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Short Version

Additive Manufacturing

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Whether it is prosthetic hands, entire cars or even human clones, the things that industrial 3D printing might be capable of producing is a topic that has captured the imagination of economic forecasters, the media and science fiction writers alike. The boundaries between fact and fiction are blurred and expectations are often exaggerated. The fact is that Additive Manufacturing, also known as industrial 3D printing, is in some respects still in its infancy. Nevertheless, it is continuously maturing – it has a huge range of potential applications and the industry has been achieving growth rates in the region of 30 percent for some years now. In 2015, it recorded global sales of 4.5 billion euros. Additive Manufacturing technologies will play an important role in tomorrow's digital, connected industrial production. For the foreseeable future, however, Additive Manufacturing is not expected to revolutionise production either technologically or in terms of value creation.

The term "Additive Manufacturing" refers to the production of parts by building up successive layers of a formless material. This makes it possible to "print" objects with a wide variety of different shapes. Additive Manufacturing operates vastly autonomous on the basis of digital 3D models. It comprises three stages: data preparation, the actual layer-by-layer building of the object and post-processing. A number of different joining methods and materials – e.g. plastics, metals or composites – may be employed, potentially in different combinations depending on the desired product attributes. The most commercially important techniques include

Fused Deposition Modelling™ and Selective Laser Melting™. The former soon became widely adopted after its patent expired in 2009, sparking a surge of interest in Additive Manufacturing. Whether a particular technology is best suited to home use, simple workshops or factories also depends on the investment cost of the equipment, which can be anywhere between 500 and over 1 million euros.

When Additive Manufacturing began to be used in the 1990s, it was initially employed for prototyping (primarily in the automotive industry) and subsequently to make casting moulds and tools. Today, it is also used to make end products including small parts, small batches and one-off items for the jewellery or medical and dental technology industries.

Additive technologies differ from conventional manufacturing technologies in several respects and have huge potential if deliberately used with respect to their specific features. Their most important benefit is their high design flexibility. Since the material is built up layer by layer until the object is produced, there is no need for moulds, which are both time-consuming and costly to make. This means that it is theoretically possible to produce any shape. The actual degree of design flexibility depends on the method used and the specific shape of the item in question. For instance, some technologies require the use of support structures that must be removed once the build is complete. In the field of medicine, Additive Manufacturing makes it possible to tailor products such as dental implants, in-the-ear hearing aids or surgical aids to patients' individual anatomy. For many geometrically complex designs and shapes, the only alternative to Additive Manufacturing would be to create them by hand. Additive Manufacturing's greater dimensional accuracy and shorter production time are also an advantage for prototyping. Nevertheless, Additive Manufacturing technologies are not yet cost-effective enough for the mass production of simple, low value-added parts and are thus unsuitable for this purpose. The ability to make a finished product in one single manufacturing step is also likely to remain little more than a vision for some time to come.

It is in the context of mass customisation that Additive Manufacturing technology can really come into its own, since it allows products to be fully customised. It is thus a key enabler of smart, connected manufacturing concepts which characterise Industrie 4.0, where product planning is focused on the customer and their individual requirements. Additive Manufacturing technologies make it possible to produce very small series down to a batch size of one without significantly adding to the cost. For instance, one US sporting goods manufacturer is now using its customers' biomechanical data to produce running shoe soles tailored to their individual running style. However, the fact that post-processing of the finished product is still relatively laborious means that the mass production of individually customised items remains the exception for the time being.

Industrie 4.0 also calls for more flexible production processes. Additive Manufacturing makes it possible for parts to be made close to the place where they are used – the primary thing that needs to be distributed to the manufacturing location is the data. All spare parts processes could benefit from this decentralised manufacturing approach, since it would mean that replacement parts could be made wherever they are needed. In the space industry, large parts could in future be made in space, eliminating the expense of having them "delivered" by shuttles. However, even though they have been made using the same data, there is often still too much variability in the properties of additively manufactured parts. We do not yet have robust machines and manufacturing processes capable of delivering reproducible output.

One significant development in the field of Additive Manufacturing is process chain digitalisation, which is spurring the development of new business models and services. Online platforms make it possible to establish a marketplace e.g. for 3D CAD models, material formulae and process parameters which can be obtained either via a one-off download and purchase or via a streaming subscription in much the same way as digital music or films. However, a number of data security, copyright and standardisation issues still need to be resolved. International norms are also currently lagging behind the reality on the ground. A great many different Additive Manufacturing technologies now exist side by side, the terminology employed is often unclear and various trademarked names are used for processes that are in some cases identical. Additive Manufacturing also has the potential to support resource efficiency in future industrial production, although more still needs to be done to assess its economic, environmental and societal impacts in a holistic manner.

Additive Manufacturing will not revolutionise industrial production. However, there is good reason to believe that it will augment established methods in many different areas. In order to fully leverage the technology's economic and environmental potential for the German economy, it will be necessary to take concerted action in the areas of research, implementation, education and funding:

Research

1) In order to improve the productivity of Additive Manufacturing and reduce its drawbacks compared to conventional manufacturing technologies, research should be conducted into production processes, materials and part properties, with the results being fed back into the systems engineering process.
2) In order to make full use of the new design flexibility opportunities, systematic research should be carried out with a view to producing concrete design guidelines covering all the different Additive Manufacturing technologies.
3) Develop new data formats for Additive Manufacturing as soon as possible.
4) Analyse the ways in which Additive Manufacturing could potentially change and impact on value networks, the economy and society as a whole.

Implementation

5) Standardise the three data sets of digital 3D geometries, material formulae and process parameters.
6) Additive Manufacturing requires dedicated quality assurance methods and processes.
7) Accelerate the implementation of basic research in industrial applications.
8) Strategies are needed for integrating Additive Manufacturing with widespread conventional manufacturing systems.
9) Creation of decision-making tools capable of meeting future strategic planning challenges in connection with Additive Manufacturing.
10) Stimulate and support a dynamic start-up scene in order to leverage Additive Manufacturing's high potential for innovation.

Education

11) Augment traditional occupational profiles for skilled workers with new skills for Additive Manufacturing technologies.
12) Make use of Additive Manufacturing's potential for teaching STEM subjects in schools.

Funding

13) Establish a research programme geared towards implementation of the dual strategy of securing Germany's position as a leading Additive Manufacturing supplier and market.

Recommendations

A number of recommendations can be made with a view to driving the development of Additive Manufacturing technologies, opening up new areas of application and optimising the industrial applications. These recommendations are aimed at focusing research funding so as to overcome the remaining practical obstacles associated with the various manufacturing technologies, establishing norms and standards in order to simplify development processes and promoting cooperation between the different actors.

In addition to government research funding agencies, the recommendations are thus primarily aimed at the leading companies where Additive Manufacturing is expected to play an increasingly important role in the future. As well as contributing through their own research into the development of materials and manufacturing techniques, the main challenge for these companies will be to rapidly establish the infrastructure needed to integrate the new additive methods with their existing production processes as efficiently as possible. For its part, government can create a favourable environment for the technologies' future development by introducing measures to support young start-ups and by making the relevant changes to school education and training curricula. In general, closer cooperation between research and industry in this field would also be desirable. Standardisation organisations such as DIN/ISO could contribute to this process.

Research

Recommendation 1: *In order to improve the productivity of Additive Manufacturing and reduce its drawbacks compared to conventional manufacturing technologies, research should be conducted into production processes, materials and part properties, with the results being fed back into the systems engineering process.*

The machine hour rate of industrial Additive Manufacturing systems is very high compared to conventional production technologies. Furthermore, the strength and quality of additively manufactured parts only rarely compare to conventionally manufactured parts. Material behaviour is also variable and has not yet been the subject of in-depth research. These are the main obstacles to the commercially viable use of the technologies for producing high volumes and high-quality parts in industrial applications. On the other hand, the various additive technologies still have a lot of untapped potential. Particularly in the automotive and aviation industries, users of the technology already have plans for high-volume production.

Recommendation 2: *In order to make full use of the new design flexibility opportunities, systematic research should be carried out with a view to producing concrete design guidelines covering all the different Additive Manufacturing technologies.*

Although Additive Manufacturing provides a high level of design freedom, there are still certain constraints such as the requirement for support structures in some cases and the need to post-process the parts. Design to Additive Manufacturing is only feasible for certain additive technologies and must take the entire process chain into account. There are currently very few basic ground rules and no specific process-oriented design engineering guidelines. These will therefore need to be formulated and incorporated into the relevant training and professional development provision together with the underlying practical know-how.

Recommendation 3: *Develop new data formats for Additive Manufacturing as soon as possible.*

The current standard .STL file format suffers from a number of problems, since important information is lost during the conversion of 3D CAD data and inconsistencies can occur. This means that extensive post-processing of the data set is often necessary. Moreover, there are numerous proprietary data formats for transporting information that cannot be saved in .STL. A concerted R&D effort will be required before data formats can be standardised. Any new data formats will need to guarantee the interoperability of equipment made by different manufacturers and ensure user access to the relevant information. They will also need to work with existing IT systems (PDM, ERP). It will only be possible to achieve widespread acceptance in the industry and among the maker community once these requirements have been met. The first steps are already being taken in this direction with new, open data formats such as .3MF.

Recommendation 4: *Analyse the ways in which Additive Manufacturing could potentially change and impact on value networks, the economy and society as a whole.*

This analysis should include upstream and downstream manufacturing processes, product use and recycling. It should evaluate the benefits in terms of social, economic and environmental sustainability arising from the new value creation structures associated with decentralised, demand-based production. One example is the reduction of the high warehousing and logistics costs involved in supplying spare parts.

Implementation

Recommendation 5: *Standardise the three data sets of digital 3D models, material formulae and process parameters.*

In the long run, the productivity and part quality improvements demanded by industrial users will require a standard, universally accepted data format that can be used for 3D models, material formulae and process parameters. It will also be necessary to develop appropriate quality criteria (e.g. indicator systems) for Additive Manufacturing. This will be critical e.g. to enabling classification of data, materials, processes and parts. Since there are also currently still some gaps in our technical and physical understanding of Additive Manufacturing processes, there is a significant research requirement concerning the generation of the three data sets. If the goal of a widespread standard data format for the three data sets is achieved, it will become much easier for product pirates to produce high-quality copies. It will therefore be essential to identify the potential threats to each of the three data sets and implement integrated protection strategies for them.

Recommendation 6: *Additive Manufacturing requires dedicated quality assurance methods and processes.*

It will be necessary to develop methods and processes for measuring, testing and verifying the quality of additively manufactured parts. This will require the relevant process parameters to be identified, monitored and adjusted during the manufacturing process using a process model.

Recommendation 7: *Accelerate the implementation of basic research in industrial applications.*

One possible approach involves strengthening pre-competitive research collaboration between the federal government and industry. The establishment of regional demonstration centres and technology clusters can also play a major role in translating research into practice. Successful pilot implementations and the use of the technology in specific industries can serve to demonstrate the opportunities and risks, as well as the range of applications that already exists today. Another concrete approach would involve the implementation of large-scale collaborative projects in the form of public-private partnerships. Last but not least, it is necessary to explore whether there is any potential in Germany's relatively weak AM start-up scene for driving improvements to Additive Manufacturing techniques.

Recommendation 8: *Strategies are needed for integrating Additive Manufacturing with widespread conventional manufacturing systems.*

The integration of Additive Manufacturing techniques with existing production processes will require the development of standard routines, process-based quality management and new machine systems capable of robust manufacturing. One key requirement will be to ensure that the automation of Additive Manufacturing systems is brought up to the level expected of conventional production systems both today and in the future. The transformation of industrial value creation that we are beginning to witness in the context of Industrie 4.0 will undoubtedly play a significant role in this regard.

Recommendation 9: *Creation of decision-making tools capable of meeting future strategic planning challenges in connection with Additive Manufacturing.*

If visions such as decentralised production and the prosumer paradigm come true, then value networks will be transformed from the ground up. In order to be prepared for this change, it will be necessary to develop scenarios for the relevant actors in these new value networks. It will also be important to create instruments for assessing the economic, environmental and societal impacts of Additive Manufacturing. Scenarios and impact assessment instruments are urgently needed decision-making tools for the strategic positioning of the actors in the industrial value network.

Recommendation 10: *Stimulate and support a dynamic start-up scene in order to leverage Additive Manufacturing's high potential for innovation.*

Germany possesses extensive know-how in the fields of production research and industrial automation and is thus well placed to make improvements to existing machinery and equipment. However, this evolutionary approach is unlikely to create completely new Additive Manufacturing technologies and business models – the potential to do this lies instead with established actors from other industries and with start-ups. In particular, public funding agencies should introduce measures to stimulate start-ups and make funding available to them in order to leverage the potential for innovation and promote a new and vibrant start-up scene.

Education

Recommendation 11: *Augment traditional occupational profiles for skilled workers with new skills for Additive Manufacturing technology.*

In the future, Additive Manufacturing will become a standard manufacturing technology in many industries. It must therefore be fully incorporated into vocational training and professional development provision. Before this can happen, teaching staff at vocational institutions will first need to receive the appropriate training. The rate at which the technologies are developing constitutes a particular challenge. It will therefore be necessary to establish digital teaching and learning platforms and make use of new knowledge transfer methods such as Massive Open Online Courses (MOOCs). In view of the high innovation rate in the field of Additive Manufacturing, it will also be necessary to determine whether professional development certificates should only be valid for a limited period of time.

Recommendation 12: *Make use of Additive Manufacturing's potential for teaching STEM subjects in schools.*

Additive Manufacturing technologies have huge potential as a teaching aid in schools. They can be employed to bring the design and manufacturing processes to life. Living labs where students have the opportunity to use 3D CAD systems and home 3D printers themselves can help to make technology more tangible and get young people excited about STEM subjects.

Funding

Recommendation 13: *Establish a research programme geared towards implementation of the dual strategy of securing Germany's position as a leading Additive Manufacturing supplier and market.*

German machine and equipment manufacturers and material developers are already global leaders in the supply of Additive Manufacturing systems and materials. At the same time, many German companies are trying to use Additive Manufacturing technologies to gain a competitive advantage. In the future, it will be important both to secure Germany's position as a leading Additive Manufacturing supplier and to create favourable conditions for Additive Manufacturing to increase German companies' competitiveness. This statement has outlined the challenges that will be encountered along the way. Overcoming these challenges will require an extensive and concerted research programme that should address the following topics:

1) Process chain automation
2) Basic materials and process science research
3) New alloys and thermomechanical treatments specifically designed for Additive Manufacturing techniques
4) Productivity improvements
5) Standard feedstocks with high purity and appropriate morphology
6) Quality control
7) Reproducibility of part properties
8) Selective modification and variation of part properties (gradient properties)
9) Multi-material processing
10) Data integrity (data privacy, data security and data consistency)
11) Safety and security in cyber-physical production systems
12) Product piracy prevention
13) Impacts of decentralised production on value networks and holistic impact assessment

Members of the Working Group

Prof. Dr.-Ing. Jürgen Gausemeier (Heinz Nixdorf Institute, Paderborn University (Spokesperson)), Prof. Dr.-Ing. Michael Schmidt (Institute of Photonic Technologies, Friedrich-Alexander-Universität Erlangen-Nürnberg and Bayerisches Laserzentrum (Spokesperson)), Prof. Dr.-Ing. Reiner Anderl (Department of Computer Integrated Design, Technische Universität Darmstadt), Prof. Dr.-Ing. Christoph Leyens (Institute of Materials Science, Technische Universität Dresden), Prof. Dr.-Ing. Hans-Joachim Schmid (Particle Technology Group, Paderborn University), Prof. Dr.-Ing. Günther Seliger (Department Assembly Technology and Factory Management, Technische Universität Berlin), Prof. Dr.-Ing. Frank Straube (Chair of Logistics, Technische Universität Berlin), Prof. Dr.-Ing. Petra Winzer (Department of Product Safety and Quality Engineering,University of Wuppertal)

Contact:

Dr Martina Kohlhuber
acatech – National Academy of Science and Engineering
kohlhuber@acatech.de
Phone: +49 (0)89 52 03 09 68

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German National Academy of Sciences Leopoldina
Jägerberg 1
06108 Halle (Saale)
Phone: +49 (0)345 472 39-867
Fax: +49 (0)345 472 39-839
Email: politikberatung@leopoldina.org
Berlin Office:
Reinhardtstraße 14
10117 Berlin

acatech – National Academy of Science and Engineering
Karolinenplatz 4
80333 München
Phone: +49 (0)89 52 03 09-0
Fax: +49 (0)89 52 03 09-900
Email: info@acatech.de
Berlin Office:
Pariser Platz 4a
10117 Berlin

Union of the German Academies of Sciences and Humanities
Geschwister-Scholl-Straße 2
55131 Mainz
Phone: +49 (0)6131 218528-10
Fax: +49 (0)6131 218528-11
Email: info@akademienunion.de
Berlin Office:
Jägerstraße 22/23
10117 Berlin