Quality Management and Estimation of Quality Costs for Additive Manufacturing with SLS

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Abstract

Selective Laser Sintering (SLS) is close to become a production technique for functional parts (Additive Manufacturing). One big difficulty remaining and to be solved in the near future is the establishment of a broadly accepted quality system and standards with acceptable costs. The contribution presents a general approach to develop an adequate Q-system for SLS and provide a cost assessment as well. Every particular phase in the SLS production was analysed in this work and appropriate actions to achieve and maintain a high Q-level are proposed. This analysis enables the assessment of the increase in component cost for different quantities of parts. For fully loaded machines, the single part price increase is acceptable and in the low percentage range.

A further considered point is the effort regarding material analysis before and during the processing. Furthermore, the finishing costs for part are also taken into account. This comprehensive approach integrates the most important quality steps of Additive Manufacturing for SLS and SLM and gives a prediction of costs for different Q-actions and the part costs add-on.

Introduction

Additive manufacturing (AM) is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining. Selective Laser Sintering and -Melting (SLS and SLM) of plastic and metal powders are part of these 'layer by layer' based additive production techniques, which are considered as the next industrial revolution [1,2]. Solidifying powders with laser radiation by means of digital data opens countless options for production of individualized parts with great freedom in complexity [3].

One drawback for these future dedicated technologies is the lack of a common quality understanding. To date there do not exist neither Standards for AM-process and -materials nor a generally accepted 'Quality Management (QM)' System. This hurdle for a prospective industrial acceptance of AM was recognized and activities by ASTM and ISO towards worldwide standards started concurrently and recently. Both committees, ISO TC 261 and ASTM F42, are still in basic discussions. We can expect comprehensive AM-Standards only some years ahead. In addition, the German association of engineers VDI prepared a recommendation for AM-processing (VDI 3405), which is in draft status actually.

Some approaches described in literature aim to improve processes quality aspects or even set up quality management system for AM in literature [4-8]. The circumstances that standardization activities are in its infancy and only few articles were published so far regarding this topic emphasize the necessity to widen the activities as to achieve a comprehensive Quality Management System for Additive Manufacturing. It is vital for the AM future.

Quality Management for Additive Manufacturing

The following introduced Quality Management (QM) System for AM, especially SLS, was developed within a research project supported by the European Commission. The project deals with all aspects of a future dedicated model for production of spare parts (project acronym: 'DirectSpare' [9]). The development of the QM-System was embedded in the elaboration of different relevant business models [10]. Within the framework of the entire model questions regarding process model, data management, data safety, quality of process, standards, certifications and some others issues are included. In order to have a clear demarcation to other aspects, the QM system described in the following is strongly focused on the manufacturing process. It concerns features of the production itself. Questions of e.g. quality of data files and process or business model are not subject of this report.

As a first step of this work, the process chain of AM was analyzed thoroughly regarding the main influence parameter. Along the process chain of SLS/SLM, five aspects are of high impact: *'Equipment', 'Material', 'Production', 'Batch'* and *'Part'* connected with *'Finishing'*. Especially in case of material it must be distinguished between polymer and metal powder, as plastic powder will usually not be used as delivered but recycled mixed and sieved by any SLS service bureau under own responsibility. Influence parameter and important aspects linked to any of these main aspects of the process chain are specified as well. All is summarized in an Ishikawa diagram as an outcome of the evaluation (see Figure 1).

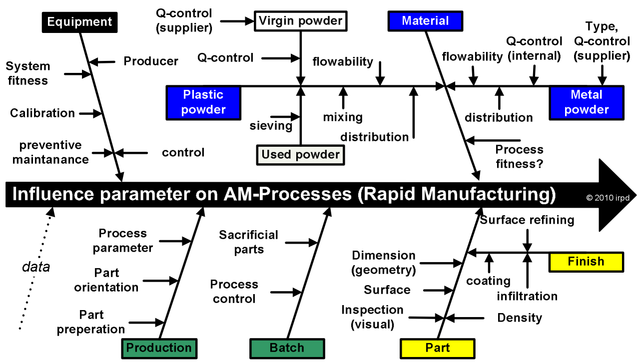

Figure 1: Parameter of production chain AM processes

The complexity of AM processes is indicated in Figure 1 and the scheme was used in the project to set up a questionnaire with Q-relevant questions. This Q-questionnaire was submitted to the project partners. Most of the questions are prepared as multiple-choice options but also comments could be given to any question. The Q-questionnaire turned out to be a valuable instrument for gaining comprehensive input to any of the process regions. The following paragraphs summarize the findings to the different aspects. It is presented along the process chain depicted in Figure 1. Any branch of the Ishikawa diagram is described individually. As a general structure the basic responsibility for any aspect is defined primary.

Equipment

The equipment fitness and performance and all the connected aspects regarding production system are under the responsibility of the part producer ('service bureau').

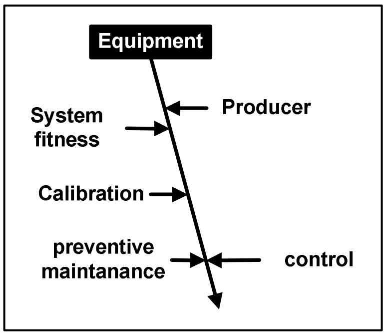

Figure 2: Q-elements of Equipment

The following Quality activities are recommended in order to fulfill basic obligations:

Conduct a logbook for any production equipment (SLS, SLM) and perform the following control and maintenance activities and document them (logbook):

- Daily: dust cleaning, remove deposits on laser window and adhere to instruction manual;
- For *system fitness* execute a periodical full service (preferably every three month) and check of laser and optical system, temperature control, inert gas supply, replacement of wear parts (filter, scraper…)

It is recommended to outsource the service to specialized and skilled people from equipment supplier or distinct service companies.

In order to verify the *system performance* a specially designed reference part (e.g. recommended by VDI 3404) must be built every month as benchmark. This retain sample is analyzed regarding: weight (density), scaling check, dimensions, tolerances, beam offset, surface roughness (different orientation) and should be stored for the whole production period of the machine.

Table 1 summarizes the recommended Q-activities for the Equipment at a glance. Some further comments are given and the frequency of actions is defined as well.

Plastic Powder

In case of Q-control of plastic powders used in SLS process, two aspects are important as cited already earlier. On the one hand, the quality of the new (virgin) powder must be verified and on the other hand at least as important the quality of the mixed powder from virgin and already used powder as well. Figure 3 summarizes the Q-elements for plastic powder. The material supplier or powder configurator must expectedly guarantee the quality of virgin SLS material respectively. However if and how certain intake control of the powder receiver should be performed or not will not be answered currently uniform. A check of thermal properties by DSC measurement (DSC = Differential Scanning Calorimetry) seems to be reasonable according to the authors. A discussion of add-on costs concerning this action is discussed in Q-costs section below.

Regarding the new (virgin) SLS powder the following material data should be supplied at least to the customer: Production identification (e.g. Charge), Powder particle size distribution ($d_{10}/d_{50}/d_{90}$), thermal properties like melting point (T_m) and recrystallization (T_c), bulk density.

Further data like BET surface ((Brunauer, Emmett and Teller, 1938). molecular weight distribution (M_w, M_n) and flowability as the quotient of bulk and tap volume (Hausner Ratio) would be preferable. The Q-activities for virgin SLS powder are summarized in Table 2.

Table 1: Recommended Q-activities Equipment/ System

Action	Documentation	Comments	F*	R*
conduct equipment logbook and machine checklist (eventually integrated in e-RP)	any relevant Q-activity (see below) and any machine problem and maintenance	conduct a logbook/checklist for every production equipment;	---	The system fitness and performance and all connected aspects regarding equipment are under the responsibility of the part producer
Cleanliness: maintain constant cleaning; sustain overall cleanness; check clarity of laser window (after every build);	any activity must be confirmed at a machine checklist	for cleaning activities see also specification of equipment supplier	daily	
System fitness: Periodical complete machine service (preferably every three month - service contract)	check of laser and optical system, temperature control, inert gas supply, replacement of wear parts (filter, scraper,…);	Service should be performed by special skilled people (e.g. machine supplier service or service companies;	quaterly	
System performance: A specially designed reference part (benchmark) must be built and analysed	benchmark part to be analysed regarding: - Weight (density) - Scaling - Tolerances - Beam offset - Surface roughness (R_a, R_z and different orientation) ??	producer without analytical equipment should have a contract with a service laboratory; Retain samples must be stored for the whole production period of the machine.	monthly	

* = F =Frequency; R = Responsibility

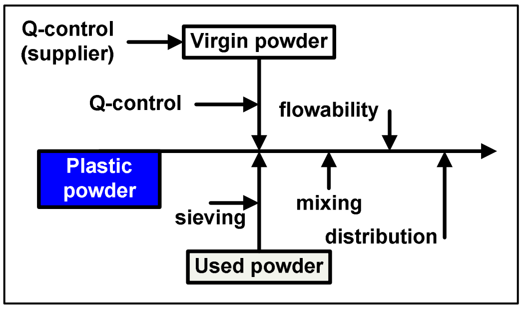

Figure 3: Q-elements of plastic powder

Table 2: Recommended Q-activities of plastic powder

Action	Documentation	Comments	F*	R**
conduct a material logbook	collect any material documentation	AM producers with a higher Q-level should control delivered powder by DSC measurement at least (check Tm, Tc); Preferebly further data are disclosed by supplier: - molec. weight distriburtion (Mw, Mn) - residual monomer content - BET surface - flowability (e.g. Hausner Ratio);	---	Suitable quality of SLS material must be guaranteed from material supplier (powder confectioner);
check delivered material data sheet regarding guaranteed value (according to agreement with material supplier)	Following data to be given at least for virgin batches: Production identification (e.g. chargen number) - Bulk density - Melt. point (T_m) - Recrystallization (T_c) - Powder distrib. (e.g. d10 / d50 / d90)		as needed	

*F =Frequency; **R = Responsibility

In contradiction to the new (virgin) plastic powders, the responsibility for the quality of the refreshed production material is assigned to the production facility ('service bureau'). Every production powder batch must be controlled and documented regarding:

- Material blending (amount of fresh and used material, mixing time and technique)
- Sieving (type and mesh size of sieve)

Preferably each production batch undergo a MFI measurement (MFI = Melt Flow Index) to assure a certain quality range. MFI turned out to be a valuable device to check SLS powders with reasonable effort. However, it has to be underlined that so far no common recommendation could be agreed for a required MFI value. It must be specified for any individual production equipment and material. Table 3 indicates the recommended Q-activities for the refreshed SLS production powder along with further comments, responsibility and frequency of action.

Table 3: Recommended Q-activities of refreshed powder

Action	Documentation	Comments	F*	R**
material blending: 3D: virgin / overflow / part cake material EOS: virgin / used material	amount of fresh and used material, mixing time and technique	control and documentation for every production batch (material logbook); refresh rate see also specification of equipment supplier	every batch	The quality of the (refreshed) production material must be guaranteed by the producer
sieving	type and mesh size of sieve	see above; prefered mesh size 140 µm		
optional: check quality by MFI measurements	MFI value for every batch	MFI value support quality assurance but need to be adjusted to any specific system and material; no common recommendation for target MFI definable	weekly	

*F =Frequency; **R = Responsibility

Metal Powder

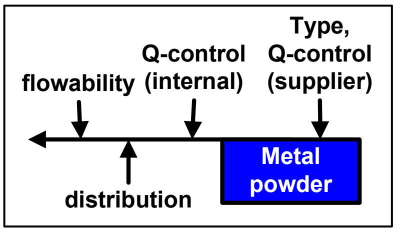

Figure 4: Q-elements of metal powder

In case of metal powders (see Figure 4) the quality check of powder quality is less complex as for plastic powder, because metal powders are usually used in SLM processing as delivered and no significant aging is recognized. However, the part producer ('service bureau') is responsible for the quality of the used powder and the following data should be documented for quality reasons: production identification (e.g. Charge), Powder particle size distribution (d10/d50/d90), flowability (if accessible), applied sieving;

Table 4 summarizes the recommended Q-activities for metal powders together with comments, responsibility and frequency of action.

Table 4: Recommended Q-activities of metal powders

Action	Documentation	Comments	F*	R**
conduct a material logbook	collect any material documentation	no particular Q-check of metal material	---	The quality of fresh metal powder must be guaranteed by the material supplier;
check delivered material data sheet regarding guaranteed value (according to agreement with material supplier)	Following data to be given at least for new batch: - Production identification (e.g. chargen number) - Powder distribution (e.g. d10 / d50 / d90)	Preferebly further data are disclosed by supplier: - chemical composition - REM / microscope picture - powder density	as needed	
sieving	type and mesh size of sieve	prefered mesh size: 48 µm	every batch	

*F =Frequency; **R = Responsibility

Production and batch

The production process and every produced batch are expectedly in the responsibility of the production facility. Figure 5 summarizes the basic Q-elements of these two branches of Ishikawa diagram of the entire process.

For quality, reasons assessment relevant production and batch parameter should retraceable.

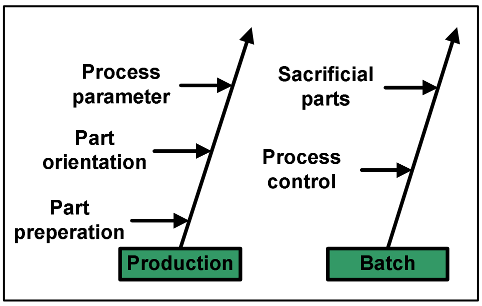

Figure 5: Q-elements of production / batch

A list of corresponding minimal data to be controlled and stored is specified in Table 5. An appropriate computer database and program should preferably contribute to the automatic recording of these data. *Remark:* A frequently discussed co-production of special sacrificial test specimen with any batch (e.g. for tensile test) is neglected for this quality model for cost reasons. Furthermore regular service bureaus have no options to analyse all the desired information regarding mechanical properties.

Table 5: Recommended Q-action of production and batch

Action	Documentation	Comments	F*	R**
record relevant production/batch parameter for every single part	part orientation within build; build parameter: laser power, scan spacing, temperature profile, scan strategy, layer thickness, laser exposure style, scan speed, hatch distance scan vector length, atmosphere	the recording and storing of these data should be preferably realised with specialized production software; e.g. eRP-System of Materialise or EOSTAT of EOS;	daily	The part production process is under the responsibility of the part producer;
comment: no standardised production of test bars for every build		production of special test bars for every build is to much effort and costs as well	---	

*F =Frequency; **R = Responsibility

Part and Finish

The Q-elements of part and finishing is depicted in Figure 6. The final part quality and the congruence of parts with initial order are under the responsibility of the part producer. A quality check and documentation on every single part includes optical inspection & dimension check, surface control (roughness) and weight (density). Furthermore, a comparison to order specification regarding ordered quantity, on time delivery, special requirements and preassembly is to be performed by the producer.

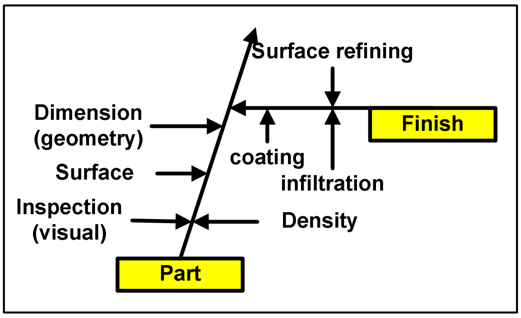

Figure 6: Q-elements of part and finishing

The final finishing of parts is under the responsibility of the 'service bureau' as well. Activities necessary and recorded to describe the quality of part finishing may be the following: infiltration (which infiltrate), surface optimization (vibratory grinding), coating (e.g. colour). Table 6 summarizes the recommended Q-activities for part and finishing with responsibility and frequency of action.

The Q-elements and activities described above aim to achieve a higher Q-level in production of AM parts. However, it means as well an increase of costs of production cost and final parts. In order to estimate the influence of Q-activities on costs a common assessment of cost rise are specified subsequently.

Table 6: Recommended Q-activities of part and finishing

Action	Documentation	Comments	F*	R**
conduct a part protocol	collect any part specification		---	The final part quality and the desired finishing is under the responsibility of the part producer;
perform quality check (qualitative)	- optical inspection & dimension check - surface control (roughness) - weight (density)		as needed	
check comparison to order specification	- part quantity - on time delivery - special requirements - pre-assambly			
perform defined finishing	- infiltration (which infiltrate) - coating (e.g. colour) - surface optimization (vibratory grinding)			

*F =Frequency; **R = Responsibility

Quality Costs

Setting up a Q-Management-System for Additive Manufacturing means to have at least a coarse estimation of the additional Quality costs in total and their influence on part price.

The following described cost model is calculated for different near to praxis production loads as following: half-loaded SLS machine, full loaded SLS machine, two and four SLS machines fully loaded.

Another important point is whether a 'service bureau' decides to perform material analysis or not in case of plastics (DSC, MFI; see section '*Plastic powder*'); this means an extra investment in equipment and measurements. Moreover the finishing of parts could have a significant influence on part prices. If automatic finishing is necessary (e.g. vibratory grinding) a further investment is required but an extensive effort of hand finishing could be avoided. All further calculations are made regarding the following assumptions:

- SLS production machine (newest generation).
- Turnover for a fully loaded machine:
  - 80 builds/Ann with
  - 50 parts/build = 4000 parts/Ann;
  - average part price 200€
- Fixed Q-costs:
  - analytical equipment (DSC, MFI);
  - equipment for vibratory grinding
- Flexible Q-costs:
  - quarterly equipment service;
  - monthly benchmark with analysis (retain sample)
  - no finishing,
  - handmade or automatic finishing;

Table 7 shows an example for such a calculation. It is considered 1 SLS machine producing 4000 parts a year for a medium part price of 200 €. Furthermore all analytical Q-activities (DSC/MFI) will be performed but it is distinguished between automatic and handmade finishing.

The last five lines of Table 7 indicate the calculated Q-costs. The overall amount of costs of Q-activities is for this example 16% and 12 % respectively. This means a reasonable amount of costs for Q-activities.

Table 7: Q-cost calculation for 1 SLS machine with analytical control of plastic powder

With material analysis	1 machine (4000 parts/year; average part price 200€)							
	handmade finishing				automatic finishing			
	fixed	flexible costs			fixed	flexible costs		
	k€	lot	50 €/h	k€/a	k€	lot	50 €/h	k€/a
Equipment (Performance & Fitness)								
Regular performance check (maintenance contract 'regular')				35				35
Monthly Benchmark (Production & Evaluation)		12	8	4,8		12	8	4,8
Material								
Analytical Equipment (DSC, MFI)	50				50			
consumables				5				5
Material control (DSC/MFI)		80	2	8		80	2	8
Production & Batch								
Build setup & process control		80	1	4		80	1	4
Part & Finish								
Final Inspection		4000	0.1	20		4000	0.1	20
Post processing (assump.: half of parts to be finished)		2000	0.5	50		2000	0.05	5
Machine for vibratory grinding					50			
consumables (vibratory grinding)								5
sum fixed costs - depreciation (10 y)	50			5	100			10
Q-costs per anno				131,8				96.8
Parts		4000				4000		
Q-costs €/part				33				24
Estimated turnover per anno				800				800
Q-cost percentage per anno				16%				12%

Q-costs as shown in Table 7 was similarly calculated for other cases of machine configuration (half-loaded machine, 2 and 4 SLS equipment) but detail results are not presented here. However the Q-costs per anno of these cases can be compared to each other and the cost analysis reveal interesting details. E.g., the influence of different finishing or analytical exertions is predictable.

Table 8 depicts the Q-cost results for the case without material analyses of introduced powder but for different finishing options. It can be recognized that in case of automatic finishing a costs decline around 5 % per part for any machine configuration resulted. An investment in automatic finishing for high-end parts seems to be reasonable. Table 9 represents the comparison of Q-costs for automatic finishing with and without material analyses. Obviously the Q-cost reduction is low (around 2%) with omitting material analyses. This means that an investment in analytical equipment is a recommended asset as the influence on part prices is just marginal.

Moreover, it can be seen in Table 8 and 9 that the 'Q-cost percentage/anno' is always in the region between 10% - 20%. This amount of costs must be calculated for the implementation of the presented Q-model.

Table 8: Q-costs for different finishing options

		handmade finish	automatic finish	
1 machine half	Q-costs/anno	88'300	73'300	
	Parts	2000	2000	
	Q-costs/part (€)	44.2	36.7	
	Estimated turnover/anno (€)	400'000	400'000	
	Q-cost percentage/anno	22%	18%	- 4%
1 machine full	Q-costs/anno	131'800	96'800	
	Parts	4000	4000	
	Q-costs/part (€)	33.0	24.2	
	Estimated turnover/anno (€)	800'000	800'000	
	Q-cost percentage/anno	16%	12%	- 4%
2 machine	Q-costs/anno	241'100	157'100	
	Parts	8000	8000	
	Q-costs/part (€)	30.1	19.6	
	Estimated turnover/anno (€)	1'600'000	1'600'000	
	Q-cost percentage/anno	15%	10%	- 5%
4 machine	Q-costs/anno	446'200	269'200	
	Parts	16000	16000	
	Q-costs/part (€)	27.9	16.8	
	Estimated turnover/anno (€)	3'200'000	3'200'000	
	Q-cost percentage/anno	14%	8%	- 6%

Table 9: Q-costs with and without SLS powder analysis

		with analyses	without analyses	
1 machine half	Q-costs/anno	88'300	76'800	
	Parts	2000	2000	
	Q-costs/part (€)	44.2	38.4	
	Estimated turnover/anno (€)	400'000	400'000	
	Q-cost percentage/anno	22%	19%	- 3%
1 machine full	Q-costs/anno	131'800	113'800	
	Parts	4000	4000	
	Q-costs/part (€)	33.0	28.5	
	Estimated turnover/anno (€)	800'000	800'000	
	Q-cost percentage/anno	16%	14%	- 2%
2 machine	Q-costs/anno	241'100	215'100	
	Parts	8000	8000	
	Q-costs/part (€)	30.1	26.9	
	Estimated turnover/anno (€)	1'600'000	1'600'000	
	Q-cost percentage/anno	15%	13%	- 2%
4 machine	Q-costs/anno	446'200	404'200	
	Parts	16000	16000	
	Q-costs/part (€)	27.9	25.3	
	Estimated turnover/anno (€)	3'200'000	3'200'000	
	Q-cost percentage/anno	14%	13%	- 1%

Conclusions

The paper presents the development and several Q-elements of a comprehensive QM-System for Additive Manufacturing. The described model is strongly focused to the manufacturing process itself. It is integrated with all features of the production: machine, material, production parameter, part and finishing. For all these topics recommendation are given for selecting reasonable Q-activities, their documentation and replication frequency.

In the second part of the work the costs of such Q-activities was modeled for several different configurations of machinery and different analysis and finishing options calculations was performed. It turned out quite obviously that the total amount of Q-costs is around 10% - 20% of total turnover and automatic finishing (vibratory grinding) is a reasonable option for cost reduction where applicable. Eventual scrap avoiding a QM system was not considered.

Acknowledgments

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