Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 54 (2016) 210 – 214
www.elsevier.com/locate/procedia

6th CLF - 6th CIRP Conference on Learning Factories

Model Factory for Additive Manufacturing of Mechatronic Products: Interconnecting World-Class Technology Partnerships with Leading AM Players

In Seong Yoo[a,*], Thomas Braun[a], Christopher Kaestle[a], Michael Spahr[a], Joerg Franke[a], Philipp Kestel[b], Sandro Wartzack[b], Joerg Bromberger[c], Erhard Feige[c]

[a] *Institute for Factory Automation and Production Systems (FAPS), Friedrich-Alexander-Universität Erlangen-Nürnberg, Fürther Str. 246b, 90429 Nuremberg, Germany*
[b] *Chair of Engineering Design (KTmfk), Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 9, 91058 Erlangen, Germany*
[c] *McKinsey & Company, Inc., Berlin & Hamburg, Germany*

* Corresponding author. Tel.: +49-9131-85-27859; fax: +49-9131-302528. *E-mail address:* In.Seong.Yoo@faps.fau.de

Abstract

The additive manufacturing (AM) model factory's aim is to establish a leading-edge learning academy for the digital and generative production of innovative mechatronic products, where the complete value chain is integrated on a single site. Short courses and deep dives enable easier access to the state of the art technologies and increase the awareness for their potentials. Anchored in key industries such as automotive, aerospace, and medical by major OEMs and regional SMEs, the AM model factory cooperates with world-class partners and leading market players. This paper displays the model factory's setup, selected technologies, exemplary courses, and benefits.

Peer-review under responsibility of the scientific committee of the 6th CIRP Conference on Learning Factories

Keywords: Additive manufacturing; digital production; mechatronics; model factory; learning academy

1. Introduction

Additive manufacturing (AM) is a key motor for the new era of production technology that is characterized by digitization, individualization, and integration of complex functionality. Leading companies are being more and more aware of the urgent necessity of employing additive manufacturing process in their production system. However, for many manufacturers, especially small- and medium-sized enterprises (SMEs), it remains the question of "what for" (specific applications) and "how" (defined process and necessary knowledge and skills).

In this paper, we present our on-working plan of the AM model factory, an all-in-one, single-site training center that is specifically dedicated to the hands-on, advanced learning in the field of AM. Being integrated in a consortium of university research institutes that are specialized in the design of function integrated mechatronic products and leading industry partners as well as cutting-edge AM machine manufactures, the AM model factory will be an unprecedented, technology learning center for globally operating innovative enterprises.

This paper is structured as follows: First, a brief overview on additive manufacturing technology and its application potentials in the manufacturing of mechatronic production will be given, from which the necessity of the AM model factory that covers end-to-end additive manufacturing process is derived. Secondly, numerous advantages and benefits that the strategic location, technical infrastructure and the academic environment of the AM model factory can bring to training participants will be explained. Lastly, the basic philosophy, aims and unique methods of the capability building in a model factory will be introduced followed by a quick peek into a training module.

2. The AM model factory

2.1. Technological background and motivation

Using additive manufacturing (AM) technology, arbitrary parts with complex geometries that were almost impossible to manufacture with conventional subtractive machining processes, can be generated from a variety of materials, e.g. polymers, metals, ceramics, glass and paper. Materials may be provided in the form of powder, wire, foil or liquid. The additive

Peer-review under responsibility of the scientific committee of the 6th CIRP Conference on Learning Factories
doi:10.1016/j.procir.2016.03.113

manufacturing enables small-size series production that fulfills high quality standards, helps maintain strategic business knowledge within the company team, and accelerates iterative product development processes taking customers' feedback into account and quickly reacting to their needs [1].

As additive manufacturing technology is changing the present landscape of the industry and market drastically, there exists an increased need for rethinking in development and production of innovative technical systems in across all industry fields.

In the aviation industry for example, the main drivers behind the AM push are the feasibility of lightweight, complex-shaped aircraft parts with increased functionality that also enables a significant reduction of production cost by eliminating assembly steps.

In electronics production, the trend of faster market launches and a higher rate of innovation has led to a steadily increasing demand for fast, flexible and easy to use series production techniques. The additive manufacturing picks up the trend of product individualized and enables future custom manufacturing in series. Furthermore, it supports the ubiquitous trend towards miniaturization by allowing more complex three dimensional shapes. One of the most demanding challenges regarding additive manufacturing in electronic and mechatronics objects is the need for multi-material-composition. Fig. 1 shows one of our first power electronics applications of additive manufactured composite system of bronze on a ceramic substrate [3].

Additive manufacturing also has opened up new business opportunities in the biomedical industry. The main driving tendency on the medical technology market is individualization. In the wide spectrum between the well-established applications such as tailored in-ear shells for hearing aids [4], and the revolutionary technology for 3D bio-printing of vascular tissues and organs, the direct digital production with the additive manufacturing technology is rapidly gaining a considerable importance in the fields of e.g. dental prosthetics, upper-limb orthepedic prosthetics [5,6], as well as in pre-operative planning in cardiology [7].

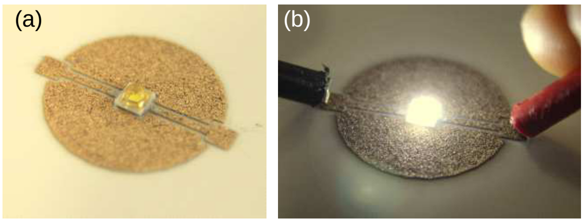

Fig. 1. A demonstrator for a power-electronics application of AM-products. (a) An electronic circuit layout on Al_2O_3 substrate, (b) high-power LED [3].

In the near future, we will continue seeing revolutions in product design enabled by AM technologies, particularly in the field of additive manufacturing of mechatronic objects as third technological stage of AM (Fig. 2) [8].

In addition to prototypes, machining tools, and casting molds, additive manufacturing processes are increasingly applied for end products [9,10]. The essential advantages of the innovative manufacturing technology are flexibility of production as well as freedom in design. Since no form-defining tools are needed the resulting unit costs are independent from lot size

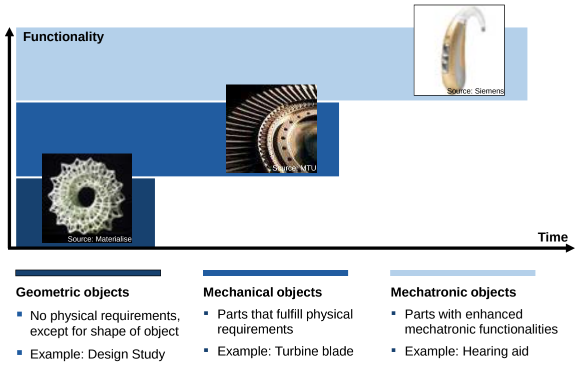

Fig. 2. The 3-step model of technology development towards additive manufacturing of function-integrated mechatronic systems [8].

[11,12]. Hence, the mass production of individualized components that are adapted to specific customer requirements is possible [13]. Contour- and stiffness-adapted implants in the field of medical technology are good examples [14]. Moreover, conventional design rules are eliminated such as the avoidance of undercuts in cast components. Thus, based on the layer-by-layer buildup, complex, cellular lightweight structures as results of structural optimizations can be produced directly [12,15], such as hinges and cabin parts in the aviation industry [16].

Further advantages are the manufacturability of multi-material systems [10,17], the integration of electrically conductive structures or optical waveguides in mechatronic parts [18,19] and the possibility to create complete movable assemblies in a single process step avoiding previously required assembly work [4], like gripper elements for handling systems [20].

Despite this almost unbounded potential of additive manufacturing, the freedom of design is still limited. Moreover, process-specific influences must be considered [21]. The anisotropic material behavior, geometric accuracy as well as surface quality depend on build-up orientation and various process parameters in AM [22,23]. For example, the manufacturable wall thickness and gap width are limited by the layer thickness as well as the raster and contour paths. Furthermore, the layer-by-layer buildup leads to stair-step effects on the surfaces and design elements like bore holes have to be oriented along the buildup orientations to avoid these effects. Moreover, temperature distributions during the manufacturing process lead to thermal distortion and therefore material accumulation as well as abrupt thickness changes have to be avoided. [24–26]

To sum up, new process-specific design rules are necessary to use the possibilities of the innovative manufacturing technology. These rules have to be considered early in the product development process, in addition to appropriate process-specific computations.

2.2. Location, infrastructure and environments

The AM model factory will be sited on a refurbished ex-industry complex in Nuremberg called "Auf AEG", where the research laboratories, production lines and testing facility of the consumer electronics group AEG were once located. Being located in the metropolitan area of Nuremberg with an international airport in the vicinity, the AM model factory is easily accessible via railway, autobahn and public transportation, not only for customers from major cities in Germany but also from all over the world. The great accessibility of the factory is a major economic advantage for customers, specifically regarding travel time and cost.

The massive concrete buildings premising on “Auf AEG” are now completely refitted and host a large number of leading-edge research centers and innovative research & development centers that are working on a large spectrum of topics. The Institute for Factory Automation and Production Systems (FAPS), a member of the initiating partners of the AM model factory is one of the major research institutes that has been settled down on “Auf AEG” (Fig. 3). The FAPS has established four of its six research groups here: Bavarian Technology Center for Electrical Drives, Electronics Production, Wiring Systems, as well as Bavarian Technology Center for Home Automation. The remaining two research groups - System Engineering and Biomechatronics - are stationed in the nearby university city of Erlangen.

Fig. 3. The research campus “Auf AEG” with its strategic location and academic environments is perfectly suited for the AM model factory.

Additive manufacturing as a disruptive technology is related to almost every research topics of the institute FAPS. Therefore, the AM model factory is expected to play an important role as a competence center for additive manufacturing, where researchers, cooperating research and industry partners that are working on a wide spectrum of correlated topics will gather to exchange their expertise and build a well-built and sustainable technology network.

In addition, the institute FAPS as a chair of Friedrich-Alexander-Univerität Erlangen-Nürnberg is already furnished with a infrastructure that is required for additive manufacturing, such as a machining workshop for post-processing of additive manufactured parts, larger rooms for seminars and conferences, and computer laboratories for computer-aided design. Furthermore, the research center is equipped with surface metrology systems, materials testing machines, a variety of microscopes, and X-ray inspection systems, which are essential instruments for quality assurance in conventional production technology, as well as in additive manufacturing.

The other research institute in the team of the AM model factory is the Chair of Engineering Design. The chair will provide the necessary design-related manufacturing knowledge about additive processes and show the potentials and restrictions of the innovative technology, so that function-integrative mechatronic products can be efficiently designed and produced meeting all particular customer requirements. Furthermore, insights in knowledge-based design, modeling, and simulation of additive manufactured products will be transferred to the customers.

Another major advantage of being an university-affiliated model factory is abundant high-quality human resources. The customers of the model factory can profit while co-working with creative minds, specifically undergraduate and PhD students. The model factory also offers a great opportunity for students and young scholars to adapt themselves to additive manufacturing, which requires an entirely different way of thinking in engineering.

With all geographical strategic benefits mentioned above, it can be positively noted that a fundamental basis for the model factory for additive manufacturing has been secured. In the following section, a detailed plan for the learning factory and a preliminary layout including AM machines and their auxiliary systems will be presented.

2.3. AM machines and equipments

In order to offer customers a broad insight into the additive manufacturing, the AM model factory will employ three major printing technologies that are versatile, widely implemented in the industry, and forward-looking: Fused deposition modeling (FDM), selective laser melting (SLM) for metals, and selective laser sintering (SLS) for polymeric materials.

In a SLM process for example, metallic raw material in powder form is selectively heated to its melting point in an inert atmosphere by a laser. The melted points then solidify and multiple infinitesimally small points can be strung together to build an almost pore-free layer. After completion of each layer, the building platform is lowered and a fresh, thin layer of metal powder is applied and the curing process is repeated successively until the model is completely built up, which leads to a characteristic layer structure of additive manufactured parts [2]. The basic principle of SLS process is comparable with that of SLM process to an extent, except that SLS process is used for polymeric powders instead of metal powders.

Each of these AM technologies have different technical requirements with regards to process flow including material handling, required infrastructures, accessory equipments, and safety requirements. Therefore, The AM model factory will be divided in 3 different workshop floors that are separated from each other with appropriate construction measures to cover each of the AM technologies respectively, especially in order to minimize conflicts between the different process flows and more importantly to prevent cross-contamination between metallic and polymeric systems. For safety and quality reasons, a workshop floor will again be split in powder preparation area and machine room, which will be filled with cutting-edge products of leading technology partners and machine manufacturers. A preliminary layout of the main workshop floor with the 3 different printing technologies is illustrated in Fig. 4.

To present the complete value-added chain of additive manufacturing on a single-site model factory, a computer laboratory for pre-processing of digital design data, a few workbenches

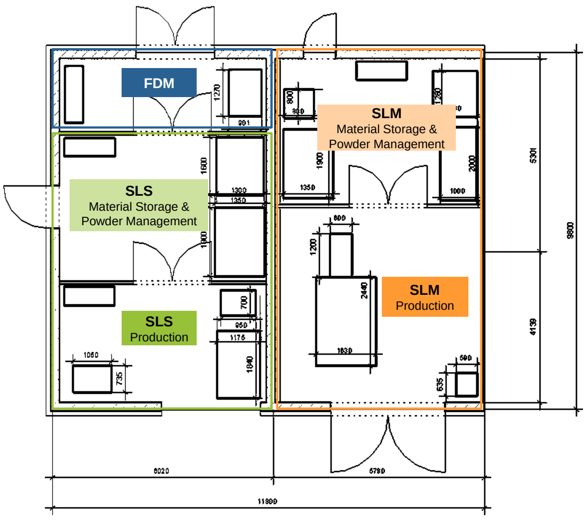

Fig. 4. A detailed layout of the AM model factory is being designed in cooperation with key partners on the market.

for manual and machined post-processing, and a quality analysis laboratory will also be integrated into the AM model factory using on the existing infrastructure of the institute FAPS.

2.4. Business model

In the AM model factory, we have three main stakeholders involved:

- University jointly develops project; provides space for the facility and co-runs it; has access to facility outside workshops
- Technology and industry partners provides equipment and content
- McKinsey provides project management, intellectual properties, and conducts workshops

All partners have depending on their investment the right to use the facility for their purposes. For example, technology partners can run customized trainings and introductory sessions for their own customers or employees. University teaches students or runs paid workshops for small- and medium-sized enterprises (SMEs).

3. Advanced learning in the model factory

3.1. Philosophy and concepts

Capability building leads to lasting improvements in any transformation program and serves as an intelligent way to scale improvements to an entire organization. Adults learn best in an environment that offers them a rich, interactive experience and the freedom to experiment and make mistakes without risk. Therefore, dedicated experiential learning facilities provide the ideal combination of real production issues and opportunities with the flexibility and freedom to fail. Experience shows that not only do people learn faster in such environments, but they also remember more and are better prepared to apply what they learn when they return to their everyday roles.

In the model factory, participants are actively involved in a wide range of exercises. They experience live scenarios via e.g. "go and see" observation of an new operating system to detect improvement opportunities, complete value stream (material and information) representation from design, manufacturing, post-processing to quality control, step-by-step teaching and implementation, which results in measurable workflow improvements, interaction with real operators to also detect management and mindset issues and observing different perfection levels of the operating system – from very basic to good practice.

3.2. Goal and structure of training modules

The purpose of the training modules is to prepare all key players in a transformation to this new technology to understand key tools for the transformation and practice with managerial tools for the future state. The training can be adjusted to other environments, such as machining or process and can be supported with classroom training, focusing on the transformation process.

In the AM model factory we will conduct training at an end-to-end view of the additive manufacturing process. We will train all capabilities needed along the 5 phases of the process: Design, manufacturing, post-processing, quality control and recycling. The trainings will be tailored to the respective audiences that spans from introductory trainings for the management level to deep-dive trainings for engineers.

3.3. Example of a training module

The following example sketches the contents of a 4-hour introductory training for AM for managerial level.

- Introduction Part 1
  - Key principles of AM, benefits and challenges
  - Global impact on value chain and functions
  - Market size, use cases, player landscape
  - Process and technology (i.e., materials, printing technologies, service requirements, quality)
- Shop floor visit (120 min.)
- E2E production process (e.g. retrofit part using selective laser sintering)
  - Create a 3D data file (e.g. from digital scanning of objects)
  - Select material (i.e. common metals and polymers)
  - Transfer into "printable" file (e.g. using standard slicing software)
  - Production planning and execution
  - Quality control and post-processing
- Introduction Part 2
  - Recommendations for OEMs on how to get started (i.e. opportunity spotting, capability and infrastructure, partner)
  - Outlook into new business models

4. Future tasks and outlook

With the AM model factory, we aim to accelerate the adoption of AM in industry applications by:

- Providing easier access to state-of-the-art AM technology for companies, particularly for SMEs with focus on E2E coverage of AM process,
- Establishing professionalized learning academy to scale-up capability building – from in-house trainings for partners and customers to university education,
- Increasing awareness among key industry players for benefits of AM technology and potential to gain operational improvements,
- Fostering cooperation among key AM players and OEMs to create market-ready products and applications,
- Offering professional services to accelerate AM adoption – creation of prototypes, introduction into series and building in-house capabilities.

The model factory provides partners with various benefits such as – increase access to customers, expand regional reach (particularly SMEs), train customers and employees in a professional way and real-life environment. Partners have exclusive access to the facility. Technology partners can use the model factory as a showcase for your latest technology innovations. Partners can intensify their relationships by conducted joint research project and they can hire new talent from university.

References

[1] Marquard E. VDI-Statusreport Additive Fertigungsverfahren. Düsseldorf: Verein Deutscher Ingenieure e.V.; 2014.

[2] Fastermann P. Welche 3D-Druck-Technologien gibt es und welche Technologie eignet sich wofür? In: Fastermann P, editor. Technik im Fokus 3D-Drucken. Berlin: Springer; 2014. p. 25-44.

[3] Syed-Khaja A, Schwarz D, Franke J. Advanced substrate and packaging concepts for compact system integration with additive manufacturing technologies for high temperature applications. In: Proceedings of the 5th CPMT Symposium Japan (ICSJ) 2015;156-159.

[4] Gibson I, Rosen D, Stucker B. Additive Manufacturing Technologies. Rapid Prototyping to Direct Digital Manufacturing. New York: Springer; 2010.

[5] Yoo IS, Hawelka F, Reitelshöfer S, Franke J. Kostenminimierte, additiv gefertigte Handprothese für den Einsatz in Entwicklungsländern. In: Weidner R, Redlich T, editors. Erste Transdisziplinäre Konferenz zum Thema "Technische Unterstützungssysteme, die die Menschen wirklich wollen". Hamburg; 2014. p. 410-419.

[6] Yoo IS, Reitelshöfer S, Franke J. Additiv gefertigte Handprothese. In: Weidner R, Redlich T, Wulfsberg JP, editors. Technische Unterstützungssysteme. Heidelberg: Springer Vieweg; 2015. p. 192-193.

[7] Otton JM, Spina R, Sulas R, Subbiah RN, Jacobs N, Muller DWM, Gunalingam B. Left atrial appendage closure guided by personalized 3D-printed cardiac reconstruction. In: JACC Cardiovascular Interventions 2015;8(7), p. 1004-1006.

[8] Franke J, Spahr M, Kuhn T, Hörber J. Additive manufacturing technologies for functionalized mechatronic integrated devices. In: Proceedings of the 11th International Congress on Molded Interconnected Devices (MID) 2014.

[9] Gebhardt A. Understanding Additive Manufacturing. München: Carl Hanser; 2012.

[10] VDI 3405. Additive Fertigungsverfahren. Berlin: Beuth; 2014.

[11] Witt G. Fertigungstechnik. München: Carl Hanser; 2006.

[12] Gruber G et al. Methodische Unterstützungsansätze für die Entwicklung additiv gefertigter Bauteile. In: Messe Erfurt GmbH, editor. Tagungsband der Rapid.Tech 2013. Erfurt; 2013.

[13] Pallari JHP, Dalgarno KW, Woodburn J: Mass customization of foot orthoses for rheumatoid arthritis using selective laser sintering. In: IEEE Transactions on Biomedical Engineering 2010;57(7).

[14] Schöne C et al. Individual Contour Adapted Functional Implant Structures in Titanium, In: Interdisciplinary Design: Proceedings of the 21st CIRP Design Conference 2011;149-153.

[15] Sembdner P. et al. Process chain for design, optimization and production of open-porous lightweight structures. In: Bartolo P et al., editors. High Value Manufacturing. London: Taylor & Francis Group; 2014. p. 463-467.

[16] Huanga R et al. Energy and emissions saving potential of additive manufacturing: The case of lightweight aircraft components. In: Journal of Cleaner Production 2015.

[17] Laumer T, Stichel T, Gachot A, Amend P, Schmidt M. Realization of multi-material polymer parts by simultaneous Laser Beam Melting. In: Proceedings of 15th International Symposium on Laser Precision Microfabrication 2014.

[18] Franke J, Goth C, Putzo S. Aerosol Jet printing on rapid prototyping materials for fine pitch electronic applications, In: IEEE 61st Electronic Components and Technology Conference 2011.

[19] Reitberger T et al. Aerosol Jet printing of optical waveguides, In: 38th International Spring Seminar on Electronics Technology 2015.

[20] Hagl R. Das 3D-Druck-Kompendium: Leitfaden für Unternehmer, Berater und Innovationstreiber. Wiesbaden: Springer Fachmedien; 2014.

[21] Simpson TW. AM needs MEs. In: Mechanical Engineering 2015;8. p. 30-35.

[22] Danjou S, Köhler P. Ermittlung optimaler Bauteilorientierung zur Verbesserung der Prozessplanung in der CAD/RP-Kette. In: RTejournal 2009;6(1).

[23] Kaddar W, Witt G. Die Festigkeit in Abhängigkeit von Scanstrategien & -optionen beim Lasersintern vom Kunststoff. In: RTejournal 2010;7(1).

[24] Wartzack S et al. Besonderheiten bei der Auslegung und Gestaltung lasergesinterter Bauteile, In: RTejournal 2010;7(1).

[25] Wegner A, Witt G. RM-gerechte Konstruktion funktionaler Bauteile. In: 15. Fachtagung Rapid Prototyping an der Hochschule Ostwestfalen-Lippe 2010.

[26] Zimmer D, Adam DO. Konstruktionsregeln für Additive Fertigungsverfahren. In: Konstruktion 2013;7/8. p. 77-82.