Research Needs and Challenges for Swedish Industrial Use of Additive Manufacturing

RAMP-UP

2016-03898 – Research Needs and Challenges – Version 2

2017-10-06

Table of contents

1. Background

The Swedish Government's Industry Ministry published a report in 2015 regarding the strategy for smart industry in Sweden (Report no: N2015.38). The report states that Additive manufacturing (AM) is a technology that is important to address due to its great potential to change the industrial transition to digital and smart industry. Further Vinnova, the Swedish innovation funding agency, published a report early 2016 "*Digitalisering av svensk industri"* concerning Digitalization of Swedish industry where AM is highlighted (ISBN 978-91-983100-0-9). This report adds to the statements that AM as a technology has great potential for digital transformation of the Swedish manufacturing industry.

To make a clear path for the Swedish industry and research providers and to gain momentum in the field of metal-AM, a roadmap containing the industrial and research needs for this field will be created. The roadmap will have a focus on the Swedish expertise and strengths, where Sweden has the potential to take a world leading role in this field. The roadmap will be created with direct input from the Swedish industry and will have its focus on AM of metallic materials and components. The focus is to create areas of excellence in AM for Sweden as well as moving the Swedish industry from being a minor user of metal-AM to becoming an industrial user of AM, taking the full advantage of the technology for industrial manufacturing.

Vinnova and SIP metallic Materials have funded a project to create this roadmap for research and innovation to industrialize AM of metals in Sweden, RAMP-UP 2016-03898. The project is performed in close collaboration with the "Swedish Arena for Additive Manufacturing of Metals" and open workshops has been arranged to get input from all stakeholders. Within the project a first report "State-of-the-art for Additive Manufacturing of Metals" (2016-03898 – State-of-the-art – Version 2.1, 22 June 2017) has been published. This second report is about research needs and challenges for Swedish industrial use of AM and the final roadmap will be based on its content. The final roadmap will be ready by the end of 2017.

2. Areas of excellence

The research and innovation questions that are appropriate to be prioritized for being addressed by the various stakeholders (academia and research institutes active in the field, as well as industry) must be necessarily synchronous with the acknowledged areas of national industrial excellence, if Sweden's industrial leadership within additive manufacturing of metals is to be ensured. The state-of-the-art report compiled as a part of this RAMP-UP project has already identified areas of specific strength within the Swedish industries, compared to the global status in the field. The prominent challenges that presently hamper industrialization of metal AM, as perceived by the leading Swedish enterprises associated with AM, have also been articulated.

Through a series of focused discussion meetings well attended by the various stakeholders, a conscious effort was made to find an intersection of the prevalent key industrial needs and existing competencies within the country to accelerate metal AM industrialization and demonstrate clear benefits that will sustain its growth. While it is gratifying to note that the areas of Swedish excellence in AM span the entire value chain, it is also crucial for any suggestive roadmap that will emerge as an outcome of this project to judiciously prioritize challenges to be specifically targeted to ensure that the existing strengths and limited available resources are not too thinly spread. This is paramount if the initiatives that will eventually be taken based on the above roadmap are to make a notable difference in enhancing the capability of the Swedish industry to attain and/or maintain international leadership in their respective business domains.

Among all the wide-ranging AM-relevant strengths that reside within Sweden, the undisputed leadership that the country has provided in terms of materials development in general, and global powder production in particular, is most striking. The country garners an impressive 25% of the global metal powder market share as a result of the niche specialization areas of Swedish powder producers such as Carpenter Powder Products, Erasteel, Höganäs, Sandvik and Uddeholm, combined with the substantive support in terms of materials research and development that they derive from the considerable domain expertise available at Swedish universities and institutes. Nonetheless, the predominant focus so far has been on ferrous powders and little of the powder production has been dedicated to AM. However, the strong materials technology position of Sweden can be a game changer both when it concerns tuning of existing materials as well as developing completely new materials to meet emergent AM needs. This can serve as an ideal foundation to undertake a concerted effort to evolve strategies for rapid material development for metal AM applications at competitive cost, using best practices from the powder technology field. Since both powder bed and blown powder technologies use powder as raw material, such an effort is integral to addressing the pressing need to augment the AM materials' portfolio to yield new functionalities and expand the application spectrum. An inspiration for this can be drawn from Sweden's well-known success in the medical sector, which was fueled by extensive research devoted to development of new types of materials and allied processes specifically for dental and medical devices segments. As a specific example, a similar focus on development of aerospace relevant light alloys for AM has the potential to not only establish a niche but also lead to other spin-off applications. Overall, the Swedish strength in powder technology is, therefore, a key enabler for the industrialization of AM.

Also intimately related to AM-specific powder production are issues related to process robustness & reproducibility, predictability of properties, recyclability and reduction of raw material costs, all of which are high on the wish-list of most potential user industries aspiring to adopt AM processes for production. For addressing any of these issues, close collaboration between powder manufacturers and AM machine builders is desirable. Sweden is fortunate to be home to some AM-related equipment suppliers, including manufacturers of both AM machines and allied equipment (like Arcam, Digital Metal and Quintus), who are leaders in their respective fields. This ensures that Sweden has a capacity to develop manufacturing excellence in AM to meet diverse end user demands at both national and international levels. The equipment suppliers are already closely engaged with industrial end-users, with Universities and research institutes serving as knowledge bridges, through recently created arenas / networks. These linkages should be exploited to derive synergy from the individual core strengths and drive industrialization of AM. The advantage of having world-leading and yet "local" powder and equipment manufacturers is further fortified by the presence of a vibrant manufacturing industry that has traditionally relied on innovation and an exceptional level of technology integration to carve out a niche, be it in terms of processes or products. Consequently, all the prominent industry segments (e.g. automotive, aerospace, energy, tooling etc.) amply recognize the value addition that can accrue through AM and either already adopt AM or are actively seeking to do so. Such strong user perspective provides a unique breeding ground for creating new business opportunities using AM.

Apart from being the major stakeholders, the industrial end-users invariably bring unique competence to the table that is eventually crucial for industrialization of AM. Such end-user industries, who already have a buy-in into the AM technologies, are essential partners in any endeavor aimed at spurring commercialization of AM. A vast majority of the leading industries in the above segments have been closely associated with the present exercise by providing their vision for the future, while identifying drivers, needs and challenges. With the AM approach graduating from being used to creating one-off prototypes to building functional parts in bulk, the Swedish industries are already utilizing their innate strength in using/transforming cutting-edge technologies to explore "engineering designs for AM" for improving manufacturability, allowing new component functionalities with virtually unrestricted freedom and realizing novel applications.

It is abundantly clear that, in addition to the challenges associated with AM process stability and product quality, a host of other issues also need to be expeditiously addressed if AM is to make significant inroads to be embraced as a mainstream manufacturing option. From a production standpoint, both digitalization and automation promise to be the cornerstones for ensuring prolific industrial use of AM techniques. For example, the current AM technologies include some manual handling that is not sustainable from both efficiency as well as environment, health and safety standpoints. Fortunately, Sweden has a long tradition of global leadership in the field of automation as well as a strong position in digitalization. Considerable expertise in these areas exists across the board: in Universities, research institutions and industries. Leveraging these strengths would move AM closer to meeting various aspirations of end-users (total process control, adaptable production/planning, traceability etc.). Almost concomitant with the digitalization of products through AM processing is the growing concern regarding cyber security. Perception of new cyber threats, ranging from IP theft to malicious sabotage of objects, has accompanied the realization that the future involves increasing dependence on digital files and their transfer to printers. Concerns on this front are gathering pace, particularly with on-demand decentralized manufacturing involving autonomous production in a remote environment being conceptualized. However, this is yet another area which is well-covered in terms of competence.

Although AM processes are deemed environmentally friendly because they are efficient from a material utilization standpoint and minimize waste, concerns regarding powder handling and sustainability of employing powder materials are gradually beginning to be expressed. In due course, these will need to be addressed as the implications are not yet fully understood. However, handling of metal powders is not new to the world leading powder manufacturers in Sweden. Their generic expertise in this field can help Sweden be a world leader as far as EHS issues in AM are concerned.

Thus, it is apparent that virtually all necessary competencies necessary to suitably address all challenges/needs/research questions, prioritized in a subsequent section based on inputs from the industrial stakeholders, are already available in Sweden. Harnessing the diverse expertise through synergistic networks to address identified pre-competitive challenges that have the potential to benefit a wide cross-section of the industry will ensure Sweden's place at the metal AM forefront.

3. Vision – 5 and 20 years

Malcolm Gladwell, *The Tipping Point,* defines the "tipping point" as a moment when an idea or trend reaches a threshold and spreads like a wildfire. Wohlers believed that Additive Manufacturing (AM) reached this point in Q3, 2012 as a result of, among other things, that many developments appeared in a way the industry had not seen before, *The Economist* published a number of papers on the subject, desk-top 3D printers gained attraction in a way that few had foreseen, high-end medical and aerospace applications became available and, sad to say, that 3D-printed guns helped to introduce 3D-printing worldwide.

Since 2012, we have seen a lot of excitements, investments, research activities, commercialization activities but also misconceptions and misunderstandings and disillusions. Cited from Wohlers Report 2017: A service provider commented: "The equipment manufacturers are overselling the capabilities of the machines and materials more than ever, which makes it more and more difficult when working with customers. Expectations are so high, making it tough to explain to them that most of the materials cannot replace injection molded parts". Even though this citation refers to AM in polymeric material, it is also valid for the status and development of metal AM.

The metal AM segment continues its impressive growth streak. Today, there are a great number of unique components that are produced with help of AM, and in some cases they poses superior microstructures, which in combination with the innovative design (AM's inherent capability of producing complex structures) have resulted in that metal AM has become an interesting option for a growing number of companies, universities and other organizations worldwide. This is also valid for additively manufactured components/parts made of other materials than metals.

According to Wohlers report 2017, the compound annual growth rate (CAGR) for AM was in the order of 28% for the time period 2013-2016 and a further growth is predicted for the upcoming 5 years.

3.1 Overall vision

For the next 5 years the overall vision is that a great number of small, medium and large sized companies have evaluated AM and thereby been able to set the direction for how to best utilize AM for strengthening their competitiveness, both nationally as well as internationally. To achieve the short term overall vision, a considerably wider industrialization of AM is needed. Sweden has long track record in a number of industries, such as aerospace, automotive, material manufacturing, energy, tooling which all will benefit in different ways.

For the next 20 years the vision is that Sweden, by a fast and resource effective industrialization, has taken a pole position in key competence as well as a prime provider in a number of areas and applications.

3.2 Business area visions

- 5 years vision
- ○ 20 years vision

Powder/material suppliers

AM is identified as a strategic area by the powder/material suppliers, who invests large efforts in production of powders dedicated to AM and R&D dedicated to AM. It is of great importance to have knowledge of how the powders behave in the printing processes and how the printing process can be optimized for a certain powder/material. Their goal is to become a key supply partner for their customers providing not only the powder but also comprehensive service and support functions.

- Preferred material partner for global production of materials, mainly powders and wires
- Long-term feedstock supply agreements to customers
- Large volume production of selected powders for direct sale to part producers
- Broaden the existing portfolio with new powder families; standard material grades as well as tailored materials for AM
- Material and solution provider giving support and service to AM part manufacturers in order for them to achieve optimal properties of the manufactured parts

- ○ Customized materials for specific markets or applications
- ○ Flexible and efficient design, manufacturing and verification tools for powders

Component suppliers/Service bureaus/Subcontractors

The visions may vary depending on the company's main business area and also on the type and size of company. Hence, 2 sub-groups have been created, namely Component suppliers with in-house printing and Service bureaus/Subcontractors. Engineer consulting companies, active in construction as well as preparation for printing, need to deepen their knowledge of the pros and cons of the printing processes but also deepen their knowledge in design for AM (DfAM). By doing that, they are prepared to act as a reliable partner supporting companies showing interest in AM as such and how to utilize the technique in the product development.

Component suppliers with in-house printing

- Printing of larger components than is possible today
- Shorter lead and print times, faster printing
- Large input of automation and digitalization through the entire manufacturing chain
- In-house production using different techniques to become a major component provider
- Tools and methods for validation of printed parts (quality assurance)
- Unique design solutions to minimize number of parts (part consolidation)

- ○ Possibility to print of even more complex parts in order to reduce the number of parts per component and thus speeding up the total production chain time
- ○ Specific design rules and guidelines applied for AM and for different materials (when necessary)
- ○ Gain market shares for the actual business areas

Service bureaus/Subcontractors

- Key subcontractor to major component suppliers and/or end users
- System supplier, that is, offer the whole chain from design via powder selection and printing to post treatment and be able to deliver a ready to use component
- Low volume serial production

- ○ Large volume serial production of selected materials and/or applications

Equipment and technology suppliers

- Build an organization structure capable of handling the foreseen growth in sales of new equipments
- Documentation procedure for part validation in operation
- Post treatment concepts for AM proven and accepted by the market

  - Increased adoption of industrial and automation metal AM in Sweden
  - Offer service and support to customers independent of the type of metal powder

End users

- Enough knowledge of AM processes to understand the possibilities/limitations to accurately specify an order to a service provider
- Robust printing processes giving a service bureau/subcontractor the possibility to print a 100% accepted part at the first trial
- Knowledge of design of components for AM (Design for AM)
- Qualified tools for validation of printed parts
- That the use of AM gives a shorter time to market for new products
- Shorter lead times from idea to finished product
- High level of data security as company sensitive corporate information are stored in manufacturing files

SMEs

As SMEs are found among the business areas above, visions given there can be applicable for them as well. General vision for end user SMEs is to establish long term relations with one or several service bureaus with good reputation to secure purchase of proper components. Knowledge of AM and design processes for AM are important for any end user independent of its size.

4. Challenges and needs and related research questions

AM of metals is a new technology under rapid development and many challenges and needs still exist. Here follows a description of the main challenges and why they are important for Swedish industry and industrialization of metal AM. Correlating research questions are identified and described briefly.

4.1 Material

Reaching good properties (very often better than the wrought counterparts) with the current state-of-the-art powder-based AM equipment is not the issue; it is rather having consistent properties, both throughout the part and part to part consistency. Achieved properties are typically material-dependent and very often hardware dependent as well as geometry dependent within the component. Typically, qualified powder is today supplied via equipment manufacturers together with the developed process parameters. Hence, there is very limited number of materials available on the market, not satisfying increasing needs of the growing end-user market. Development of the materials for AM is very time and cost demanding process, depending on the material type. Hence, materials can be divided into easy-to-build materials and difficult-to-build materials, depending on the metallurgical constrains. Taking into account strong position of the Swedish industry and academia in the powder field, material development is identified as one of the key research areas.

Challenges:

- Too few qualified powder materials for AM
- Materials design not tailored for AM
- Powder solutions for rapid materials development
- Powder solutions for multi-material builds
- Tunable microstructures
- Consistent and predictable properties

Research questions:

1. How can existing powder for other use be adopted for specific AM process?
2. How should powder be tuned with respect to characteristic properties?
3. How does powder react during the specific AM process?
4. How should powder be characterized?
5. How sustainable is its re-use in dependence on AM technology and alloy?
6. How can post-AM processing be optimized?
7. How can microstructure and the final properties be controlled and modelled throughout the final part with its geometrical variations?
8. How can difficult-to-build materials be processed?

4.2 Part and system design

Design for AM incorporates the visual design of the components, build directions, mechanical properties, but also other features related to e.g. functionality. Challenges for additive manufacturing of metal parts are to use the advantage of design freedom that is not possible for castings or machined parts.

Challenges:

- When changing from one 3D printer to another the whole design and layout process and parameters has to be recycled
- Limited size of components
- Most of the existing design tools do not account for the advantages and disadvantages of 3D printing – creating a need for design standards.
- Need for design guidelines for AM regarding geometrical possibilities and limitations, e.g. lattice structures, conformal cooling channels etc.
- Need for design guidelines for AM process behaviors, e.g. shrinkage during melting in PBF, anisotropy etc.
- Knowledge regarding design opportunities regarding e.g. compilation of multiple assembly parts into one functional part
- Optimization procedures for both product performance and reducibility

Research questions:

1. How to incorporate restrictions of the process effectively into the design optimisation process?

2. How to design and orient components for various AM process?
3. How to design for optimal post processing?
4. How to incorporate thermal stress modelling (during processing) into the design process?
5. How to design for material behavior (differential microstructures compared to traditional manufacturing)?
6. How to design for geometrical assurance?
7. How to design for functionality of final component?
8. How can the build part geometry be simulated before printing?
9. How can the process parameters needed to fulfil component requirements be simulated before printing?
10. Which design rules can be set to receive actual required mechanical properties?
11. How should a new CAD software format that is true to the native CAD model look like?

4.3 Process stability and product quality

The industrial stakeholders have been particularly forthright in outlining their process/product related requirements that they anticipate to directly influence their near-term and extended visions relating to implementation of AM. Consistent with the visions outlined, it appears appropriate to segregate their needs as short-term (< 5 years) and long-term (> 5 years). In the immediate future, enhancing process robustness and reproducibility, as well as process and material predictability, are to be accorded highest priority. These have a direct impact on product quality and are driven by both external (component design, raw materials quality, conditions of the operational environment etc.) and internal (process parameters) considerations, thereby making process stability a multidimensional challenge.

Methods for process and product qualification are also closely intertwined with the above. Testing and demonstration of AM-produced parts in diverse industry segments is yet another pressing need, in view of its linkage to industrial adoption of AM. Research directed towards the above will have to be complemented by efforts aimed at improving in-process control, development of 'smart' post-processing of AM-built parts and recycling of powders. Although at a slightly lower priority level, research questions pertaining to the closely linked areas of process simulation and rapid process development, as well as non-destructive testing and smart automation, are also deemed important by the industry.

Understandably, the long-term needs identified by the industry are aimed at empowering them to usher in an era of widespread adoption of metal AM. For example, consistent with the aspiration to achieve superior functional properties through multi-material builds and to reach the goal of accomplishing appropriate designs for material anisotropy, feedback control loops for AM processing will be a primary requirement. Such control is also necessary for defect free production. High speed processing of builds with improved surface finish is also deemed a key requirement to ensure techno-commercial viability of metal AM.

4.4 Production

Challenges: development of AM technologies has historically been in the context of prototyping resulting in machine designs and processing methods suitable mainly for solo operations, posing several constraints on AM's way to be a production technology. Limited size of builds, processing speeds, lack of continuous process and information flow, and automation in powder, part handling and post processing, are some of the critical constraints in this regard.

Research questions:

1. What are the major limitations in designing AM machines which may otherwise be conveniently connected to production lines, both upstream and downstream?
2. What are the opportunities in automation both at machine and production system level and how can automation help improving productivity in single machine and in a cluster of machines?
3. How much a closed loop of powder flow, through fully automated delivery to and recovery from the build process, can shorten product lead-time, improve powder utilisation, and improve process ergonomic besides the work environment?
4. What are the critical aspects in information flow and management so that the efficiency and reliability in a production line, including both AM and conventional processes can be ensured for desired throughput and quality?
5. How can we quantify economic and competitive advantage of AM technologies at the manufacturing systems level keeping in mind that they have the potential of improving engineering performance, reducing the number of upstream supply chains, reducing part inventory and management while offering the opportunity of localised production setup?
6. How can productivity be increased and enable higher volume production?

4.5 Environment, health and safety

Challenges: AM is still in its infancy and lacks knowledge in several allied areas, including environment, health and safety (EHS) as well. Metal powders may be both toxic and explosive therefore the work environment has to be clean from suspended powder particles, as the sizes involved can be injurious for breathing, eyes and uncovered cuts. At least three aspects, i.e. air quality, powder handling and fire protection, need serious attention.

Keeping in mind that AM has much greater potential as the technology of hobbyists (already clear in case of plastics), the EHS issues may be more prevalent in general public. This will require that public awareness in this field is emphasised and special requirements are brought in place through regulations, similar to the field of hobby drones etc.

Research questions:

1. Is the knowledge on EHS, for example from conventional materials processing industry and specifically from powder metallurgy, enough and compatible with the needs of the metal AM environment?
2. What additional requirements the AM puts on the EHS aspect when compared to a traditional powder metallurgy environment?
3. How can the sustainability of powder materials from AM, measured by LCA, be improved by for example powder recycling?
4. Do we have enough knowledge and understanding of exposure to LASER and EB energy sources and their impact on human health?
5. What is the potential of metal AM to become a hobby technology and its implications in terms of EHS in the public sphere?

4.6 Standards and certification

Standardisation and certification are necessary for the evolution and usage of the additive manufacturing technology, but are in the early stages. The European work within ISO/TC 261 follows the standardisation roadmap “Additive Manufacturing: SASAM Standardisation Roadmap, 2014” (http://rm-platform.com/index.php/downloads2/download/2-articles-publications/607-sasam-standardisation-roadmap-2014) and development of joint international standards are preferred. As part of a gap analysis resulting from the America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC) AM roadmap presented in February 2017 ASTM F42 identified a list of 16 projects offered to ISO/TC 261 for joint development, appendix 1. ISO/TC 261 accepted the list for joint development and it will be further discussed during the plenary meeting in Stockholm in mid-September 2017.

The local Swedish group SIS/TK 563 is active within the international standardisation work and there is no need to make a separate standardisation roadmap for Sweden. However, it is important to give input from Sweden on industrial needs for standards and certificates to the existing groups. It could also be a task for Sweden to develop certain standards, within our areas of excellence.

Challenges for setting up standards are:

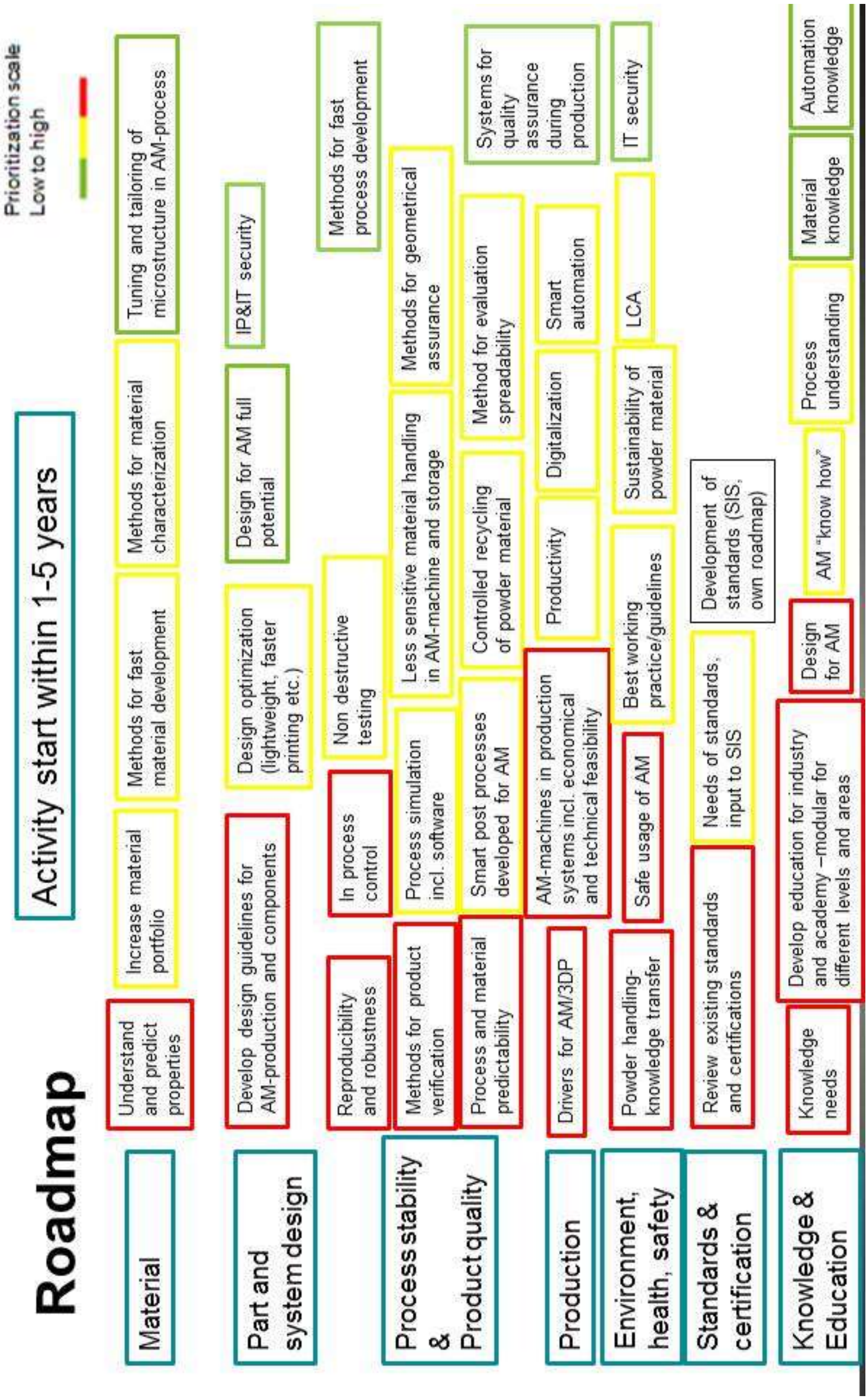
- The variation of parameters needed from one 3D printer to another to manufacture a component.
- Large volumes of printed test pieces to create reliable statistics to set up design limitations of mechanical properties, weight to stress ratio, need for heat treatment etc.
- The vast amount of statistics needed from all machine builders to create minor set up of parameters when comparing which machine to use for making a specific component.
- Testing of all new materials developed for printing to fulfil the demands of end users.

4.7 Knowledge and education

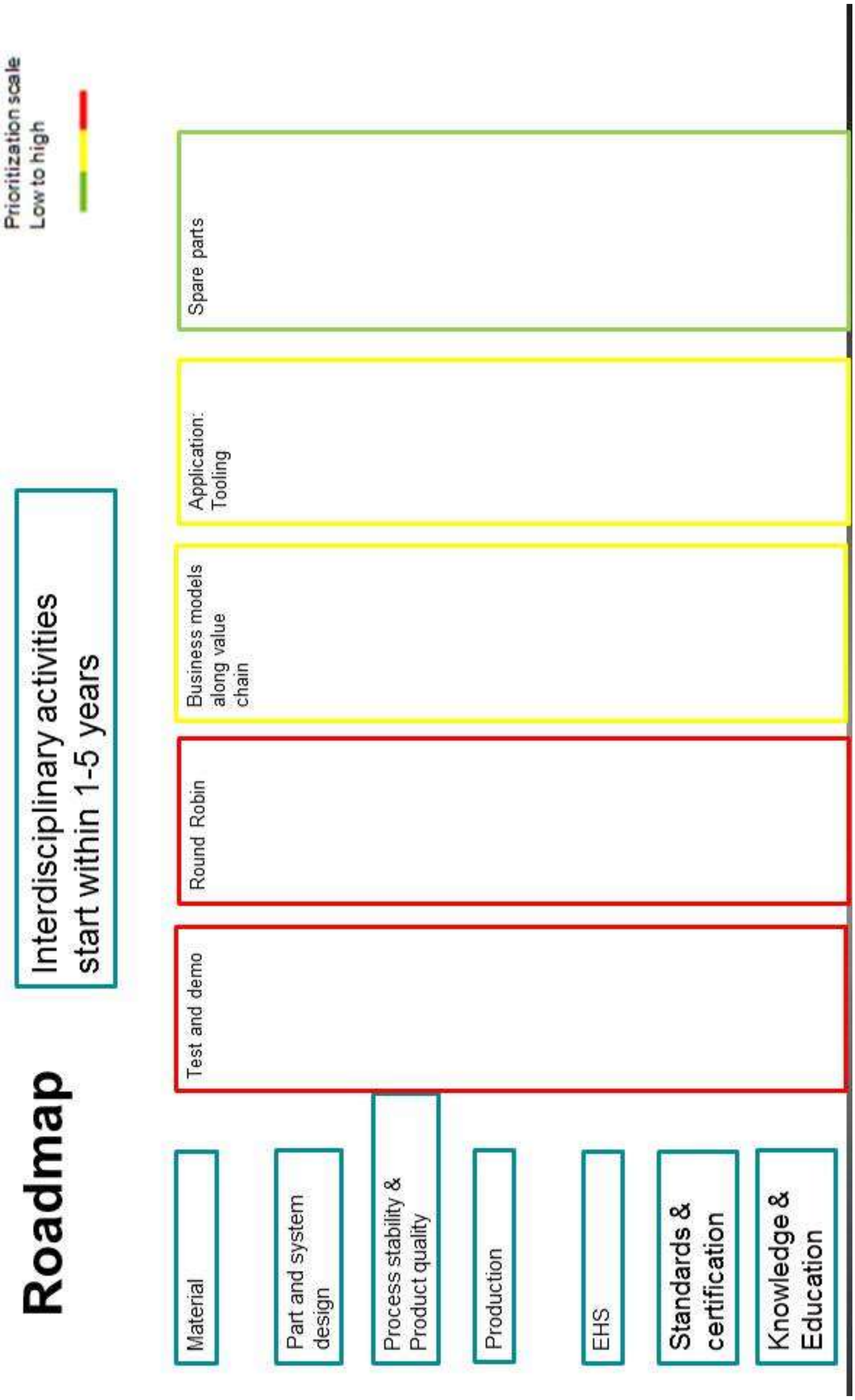
If the intended proliferation of AM across diverse industry segments is to be realized, knowledge and education will play a crucial role in meeting the strong demand of competent engineers and designers well-trained in various facets of AM, to facilitate rapid technology integration and long-term growth. The foremost priority is in fulfilling the multi-dimensional knowledge needs of the industrial stakeholders, spanning product design & optimisation, machine design, materials, processes & production systems, modelling & simulation, testing methods, among several others, as they strive to accelerate their involvement in AM. This requires development of an educational portfolio, encompassing covering identified knowledge gaps and needs for future development, at different levels and competencies to assure availability of employable AM specialists consistent with developing industrial requirement. Increase in number of persons with specialized competence in metal AM developed through PhD theses will ensure availability of expert manpower to industry to spur innovation. Increased mobility through industrial PhD students is another desirable pathway, as it ensures effective skill transfer from the academia. Apart from the above avenues for more highly trained personnel, a constant stream of individuals trained in AM would also be needed. For this purpose, developing formal academic programs that impart professional education and skill development opportunities in AM at the bachelor and MSc level are the most important. Some Swedish universities have already begun offering such courses. A PhD course under the Production 2030 framework is also being offered. Summer schools imparting knowledge and/or special training in specific areas of AM, e.g. “design for AM’, or special on-site Workshops at company locations or short one-week professional courses could also be considered on a need basis. Strengthening international competitiveness and visibility of the research groups in Sweden and establishment of world-leading research centers focusing on different aspects of metal additive manufacturing will be an important long-term investment that will ensure sustained competence development.

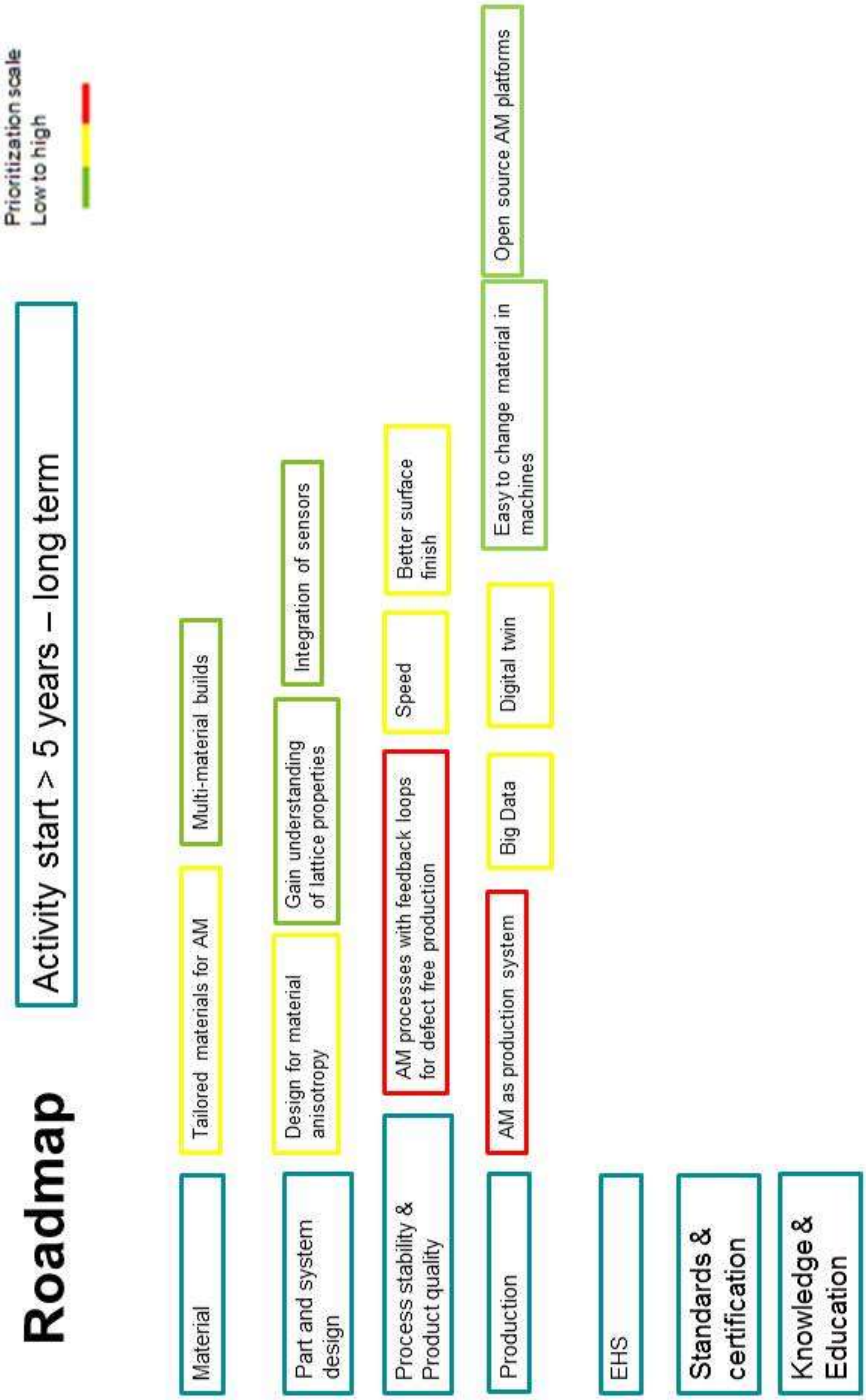
5. Roadmap – visual draft

Visual representation of the needs supplied by all research partners and others in a general time scale. The magnitude of priority is also indicated in the visual roadmap. This first visual draft will be used a basis for the final roadmap at the end of the project. The first two pictures on the following pages are for activities starting from 1-5 years and the third picture is for activities starting after 5 years or later.



Roadmap
Activity start within 1-5 years
Prioritization scale
Low to high
Material
Understand and predict properties
Increase material portfolio
Methods for fast material development
Methods for material characterization
Tuning and tailoring of microstructure in AM-process
Part and system design
Develop design guidelines for AM-production and components
Design optimization (lightweight, faster printing etc.)
Design for AM full potential
IP&IT security
Reproducibility and robustness
In process control
Non destructive testing
Methods for fast process development
Process stability & Product quality
Methods for product verification
Process simulation incl. software
Less sensitive material handling in AM-machine and storage
Methods for geometrical assurance
Process and material predictability
Smart post processes developed for AM
Controlled recycling of powder material
Method for evaluation spreadability
Systems for quality assurance during production
Production
Drivers for AM/3DP
AM-machines in production systems incl. economical and technical feasibility
Productivity
Digitalization
Smart automation
Environment, health, safety
Powder handling-knowledge transfer
Safe usage of AM
Best working practice/guidelines
Sustainability of powder material
LCA
IT security
Standards & certification
Review existing standards and certifications
Needs of standards, input to SIS
Development of standards (SIS, own roadmap)
Knowledge & Education
Knowledge needs
Develop education for industry and academy –modular for different levels and areas
Design for AM
AM "know how"
Process understanding
Material knowledge
Automation knowledge


Roadmap
Interdisciplinary activities start within 1-5 years
Prioritization scale
Low to high
Test and demo
Round Robin
Business models along value chain
Application: Tooling
Spare parts
Material
Part and system design
Process stability & Product quality
Production
EHS
Standards & certification
Knowledge & Education


Roadmap
Activity start > 5 years – long term
Prioritization scale
Low to high
Material
Tailored materials for AM
Multi-material builds
Part and system design
Design for material anisotropy
Gain understanding of lattice properties
Integration of sensors
Process stability & Product quality
AM processes with feedback loops for defect free production
Speed
Better surface finish
Production
AM as production system
Big Data
Digital twin
Easy to change material in machines
Open source AM platforms
EHS
Standards & certification
Knowledge & Education

6. Proposal for call for projects

From the input that has been provided by the industry, from activities ongoing in similar industry segments, as well as from the current state of the art from the AM industry, the following areas is proposed to be prioritized in the near future. During the workshop on the 12th of September 2017, the participants agreed on some prioritized areas, while there were different opinions regarding the urgency of others. The proposed areas have been grouped and prioritized accordingly.

<u>Priority 1 (all stakeholders at the workshop agreed on those topics)</u>

Robustness in process and production including automation and in-process control– This is considered to be the area of highest priority based on industry input due to its industrial high value. Vinnova stated in its report *Digitalisering av svensk industri* that major challenges needs to be overcome for AM to gain industrial acceptance and that research regarding optimal use of AM in areas e.g. geometry, material, density etc. is much needed. The research questions regarding robustness incorporate several areas that lay the ground for robust AM usage and needs to be investigated. The research must start in the following challenges, before more in depth knowledge can be obtained.

- Process parameters correlation – how is the various process parameters affecting the material and the resulting component
- Reproducibility – how to produce the same part with maintained material properties several times in different machines
- Methodology to obtain a "first time right" process, where no iteration of the process is needed
- Tools for improved robustness e.g. automation and in process control

The research questions will accelerate the basic AM knowledge in Sweden and will provide the possibility for Sweden to take a world leading position on optimal use of AM.

Materials for AM – Today's available materials for metal AM are limited to a handful alloys. The low number of alloys puts a limitation to AM usage for component manufacturing.

The following points must be understood and investigated for increased understanding and AM usage:

- Understanding of material behavior and prediction of material behavior
- Development of new materials for AM
- Methods for faster materials development
- Methods for fast materials characterization applicable for AM

Further, materials engineering is a strong industrial genera in Sweden, where multiple of the market leading companies are Swedish. To grow Sweden's position in this field, a focus must be put in the area.

Priority 2 (many stakeholders at the workshop agreed)

Design for AM including research level education – By designing for AM the full potential of AM can be utilized and the costs can be reduced. However, methods for design optimization from idea to printing are still not commonly available and the optimization require a lot of personal knowledge and experience of different AM-processes. Design for AM must be based on knowledge and understanding of the coupling between material, process, geometry and properties. There is a need for establishing design guidelines for AM-production and components, as well as developing a research level education in this field.

State-of-the-art, world leading research - Expertise in some areas related to metal-AM is already present in Sweden, and researchers with world leading potential is currently struggling to explore ideas that can be the next step in AM. This high hanging fruit must in parallel be able to be explored to come up with the next "big thing" in AM. Examples are, unconventional and exotic materials including materials tailoring, new energy sources, new types of raw materials etc. This is not the most urgent research area for industrialization of AM of metals, but rather a high risk and long term activity, and, if successful, will give Sweden a strong position on the world market.

Priority 3 (highlighted by some stakeholders at the workshop, but not all agreed)

Economic feasibility of AM - To obtain the full benefit of AM, it is important that business models regarding AM is thoroughly investigated. Feasibility studies are needed to investigate:

- Direct use of AM in a production system
- Investigation on when to use AM compared to traditional technologies
- Development of new business models of metal-AM production of components

Productivity – Increased productivity in the different steps of the production chain is important for profitability, reduced lead times and resource efficiency. Design for AM (including support structures) could be another way to increase productivity by building less material. High volume production by AM would enable implementation also in more cost driven business areas like automotive. The main research question would be:

- How could the productivity be measured and increased while retaining sufficient performance of the system or component?

Round robin/bench marking of different AM-processes - Show possibilities and limitations, build generic knowledge and identify research questions. A reduced bench marking study is currently performed within the Arena, but a more comprehensive study might be suitable as a special project.

Important application area for Sweden

One application area that is important for Sweden is **tooling**. Stakeholders in this area cover the whole value chain; material suppliers, tool makers, tool users and end users. Some end users have identified this to be their first industrial implementation of AM, with a smaller threshold than direct printing of metal parts. The most important research questions around tooling can be included in the prioritized research areas above.

7. Recommendations for project strategy

From discussions with industry, institutes and academia it is concluded that many of the current research AM projects have a too small budget. It is therefore difficult for research providers to fully dig into the research question and provide a conclusive result, often the result is only “half way there”. With larger project it should be possible to reach higher TRL-levels, which will speed up the industrialization.

→It is therefore proposed, and the wish from both research providers as well as industry, that the projects’ budgets are increased form today’s 3-5 MSEK to at least 8-10 MSEK. In order to speed up the industrialization the project times should still be around 3 years, although it will be a challenge for the research providers.

→It is proposed, that projects should aim for increasing the TRL-level from TRL3 or TRL4 up to TRL5 for larger projects. In order to reach this in 3 years, a sharp mid-term assessment with respect to deliverables will be needed.

Up until today the focus of the various projects has been wide spread over many different areas, covering everything from tooling manufacturing to powder characterization to environmental impacts; all projects spread in small batches. Usually AM projects are “squeezed and adapted” to fit funding calls that often is focused on conventional manufacturing.

→ It is proposed to have more coordination of AM research and that a thorough agenda based on the final roadmap from RAMP-UP is created. Resources can then be efficiently divided into the current important area of metal-AM and drive the development towards a clear goal for industrialization.

To speed up the industrialization of AM in Sweden it is important with knowledge sharing and dissemination of results.

→ It is proposed to have a joint plan for dissemination for all projects and to facilitate and encourage cooperation between different projects. An explicit suggestion came up at the workshop; if all projects prepared course material based on their results, this could be incorporated in AM-courses both for industry and academia.

8. Acknowledgement

This project was funded by Vinnova and is a special project within SIP Metallic Materials. This is a collaborative work from all the project partners and the group is thankful from all help and support from other stakeholders around Sweden, the Swedish Arena for Additive Manufacturing of Metals and from our network around the globe. More than 50 persons participated actively in the workshop on 12th of September 2017, when a draft of this report was discussed. The project group consists of the following research organizations and companies:

Swerea KIMAB
Swerea IVF
Swerea SWECAST
Chalmers
Högskolan Väst
KTH

Arcam AB
Carpenter Powder Products AB
Construction Tools PV AB
Höganäs AB
GKN Aerospace AB
Quintus Technologies AB
Saab AB
AB Sandvik Machining Solutions
Scania CV AB
Siemens Industrial Turbomachinery AB
Uddeholm AB