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Additive Manufacturing – an introduction to the activities of Collaborative Research Centre CRC 814

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Abstract

With almost unlimited freedom of design, additive manufacturing technologies open up new perspectives to achieve individual solutions. These types of manufacturing techniques barely set any limits to the spirit of innovation. Due to this fact additive manufacturing techniques follow the trend towards customized products and will allow for serial production in the future. Especially powder and beam based polymer and metal processing are certified to have a high suitability for achieving industrial requirements. Despite the high potential of beam melting of polymeric powders, the step into serial production of highly individualized products was yet not realized. Nevertheless the medial driven hype related to additive processes is still increasing, although a lack in scientifically assured knowledge about basic interactions on material, process and part property level appears.
The Collaborative Research Centre 814 – Additive Manufacturing (CRC 814), established 2011 in Erlangen by German Research Foundation (DFG), investigates further mentioned various interactions between materials, processes and part properties. Therefore metal as well as polymeric powders are focused concerning their processing in beam based manufacturing techniques (e.g. laser beam melting and electron beam melting). Furthermore the built up of multi-level simulation models and the setup of inline measurement systems is performed.
Within this invited lecture an overview about the interdisciplinary research activities of CRC 814 is given, presenting basic aims as well as latest results.

Keywords: Additive Manufacturing, Research, selective laser melting of polymers, selective laser melting of metals, selective electron beam melting, powder, simulation

1. Introduction

Wherever innovations and personalized products are desired: With almost unlimited freedom of design, additive manufacturing technologies open up new perspectives to achieve design solutions. These types of manufacturing techniques barely set any limits to the spirit of innovation. Additive manufacturing techniques follow the trend towards customized products. Despite these high potentials additive manufacturing processes are mainly established for prototyping applications. The step into series production has not been realized yet. A reason for this situation is the lack in fundamental knowledge about materials, processes and parts in the relation with additive techniques. To convert the potentials included in additive manufacturing techniques so that they can be used for multifunctional components, the new Collaborative Research Centre 814 does fundamental research on that technology [1]. Thereby powder and beam based processes are focused to ensure a nearly entire investigations. The scientific structure takes the fundamental principle up.

2. Scientific Structure

The most important thing here is to look at the process chain from beginning to end. This not only includes design and process simulation, but also especially characteristics, creation and modification of suitable materials and their reactions in the molding process, up to the final component. In addition the CRC 814 creates the basics for the production of geometrically complex and highly functionalized multi-material systems, as well as for computer-aided component design and mechanical testing. It is divided into three major-areas:

- Project-area A: Powder- / Materials
- Project-area B: Processes
- Project-area C: Components

To achieve the challenging targets of the “Additive Manufacturing” Collaborative Research Centre, the 814 sub-projects closely work together on all levels.

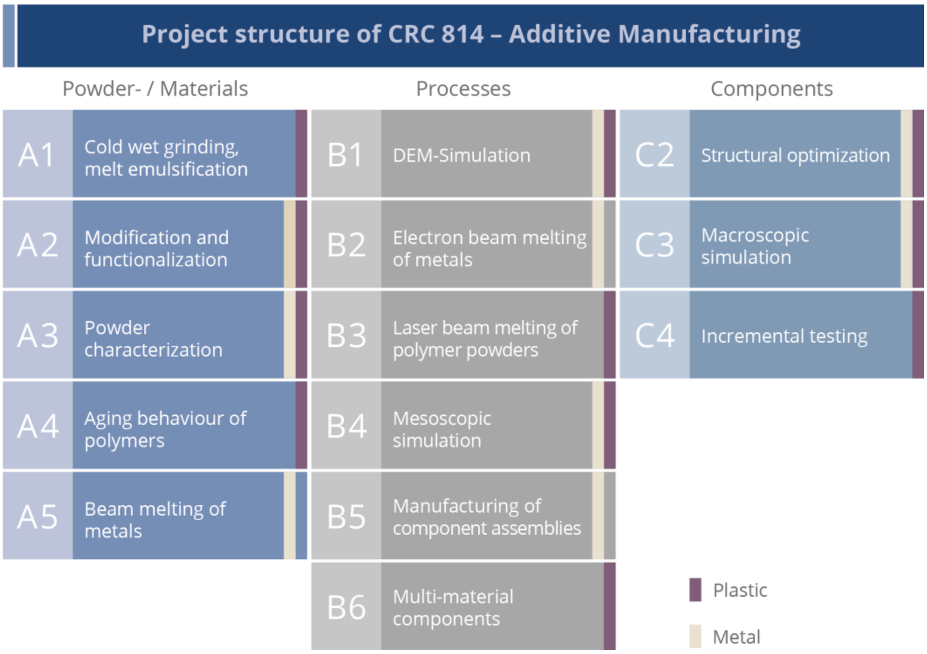

Fig. 1. Project structure of the Collaborative Research Centre CRC 814

Therefore three different interdisciplinary workgroups have been established, to serve as forum for a structured cooperation between different sub-projects. The workgroups deal with the interface-topics “powder technology”, “metrology” and “simulation”. Examples for the work of the different groups are given within the following chapters.

3. Scientific contents of CRC 814

3.1. Powder-/Materials

The project area A "Powder- / Materials" carries out fundamental studies on the in powder-based additive layer manufacturing of the used plastics and metals. The focus in this area lies on the preparation of plastic and metal powders for these processes, the knowledge of process-relevant materials and powder properties and their influence in the manufacturing process. Thus project area A includes key aspects of powder preparation and their application properties, which have a great influence on the consolidation processes and the later part properties.

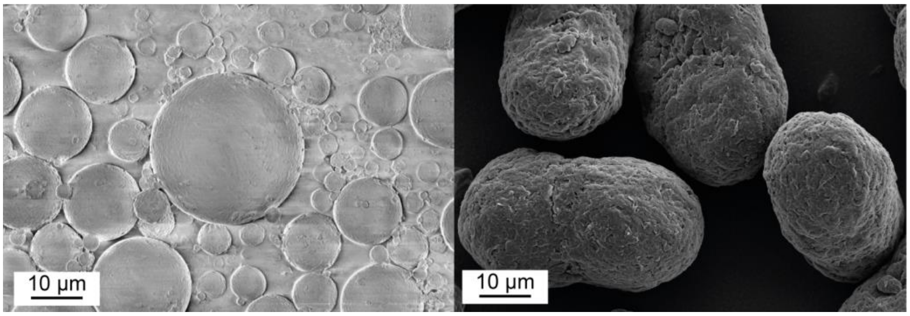

Fig. 2. left: polybutylene terephthalate PBT particles produced by cold wet grinding and additional rounding at the Collaborative Research Centre 814, right: commercial polyamide 12 (PA2200) laser melting material from EOS GmbH

One goal of the Collaborative Research Centre 814 is to create new, optimized particle systems for additive manufacturing of polymer components. Two alternative process routes are investigated to produce the precursor materials. Particle systems with particle sizes ranging from 2 to 50 µm and optimized flow and packing properties are produced using cold wet grinding [2, 3] and melt emulsification with integrated surface functionalization. In the case of cold wet grinding polymeric materials are ground in an agitator bead mill at a temperature below their glass transition. During melt emulsification, the polymer precursor is melted in a liquid non-solvent medium. After cooling of the emulsion, solidification of the polymer, and separation of the liquid phase, this process provides materials in powder form. Products from cold wet grinding must be rounded in an additional process step to improve flowability. In the case of melt emulsification spherical particles are obtained directly. Polybutylene terephthalate PBT powder, which was produced at the Collaborative Research Centre (see Fig. 2) was successfully manufactured by selective laser melting [4].

Furthermore the modification and functionalization of polymeric and metal powder in order to create new material systems or to improve specific material properties are focused in the CRC 814. In this case both physical and chemical process routes were investigated. The spheroidization of the grinding products belongs to the physical process route. Here, the ground particles are molten in a downer reactor [5]. Chemical vapor deposition (CVD), atomic-layer-deposition (ALD), and plasma activation are used to produce multi-material systems with novel material- and process related properties [6]. This is another process route that allows the manufacture of multi-material systems and the introduction of particle-scaled additives into the sintering process.

Additional to the production of new polymer powders the CRC 814 characterizes material properties with a focus on inter-particle interaction and thermal properties. Determining factors for beam melting processes are dense packing, powder flow, powder coating behaviour, melting and crystallisation properties of the polymer, melt rheology, and interface phenomena [7]. Melting experiments with spatially defined particle structures are performed to gain understanding of the beam melting process [8]. Calorimetric (e.g., high-speed DSC) methods are used and adapted to real process conditions to study the influence of thermal conditions [9]. The results of this part of the research project will contribute to a more in-depth understanding of the melting processes encountered.

Due to high temperatures in the building chamber and long process times during laser melting processes of polymers degradation of the polymeric material occurs. These degradation processes also decrease the reproducibility of the manufacturing process, resulting in inconsistent component properties. Consequently one goal of CRC 814, A4 is the systematic investigation of the time- and temperature dependent aging behaviour and to improve the performance and reproducibility of additive layer manufacturing for the individual series manufacturing of products and components. First of all polyamide 12 powder was stored under defined atmospheric and thermal condition to detected relevant aging mechanism [10]. Afterwards these results were used and combined with processing experiments to derive a time and temperature dependent aging model. This model allows the prediction of the aging state of the used material in dependency of processing time and temperature [11].

Part of the sub-project A5 is to investigate the manufacture of components from novel powders by selective laser melting of metal. These special powder systems will facilitate the flexible production of components with locally defined, specific material properties based on high- and maximum strength aluminum alloys using laser melting technologies [12]. Elemental powder mixtures with different particle sizes and particle size distributions are used. They will form alloys with a variety of structural properties during the laser melting process.

3.2. Processes

In area B "processes" a comprehensive understanding of the process was created. For this first test facility existing systems have been adapted to the demands of fundamental research. For example appropriate processing techniques have been built up for achieving demands of fundamental research. Especially certain, size reduced building chambers were manufactured. Consequently even very small amounts of individual powders (metals as well as polymers) can be processed. In addition, a unique user-programmable laser melting system has been constructed for the processing of polymeric powder systems. This system represents a novelty in the research community and opens up further new processing strategies due to its open software and hardware structure. For the production of multi-material components simultaneous exposure system was realized by means of micro-mirror-array-technology. In addition, a method for manufacturing large components based on a pre-formed sheet metal body was explored. Due to this technique additive manufactured functional elements can be implemented in the sheet metal body. Thus the functional density of the sheet metal bodies can be increased. Hence the flexibility of additive manufacturing is combined with the high production speed and efficiency of sheet metal forming processes. Furthermore individual measurement setups have been investigated for achieving a look insight the processes, especially the melting pools during laser treatment of a layer. Exemplary a thermographic and a high-speed camera system can be mentioned here. Based on the directly out of processes collected data, a correlation with investigated material behaviour is possible. Furthermore important input values for simulation models are provided, like shown in [13].

By using DEM-Simulation the sub-process of powder coating is simulated. Especially phenomena like packing densities as function of used coating tool (rake or roller) are simulated [14, 15]. Based on these numerical studies feedback for an optimal powder design (shape, size) as well as individual processing strategies can be derived. For example experiments for polymeric powder showed a correlation between part density and used coating tool as well as coating speeds, which might be the result of varying forces on the powder during the coating process [16 - 18]. In the following exposure process, varying strategies have been explored. For metals quasi-multi-beam writing strategies were focused, using an electron beam melting system, which is equipped with a high-speed camera system. Based on this setup, the melt pool behaviour could be investigated and transferred in simulation models, simulating the melt pool dynamics, temperatures and solidifications [19 - 21]. For polymer material systems different speeds of energy input (for a constant level of overall energy input) have been faced, due to the typical time and temperature dependent material behaviour of polymers. It could be shown, that for varying speed of energy input the applied heating rate in the polymer differs, resulting in a differently shaped melting pool [22, 23]. Due to these investigations it could be shown, that beneath absolute energy input also the speed of energy input is a limiting factor for the usable processing window of the investigated PA12-Material, which has to be taken into account in future processing strategies.

Beneath prior shown investigations of traditional beam melting processes new processes for manufacturing multi-material parts have been setup. First multi-material parts, out of different polymers, could be processed by using a two-beam-source melting system, equipped with a simultaneous powder coating system [24, 25]. Furthermore by electron beam melting functionalized sheet metal parts could be manufactured and investigated [26, 27]. Especially the connection between different materials was focused from metal as well as polymer point of view.

3.3. Components

In close cooperation of the project areas “Powder-/Materials” and “Processes”, with project area C “Components” explores, comprehensive strategies for the design, process-design and -modeling, and quality assurance in the additive processes.

Today, topological optimization methods are an integral part of the development cycles in the automotive and aerospace industries. These methods pursue the goal to minimize the amount of a given material distributed in the component while the resulting structure withstands a given load. During powder and beam based additive manufacturing, material properties undergo process-related, local fluctuations. This phenomenon is the focus in the course of the development of a novel process for the optimized design of additive manufactured components. In the first phase the researcher of the CRC assumes that optimization on the component level can be achieved by using process parameters to control component properties with sufficient precision [28]. In the further course of the project we will target robust design optimization considering material property variations that cannot be controlled.

The high temperatures and temperature gradients encountered during selective laser melting of polymers and metals or selective electron beam melting caused by the high energy imparted by the laser or electron beam may result in internal stresses and warpage of the component. Therefore the mail goal of the sub-project C3 is the modelling and simulating of the laser and electron beam melting process [29] in order to reduce warpage and stresses of the components. In order to macroscopically simulate the processes, the CRC developed a numerical tool based on a non-linear, thermo-mechanical finite element model that will be implemented with the help of *deal.II*, a software library specialized on finite element methods. The finite element mesh refines adaptively to allow for the precise determination of processes in the vicinity of the electron beam, which are of particular interest. The simulation results for temperatures and temperature gradients encountered during the process obtained so far are in good agreement with values obtained experimentally [13].

Process fluctuations in selective laser melting of plastics, may cause unacceptable decreases in quality. Component defects may include excessive dimensional and strength variations, which currently can be detected only after the process cycle is completed. Measuring/testing implemented into the process and subsequent process control based on the measuring results are necessary in order to significantly reduce these defects. A method for in-line incremental measurements after each built layer is developed during sub-project project C4 [30]. Goal of the project is the qualification of measuring and testing technologies and of strategies for incremental in-line inspection of additive manufacturing processes. Within the CRC a prototype of an optically measuring system is integrated into a selective laser melting device in order to derive process-specific monitoring techniques [31].

4. Area-spanning investigations

Within the workgroups of the CRC 814 the different results of single sub-projects are moderated and related to each other with the objective of the investigation of complex interdisciplinary questions.

In the workgroup “powder technology” basic and applied problems of powder technology were wrought. These include target adjusted analysis, such as a comparison of applied and scientific measurement methods for flowability (funnel vs. tensile tester) of a bulk material, or the pulverization of PBT-material meeting demands of fundamental research. Hence Polybutylene terephthalate PBT powder was produced and processed continuously in various sub-projects. For the processing of metal powders the workgroup defines requirements for a usable functionalization of titanium powders.

One important mission of the workgroup “metrology” is the comparison of various measurement principles referenced to special requirements of additive manufacturing processes and parts. For example the characterization of surface roughness of additive manufactured components was focused, comparing optical and tactile methods. Also performed measurements were compared to polymeric and metallic components. Consequently systematic measurement errors could be identified and a comparability between results of metal and polymer parts could be ensured. Nevertheless limitations of individual measurement technologies for the material system were discussed.

Major goal of workgroup “simulation” was the connection of different scales of additive manufacturing processes. On the one hand calculations done for single particles had to be referenced to simulations done for whole building chamber. The definition of input and output sources between different sub-projects was initiated and accomplished. Furthermore verification of simulations was performed in cooperation with processing sub-projects [13].

5. Conclusion

The CRC 814 combines various scientific disciplines in one research project. Beginning with the investigation of material systems, related processes are explored and transferred in simulation models. In the case of powder new polymeric as well as metal powders were produced and manufactured by powder and beam based additive manufacturing techniques. New additive processes were set up for example to generate polymeric multi-material-components and component assembles of transformed sheets with additive structures. Within the simulation the whole process chain from the material coating up to a multi-layer processes can be represented. Thus knowledge on different levels is created with the aim to qualify powder and beam based additive manufacturing for production of highly functionalized multi-material parts. Beneath the setup of unique processing and measurement techniques various models have been established and related to experiments.

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