Chapter 2
ESA's Materials Science in Space Programme

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1 Introduction

Within ESA, its member and cooperating states are working together on space research and technology and their space applications. Activities relating to the exploration destinations Low-Earth Orbit, Moon and Mars are integrated into a single European Exploration Programme (E3P), of which the "Science in Space Environment" (SciSpacE) element is concerned with the scientific research on the ISS, non-ISS space platforms and space-environment analogues. SciSpacE and its preceding "European Programme for Life and Physical Sciences in Space" (ELIPS) are and have been providing the scientific communities in the relevant disciplines with experiment opportunities using these platforms since the start of ISS utilisation at the turn of the century and as an extension of the initial European microgravity programmes going back to the 1980s. Descriptions and results of these experiments are archived in a publicly accessible and searchable ESA repository [1].

The overall motivation for conducting science in a space environment is that this reveals features of terrestrial life and physical processes that cannot be observed and/or controlled on Earth. Aspects of interest include – but are not limited to – the reduced-gravity condition, the otherwise extreme conditions (in their possibly wide sense, ranging from radiation and temperature variations to remoteness and confinement) and the vantage point for Earth as well as for deep space.

Research activities that are being developed and conducted in this context are correspondingly diverse. These research activities are being guided by the so-called science roadmaps (or research agendas) that have been established by the European scientific communities for the respective domains and are documented in [2] – with an updated second issue that now also includes the Moon and Mars destinations to be

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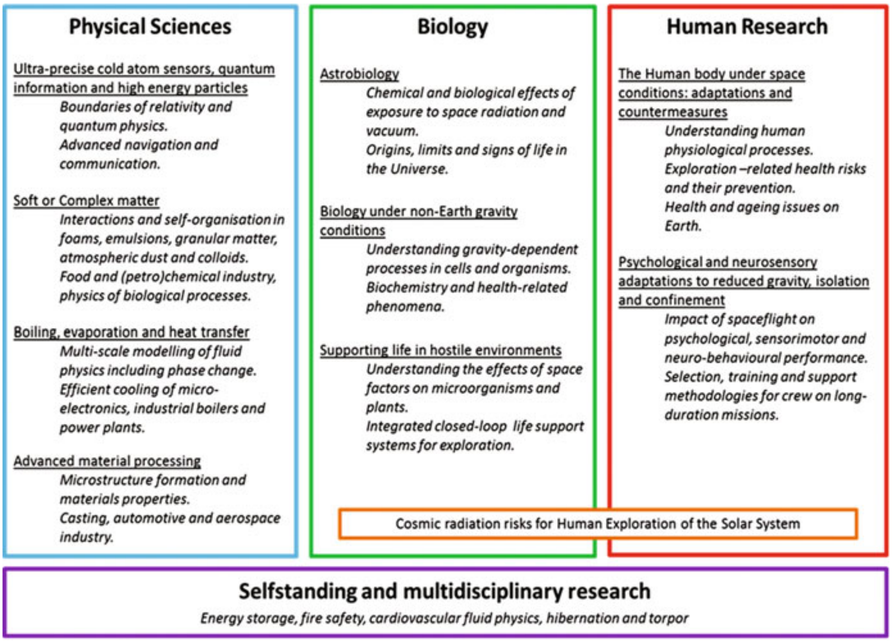

Fig. 2.1 ESA's top-level roadmap themes for Low-Earth Orbit research activities

published in 2021. Roadmap themes are structured as shown in Fig. 2.1, with materials science being covered in the physical sciences box under the title Advanced Material Processing. Here, the implication of a reduced-gravity environment (typically <10^{-3} g) is that no buoyancy/sedimentation and thereby that diffusive conditions exist in experiments involving multiple phases such as in solidification, as well as in a variety of other physical sciences experiments.

This chapter is dedicated to the materials science in space programme as supported by ESA. Following a general outline in terms of research topics and (on-orbit) facilities that have been realised or are being planned, particular attention is given to the activities relating to electro-magnetic levitation, being a major constituent of the reported research in this book. The latter includes brief descriptions of how the research is organised, which samples are selected and what research outputs have been generated to date. Finally, benefits for Earth and industrial relevance of the investigations in this materials science programme are addressed in broad terms.

2 The Materials Science Programme

As outlined above, a reduced-gravity environment offers specific opportunities for experiments involving a phase transition and aiming to study phenomena that are obscured in experiments on Earth by buoyance/sedimentation and the convection resulting from that. For materials science this means that the field of solidification physics is of particular interest.

Figure 2.2 lists the main topical scientific challenges in this domain. As one of the first steps – and often even the single step – in the processing of materials, solidification from the melt inevitably leaves its fingerprints in the (semi)-finished product. Hence, it is essential to understand the properties of the molten state and the solidification mechanisms in order to tailor the processing route and to achieve satisfying microstructures to meet functional performance requirements.

Advances in these areas are key to further improve the quantitative and predictive modelling and simulation of liquid-state manufacturing processes. This is to the benefit of the industrial manufacturing of semi-finished products (e.g. slab, billet, bloom, ingot) and shape castings, as well as of processes entailing rapid solidification such as high-pressure die casting, strip casting, welding, atomisation, spray forming and additive manufacturing (3D printing). Enhanced process control implies an increase in production efficiency and a reduction of energy consumption and scrap material, rendering these manufacturing processes more efficient and sustainable. Also, reductions in weight or improvements in (mechanical) performance may be achieved through optimised casting.

Deriving from these overall scientific challenges, ESA's materials science roadmap identifies the following major research areas of interest for reduced-gravity experimentation:

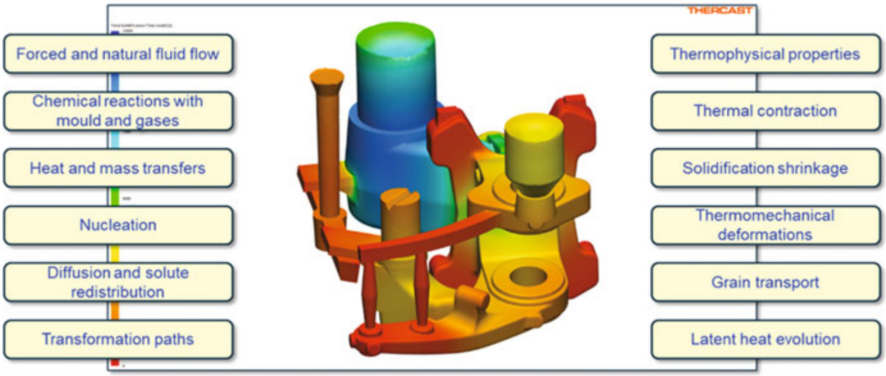

Fig. 2.2 Fundamental aspects of casting a complex component, here shown in relation to the total solidification time predicted for a steering knuckle (Image: Courtesy of S. Andrietti (TRANSVALOR))

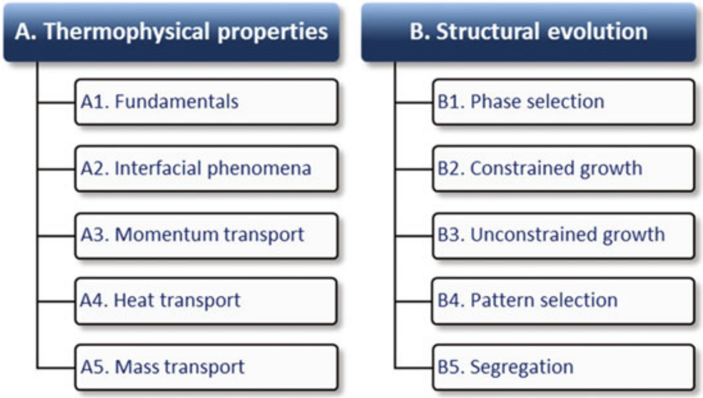

Fig. 2.3 Physical phenomena from processing and properties to solidification (micro)-structure in materials

- The reliable determination of the *thermophysical properties* of (metallic and other) materials, notably of melts.
- The investigation of *structural evolution* in materials during liquid-solid phase transition, requiring the reliable determination of the formation of phases and of selection mechanisms at the relevant length scales.

Figure 2.3 depicts the physical phenomena distinguished within these areas. For each of these, several (sub)-topics are identified with a rationale for space experimentation. Pattern selection (B4), by means of random example, consists of the topics of dendritic growth, peritectic growth and eutectic growth. These topics are further specified and described in relation to the underlying mechanisms in the concerned roadmap document.

Through ESA's E3P and its predecessor programmes, several materials science facilities have meanwhile been developed and are being operated on board the ISS. Typically, they are designed as multi-user and multi-purpose facilities, meaning that they are accessed by multiple science teams to enable experiments with distinctly different research objectives and experiment protocols. The facilities are introduced below, with some further details listed in Table 2.1:

- *Materials science laboratory (MSL)*. This facility is for metal-alloy solidification and crystal growth of semiconductor materials. A rod-shaped sample is molten and then directionally solidified while being moved in axial direction versus the heating elements under a maintained thermal gradient. Processed samples are downloaded for microstructural evaluations. The MSL is operational since 2009 and is located in NASA's Materials Science Research Rack in the Destiny module. It is being utilised under a joint implementation plan between ESA and NASA.
- *Electro-magnetic levitator (EML)*. This facility is for containerless processing of liquid metals and semiconductor materials. An electrically conductive spherical

Table 2.1 Key features of ESA's materials science facilities for solidification physics on board the ISS

Aspect	Materials science laboratory	Electro-magnetic levitator	Transparent alloys	X-ray facility
Research area(s)	Directional solidification	Containerless processing	Directional solidification	Directional/isothermal solidification[a]
Heating	Bridgman furnace	Induction system (separate positioning coil)	Bridgman furnace	Gradient furnace, isothermal furnace
Hardware options	Two exchangeable furnace inserts; rotating magnetic field	Trigger needle, chill-cooling plate (oxygen sensing and control system)		Exchangeable micro-focus X-ray source
Sample exchange	Individual sample cartridges	Carrousel with 18 samples	Individual sample cartridges	Individual sample cartridges
Sample geometry	Rod-like 3D (e.g. ∅8 mm)	Spherical (∅6–8 mm)	Rectangular 3D (e.g. thickness 1–10 mm)	Flat quasi-2D (thickness ~0.2 mm)
Sample materials	Wide range of material types and alloy compositions (metals, semiconductors)	Wide range of material types and alloy compositions (metals, semiconductors)	Organic model alloys (e.g. SCN-DC) with optical transparency	Metallic alloy systems and compositions (e.g. Al-based alloys) with adequate X-ray contrast
Operating temperature	≤1400 °C	≤2100 °C	≤170 °C	≤900 °C
Runs per sample	Single	Multiple	Multiple	Multiple
Control parameters	Temperatures (hot/cold zones), sample translation speed, magnetic field	Coil voltages (including modulation and pulses), processing atmosphere	Temperatures (hot/cold zones), sample translation speed	Temperatures (hot/cold zones), sample translation speed
Diagnostics	Thermocouples	Optical cameras, pyrometer, sample coupling electronics	Optical cameras (resolution ~1 μm), thermocouples	Trans-illumination: camera with scintillator (resolution ~3–5 μm), thermocouples
Post-flight sample analysis	Full suite of analytical tools (including 3D numerical model validation)	Full suite of analytical tools (including 3D numerical model validation)	None (mostly not needed)	Additionally possible

[a]Other experiment types (diffusion, foaming, etc.) are to follow in due time

sample is molten and maintained in place by an electro-magnetic field. Distinct heating-cooling cycles enable high-accuracy measurements of thermophysical properties (specific heat capacity, surface tension, viscosity, etc.) and the study of solidification kinetics (undercooling and nucleation, growth velocity, etc.). The

EML is operational since 2015 and is located in the European Drawer Rack in the Columbus module. The facility and its extensions and sample batches are a co-development of DLR and ESA. It is being utilised under an agreement between ESA, NASA and Roscosmos.

- *Transparent alloys (TA)*. This facility is for solidification of organic substances serving as transparent analogues for metallic alloys. Flat samples are molten and then directionally solidified in a fashion similar to MSL but under the in situ observation of the solidification dynamics by optical means. TA is operational since 2018 and is being utilised for successive experiment campaigns in NASA's Microgravity Science Glovebox in the Destiny module.
- *X-ray facility (XRF)*. Being in the development stage still, this facility is for metal-alloy solidification as well as for other experiment types using a micro-focus X-ray source for in situ diagnostics. For materials science, it is building on heritage from previous parabolic flight and sounding rocket missions involving trans-illumination (radiography) experiments on directional and isothermal metal-alloy solidification, diffusion in metallic melts and metal foaming.

In addition, SciSpacE enables access to other ESA platforms (parabolic flight, sounding rocket), including ground-based facilities (drop tower, large diameter centrifuge) for preparatory and supplementary research.

3 EML Activities

Electro-magnetic levitation in space has a long heritage. An EML can be operated under terrestrial conditions as well, but in a reduced-gravity environment, the required levitation/positioning power is much lower. This means that the molten sample better retains its spherical shape and that convection (fluid flow) remains limited, leading to a higher accuracy of the measurements than on ground and enabling the study of phenomena undisturbed by gravitational effects. Moreover, the regime of undercooling (i.e. metastable region of the phase diagram) becomes better accessible.

Early missions under TEMPUS[1] denominator were in SpaceLab using the IML-2 (1994) and MSL-1 (1997) facilities; on sounding rockets TEXUS 42 (2005), TEXUS 44 (2008) and TEXUS 46 (2009); and in parabolic-flight campaigns (since the late 1980s and with technical improvements continued regularly by DLR to date). Techniques and methods for specific (property) measurements and evaluations were developed among others, and exploratory scientific investigations were conducted in reduced gravity. This then led to the development and operation of the ISS-EML and the associated sample batches in recent years.

[1] "Tiegelfreies ElektroMagnetisches Prozessieren Unter Schwerelosigkeit" in German ("Container-less electromagnetic processing in zero-gravity" in English translation).

ESA's research in the physical sciences is organised through projects selected in so-called Announcements of Opportunity (AO). Each with their own scientific scope and objectives, these projects are commonly initiated in parallel with the conceptual and actual development of the scientific payloads. In that sense they are typically long-standing projects for which scientific yield is ramping up with these payloads becoming operational. To confirm scientific relevance and interest, AO projects are subject to recurring 3-yearly external reviews. The project pool for materials science currently consists of some 20 different research projects, involving international teams from universities, research organisations and industry that are not only limited to the ESA member states subscribing to this programme but also include other participants from across the globe. The following AO projects (acronyms and full titles) are involved in EML activities:

- *CCEMLCC*: Chill cooling for the electro-magnetic levitator in relation to continuous casting of steels
- *COOLCOP*: Undercooling and demixing of copper-cobalt alloys (*merged with LIPHASE*)
- *Electrical resistivity*: Electrical resistivity measurement of high-temperature metallic melts (*completed*)
- *ICOPROSOL*: Thermophysical properties and solidification behaviour of undercooled Ti-Zr-Ni liquids showing an icosahedral short-range order
- *LIPHASE*: Liquid-phase separation in metallic alloys (*merged with COOLCOP*)
- *MAGNEPHAS*: Study and modelling of nucleation and phase selection phenomena in undercooled melts – application to magnetic alloys of industrial relevance
- *METCOMP*: Metastable solidification of composites – novel peritectic structures and in situ composites
- *MULTIPHAS*: Multiphase solidification – eutectic and intermetallic solidification and glass formation
- *NEQUISOL*: Non-equilibrium solidification, modelling for microstructure engineering of industrial alloys
- *OXYTHERM*: Thermophysical properties of liquid alloys under oxygen influence
- *PARSEC*: Peritectic alloy rapid solidification with electro-magnetic convection
- *SEMITHERM*: Investigations of thermophysical properties of liquid semiconductors in the melt and in the undercooled state under microgravity conditions
- *THERMOPROP*: Thermophysical properties of liquid metals for industrial process design

In addition, several other research projects are involved through agreements with other space agencies: ELFSTONE and its predecessor LODESTARS, QUASI and USTIP (for NASA) and PERITECTICA (for Roscosmos).

Matters of common interest to the EML community are being addressed in the Investigators Working Group (IWG), in which all science teams with accepted experiments as well as executives of the agencies and other involved parties are represented. This includes not only the discussion of programmatic and operational issues but also the presentation of acquired results and sharing of lessons learnt. Overall goal of this scientific coordination forum is to maximise science return within the scope of available resources. More information on the IWG is given in [3, 4].

Sample materials for the successive ISS-EML sample batches are selected by peer review from research proposals following a dedicated AO and at a pace in line with the development and processing of the sample batches. Samples have to be qualified for flight on the ISS by precursor TEMPUS parabolic flight or the like, demonstrating technically sound and safe levitation processing in reduced gravity. Tables 2.2,

Table 2.2 EML sample batch 1 overview: prime proposer (●) and other interested projects (○)

ID no.	Sample designation	CCEMLCC	COOLCOP	Elec. resist.	ICOPROSOL	LIPHASE	MAGNEPHAS	METCOMP	MULTIPHAS	NEQUISOL	OXYTHERM	PARSEC	SEMITHERM	THERMOPROP	ELFSTONE	QUASI	LODESTARS	USTIP
1	Al40Ni60									●				○		○		
3	Cu75Co25		●													○		
4	Cu89Co11		●													○		
6	Fe45Co55						●					○			○	○		
7	Fe50Co50						●					○			○	○		
9	FeCr21Ni19											○		●			○	
10	Ni13.8Al6.6Cr7.6Co2.1Ta1.6W1.0Re1.0Mo0.05Hf *(LEK94)*													●				
11	Ni5Al8Cr5Co6Ta8W2Mo1.5Ti *(MC2)*													●				
12	TiAl6V4													●				
13	Zr70Cu13Ni9.9Al10.3Nb2.8 *(VIT106A)*								○					●		○		
14	Ni96Ta4+Ta2O5							●										
15	Ni98Ta2+Ta2O5							●										
18	Zr									○				●				
21	Zr57Nb5Cu15.4Ni12.6Al10 *(VIT106)*								○					○		●		
22	Nd18Fe73B9						●					○						
23	NiCr2Co3Mo0.4Al5.7Ti0.2Ta8W5Nb0.1Hf0.03Re6 *(CMSX-10)*													●				
42	Al40Ni60									●				○		○		
43	Cu75Co25		●													○		

Table 2.3 EML sample batch 2 overview: prime proposer (●) and other interested projects (○)

ID no.	Sample designation	CCEMLCC	COOLCOP	Elec. resist.	ICOPROSOL	LIPHASE	MAGNEPHAS	METCOMP	MULTIPHAS	NEQUISOL	OXYTHERM	PARSEC	SEMITHERM	THERMOPROP	ELFSTONE	QUASI	LODESTARS	USTIP
2	Al75Ni25									●				○				
5	FeC0.05Si0.2	●												○				
16	Ge												●			○		
17	Si50Ge50												●			○		
20	FeC0.9Si0.2	●												○				
24	Al65Ni35									●				○				
25	Al89Cu11									●				○				
27	Cu50Zr50								●					○		○		
28	Cu67Co33		●													○		
29	Fe90B10						●					○		○	○			
30	Si25Ge75												●			○		
34	Zr52.5Cu17.9Ni14.6Al10Ti5 *(LM105)*													●		○		
36	Zr64Ni36			●								○				○		○
38	Zr-O(0.1)			○					○				○	●	○			
39	Ti39.5Zr39.5Ni21				●							○		○	○	○		
40	Fe60Co40						●					○			○			
44	Ti48.5Al47.6Nb2Cr1.9													●				
45	Fe57.8Ni19.2Mo10C5B8													●				

2.3 and 2.4 give the respective overviews of the sample batches 1, 2 and 3 (each consisting of 18 samples) along with the involved research projects. Altogether the samples cover a wide range of material classes (steels, superalloys, aluminium alloys, titanium alloys, bulk metallic glasses, high-entropy alloys, semiconductor materials and so on) for diverse application areas and include model alloys (research materials) as well as commercial alloys. Sample batches 1 and 2 were processed in the periods 2015–2018 and 2017–2021, respectively, with reprocessing of samples and intermediary swaps between the batches involved as well. Processing of sample batch 3 is to start in 2021. Sample batch 4, which also includes samples from newly entering research projects, is in preparation.

The scientific output of the EML activities has meanwhile accumulated to hundreds of publications and covers PhD/MSc theses, journal papers, conference

Table 2.4 EML sample batch 3 overview: prime proposer (●) and other interested projects (○)

ID no.	Sample designation	CCEMLCC	COOLCOP	Elec. resist.	ICOPROSOL	LIPHASE	MAGNEPHAS	METCOMP	MULTIPHAS	NEQUISOL	OXYTHERM	PARSEC	SEMITHERM	THERMOPROP	ELFSTONE	QUASI	LODESTARS	USTIP
31	Si75Ge25												●			○		○
41	Zr47Cu47Al6												○	○	○	●		○
47	FeC1.5Mn0.6Si0.6Cr12Mo1V1	●												○				
48	FeC1.5Mn0.6Si0.6Cr12Mo1V1	●																
50	Ti45Zr45Ni10				●									○	○	○		○
52	Co38.5Si61.5					●						○			○			○
56	Al96Fe4									●				○	○			○
57	Si95Ge5									●			○					○
66	Ti50Al50						○					●			○			○
67	Fe90Ni10						●					○			○			○
70	Zr80Pt20								○							●		○
81	Pt57.5Cu14.7Ni5.3P22.5													●		○		○
83	Fe25Cr25Ni25Co25													●				○
84	Fe72Cr17Ni11											○		○	●			○
86	Fe72Cr13Ni15											○		○	●			○
90	FeSi3													●				○
93	ZrSn1.3Fe0.2Cr0.1O0.13													●				○
94	ZrNb2.5O0.11Fe(x)													●				○

papers and other contributions (such as presentations and posters). Figure 2.4 gives the breakdown of documented published works during the past two decades for the various research projects. About half of these publications are (peer-reviewed) journal papers. Notably this inventory does not only consider publications relating to the ISS-EML but also to EML experiments on sounding rocket, parabolic flight and other microgravity platforms, on-ground (preparatory and reference) work and on modelling. A comprehensive list of publications, updated to the time of its publishing, is included as an annex to this book.

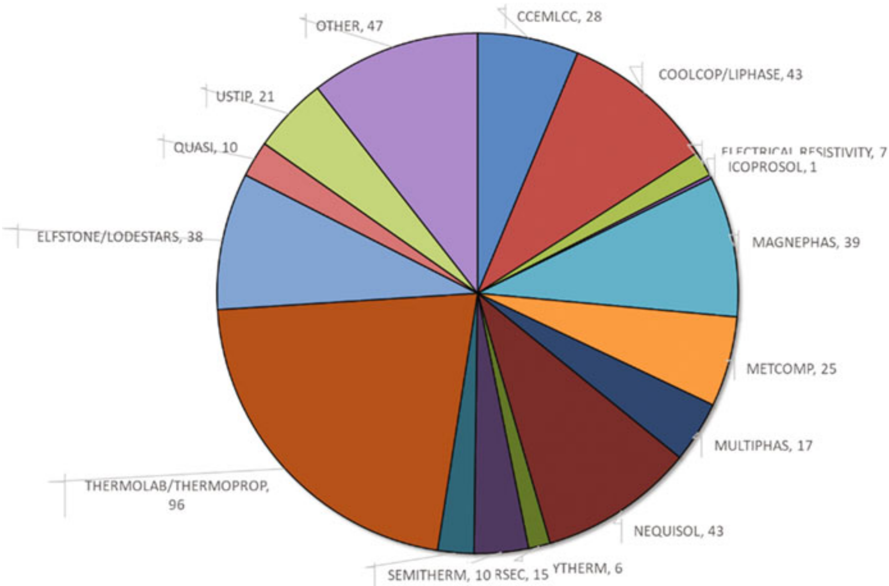

Fig. 2.4 EML-related publication output since 2001 – total count: 446, of which 8 PhD/MSc theses, 18 book chapters, 241 journal papers, 57 conference papers with presentations and 122 other contributions (presentations, posters, etc.)

4 Benefits for Earth and Industrial Relevance

The outcome of ESA's space research programme on materials science consists of benchmark data on thermophysical properties of (metallic and other) melts and the structural evolutions during the liquid-to-solid phase transition. These experimental data are of an unprecedented accuracy and reliability due to their origination in a reduced-gravity environment. This information results in both a better understanding of the fundamental solidification mechanisms and validation of theoretical models describing these mechanisms, as well as in more accurate data to feed into these models. As implemented into simulation software, this enables scientists to deepen their insights and industrial manufacturers to better design and control their processes. Thus, microstructures of materials and thereby their mechanical and physical properties can be better forecast, and novel routes can be explored upfront virtually rather than empirically. Among others, this is to the benefit of conventional continuous and shape casting (for semi-finished and finished products, respectively); investment casting including directional and single-crystal production methods, spray forming, gas atomisation (for powder production) and other deposition techniques (for coatings); and additive manufacturing through the liquid state.

The materials that are addressed in this programme can broadly be categorised as follows.

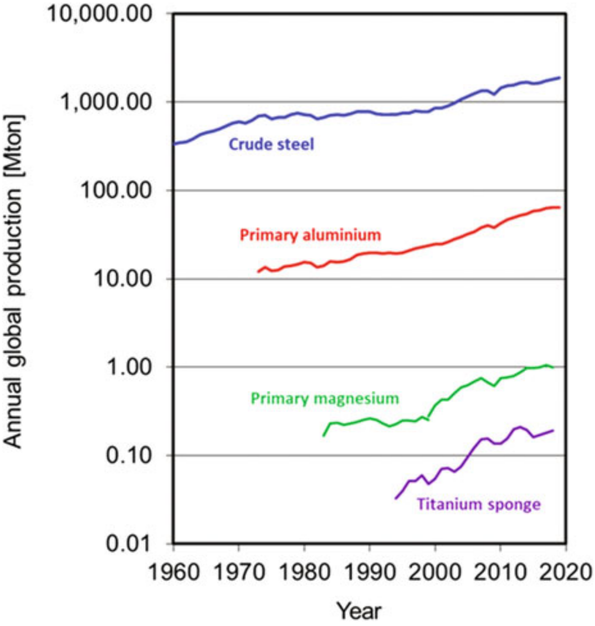

Fig. 2.5 World production of metals from ore

- *Structural materials*. Metals that are used for structural applications include steel and aluminium. Figure 2.5 – compiled from various sources [5–9] – shows that the global production of these metals is steadily growing for many decades now and that since the turn of the millennium this growth is even accelerating in pace. Metal production and manufacturing activities are major drivers for the economy. To save on resources and limit waste, the recycling of these metals has traditionally been high and is increasing still. Steel and aluminium alloys are used extensively due to their favourable combination of mechanical properties (strength and toughness) at low to moderate costs. This includes durable goods such as for building/infrastructure and for automotive, as well as goods with short cycle times such as for packaging. With steel being a traditional material of choice for construction and cars, aluminium has now firmly established itself as well for notably the latter due to its light-weighting potential. Competition between steel and aluminium in certain application areas such as automotive body parts came with several advancements in materials like dual-phase steels and (paint) bake-hardening aluminium alloys, to name just a few. Magnesium alloys are used for light-weight automotive and electronics applications (casings), and titanium alloys are used for corrosion-resistant high-strength applications (jet engine parts), among others. Besides structural applications, such metals are also used in other domains such as for energy applications (electrical steel) and biomedical applications (stainless steel and titanium implants).
- *High-performance materials*. Certain engineering materials have to serve under extreme conditions, be it at very high or low temperatures, very high mechanical/dynamical loading or a very corrosive or otherwise aggressive environment but

most commonly being a combination of these. In line with that, they are also called materials for extreme environments. To withstand such diverse conditions, a variety of metallic and non-metallic material classes have been and are being further developed; the following is limited though to those sub-sets that are of relevance in the current context. High-temperature materials like (nickel-, cobalt- or iron-based) superalloys are used in aircraft jet engines and land-based gas turbines and are thus enablers for long-distance mobility and energy generation. Drivers for alloy development are creep, fatigue and oxidation resistance but also light-weighting; manufacturing challenges consist in geometric structures becoming more and more complex due to the integration of advanced cooling concepts, the exploration of additive manufacturing processes and so on. Advancements for these aerospace and power applications are to further increase energy efficiency, reduce emissions and enhance service lifetime. Non-degradable bio-passive materials like cobalt-chromium alloys, nickel titanium ("nitinol"), stainless steel and titanium alloys are used for implantable medical devices such as for hip replacements and cardiovascular stents. Here, alloy and manufacturing developments aim for enhanced biocompatibility and in-service performance; additive manufacturing technologies are of interest for low-volume series and one-offs, such as for trauma surgery. Advancements in implant materials contribute to the quality of healthcare (less invasive interventions and patient discomfort) and thus add to the quality of life, notably in aging societies.

- *Functional materials*. Among these there are materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli; an important category which is of interest here is that of the semiconductor materials. Commonly consisting of crystalline inorganic solids, their electronic properties depend controllably on impurities (doping) and defects, and with that their quality depends heavily on the solidification process with which they are manufactured. Silicon is the most common semiconductor material in integrated circuits and solar cells. Other semiconductor materials such as germanium, gallium arsenide and cadmium telluride are also of importance for computers and photovoltaics, as well as for detectors. With that, this category of materials is essential for ICT and (renewable) energy applications. Magnetic materials such as Nd-Fe-B permanent magnets and Fe-Si soft magnets are yet another example of functional materials, of relevance to applications in the same domain.
- *Novel materials*. Besides the established material classes, there are novel materials and alloy concepts that could become game changers for existing and future applications due to their unprecedented properties. These materials have no substantial market volume or share to date (although niche applications exist), but have a potential for that pending their further research and development. Bulk metallic glasses (BMGs) are metallic alloys that solidify in a non-crystalline, amorphous state and by that exhibit properties like exceptional hardness, elasticity and corrosion resistance. BMGs can be based on zirconium or copper but are also developed with titanium, iron, palladium and platinum. They are of interest for application in aircraft, spacecraft and car components; gears, fashion and sport

equipment; as well as in medical devices. Several companies are already adopting manufacturing processes – requiring distinct solidification rates – to produce BMG components. These processes include conventional casting, injection moulding and liquid-state additive manufacturing. Besides structural components, BMGs are also of interest as coating materials. High-entropy alloys (HEAs) are materials that deviate from the conventional alloying paradigm in that they are formed by mixing equally large proportions of four or more chemical elements (thus exhibiting high configurational entropy in their crystalline state). This can be used to design materials with considerably improved strength-to-weight ratio, fracture toughness and/or corrosion resistance versus conventional alloys. Commensurate with this approach, the number of conceivable alloying combinations is astronomical, but FeCrMnNiCo, NiCrFeCoAl and TiVZrNbTa are among the best-known examples. Potential applications for HEAs (also called concentrated multi-component alloys) are in harsh environments such as in aircraft turbines, as well as in space exploration. The crystal-lattice distortion typical for HEAs may also be used for solid-state (interstitial) hydrogen storage, presenting a possible other avenue for development.

5 Conclusion

ESA has consistently been developing a reduced-gravity research programme on physical and life sciences for several decades. For materials science, the programme presently provides experiment opportunities to about 20 ESA (plus associated NASA and Roscosmos) research projects, each with their own scientific objectives and activities on specific topical challenges in the field. Altogether the project consortia gather hundreds of materials scientists from academia as well as from industry and from across the globe. The programme is currently using three materials science facilities on board the ISS (with a further one in development), as well as various scientific payloads for other ESA platforms. Among these, the ISS-EML is since 2015 being successfully operated and is providing a steady stream of original scientific results for the successively processed sample batches that cover a wide spectrum of structural, high-performance, functional and novel materials. Acquired scientific results – as also presented in this book – advance the fundamental understanding in solidification physics (thermophysical properties, structural evolutions) and serve to validate and enhance modelling capabilities.

Acknowledgements Space research is a long-standing effort of many actors, all of which are recognised for their indispensable contributions: numerous teams at ESA and other space agencies, user support and operations centres and industry. In addition, the ESA member states participating in SciSpacE and the national space agencies are acknowledged for their support. And naturally, without a committed scientific community, there would be no reduced-gravity research programme. The quoted publication list in the section on EML activities was initiated by I. Silkina (ESA), and the section on the benefits for Earth and industrial relevance was iterated with M. Mohr (Ulm University).

References

1. Erasmus Experiment Archive. https://eea.spaceflight.esa.int/portal/
2. N.N., *Roadmaps for Future Research: A Redefinition of Strategic Goals for Future Space Research on the ISS and Supporting Research Platforms,* (European Space Agency, Directorate of Human Spaceflight and Robotic Exploration, 2016). http://esamultimedia.esa.int/docs/HRE/SciSpacE_Roadmaps.pdf
3. I. Egry, D. Voss, Present activities of the investigators working group (IWG) for the electromagnetic levitator (EML) on ISS: A status report. J. Jpn. Soc. Microgravity Appl. **27**(4), 178–182 (2010). https://doi.org/10.15011/jasma.27.4.178
4. D.M. Matson, Maximizing scientific return from shared facilities working in space: ESA's investigator working group for the ISS-EML facility. Int. J. Microgravity Sci. Appl. **37**(3), 370301 (2020). https://doi.org/10.15011/jasma.37.3.370301
5. World Steel Association. https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html
6. The International Aluminium Institute. https://www.world-aluminium.org/statistics/primary-aluminium-production/#data
7. International Magnesium Association. https://www.intlmag.org (1983–1999)
8. U.S. Geological Survey. https://www.usgs.gov/centers/nmic/magnesium-statistics-and-information (1999–2018, excluding US)
9. U.S. Geological Survey. https://www.usgs.gov/centers/nmic/titanium-statistics-and-information (excluding US)