European Commission

Metallurgy made in and for Europe

The Perspective of Producers and End-Users

Roadmap

Research and Innovation

EUROPEAN COMMISSION

Directorate-General for Research and Innovation
Directorate D – Key Enabling Technologies
Unit D.3 – Advanced Materials and Nanotechnologies

Contact: Achilleas Stalios

E-mail: Achilleas.Stalios@ec.europa.eu
RTD-PUBLICATIONS@ec.europa.eu

European Commission
B-1049 Brussels

EUROPEAN COMMISSION

Metallurgy made in and for Europe

The Perspective of Producers and End-Users

Roadmap

Edited by Achilleas Stalios
Rapporteurs: Victoria Folea and Edmond Cahill

2014 Directorate-General for Research and Innovation

Acknowledgements: Special thanks are due to the European Technology Platform for Advanced Engineering Materials and Technologies (EuMaT), as well as to the Materials Science and Engineering Expert Committee (MatSEEC), for their kind assistance to the organisation, follow-up and carrying out of this work.

LEGAL NOTICE

Luxembourg: Publications Office of the European Union, 2014

ISBN 978-92-79-43310-8
doi 10.2777/11914

Contents

1 INTRODUCTION

On the 28th of October 2010 the European Commission adopted the Communication on "An integrated industrial policy for the globalisation era" on the initiative of Vice-President Antonio Tajani and where the main message was "Industry must be placed centre stage if Europe is to remain a global economic leader". This Communication, a flagship initiative of the Europe 2020 strategy, sets out a strategy that aims to boost growth and jobs by maintaining and supporting a strong, diversified and competitive industrial base in Europe offering well-paid jobs while becoming more resource efficient.

There are 90 naturally occurring chemical elements on Planet Earth. Eighteen elements are classically described as non-metals (e.g.: noble gases and halogens), seven as half-metals. The remaining 65 chemical elements are metals, 60 of which are commercially available. Metals and alloys are essential for a vast number of industries and industrial products. Some 20+ metals are considered "critical" for Europe's industrial future.

Metallurgy concerns the materials science and the technology of metals, the processing, product building and industrial exploitation of metals. It is the core activity underpinning primary metals production, alloying and processing, production and material flow (e.g.: reuse and recycling). These activities account for 46% of the total manufacturing value and 11% of the total gross domestic product (GDP) in the European Union.

Metals and metal processing technology have named civilization periods such as bronze and iron ages.

At present metallurgy requires expenditures of energy, extraction of primary and secondary raw materials – coal, ore, use of expensive alloying elements, pre-processing, etc. However, such expenditures continue to decline as processes become more efficient and proficient, limiting the risk of pollution. The development of new technologies, including nanotechnologies, raw material and waste minimization and advanced energy conservation has always been at the forefront of metallurgical process innovations.

Thus, further development of material science and metallurgy provides opportunities for the foreseeable future to enhance classical metallurgy, taking into consideration its major problems in economy, energy, environmental and social directions, with enhanced existing and fundamentally new processes. These processes will have a significant impact on both the global economy and the social image of society.

The strategy of the metallurgy industry has had and will continue to have four main thrusts:

- Meeting new demands on new products and applications and promoting product innovations to meet the eternal needs of new social and economical challenges
- Enhanced materials properties and performance
- Improved exploration, mining, metal recovery thanks to extractive metallurgy, manufacturing and processing, recycling
- Enabling technologies and infrastructure.

The field of metallurgy covers the entire innovation landscape from extracting metals from a resource (whether primary or secondary), discovering scientific basics to developing new applications and products, large-scale production innovation, monitoring metallurgical changes of the materials under service conditions, recycling the materials. Metallurgy contributes significantly to solutions of the grand societal challenges in Europe.

Historically, Europe has been strong in metallurgy. However, to compete today with America and Asia and to maintain its patent priority on metal-based products, Europe must increase its efforts to make metallurgical discoveries and develop innovation in its products and production capabilities. Many stakeholders have pointed to the necessity of reinforcing Europe's strategic industrial strength in metals. They have called for a pan-European effort to strengthen the "metallurgical infrastructure" in Europe consisting of academic, industrial and governmental organizations through a dedicated R&D and Innovation programme for metallurgy in Europe.

It was recognised that for this effort to be successful, it must fulfil four standard quality criteria:

- The goal of the programme must be ambitious and ground breaking,
- The teams engaged must be at the frontier of science,

- The benchmarks and milestones must be appropriate and adequately measureable,
- The control feedback must be accurate, fast and effective in directing the programme.

WHY THIS ROADMAP?

A roadmap identifies alternate technology paths for meeting certain performance objectives. It is driven by a market need and is an important tool for collaborative technology planning and coordination for companies.

Roadmapping is a planning process to help identify, select and develop technology alternatives to satisfy a set of (final) product needs. It also serves give confidence to funding providers to commit resources.

Even today there is a tendency for forward planning to be a linear extrapolation from current competences and capabilities which results in a future of limited opportunities (Figure1). By focusing on areas of future need and projecting backwards to the present, a broader scope of potential can be addressed and multiple pathways found to reach the targets (Figure 2). There are a range of methodologies which support this approach

Linear Extrapolation: The Corporate 'Mission'

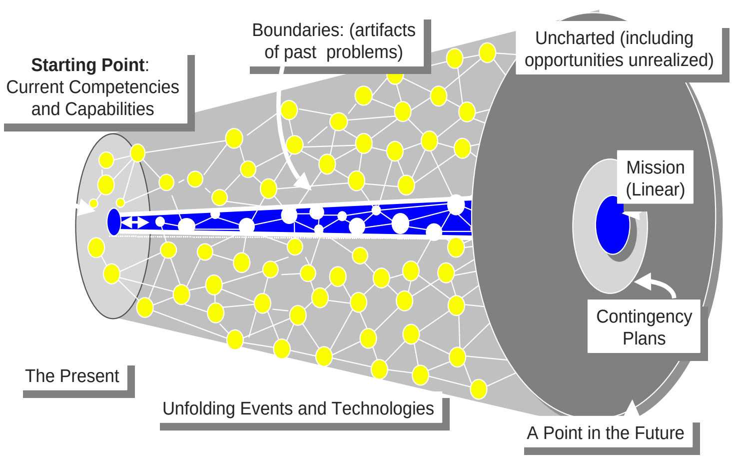

Fig. 1.

Managing the Future from the Present

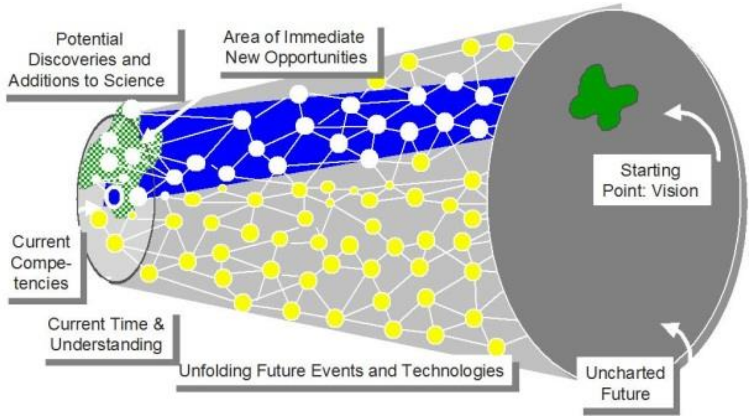

Fig. 2.

(Source: Lecture by Rebecca Radnor, North Western University 1999 Culture Issues in Global Technology Relations)

The approaches employed in pursuing a Figure 2 methodology will cater for the inclusion of disruptive concepts. These approaches are equally valid at the level of Member States and the EU.

Benefits of Roadmaps

Roadmaps provide cross-functional understanding of strategic issues and sensitization to technology trends, gaps in technology in meeting needs and competitive position for technology. They also provide an easily understood process for communicating issues regarding allocation of resources. They promote management of projects through structured technology review and learning that can be applied when evaluating future technology opportunities.

2 METHODOLOGY

The first step on this route was to take stock of metallurgy in Europe today, map the existing infrastructure, identify the strengths and weaknesses, and to develop a roadmap for academia and industry. It focuses on the perspectives of end-users and producers. The exercise focuses on the time scale 2020-2030 and sketches product demand until 2050.

This roadmap focuses on metallurgy products for new materials and improved material performance rather than processes, which in principle are addressed within the proposed PPP SPIRE, other than standard metallurgy used for basic steel or aluminium-based products. As far as steel is concerned this roadmap is complementary with that made by ESTEP (The Steel European Platform).

However, the entire innovation cycle for new and multigrade metals and their processing needs to be addressed more consistently in Europe. End-users and near-net-shape manufacturers benefit from new metallurgy performances once these have been processed and tested on industrial scale. Metallurgical science for new materials and improved material thus needs process know-how for constant back-up and for improving functional links between the material and its processing. In that context the industrial value chain is vital part of the "metallurgical infrastructure" in Europe. The sectors chosen for this roadmap were three transport sectors, (Marine, Surface and Aeronautics), Consumer Goods, Construction, Tooling, Energy, and Electronics. These sectors cover almost the full range of metal use and represent a wide array of disparate demands on metallurgy. A further report was prepared on Enabling Tools, which covered a subject of critical importance for all sectors across the field of metallurgical science and exploitation.

The design of the Roadmapping Process was outlined by the Steering Group and was finalised following consultation on the 30th of September 2013 with the rapporteurs. The exercise was launched in an initial workshop for experts, rapporteurs and stakeholder representatives on the 7th and 8th October 2013. At this workshop the wide range of stakeholders and representative bodies presented their vision for the future of metal materials and metallurgy over the time horizon of the roadmap and provided a picture of end-user requirements. The Sector groups of experts, with their rapporteurs, then commenced a review of the state of the art for metallurgy and metals in each sector and began assembling information on the needs and challenges facing each sector. During October and early November the Sector groups refined their reports. These were supplied to the rapporteurs of the main report, which was drafted in November. At a workshop for Sector group rapporteurs on the 10-11th December 2013 the final sector inputs to the roadmap were agreed and the main report rapporteurs completed the Roadmap on 12-13th December in Brussels.

The structure of the Sector reports followed a template agreed between the Steering Group and the rapporteurs.

1. Status quo: state of the art and on-going research EU Metallurgy capacity and competences (strengths and weaknesses)
2. Challenges – Needs
3. Medium term goals - recommendations (by 2020)
4. Long term goals - recommendations (beyond 2020)
5. Champions for point 3 and 4.
6. Horizontal issues (Life cycle-recycling- environmental issues-education-standardization).

Boundary conditions

The Metallurgy Roadmap provides a detailed agenda of the efforts needed over the next 20 to 40 years on R&D for metal materials applications in the EU, based on the best available information today. In view of the large scope of the field of materials research and its horizontal character, this Roadmap needs to be seen in conjunction with and complementary to a range of other initiatives in the broader materials research horizon. On the edge of this Roadmap is the challenge of metals supply to Europe. Unlimited and affordable metal supply is not a reality anymore and specific challenges related to securing metal supply, and more generally raw materials supply to Europe has been investigated and reported in different roadmaps, including the EIP-RM SIP (European Innovation Partnership on Raw Materials Strategic Implementation Plan). Amongst the proposed solutions, metallurgy, and in particular ***extractive metallurgy*** represents a significant asset for Europe to take back the leadership on metal supply as Europe ambitions to discover innovating ways to sustainably and economically recover metals from more complex and lower grade resources. Another approach is the broader materials research substitution of one type of material for another as response to application drivers. The Metallurgy Roadmap is focussed on responses from the metal materials sector to the same application drivers. Specifications of desired properties and performance indicators should be recognised as current minimum standards to be achieved which may have to be modified as time passes to reflect the dynamic nature of the field.

Each of the sectoral reports has focused on the requirements of the particular sector to meet future application needs. As a result, for individual metals, a range of desired properties and performance criteria have emerged. The Roadmap will focus particularly on the highest level of requirement in each case. Where lower levels of performance are needed in individual sectors issues of scale and cost will dictate materials choices.

A co-ordinated approach for metallurgical development will be critical to success

The innately disjointed and multidisciplinary character of the metallurgical community presents barriers to creating the required networks for sharing results and information. One of the principal challenges is to encourage scientists to continue acting not as individual researchers but as part of a powerful network collectively analysing and using data generated by the larger community. These challenges must be overcome by intensifying and reinforcing the trends in this direction.

Rapid advances in metallurgical discovery and design will be realized not merely through one-to-one interactions or existing relationships, but also through manifold layers of association among state and Commission agencies, academia, and industry. The implementation of the roadmap needs to develop and support a coordinated effort to establish the infrastructure and protocols to facilitate collaborations among academic, government, and industrial participants, both by function (experimentalists, engineers, theoretical scientists, and computer scientists) and institution (academia, research laboratories, small and medium enterprises, and large companies). New partnerships will need to be promoted between manufacturers and software developers to rapidly convert science based metallurgical computational tools into engineering tools.

The ultimate goal would be to generate computational tools that enable real-world materials developments, that optimize or minimize traditional experimental testing, and that predict materials performance under diverse product conditions. An early benchmark will be the ability to incorporate improved predictive modelling algorithms of materials behaviour into existing product design tools.

Achieving these objectives will require a focus in three necessary areas:

(1) Creating accurate models of materials performance and validating model predictions from theories and empirical data;

(2) Implementing an open platform framework to ensure that all codes are easily used and maintained by all those involved in metallurgical innovation and deployment, from academia to industry;

(3) Creating software that is modular and user friendly in order to extend the benefits to broader user communities.

An additional barrier to more rapid materials deployment is the way materials currently move through their development continuum (see Figure 3), which is the series of processes that take a new material from conception to market deployment. It comprises seven discrete stages, which may be completed by different engineering or scientific teams at different institutions. This system employs experienced teams at each stage of the process, but with few opportunities for feedback between stages that could accelerate the full continuum.

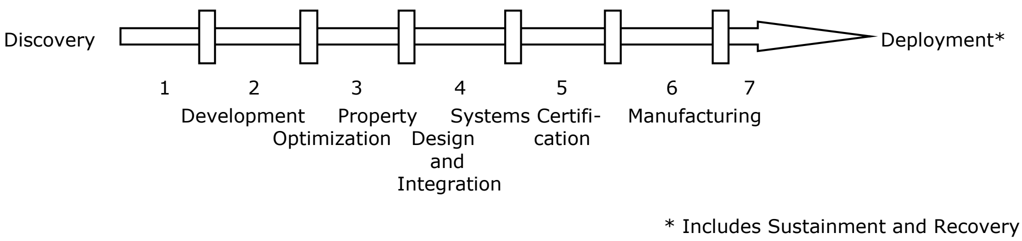

Fig. 3: Materials development continuum
Source: Material Genome Initiative, Office of Science and Technology Policy June 2011 Washington DC. USA

For three decades technological change and economic progress have depended to an increasing degree on the development of new material solutions. Within this metals and metallurgy have contributed significantly. To meet international competition in global markets and maintain its position in the future development and deployment of advanced materials, Europe must perform both faster and at lower cost than its current capabilities allow. Currently, the time frame for deploying new classes of materials into applications is very long, typically between 10 and 20 years from initial research discovery to first use. The time scale for metals and metallurgy is similar.

It is recognised that scientific discovery and technological development are not totally amenable to advance management concepts, however that does not mean that application of management principles to the processes of discovery and development should not be rigorously pursued.

The lengthy time frame for materials to move from discovery to market arises in part from the persistent reliance of materials research and development programs on scientific insight and trial and error experimentation. Much of the design and testing of materials is currently performed through time consuming and repetitive experiment and characterization loops. Some of these experiments could potentially be performed virtually with powerful and accurate computational tools, but that degree of accuracy in such simulations is not yet available. Efforts should be continued to increase the levels of accuracy in simulations to the extent possible.

Lesson could be learned from developments in the automotive industry where the development cycle for new products has been reduced from 10 years+ to 3 years by applying concepts of concurrent engineering and development. This transformation required a range of newly learned behaviours around co-operation and information sharing. The application of this approach would have to be co-ordinated with the early development phases when the producing and testing of new concepts would involve sequential activity.

3 CHALLENGES AND OPPORTUNITIES FOR EUROPE

3.1 CURRENT ISSUES

Over the last 30 years the popularity of metallurgy as a science area in academia has not mirrored its economic value.

3.1.1 Transport Sector (Surface, Marine, Aerospace)

Surface transport

With respect to surface transport work is still being carried out in Europe in the following areas:

for example:

Coatings

- Zn and Zn alloy coatings for corrosion protection
- Physical vapour deposition (PVD) especially in the automotive industry as an alternative to hot dip galvanizing (HDG) to reduce coating weight and enhance durability
- Thermal barrier ceramic coatings (e.g. functionally grades materials) to reduce engine bay temperatures
- Nano-tribology – lubricity at nanoscale
- Chemical vapour deposition (CVD) and plasma assisted chemical vapour deposition (PACVD) for wear protection and friction reduction within powertrain applications
- Thermal sprayed coatings for friction and weight reduction within combustion engines

However, as in many other areas of metallurgy research and development, the metallurgical coatings industry in Europe is fragmented and better coordination of activities would be desirable.

Powder metallurgy (PM)

This is perhaps the most significant area of metallurgy research in Europe where the turnover for PM products is over 6 billion euro per annum (EPMA report, 2011).

Alloy development

The EU is the second largest producer of steel in the world, employing over 360000 people, with an output of over 177 million tonnes a year, accounting for 11% of global output.

The EU remains a world leader in the design and production of high added-value grades. There have some development is advanced high strength steels (AHSS) but those have been mainly in the Asia (Japan, Korea, China) and US. These steels are in the same family as TRIP steels and are hardened by phase transformation, and the microstructure may include Martensite, Bainite and retained Austenite.

One area where research in Europe has been carried out in collaboration with Japan and the USA is the area of "high temperature steels". Although this work is driven by requirements in high temperature plant applications (supercritical boilers etc.), there is interest for engine applications (engine liners, exhaust systems manifolds, turbolader). Work in this area, in addition to new steel development, also includes research to refine the prediction of material long term fracture strength and creep-fatigue interaction from relatively short to medium term tests.

In railway applications there is work carried out on steels for track applications. However, new grades of steel are difficult to introduce due to homologation issues. (C-Mn steels are used currently). This is an issue that has to be overcome because increase in payload of rail vehicles demands track steels with strength in the area of 1000-1100MPa, and hardness 300-320 HBW, aiming at 400HBW).

The application of novel steel grades is occurring, especially multi-phase (bainitic and superbainitic) ultra-high strength steels (>1500 MPa) are promising and are being introduced into the market. Weldability of these steels is a critical factor in this respect, and a deeper understanding of the influence of welding thermal cycles on the microstructural development and the mechanical properties upon dynamic loading has to be developed. New coating systems are needed in order to have improved corrosion performance as an enabler for a more intensive use.

Alloy development where work has been continuing in Europe is in the area of light metals such as aluminium and magnesium alloys for automotive applications. Areas of research include higher strength alloy development, coating technologies, weldability (joining technologies) and lightweight metal foams.

Perhaps the biggest barrier to new alloy development in Europe (and elsewhere) is the lack of economically viable production processes, missing joining methods and fully understanding of risk on cut edge sensitivity etc.

Metal Matrix Composites (MMC)

MMCs are another area where research has been carried in Europe to produce strong and light critical components for transport applications. The work on MMCs has concentrated mainly on engine components. Apart from valve seat inserts MMC's have not been used in car industry so far, due to the lack of understanding, cost and difficult machinability. Research is ongoing with, as yet, few applications having reached the market.

Marine transport

The Marine sector has been defined as a part of the overall transport groups, and consequently the considerations have been limited to the transport area, mainly shipbuilding. However, in a broad sense, the Marine sector~~s~~ may address many other areas with relevant metallurgical impacts. Among these sectors are: offshore structures, oil & gas pipelines, deep sea mining, welding, light-weight alloys etc. Many of the metallurgical aspects addressed by these sectors are somewhat similar, in their fundamental aspects, to the ones encountered in shipbuilding.

Innovation in Marine sectors is characterized by a progressive improvement in technologies which usually do not result in disruptive breakthrough. Top priorities for adopting new technologies in this sector are ensuring reliability along with financial benefits and this means that we are speaking of a rather steady development of existing proven technologies. Nevertheless it should be kept in mind that even with marginal progress the impact from the application is extreme considering the large extent and role of the international marine industry. By its very nature the marine business cannot be restricted to single nations or even continents, so any developments affect the maritime community worldwide. These trends are reflected in the evolution of materials used in the marine sectors. Due to the large volume of materials involved in marine constructions the use of better and improved materials (existing or not yet existing) it is quite restricted by the cost benefits ratio. Any increase in cost has to be clearly justified by a net return in terms of operational performance~~s~~ which offsets the initial investment in a reasonable time scale.

From a metallurgical point of view this limits the range of potentially feasible solutions that could in principle be proposed to face the challenges that shipping is confronted with. These challenges are mainly concerned with increased energy efficiency and better environmental protection combined with good financial performance.

Aerospace

The aerospace sector is relatively well organised, with sector level initiatives such as the Clean Sky JTI defining much of the detailed and specific research agenda involving metals in Europe. Clean sky has high level technology behind the shopping list approach of the open calls: only 1/3 of the budget is for competitive calls. The Clean Sky JTI2 follow-on programme begins next year.

One of the strengths that emerges from testing in operating conditions of the aeronautical sector is that there are no critical technology gaps that are not being covered. However, weakness areas for metal in aerospace are in corrosion, damage tolerance, weight/strength ratio, thermal capability and manufacturing cost/price, (but not comparatively with regard to composites). In fracture mechanics terms, Kc presents a weakness for fatigue.

Considerable effort is also being made in near net-shape or net-shape manufacturing of aeronautical components, which currently would still involve a long process chain.

The ACARE (Advisory Council for Aviation Research and Innovation in Europe) goals which are driving innovation within the sector are towards reductions per passenger kilometer of 75% CO2, 90% NOx, 65% noise by 2050. This will result in the long term products which have been typical for this sector.

3.1.2 Construction Sector

Due to their intrinsic properties, metals are today widely used in the building and construction sector, be it as foundation piles, structural material, reinforcements, cladding, roofing, window frames, plasterboard studs, doors, balconies, fences, composite floors, roofing fasteners, partitions and ceilings, plumbing, gutters, sanitary pipes and equipment, heating equipment, chimneys, foils for insulating materials, solar panels, baths, kitchens and many other applications. Mainstream materials being used at present are Steel/ Iron, Aluminum, Copper, Zinc and Stainless Steel. Markets are emerging for new applications for Titanium and other more noble materials. Competing composite materials are however also emerging on the market, in some of them however metals are used as reinforcement or surface finish.

Clearly in nearly all applications there are specific property features which make metals essential for buildings. As an example in structural application metals' high strength and stiffness allow for "doing more with less" and for a "large freedom for designers". Metals' noteworthy durability ensuring a very long service life without degradation allows them, eventually with appropriate surface treatments, to be weatherproof, seismic proof, corrosion resistant, immune to the harmful effects of UV radiation, etc.

It is very important to note that in the construction sector regulations, standardization and attestation of conformity are critical from a safety point of view as well as from the point of view of insurance of responsibilities and assurance of an open and free market. The need for standardization and innovation all at the same time is an important paradox for the construction sector.

3.1.3 Consumer Goods Sector

The challenges identified relate mainly to requirements for improvements in product performance in the areas of surfaces which are easy to clean, durable, resistant to corrosion, wear and bio-fouling. Other needs relate to avoiding colour variation over time and improved aesthetics of products.

The enhanced material properties and performance will centre on developing tailored surface treatments to improve specific characteristics (corrosion resistance, wear resistance, bio fouling, IR reflectivity properties, tactile, appearance, temperature resistance, cleanability and self-healing properties).

The improved manufacturing and processing will focus on near net shaping by conventional production techniques (improved forming processes, including material properties), reducing the number of processing steps, integration of material design, avoiding material and energy waste.

Other processing improvements will require enhanced technologies for joining dissimilar materials and the development of testing protocols to validate predictions and control of wear, corrosion and durability.

Some current challenges relate to problems with the formability of high strength materials where material cost is commercially important. Modelling and simulation processes will require improved understanding and quantification of physics and material influence on product performance (friction, wear, corrosion, fatigue) and implementation in numerical models. This illustrates the character of metallurgy as an independent scientific discipline.

Well documented and standardized material characterization (e.g. damage, fracture) will be required and will need to be incorporated in commercially available models.

Although simulations have been improved enormously due to increase in computational power, cloud computing and better algorithms, the predictability is still limited due to lack of accurate material data and very limited commercial use of simulations by industry.

Through Process Modelling (TPM), including Knowledge-based material design, from material production to part manufacturing and finishing processes will be needed to facilitate the supply chain in improving performance, costs, reliability and quality.

3.1.4 Electronics Sector

The challenges facing metals and the metals industry in the electronics sector derive mainly for the continuing drive for miniaturisation of devices and components. One consequence of the advance in miniaturisation is the increasing demand for materials that can operate at high temperature and in many cases at severe (harsh) and demanding conditions. Many of the traditional materials for electrical and electronic application are unsuitable for the emerging conditions. Current metals and alloys cannot meet the highly demanding performance requirements (operating at high operating temperatures, corrosive environments (e.g. gas and emissions sensors). Disruptive technologies are called for to develop suitable materials such as grapheme.

The electronics sector has for many years been a major consumer of precious metals. Despite the amounts in each application being small, the expanding volume of product used has triggered a drive to develop alternative materials with equivalent properties at lower cost. The preferred substitutes of precious metals should be produced in EU to enhance EU economy.

The sector also faces the possibility of restricted supply of rare earth metals which it also uses extensively. This calls for the application of strategic materials management to recover or substitute metal alloys. The sector continues also to respond to regulatory pressures which seek to remove toxic materials from the product chain.

The electronics sector faces material challenges in the production of micro- and nano-based electro mechanical systems (MEMS and NEMS) concerning the materials that are used in components. Specifically, since these devices operate at a size scale far below that of typical mechanical devices, surface forces such as adhesion and friction may dominate over other forces in the system, leading to possible failure of devices. Challenges arise in device design, fabrication, processing, functionalization and testing.

Some of the challenges facing the consumer electronics segment mirror those already outlined for the consumer goods sector. Portability of devices demands light materials which are durable and robust. Meeting these criteria is becoming increasingly challenging for metal materials.

The electronics sector also faces challenges in the area of modelling and simulation. As the sector moves increasingly to processes at the nano level, improvements will be imperative involving further development and the combination of the existing characterization methods at difference scales, appraising the ability to understand the relationship between materials structure and their functionality (mechanical/physical properties, resistance to wear, long term functionality and reliability, etc.).

3.1.5 Energy Sector

The European energy scene has a wide range of actors, technologies and strategies. Safe supply of energy at low cost is one key driver, but energy mix, sustainability, energy distribution and storage are equally important. Besides increasing amount of renewables there remains also the need for advanced fossil and nuclear energy (including demonstration of Generation IV technology). Materials are key elements in all these scenarios and materials needs have therefore already been covered in the EU-Energy roadmap. The metallurgy roadmap considers only the requirements for metallic materials.

Increasing the operation temperature to increase thermal efficiency is the main driving force behind several fossil fuel power plants. Particularly the combination of power plants with carbon capture and sequestration introduces extra energy demands. Supercritical and Ultra-supercritical steam generation requires high pressure and temperatures from 650°C to 720°C and even higher. Materials for those temperatures with the required strength (yield and creep) need to be improved or developed. Higher temperatures, more demanding environments (chemical, irradiation) and longer design life are challenges for future plants in general.

Part of these requirements is also true for renewables like geothermal plants, solar thermal plants or bio-fuel combustion. Materials needs for windmills or photovoltaics are rather for functional elements like magnets, contactors and connectors. Those components contain either rare earth (magnets) or precious metals which should be reduced or eliminated due to limited availability, cost and environmental burden.

Structural elements like supports for solar towers or large windmills, as well as transmission of energy carriers, piping or energy storage are also important.

Finally metal production mills themselves need much energy and produce carbon emissions. Both need to be kept in mind and the effort already broadly engaged continued in the future.

3.1.6 Tooling Sector

Equipment and tooling is a key component of the metallurgy industry. Several R&D studies are related specifically to improving equipment and tooling, such as reducing time to market and improving quality. Improving the speed and capacity of existing equipment to increase output while avoiding additional capital expenditures and developing diagnostic methods to monitor product quality, will improve metal industry's capabilities. Miniaturization trends require smaller tool features (up to ~100µm) that are currently expensive and time-consuming to manufacture and have insufficient lifetime.

In all industrial manufacturing processes that are based on tooling (such as production of metal, polymer, ceramic parts), it is important that the production runs are trouble free. The chain from tool design to tool maintenance includes different steps, tool design, tool material, heat treatment, tool production, including surface treatments, work-piece material, production conditions and tool maintenance. To achieve good productivity and tooling economy, it is essential that the right tool is selected and that all steps in the chain are correctly followed.

Tooling falls into two main categories, forming tools and cutting tools. Tools are required to operate in a range of conditions including severe environments and continuous operations.

Tool wear and failure are a continuing challenge to metallurgical science. European strengths in tooling are centred on the high quality of knowledge and competences in the area. Advanced metallurgical processing is a European strength. Several European companies are worldwide suppliers and have branches outside Europe. Europe is still one of the strong competitors in the world in high-end tools and holds a strong position in surface engineering (treatments and coatings development). Weaknesses in the European tooling sector centre on difficulty in innovation because of short-term management horizons, lack of adequate knowledge on tool microstructure, models to predict tool life and identification of wear and damage mechanisms. Other problems lie in access to critical raw materials, systems for transfer of knowledge, impending shortage of qualified personnel and new strong competitors globally. With the move of the volume casting industry to China it will be important to keep knowledge on tools in Europe to support the high-level casting of alloys, for instance Ti-Al.

3.2 Challenges and risks for Europe

- Europe's metal producers are facing increasingly fierce global competition. Research and Innovation continuing to support industry are therefore essential for EU industry to remain competitive.

  See detailed recommendations in complementary roadmaps (EIP-RM SIP, ERAMIN, ETP-SMR SRIA (European Technology Platform for Sustainable Mineral Resources Strategic Research and Innovation Agenda), Critical Raw Materials Report, ERECON (to be published in 2014)…)

- Keep metals in the forefront as performing, affordable, robust and attractive material solutions to end-user needs.

- Keep high added-value (quality) metallurgical capabilities to compete on worldwide market products (improve EU competitiveness in terms of value).

  What is needed:

  - Improved focus on metallurgical education / Increase attractiveness of metallurgy as career.
  - Better fit between academic output and industry real needs in term of skills; continuous education (life-long learning),
  - There is a consensus within the scientific community that there is a lack of focus into traditional metallurgical research and the effort for development of new metallic materials and alloys has been limited. To encourage metallurgical research and innovation requires more cooperation, collaboration between research organisations and industry, which also includes the need for an innovative and dynamic, European level Metallurgical Research Infrastructure.

- There is a risk posed by the ongoing supply position of raw materials, including "critical materials" (*see critical raw materials report for details*). The problem of EU supply vulnerability needs to drive an increased focus on the "raw materials value chain", including extractive metallurgy and its specific challenges for sustainable and affordable production of metals from primary and secondary resources, cf *EC initiatives related to raw materials (EIP – European Innovation Partnership on raw materials, KIC – Knowledge Innovation Community on raw materials, ERAMIN, ETP-SMR SRIA…).*

What is needed:

- Innovative sustainable and bankable metallurgical processes to produce raw materials from lower grade and more complex resources (whether primary or secondary)
- Search for alternatives, substitutes applications
- Recycling, from waste collection to solving waste valorization specific technical challenges

- There is insufficient support for the entire knowledge-chain from basic research in metallurgy to industrial applications in Europe. Only a few of the European scientific results / outputs in metallurgy have been transferred to industrial products manufactured in Europe.

  What is needed:

  - EU R&D programmes, in particular Horizon 2020 – Excellent Science, to put more emphasis on all TRL metallurgical research (from low t*o much higher technology readiness levels*)
  - Effective knowledge transfer to European industry. Address the entire innovation cycle in Europe.
  - Shortening of the cycle to transform new materials into products by improving functional links between actors from an early stage in the process (from materials to manufacturers), including addressing certification and regulatory issues.
  - Consider two aspects of innovation: new material development; improvement of existing materials by incremental research, and materials' processing
  - Consider the development of material processes oriented toward the production of multifunctional/multigrade material

- Industrial competitiveness requires the reduction of the cost and shortening of the development cycle for a new product development, which in turn requires enhanced capability in modeling and simulation

  What is needed:

  - Dedicated European initiative to integrate Europe's effort in modelling for metal production and metallic materials, and to improve modelling and simulation capability. Material performance can be predicted by numerical analysis of data leading to empirical relations and by physics/chemistry models. These two types of analysis can be done at multi-scales and the material models integrated into appropriate design platforms for industry use.
  - State-of-the-art testing facilities for cutting-edge technology validation in real environment.

3.3 Opportunities for Europe

The next part gives an overview of the main driving forces required to move research and innovation forward in the field of metallurgy in Europe.

Transport sector (Surface, Marine, Aerospace):

In view of the limited energy resources and increasing environmental concerns, the main driving forces of the research in almost all the industrial sectors are energy efficiency and safety.

- Efficient recycling: From 2015 95% in weight of vehicle components should be re-used or recovered (the "End of life Vehicles" directive). Experience has shown that steel is a good candidate for this because it is a relatively environmentally friendly material to produce, process and recycle.

- Lightweighting: A main trend is to move towards lower weight vehicles, vessels, structures to **improve energy efficiency** in response to the forthcoming environmental legislation including life cycle design.

  By 2020 it is required that new cars do not emit more than an average of 95 grams of CO_2 per kilometer. This implies pushing weight reduction in automotive components both in traditional ICE and new concept electric/hybrid propulsion vehicles through the adoption of lighter or stronger metals and alloys for body, chassis and powertrain systems. In terms of rail vehicle design lightweighting is also an issue, creating a demand for stronger and lighter metals and alloys.

  Many studies have addressed the use of improved materials ranging from High Strength Steel, Aluminium, Sandwich Structure, aiming to reduce the weight. Most of the limitation in the use of such materials is in the cost increase of production even if the material costs have a marginal impact on the overall production cost. Nevertheless, the use of new (non-conventional) materials may imply additional cost related to changes in the usual production processes but which would be expected to have a beneficial effect on the overall through life costs.

  The high level drivers set out previously by ACARE lead to metals technology requirements in reduction in mass, increased temperature capabilities, and reduced cost.

  There is an overall need to introduce bionic approaches (inspired by nature) to optimize the structural load, and which will have a significant impact on the underlying metallurgical technology.

- Product quality and durability: This requires the development of better coatings and material surface modifications to enhance durability. Metal surface treatment/condition will have an important influence on the final protection barrier for marine applications. New alloys for propellers with better cavitation and corrosion resistance will need to be developed. Improving corrosion resistance, by the use of alternative materials and materials for coatings to **increase the in-service life** of the marine structure and vessels and mechanical components, will lead to a reduction in life costs.

  Corrosion protection must be achieved within the constraints of REACH compliance. Traditional high performance coating processes using highly active (and hence environmentally unfriendly) chemical solutions have to be replaced as the standards for corrosion and wear protection are increasing.

Construction sector:

The main drivers for innovations with respect to materials used in constructions are economical and regulatory[1]. The requirements for materials used in the sector have been compiled in harmonised European standards (hEN) and European Assessment Documents (EAD).

The essential requirements covered by the Construction Products Regulation (EU) No 305/2011 (CPR) relate to:

- Mechanical Resistance and Stability
- Safety in case of Fire
- Hygiene, Health and the Environment
- Safety in Use
- Protection against Noise
- Energy Economy and Heat Retention

One of the key new additions to the CPR is a requirement on sustainability, especially on the sustainable use of natural resources (i.e. the Basic Works Requirement no. 7).

It is to be noted that over the last few years, under the impetus of the re-cast Energy Performance of Buildings Directive (EPBD)[2], a high focus has been put on the development of « Nearly Zero Energy Buildings ». The EPBD establishes a common framework of measures for the promotion of energy efficiency within the

[1] Construction Products Directive (EU) No 89/106/EEC (CPD), Construction Products Regulation (EU) No 305/2011 (CPR)

[2] Directive 2012/27/EU on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC [OJ L315 p.1]

Union in order to ensure the achievement of the Union's 2020 20% headline target on energy efficiency and to pave the way for further energy efficiency improvements beyond that date. It lays down rules designed to remove barriers in the energy market and overcome market failures that impede efficiency in the supply and use of energy, and provides for the establishment of indicative national energy efficiency targets for 2020.

The re-cast EPBD requires that from 2019 onwards 'all the new buildings occupied and owned by public authorities are nearly zero-energy buildings' (nZEB) and by the end of 2020 'all new buildings are nearly zero- energy buildings', i.e. they nearly produce more energy than they use. This directive has undoubtedly been an important driver for innovation in the construction sector as well on the level of building technologies and material characteristics. Important to note here too is that a general trend can be seen where systems develop from being passive to become active.

Some important characteristics are to be retained as well. Materials which can develop a large volume market have more power to become mainstream practice in the sector. In the same reasoning it is to be remembered that "Super Sophisticated Materials" in many cases cannot compete with "Robust Tolerant Systems".

Tailoring of the characteristics of the materials and improvement of their durability at reduced costs have big potential for further development. Markets are emerging for new applications where metals are used as reinforcement or surface finish in hybrid composites.

Consumer Goods Sector

The main opportunities will lie in the development of tailored surface treatments, use of smart materials including shape memory alloys, and self- repairing materials.

Through Process Modeling (TPM) will enable knowledge-based material design and optimization of the entire supply chain leading to improvement of performance, costs, reliability and quality.

Electronics Sector

The continuing drive for miniaturization provides an opportunity for Europe to build on current micro and nano-manufacturing capabilities related to metals.

Europe's position in management of the full materials value-chain can be exploited in the field of portable electronic devices to achieve a more efficient life-cycle control of critical metals used.

Opportunities arise in developing surface modification of metal and copper based alloys to eliminate the need to electro-plate electrical contact areas with precious metals, and to provide better corrosion resistance e.g. in sulphurous environments.

High-accuracy measurement and computational techniques for determining properties of new alloys, including high-precision experiments in microgravity using electromagnetic levitation are needed.

Energy Sector

Increasing temperature of operation offers the opportunity to improve thermodynamic processes which yield more energy efficiency. Advances in metallurgy amd material science are needed to achieve higher temperature operation.

An opportunity exists to accommodate the expected harsh operating conditions using powder metallurgy. Gradient or layered structures bring the required properties of a component to the level needed. Powder metallurgy could also be interesting for complex shaped parts like headers.

Tooling Sector

a. Forming tools. Improve tool life by modifying the surface properties in the tooling (i.e. wear resistance, toughness, hardness, fatigue, thermal stability and chemical stability), new surface treatment, coatings and/or lubrication including self-lubricated surface and coatings for lubricant free high temperature forming. Improve tool life by developing a new class of tool material and/or surface treatments, especially for high temperature processes. Develop forming tools from design while shortening tool delivery time by exploiting additive manufacturing and new tooling-process chains. Develop new materials and processes for manufacturing forming tools with improved control of the microstructure and properties. Miniaturisation of products offers opportunities to develop micro-tools and tools with micro- and nano-structured functional surfaces.

b. Cutting Tools. Develop new materials for cutting tools (e.g., new binders instead of Coin WC, using TiC and binder-less processes for cutting-tool manufacturing). Develop new coatings for dry (coolant-free) machining difficult to cut materials e.g. hardened steel. Further develop non-conventional machining techniques for high quality tool-making. Develop cutting tools for micro-manufacturing

3.4 Stakeholders' viewpoints

The Commission sought and received the views of many businesses and interest groups during the development of the Metallurgy Roadmap, through debates and workshops, position papers, personal interactions. At these interactions there were present European associations, European Technology Platforms, networks of research organizations and companies.
The Science Position Paper of the European Science Foundation on a programme for Metallurgy in Europe for 2012-202[3] was included in the roadmap considerations. The summary requirements in this Position Paper have been reflected and confirmed in the outcomes of the roadmapping exercise.

The European stakeholders presented their viewpoints on key trends and challenges for metallurgy in Europe. Their points can be organised along five broad lines:

- Manufacturing
- New and improved materials and material data availability
- Recycling and recovery
- Modelling and simulation
- Energy efficiency

In **Manufacturing**, the following categories were considered by most of European associations and Technology Platforms: (i) *Powder metallurgy and Forming*; (ii) *Joining technologies*; and (iii) *Improved processes*.

(i). Powder metallurgy and Forming. Among the industry requirements for research that were highlighted by the European stakeholders there were mentioned: new powder metallurgy alloys for high temperature components; net-shape forming and powder metallurgy; novel design, metal processing and optimisation in powder production ; novel metal processing including improved alloy production, metal forming, near-net-shape and additive manufacturing with metal powder; adapted primary shaping processes like powder metallurgical techniques (components) or spray-compacting (semi-finished products) allowing the design of new (overall or local) microstructures. Most of the research and industry requirements in forming and powder metallurgy were considered within the Roadmap by the sectors Transport, Electronics, Energy, Consumer Goods and Tooling. Different solutions are already on the market.However, the key barriers to implemention are the costs. This aspect should be addressed before developing a new alloy. Forming of UHSS and high strength aluminum alloys is recommended.

[3] 'Metallurgy Europe – A Renaissance Programme for 2012-2022', Science Position Paper of the Materials Science and Engineering Expert Committee (MatSEEC) of the European Science Foundation, 2011

(ii). Joining technologies. Main industry requests in terms of research and innovation needed for joining technology referred to improved joining techniques for similar and dissimilar materials; develop a better understanding of the effect of joining technologies on aluminium alloy properties, including corrosion; reliable joining solutions and technologies; optimised joining technologies for multi-materials taking into account the microstructure; developments in joining technology (laser welding, arc welding, adhesive bonding, mechanical riveting, joining of different materials). Most of the research and innovation requirements in joining technology were addressed within the Roadmap by the sectors Transport, Consumer Goods, Electronics, Energy, and Tooling.

(iii). Improved processes. The European stakeholders considered that research and innovation on processes, especially on those enabling metal recovery and new metal-based materials/products with enhanced performance and new functionality should be a part of this Roadmap, and therefore this request is addressed within all sectors. According to stakeholders' viewpoints, the improved processes can relate to enhanced energy efficient processes; disruptive technologies for next generation alloys, composites and new production processes; surface treatment processes for component life extension and corrosion protection; Net-shape manufacturing to shorten the process chain and to reduce the cost.

The category **New and improved materials** grouped the issues raised by the European stakeholders in (i). *Metals and alloys*; (ii). *Coatings and treatments*; (iii). *Functional and multi-functional materials*; (iv). *Metal Matrix Composites and Metal Foams*; and (v). *Improved material performance*.

(i). Metals and alloys. Most of European stakeholders included metals and alloys among their main needs for research and innovation: multi-metals; new metals; conventional alloys (new single crystal alloys for HT turbine blades. weldable alloys for temperatures higher than IN718 and Ti-6-4 for engine structures); conventional materials mechanical behaviour and damage (Cr-base alloys, Ni-base alloys, Ti-alloys); new alloys; develop a better understanding of alloy behaviour during thermo-mechanical processing; develop a more in-depth understanding of the effect of trace elements on the properties of recycled alloys; a better understanding of the corrosion - strength - formability balance of high-strength aluminium alloys; accelerated synthesis, discovery and insertion of new alloys into real applications; higher temperature capabilities and alloy phase stability, especially for energy systems or other extreme environments ; aluminum alloys (cost reduction by use of secondary alloys, foams); designing alloys for high recycling rates; High strength metallics / alloys made with abundant alloying elements; scatter of alloying elements in the production process and properties of highly stressed components made of recycled alloys (secondary raw materials); multi-physical damage of new magnet alloys; advanced high performance steels, especially high strength and high ductility steels; steel with lower density than carbon steels; austenitic steels and ferritic-martensitic steels but also nickel based super alloys; new metals and alloys to meet functional requirements, strength, corrosion, wear, conductivity).

(ii). Coatings and treatments. Research should address the industry needs with respect to developments, for instance, in coating technologies (new alloys, thinner coatings); advanced coatings for heat management in steel building envelopes; improved after-/surface treatment methods; surface treatment processes for component life extension, corrosion protection and improved functional properties. The requirements for research and innovation in this area were addressed within the Roadmaps of the sectors Transport, Electronics, Consumer goods, Tooling and Steel(ESTEP).

The industry requirements related to **(iii). Functional and multi-functional materials**; **(iv). Intermetallics** (for example, TiAl used in turbine blades; high temperature intermetallics); and **(v). Metal Matrix Composites** and Metal Foams were addressed withinn the Roadmap by sectors Transport, Energy, Construction. The broad category of **(vi). Improved material performance**, including **lightweight** (for instance, mechanic performance; environmental performance and REACH compliance; multi-parameter optimisation of performance; predictability of product performance) was addressed in the Roadmaps of all sectors.

The **Recycling and recovery** category of challenges raised by the European stakeholders (, as well as the **Modelling and simulation**, were addressed in the Roadmaps within each sector, and the key issues of **Energy efficiency** were considered in the Steel, Transport and Consumer goods sectors.

	Representatives of Stakeholders	Sectors addressing the issues in the Roadmap
Manufacturing		
Powder Metallurgy and Forming	ACARE, EPMA, EUCAR, MANUFUTURE	Transport, Electronics, Energy, Consumer Goods, Tooling,
Improved processes	CLEPA, EPMA, EUCAR, EUnited Metallurgy, EAA, ERTRAC, ESTEP, NAMTEC	All Sectors
Joining Technologies	ACARE, CLEPA, ERTRAC, ESTEP, EUCAR, EPMA, M2i MANUFUTURE	Transport, Consumer Goods, Electronics, Energy, Tooling
New and improved Materials		
Metals and alloys	ACARE, CLEPA, EPMA, ERTRAC, ESTEP, EUMAT, EUCAR,	All Sectors
Coatings and Treatments	ACARE, CLEPA, ESTEP, EUMAT, MANUFUTURE, European Copper Institute	Transport, Electronics, Consumer Goods, Tooling
Functional and Multi-functional materials	ACARE, ESTEP, EUMAT, MANUFUTURE, EMIRI	Transport, Construction,
Intermetallics	ACARE, EUMAT, SNETP	Transport, Energy
Metal Matrix Composites	EUMAT, European Copper Institute, M2i	Transport
Improved material performance	CLEPA, EAA, ESTEP, M2i, EUCAR, Copper Alliance, BeST	All Sectors
General		
Recycling and recovery	ACARE, EUROMETAUX, EPMA, MANUFUTURE, BeST,ESTEP	All Sectors
Modelling and Simulation	ACARE, CLEPA, EAA, ERTRAC, ESTEP, EUCAR, EUMAT, EPMA, MaTSEEC, M2i, NAMTEC, SNETEP	All Sectors
Energy efficiency	ACARE, ALUINVENT, CLEPA, ERTRAC, EUCAR, EUMAT, EPMA, EUROALLIAGES, European Copper Institute, EMIRI.	Transport, Consumer goods, Construction, Energy.

4 2020 RESEARCH AND INNOVATION FOCUS AREAS

4.1 Transport sector (Surface, Marine, Aerospace)

4.1.1 Improve energy efficiency and material capability performance

- **Optimized metallic alloy designs to provide high strength** (for weight reduction in conjunction with reduced life cycle impact on GWP) whilst maintaining or increasing current levels of yield strength/ultimate tensile strength ratio with excellent ductility and fatigue characteristics are needed. These materials should consider moving beyond the status quo with respect to the design, production, skill sets and support processes.

  Typical challenges-needs:

  Steel

  - Optimise high-strength thermomechanically controlled processed steels (TMCP) and/or high strength quenched and tempered steels to be more user friendly than the traditional steels, with the aim of reducing welding man-hours, shortening of welding lines, elimination of cutting steps, stabilization of fabricated part quality and reduction in control costs;
  - Develop High Strength Steels (HSS) e.g. High Strength Low Alloy (HSLA), Ultra-Low Carbon Bainitic (ULCB) steels with improved corrosion resistance at affordable price;
  - Third steel generation A-UHSS (Advanced Ultra High Strength Steel) for body in white lightening processed through cold forming technologies. Thanks to these grades it is possible to maintain the same performance while reducing thickness and saving weight;
  - Large scale production of low density steels containing significant amounts of Aluminum, e.g. Mn-Al-C (Triplex) steels for body-in-white applications
  - Improve the strength of steels employed in hot press forming technologies. The current target is for high strength steel (1500MPa) with better formability (>10% elongation). Another focus will be on the development of low cost production routes for advanced high strength steels;
  - Improved weldability of bainitic steels for rail track applications (high strength, high wear resistance), as demands for higher capacity (payload) are increasing.
  - Cold formed steels (use of sections for rail body manufacture). There is a need to understand the behaviour of these materials, control of processing characteristics and improve performance (e.g. reduce/ control spring back);
  - research on steel alloys with high strength, wear and corrosion resistance (similar to stainless steels) but at lower cost;
  - New duplex structure stainless steels obtained with low costs alloying elements, providing both increased mechanical characteristics (improving energy efficiency and payload carrying capacity) and seawater corrosion resistance
  - Zinc plated steel sheets as widely used in automotive production

- **Use of non-ferrous alloys for example aluminium as an alternative solutions for large structures**. Development of such structures will probably require less new alloy design whilst technological aspects such as joining similar/dissimilar material will need to be addressed. The focus on weldability and capability to implement solutions will be important factors.

  Typical challenges/needs:

  Aluminium

- Extend the use and qualities of 5xxx to 6xxx alloy grades;
- Modify alloys and heat treatment procedures to achieve more efficient age hardening
- Improve mechanical properties, e.g. by small grain size (sub-100nm microstructures).
- Move to higher strength weldable alloys such as 7xxx series;
- Improve mechanical properties of joints when welded;
- Improve fatigue life and corrosion performances;
- Extended design concepts by use of specialty extrusions;
- Assess 5xxx Al-Mg alloys with high balanced Mg content (improved strength and formability including control of corrosion resistance);
- Improve protection technologies to insulate aluminium to prevent the galvanic action;
- Improve welding characteristics with similar / dissimilar material (incl. steel)
- Higher temperature capability of aluminium, beyond 250°C(300°C)
- Al-Li alloys (2098, … etc.) to broaden the supply base
- Al-Mg-Sc alloy systems for weldability

Titanium

Titanium remains a critical material for aero applications driven by challenges in temperature, mass and corrosion resistance. Although titanium has significant performance advantages, its cost curtails drastically its application. Its use is limited to a few critical components particularly in aerospace applications. Titanium is a very interesting material for light weighting also in the transport sector. It has a similar specific stiffness to steel and aluminium alloys but is intermediate in stiffness between them. Titanium alloys can be produced with higher strength than aluminium alloys and it is possible to surface treat (e.g. nitride) the titanium to deliver similar surface properties to hardened steel, something which cannot be achieved by any treatment of aluminium. Titanium is the most formable of the structural metals (highest limiting drawing ratio). Those attractive properties have not been exploited more widely on the grounds of cost, with applications limited to high end aerospace and motor racing components.

- Reduction of production costs (and energy use) for Ti production and refinement through near net shape manufacturing (material use efficiencies) or raw material production through e.g. electrolytic deoxidation (material production efficiencies)

- Research is needed on alternative production processes to produce much cheap titanium alloys (e.g. one such process, the electrochemical "Fray" process has not progressed further than a laboratory demonstration)
- In addition, there will be a need to investigate the cost-effective joining and surface treatment of titanium produced by this new process.

Copper:

- Research is needed to meet all the electrical challenges/needs that will be fulfilled by developments in the use of copper
- Light weighting of electrical conductors in vehicles
- Support of new, more efficient electrical alloys for use in electric vehicles

- **Defect-based metallurgy.** There exists already at the concept development stage pioneering programmes which would shift the basis of design for products, materials and processes from using predetermined mechanical property allowable to predictions of properties by making allowances for specific defects. This fundamental philosophical shift in position would be underpinned by access to high power computing facilities and an increased general depth of capability in the modelling and simulation of materials. The constraints in design optimisation are quality, safety, and functionality. The consequences of this move would be: a change in the certification method; integration of the design which shows an increased depth of capability and connectivity in simulation of material / process performance, assembly and environmental condition; and reducing cost constraints on materials innovation. This principle is founded on three pillars: simulations; process control; and defect assessment through Non Destructive Inspection, NDI, assessing the structural strength doing lifecycle analysis. These are practically linked through a design platform running on HPC (high performance computing), and underpinned by emerging capability in virtual engineering and visualisation. The common factor in this is the size of the characteristic defect which can be discerned. There would be a downward progression in scale of defect for material, manufacturing, assembly (from tolerances), phase (Visible Impact Damage (VID), Barely Visible Impact Damage (BVID), unpredictable defect (low probability large defect). This makes the iterative loops easier for innovation and would have a direct impact on the overall competitiveness of the European sector globally. One of the ACARE objectives is in the ability of the sector to be agile in new product generation. This would significantly enable that.

- **Intermetallics**. Intermetallics offer a way of breaking out of the constraints of conventional alloy systems based around a single element. The European supply chain has been developing for these, with FP projects and university research, everywhere. GfE in Nuremberg are making these and have the capacity to satisfy the foreseeable needs of the European Aero sector. TiAl intermetallics are already being developed for propulsion systems where the drivers are temperature capability and density. TiAl should be considered an extension of Ti alloy groups, extending the 550°C Ti temp ceiling to 800-900°C, with Nb, Mn. Other intermetallics, NbSi for high temperature: 1300-1500°C. These offer e.g. significant mass reductions in low-pressure turbine components. Aluminium alloys are limited to ~200°C today, but the aero sector needs a capability of ~300°C, which would have a big impact on design choices as this temperature zone for structures is normally the territory of steels and titaniums. Al-Ni intermetallic alloys should be capable of handling these intermediate temperatures. This is an area of technology, though, which up to now which has been characterised more by technical papers than scientific articles. Although offering attractive in-service performance, these materials are difficult to cast, weld, form, machine, etc. This represents a branch of metallurgy which has been creating expectations for many years, straddling a niche for high temperature applications in gas turbines, but also driven by, and impacting on, utility power generation.

- **<u>Powder processing and metallurgy.</u>** There is a need for establishing an appropriate and robust supply chain for powder metallurgy materials. Powder metallurgy represents a method for manufacturing materials which are otherwise impossible to make, e.g. GE using titanium alloys introducing boron through this route which cannot be solidified using conventional means. Upscaling in size and production volumes are a necessary precursor for enabling a greater momentum in innovation in this technology field. Powder metallurgy sits nicely together with intermetallics, and potentially also with additive manufacturing, as this is a route for the production of difficult microstructures, like nanostructured material for higher temperature applications in airframe as well as propulsion. These need to be linked within an overall capability.

- **<u>Improved metal alloys for production and metallic coatings resistant to cavitation</u>**. Metal barrier coatings with antifouling properties.

- **<u>Development of (large-scale) metal-foam sandwich materials</u>** (weight reduction of up to 20% is achievable). Improvement of welding technology is required for such sandwich materials, in particular for Aluminium (core) - Steel (skin) sandwich. It is envisaged that the most economical way of metal skin – aluminium foam sandwich panel manufacturing can be the foam casting into metallic plates therefore technology developments on this field is essential. There are proposals to move to metal car body panel thicknesses of the order of 0.1-0.3mm. Ideas for the manufacture of such materials and their processing are therefore required.

- Emphasis should be given to the cost aspects of the ship building process with respect to joining/welding (consolidated and innovative techniques):

- **Laser welding**. The main focus is its potential to decrease welding related distortion and the rework associated with it. Fibre laser technology appears to have potential for robotised welding as well welding in the dock area.
- **Friction stir welding**
- Assessment and qualification of **Cold Metal Transfer** technology. High potential to reduce heat input and distortion and possibility to apply to both steel and aluminium.
- Development of improved solutions for bonded joints connecting composite sandwich superstructure modules to the steel hull.

- **Multifunctional materials**: The 2030 design environment would maybe include morphing wings, multifunctional materials through Shape Memory Alloys, smart materials. Today the wing is fixed, designed for strength. This evolving design approach would bring dynamic performance into play.

- **Composites and multi-material solutions**: Hybrid structures involving metals and non-metals are the most common design solutions. Composites structures still have issues with brittleness and damage tolerance which metallic structures fundamentally can exceed or circumvent. The main battleground for the aerospace sector is in mid-weight aircraft fuselage: for frames the critical factor is strength; for panels it is fatigue. This introduces the need for further applications for e.g. GLARE and corrosion protection for multi-material components and assemblies.

- Another issue of concern for the rail industry is **overhead lines**. Find cheaper, well conducting and wear resistant metals and alloys for overhead lines (This latter requirement is also an issue addressed by the energy industry (power transmission).

4.1.2 Increase in-service life

- **Corrosion and fatigue resistance** will need to be addressed providing cost effective solution to these problems. From a metallurgical point of view better corrosion resistance will imply improved alloy design where high cost alloying elements will be replaced by lower cost additions in line with existing trends for substitution of critical materials in ferrous and non-ferrous alloys. These complimentary substitutional additions will also address improvements to fatigue characteristics. - Improved current cathodic protection applied on whole hull

  Improvements in corrosion resilience, and corrosion protection, can be introduced straight into current products without significant knock-on changes. New materials with improved corrosion understandings and consideration must be cahieved within the practical constraints imposed by REACH

- **Functionalization and/or preparation techniques** for increasing external protective coating adhesion and long life operational effectiveness will be required.

- **Physical deposition for metallic/non-metallic barriers** for developing alternative metal/metal coatings (corrosion, tribo-corrosion and fouling protection) which are better able to address new environmental restrictions compare to chemical based solutions.

- **<u>New materials (new alloys) for vibration damping</u>.** Noise and vibration reduction are two areas of concern for both the automotive and rail industries, which raises the demand for new materials (new alloys) for vibration damping. Currently, metals for vibration damping include shape memory alloys, ferromagnetic alloys and some other alloys. There is a need to improve the performance of such materials and also reduce production costs

- **<u>Multi-material approach and "hybrid" structures</u>.** As the desire for even lighter structures increases there is the need to introduce a multi-material approach and "hybrid" structures, i.e. structures made up of two or more dissimilar materials. This raises the issue of improved dissimilar material joining techniques.

- **<u>New / advanced casting technologies</u>.** Casting is still important for surface transport (mainly engine component manufacture). New / advanced casting technologies should be introduced to enhance quality and reduce costs (e.g. further work on squeeze casting –improve control and process modelling). New cast iron structures (e.g. compacted graphite iron) can be introduced compromising between the desired mechanical properties and the required thermal conductivity. The complex failure mechanisms under Thermo Mechanical Fatigue loading conditions and environmental conditions and their relation to microstructural variables should be properly understood.

  There should be continuing development of die-casting of copper and copper alloys (e.g., for the rotors of induction motors for electric vehicles

- **<u>New environmentally friendly antifouling techniques</u>** or processes (Marine applications)

4.1.3 Safety improvement

- **<u>Production</u>**. Any improvements in materials and their use must comply with the current work place safety regulations without increasing the health risks to workers.

- **<u>Operation</u>**. The adoption of any new materials should maintain the current and potentially more stringent fire resistance regulations. This implies the development and use of novel metal base configurations combining different materials with fire retarding capabilities e.g. sandwich panels with core and/or foil type metals.

- **<u>End-of-life</u>**. The possibility of developing future metal structures with a limited need for chemical coatings and treatments will result in more readily recoverable material. This achievement will deal with the development of surface treatments based on metallic coatings.

4.2 Construction sector

The internal time-clock time of the construction industry is measured in decades not months and quite different from the one of transport industry and surely the ICT evolutions.
Consequently, the innovation speed will be different for the construction sector and, therefore, medium term goals for 2020 will be concentrating on implementing existing technology from other sectors rather than on developing new technologies.

The sector's challenges / needs for 2020 are targeting especially the following issues:

- Promoting technology transfer in the sector of existing technologies
- Setting up of demonstration and pilot case projects
- Investing in courses and education

4.3 Consumer Goods Sector

The Consumer Goods industries is striving to improve product performance to stay competitive against commodities imported from outside Europe, especially from Asia, The knowledge of conventional metallurgical techniques (such as casting, molding, forming, joining, machining, heat and surface treatment), used in mass-manufacturing, can only be kept in Europe by increasing resource and process efficiency and product quality. Advanced integrated process and material modeling is required, including substantial improvement in data quality, acquisition and models for quantitative description and Through Process Modeling (TPM). Besides applying new better and cost efficiently manufacturable materials the development of suitable surface modifications is a medium term target area.

Specific surface aspects of consumer goods are identified to help make a difference. This includes the development of metals and suitable surface materials and compositions with durable, corrosion resistance that avoid (or at least control) dissolving / leakage of harmful substances and interaction. Furthermore it requires "easy-to-clean" surfaces with specific properties:

a) hydrophobic and/or super-hydrophobic) having a low surface energy (e.g. for super-hydrophobic equal or less than about 15-18 [mN/m] – water contact angle $\geq$ 150 degree)
b) hydrophilic and/ or superhydrophilic): high surface energy (e.g. for super-hydrophilic more than about 70 [mN/m]- water contact angle $\leq$ 5 degree)

In manufacturing near net shaping by conventional production techniques (improved forming and casting processes, including prediction of material properties), reducing the number of processing steps and integration of material design avoiding material and energy waste are key medium term targets.

The development and deployment of anti-microbial copper for use in reducing the spread of pathogens from touch surfaces in medical and food-preparation environments is also required.

4.4 Electronics Sector

The medium term requirements for the electronics sector include:

- Development of advanced alloys for use at high temperatures
- Exploitation of Tantalum in advanced electronic applications
- Development of ductile materials for flexible electronic devices
- Further development of existing processes and tooling for micro and nano scale components for advance electronics applications
- The replacement of the industrialised CIGSSe (Cu(In,Ga)(S,Se)2) absorber material for use in thin film solar cells
- Investigate the low temperature processes compatible with organic electronics
- The development of new cost-effective processes, such as severe plastic deformation (SPD) processes with higher throughput and up scaling capacity is a need in order to produce nanostructured materials for advanced electronics applications.
- Enhance functional performance of beryllium alloys and compounds for advanced uses in micro- and nano-electronics.

4.5 Energy Sector

The medium term requirements for the energy sector include:

- Advanced austenitic steels for supercritical combined cycle plants (yield strength+ 100 MPa/500 000 hours creep at 670°C)

- Establish advanced tools for surface optimization/treatment under extreme environments in energy related applications (including advanced fission) to improve value of metallic materials up to 670°C

- Provide materials and tools for component production for advanced metallic blades for ultra high temperature gas turbine applications as well as for intermediate heat exchangers (1200°C): DS/SC steels, ODS, fibre reinforced metals, intermetallics, including TBCs (thermal barrier coatings)

- Provide paths towards reduction (avoiding) of rare earth elements in magnets used for motors and drives (including rare earth and precious metal recycling). Development of alternative concepts for motors and drives in a systemic approach. This includes the development of materials for new commutator technologies that allow the use of wound-rotors in wind generators for increased efficiency and decoupling from the geopolitical supply challenges of rare earth materials, e.g. permanent magnet rotors as an alternative to wound rotors.

- Provide the basis to develop European manufacturers towards an international leading position in contactors and functional layers on large metallic surfaces based on cheaper elements with high purity metallic components by development of type of layers and respective application techniques

- Improve components for transport of energy and energy carriers (e.g. advanced aluminium and copper alloys) as well as for energy storage both electrical and thermal.

4.6 Tooling Sector

The medium term requirements for the tooling sector include:

- Develop modification to the surface properties **of** tooling (i.e. wear resistance, toughness, hardness, fatigue, thermal stability and chemical stability) to improve tool life.

- Develop approaches to additive manufacturing for designing complex tools and reduce delivery time.

- Improve procedures for repairing dies and moulds.

- New materials and processes for manufacturing forming tools with improved control of the microstructure and properties.

- Advanced tools for applications with complex geometries and require upper dimensional accuracy (i.e. using moving parts in the tooling).

- New materials for cutting tools (i.e., new binders instead of Co in WC, using TiC).

- Machining of difficult to cut materials that possess excellent mechanical properties or hardened steel can open up opportunities of utilizing them comprehensively and save energy required for heat treatment.

- Understanding the tool behaviour and microstructure.

- Monitoring performance. Monitoring tool behaviour and conditions (i.e. sensor in a tool, noise analysis).

5 DEVELOP RESEARCH AND INNOVATION IN METALLURGY TO 2050

5.1 Transport sector (Surface, Marine, Aerospace)

1. MMCs have applications in automotive manufacture. There is a need for even higher strength, ductility, corrosion and wear resistant MMCs. Currently in Japan there are developments for the use of MMCs for gear manufacture. A European example is ultraconductive copper that is now under development in the EC's Ultrawire project
2. In EU there are the right competences for "Functionally graded" materials that can find applications in braking systems, transmission systems. Functionally graded materials can be produced either through new metallurgical techniques, metal matrix composites, multi-layer surface technologies etc. Research will be required on grain size control, interface/interphase adhesion, interface/interphase properties etc.)
3. Improve aluminium alloy recyclability. (e.g. remove Fe or make better primary and secondary alloys with better processing for sheet production). This can be viewed as both a short and long term goal. If new alloy developments are successful and new alloys are introduced then suitable improved recycling methods would be necessary.
4. Staying with the issue of recyclability as future designs are likely to include several different types and grades of material, new multi metal and multi material solutions for recyclability and disassembly need to be developed, as well as solutions to separate/purify/ recycle.
5. 3-D printing, additive manufacturing, developing suitable powders – This is an area that is gathering momentum as a promising future technology with several applications from medicine to aeronautics. The work should concentrate in the development of suitable powders for metallic component manufacture. One area where 3D printing would be applicable is the replacement of casting with 3D printing for more efficient engine designs.
6. Development of high strength and high conductivity alloys for non-rare-earth induction motors for use in EV traction and elsewhere in the vehicle (high efficiency motors for blowers, window-lifting, convenience features, windscreen wipers, fuel pumps, starter/generators)
7. Magnesium alloy sheet technologies based on hot forming process.
8. Development of physical surface metal treatments/barriers for improving corrosion resistance and antifouling (painting less)
9. Intermetallics for high temperature operation, NbSi for example. Existing alloy systems based on modification of single metal species have reached near the limit of their capabilities. The significant advances will come from the use of intermetallic phases as the primary phase. This would require underpinning fundamental
10. Development of a new design concept, e.g. allowables to defect based. Macro scale the measure is Kc. Modelling of performance
11. Hybrid metallic/non-metallic material solutions, incorporating interface technologies, sandwich layups.
12. Morphing, functional, smart, adaptive metallic and hybrid materials.

13. Metallic foams appear to be promising materials but are still relatively expensive and the technology is not mature (with the exception of some aluminium foams). The possibility of development of metal foams (high stiffness low density) is of particular interest to the surface transport industry and long term research towards this should be carried out.

5.2 Construction sector

Our future cities should be energy neutral or positive, resource efficient, and multicultural and inclusive. At the same time the renovation rate in the construction sector is low, i.e. 1 up to 2%, so many buildings of today will still be here in 2050. Due attention is thus to be given in our 2050 visions to the already existing building stock and its renovation. Metal-based solutions for renovation or for new buildings could then be designed not only to satisfy the technical and safety requirements but also to significantly contribute to the energy performance of the whole building.

Mechanical resistance and stability

The construction must be designed and built in such a way that the loadings that are liable to act on it during its construction and use will not lead to (a) collapse of the whole or part of the works, (b) major deformations to an inadmissible degree, (c) damage to other parts of the works or to fittings or installed equipment as a result of major deformation of the load-bearing construction, and (d) damage by an event to an extent disproportionate to the original cause.
Therefore strength and deformability of the materials used play an important role. Innovations for structural materials or materials used as reinforcement could be situated on the level of developing:

- "high strength materials" with high ductility in order to give sufficient warning before collapse
- materials with high rigidity and stiffness for example to prevent buckling of slender elements, e.g. foam materials could be considered to attain higher stiffness
- light materials generating a lower own weight, yet here it should be remembered that "ultra-light structures" might generate other problems, for example in relation to vibrations, thermal inertia and alike

Safety in Case of Fire

Constructions must be designed and built in such a way that in the event of an outbreak of fire (a) the load-bearing capacity of the construction can be assumed for a specific period of time, (b) the generation and spread of fire and smoke within the works are limited, (c) the spread of fire to neighboring construction works is limited, (d) occupants can leave the works or be rescued by other means, and (e) the safety of rescue teams is taken into consideration.

Reaction to fire of metallic materials is clearly a good intrinsic characteristic. Innovation can be situated on the level of the development of fire safe steel using inclusion of carbides. Fire safety is a crucial problem for steel constructions. It is realistic to develop materials with better performances. Attention must be paid to passive as well to active fire protection.

Hygiene, health and the environment

Construction work must be designed and built in such a way that it will not be a threat to the hygiene or health of the occupants or neighbors, amongst others as a result of any of the following issues: (a) the emission of particles, toxic gas or dangerous radiation, (b) the pollution or poisoning of the water or soil, (c) faulty elimination of waste water, smoke, solid or liquid wastes, (d) the presence of damp in parts of the works or on surfaces within the works. Surface treatments can be necessary to combat Sick Building Syndrome and should be adapted to specific use cases. Anti-bacterial treatments can bring a solution here. Anti -microbial copper alloys surfaces could for example be used as they have proven to be effective. Also coating with TiO_2 can be considered to make surfaces, for example facades, self-cleaning. Monitoring of the air quality in ventilation pipes can also be relevant to determine if intervention is needed.

Related to health it could also be of importance to consider the potential impact of electro-magnetic radiation. Metal surface can bring a solution here as well. Also the use of materials technologies to manage bio-pathogens/microbes, such as anti-microbial copper would represent improvements.

At last also in the recycling process possible health hazards has to be aware of, especially care should be taken of any potential influences of radioactive contamination on recycling process.

Safety and accessibility in use

The definition of this essential requirement is limited to the risk of violent and immediate bodily injuries arising for persons in or near the construction, for any reason. In fact this requirement refers to three large families of risks (a) slips, falls, impacts; (b) burns, electrocutions, explosion; (c) accidents, as for example, those resulting from vehicle movements.

Opportunities for future developments are identified in the following fields:

- monitoring sensors in networks (e.g. RFID, textile grids) in walls to provide in: tracking of people, intrusion prevention, implement intelligent house with embedded systems providing wireless electricity
- work on aspects related to indoor navigation, building information management, and user’s interaction for example using a reactive environment guiding people in their movements.

Protection against noise

The protection can involve the following different aspects (a) protection against airborne noise from outside or from another attached enclosed space, (b) protection against impact noise and equipment noise, (c) protection against excessive reverberant noise. Especially in relation to the protection from noise resulting from inside the construction and for example induced by (low frequency) vibrations, metallurgical solutions can be found. Here developments of high-damping materials can be considered to decrease vibration and noise levels of machines and structures. Opportunities can be situated in relation to Fe- 12Cr-based alloys and Fe-Al-Si alloys (Serena®). These steels exhibit high damping capacity combined with rather good mechanical and corrosion properties. In more extreme conditions development of low cost copper alloys for use in buildings to damp in-service vibrations as well as seismic energy during earthquakes would be an advance.

Energy economy and heat retention
The construction must be energy efficient in use having regard to the climatic conditions of the location and the intended use of it. For that purpose energy economy provisions may be related to the energy uses, space heating and cooling, humidity control, sanitary hot water production, ventilation.

Here metallurgy can play a very important role in relation to the development of systems for: HVAC, ventilation, isolation, energy production, energy capture, energy storage, and integration of functions such as energy production, storage and transport in one single element. New composites like highly conducting carbon nanotubes embedded in Cu wires can play an important role both in the economy and in the efficiency of the electrical energy transport.

The building envelope is in many respects essential, and need to incorporate many functions surely as building more and more can be expected to evolve from a totally passive concept to become more active elements in the Built Environment. Facades will need to incorporate many technologies. Heat reflecting windows incorporating metallic tin-oxide coatings and films will be necessary. The use of phase change materials and dynamic facades is expected to boom.

In the case of marine and offshore applications: new corrosion protecting systems can be provided by metallurgical solutions.

5.3 Consumer Goods Sector

The longer term targets for the consumer goods sector will include:
- Improved surface characteristics in
  - tactile properties
  - self-repairing
  - capable of sustaining forming operations
- Knowledge-based material design to optimize product performance by through-process models, leading to new materials (e.g. stainless steel grades) including process routes(e.g. heat treatments) that enable higher formability and better product performance
- Net shaping of metal parts by TPM (through process modeling)

5.4 Electronic Sector

- Research and development of non-corrosive alloys or metallic matrix composites for fuel cells applications is required to overcome the intrinsic deficiencies of the current material (i.e. high-temperature stability, cost, etc.).
- Reduce thermal conductivity of thermo-electric materials down to a limit that will allow ZT reaching a meaningful value.
- Develop high-performance bulk TE materials
- Develop materials, which show considerably better electromigration resistance than existing ones such as the copper-nanocarbon composites being developed currently in Japan.
- Development of innovative metal materials in bioelectronics.

5.5 Energy Sector

- Advanced austenitic steels for Ultra Super Critical Combined Gas operation (yield strength + creep 100 MPa/500‘000 hours up to 8000C)

- Establish advanced tools for surface optimization/ treatment under extreme environments in energy related applications (including advanced fission) to improve value of metallic materials up to 800^0C.

- Develop advanced metallic blade materials for USC-and UHT gas turbine applications as well as for intermediate heat exchangers: DS/SC steels, ODS, fibre reinforced metals, intermetallics, including TBCs, to provide for component production.

- Improve components for transport of energy and energy carriers (e.g. advanced aluminum and copper alloys) as well as for energy storage.

5.6 Tooling Sector

- Knowledge based design and fabrication of forming tooling (i.e. gradient material, shell structure) for managing the specific thermal, mechanical and wear conditions in the tooling during the process.

- Improve the high temperature resistance to service damages

- Active moulds for plastic parts: mechanically and thermal active moulds (in area). With increased heat dissipation capability and reducing mechanical movements when releasing the parts (i.e. CuBe insert for dissipating the heat).

- Forming tools with low-friction and non-stick surfaces and complex 3D shapes for nano- and micro-forming.

- Highly durable, self-lubricating ceramic tools, cheap enough to be disposed of and recycled or reclaimed through additive repairing process.

- Shorten the delivery time for tools by developing easy to machine steels that could be heat treated afterwards for having high hardness (i.e. 1000 MPa).

- Developing cutting tool without W or other expensive materials (i.e. Co, Cr.). Need to address the availability of critical raw material.

6 CROSS-CUTTING ISSUES

6.1 Enabling Tools

Drivers/Industrial Needs

Enabling tools for metallurgy-related research, development and applications (RDA) include modelling tools, infrastructure for RDA and skills-related. In general, industry still seeks focused /improved applications of the modelling techniques and software-tools. These techniques and tools should be able to support physics-based modeling and experimental verification testing, design of tailored micro-structures and assessment of micro-structure changes – models leading to predictive design/characterization. Considering the cross-sector nature and value chains of metal materials, predictive models on material performance during the life-time and multi-scale and multi-physics modelling are needed. But in many cases the physical mechanisms underlying failures of components which limit their life in service are poorly understood. Examples include oxygen embrittlement of superalloys in aerospace, hydrogen embrittlement of high strength steels and superalloys in the oil and gas industry, stabilities of microstructures in steels exposed to long-term irradiation in nuclear reactors, and cold dwell fatigue of titanium alloys in aerospace. Here we find a severe shortage of metal physicists with the insight and knowledge to unravel the physics of the problem and formulate a mathematical model and computational strategy to solve it. There is also an urgent need to address "lack of reliable material data" in industry for the modelling of materials/interfaces, processes and uses under service conditions, especially for new materials, new material conversion processes and products used in harsh environment and severe conditions. In this regard the roadmap strongly supports the thrust of NMP-20-2014, Topic: Widening materials models.

There exists a significant gap in modelling of powder metallurgy processes particularly predictive models. There are currently tools that would enable better modelling of failure down to the microstructural level. Such techniques need to be improved and a database of where engineers and scientists can gain access to materials property data created.

Advanced enabling tools for NDT for the aviation industry and the energy industry, such as power plants, are also needed. Advanced modelling is needed to support development of advanced manufacturing of engines and components to address: new materials, conventional alloys, net-shaping capability, intermetallic and ceramic materials. Modelling of a completed material recycling process or process chain remains to be achieved to support "Environment Metallurgy" and "Eco-Design".

Strength of EU in modelling/enabling tools

The strength of EU in materials modelling, including metals, may be summarized as follows: Europe plays world-wide leading roles in computational materials science. Europe has contributed significantly to the world-wide development of Electronic models, Atomistic models (including Molecular dynamics), and Meso-scopic models, and these are used in a multi-scale approach to simulate phenomena in metallic materials, metal-liquid engineering and coatings. The electronic structure community in Europe is extremely well connected through the psi-k network (www.psi-k.org), with more than 1400 members.

Weakness of EU in modelling/enabling tools

The weaknesses of EU in materials modelling, including metals, may be summarized as follows:

- Need for scale at European level
- Lack of synergy in existing activity at the mesoscale and to some extent at the macroscale.
- Lack of effective collaborations between physics/chemistry scientists/researchers and metal processing researchers and engineers, stemming from the abandonment of metal physics in many university departments of physics.
- Lack of experience/skills in and facilities for using advanced modelling tools in industry

The future of the European industry is associated with a strong modelling capacity, as identified in the Report on "Modelling in FP7 NMP Programme Material Projects" (EC, May 2013). The key challenges are:

(1). Developing material-industry as service, rather than as traditional suppliers, which demands more "materials by design" to meet customers' needs and the use of more holistic approaches and life-cycle considerations.

(2). Meeting shorter product development cycle and high-quality products which means more robust tools, more efficient computations and more accurate results.

(3). Moving from "*Modelling for industry*" to "*Modelling by industry*", which means shifting efforts from laboratory-centred modelling activities to helping industry equip itself with advanced modelling tools and skills. This will require a cultural change in companies where a modelling capability is regarded as an economic necessity to have in house, rather than outsourcing it to universities.

(4). Developing more accurate and accessible material data within a short time-scale

(5). Persuading physicists to return to fundamental studies of defects in metals to rebuild metal physics across Europe following decades of decline and lack of funding.

Establishing an EU Materials Innovation Infrastructure Programme should be considered as one of the main medium term goals

In general, such a programme should adopt the following objectives:

- To improve/extend capabilities of existing models and computational methods and codes;
- To develop and improve databases for existing and new material systems and realise true data-sharing in Europe;
- To integrate existing simulation tools/computational platforms for metallurgy-related applications;
- To improve and develop model-validation tools and experimental tools in general.
- To develop a collaboration programme to establish a shared metallurgy database
- To educate a generation in the fundamental physics of defects and defect processes in metals in universities to equip manufacturing companies with the people they need to develop in house modelling capability.

EU funding in medium terms should be focused more on the integration of models and tools and research effort at the European level, rather than developing individual models and tools for a limited number of applications.

Long term goals should include: considerably shortening time-scale from developing material models, new algorithms for computing, code development/realisation, to industry applications; and enabling "Through Process Modelling", "Materials by sindustry to the industry as service which fast meets customers' requirements on designed properties and life performance for a particular material-system.

Long term goals should include a fully established, carefully planned, integrated, coordinated **Europe's Material Innovation Infrastructure**, which covers all kinds of materials, processes and uses identified/needed by EU industry and end-users.

Research Topics and Champions

To achieve the goals in a medium term, we suggest the European Commission consider the topics recommended below as "champions" in the area of enabling-tools.

Topic 1: High-throughput experimentation and assessment for the construction of a material database for advanced materials to meet urgent industrial needs. It should include in future calls advanced material-characterisation instrumentation and fast procedures for the development and validation of a co-ordinated materials database with a clear emphasis on metallurgy.

Topic 2: Modelling of New Metallic-Materials with Life-Time Approach and Creation of European Metallic-Material-Models Library. Significant results in material-modelling have been made/achieved in Europe. However, to fully take advantages of these for the benefit of the industry, these need to be further developed and need to connect the whole life-cycle process (e.g. considering design, manufacturing, environment, and recycling) to meet latest and future industry needs.

Topic 3: Integrated Computational Platform for Life-Metallurgy-Engineering and Product Innovations. An integrated computational platform is needed to: support Europe in metal-product innovations; enable much more efficient "Materials by Design" and moving towards "Material-industry as a service"; significantly shorten the material development cycle; and effectively monitoring and predicting metals' life-time performance, etc. It would need to integrate different models, material-databases, computational techniques and software-tools, to address all material-processing steps, life-time performance prediction for both existing and emerging materials.

Topic 4: European Network of Excellence for Enabling Tools for Metallurgy. A European Network of Excellence (NOE) in metallurgical enabling-tools could be a vehicle to drive and facilitate such integration effectively and to act as a executing body to address many cross-cutting issues, e.g. a European Platform (virtual institute) of Metal Physics to work closely with metallurgically based industries to identify fundamental mechanisms of deformation and failure through a combination of characterization, mechanical testing and simulations based on physical models. This platform would also provide education and training in metal physics for engineers and metal physicists in industry.

Topic 5: Identify common fundamental deformation and failure processes across a range of industrial sectors, including nuclear power, aerospace, automotive and metal production, and formulating theoretical and computational strategies to model them. Examples include fatigue crack initiation, slip transmission at interfaces, hydrogen embrittlement, micro-structural evolution under irradiation and concomitant changes to the ductile to brittle transition, and plastic deformation under shock loading.

6.2 Life Cycle Assessment

- <u>Product/structure life cycle. Life cycle assessment (LCA)</u>. Like other heavy industries, transport sector involves the use of materials and practices that can impact the environment and contribute to climate change. For example, the in-service life of a ship can extend to more than 30 years, this impact continues through the life of the vessel and finally plays a role at the demolition of the outranged ship.

  The life cycle assessment involves the whole spectrum of intervention that a material could have on the environment, for example the carbon footprint associated with the production, transportation and final disposal of materials used in production and operation. A large number of materials and practices used in the transport sector have significant environmental, climate change and other impacts

  The way ahead in terms of environmental compatibility and green profile for new materials and processes in the industry should focus on following issues:

  - Lifecycle analysis on ships hull and buildings;
  - Waste streams for materials;
  - Green recycling: development of the framework;
  - Pre-cleaning practices;
  - Pre-cleaning seminars and demolition investigations: everything that should be done before the beginning of the recycling of the ship or buildings;

  More specifically and from a metallurgical point of view the most significant activities with environmental impact are subdivided in four main phases namely:

  - Production of the metals
  - Assembling
  - Maintenance and repairs through the in-service life
  - Demolition

  Shipbuilding and maintenance/repairs are performed mainly in shipyards and include metal working activities like thermal cutting welding and grinding. Surface treatment operations like grid blasting and metal surface preparation are also critical considering the shipyard environment in the sea but also very often direct access to urban areas.

  In the construction sector it is important to separate materials stone, glass, metals…. Developing a Life Cycle Concept from within the design stage is becoming a must as well as "Cradle to Cradle" design considerations. Dismantling is in this respect also an issue it itself, and design for dismantling will become a real need.

Emphasis should also be given to the steel production itself. From an environmental life-cycle perspective efforts should be made to minimize the environmental impact of the production of the steel used for shipbuilding. This could be done through the establishment of green supply management strategies that would pay close attention to raw material extraction methods and the energy used to produce the steel. In addition to the optimization of steel production processes, environmental performance could also be improved by optimizing various properties of the steel itself.

6.3 Recycling and Recovery

Recycling of manufacturing scrap (swarf, etc.) is already well advanced in supplier base –however, it needs improvements in quality, cost, cleanliness and a tighter iteration loop returning specific (and therefore higher value) alloy scrap back into the same material supply chain.
Buildings account for 40% of the total European energy consumption and a third of CO_2 emissions. Furthermore construction and demolition waste is also one of the heaviest and most voluminous waste streams generated in the EU. It accounts for approximately 25% - 30% of all waste generated in the EU and consists of numerous materials, including concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, etc. Construction industry has thus an important environmental footprint. Sustainable use of energy and natural resources in the construction industry is thus more than a must. Refurbishing, Reuse of (structural) elements and Life Cycle Thinking have an important place to take. Recyclability of all materials used is more than essential.

Increased attention is needed on recovery of precious metals from e-waste by biometallurgy. hydrometallurgical processing and pyrometallurgical recovery.

In general all sectors are committed to recycling and recovery of metal materials and to being compliant with REACH requirements. Enhancement of processes and practices to continue this trend will emerge from the Roadmap.

6.4 Standardisation

Greater levels of standardisation are required in the communication of data, particularly material performance data for design and simulation purposes, as well as the material and process computational models.

For the Construction sector standardisation and technical approvals are conditions sine qua non to get new products in the market.

For Consumer Goods there is a need for standards in relation with new testing protocols (antifouling, anti-microbial, friction drag, tactile, friction, wear, corrosion, fatigue under extreme conditions, release….).

Cooperation of the European Commission with leading standardisation organisations in order to provide a common policy and standards in the area of metal tooling should be created. Especially, to define the end of use, the environmental issues, as well the materials properties and processes.

6.5 Education and Skills (see priorities for 2020)

Industry needs more highly skilled people in metallurgy. Shortage of the qualified graduates/engineers in metallurgy and metal processing in general is a major concern.

The continuous advancement of quality skills of scientists and engineers is essential for the improvement of knowledge and for ensuring technological development and the enhancement of European innovation in the area of metallurgy. This can be achieved through the upgrading of existing related education and training programs. Also both basic skills and advanced training can be accomplished by the development of new programmes addressing research and innovation, tailored to the current and future needs of our society. There is a particular need to rebuild metal physics in Europe. European capability in metal physics is confined to a few centres, and not all of them have strong links to industry.

In general there is a need for an improved focus on metallurgical education / Increase attractiveness of metallurgy as career stressing particularly systemic understanding and translate new research methods to metallurgy. Education on conventional metallurgy should be promoted with the use of case studies highlighted. Education in metal physics is also necessary.

Europe is facing a big challenge in maintaining the knowhow and capacities in the tooling industry. Despite the strong position in the sector, the transfer of production sites to other countries worldwide is decreasing the skilled workforce in Europe. On one side, strong relationships with the educational institution and the tooling industry should be developed and maintained.

7 PRIORITIES FOR RESEARCH AND INNOVATION ("CHAMPION" TOPICS)

The champion topics represent the consensus by the experts on the areas of research, development and innovation which are most important to address in the upcoming programmes to ensure that Europe retains a strong competitive position in world metallurgy. The topics are listed for each area in order of priority. Naturally there is some degree of overlap between sectors but it is important that the specific sectoral needs are considered in drafting and scoping new programmes.

Area 1. Transport Sector (Surface, Marine, Aeronautics)

T1 - New grades of steel with higher strength, formability, corrosion resistance, and joining ability (Automotive / Rail Targets: Steel – UTS >1400MPa, elongation >10%, or HB>400).

T2 - Improved strength, formability, corrosion resistance of 2000, 5000, 6000, 7000 alloys (of parent metals and welds)

T3 - Development of novel aluminium compound metal/metal and/or metallic/non-metallic structures (sandwich structures).

T4 - Development of new environmental friendly technologies for joining similar and dissimilar materials.

T5 - Extended use of aluminium compound metal structure with increased fire resistance.

T6 - Defect based metallurgy.

T7 - Intermetallics.

T8 - Powder processing and metallurgy.

Area 2. Construction Sector

Considering their specific properties of lightweight, strength, durability, formability and recyclability, metal-based solutions will continue to play a key role in the future within the building sector not only as part of the structure but also as part of the building envelop. Hence, metals will influence to a large the energy performances, the maintenance and the durability of building fabrics. This key role is not only important for new buildings but is also even more crucial for renovation which appears as the most significant challenges that EU will face in the next decades within the construction sector. Indeed, metal solutions thanks to their lightness and flexibility are specially adapted to the specific requirements of the renovation sector.

Considering the key role of metals in the future of building envelops, the development of intelligent multi-functional surfaces properties appear as a breakthrough innovation which will reinforce the role of metals in sustainable buildings and will maximise their contribution to a more resource efficient Europe. These multi-functional surface properties, generated by specific surface metallurgy, surface treatments or coatings, should address the following aspects: maintenance, cleaning, hygiene, heat and electricity production, heat conservation, durability and/or self-healing.

Champion topics
CON1 - Technology Transfer, Demonstration in Pilot Cases and Education (2020)
CON2 - Developing intelligent multi-functional surface properties for metal building components and solutions (2025)

Hence, the main target in the construction sector should be: "*Developing intelligent multi-functional surface properties for metal building components and solutions".*

These tailor-made surface properties will definitely positions metal solutions as key enablers towards more sustainable buildings, this in different applications ranging from windows, ventilation ducts, facades, kitchens, indoor walls, etc.

Area 3. Consumer Goods Sector

CG1 - Tailored Surface treatments to improve performance (wear, corrosion, fatigue, temperature, bio-fouling resistance) and consumer acceptance (tactile properties, appearance, IR reflectance, cleanliness), testing and modelling behaviour to predict performance and avoiding any damage to the environment (control release eco-toxicity).

CG2 - Development of near net shaping capabilities with conventional production techniques

Area 4. Electronics Sector

EL1 - Replacing precious metals in electronics by developing new alloys and through research into surface modification of metal and copper based alloys for electro-plating contact areas. (2017)

EL2 - Improved metal systems and fabrication processes for metallic components with features at the micro- and nano-scale and tailored electrical and mechanical properties are needed for MEMS/NEMS structures and future technologies. (2016)

EL3 - Innovative metal alloys (including the next generation of Beryllium alloys) and reinforcements for advanced electronic applications (i.e. fuel cells, battery casings, packaging, etc.) with excellent mechanical properties, high thermal and electrical conductivity and highly resistant to corrosion. (2017)

EL4 - Soldering compounds that provide good electrical contacts with no bridging, excellent wetting and good throughput for smaller devices. (2018)

EL5 - Alternative metals with better performance in narrow wires than the current state-of-the-art Cu-based technology. (2015)

EL6 - For copper alloys, disruptive technology innovation such as developing manufacturing methods for thin strip products. (2019)

Area 5. Energy Sector

EN1 - Advanced austenitic steels for supercritical combined cycle plants (2019)

EN2 - Advanced techniques for surface optimization/treatment under extreme environments to improve operation of metallic materials up to 800°C (2014)

EN3 - DS/SC alloys, (2014) ODS, fibre reinforced metals, (2014) intermetallics, (2019) including TBCs (thermal barrier coatings) (2014) for turbine blades and process heat exchangers

EN4 - Alternative concepts for magnetic materials in motors and drives in a systemic approach (2020-2025)

EN5 - Provide low resistance materials for energy transport and advanced materials for energy storage (2014)

Area 6. Tooling Sector

TO1 - Modifications to the surface properties in the tooling to improve tool life.

TO2 - Tailor-made tools by additive manufacturing.

TO3 - Knowledge based design fabrication of tooling (e.g. functionally gradient material, nanostructured alloys, metallic matrix composites, shell structure) for managing the thermal, mechanical and wear conditions in the tooling during the process.

TO4 - New materials and processes for manufacturing forming tools with improved control of the microstructure and properties.

TO5 - Machining of difficult to cut materials that possess excellent mechanical properties.

TO6 - New materials for cutting tools (i.e., new binders instead of Co in WC, using TiC).

TO7 - Advanced tools for applications with complex geometries and require upper dimensional accuracy (i.e. using moving parts in the tooling).

Area 7. Enabling Tools

ET1 - High-throughput experimentation and assessment for the construction of metal material database for advanced materials to meet urgent industrial needs. (2015)

ET2 - Modelling for New Metallic-Materials with Life-Time Approach and Creation of European Metallic-Material-Models Library. (2016)

ET3 - Integrated Computational Platform for Life-Metallurgy-Engineering and Product Innovations to support Europe in metal-product innovations; enable much more efficient "Materials by Design" and moving towards "Material-industry as a service"; significantly shorten the material development cycle; and effectively monitoring and predicting metals' life-time performance, etc. (2018)

ET4 - European Network of Excellence for Enabling Tools for Metallurgy to drive and facilitate integration effectively and to act as a executing body to address many cross-cutting issues, e.g. a European Platform (virtual institute) of Metal Physics to work closely with metallurgically based industries to identify fundamental mechanisms of deformation and failure through a combination of characterization, mechanical testing and simulations based on physical models. This platform would also provide education and training in metal physics for engineers and metal physicists in industry. (2015)

ET5 - Identification of common fundamental deformation and failure processes across a range of industrial sectors, including nuclear power, aerospace, automotive and metal production, and formulating theoretical and computational strategies to model them. Examples include fatigue crack initiation, slip transmission at interfaces, hydrogen embrittlement, micro-structural evolution under irradiation and concomitant changes to the ductile to brittle transition, and plastic deformation under shock loading.

8 LINK-UP "CHAMPION" TOPICS TO HORIZON 2020

Factories of the future, (FoF), PPP

Resource-efficient Processing Industry, (SPIRE), PPP

Energy-efficient Buildings, (EeB), PPP (CON2)

Green Vehicles, (EGVI) PPP

Fuel Cells and Hydrogen, (FCH) JTI

Aeronautics and Air Transport, (Clean Sky) JTI

Nanoelectronics, (ENIAC) JTI

Active and healthy ageing, EIP

Sustainable Agriculture, EIP

Smart cities and communities, EIP

Raw materials, EIP

Water, EIP

	Surface	Marine	Aerospace	Construction
2050 Vision (Long term goals)	Steel foams. Higher strength, ductility, corrosion and wear resistant MMCs. Functionally graded materials. Improved aluminium alloy recyclability. Multi metal and multi material solutions for recyclability and disassembly. 3-D printing, additive manufacturing, develop suitable powders. Magnesium alloy sheet technologies based on warm forming process.	Physical surface metal treatments / barriers for improving corrosion resistance and antifouling.	Intermetallics for high temperature operation (NbSi). Hybrid metallic / non-metallic material solutions. Morphing, functional, smart, adaptive metallic and hybrid materials.	Mechanical resistance and stability. Safety in case of fire. Hygiene, health and environment. Safety and accessibility in use. Protection against noise. Energy economy and heat retention.
2020 (Medium term goals)	New grades of steel and aluminium alloys	High strength ferrous based materials with improved corrosion characteristics. Novel aluminium compound metal/ metal **foam** and/or metallic/non-metallic **sandwich** structures. New environmental friendly technologies for joining similar and dissimilar materials. Extended use of aluminium compound metal structure.	Online process and NDI control. Defect based metallurgy. Intermetallics. Powder processing and metallurgy.	The renovation and construction of buildings and infrastructure. Life-cycle approach will be widely applied; new buildings will be nearly zero-energy and highly material efficient. Policies for renovating the existing building stock will be in place so that it is cost-efficiently refurbished at a rate of 2% per year. 70% of non-hazardous construction and demolition waste will be recycled. Extended use of aluminium compound metal structure with increased fire resistance.
2013 (Current issues)	Improve energy efficiency Increase the in-service life Safety improvement			Technology transfer Demonstration and pilot case projects Education

	Electronics	Tooling	Consumer Goods	Energy
2050 Vision (Long term goals)	Innovative alloys and reinforcements for advanced electronic applications with excellent mechanical properties, high thermal and electrical conductivity and high corrosion resistance Disruptive technology innovation for copper alloys. **Further** developments in Nano- **mechanical measurement techniques.** Reliable modelling tools that demonstrate the link between atomic-level structure and the mechanical, chemical and physical properties of the metallic components used in electronics applications.	Knowledge based design fabrication of forming tooling (i.e. gradient material, shell structure,...) for managing the thermal, mechanical and wear conditions in the tooling during the process. Shorten the delivery time for tools by developing easy to machine steels that could be heat treated afterwards for having high hardness (i.e 1000 MPa). Active moulds for plastic parts: mechanically and thermal active moulds (in area). Decreasing heat from the parts and reducing mechanical movements for when releasing the parts.	Improved surface characteristics in • tactile properties • self repairing • capable of sustaining forming operations Knowledge based material design to optimize product performance by through-process models, leading to new materials (e.g. stainless steel grades) including process routes (e.g. heat treatments) that enable higher formability and better product performance Net shaping of metal parts by TPM	Advanced austenitic steels for USCCG (yield strength + creep 100 MPa/500‘000 hours at 8000C) Replacement of rare earth elements in motors and drives; concepts for alternative motor/ drive developed. New production routes for very clean foils. Replacement/ minimization of precious metals and rare earth elements. Develop additive manufacturing systems for advanced metallic components (e.g. gradient materials)
2020 (Medium term goals)	**Development in Nano-mechanical measurement techniques.** Durable and robust light materials for portable devices. Improved solder material for miniaturised applications. **Cost effective Severe Plastic Deformation (SPD) for producing advanced nano-structured materials.** Combination of the existing characterization methods at different scales, increasing understanding of the relationship between materials structure and their functionality.	Shorten the delivery time for tools by additive manufacturing. Understanding and modelling tooling behaviour and microstructure. New materials and processes for manufacturing forming tools with improved control of the microstructure and properties. Modelling of the evolution of microstructure during processing. Machining of difficult to cut materials that possess excel lent mechanical properties. Tools for micro-scale applications.	Tailored **Surface treatments** to improve specific characteristics. Improved understanding and quantification of physics and material influence on product performance and implementation in numerical models. Well documented and standardized material characterization and commercially available models. Near net shaping by conventional production techniques. **3-d printing** prototypes.	Advanced austenitic steels for USCCG (yield strength + creep 100 MPa/500‘000 hours at 6700C) Establish advanced tools for surface optimization/ treatment under extreme environments in energy related applications up to 6700C. Reduction of amount of rare earth element in permanent magnets. Advanced metallic blade materials for USC-and UHT gas turbine.
2013 (Current issues)	Miniaturisation Cost of materials Raw material supply	Tool wear and failure Replacing critical raw materials Shorter delivery time for toolssupply	Improve product performance by new materials and surface modification Models lack accurate material data.	More demanding operating environments Materials for energy transportation

List of abbreviations

A-UHSS	Advanced Ultra High Strength Steel
BVID	Barely Visible Impact Damage
Co in WC	Nano-grained Tungsten Carbide-Cobalt
CPD	Construction Products Directive
CPR	Construction Products Regulation
DS	Directionally solidified
EAD	European Assessment Documents
EIP	European Innovation Partnership on raw materials
EPBD	Energy Performance of Buildings Directive
GDP	Gross Domestic Product
HBW	*H* hardness; *B* Brinell and *W* from the material of the indenter; tungsten (wolfram) carbide.
HDG	Hot dip galvanizing
hEN	harmonised European standards
HPC	High performance computing
HSLA	High Strength Low Alloy
HSS	High Strength Steels
HT	High Temperature
HVAC	Heating; ventilation and air conditioning

ICE	internal combustion engine
IR	Infra red
Kc	K specifies stress distribution at crack tip. Kc critical fracture toughness
KIC	Knowledge Innovation Community on raw materials.
LCA	Life cycle assessment
MEMS	Micro- based electro mechanical systems
MMC	Metal Matrix Composites
NDI	Non destructive inspection
NEMS	Nano-based electro mechanical systems
nZEB	nearly Zero-Energy Buildings
ODS	Oxide Dispersion Strengthened
PM	Powder metallurgy
PVD	Physical Vapour Deposition
REACH	Registration; Evaluation; Authorisation and Restriction of Chemicals.
RFID	Radio Frequency Identification
SC	Single Crystal
TBC	Thermal Barrier Coating
TiC	Titanium Carbide
TMCP	Thermo-mechanically controlled processed steels

TPM	Through Process Modelling
UHT	Ultra High Temperature
ULCB	Ultra-Low Carbon Bainitic steels
USC	Ultra Super Critical
UV	Ultra Violet
VID	Visible Impact Damage

HOW TO OBTAIN EU PUBLICATIONS

Free publications:

- one copy:
  via EU Bookshop (http://bookshop.europa.eu);
- more than one copy or posters/maps:
  from the European Union's representations (http://ec.europa.eu/represent_en.htm);
  from the delegations in non-EU countries (http://eeas.europa.eu/delegations/index_en.htm);
  by contacting the Europe Direct service (http://europa.eu/europedirect/index_en.htm) or
  calling 00 800 6 7 8 9 10 11 (freephone number from anywhere in the EU) (*).

  (*) The information given is free, as are most calls (though some operators, phone boxes or hotels may charge you).

Priced publications:

- via EU Bookshop (http://bookshop.europa.eu).

Priced subscriptions:

- via one of the sales agents of the Publications Office of the European Union
  (http://publications.europa.eu/others/agents/index_en.htm).

KI-05-14-048-EN-N

European industry must increase its efforts to make metallurgical discoveries and modernise its production capabilities. New, more competitive and improved products must be invented based on innovative metallurgical processes.

This roadmap identifies alternative technology paths for meeting certain performance objectives. It focuses on metallurgy dependent products with improved materials performance rather than processes.

It is driven by the market requirements and it is an important tool for collaborative technology planning and coordination for metallurgical industries. It puts forward key metallurgy research needs and innovation activities to advance metallurgy-based technologies for the next 10-20 years and beyond. It will help to identify, select and develop technology alternatives to satisfy a set of final product characteristics. It also serves to give confidence to funding policy makers, committing resources.

Studies and reports

Publications Office

doi:10.2777/11914