Development of an Additive Manufacturing Quality System **for Gas Turbine Engine Part Production**

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Introduction

Selective laser melting (SLM) is a powder bed fusion additive manufacturing (AM) process which occurs at a high metal melting temperature. High local temperature gradients and brief cooling effects can cause residual stresses and part deformation during 3d printing, the consequences of which can be additional surface treatment and reduced productivity for the process. To understand how to control the formation of AM residual stresses and part form deformation, a reliable method to investigate influences between technological parameters and quality behaviours is required. There are basic physical mechanisms of the selective laser melting process that can lead to part distortion and cracking: high temperature gradients, high viscosity and surface tension of the molten powder zone, un-melted powder and oxidized particles.

The following variables of the SLM process can be established as the most important:

1. Powder, composition, size distribution, shape, and thickness of the melting layer;
2. Laser, power, spot size, beam spatial distribution, scanning velocity and protective gas atmosphere; and
3. Strategy of additive manufacturing

The main target of our research was to find and control the optimum SLM process parameters to minimize printed part roughness, its residual stresses and part deformations. An SLM quality system for gas turbine engine parts production should be based on an interaction model of the technological factors affecting the quality of the final fabricated parts.

There are three main methods for predicting the temperature distribution and residual stress during the SLM process:

1. Simulation methods,
2. Experimental work, and
3. Combined simulation and experimental approach

Since it is difficult to predict part distortion in micro detail due to enormous computational resources being required, a SLM process for a practical part can be divided into three scales; micro scale, meso scale and macro scale. With this type of approach, the temperature history and residual stress fields during the SLM process can be predicted. Thermal information has to be transferred through micro scale laser scanning, meso scale layer hatching, and macro scale additive part build-up.

Description of our SLM Model

The laboratory of additive technology at Samara National Research University developed a model of influences on the SLM process parameters of quality by way of an Ishikawa diagram. The quality of the final additive manufactured part can be decided by powder properties, process parameters, SLM

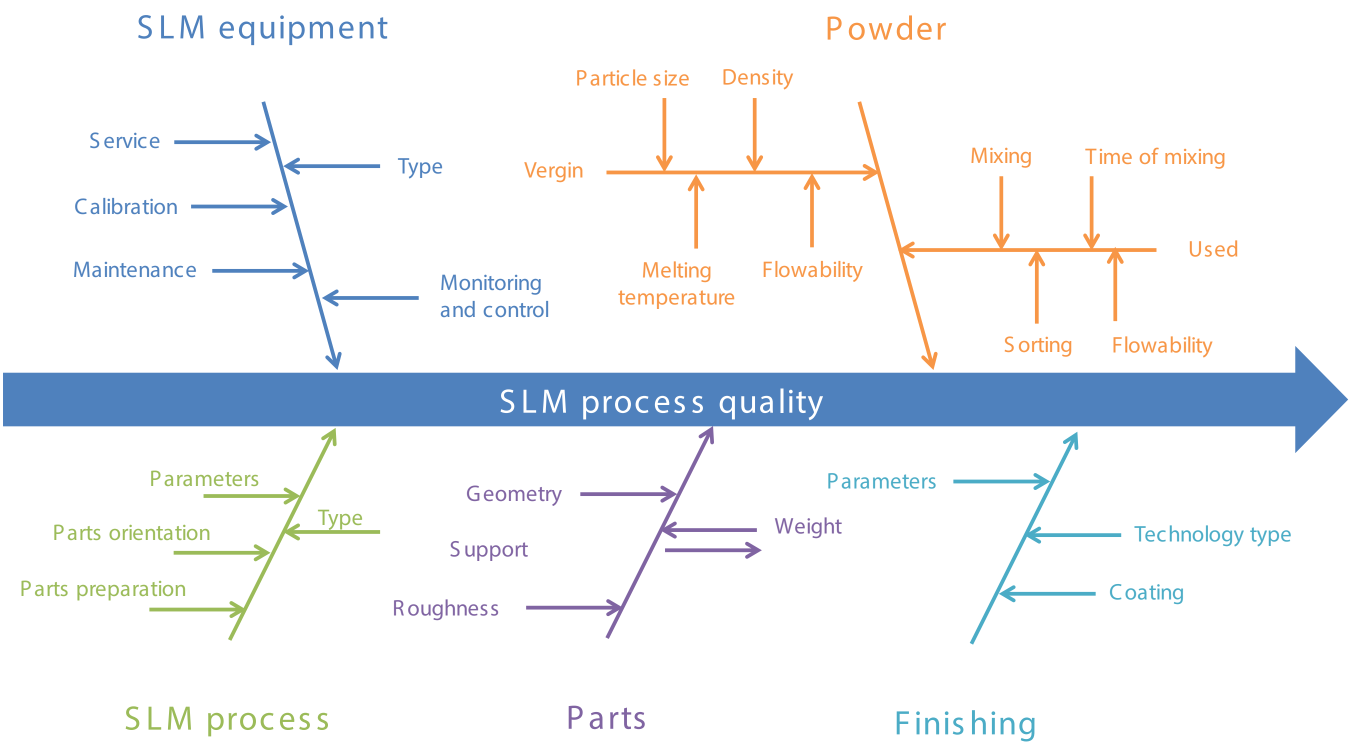

Figure 1. Ishikawa diagram of a SLM process' quality

equipment characteristics, finishing and detail behaviours as shown in Figure 1.

SLM equipment characteristics are determined by the type of 3d printer, the monitoring system, kind of technologies used, and its frequency of service and maintenance. In order to ensure technological accuracy, it is recommended to calibrate the production system and to build in every month test samples as the benchmark for complex shapes. Then it is necessary to check weight (density), dimensions, tolerances, and surface roughness under different part orientations. Quality maintenance requires keeping the equipment's daybook rigorously where all actions are recorded: powder changing, cleaning, stopping, optic system controlling, and parts replacement. Powder analysis includes understanding of the particle size distribution and particle shape using scanning electron microscope. Furthermore, it is necessary to evaluate powder 'flowability' and its apparent density. A SLM quality system should therefore include registration of the qualitative and quantitative parameters of powders especially the proportion of mixed powders. In addition, the main material quality parameter is the rate of sieved and reused powder in a subsequent process powder.

It is clear that an additive part quality is therefore dependent on SLM process parameters which should be controlled and managed. In order to determine the optimal AM built parameters with the aspired objectives and technical requirements, there is a need to consider many factors, such as cost, time, part quality, batch quantity all together. For simplifying this task, we developed a database of SLM technological parameters for domestic powders: aluminium, titanium, heat resistant steel, stainless steel. We produced this database in the PDM system, Teamcenter Manufacturing. The input technological parameters were all the influences on part quality: scan speed and laser power, the powder layer thickness, the hatching distance, the hatching angle.

Development of the SLM Quality System

In our study (reference 1), an effort to better understand the factors influencing part quality resulted in us developing an evaluation method. Technological parameters were divided into two types: those controlled by the operator of the additive machine (inputs) and those defined by the final part's functional use (limiting conditions).

The input SLM parameters were:

1. Gas atmosphere concentration (percentage of oxygen);
2. Powder layer thickness; and
3. Set of 3d printer process conditions: scan speed, laser power, hatching.

The limiting SLM conditions were:

1. Powder behaviours,
2. Geometry accuracy, and
3. Powder grain size.

The input parameters influenced the SLM process by the way of the layer thickness increasing effort on the bed fusion while the density of melting material is decreasing. Another example of the input parameters' influence is if we increase the oxygen concentration in the building camera a melting material becomes more crack-sensitive. We therefore proposed to use a SLM

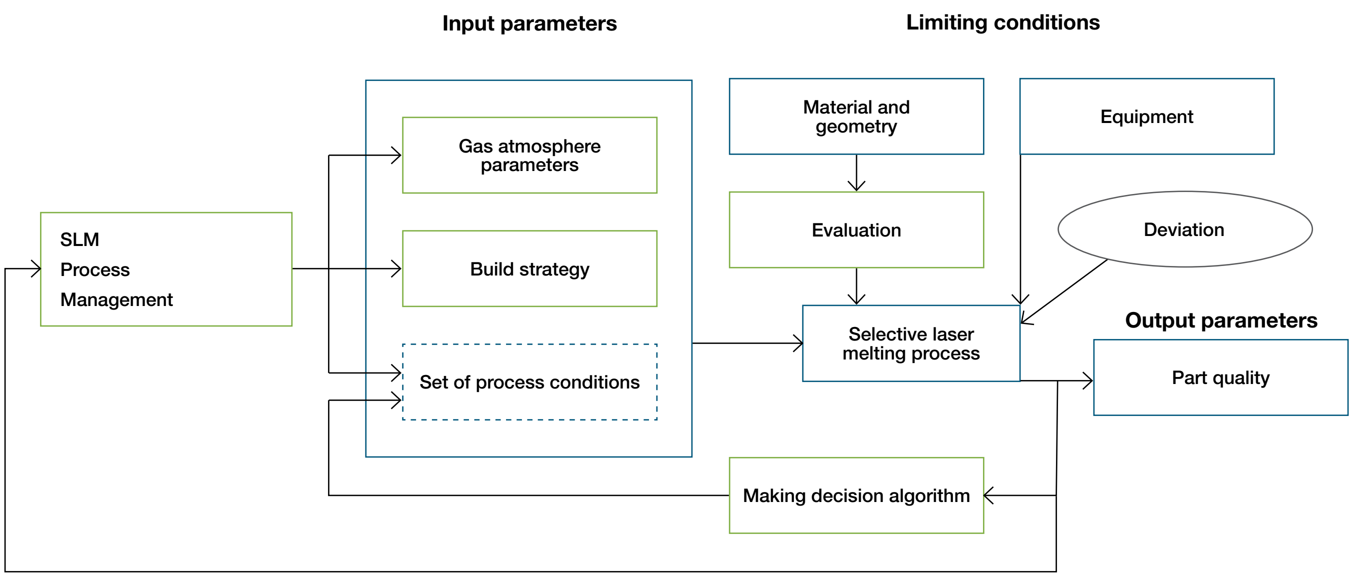

Figure 2. Schematic of the SLM quality system

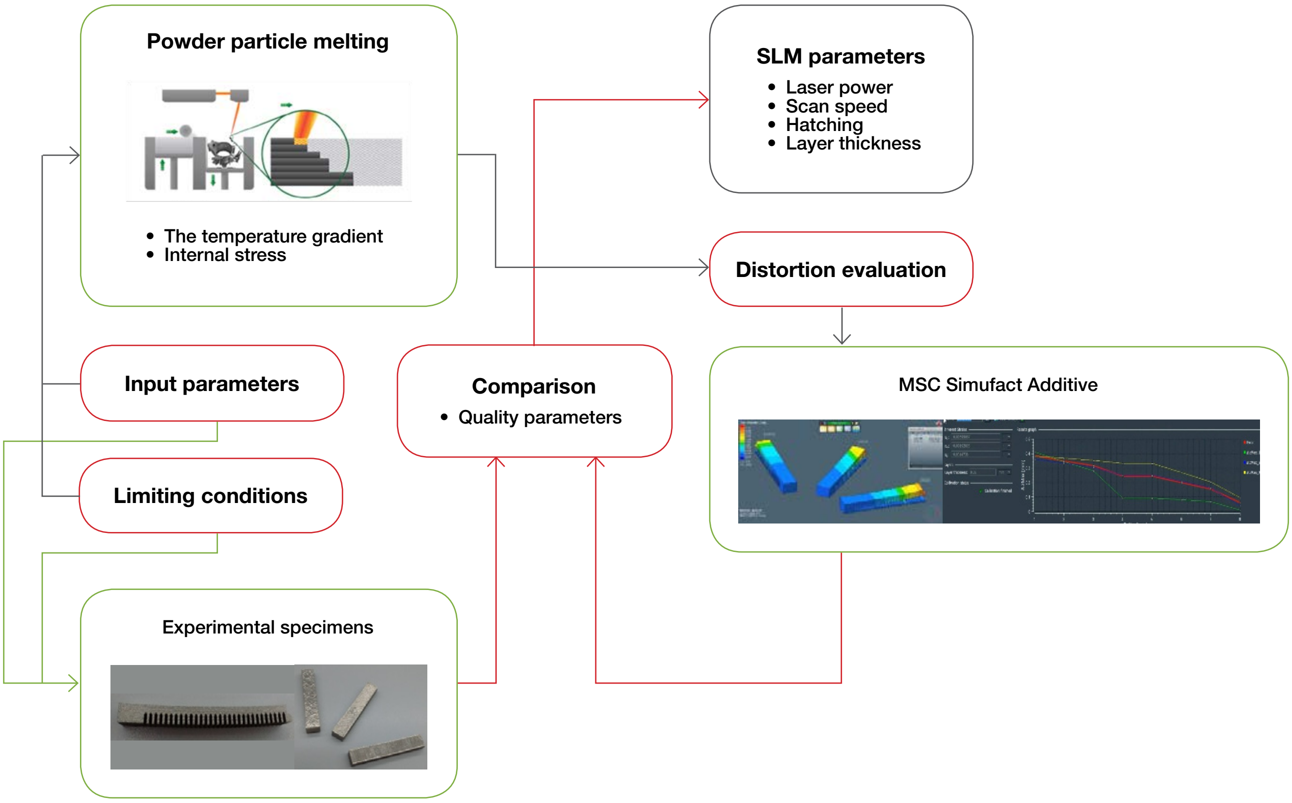

Figure 3. Our proposed SLM quality system

quality system which is based on managing and controlling of input parameters taking into account the limiting conditions. The main blocks of the proposed SLM quality system are shown in figure 2. In order to select the appropriate set of technological parameters, the system uses a making-decision algorithm, and selection of input parameters depends on the link between part requirements (accuracy, geometry, surface) and building regimes for corresponding material and mechanical behaviors. The main idea of this quality system is that decision and denoting of SLM parameters are based on experience, and our statistical database is included in the making-decision algorithm. After each part is manufactured 'successfully', its database record's input parameters with certain limiting conditions are recorded as meaning that all quality requirements are satisfied.

The making-decision algorithm should include not only the statistical database, but a method of quality prediction. The prediction of accuracy and surface behaviors found in the physical process during SLM: temperature gradients and distortions, internal stresses and deformations. For this approach we needed the ability to both monitor the SLM process and to manage this process. Such a system is the key step to achieving digital manufacturing transformation according to the well-known Industry 4.0 concept.

Figure 3 illustrates the developed additive manufacturing quality system we devised for SLM. It should be noted that we needed an engineering simulation model of the SLM process for better understanding of the link between input and output parameters under different limiting conditions. We achieved this by employing the predictive simulation tool, Simufact Additive, from MSC Software.

Simulation techniques have been widely used to predict residual stresses and part distortions in the SLM processes. But they are only suitable for analyzing the thermal-mechanical model to predict residual stresses and distortions of a sintered specimen. For an original SLM part, it is difficult to predict part distortion due to requiring millions of micro-scale laser scans which will increase the computational hardware requirement prohibitively. However, Simufact Additive allowed us to compare numerical and experimental results and to develop a multi scale approach to achieve acceptable accuracy of part distortion and internal stress. As already mentioned, if we divide a SLM process for a practical part into three scales such as micro scale, meso scale and macro scale; with this approach, the temperature history and residual stress fields during the SLM process can be predicted. Thermal information can be transferred through micro scale laser scanning, meso scale layer hatching, and macro scale part build-up. The aim of our research was to develop a perspective quality system for the SLM process based on a making-decision algorithm and predicting the part quality by SLM process simulation in consideration of the temperature distribution and internal stress

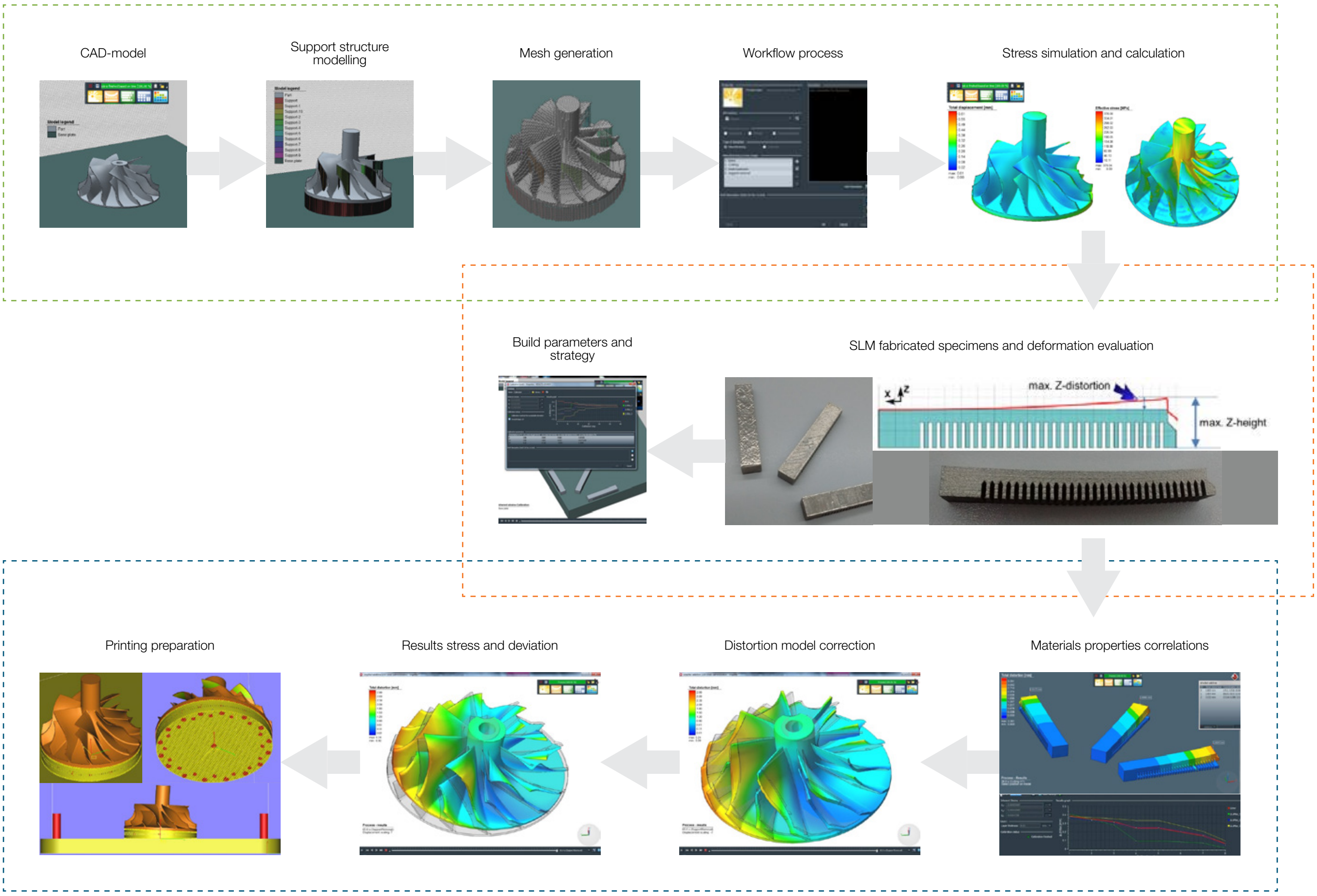

Figure 4. SLM distortion prediction by Simufact Additive for a Gas Turbine printed part

in the workpiece. For developing the SLM quality system, a conceptual model was established. We chose to simulate the entire metal SLM process of a gas turbine engine part including Simufact Additive predictions: build, baseplate cutting and support removal process (see figure.4). Simufact Additive allowed us to predict the distortion and residual stresses in the turbine blade part and guided the quality system in how to pre-compensate to ensure a quality part was printed the first time right. Process control variables were selected in Simufact Additive to optimize this SLM process to reduce printing time and material waste successfully.

Summary and Conclusions

We developed a model of all the influences of additively manufactured SLM process parameters for a gas turbine part based on quality and influencing parameters as described by an Ishikawa diagram. The SLM quality system includes technical-organizational methods of managing and controlling the SLM process. For getting the required part quality influence factors correct, factors must be considered such as limiting conditions (material properties, equipment specifications), and input parameters (building conditions and process parameters). However, during the SLM process, the localized increased compression and tension caused by large temperature gradients and fast cooling of the 3d printing process can lead to significant internal stresses in the workpiece and consequent shape deformation. Simufact Additive was a major predictive simulation tool to avoid this and for the success of our proposed SLM quality process.

Reference

1. "Development of SLM quality system for gas turbines engines parts production", V V Kokareva, V G Smelov, A V Agapovichev, A V Sotov, and V S Sufiiarov, ISPCIET'2018, IOP Conf. Series: Materials Science and Engineering, 441 (2018) 012024