributed poster and paper	Energetic materials community	~20	TOMSK, UBRUN	Vorozhtsov S., Vorozhtsov A., Eskin D.; "High energy compaction of Al-TiB_2, Al-TiC and Al-Al_2O_3 master alloys for modification of light alloys structure"; *Proceedings of the 45th International Annual Conference of the Fraunhofer ICT* (2014): 79/1–8	F
33	06/2014	Poster	Scientific materials community		INPG, ESA	Daudin R., Terzi S., Lhuissier P., Alvarez M., Boller E., Salvo L.; "3D microstructure of sub microns reinforced metal matrix composites: Post mortem and in situ tomography analysis"; *2nd International Congress on 3D Materials Science 2014 (3DMS 2014)*; June 29 – July 2, 2014; Annecy (FR)	F
34	07/2014	Journal paper	Scientific materials community	N/A	ESA, TOMSK, UniGre, POLITO, INPG, HZG	Sillekens W.H., Jarvis D.J., Vorozhtsov A., Bojarevics V., Badini C.F., Pavese M., Terzi S., Salvo L., Katsarou L., Dieringa H.; "The ExoMet project: EU/ESA research on high-performance light-metal alloys and nanocomposites"; *Metallurgical and Materials Transactions A* 45 (2014): 3349–3361 (DOI 10.1007/s11661-014-2321-2)	F
35	07/2014	Contributed presentation	Scientific materials community	~50	INPG, ESA	Daudin R., Terzi S., Lhuissier P., Boller E., Rack A., Salvo L.; "4D *in situ* solidification of Al-Si alloys with and without ultrasonic treatment"; *4th International Conference on Advances in Solidification Processes* (ICASP-4); July 8–11, 2014; Old Windsor (UK)	P
36	07/2014	Poster	Scientific materials community	…	UBRUN	Sreekumar V.M., Hari Babu N., Eskin D.G., Fan Z.; "Grain refining potency of an oxide based master alloy in aluminium alloys"; *4th International Conference on Advances in Solidification Processes* (ICASP-4); July 8–11, 2014; Old Windsor (UK)	F
37	07/2014	Poster	Scientific materials community	…	UBRUN	Djan E., Hari Babu N., Eskin D.G., Fan Z.; "In-situ processing of an Al-5Ti-B master alloy using ultrasound"; *4th International Conference on Advances in Solidification Processes* (ICASP-4); July 8–11, 2014; Old Windsor (UK)	F
38	09/2014	Journal paper	Scientific materials community	N/A	UniQue	Liang D., Liang Z., Zhai Q., Wang G., StJohn D.H.; "Nucleation and grain formation of pure Al under pulsed magneto-oscillation treatment"; *Materials Letters* 130 (2014): 48–50 (DOI 10.1016/j.matlet.2014.05.058)	P
39	09/2014	Journal paper	Materials science and engineering community	N/A	UniRou, POLITO, HZG	Mounib M., Pavese M., Badini C., Lefebvre W., Dieringa H.; "Reactivity and microstructure of Al_2O_3-reinforced magnesium matrix nanocomposites"; *Advances in Materials Science and Engineering* (2014): ID 476079 (DOI 10.1155/2014/476079)	F

40	09/2014	Contributed presentation and paper	Scientific materials community	60–70	IMDEA	Cepeda-Jiménez C.M., Molina-Aldareguia J., Gutierrez-Urrutia I., Pérez-Prado M.T.; "Study of the dominant deformation mechanisms in pure magnesium by in-situ testing and trace analysis"; *Proceedings of the 35th Risø International Symposium on Materials Science: New Frontiers of Nanometals* (2014): 221–228	F
41	10/2014	Contributed presentation	Materials science and engineering community	20–25	HZG	Katsarou L., Vorozhtsov A., Dieringa H.; "Processing and compression creep response of AlN reinforced magnesium alloy Elektron21"; *22nd International Conference on Materials and Technology*; October 20–22, 2014; Portorož (SI)	F
42	12/2014	Journal paper	Scientific materials community	N/A	UniQue, UBRUN	Wang G., Dargusch M.S., Qian M., Eskin D.G., StJohn D.H.; "The role of ultrasonic treatment in refining the as-cast grain structure during the solidification of an Al-2Cu alloy"; *Journal of Crystal Growth* 408 (2014): 119–124 (DOI 10.1016/j.jcrysgro.2014.09.018)	P
43	12/2014	Journal paper	Scientific materials community	N/A	NTNU	Mirihanage W.U., Falch K.V., Snigireva I., Snigirev A., Li Y., Arnberg L., Mathiesen R.H.; "Retrieval of 3D spatial information from fast in-situ 2D synchrotron radiography of solidification microstructure evolution"; *Acta Materialia* 81 (2014): 241–247 (DOI 10.1016/j.actamat.2014.08.016)	P
44	01/2015	Journal paper	Materials science and engineering community	N/A	TOMSK, UBRUN	Vorozhtsov S., Zhukov I., Vorozhtsov A., Zhukov A., Eskin D., Kvetinskaya A.; "Synthesis of micro- and nanoparticles of metal oxides and their application for reinforcement of Al-based alloys"; *Advances in Materials Science and Engineering* (2015): ID 718207 (DOI 10.1155/2015/718207)	P
45	01/2015	Journal paper	Scientific materials community	N/A	UBRUN	Sreekumar V.M., Hari Babu N., Eskin D.G., Fan Z.; "Structure-property analysis of in-situ Al-$MgAl_2O_4$ metal matrix composites synthesized using ultrasonic cavitation"; *Materials Science and Engineering A* 628 (2015): 30–40 (DOI 10.1016/j.msea.2015.01.029)	F
46	02/2015	Journal paper	Scientific materials community	N/A	IMDEA	Cepeda-Jiménez C.M., Molina-Aldareguia J.M., Pérez-Prado M.T.; "Effect of grain size on slip activity in pure magnesium polycrystals"; *Acta Materialia* 84 (2015): 443–456 (DOI 10.1016/j.actamat.2014.10.001)	F
47	02/2015	Journal paper	Scientific materials community	N/A	IMDEA	Cepeda-Jiménez C.M., Molina-Aldareguia J.M., Carreño F., Pérez-Prado M.T.; "Prominent role of basal slip during high-temperature deformation of pure Mg polycrystals"; *Acta Materialia* 85 (2015): 1–13 (DOI 10.1016/j.actamat.2014.11.013)	P
48	03/2015	Contributed presentation and paper	Scientific and industrial materials community	…	UBRUN, TOMSK	Eskin D.G., Hari Babu N., Vadakke Madam S.K., Tamayo J., Vorozhtsov S.A., Vorozhtsov A.B.; "Application of external fields to the development of aluminum-based nanocomposite and master alloys"; *TMS2015 Annual Meeting Supplemental Proceedings*; Wiley–TMS, Hoboken NJ (2015): 19–24 (DOI 10.1002/9781119093466.ch3)	F
49	03/2015	Contributed presentation and paper	Scientific and industrial materials community	…	UniMan, UBRUN, ESA, NTNU	Xu W.W., Tzanakis I., Srirangam P., Terzi S., Mirihanage W.U., Eskin D.G., Mathiesen R., Horsfield A., Lee P.D.; "In situ synchrotron radiography of ultrasound cavitation in a molten Al-10Cu alloy"; *TMS2015 Annual Meeting Supplemental Proceedings*; Wiley–TMS, Hoboken NJ (2015): 61–66 (DOI 10.1002/9781119093466.ch9)	F

50	03/2015	Contributed presentation and extended abstract	Scientific and industrial materials community	~25	ESA	Sillekens W.H.; "The ExoMet project: EU/ESA research on high-performance light-metal alloys and nanocomposites"; *Magnesium Technology 2015* ; Wiley–TMS, Hoboken NJ (2015): 373–375 (DOI 10.1002/9781119093428.ch69)	F
51	03/2015	Contributed presentation	Scientific and industrial materials community	…	UniGre	Manoylov A., Bojarevics V., Pericleous K.; "Modelling the breakup of nanoparticle clusters in MMNCs under the external fields"; *TMS 144th Annual Meeting & Exhibition* ; March 15–19, 2015; Orlando, FL (USA)	F
52	03/2015	Contributed presentation	Scientific and industrial materials community	…	UniGre	Pericleous K., Bojarevics V., Djambazov G.; "Contactless ultrasound generation in a crucible"; *TMS 144th Annual Meeting & Exhibition* ; March 15–19, 2015; Orlando, FL (USA)	F
53	03/2015	Contributed presentation	Scientific and industrial materials community	…	UniGre, INPG	Garrido Pacheco M., Bojarevics V., Fautrelle Y., Davoust L.; "Dispersion of nanoparticles in magnesium and aluminum alloys using magnetic fields"; *TMS 144th Annual Meeting & Exhibition* ; March 15–19, 2015; Orlando, FL (USA)	F
54	03/2015	Contributed presentation	Scientific and industrial materials community	…	ESA, INPG	Terzi S., Daudin R., Salvo L., Lhuissier P., Boller E., Rack A., Sillekens W., Jarvis D.J.; "Ultrasonic melt processing of metal matrix composites: A 4-D experimental study of solidification and remelting"; *TMS 144th Annual Meeting & Exhibition* ; March 15–19, 2015; Orlando, FL (USA)	F
55	03/2015	Contributed presentation	Scientific and industrial materials community	…	UBRUN	Joshi U., Sreekumar V.M., Eskin D., Nadendla H.B.; "Development of Al-B-C master alloy under external fields"; *TMS 144th Annual Meeting & Exhibition* ; March 15–19, 2015; Orlando, FL (USA)	F
56	03/2015	Invited presentation	Scientific and industrial materials community	…	UniGre	Bojarevics V., Pericleous K.; "Magnetic suspension melting developments"; *TMS 144th Annual Meeting & Exhibition* ; March 15–19, 2015; Orlando, FL (USA)	P
57	03/2015	Contributed presentation	Scientific and industrial materials community	…	TOMSK, UBRUN	Vorozhtsov S.A., Eskin D.G., Tamayo J., Vorozhtsov A.B., Averin A., Promakhov V.V., Averin A., Khrustalyov A.P.; "The effect of external fields and application of novel dense master alloys to increase the physico-mechanical properties of light alloys"; *TMS 144th Annual Meeting & Exhibition* ; March 15–19, 2015; Orlando, FL (USA)	P
58	03/2015	Poster	Scientific and industrial materials community	…	UniMan	Xu W.W., Horsfield A.P., Wearing D.J., Lee P.D.; "First-principles calculations of Mg-MgO interfacial free energies"; *TMS 144th Annual Meeting & Exhibition* ; March 15–19, 2015; Orlando, FL (USA)	F
59	04/2015	Journal paper	Scientific materials community	N/A	IMDEA	Cepeda-Jiménez C.M., Molina-Aldareguia J.M., Pérez-Prado M.T.; "Origin of the twinning to slip transition with grain size refinement, with decreasing strain rate and with increasing temperature in magnesium"; *Acta Materialia* 88 (2015): 232–244 (DOI 10.1016/j.actamat.2015.01.032)	P

60	04/2015	Journal paper	Scientific physics community	N/A	WIGNER	Rátkai L., Szállás A., Pusztai T., Mohri T., Gránásy L.; "Ternary eutectic dendrites: Pattern formation and scaling properties"; *The Journal of Chemical Physics* 142/15 (2015): 154501 (DOI 10.1063/1.4917201)	P
61	06/2015	Contributed presentation	Computational materials science community	30–40	UniMan	Xu W., Horsfield A.P., Lee P.D.; "Multi-scale modelling of interfacial energies on the nanoscale: From analytical to quantum mechanical"; *TMS 3rd World Congress on Integrated Computational Materials Engineering*; May 31 – June 4, 2015; Colorado Springs, CO (USA)	P
62	07/2015	Journal paper	Scientific materials community	N/A	UBRUN	Joshi U., Sreekumar V.M., Eskin D., Nadendla H.B.; "Development of Al-B-C master alloy under external fields"; *Metallurgical and Materials Transactions A* 46 (2015): 2862–2869 (DOI 10.1007/s11661-015-2926-0)	F
63	07/2015	Journal paper	Scientific materials community	N/A	TOMSK, UBRUN	Vorozhtsov S.A., Eskin D.G., Tamayo J., Vorozhtsov A.B., Promakhov V.V., Averin A.A., Khrustalyov A.P.; "The application of external fields to the manufacturing of novel dense composite master alloys and aluminum-based nanocomposites"; *Metallurgical and Materials Transactions A* 46 (2015): 2870–2875 (DOI 10.1007/s11661-015-2850-3)	P
64	07/2015	Journal paper	Scientific materials community	N/A	UniGre	Bojarevics V., Djambazov G.S., Pericleous K.A.; "Contactless ultrasound generation in a crucible"; *Metallurgical and Materials Transactions A* 46 (2015): 2884–2892 (DOI 10.1007/s11661-015-2824-5)	F
65	07/2015	Journal paper	Scientific materials community	N/A	UniGre	Manoylov A., Bojarevics V., Pericleous K.; "Modeling the break-up of nano-particle clusters in aluminum- and magnesium-based metal matrix nano-composites"; *Metallurgical and Materials Transactions A* 46/7 (2015): 2893–2907 (DOI 10.1007/s11661-015-2934-0)	F
66	07/2015	Journal paper	Scientific materials community	N/A	IMDEA	Sánchez-Martín R., Zambaldi C., Pérez-Prado M.T., Molina-Aldareguia J.M.; "High temperature deformation mechanisms in pure magnesium studied by nanoindentation"; *Scripta Materialia* 104 (2015): 9–12 (DOI 10.1016/j.scriptamat.2015.03.012)	P
67	07/2015	Journal paper	Scientific materials community	N/A	IMDEA	Sánchez-Martín R., Pérez-Prado M.T., Segurado J., Molina-Aldareguia J.M.; "Effect of indentation size on the nucleation and propagation of tensile twinning in pure magnesium"; *Acta Materialia* 93 (2015): 114–128 (DOI 10.1016/j.actamat.2015.04.005)	P
68	07/2015	Keynote presentation	Scientific materials community	30–40	INPG, ESA	Daudin R., Darlapudi A., Villanova J., Lhuissier P., Scheel M., Boller E., Terzi S., Salvo L., Martin C.; "4D X-ray tomography: Recent technical developments and applications"; *9th European Solid Mechanics Conference (ESMC 2015)*; July 6–10, 2015; Leganés-Madrid (ES)	P
69	07/2015	Contributed poster and paper	Materials science and engineering community		HZG, UniRou	Katsarou L., Mounib M., Lefebvre W., Dieringa H.; "Magnesium alloy Elektron21 reinforced with AlN: Processing, microstructure and compression creep response"; *20th International Conference on Composite Materials (ICCM20)*; July 19–24, 2015; Copenhagen (DK)	F

70	07/2015	Journal paper	Scientific light-metals community	N/A	UBRUN	Sreekumar V.M., Hari Babu N., Eskin D.G., Fan Z.; "Development of new oxide based master alloys and their grain refinement potency in aluminium alloys"; *Materials Science Forum* 828–829 (2015): 23–28 (DOI 10.4028/www.scientific.net/MSF.828-829.23)	F
71	07/2015	Journal paper	Scientific light-metals community	N/A	HZG, UBRUN	Dieringa H., Das S., Eskin D., Fan Z., Katsarou L., Horstmann M., Kurz G., Mendis C., Hort N., Kainer K.-U.; "Twin-roll casting after intensive melt shearing and subsequent rolling of an AM30 magnesium alloy with addition of CaO and SiC"; *Materials Science Forum* 828–829 (2015): 35–40 (DOI 10.4028/www.scientific.net/MSF.828-829.35)	F
72	07/2015	Journal paper	Scientific light-metals community	N/A	UBRUN	Eskin D.G.; "Ultrasonic melt processing: Achievements and challenges"; *Materials Science Forum* 828–829 (2015): 112–118 (DOI 10.4028/www.scientific.net/MSF.828-829.112)	P
73	07/2015	Contributed presentation	Scientific light-metals community	110	UBRUN	Sreekumar V.M., Hari Babu N., Eskin D.G., Fan Z.; "Development of new oxide based master alloys and their grain refinement potency in aluminium alloys"; *7th Light Metals Technology Conference (LMT 2015)*; July 27–29, 2015; Port Elizabeth (SA)	F
74	07/2015	Contributed presentation	Scientific light-metals community	~20	HZG, UBRUN	Dieringa H., Das S., Eskin D., Fan Z., Katsarou L., Horstmann M., Kurz G., Mendis C., Hort N., Kainer K.-U.; "Twin-roll casting after intensive melt shearing and subsequent rolling of an AM30 magnesium alloy with addition of CaO and SiC"; *7th Light Metals Technology Conference (LMT 2015)*; July 27–29, 2015; Port Elizabeth (SA)	F
75	07/2015	Contributed presentation	Scientific light-metals community	110	UBRUN	Eskin D.G.; "Ultrasonic melt processing: Achievements and challenges"; *7th Light Metals Technology Conference (LMT 2015)*; July 27-29, 2015; Port Elizabeth (SA)	P
76	07/2015	Journal paper	Scientific materials community	N/A	INPG, ESA	Daudin R., Terzi S., Lhuissier P., Salvo L., Boller E.; "Remelting and solidification of a 6082 Al alloy containing submicron yttria particles: 4D experimental study by in situ X-ray microtomography"; *Materials and Design* 87 (2015): 313–317 (DOI 10.1016/j.matdes.2015.07.141)	F
77	09/2015	Contributed poster	Scientific physics community	N/A	WIGNER	Tóth G., Pusztai T., Kvamme B., Gránásy L.; "Multiphase-field theories of crystallization: A comparative study"; *Fifth European Conference on Crystal Growth*; September 9–11, 2015; Bologna (IT)	P
78	09/2015	Contributed presentation	Scientific and industrial materials community	30	HZG, UniRou	Katsarou L., Dieringa H., Mounib M., Lefebvre W.; "Herstellung, Mikrostruktur und Druckkriechverhalten der nanopartikel-verstärkten Magnesiumlegierung Elektron21"; *Werkstoffwoche 2015 – Congress and Industrial Exhibition*; September 14–17, 2015; Dresden (DE)	F
79	09/2015	Contributed presentation and paper	Computational materials science community	~20	UniGre	Manoylov A., Bojarevics V., Pericleous K.; "Modelling the formation and breakup of particle clusters in metal melt subjected to external fields"; *Proceedings of the 4th International Conference on Particle-based Methods – Fundamentals and Applications* (PARTICLES 2015): 1–12	F

80	11/2015	Journal paper	Scientific materials community	N/A	UniQue	StJohn D.H., Prasad A., Easton M.A., Qian M.; "The contribution of constitutional supercooling to nucleation and grain formation"; *Metallurgical and Materials Transactions A* 46 (2015): 4868–4885 (DOI 10.1007/s11661-015-2960-y)	P
81	11/2015	Journal paper	Scientific materials community	N/A	WIGNER	Tóth G.I., Pusztai T., Gránásy L.; "A consistent multiphase-field theory for interface driven multi-domain dynamics"; *Physical Review B* 92/18 (2015): 184105 (DOI 10.1103/PhysRevB.92.184105)	P
82	11/2015	Journal paper	Scientific physics community	N/A	UniMan	Xu W., Horsfield A.P., Wearing D., Lee P.D.; "First-principles calculation of Mg/MgO interfacial energies"; *Journal of Alloys and Compounds* 650 (2015): 228–238 (DOI 10.1016/j/jallcom.2015.07.289)	P
83	11/2015	MSc thesis	Materials community	N/A	HZG	Teng F.; *Mechanical properties and corrosion behaviors of alumina nanoparticles reinforced pure magnesium*; MSc thesis, Rheinisch-Westfälische Technische Hochschule Aachen (2015)	F
84	12/2015	Poster	Scientific materials community		UniGre	Manoylov A., Bojarevics V., Djambazov G., Pericleous K.; "Multi-scale modelling of nano-particle clusters in aluminium melt subjected to the external fields"; *Predictive Multiscale Materials Modelling Workshop*; December 1–4, 2015; Cambridge (UK)	F
85	12/2015	Presentation	Scientific materials community	~30	UBRUN	Eskin D.; "Ultrasonic processing of molten and solidifying aluminium alloys: Overview and outlook"; *Advances in Materials and Processing Technologies* (AMPT2015); December 14–17, 2015; Madrid (ES)	P
86	12/2015	PhD thesis	Scientific materials community	N/A	UniRou	Mounib M.; *Electron microscopy characterization of magnesium based composites and aluminium master alloys processed under the influence of external fields*; PhD thesis, University of Rouen (2015)	F
87	01/2016	Journal paper	Scientific materials community	N/A	IMDEA	Cepeda-Jiménez C.M., Molina-Aldareguia J.M., Pérez-Prado M.T.; "EBSD-assisted slip trace analysis during in situ SEM mechanical testing: Application to unravel grain size effects on plasticity of pure Mg polycrystals"; *JOM* 68/1 (2016): 116–126 (DOI 10.1007/s11837-015-1521-6)	P
88	02/2016	Journal paper	Scientific materials community	N/A	HZG, UniRou, TOMSK, POLITO, IMDEA	Katsarou L., Mounib M., Lefebvre W., Vorozhtsov S., Pavese M., Badini C., Molina-Aldareguia J.M., Cepeda Jimenez C., Pérez Prado M.T., Dieringa H.; "Microstructure, mechanical properties and creep of magnesium alloy Elektron21 reinforced with AlN nanoparticles by ultrasound-assisted stirring"; *Materials Science & Engineering A* 659 (2016): 84–92 (DOI 10.1016/j.msea.2016.02.042)	F
89	02/2016	Journal paper	Scientific materials community	N/A	UniMan, UBRUN	Mirihanage W., Xu W., Tamayo-Ariztondo J., Eskin D., Garcia-Fernandez M., Srirangam P., Lee P.; "Synchrotron radiographic studies of ultrasonic melt processing of metal matrix nano composites"; *Materials Letters* 164 (2016): 484–487 (DOI 10.1016/j.matlet.2015.11.022)	P

90	02/2016	Invited presentation and extended abstract	Scientific and industrial materials community	~80	WIGNER	Gránásy L., Podmaniczky F., Tóth G.I.; "Phase-field crystal modeling of nucleation including homogeneous and heterogeneous processes, and growth front nucleation"; *TMS 145th Annual Meeting & Exhibition*; February 14–18, 2016; Nashville, TN (USA) [abstract in: Frontiers of Solidification; eds. Kurz W., Dantzig J., Karma A., Hoyt J.; EPFL Materials Science, Lausanne (2016): 23–26]	F
91	02/2016	Contributed presentation and paper	Scientific and industrial materials community	…	UniQue	Wang G., Wang E.Q., Prasad A., Dargusch M., StJohn D.H.; "Grain refinement of Al-Si hypoeutectic alloys by Al3Ti1B master alloy and ultrasonic treatment"; *Shape Casting: 6th International Symposium*; Wiley–TMS, Hoboken NJ (2016): 143–150	P
92	02/2016	Poster and pitch presentation	Scientific and industrial materials community	~40	ESA	Sillekens W.H.; "The use of *in-situ* imaging methods in the research and development of magnesium-based nanocomposites"; *TMS 145th Annual Meeting & Exhibition*; February 14–18, 2016; Nashville, TN (USA)	F
93	03/2016	Journal paper	Scientific materials community	N/A	UniQue, UBRUN	Wang E.Q., Wang G., Dargusch M.S., Qian M., Eskin D.G., StJohn D.H.; "Grain refinement of an Al-2 wt%Cu alloy by Al3Ti1B master alloy and ultrasonic treatment"; *IOP Conference Series: Materials Science and Engineering* 117/1 (2016): 012050 (DOI 10.1088/1757-899X/117/012050)	P
94	04/2016	Journal paper	Scientific materials community	N/A	IMDEA	Cepeda-Jiménez C.M., Pérez-Prado M.T.; "Microplasticity-based rationalization of the room temperature yield asymmetry in conventional polycrystalline Mg alloys"; *Acta Materialia* 108 (2016): 304–316 (DOI 10.1016/j.actamat.2016.02.023)	P
95	04/2016	Presentation	Scientific nanotechnology community	40–50	UniBir	Adkins N., Shevchenko D., Griffiths W.; "The production of light alloy metal matrix composites containing nanoparticles"; *2nd World Congress and Expo on Nanotechnology and Materials Science*; April 4–6, 2016; Dubai (UAE)	F
96	04/2016	Journal paper	Scientific materials community	N/A	UniMan	Wearing D., Horsfield A.P., Xu W., Lee P.D.; "Which wets TiB_2 inoculant particles: Al or Al_3Ti?"; *Journal of Alloys and Compounds* 664 (2016): 460–468 (DOI 10.1016/j.jallcom.2015.12.203)	P
97	06/2016	Journal paper	Scientific physics community	N/A	IMDEA	Cepeda-Jiménez C.M., Hernando A., Barandiarán J.M., Pérez-Prado M.T.; "Onset of room temperature ferromagnetism by plastic deformation in three paramagnetic pure metals"; *Scripta Materialia* 118 (2016): 41–45 (DOI 10.1016/j.scriptamat.2016.03.002)	P
98	06/2016	Presentation	Scientific computational community	~20	UniGre, UniBir	Bojarevics V., Djambazov G., Lebon G.S.B., Manoylov A., Pericleous K.A., Burnard D.J., Griffiths W.D., Shevchenko D.; "Dispersion of nano particles in melts using electromagnetic wave action"; *VII European Congress on Computational Methods in Applied Sciences and Engineering* (ECCOMAS Congress 2016); June 5–10, 2016; Crete (GR)	F
99	06/2016	Presentation and paper	Scientific computational community	~100	UniGre	Manoylov A., Djambazov G., Bojarevics V., Pericleous K.; "Multiple timescale modelling of particle suspensions in metal melts subjected to external forces"; Proceedings of the *VII European Congress on Computational Methods in Applied Sciences and Engineering* (ECCOMAS Congress 2016)	P

100	06/2016	Presentation and paper	Scientific and technical physics community	~40	INPG, UniGre	Garrido M., Davoust L., Bojarevics V., Fautrelle Y.; "Reinforcement of magnesium matrix with SiC particles using a travelling magnetic field"; *Proceedings of the 10th PAMIR International Conference – Fundamental and Applied MHD (PAMIR10)*	F
101	06/2016	Presentation	Scientific and technical physics community	~50	UBRUN, UniGre	Tzanakis I., Lebon G.S.B., Eskin D.G., Dezhkunov N., Pericleous K.; "Evaluation of a calibrated cavitometer for the measurement of cavitation activity in liquid aluminium and water"; *15th Meeting of the European Society of Sonochemistry* (ESS-15); June 27 – July 1, 2016; Istanbul (TK)	P
102	07/2016	Journal paper	Scientific physics community	N/A	UniMan, UBRUN	Xu W.W., Tzanakis I., Srirangam P., Mirihanage W.U., Eskin D.G., Bodey A.J., Lee P.D.; "Synchrotron quantification of ultrasound cavitation and bubble dynamics in Al-10Cu melts"; *Ultrasonics Sonochemistry* 31 (2016): 355–361 (DOI 10.1016/j.ultsonch.2016.01.017)	P
103	09/2016	Journal paper	Scientific materials community	N/A	NTNU, ESA	Casari D., Mirihanage W.U., Falch K.V., Ringdalen I.G., Friis J., Schmid-Fetzer R., Zhao D., Li Y., Sillekens W.H., Mathiesen R.H.; "α-Mg primary phase formation and dendritic morphology transition in solidification of a Mg-Nd-Gd-Zn-Zr casting alloy"; *Acta Materialia* 116 (2016): 177–187 (DOI 10.1016/j.actamat.2016.06.035)	F
104	12/2016	Journal paper	Scientific materials community	N/A	UniMan	Xu W.W., Horsfield A.P., Wearing D., Lee P.D.; "Diversification of MgO//Mg interfacial crystal orientations during oxidation: A density functional theory study"; *Journal of Alloys and Compounds* 688 (2016): 1233–1240 (DOI 10.1016/j.jallcom.2016.07.092)	P

* Underlined: presenting author   ** ExoMet share in publication: F = full, P = in part

Table B.2 Other dissemination activities contributed by the consortium members

#	DATE	PUBL. TYPE	AUDIENCE TYPE	SIZE	PART.(S)	REFERENCE*	F/P**
1	08/2012	Internet communication	General public	N/A	HZG	N.N.; "Nanoparticles strengthen magnesium"; website news item, Helmholtz Zentrum Geesthacht – http://www.hzg.de/public_relations/press_releases/033318/index_0033318.html.en	F
2	01/2013	Internet communication	General public	N/A	HZG	N.N.; "Physical processing of molten light alloys under the influence of external fields"; website news item, Helmholtz Zentrum Geesthacht – http://www.hzg.de/science_and_industrie/eu_projects/fp7/key/032379/index_0032379.html.en	F
3	01/2013	Internet communication	General public	N/A	IMDEA	N.N.; "EXOMET (Physical processing of molten light alloys under the influence of external fields)"; website news item, IMDEA Materials – http://www.materials.imdea.org/research/projects/EXOMET	F
4	01/2013	Internet communication	General public	N/A	R-Tech	N.N.; "Physical processing of molten light alloys under the influence of external fields"; website news item, Steinbeis Advanced Risk Technologies – http://www.risk-technologies.com/PagePreview.aspx?pag=1329&blockID=-255&pst=6,7	F
5	03/2013	Internet communication	General public	N/A	UniGre	N.N.; "Greenwich experts aim to transform the future of travel"; website news item, University of Greenwich – http://www2.gre.ac.uk/about/news/articles/2013/a2567-koulis-pericleous3	F
6	03/2013	Guest lecture	MSc/PhD engineering students	~30	UBRUN	Eskin D.G.; "Application of external fields to technology of metal-matrix composite materials"; March 26, 2013; Tomsk State University, Tomsk (RUS)	F
7	04/2013	Presentation	General public	…	UniMan	Lee P.D.; "Synchrotron Imaging of Engineering Materials"; The Institution of Engineering and Technology; April 16, 2013; London (UK) – http://www.theiet.org/events/local/177452.cfm	P
8	04/2013	Corporate communication	General public	N/A	IMDEA	N.N.; "EXOMET: Physical processing of molten light alloys under the influence of external fields"; *Annual Report 2012* , Institute IMDEA Materials (2013): 41–42	F
9	04/2013	Poster	General public	N/A	HZG	Dieringa H., Hort N., Kainer K.U.; "European project ExoMet: Physical processing of molten light alloys under influence of external fields"; permanent in-house display; Helmholtz-Zentrum Geesthacht, Geesthacht (DE)	F
10	04/2013	Internet communication	General public	N/A	TOMSK	N.N.; "25–27 March. Wim Sillekens, representative of the European Space Agency"; website news item, Tomsk State University – http://www.tsu.ru/english/about_tsu/news_events/30950/	F
11	05/2013	Internet communication	General public	N/A	PRECER	Jacobsson L.; "Precer and ESA in a 20 MEURO project"; website news item, Precer (Stiftelsen Inova Innovation News) – http://www.inova.nu/index.php/en/component/content/article/910	F

12	06/2013	Guest lecture	Bachelor students Mechanical Engineering	30 (+ web video)	ESA	Sillekens W.H.; "Het ExoMet-project: EU/ESA-onderzoek naar aluminium- en magnesiumlegeringen en nano-composieten" – part of the course Materials Science ("Materiaalkunde 2"; WB6201, quarter 4) by Prof.dr.ir. J. Sietsma; June 6, 2013; Delft University of Technology, Delft (NL)	F
13	06/2013	Association assembly presentation	Materials community	30	ESA	Sillekens W.H.; "Het ExoMet-project: EU/ESA-onderzoek naar aluminium- en magnesiumlegeringen en nano-composieten"; *VeMet-dag 2013: Metaalkunde, kiem tot groei*; June 26, 2013; ESA–ESTEC, Noordwijk (NL)	F
14	05/2014	Invited presentation	Numerical modelling user community	~50	ESA	Sillekens W.H.; "The ExoMet project: EU/ESA research on high-performance light-metal alloys and nano-composites"; *ESI Global Forum 2014*; May 21–22, 2014; ESI, Paris (FR)	F
15	05/2014	Guest lecture	Bachelor students Mechanical Engineering	70 (+ web video)	ESA	Sillekens W.H.; "Het ExoMet-project: EU/ESA-onderzoek naar aluminium- en magnesiumlegeringen en nano-composieten" – part of the course Materials Science ("Materiaalkunde 2"; WB6201, quarter 4) by Prof.dr.ir. J. Sietsma; May 27, 2014; Delft University of Technology, Delft (NL)	F
16	06/2014	Poster	Materials science and engineering students	…	UBRUN	Djan E., Vadakke Madam S., Tamayo-Ariztondo J., Hari Babu N., Eskin D.G., Fan Z.; "Development of a novel grain refiner using external fields"; *2014 National Student Conference in Metallic Materials*; June 26–27, 2014; Sheffield (UK)	F
17	06/2014	Permanent in-house display	General audience		UniMan	Srirangam P., Zhang Y., Xu W., Lee P.D.; "Imaging and Modelling Nano Particulate Composites to Manufacturing the Future"; The University of Manchester, Manchester (UK)	P
18	07/2014	Contributed presentation	Materials science and engineering community	…	HZG	Kainer K.-U., Dieringa H., Hort N.; "Magnesium matrix composites for transportation industries"; *22nd Annual International Conference on Composites/Nano Engineering* (ICCE-22); July 13–19, 2014; Malta (MT)	P
19	09/2014	Guest lecture	Sub-atomic physics research community	~30	ESA	Sillekens W.H.; "Magnesium alloys, their processes and applications"; September 5, 2014; National Institute for Subatomic Physics (NIKHEF), Amsterdam (NL)	P
20	11/2014	Association assembly presentation	Materials community	~25	ESA	Sillekens W.H.; "The ExoMet project: EU/ESA research on high-performance light-metal alloys and nano-composites"; *DGM Fachausschuss Aluminium*; November 25, 2014; ESA–ESTEC, Noordwijk (NL)	F
21	06/2015	Presentation and queries	Secondary-school students	~30	ESA	Sillekens W.H.; "ESA and its materials research"; June 3, 2015; Stedelijk Gymnasium Leiden, Leiden, Netherlands	P
22	09/2015	Exhibition	Scientific and industrial materials community	…	HZG	N.N.; "MagIC Exhibition booth"; *Werkstoffwoche 2015 – Congress and Industrial Exhibition*; September 14–17, 2015; Dresden (DE)	P
23	09/2015	Presentation / booth	Steinbeis Network	~700	R-Tech	Quintero F.A.; "Physical processing of molten light alloys under the influence of external fields (ExoMet)"; Steinbeis Day; September 25, 2015; Plieningen–Stuttgart (DE)	F

24	09/2015	Internet communic-ation	General audience		EC	N.N.; "Results in brief"; CORDIS cummunication, linked to the project's permanent factsheet – http://cordis.europa.eu/project/rcn/103659	F
25	01/2016	Poster	Scientific and industrial materials community	N/A	R-Tech	Kara G.; "Physical processing of molten light alloys under the influence of external fields (ExoMet)"; *Multi-scale and multi-physics materials modeling for advanced industries*; industrial workshop; January 26–27, 2016; Madrid (ES)	F
26	04/2016	Internet video lecture	School and university students	N/A	INPG	Garrido M.; "Metal-matrix composites and their electromagnetic processing"; on YouTube – https://www.youtube.com/watch?v=EeZMuPTruXs	F
27	04/2016	Internet video lecture	School and university students	N/A	TECNA	Azurmendi Apalategui N.; "Microwave heating technology"; on YouTube – https://www.youtube.com/watch?v=nNs_8ytydwU	F
28	04/2016	Internet video lecture	School and university students	N/A	NTNU	Casari D.; "X-ray microscopy of metallic alloys"; on YouTube – https://www.youtube.com/watch?v=lvV_Uqx4znU	F
29	06/2016	Magazine article	Steinbeis Network, partners and customers	~26,000	R-Tech, ESA	Jovanovic A., Quintero F.A., Kara G., Sillekens W.H.; "New light-weight materials for new technology applications"; *Steinbeis Transfer Magazine* (2016/02): 20–21 *(German and English versions)*	F
* Underlined: presenting author			** ExoMet share in publication: F = full, P = in part				

B.2 Exploitable foreground and plans for exploitation

Table B.3 List of applications for patents, trademarks, registered designs, etc.

#	TYPE OF IP RIGHTS	CONFIDENTIAL	FORESEEN EMBARGO DATE dd/mm/yyyy	APPLICATION REFERENCE(S)	SUBJECT OR TITLE OF APPLICATION	APPLICANT(S)
1	Patents	No	24/12/2014	WO 2014/202130 A1	Method of manufacturing a metal matrix composite component by use of a reinforcement preform	European Space Agency
2	Patents	No	05/03/2015	WO 2015/028065 A1	Manufacturing of a metal component or a metal matrix composite component involving contactless induction of high-frequency vibrations	European Space Agency

Table B.4 Identified exploitable foreground

TYPE	DESCRIPTION	CONFIDEN-TIAL	FORESEEN EMBARGO DATE dd/mm/yyyy	PRODUCT(S) OR MEASURE(S)	SECTOR(S) OF APPLICATION	TIMETABLE, COMMER-CIAL OR ANY OTHER USE	PATENTS OR OTHER IPR EXPLOIT-ATION (licences)	OWNER & OTHER BENEFICIARY(S) INVOLVED
Commercial exploitation	Novel grain-refining master alloys for aluminium, produced by melt treatment with external fields (e.g., ultrasound)	Yes	T.b.d.	Grain-refining master alloys	Aluminium foundry industry	T.b.d.	T.b.d.	KBM, UBRUN
Commercial exploitation	Elektron21-based nanocomposite materials with enhanced creep resistance	Yes	T.b.d.	High-performance high-temperature lightweight drive-train sand- and gravity-cast components (e.g.,	Base-metal industry; foundries; component and sub-system suppliers; end	T.b.d.	T.b.d.	HZG, TOMSK

TYPE	DESCRIPTION	CONFIDEN-TIAL	FORESEEN EMBARGO DATE dd/mm/yyyy	PRODUCT(S) OR MEASURE(S)	SECTOR(S) OF APPLICATION	TIMETABLE, COMMER-CIAL OR ANY OTHER USE	PATENTS OR OTHER IPR EXPLOIT-ATION (licences)	OWNER & OTHER BENEFICIARY(S) INVOLVED
				gear boxes)	users (notably aero-space)			
Commercial exploitation	AM50/AM60-based grain-refined materials with enhanced mechanical performance	Yes	T.b.d.	Crash-relevant lightweight high-pressure die cast (?) components (e.g., seat frames, steering columns/wheels)	Base-metal industry; foundries; component and sub-system suppliers; end users (notably automotive and aero-space)	T.b.d.	T.b.d.	HZG, TOMSK
Commercial exploitation	Electro-magnetic top-coil arrangement in conjunction with an inductive melting furnace for (in-situ) synthesis of master alloys and (nano)-composite materials	Yes	05/03/2015	Add-on equipment for existing furnaces; equipment for melt preparation	Aluminium and magnesium alloy suppliers; foundries	T.b.d.	WO 2015/0280 65 A1	ALD, ESA, UniBir, UniGre
Commercial exploitation	Electro-magnetic flow-nozzle arrangement for in-line de-agglomeration and dispersion of grain-refining particles in aluminium master alloys	Yes	T.b.d.	Aluminium master alloys with enhanced particle-size and spatial distribution, yielding better grain-refining efficiency	Foundries	T.b.d.	T.b.d.	ALD, INPG, KBM, UniGre
General advance-ment of knowledge	Theoretical/numerical tools for describing mixing, dispersion and de-agglomeration of particles in a metal melt under the	No	N/A	Non-commercial simulation software; follow-up and spin-off scientific research (to enhance fundamental	EC and national research programmes; industrial stakeholders	T.b.d.	T.b.d.	UniGre

TYPE	DESCRIPTION	CONFIDEN-TIAL	FORESEEN EMBARGO DATE dd/mm/yyyy	PRODUCT(S) OR MEASURE(S)	SECTOR(S) OF APPLICATION	TIMETABLE, COMMER-CIAL OR ANY OTHER USE	PATENTS OR OTHER IPR EXPLOIT-ATION (licences)	OWNER & OTHER BENEFICIARY(S) INVOLVED
	influence of electro-magnetic fields			understanding) and technological development services (e.g., of coil designs)				
Commercial exploitation	Numerical models, describing the mixing of micro- and nanoparticles in a metal melt	Yes	T.b.d.	Commercial simulation software; industrial engineering services	Equipment manufacturers; foundries; OEMs; universities and research organisations	T.b.d.	T.b.d.	ESI
General advance-ment of knowledge	Theoretical/numerical tools for describing micro-structure formation in magnesium-based composite materials	No	N/A	State-of-the art phase-field course for PhD students	Doctoral MSE training centres of universities	Course could be delivered from 2017	T.b.d.	WIGNER
Commercial exploitation	Aluminium- and magnesium-based cast components with enhanced performance	Yes	T.b.d.	Structural castings (seat frames, satellite frames); electrical cabling	Automotive; aero-space	T.b.d.	T.b.d.	Airbus-F, Airbus-G, BrabAl, CRF, ESA, VOLVO
General advance-ment of knowledge	Scientific publications and other dissemination activities	No	N/A	A raised academic reputation on the topic of aluminium- and magnesium-based grain-refined and nanocomposite materials	(Inter)national research and educational funding; global student and professional population	T.b.d.	T.b.d.	ESA, HZG, IMDEA, INPG, NTNU, R-Tech, TOMSK, UBRUN, UniGre, UniMan, UniRou, UniQue, WIGNER
General	Methodology for studying	No	N/A	Characterisation tool;	EC and national	T.b.d.	T.b.d.	IMDEA

TYPE	DESCRIPTION	CONFIDEN-TIAL	FORESEEN EMBARGO DATE dd/mm/yyyy	PRODUCT(S) OR MEASURE(S)	SECTOR(S) OF APPLICATION	TIMETABLE, COMMER-CIAL OR ANY OTHER USE	PATENTS OR OTHER IPR EXPLOIT-ATION (licences)	OWNER & OTHER BENEFICIARY(S) INVOLVED
advance-ment of knowledge	plasticity micromechanics of magnesium alloys and other anisotropic metals			follow-up and spin-off scientific research (to enhance fundamental understanding) and technological development services (e.g., of more ductile magnesium alloys)	research programmes; industrial stakeholders			

Further explanations as to the identified exploitable foreground are as follows.

- **Novel grain-refining master alloys for aluminium, produced by melt treatment with external fields (e.g., ultrasound).** The innovativeness of this result is in the higher efficiency of grain refinement (lower addition and/or enhanced product quality) versus conventional TiB-based master alloys.
- **Elektron21-based nanocomposite materials with enhanced creep resistance.** The innovativeness of this result is in the higher application temperatures (≥240 °C) and/or extended lifetime of magnesium castings by incorporation of AlN or Al_2O_3(-AlOOH) nanoparticles.
- **AM50/AM60-based grain-refined materials with enhanced mechanical performance**. The innovativeness of this result is in the higher strength and ductility of magnesium castings by incorporation of AlN or SiC (nano)-particles.
- **Electro-magnetic top-coil arrangement in conjunction with an inductive melting furnace for (in-situ) synthesis of master alloys and (nano)-composite materials.** The innovativeness of this result is in the efficient mixing and dispersion of particles in aluminium and magnesium melts, including cavitation.
- **Electro-magnetic flow-nozzle arrangement for in-line de-agglomeration and dispersion of grain-refining particles in aluminium master alloys.** The innovativeness of this result is in the pre-industrial set-up for continuous treatment of particle-containing melts.
- **Theoretical/numerical tools for describing mixing, dispersion and de-agglomeration of particles in a metal melt under the influence of electro-magnetic fields.** The innovativeness of this result is in the multi-physics and multi-scale coupling of models.
- **Numerical models, describing the mixing of micro- and nanoparticles in a metal melt.** The innovativeness of this result is in the algorithm for de-agglomeration of particles and break-up of particle clusters, as well as in the coupling of solidification with electromagnetics.
- **Theoretical/numerical tools for describing microstructure formation in magnesium-based composite materials.** The innovativeness of this result is in the inclusion of heterogeneous nucleation and (nano)-particle to solidification-front interaction.
- **Aluminium- and magnesium-based cast components with enhanced performance.** The innovativeness of this result is in the actual components using novel grain refiners or nanoparticle additions beyond the laboratory scale.
- **Scientific publications and other dissemination activities.** The innovativeness of this result is in the reports on original scientific results from the project of a non-confidential nature, leading to academic credits in terms of citations and recognitions (keynote/invited lectures, reviews for and editorials in top-tier journals).
- **Methodology for studying plasticity micromechanics of magnesium alloys and other anisotropic metals.** The innovativeness of this result is in the new approach for quickly and effectively characterising plasticity of anisotropic metals, using advanced characterisation techniques (including nano-indentation) and finite-element simulation.

PART C Report on Societal Implications

A General Information

Grant Agreement Number:	FP7-NMP3-LA-2012-280421
Title of Project:	**Physical Processing of Molten Light Alloys under the Influence of External Fields**
Name and Title of Coordinator:	Dr W.H. Sillekens

B Ethics

1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	*No*
2. Please indicate whether your project involved any of the following issues (tick box)	
RESEARCH ON HUMANS	
• Did the project involve children?	*No*
• Did the project involve patients?	*No*
• Did the project involve persons not able to give consent?	*No*
• Did the project involve adult healthy volunteers?	*No*
• Did the project involve Human genetic material?	*No*
• Did the project involve Human biological samples?	*No*
• Did the project involve Human data collection?	*No*
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	*No*
• Did the project involve Human Foetal Tissue / Cells?	*No*
• Did the project involve Human Embryonic Stem Cells (hESCs)?	*No*
• Did the project on human Embryonic Stem Cells involve cells in culture?	*No*
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	*No*
PRIVACY	
• Did the project involve processing of genetic information or personal data (e,g., health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	*No*
• Did the project involve tracking the location or observation of people?	*No*
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	*No*
• Were those animals transgenic small laboratory animals?	*No*
• Were those animals transgenic farm animals?	*No*
• Were those animals cloned farm animals?	*No*
• Were those animals non-human primates?	*No*
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	*No*

• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	*No*
Dual Use	
• Research having direct military use	*No*
• Research having the potential for terrorist abuse	*No*

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	**Number of Women**	**Number of Men**
Scientific Coordinator	0	2
Work package leaders	4	15
Experienced researchers (i.e. PhD holders)	19	80
PhD Students	1	7
Other (ADMIN, LEAR)	40	38

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	25
Of which, indicate the number of men:	21

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?	○ ●	Yes No

6. Which of the following actions did you carry out and how effective were they?

	Not at all effective				Very effective
❑ Design and implement an equal opportunity policy	○	○	○	○	○
❑ Set targets to achieve a gender balance in the workforce	○	○	○	○	○
❑ Organise conferences and workshops on gender	○	○	○	○	○
❑ Actions to improve work-life balance	○	○	○	○	○
○ Other:					

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

● No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

● Yes- please specify: guest lectures at schools and universities

○ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

● Yes- please specify: internet (YouTube) science videos

○ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

● Main discipline: Other engineering sciences (metallurgical and materials engineering)

●	Associated discipline: chemical sciences	●	Associated discipline: mathematics and computer sciences

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*	● ○	Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

● No
○ Yes- in determining what research should be performed
○ Yes - in implementing the research
○ Yes, in communicating /disseminating / using the results of the project

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

○ No
● Yes- in framing the research agenda
○ Yes - in implementing the research agenda
○ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
● Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
○ No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport	 ●

13c If Yes, at which level?

- ○ Local / regional levels
- ○ National level
- ● European level
- ○ International level

H Use and dissemination	
14. How many Articles were published/accepted for publication in peer-reviewed journals?	51
To how many of these is open access provided?	
How many of these are published in open access journals?	0
How many of these are published in open repositories?	0
To how many of these is open access not provided?	51
Please check all applicable reasons for not providing open access:	
■ publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ■ no funds available to publish in an open access journal ❑ lack of time and resources ■ lack of information on open access ■ other: lots of results were published at conferences and in their proceedings as well, the manuscripts of which are generally shared in repositories such as ResearchGate; some researchers have objections against open-access publishing	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	2

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	0
	Registered design	0
	Other	0

17. How many spin-off companies were created / are planned as a direct result of the project?	0
Indicate the approximate number of additional jobs in these companies:	

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑	Increase in employment, or	❑	In small & medium-sized enterprises
❑	Safeguard employment, or	❑	In large companies
❑	Decrease in employment,	■	None of the above / not relevant to the project
■	Difficult to estimate / not possible to quantify		

19.	**For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:**	*Indicate figure:*
	Difficult to estimate / not possible to quantify	■

I	**Media and Communication to the general public**
20.	**As part of the project, were any of the beneficiaries professionals in communication or media relations?** ○ Yes ● No
21.	**As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?** ○ Yes ● No

22 **Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?**

❑	Press Release	■	Coverage in specialist press
❑	Media briefing	■	Coverage in general (non-specialist) press
❑	TV coverage / report	❑	Coverage in national press
❑	Radio coverage / report	❑	Coverage in international press
■	Brochures /posters / flyers	■	Website for the general public / internet
❑	DVD /Film /Multimedia	■	Event targeting general public (festival, conference, exhibition, science café)

23 **In which languages are the information products for the general public produced?**

❑	Language of the coordinator	■	English
❑	Other language(s)		