Materials Science and Engineering Expert Committee (MatSEEC)

Metallurgy Europe – A Renaissance Programme for 2012-2022

Science Position Paper

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The aim of MatSEEC is to enhance the visibility and value of materials science and engineering in Europe, to help define new strategic goals, and evaluate options and perspectives covering all aspects of the field.

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Contents

Foreword 3

1. Introduction 4

2. Future Requirements 6

3. Future Research Topics to be Addressed 7

Material discovery 7

Novel design, metal processing and optimisation 8

Fundamental understanding of metallurgy 9

Abbreviations 10

Annexes 11

Annex 1. List of Experts, Contributors and Industrial Beneficiaries 12

Annex 2. Potential Beneficiaries from European Industry 14

Annex 3. References 15

Foreword

The Materials Science and Engineering Expert Committee (MatSEEC), founded at the European Science Foundation in October 2009, hereby presents this position paper entitled "Metallurgy Europe". This document was developed by a working group led by Professor David Jarvis and consisting of Professor Dierk Raabe, Professor Robert Singer, Professor Paul Van Houtte, Dr Constantin Vahlas, Professor Neil Alford, Professor Krzysztof Kurzydlowski, Professor Risto Nieminen, Professor Andreas Mortensen, Professor Herbert Gleiter, Professor Michael Loretto, Professor Yves Brechet and Professor Hans-Jörg Fecht.

Europe is very prominent in the field of metallurgy – not only in academic research and invention, but also in industrial alloy production, down-stream processing, end-user applications and recycling. Metals and alloys can be found in a wide range of high-tech products such as airplanes, cars, trains, ships, satellites, propulsion systems, power-generating turbines, batteries, fuel cells, catalytic reactors, wind turbines, magnets, electrical cabling, pipe lines, robots, orthopaedics, computers and mobile phones, and many, many more. A modern world without metals and alloys is inconceivable.

In order to maintain the high standard of living in Europe, it is essential to keep investing in the next generation of metallic products. This will help us aim for the future and tackle some of the societal challenges related to energy, renewables, climate change reduction, health care and job security.

Many national studies have recently been carried out in Europe. They have all concluded that metallurgy, as a fundamental and applied research topic, is suffering from low levels of public investment and student enrolment. More must be done to promote R&D in this field in Europe.

Furthermore, given the huge added-value of metal products, totalling 1.3 trillion Euros per annum, Europe must increase and coordinate its efforts across the entire materials value chain – from material discovery, alloy design, processing, optimisation, to scale-up and in-service deployment. This will enable European companies to accelerate significantly the pace of innovation in metallurgy.

MatSEEC recommends the creation of the "Metallurgy Europe" research and development programme, based on substantial and sustained contributions from the EC (Horizon 2020), national funding agencies, EU industry, EIROforum partners and academia. This report calls European decision-makers and funding agencies to act and to implement this central recommendation.

Dr Patrick Bressler
MatSEEC Chair

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1. Introduction

Key Recommendations

Metallurgy is a fascinating field, full of modern discoveries, commercial opportunities and industrial utility. To help solve the grand challenges facing society, it is imperative to continue investing in high-value metal products and their manufacture. European industry, academia and funding agencies now have a once-in-a-generation opportunity to establish a vibrant, well-coordinated and large-scale ***"Metallurgy Europe"* Research Programme** that can design, develop and deploy the next set of revolutionary alloys and composites for key industrial applications, including **energy, renewables, mobility and health**[1,2]. This programme initiative is timely, practically useful and economically necessary. Therefore, the ESF's Materials Science and Engineering Expert Committee (MatSEEC) recommends:

- The creation of the ***"Metallurgy Europe"*** research programme, based on public and private contributions from the EC (*Horizon 2020*)[3], national funding agencies, EU industry, EIROforum partners and academia
- Sustained and substantial funding of the order of 100 M€/yr for at least 10 years.

No other materials have contributed more to the **technological progress of humankind** over the past 10,000 years than metals and alloys. In fact, alloys have influenced human life so profoundly that some have become synonymous with different eras of human development – the Copper Age, the Bronze Age, the Iron Age and the Nuclear Age.

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, renewables, aeronautics, space, security, automotive, shipping, electrical and chemical engineering, scientific equipment, machinery, factory tooling, construction, packaging, computing and health care. **Without metals and alloys the modern world would be inconceivable and could not function successfully.**

There are 87 known metals in the periodic table, 60 of which are commercially available. Amongst them, the most commonly used industrial alloys are based on Fe, Al, Cu, Ni, Cr, Zn, Pb and Sn. More specialised metals include for example Ti, Mg, Co, Mn, Mo, V, Y, Zr, Nb, Ta, Hf, W, Re, Be, Ca, Na, K, Li, In, Ga, Ge, Cd, Hg, Bi, Sb, La, Ce, Pr, Nd, Gd, Sm, Sc, Sr, Th and U; while the precious metals comprise Ag, Au, Ir, Os, Pd, Pt, Rh and Ru. These metals and their alloys can be found in a **wide range of products** such as aircraft, cars, trains, ships, satellites, propulsion systems, power-generating turbines, batteries, fuel cells, catalytic reactors, wind-turbine magnets, electrical cabling, robots, orthopaedics, computers and mobile phones – to name but a few. Just as an example, a standard laptop computer can contain over 20 different metals, many of which are considered **"critical"** to Europe[4].

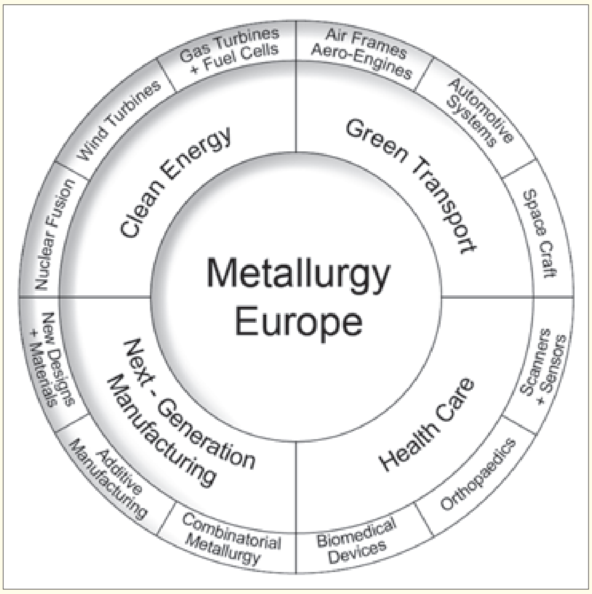

Figure 1. Programme overview

As a result of the **ubiquity of metals** it is no surprise that the metal industry, and its associated branches, is one of the largest technical sectors in the EU. The combination of primary metal production, alloy creation, downstream processing, integrated metal products and alloy recycling accounts for 46% of all EU manufacturing value and **11% of the EU's total gross domestic product** (GDP)[5]. This equates to an added value of about €1.3 trillion annually in the EU alone, or €3.5 billion per day.

In addition to economic value, metallurgy can make a very significant contribution to a number of the future **challenges facing EU society**[4,6,7,8,9]. These include:

- **the careful use, saving, preservation and recycling of raw materials**
- **the development of CO_2-reducing technologies and renewable energy sources**
- **the modernisation and energy efficiency of EU transport systems**
- **the promotion of EU security and consumer safety**
- **the development of improved health care products for an ageing population**
- **the stimulation of the EU manufacturing sector**
- **sustainable product development and resource efficiency in general**

In order to secure strategic industrial strength in these areas, it is imperative that the EU's scientific and industrial communities continue making new metallurgical discoveries. To compete successfully with the US, China and Japan and claim patent priority on new metal-based products, **European companies must be able to significantly accelerate the pace of material discovery, alloy design, processing, optimisation, scale-up and deployment**. Failure to do this will put Europe at a serious disadvantage – technologically and economically.

Rather unfortunately, metallurgical research in academia has suffered over the past 15 years, being seen by many funding agencies as a "twilight topic". As a result, there have been relatively low levels of public investment and student enrolment in metallurgy in most EU countries, as clearly noted in many national studies[10,11].

However, a renewed optimism is now emerging in the metals sector, and European industry is clearly calling for a unifying programme to stimulate high-value metallurgical research. The establishment of a vibrant and well-coordinated ***"Metallurgy Europe"* Programme**, involving industry, academia and governmental agencies is timely, practically useful and economically necessary. The full value and impact areas of the ***"Metallurgy Europe"*** research programme are captured in Figure 1.

Support for this multidisciplinary programme is significant. The attached list of benefitting companies, as a collective, represents over a tenth of the EU economy. **Sustained and substantial funding of the order of 100 M€/yr for at least 10 years is required, in order for the *"Metallurgy Europe"* Programme to be most effective.** This would represent a strategically leveraged combination of public and private contributions from the EC (*Horizon 2020*), national funding agencies, EU industry, EIROforum[12] partners and academia. Major involvement of SMEs (>25%) is also anticipated in such a programme.

Based on two years of consultation with over 150 key industrial, academic and governmental organisations working in the field of metallurgy and metal products, a highly ambitious research programme has materialised. **This research programme has identified 17 future material requirements and 50 cross-sectoral metallurgical R&D topics, to be funded during the 2012–2022 time period.** Such a flagship programme would fund 400–500 researchers across Europe, with strategic connections to other countries such as Australia, Brazil, Canada, Israel, Russia and South Africa.

2.
Future Requirements

The future requirements for **metals, alloys** and **metal matrix composites** include *inter alia*:

(i) the accelerated synthesis, discovery and insertion of new alloys into real applications;
(ii) higher *specific* mechanical performance for lightweight structural alloys;
(iii) higher temperature capabilities and alloy phase stability, especially for energy systems or other extreme environments;
(iv) new lightweight and damage-resistant material architectures, in particular for transportation;
(v) new durable alloys for pipelines, supercritical CO_2 transport, gasification and geothermal plants;
(vi) better biocompatibility and/or resorbability for medical applications;
(vii) improved understanding and control of degradation, corrosion and irradiation phenomena;
(viii) special physical or multifunctional properties (such as thermoelectric, magnetic, superconducting, shape memory, optical, phononic, acoustic);
(ix) alloy design aided by sophisticated modelling, genetic algorithms, neural networks and inverse modelling techniques[13];
(x) more predictive, physically-based simulation of properties and processing behaviour of metal products;
(xi) embedded sensors, diagnostic capabilities, in-process monitoring and closed-loop process control;
(xii) advanced material and defect characterisation using microscopy (photons, electrons, ions), X-rays, neutrons, positrons or sonic methods;
(xiii) precise measurement and prediction of thermophysical, thermomechanical, thermodynamic, thermocapillary, wetting and diffusive properties in multi-component metallic systems;
(xiv) novel metal processing including improved alloy production, metal forming, near-net-shape and additive manufacturing, powder processes, HIPping, heat treatment, surface treatment, corrosion protection, joining techniques and recycling;
(xv) lifetime performance assessment, including time-dependent microstructural evolution and multi-parameter optimisation of performance[13];
(xvi) resource-efficiency and more widely available or lower cost constituent elements[4];
(xvii) better environmental performance, REACH compliance, recyclability and sustainability, tracked by ISO-guided life-cycle analyses (LCA).

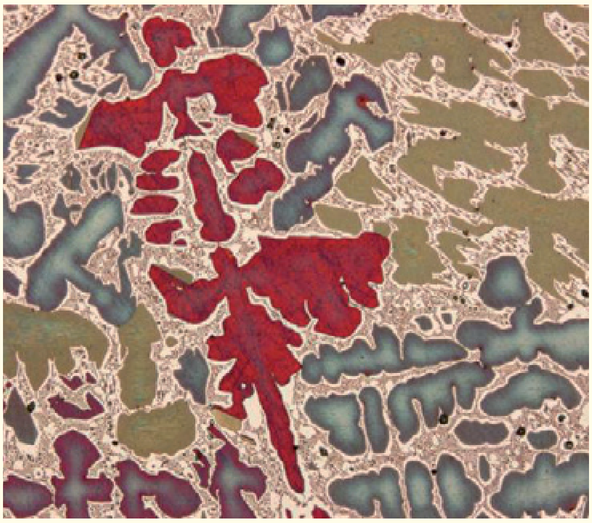

Figure 2. Cast dendritic microstructure of a bronze alloy

3.
Future Research Topics to be Addressed

Fifty research topics have been identified as having **high strategic and technical value for European industry in the coming decades.** These topics are categorised according to (i) material discovery, (ii) novel design, metal processing and optimisation, and (iii) fundamental understanding of metallurgy. They naturally comprise R&D activities on theory, experimentation, modelling, material characterisation, property testing, prototyping and industrial scale-up. The following list is of strong interest to a variety of industrial sectors.

(i) Material discovery:

- **high-throughput synthesis and combinatorial screening technology** to accelerate the discovery and implementation of new high-performance alloys and other next-generation materials;
- **metal–matrix composites** (MMCs), employing both micro and nano-scale reinforcers, for a variety of lightweight structural components (Mg, Al, Ti), thermal (Cu, Al), low-friction, wear, impact-resistant, electrical applications, as well as biocompatible materials;

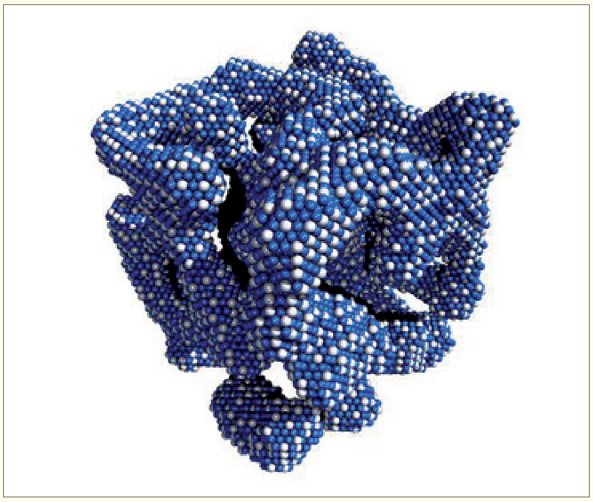

Figure 3. Atomistic model of advanced NiAl alloy catalysts

- lightweight high-strength **intermetallics** (e.g. aluminides, silicides and ductile lanthanides) as well as **cermets** for turbo-machinery, aero-engines and space applications;
- **high-entropy** multi-component solid solution alloys with unique structural properties, of interest for high temperature applications;
- **core-shell precipitation-hardened alloys** (e.g. Al–Li–Sc, Al–Mg–Sc, other), and associated heat treatment protocols, for high-specific strength components;
- high-strength **TRIP and TWIP steels, super-bainite alloys, new ODS steels** and **bearing steels,** for numerous structural, transport, energy and security applications;
- **refractory alloys** (e.g. W, Ta, Re, Hf, Nb, Mo, V, PGMs) for the most extreme high-temperature and oxidative environments, including also nuclear fusion plasma-facing applications;
- lightweight and new **bulk metallic glasses** (e.g. Mg, Al, Ti, Fe-based BMGs), and their amorphous/crystalline composites, for niche structural, functional, tribological, corrosion-resistant, biomedical and micro-part applications;
- **quasicrystalline** and **complex metallic alloys** (CMAs) with unique crystallography, mechanical, physical, tribological and chemical properties;
- **shape memory alloys** (SMA) and foams, both thermally and magnetically-induced, for morphing structures, large-extension actuators, vibration dampers, sensors, heat engines and biomedical components;
- **magnetocaloric alloys,** based on low-cost widely-

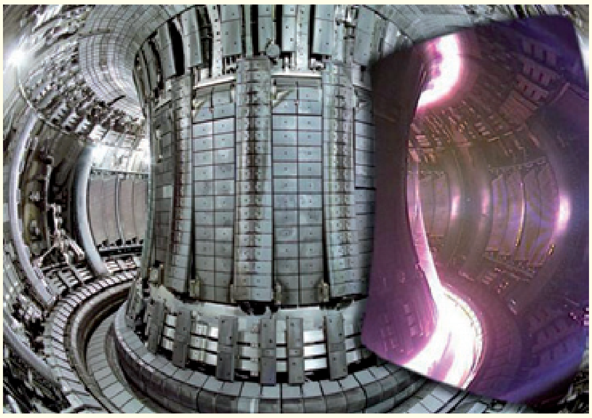

Figure 4. JET nuclear fusion reactor

available elements, for application in cooling and novel refrigeration systems;
- nanoscale **magnetic material mixtures** for high-energy product in permanent magnets, also targeting reduced rare earth element content (e.g. Nd, Dy);
- doped, micro- and nanostructured high-ZT **thermoelectric alloys** for heat recovery, energy harvesting and Peltier cooling;
- ductile metallic-based higher-T_c **superconducting alloys** for electrical and magnetic applications, such as in wind turbines, MRI scanners, power transmission (ideally, alloys that function without helium cooling);
- nanostructured **energetic metal/alloy powders** for pyrotechnic applications and propulsion systems;
- **metal-based catalysts and electrodes** for electro-chemical cells, hydrogen fuel cells, electrolysis units, hydrogenation chemical reactors, based on either PGMs or new alternatives;
- non-consumable corrosion-resistant **inert anodes** of use in metal oxide electrolysis (Al, Fe, Ti, etc.);
- novel **nanocrystalline metal hydrides** (e.g. Mg, Al or Li-based) with very fast ab- and desorption kinetics, for hydrogen storage.

(ii) Novel design, metal processing and optimisation:

- **ultra-lightweight and cellular architectures**, including metal foams, hollow spheres, wire-woven structures, hollow-tube microlattices, hybrid structures, interlocking blocks and auxetics, for broad application in damping, energy transport, battery storage, thermal protection, catalysis, as well as biomedical stents and orthopaedic devices;
- **nanocrystalline multifunctional alloys** produced by innovative processes such as severe plastic deformation (SPD) or accumulative roll bonding (ARB) for various structural components;
- **bulk nanostructured Al and Cu alloys** for advanced electrical conductors with high strength and electrical conductivity;
- fine-grained Ti or Al alloys for **superplastic forming** (SPF), for transport structures;
- other **innovative forming techniques,** such as incremental sheet forming (ISF), explosion forming or creep forming;
- new metallurgical methods for **powder production** and powder metallurgy, including for example new atomisation, cold spraying, spray forming and coating techniques;
- laser, electron-beam or plasma-arc **additive manufacturing** (AM) of complex 3D-shaped components, including functionally graded structures with variations in chemical composition, microstructure and/or porosity; as well as new surface treatment protocols like laser nitriding or surface glazing;
- novel AM processes that use low-cost, **environmentally friendly feedstock materials**, such as powder or meltless wire blends;
- processing methodology and establishment of **new design rules**, especially relevant to AM (above);
- **nanostructured templated and hierarchical surfaces** (e.g. in Cu) via electrodeposition, for use in boilers, heat exchangers and pipes;
- **pressure-infiltrated casting, micro-casting and imprinting** of alloys, composites and BMGs, for

Figure 5. Ariane V rocket

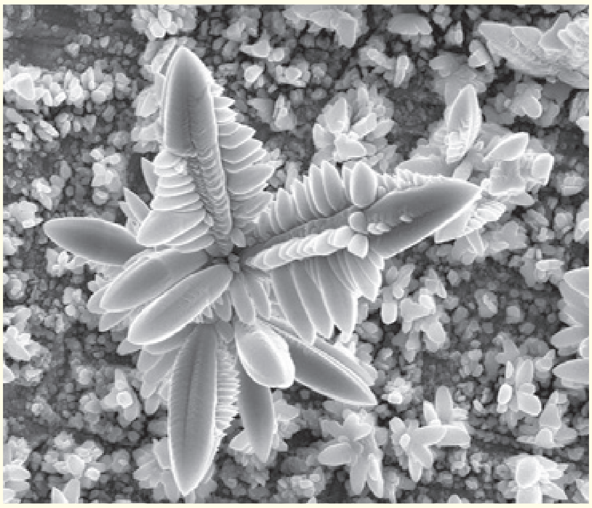

Figure 6. SEM image of a magnesium dendrite
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specialised components, micro-parts, micro-fluidic and MEMS devices;
- **coating and corrosion protection technologies**, including sol–gel, electrodeposition, CVD, PVD, magnetron sputtering and ionic liquid techniques;
- **de-alloying techniques** to produce nano- and microporous metals for catalysts, coatings, filters, biomedical scaffolds, etc;
- **embedded sensing** within metallic components, including thermocouples, strain and stress gauges, as a way of gaining critical thermomechanical information;
- **metallic phononic and sonic crystals** for future sound damping and thermal management;
- **water- and ice-repellent metallic surfaces**, for offshore, maritime, aerospace and Arctic applications;
- **metallurgy of surfaces and interfaces** in order to design parts with improved corrosion, wear and fatigue properties, as well as novel interfaces with polymers for gluing;
- novel **metallurgical processing under the influence of external fields**, such as power ultrasound, electromagnetic fields, microwave treatment, electrical pulsing, laser shock peening or sonoelectro-chemistry;
- novel processing of **metallic emulsions**, based on immiscible monotectic alloys, in order to create two-phase micro/nanostructures for functional applications;
- **low melting-point liquid alloys for heat transfer** e.g. high-conductivity heat exchangers, solar thermal collectors, MHD generators or liquid metal batteries;
- **joining similar metals,** as well as **dissimilar materials** such as Al and Fe via friction stir welding, or Ti and CFRP;
- radically new and **biologically inspired approaches** to the design of metallic alloy structures and surfaces, for example hierarchical alloys/foams/composites, vascular-shaped cooling channels, superhydrophobic or low-drag surfaces;
- **cost-conscious alloys and structures for developing world and humanitarian aid** applications, including water filtration, moisture/fog collectors, solar thermal collectors, solar cookers, off-grid thermoelectric roofing, rapidly-deployable tents and habitats;
- **recycling and refinement** of high-tech metals, especially waste powders, swarf and machine chips, containing critical materials such as rare-earth elements, Ti, PGMs, Nb, Ta, Co, Ni, Cu, Mg, etc;
- **metallurgical processing and purification of rare-earth elements,** supplied by EU autonomous sources (e.g. in Scandinavia).

(iii) Fundamental understanding of metallurgy:

- **computational alloy design** aided by electronic and atomistic modelling (DFT, MD, kMC), microstructural and micro-mechanical simulation, genetic algorithms, data mining and neural networks;
- predictive **computer modelling of degradation phenomena**, such as oxidation, corrosion, stress-corrosion cracking, fatigue, creep, wear, radiation damage, liquid metal embrittlement and hydrogen embrittlement;
- the above **multi-scale modelling strategies** shall focus on virtual design, virtual processing and virtual testing of advanced metallic alloys for engineering applications, so that new materi-

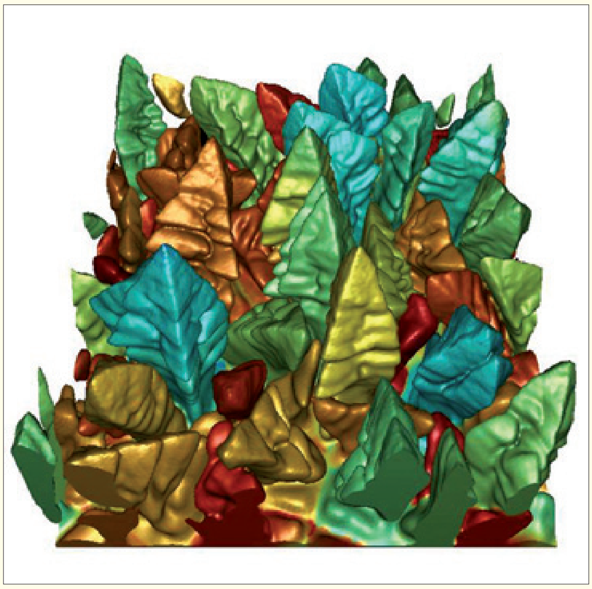

Figure 7. Simulation of titanium aluminide columnar dendrites
© L. Granasy, Wigner Research Centre, Hungary

als can be designed, tested and optimised before they are actually manufactured in the laboratory or factory;

- fundamental studies of **nucleation**, modelling solid–liquid interface free energies and the **discovery of novel grain refiners,** for the purposes of producing very fine-grained equiaxed cast microstructures;
- high-accuracy measurement and computational techniques for determining **thermophysical, thermomechanical, thermodynamic, diffusive, thermocapillary and wetting properties** of new alloys, including high-precision experiments in microgravity using electromagnetic levitation;
- pushing the frontiers of ***ex-* and *in-situ* characterisation of nano/microstructures**, towards an improved understanding of nucleation, defects, dislocations, deformation and damage mechanisms, as well as solid-state transformations. This requires improved methods, in particular in 3D atom probes, high-resolution electron microscopy (HR-SEM/TEM), and powerful large-scale facility X-ray/neutron-based diffraction, scattering, imaging and spectroscopy for time-resolved and *in-situ* studies of structure assembling/response during realistic processing/working conditions;
- new approaches for studying **grain boundary engineering**, hetero-interface design, micro- and nano-texture, twinning, recrystallisation and spinodal decomposition of alloys;
- mechanistic understanding and **life prediction** for complex degradation mechanisms at high temperature resulting from interacting mechanical and environmental effects;
- deep understanding of **fracture and damage mechanics** of newly developed alloys, composites and material architectures;
- alloy behaviour and fracture mechanics, in particular at **cold and cryogenic temperatures**, for Arctic, offshore and space applications;
- reliable databases containing eco-information about commercial elements and alloys, for the purposes of **life-cycle assessment** and **environmental auditing** of new metallic products, as well as **REACH-compliant** alloy design strategies;
- promotion of **quality assurance** and **waste elimination** schemes, such as *Gemba Kaizen*. Only with good quality assurance, standardisation and waste reduction can the aforementioned metallurgical research be properly transferred to industry and converted into high-quality, high-added-value products.

Figure 8. Additively manufactured titanium components for aerospace © Norsk Titanium, Norway

Abbreviations

CFRP: Carbon Fibre Reinforced Composite
CVD: Chemical Vapor Deposition
DFT: Density Functional Theory
kMC: Kinetic Monte Carlo
MD: Molecular Dynamics
MEMS: Microelectromechanical systems
MHD: Magneto-Hydrodynamics
MRI: Magnetic Resonance Imaging
PGMs: Platinum Group Metals
PVD: Physical Vapor Deposition
SEM: Scanning Electron Microscopy
TEM: Transmission Electron Microscopy
TRIP: Transformation Induced Plasticity
TWIP: Twinning Induced Plasticity
ZT: Figure of Merit

Annexes

Annex 1. **List of Experts, Contributors and Industrial Beneficiaries** (non-exhaustive)

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- Professor David Wimpenny, *MTC, Coventry and De Montfort University, Leicester, UK*
- Professor Philip Withers, *University of Manchester, UK*
- Professor Xinhua Wu, *ARC CoE Design in Light Metals, Australia*
- Professor Michael Zehetbauer, *University of Vienna, Austria*
- Professor Sybrand van der Zwaag, *TU-Delft, The Netherlands*

Annex 2. **Potential Beneficiaries from European Industry** (non-exhaustive)

Metallurgy sector
- ThyssenKrupp
- Tata Steel Europe
- SSAB
- ArcelorMittal
- Sandvik
- Salzgitter
- Outokumpu
- Magnesium Elektron
- Hydro Aluminium
- Norsk Titanium
- Scatec Group
- Johnson Matthey
- Alfa Aesar
- Aubert & Duval
- Plansee
- Elkem Group
- Molycorp Silmet
- Less Common Metals
- Bruker Superconductors
- Rheinmetall
- London & Scandinavian Metallurgical Co.
- Wieland Group
- Advanced Metals Group – AMG
- Aurubis
- Evonik
- Intrinsiq Materials
- Umicore
- Swissmetal
- Heraeus Group
- NNT Boron
- Nickelhütte
- BASF
- GfE Metalle
- Novelis

Advanced manufacturing sector
- Arcam
- Renishaw
- Irepa Laser
- Trumpf Group
- Concept Laser
- The Welding Institute (TWI)
- Bodycote HIP
- TermoGen
- AdaptaMat
- Flame Spray Technologies
- Manufacturing Technology Centre
- Materialise
- AvioProp
- Flamac
- Tecnalia
- Access
- Tital Feinguss
- Precicast
- Sulzer Group
- SKF Group
- Doncasters Group
- Brabant International
- Mahle Group
- Schaeffler Group
- TLS Technik
- Sandvik Osprey Powder Group
- InnovalTec
- ESI Group
- Granta Design
- Magma
- Fraunhofer Gesellschaft
- Ceram
- ThermoCalc
- NPL Ltd
- BAM
- PX Group
- CSEM
- ALD Vakuum Technologies
- Rübig
- Hauzer Techno Coating
- Oerlikon
- VTT Technical Research
- GKN Sinter Metals
- Boehler Forging
- EOS
- Raufoss Technology
- LPW Technology
- MBN Nanomaterialia
- Hoffmann Group
- Turbocoating
- Gervaux

Aerospace sector
- Thales Group
- EADS Innovation Works
- Astrium
- Airbus
- Eurocopter
- Rolls-Royce
- Avio Group
- Safran Group
- MTU Aero Engines
- Fokker Technologies
- Bombardier
- Finmeccanica
- BAE Systems
- Ruag Group
- Sener Group
- Dassault Aviation
- Volvo Aero
- SSTL
- OHB-System
- Saab

Automotive sector
- Volvo Group
- Jaguar Land Rover
- Centro Ricerche Fiat
- PSA Peugeot Citroen
- Renault
- Volkswagen
- BMW
- Daimler
- MAN Group
- Bosch
- Kolbenschmidt Pierburg
- Valeo
- Piaggio
- Precer Group

Energy sector
- Siemens
- ABB
- Areva
- Rolls-Royce
- Alstom
- ITER
- Vestas
- Gamesa
- Doosan Babcock
- Vattenfall
- MAN Turbo
- Ansaldo Energia
- BP
- Shell
- Statoil
- Total
- Kvaerner

Biomedical sector
- Stryker
- Sandvik Medical Solutions
- Renishaw
- Biotronik
- Philips Healthcare
- Geratherm Medical
- Bruker AXS
- Timplant
- Simex Medizintechnik

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