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Identification of in-line defects and failures during Additive Manufacturing Powder Bed Fusion processes

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Abstract. Additive Manufacturing (AM) processes are enablers of new approaches in the field of production and design engineering, product design and business modelling. Beginning to view additive manufacturing in an industrial environment, reliable statements about the product quality are indispensable. Statements regarding compliance with geometric tolerances and exact quantifiable physical parameters, in terms of product certification are therefore imperative. The quality of the components must not only be sustainably secured but also reproducible at any time. Quality control and quality assurance are the prerequisite for highly customized unique parts, or even batch size 1 product, that can be produced by additive manufacturing as efficiently as conventional mass-produced parts. This paper will discuss an approach for the identification of in-line defects and failures during Additive Manufacturing Powder Bed Fusion processes using the example of the Selective Laser Sintering process.

1 Introduction

Additive Manufacturing (AM) processes are enablers of new approaches in the field of production and design engineering, product design and business modelling. The need for additive production is constantly increasing (see Fig. 1.), as the AM processes are the only ones which allow digital fabrication of products that simultaneously require: *functional integration* - means implementing as many technical functions as possible into as few parts as possible [1]; *complex geometries* – from free-form surfaces to weight-based topologies [2]; and *individualisation* - a strong personalization and adaptation to the customer`s needs being possible at any time.

Nowadays not only plastic and metal components are additively manufactured, but also function-integrating solutions for fibre-reinforced composites [3]. In the near future multiple materials will be used in one build process and even application-specific cavity structures and functionally gradient materials will be possible.

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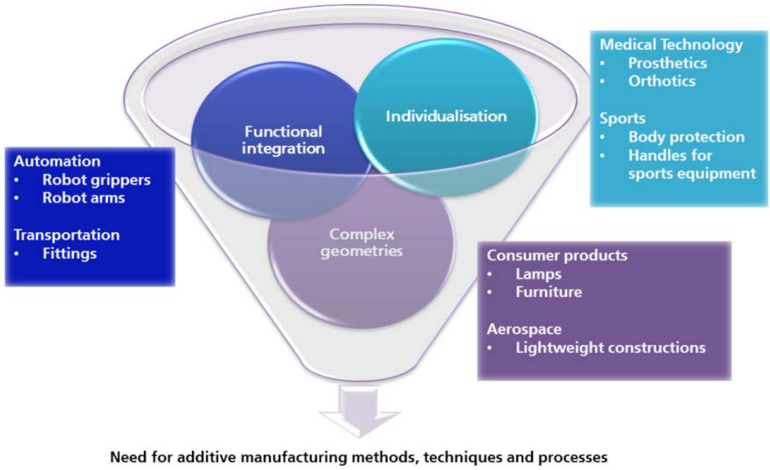

Fig. 1. Individualised products with complex geometries and integrated functionalities require an additive production.

Beginning to view additive manufacturing in an industrial environment, reliable statements about product quality are indispensable. Statements regarding compliance with geometric tolerances and exact quantifiable physical parameters, in terms of product certification are therefore imperative. The sooner these parameters can be obtained or even in-process influenced, the higher the efficiency of AM processes is. The quality of the components must not only be sustainably secured but also reproducible at any time.

Quality Control (QC) and Quality Assurance (QA), meaning the immediate product respectively process monitoring, are the prerequisite for highly customized unique parts, or even batch size 1 products, that can be additively produced as efficiently as conventional mass-produced parts.

Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) are for industrial contenders, ranging from the medical field to automotive and aerospace applications, the two most important AM Powder Bed Fusion (PBF) technologies. PBF is one of the seven categories of AM processes, as defined in ISO/ASTM 52900-15 [4].

The primary focus of research in measurements for real-time control of AM PBF has been associated with determining the geometry and the temperature profile of the heat affected zone, which is the area near and including the melt-pool that is directly affected by high local temperatures [5]. For the in-line quality monitoring the question, still without a comprehensive scientific answer, is: which are the overall effects of the influencing parameters (see Fig. 2.) on AM processes having an appearance during the manufacturing process itself? Only when these effects are clearly determined, the defects and failures during AM PBF processes can be accurately defined and used for the development of an overall in-line QC system followed by an in-situ optimization of PBF processes.

It is widely known that the relationships between the parameters in the PBF process are complex [5], a fact which hinders the development of in-line QC and in-process optimization systems. In this context the scope of this paper is to identify and determine the in-line defects and failures during AM PBF processes, using the example of the SLS process. The focus on especially this AM PBF process is driven by the fact that SLS is one of the main technology that can be used to produce functional parts, even for low series production.

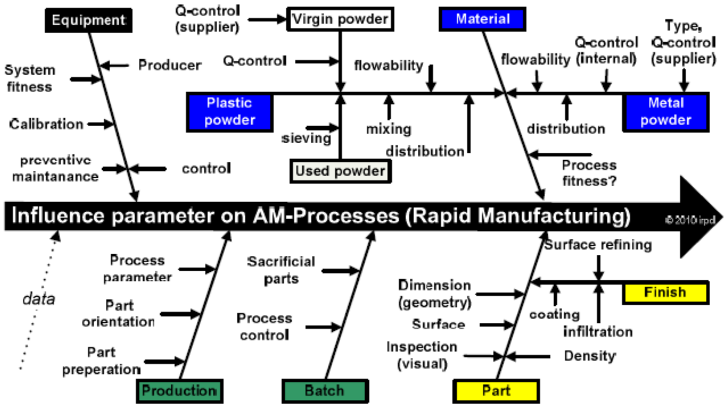

Fig. 2. AM PBF production chain - influencing parameters [6].

2 Identification and determination of in-line defects during the SLS manufacturing process

2.1 Quality management for additive manufacturing

An obstacle for a future industrial acceptance of AM is the fact that neither Quality Standards nor a generally accepted Quality Management (QM) Standard or System for the AM processes are nowadays available.

The quality of the manufactured parts and their designed functionality (e.g. grippers, see Fig. 3.) can be very easily impaired, taking into consideration the variety of the parameters that are influencing the AM process.

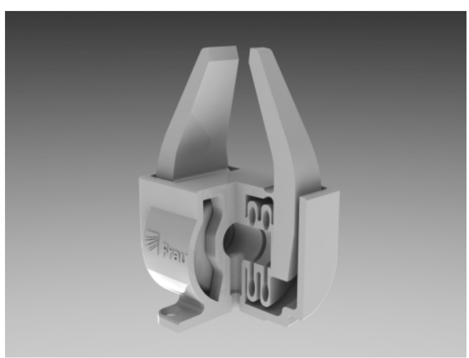

Fig. 3. 2-Finger angular gripper from Fraunhofer IPA.

Up to date preventing and/or detecting all defects and faults in PBF AM manufactured products is nearly impossible because the processes are influenced by numerous parameters, that can be summarized in four QM categories: *Equipment*, *Material*, *Production* including Batch and *Part* including Finish (see Fig. 2.) [6].

Starting from these QM categories, a comprehensive approach for the determination of the in-line defects and failures detectable during the manufacturing process was developed and implemented in order to set the premises for an overall in-line QC respectively for an in-process monitoring system for the SLS processes.

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2.2 In-line defects during the SLS manufacturing process

Due to a deductive approach based on a qualitative top-down Fault Tree Analysis, going through each QM category, respectively subcategory, the corresponding quality influencing factors and respectively their manufacturing effects have been identified. The in-process appearances of these effects are the in-line defects (see Fig. 4.) during the SLS process, defining the overall tasks for an in-line QC system and being elementary for a future in-situ process optimisation.

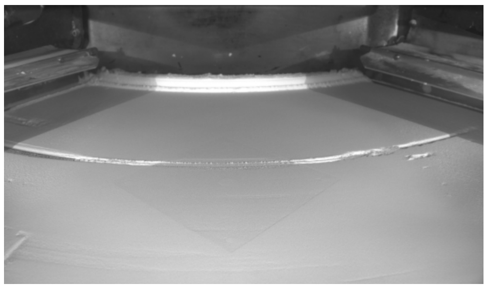

Fig. 4. Example of grave defects in the powder layer during the SLS manufacturing process: view of the powder layer after application [source: Fraunhofer IPA EOS FORMIGA P 100].

2.2.1 Equipment

Three QM subcategories were identified: uncleanness of the system, system fitness influenced by errors of system components and the system performance, influenced by inadequate functionality of the system (see Table 1). For example, taking into consideration the uncleanness of the system: one of the quality influencing factors in this case are the depositions on the laser window, which can directly influence the laser power respectively the elongation at break and the strength of the built part.

The in-process appearances of these are not only the deposits on the laser windows themselves but also geometrical distortions and even inappropriate layers' adhesion. These are the in-line defects respectively the tasks of the future in-line QC system.

Table 1. Equipment – in-line defects and failures as identified future tasks for an in-line QC system.

Quality Management aspects for AM		**Quality influencing factors**	**Effects of the factors**	**In-line defects and failures**
Equipment	Uncleanness of the system	deposits on laser window	low laser power, small elongation at break, low strength of the part	*inappropriate layers' adhesion, geometrical layer and part distortions, deposits on laser window*
		impurities	strength and even geometry of part impaired	*impurities in layer*
	System fitness influenced by errors of system components	laser and optical system	to low or to high laser power, small elongation at break, low strength of the part, thermal damage in case of too high laser power	*inappropriate layers' adhesion, geometrical layer and part distortions, melting of the edge zone depending on the geometry, porosity*
		temperature	geometry and	*inconstant*

Equipment		control	strength of part vitiated	*temperature*
		inert gas supply	burning of the layer	*melting of the part, black sintered*
		wear parts (e.g. seals, material supplier)	powder supplier damaged	*streaky, scaly, powder layer*
			tilted build platform	*tilted layer geometry*
			build platform got stuck or lost the height information because of defects of the stepper motor	*layers' overlapping, layers' sintering failed*
	System performance influenced by inadequate functionality of system	powder application performance	homogeneity of the generated powder layer affected	*inhomogeneity of the layer thickness*
			density variation of the powder layer	*density variation of the powder layer*
		Scaling	scaling factor variations	*geometrical deviations and distortions of the sintered layer*
		tolerances	inadequate tolerances	*geometrical deviations of the sintered layer*
		beam offset	inadequate layer sintering	*geometrical deviations and distortions of the sintered layer*
		low scan speed	high porosity and low density	*porosity, inhomogeneity*
		surface roughness	layer and part surface roughness variation	*layer and part surface roughness*

2.2.2 Feedstock

The feedstock is the bulk raw material supplied to the AM building process [4]. Two QM subcategories were identified: the virgin and the used powder. Exemplary, taking into consideration the virgin powder: the grain shape and its size distribution, as one of the quality influencing factors, are influencing the homogeneity of the applied powder layer and of the final part as well as the strength of the SLS manufactured object.

The in-process appearance of the effects of the quality influencing factors is the grain size. The quality influencing factors, their effects and the identified in-line defects and failures are presented in Table 2.

Table 2. Feedstock – in-line defects and failures as identified future tasks for an in-line QC system.

Quality Management aspects for AM		**Quality influencing factors**	**Effects of the factors**	**In-line defects and failures**
Feedstock	Virgin powder	grain shape and grain size distribution	inhomogeneity of the generated powder layer and final part, strength of the part impaired	*different grain sizes, grain shapes levels*

		thermal properties like melting point and recrystallization	inadequate layer sintering	*inconstant temperature on sintering point, inappropriate layers' adhesion*
		bulk density	affected processability	-
	Used powder	type and mesh size of sieve (preferred mesh 140 µm)	grain size variation, strength of the part vitiated	*different grain size, inhomogeneity of the powder layer*
		Melt Flow Index (MFI)	mechanical strength	-

2.2.3 Production

In this case also two QM subcategories were identified, namely: the part preparation and orientation as well as the process parameters during manufacturing (see Table 3). Also in this case, considering the atmosphere in the process chamber, as one of the quality influencing factors, the burning of the layer was deducted as effect of this factor.

The in-process appearance of these effects is the melting of the part respectively a "black sintered" layer.

Table 3. Production – in-line defects and failures as identified future tasks for an in-line QC system.

Quality Management aspects for AM		**Quality influencing factors**	**Effects of the factors**	**In-line defects and failures**
Production	Part preparation and orientation	resolution of the STL file	part accuracy affected	*high surface roughness*
		part orientation	inadequate sintering	*part and layer orientation failure*
	Process parameter during manufacturing	laser power	inadequate sintering	*inappropriate layers' adhesion, geometrical layer and part distortions, melting of the edge zone depending on the geometry, layer porosity*
		scan, sintering speed	inadequate sintering	*inconstant sintering speed*
		scan, sintering line	inadequate sintering	*scan line deviation*
		temperature profile	inadequate layer sintering	*inconstant temperature on sintering point, inappropriate layers' adhesion*
		layer thickness	part homogeneity affected	*variation of layer thickness, inhomogeneity*
		laser exposure style	-	-
Production	Process parameter during manufacturing	hatch distance	overlap area between two hatch lines	*inappropriate hatch distance, inappropriate layers' adhesion*
		atmosphere	burning of the layer	*melting of the part, black sintered*

		skywriting	melting of the edge zone is not correct	*skywriting length variations, melting of the edge zone, geometrical layer and part distortions*

2.2.4 Part

The QM subcategories, with respect to the Total Quality Management (TQM) of the part, are the part protocol and the quality check. For example, considering the recording of the entire product manufacturing process for each part produced, as one of the quality influencing factors, we deduct as an effect the fact that a part quality report is unaccounted for the end-user of the respective SLS part. If the SLS produced part has complex functionalities integrated, and not only then, a quality protocol of each layer respectively of the object as a whole is imperative. In this case the in-line task for a QC system is the recording of each and any quality part information in a protocol.

The quality influencing factors, their effects respectively the in-line tasks for a QC system are presented in Table 4.

Table 4. Part –identified future tasks for an in-line QC system.

Quality Management aspects for AM		**Quality influencing factors**	**Effects of the factors**	**In-line QC system tasks**
Part	Part protocol	recording the entire product manufacturing process for each part	no reproducibility and reliability is given	*collect any quality part information in a protocol*
	Perform quality check	incomprehensive quality control	part distortions, vitiated mechanical strength, etc.	*identification of all in-line defects and failures (see Table 1 to Table 3)*

2.2.5 Results

In Table 5 all in-line defects and failures, as future tasks for in-line QC and in-situ optimisation of SLS processes, are summed up in connection with the quality influencing factors.

These results will be the basis for correction and/or mitigation of the failures on the SLS processes with respect to the quality aspects. Therefore a systematic, rigorous Design of Experiments (DoE) approach will be implemented in order to ensure the generation of valid conclusions for the ranking of the severity and probability of the quality influencing factors, respectively of the deducted in-line defects and failures.

Table 5. In-line defects and failures during AM PBF processes using the example of SLS.

Quality influencing factors	**In-line defects and failures during the SLS process**
deposits on laser window	*inappropriate layers' adhesion, geometrical layer and part distortions, deposits on laser window*
impurities	*impurities in layer*
laser and optical system	*inappropriate layers' adhesion, geometrical layer and part distortions, melting of the edge zone depending on the geometry, porosity*

temperature control	*inconstant temperature*
inert gas supply	*melting of the part, black sintered*
wear parts (e.g. seals, material supplier)	*streaky, scaly powder layer*
	tilted layer geometry
	layers overlapping, layers sintering failed
powder application performance	*inhomogeneity of the layer thickness*
	density variation of the powder layer
scaling	*geometrical deviations and distortions of the sintered layer*
tolerances	*geometrical deviations of the sintered layer*
beam offset	*geometrical deviations and distortions of the sintered layer*
low scan speed	*porosity, inhomogeneity*
surface roughness	*layer and part surface roughness*
grain shape and grain size distribution	*different grain sizes, grain shapes levels*
thermal properties like melting point and recrystallization	*inconstant temperature on sintering point, inappropriate layers' adhesion*
type and mesh size of sieve	*different grain size, inhomogeneity of the powder layer*
resolution of STL file	*high surface roughness*
part orientation	*part and layer orientation failure*
laser power	*inappropriate layers' adhesion, geometrical layer and part distortions, melting of the edge zone depending on the geometry, layer porosity*
scan, sintering speed	*inconstant sintering speed*
scan, sintering line	*scan line deviation*
temperature profile	*inconstant temperature on sintering point, inappropriate layers' adhesion*
layer thickness	*variation of layer thickness , inhomogeneity*
hatch distance	*inappropriate hatch distance, inappropriate layers' adhesion*
atmosphere	*melting of the part, black sintered*
skywriting	*skywriting length variations, melting of the edge zone, geometrical layer and part distortions*

3 Conclusions

This paper presents an approach to identify the in-line defects and failures during Additive Manufacturing Powder Bed Fusion processes using the example of SLS.

The obtained results, having as objective to locate risks and thus to assure the quality of the final SLS manufactured product, will merge in the development of a production accompanying QC system applied in order to monitor and control in real-time SLS processes. This in-line QC system will not only cover, as up to date, the in-process measurements of surface temperature, residual stress and geometry [5], but also all other in-process appearances of quality influencing factors for SLS processes. At the same time the results are the background for an in-situ optimisation system.

Future work will be a DoE for a SLS production facility in order to rank the severity and probability of the quality influencing factors, respectively of the in-line QC and in-situ optimisation system tasks. An action plan to solve the ranked tasks, in form of a hardware and software platform will be completed.

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References

1. J. Breuninger, R. Becker, A. Wolf, S. Rommel, A. Verl, *Generative Fertigung mit Kunststoffen: Konzeption und Konstruktion für Selektives Lasersintern [Additive Manufacturing withplastics: design andconstructionforSelective Laser Sintering]* (Springer Vieweg, 2012)
2. R. Becker, A. Grzesiak, A. Henning, Assem. Autom. **25**, 262-266 (2005)
3. R. Geiger, S. Rommel, J. Burkhardt, T. Bauernhansl,wt-online **3**, 169-174 (2016)
4. ISO/ASTM 52900-15, *Standard Terminology for Additive Manufacturing – General Principles – Terminology*, ASTM International (West Conshohocken, PA, 2015)
5. M. Mani, B. Lane, A. Donmez, et al., *Measurement Science Needs for Real-time Control of Additive Manufacturing Powder Bed Fusion Processes* (NIST Interagency/Internal Report-NISTIR 8036, 2015)
6. M. Schmid, G. Levy, DDMC (2012)