RULE-BASED FREE-FORM DEFORMATION FOR ADDITIVE LAYER MANUFACTURING

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Abstract

Additive Layer Manufacturing (ALM) provides manufacturing of nearly arbitrary geometries flexibly and economically. The part properties, which are reachable by state-of-the-art systems, are able to fulfill the customer requirements in terms of series and spare part production. Nevertheless, there still arise problems prohibiting the prevalent application of those techniques. The presented approach focuses on a rule-based Free-Form Deformation (FFD) for ALM. The machine is characterized by a set of rules, which is identified through observable properties extracted from precedent building processes. Adapting and applying the FFD algorithm, a pre-deformation of desired geometries based on exclusively geometric rules is achieved. Using an exclusively geometric deformation technique, CAD data is deformed before manufacturing to provide higher part quality by considering the unique characteristic of a machine.

Introduction

In the field of manufacturing technologies there is an increasing demand for commodities which fulfill the requirements of highly customized specifications. Until now, an economical production often correlates with a high number of units. However, by means of flexible manufacturing technologies like ALM, small batches as well as single parts can be produced efficiently. Hence, ALM techniques can be assigned to the production concept of mass customization [1]. There is a fundamental shift in market requirements towards brief production times and continuous interfaces between engineering and fabrication. The indicator *time-to-market*, or to be more general, the indicator *time-to-success*, is a figure for contemporary products that becomes more and more important. Industries benefiting from ALM can be found amongst others in the fields of consumer products, medical applications, industrial machines and aerospace applications [2]. Traditionally, ALM technologies are classified according to the materials they process, like plastics, metals, ceramics or composites [3]. Despite having extensive advantages compared to conventional manufacturing technologies [4], ALM still has several process deficiencies, which constrain a further growth [5]. Different approaches are taken to compensate these deficiencies. The presented approach extends the existing ones by considering the *characteristic* of a machine, i.e. its unique behavior, or in general the environmental conditions surrounding the process chain. Therefore, rules are deduced from observable properties and subsequently applied to an extended process chain. In the following, we first show the state of the art of ALM techniques. We then present the approach for a rule-based superposed closed-loop control with the necessities for its application and demonstrate the use of the proposed methodology for the polymer-based laser sintering process.

State of the art

ALM is defined as the process of fabricating three-dimensional models and devices by joining material layer upon layer [6]. The material can be powder, wire or liquid. For solidification, predominantly a deflected laser is used. The process chain is characterized by a rapid, flexible and straight manufacturing process extracted and planned from data exported directly from Computer Aided Design (CAD) systems. Intermediate stages, such as tool manufacturing, are unnecessary [7]. The whole manufacturing process can be subdivided into three phases, which are processed in a successive manner (cf. Figure 1). First of all, during a *Pre-Process-Phase*, the CAD data is set up, i.e. positioned within a virtual process chamber, supplied with support structures (if required) as well as transformed into a machine-dependent data format. Furthermore, the machine is set up and the required infrastructure is allocated. Secondly, during the *In-Process-Phase*, the parts are manufactured and the process parameters are controlled by a local closed-loop control. During the third step, the *Post-Process-Phase*, the produced parts are cleaned and refinished. Finally, the parts are checked by means of a quality inspection, e.g. a randomly visual appraisal, a complete surface digitizing or a mechanical stress test. The aim of the quality inspection is to decide, whether the imposed requirements have been fulfilled or not.

The given process sequence proves to be disadvantageous, since it is completely forward-oriented. The information about completed building processes is not used in a systematic manner for subsequent processes so far. First of all, the information is used implicitly by the operators, which gather it within a learning process. Furthermore, the unique characteristic of a machine is not considered by the given process chain. A first approach in the form of an automated calibration module for laser melting was presented by [8]. Here, a single evaluation part was produced and measured once per machine. The measurement data was aggregated to parameters which are used by the machine's control system. The proposed part covered the whole process chamber. However, a local distribution of laser beam power was identified by [9]. Herein a strong dependency between laser beam power and structure of material was identified, which also influences the mechanical properties. [10] referred to local strain and stress within the parts, which are based on the temperature gradient in the process chamber. [11] provided an evidence for the local resolution of the temperature profile within a powder bed. This can lead to the deformation of a part depending on its position. The resulting shortcomings of the parts were explained in detail by [11], [12] and [13]. In summary, there is a strong necessity for the acquisition and compensation of a *machine characteristic*. The existing approaches do not take adequately into account the characteristic, which is induced by aging, abrasion, tolerances and environmental conditions.

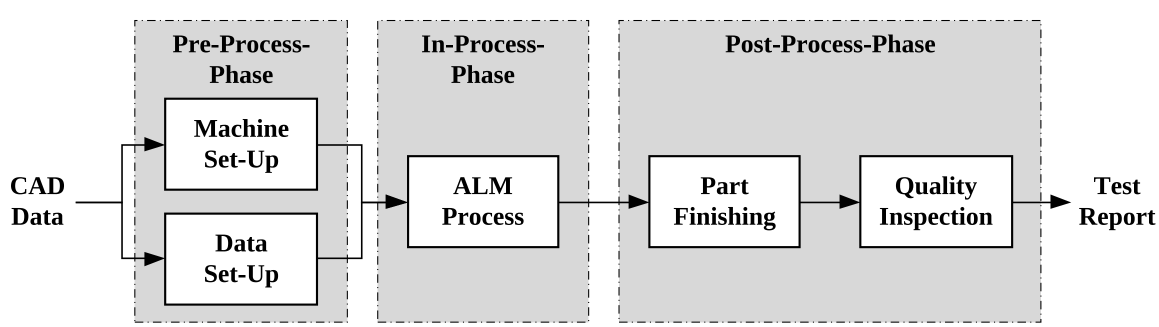

Figure 1 – ALM process chain

Aims

The aim of the presented approach is to increase the quality of parts which are manufactured by laser sintering. Primarily, geometrical properties are considered. In general, the presented approach is appropriate for dealing with other properties, too, like mechanical or optical ones. The characteristic of a machine shall be detected, visualized and compensated. For this, the given process chain is extended by a superposed closed-loop control which is driven by rules. Using empirically identified properties and rules, which are deduced from parts manufactured in precedent building processes, the data is fed back into the existing process chain. Additionally, the experiential knowledge of operators can be formulated and shall be used to optimize the quality of the parts. An exemplary implementation of the superposed closed-loop control has been realized using FFD. FFD is an approach commonly used in computer graphics applications that transforms the geometry of an object in a free-form manner. Geometric data gained from former building processes is used to characterize the machine and to pre-deform CAD data of parts before the manufacturing process using the presented rule-based approach and FFD.

Approach

In the following, we present the concept of implementing a rule-based superposed closed-loop control. The extension of the existing process sequence is demonstrated. Subsequently, the generation of rules is discussed and the requirements, needed to be fulfilled to apply the approach, are presented.

Rule-based superposed closed-loop control

As shown in Figure 2, the process sequence for ALM processes, i.e. Pre-Process, In-Process and Post-Process phase, remains unchanged. This sequence is now extended by a control structure that gathers the information about the process chain needed to implement a feedback control for the desired parameters. The information gathered from In-Process and Post-Process phases, e.g. part, protocol and measurement data, and the information gathered from the

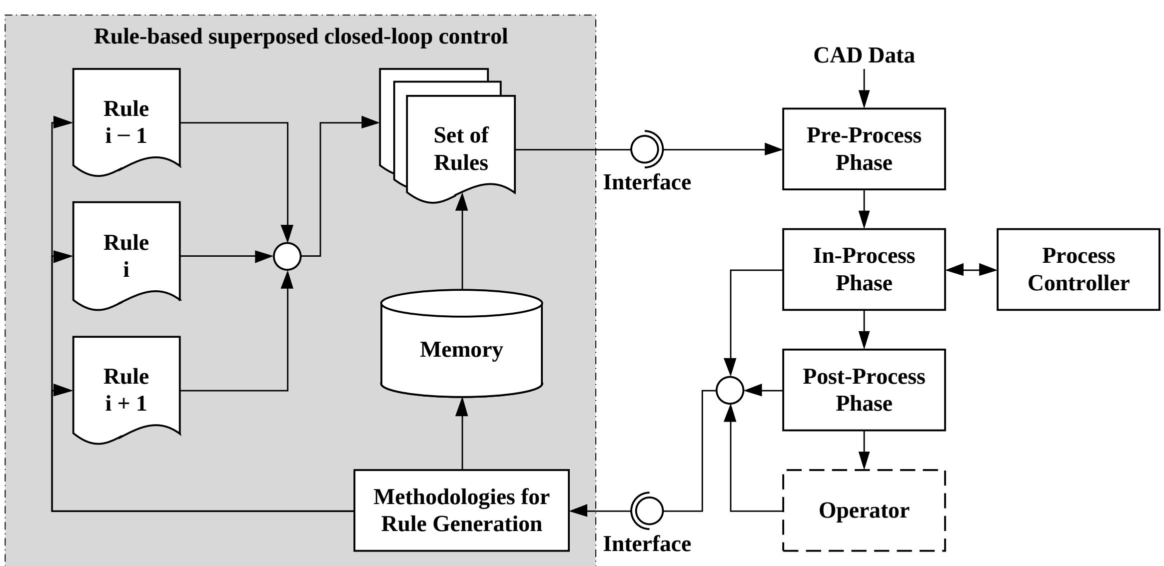

Figure 2 – Rule-based superposed closed-loop control

operator's experiential knowledge, e.g. through interviews and surveys, is coupled through an interface into the methodologies providing the generation of rules. For a single process chain, i.e. machine, any number of rules may be generated. Depending on their type, rules must be combined into a *set of rules* and then be configured using the parameters from the storage. The resulting set of rules represents the information used to control both Pre-Process and In-Process phases through an appropriate interface similarly to the interface for the methodologies for rule generation. To apply the presented approach, the following requirements need to be fulfilled: First of all, the properties, that shall be controlled, must be observable directly or indirectly (*observability*). Secondly, the properties must be controllable (*controllability*).

The terms *observability* and *controllability* will be discussed later. In the following, the different rule types and their application, as well as the generation of rules from existing knowledge are presented.

Types of rules

The term *rule* refers to a map from a set of observed parameters to a set of controlled properties and contains the information needed to control a specific machine or process property. Rules are used in purpose of describing the actions necessary to optimize the observed plant behavior. To describe process parameters, machine parameters and the plant's behavior, rules need to provide the opportunity to be formulated either generically or specifically. Therefore, rules can be either used as *verbal*, *logical* or *analytical* expressions. A *verbal rule* may contain a large amount of information and a large degree of generality. Because operators often cannot determine the manufacturing plant's behavior properly or in a mathematical way, verbal rules are intended to describe the plant or process behavior intuitively and without constraint on syntax. Verbal rules may therefore describe both simple as well as complex correlations and are very tolerant towards handling unclear statements, e.g. measuring inaccuracies. Less complex phenomena or correlations with a more specific character may be mapped using *logical rules*. A logical rule is a machine-readable statement and contains elements that may only assume two different states: true or false. In general, a logical rule is formulated as an "IF-THEN"-statement:

$$IF \text{ (assumption) } THEN \text{ (conclusion)} \quad (1)$$

The *assumption* usually contains the observed parameters, whereas the *conclusion* contains the parameters used to control the desired process or machine properties. Comparing to verbal rules, logical rules refer to less complex phenomena and are used to describe specific behavior. *Analytical rules* represent a direct mathematical map from a set of observed parameters to a set of properties used to control the desired process or machine properties. Depending on the type of phenomenon, an analytical rule may either be very simple or complex. In general, an analytical rule is characterized as a definite mathematical description on how to adapt a controllable parameter and can therefore not be described generally.

Furthermore, rules may be distinguished into abstract and configured rules. An abstract rule refers to an expression that does not represent a specific machine or process, but a machine or process type in general. Abstract rules are not directly applicable. They are generated directly from the methodologies of rule generation and may be combined into rule sets which are then parameterized with the specific data from the data storage.

	abstract	configured
verbal	"To prevent shrinkage in Z-direction, the geometry of a part at a special position manufactured in a specific machine needs to be pre-scaled"	"The geometry of a part manufactured in machine *2* at position *50 ×70 × 20 mm (X × Y × Z)* needs to be pre-scaled in Z-direction by *1.2 %*"
logical	IF (Machine(a), Position(x, y, z)) $THEN$ Prescale_Part_Z(c)	IF (Machine(2), Position(50, 70, 20)) $THEN$ Prescale_Part_Z(1.012)
analytical	$x_{i,\ \text{new}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & c \end{pmatrix} \cdot x_i$	$x_{i,\ \text{new}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1.012 \end{pmatrix} \cdot x_i$

Table I – Types of rules

In many cases, verbal rules may also be formulated as logical or analytical rules. For the example "shrinkage in Z-direction", Table I shows the comparison of a possible verbal, logical and analytical rule that are first formulated abstractly and then configured for a machine.

In this case, the phenomenon "shrinkage in Z-direction" is formulated in general using a verbal rule identifying the machine-dependent shrinkage of a part in Z-direction. The same rule may be formulated logically, whereat the parameter *a* represents the specific machine, the part position is represented by its *x, y* and *z* values and the pre-scaling factor is represented by the variable *c*. A correspondent analytical rule may be formulated as a pre-deformation description, in this case using a matrix-vector multiplication that is evaluated for each vertex in the part's geometric representation. The value *c*, analogously to the same parameter in the logical rule, represents the pre-scaling factor. The used parameters need to be configured in the parameterization step. In the presented scenario, a part manufactured in machine *a = 2* at its target position *50 × 70 × 20 mm (X × Y × Z)* needs to be pre-scaled in Z-direction by *c = 1.2 %*. The correspondent configured rules are presented in the right column of the table.

Rule configuration and application

The rule sets contain configured rules which are valid for a specific machine and which may be applied directly to the process. In Figure 3, the rule set *A* contains the abstract rules *i – 1* and *i*

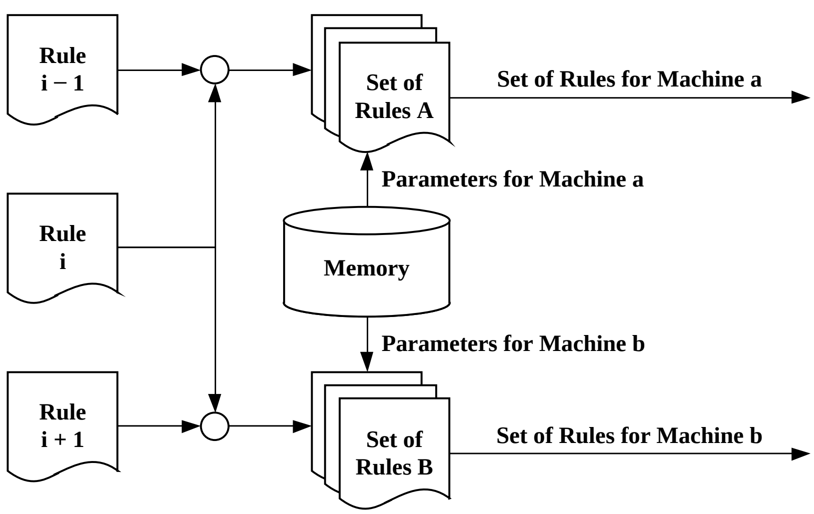

Figure 3 – Generation of Rules

and is parameterized with the parameters for machine *a* in the data storage. Another collection of rules is configured for machine *b*. The rule set *B* contains the abstract rules *i* and *i + 1* and is configured with the parameters for machine *b* in the data storage. A rule set does not need to contain all existing rules. In the example, the rule set *A* does not contain rule *i + 1*. Rules can be generated on different ways. If machine *a* contains a unique feature, a single rule may be generated to represent this behavior. Furthermore, an abstract rule may be generated based upon the observed behavior of machine *b*, but may also be adapted to describe a similar behavior of machine *a* using a configured rule. The rule set configured for machine *b* may also be used temporarily for analyzing the behavior of machine *a*.

Depending on the type of the rule, i.e. verbal, logical or analytical, rules are often not directly applicable for the closed-loop control of the process parameters. Before being applied, abstract rules need to be parameterized and transferred into configured rules. Depending on the type of formulation, a parameterization may be difficult. In general, verbal rules are not directly applicable for the superposed control, and must therefore provide an interface to a machine-readable formulation, e.g. value tables. As mentioned above, logical rules are directly applicable because of their machine-readable character. Furthermore, analytical rules may also be directly applicable depending on their complexity and the type of formula. If a rule is not directly applicable, an appropriate interface has to be implemented.

Observation of properties

For the generation of rule sets, it is necessary that the considered properties are observable. In a formal sense in the domain of control theory, a parameter is said to be *observable*, if its exact value can be determined from measurements of an output signal [14]. In the case of observing properties in terms of generating rule sets, the property has to be determined properly after the manufacturing process. Furthermore, the expectancy value for the properties must also be determinable during parameterization of the process steps. In general, the system behavior of ALM plants cannot be identified efficiently for the whole building chamber. Therefore, techniques for interpolating or approximating the properties systematically must be used. Properties are then measured at discrete points in the building chamber to reduce complexity, the states between the discrete measurement positions must be approximated or interpolated.

Properties may be observed on different ways for the generation of rule sets. For the formulation of verbal rules, pragmatic expressions can be used. Furthermore, concrete parameters may be identified directly through empirical measurement processes, e.g. for geometric or mechanical properties. Exemplary concrete values are location-dependent shrinkage and beam offset factor.

Controllable Properties

After having considered the properties‘ observability, a property also needs to be controllable. In a formal sense in the domain of control theory, a parameter is said to be *controllable*, if there exists a control signal that influences the parameter causally determined [14]. Concerning the presented approach, a property is controllable, if it may be controlled through parameterization of process input data. The considered properties are controlled through the configured rule sets. Depending on the type of the utilized rules, an appropriate interface may be implemented to transform the identified rules into a machine-readable algorithm used to adapt the process parameters, as mentioned above. Especially for verbal rules, the mapping to the process may be difficult and may also be done iteratively. Therefore, geometric data, e.g. shrinkage, warpage that has been identified through empirical measurement processes may be mapped easily. This is shown in the following application example.

Application Example

For ALM processes, especially shrinkage in all three directions in space *(X, Y, Z)* is problematic. For the optimization of the part geometries using the presented approach, an application example is shown. The generation of exemplary verbal, logical and analytical rules is presented. Subsequently, the mapping of a generated rule set using Free-Form Deformation (FFD) is shown. The results are presented and discussed.

Introduction of the application example

In the following, the extrapolation of the shrinkage in Y-direction and the shrinkage which takes place on top surfaces (cf. Figure 4) is considered. On the left hand side, Figure 4 shows an exemplary part which was manufactured by polymer-based laser sintering. On the right hand side, a schematically cross section is visualized. The upper edge of the part is superelevated by the height *b* and in the range *a* from the border. The physical reasons for this deficiency are discussed in detail by [11]. However, the specific values for *a* and *b* are yet unknown.

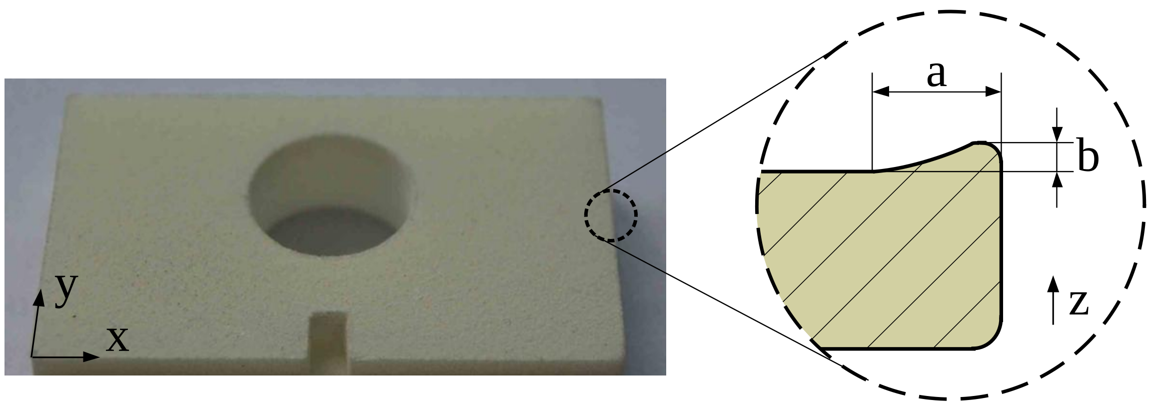

Figure 4 – Superelevation at upskin facets

To evaluate the presented approach, an EOS P 730 is used. The building chamber of the considered ALM system has the dimensions *670 × 360 × 550 mm (X × Y × Z)*. The operators' knowledge shall be used to identify verbally formulated rule sets. Furthermore, parts are manufactured and then measured to identify concrete geometric data needed to implement the superposed closed-loop control.

Generation of exemplary rules

For the generation of exemplary rules, it is important to compensate the operators' pragmatic knowledge on the one side and the values identified from precedent building jobs on the other side. However, the characteristic properties "shrinkage in Y-direction" and "superelevation at upskin facets" must be considered. From precedent building processes, the operator identified that in the upper edge area of manufactured parts in ALM systems the material superelevates. To compensate this phenomenon, an abstract verbal rule may be formulated as follows:

"In upskin facets of parts, the upper edge must be lowered." (2)

As mentioned above, this pragmatically formulated rule may not be used directly to optimize the manufacturing process. Therefore, this verbal rule may be transformed into a logical rule:

$$IF \text{ (Upskin\_Facet \& Upper\_Edge\_Area) } THEN \text{ Lower\_Upper\_Edge\_Area}(a, b) \tag{3}$$

The parameters a and b are machine-dependent parameters that must be determined empirically. Formulating an analytical rule is not necessary in this case, because the phenomenon has been identified effectively. The upskin facets and upper edge areas can be extrapolated from the CAD data. The intended conclusion, i.e. lower the upper edge areas, is done by an algorithm.

Furthermore, there are shrinkage effects that affect the part geometries. To improve the parts' geometries, it is obvious to use an exclusively geometric approach, i.e. using an inverse pre-deformation of the part geometry. Formulating this technique verbally or logically might be very complex and inefficiently. Therefore, an analytical description has been chosen. A simple analytical description might look as follows:

$$x_{i,predeformed} = x_{i,desired} - \Delta x_i \tag{4}$$

In this formula, $x_{i,predeformed}$ represents the predeformed geometry, $x_{i,desired}$ the desired geometry and Δx_i is the identified error due to shrinkage. This formula then has to be evaluated for each point of the part geometry. A rule set resulting from the presented rules is generated after configuration.

Identification of Observable Properties

To identify the necessary parameters to configure the presented rules, two building processes have been implemented in a first step. For the identification of the property "shrinkage in Y-direction", the dependency on the positioning of the parts has been identified in three different Z-layers. 88 parts have been manufactured evenly distributed over 3 Z-layers. The utilized material is PA2200, which has been mixed with 50 % of fresh powder.

After the manufacturing process was completed, the parts were measured. The results of this second step are shown in Figure 5. A surface plot was used to compensate measurement uncertainties, legitimated because drastic changes in curve shapes are not expected. It matters to underline that the illustrated property represents the shrinkage values in Y-direction applied over the X- and Y-positioning values. The Z-layers are illustrated exemplarily because the missing layers are quite similar to the illustrated ones. As can be seen from the plots, the shrinkage value depends strongly on the XY-position of the parts. The compensation value of 3.2 %, which has been used independently from the position, is considered in the measurement values. For the identification of the parameters necessary to configure the rule set, empirical approaches are now considered. For the configuration of the logical rule (cf. (3)), the machine-dependent parameters a and b have to be determined. This is done through empirical analyses with operators. Furthermore, the deviation from the ideal geometry must be identified to configure the analytical rule (cf. (4)). As mentioned above, the deviation from the desired geometry cannot be identified efficiently for the whole building chamber. In the presented application example, the parts

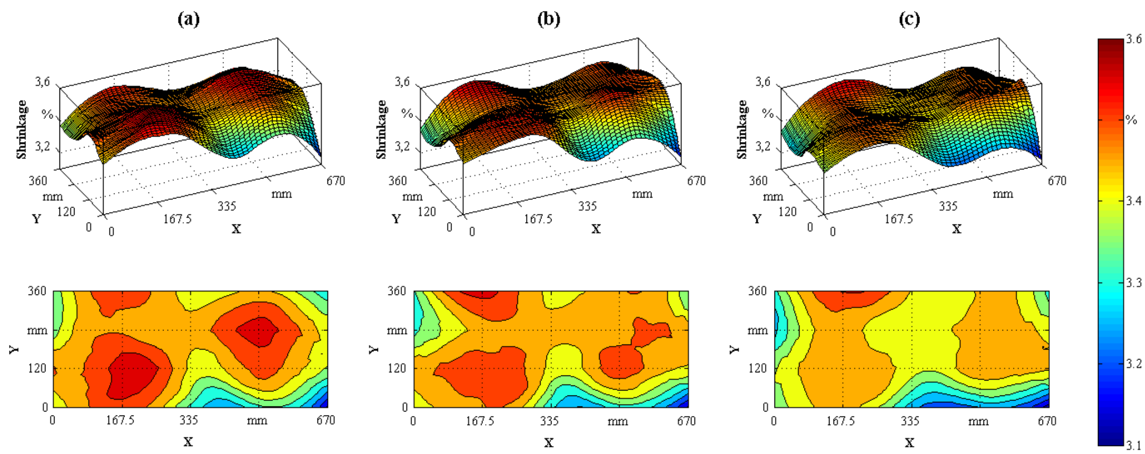

Figure 5 – Shrinkage in Y-direction, (a) at Z = 5 mm, (b) at Z = 54 mm, (c) at Z = 103 mm

intended to be measured have been manufactured evenly distributed over the building chamber. To determine the shrinkage values for the chamber, the property needs to be measured properly in all directions of space.

Controlling the desired properties

Subsequent to the identification of the machine-dependent parameters, an appropriate interface needs to be implemented to map the information to the adaptation of the process parameters. In the following, a geometric approach using FFD is applied. The FFD method has been presented in [15] and is commonly used in computer graphics applications. It represents a method to transform the geometry of an object in a free-form manner. The considered object is not deformed by FFD itself, however, a superposed uniform structure, the control grid, is changed. At first, a local coordinate system is defined, which may be congruent with the machine coordinate system. Each point (x, y, z) is then described explicitly by its correspondent coordinates (s, t, u) in the new coordinate system:

$$\boldsymbol{x} = \boldsymbol{x}_0 + s\boldsymbol{S} + t\boldsymbol{T} + u\boldsymbol{U} \tag{5}$$

The vectors $\boldsymbol{S}$, $\boldsymbol{T}$ and $\boldsymbol{U}$ represent the directions of the new coordinate system; the vector $\boldsymbol{x}_0$ is the origin of the new coordinate system. The (s, t, u) coordinates may then be calculated using linear algebra:

$$s = \frac{\boldsymbol{T}\times\boldsymbol{U}(\boldsymbol{x}-\boldsymbol{x}_0)}{\boldsymbol{T}\times\boldsymbol{U}\cdot\boldsymbol{S}},\ t = \frac{\boldsymbol{S}\times\boldsymbol{U}(\boldsymbol{x}-\boldsymbol{x}_0)}{\boldsymbol{S}\times\boldsymbol{U}\cdot\boldsymbol{T}},\ u = \frac{\boldsymbol{S}\times\boldsymbol{T}(\boldsymbol{x}-\boldsymbol{x}_0)}{\boldsymbol{S}\times\boldsymbol{T}\cdot\boldsymbol{U}} \tag{6}$$

In a next step, a grid of control points is imposed. Those control points form $l + 1$ planes in the $\boldsymbol{S}$ direction, $m + 1$ planes in the $\boldsymbol{T}$ direction and $n + 1$ planes in the $\boldsymbol{U}$ direction. The resulting control grid $\boldsymbol{P}_{ijk}$ is a lattice with uniform distances in each direction:

$$\boldsymbol{P}_{ijk} = \boldsymbol{x}_0 + \frac{i}{l}\cdot\boldsymbol{S} + \frac{j}{m}\cdot\boldsymbol{T} + \frac{k}{n}\cdot\boldsymbol{U} \tag{7}$$

To deform the object, the control points have to be removed systematically. The resulting deformation function $\boldsymbol{x}_{ffd}$ is then defined by a trivariate tensor product Bernstein polynomial:

$$\boldsymbol{x}_{ffd} = \sum_{i=0}^{l} \binom{l}{i} (1-s)^{l-i} s^i \sum_{j=0}^{m} \binom{m}{j} (1-t)^{m-j} t^j \sum_{k=0}^{n} \binom{n}{k} (1-u)^{n-k} u^k \boldsymbol{P}_{ijk} \quad (8)$$

The vector $\boldsymbol{x}_{ffd}$ denotes the Cartesian coordinates of the deformed point; $\boldsymbol{P}_{ijk}$ are the Cartesian coordinates of the displaced control points.

For the pre-deformation of parts manufactured in ALM systems, each control point in the control grid of the FFD represents a measurement value identified for the specific machine. Unfortunately, as can be seen in formula (8), the degree of the curvature of the resulting deformation function depends on the number of control points used for the deformation. Furthermore, the FFD only supports uniform and Cartesian lattices. For the pre-deformation of parts that are manufactured in ALM systems, a lot of data is necessary. This data is often not uniformly distributed over the building chamber. Parts are manufactured concentrated at critical positions that shall be examined. Therefore, the FFD defined in [15] must be adapted for the application for ALM process optimization. As FFD can be used globally or locally, the building chamber is now segmented into smaller local control grids, which will be referred to as *control volumes*. Each control volume then represents an FFD control grid consisting of only four points. To generate those control volumes from the building chamber volume, a refinement technique has been developed. Each point that has been measured in terms of representing a control point for the FFD is inserted into its parental volume generating new child volumes from it. Therefore, a point inserted on the edge of a volume generates 2 new volumes (cf. Figure 6 (a)), a point inserted on the face of a volume generates 4 new volumes (cf. Figure 6 (b)) and a point inserted into the center of a volume generates 8 new volumes (cf. Figure 6 (c)). In this figure, a red diamond represents the inserted new control point, whereas a blue circle represents the generated corner point of a new control volume. Points that overlay each other have to be interpolated linearly. This technique is applied for each measurement value that has been identified for the building chamber. Subsequently, the FFD (cf. (8)) is applied for each of the resulting control volumes.

On the one hand, the FFD is applied to reduce shrinkage effects through a systematical pre-deformation. For this systematic and mathematically founded compensation, the empirically determined measurement points are used. On the other hand, the superelevation at upskin facets may be compensated through manual deformation of the resulting control grid before applying

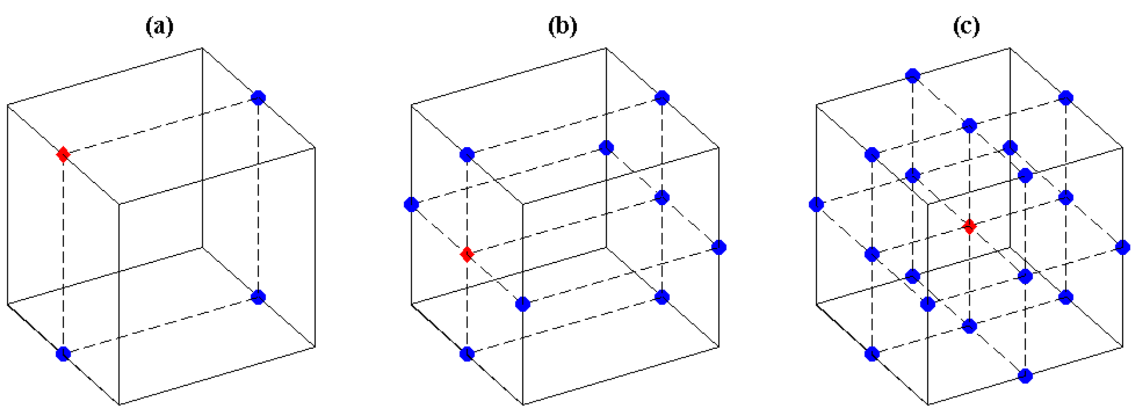

Figure 6 – Adaption of the FFD algorithm

the FFD. Using this technique, the logical and verbal expressions defined in (2) and (3) are also considered. Therefore, the FFD approach compensates the information on the observable properties “shrinkage in Y-direction” and “superelevation at upskin facets”.

Conclusion and Future Work

The existing process sequence is suboptimal, since existing information is not used for subsequent processes. Research studies identified a strong variation of process parameters within the building chamber. Hence, it is not eligible to use constant values. However, existing approaches do not take into account this fact adequately. Furthermore, the special behavior of a machine, which is observable by the operators, is completely neglected. The presented approach proposes the extension of the process sequence by a rule-based superposed closed-loop control. For this purpose, controllable properties are gathered, analyzed and transformed into abstract rules. Combined with parameters, these abstract rules can be merged into rule sets and can be applied in a controllable manner to the process. In particular, geometric part properties shall be optimized by the given approach. In principle, the approach can be used for further properties, too, which is subject of further research activities. The usage of the approach was demonstrated within an application example. At this, the characteristic of an EOS P 730 has been visualized. In future research projects, the usage of the approach for the reduction of warpage is persued.

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