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Production-integrated Markings for Traceability of AM Parts in the Context of Industry 4.0

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Abstract

Traceability is often mentioned as one fundamental requirement to reach the vision of Industry 4.0, the next industrial revolution. As Additive Manufacturing (AM) is a technology with high relevance in the scope of Industry 4.0 this paper focuses on production-integrated markings for traceability of additively manufactured parts. Even industries that are not focusing on products with critical functionality using markings for quality management and liability exclusion can benefit a lot from identifiability of products. Markings can be understood as a kind of individualization of parts. As individualization does not increase production costs when using AM and the effort for integration of markings can be minimized by software in particular for high batch production, product marking should be an obligatory process step. This paper comprises various applications that can be achieved due to markings as well as different ways to embed a marking at least partly automatically.

Introduction

Industry 4.0 is a term that comprises a lot of different topics in the field of advanced information and communication technologies (ICT) aiming at the next industrial revolution. The vision is to automate production of goods much further so that less manual work needs to be done but customers requirement should be satisfied as well as never before. To minimize the work load was a goal from time immemorial. As shown in *Figure 1* the first industrial revolution came along in 1750 AD with powering machines by steam substituting muscle power. 120 years later new concepts of labor division and assembly lines powered by electricity revolutionized industrial fabrication again. Then again 99 years later the third industrial revolution driven by electronics and first ICT approaches came up with new capabilities for automation so that even multi-variant series production became economically possible. Nowadays the technological progress like "internet of things and services" and "cyber physical systems" will enable smart factories with an even higher degree of automation. Thus with Industry 4.0 new more dynamic business models will come up focusing on individualization, flexible and more efficient production. [BAU14] The German Federal Ministry of Education and Research stated out that the increase of production efficiency is mainly based on those new communication strategies that connect human beings with machines and resources. [BMBF13] To achieve these advantages and a higher level of communication holistically in the value chain there a new requirements to be considered and implemented not only digitally but also physically in the products. This paper concentrates on the interface between the digital and physical world so that parts or products manufactured additively can be traced back from physical to its digital representative due to direct marking. Main issues that will be discussed are

- Properties and applications of markings in industry 4.0
- How to mark a product digitally for AM – an approach for automation
- How to derive specifications for markings with respect to manufacturability

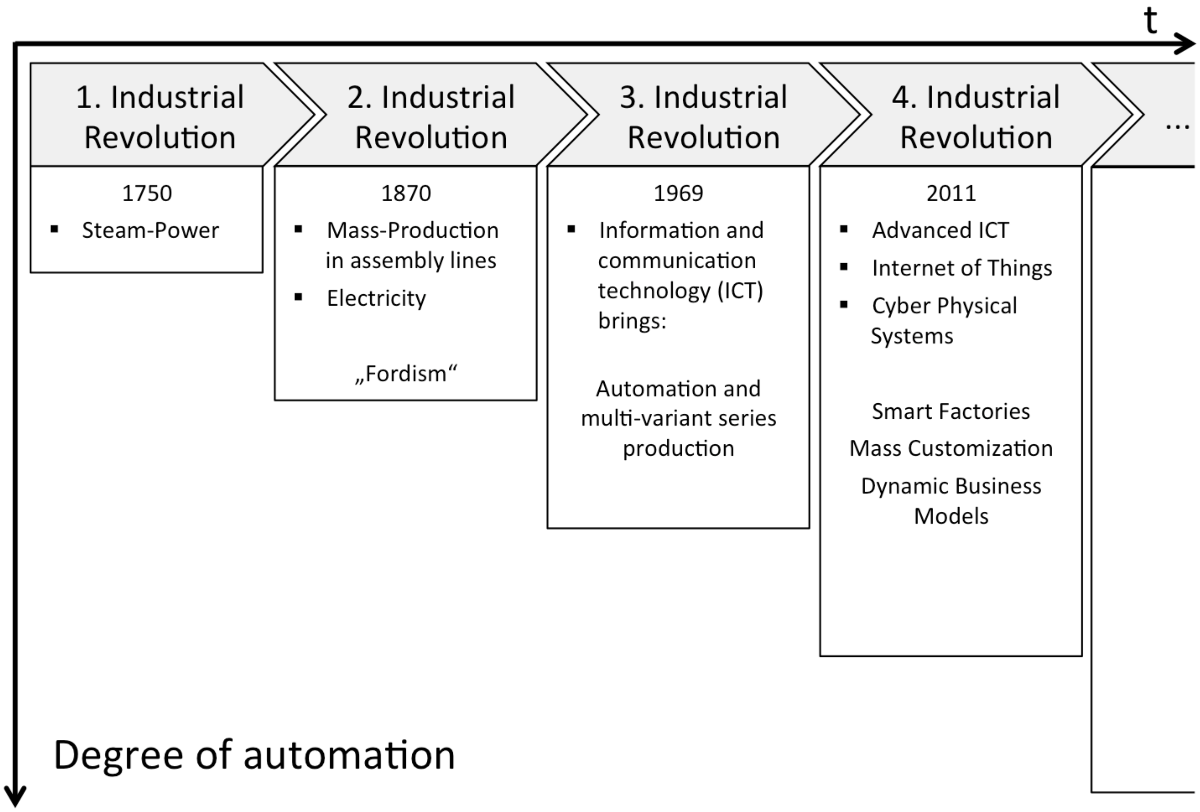

Figure 1: 4 levels of industrial revolutions (acc. to Bauernhansl 2014)

Properties and applications of markings in industry 4.0

The properties of markings and requirements they have to meet vary from application to application. But for example the terms “identification” and “authentication” are often equated in public media. To achieve a common understanding the following definitions according to Harris and Trojahn are used in this paper [Har10][Tro16]:

- Identification is a process where information is given by a human being, a machine or a product showing or telling who or what it is.
- Authentication can be seen as the process following to an identification process. Here the information given in the identification process will be proofed whether the information are valid.

The information that comes up by an identification process is not mandatorily unique. For example a product that is marked with a bar code or similar is not distinguishable from a product counterfeit with the same bar code, at least not only due to the marking. [GÜN10] Using authentication markings each product becomes unique and can be traced back to its digital representative and its production data if those have been stored. Thus a product counterfeit can be distinguished clearly from the original one. But as it is one additional process it is more effort to authenticate human beings or a product in comparison to a simple identification. Furthermore the requirements for the physical marking are higher as an authenticating characteristic needs to be added. *Figure 2* visualizes the comparison of unambiguous assignment of identifying vs. authenticating markings.

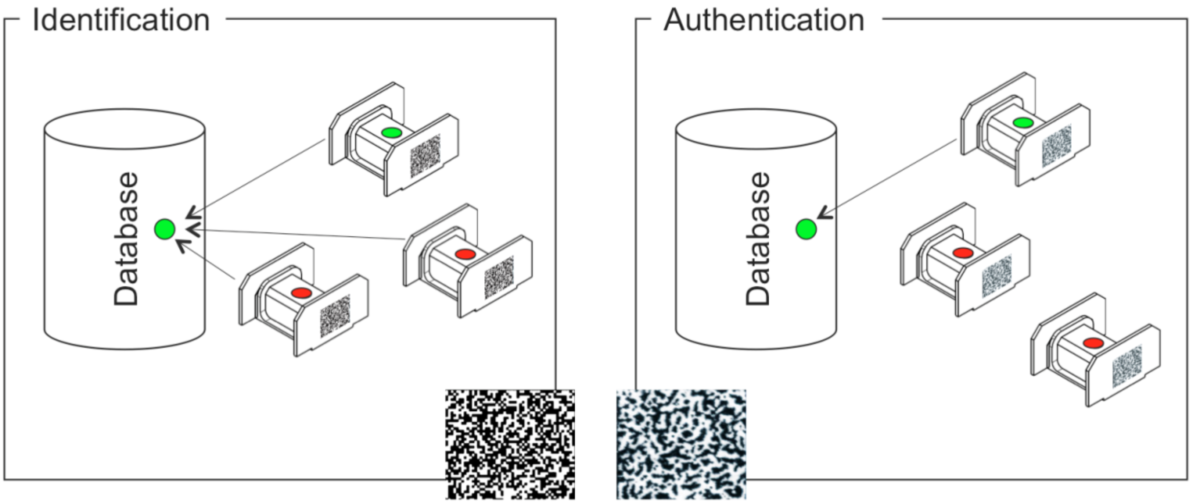

Figure 2: Uniqueness of marking for identification and authentication (markings by Schreiner Prosecure)

Direct product markings are comparable to biometrics used for authentication of human beings. They consist of individual physical characteristics and are inseparable joined to the product. [JFR08b, DG04] The markings shown in *Figure 2* differ in terms of uniqueness. While the left one only provides information the right one is not copyable due to physical characteristics and thus a marking for authentication purposes. Various scientific publications mention a couple of requirements and criteria that should be met by a biometric authentication process. Due to the similarity of application those criteria have to be considered for direct product marking as well: *universal validity, uniqueness, perdurability, measurability, efficiency, acceptability, bypassing of process.* [PPJ03, JBP02, Cla94, IEE10]

Traceability as one thing that can be achieved using the possibilities of ICT and physical markings is mentioned as a basis for industry 4.0. [VDMA16b] There are four large areas that benefit a lot from traceability:

- Quality Management
  In this area traceability of products can help to avoid unjustified product liability. For example when thinking about counterfeits that are responsible for a customers' damage or production stop that result in economical losses an unambiguous tracing from the physical product to its digital representative and its production data becomes very important. [GGL12] Economical losses in 2016 caused by product piracy - only of the German mechanical and plant engineering industry - sum up to € 7.3 billion. [VDMA16a] Processing of customer complaints, product call-backs and proof of warranty claims are further applications. Depending on the economical dimensions and product values the requirements for the complexity of physical markings vary to meet the characteristics of identification or authentication. The use in this area is not that time-critical as in the following.

- Production
  Markings can be used for automation of production lines for example to guide a customized part to its assembly. In this area time efficiency in terms of readability is more important and can only be achieved using machine-readable markings. Here traceability is very beneficial to optimize the process continuously due to the fact that cycle times can be analyzed and monitored very part specific. As all products and batches are well known internally there is no need for authenticating characteristics.

- After Sales
  After Sales can profit from traceability when products need to be identified due to maintenance, repair and overhaul processes. For example service staff is able to reduce effort by receiving case based information available using ICT and product markings. For this application identifying markings are sufficient but thinking about imitated spare parts causing errors in plants or production lines it might be helpful if service staff is able to determine imitations.

- Logistics
  Markings in this area are well known all over the world as mails and parcels are shipped around the world based on bar codes or similar codes with a higher data volume like matrix codes. In most cases adhesive tags are used. These can be printed and reach a high resolution to ensure machine-readability. The idea here is to link the information flow with the physical flow of goods. This application is very similar to the one described for production but external. Authentication is not that necessary as the logistics chain is mainly closed or only accessible via trustworthy portals.

The areas described above show how traceability contributes to automation processes and highlight its relevance for industry 4.0. But the need for authentication processes is not necessarily required to achieve a higher degree of automation but to increase trustworthiness. The current state of the art does not provide best practices or even specifications for any kind of machine-readable direct product marking usable for AM. Therefore the following section will present potentials of AM in general to derive a suitable test specimen set-up to come to a best practice solution later on. The test set-up will focus on identifying markings as this is a required step to achieve authentication in a second step.

Potentials and capabilities of AM to integrate markings

Traceability of additive manufactured products is stated out to be a door-opener for the broad use of this innovative technology in various industries. In particular for branches dealing with critical functionalities like the automotive, aerospace or medical industry it is very important for qualification. [ReMe15] But how to integrate it directly during production?

While subtractive manufacturing processes just change the geometry of a given and specified material [DUB97], using AM the material and its properties are generated during the manufacturing process. Only based on digital product data designed in CAD software a build job can be prepared for AM. Process parameters have to be defined to ensure the manufacturability and required quality. For example the layer thickness is one parameter relevant for build speed as well as for part quality. It defines in how many layers the CAD file is split up digitally and build up in the AM process physically. Afterwards the part is generated layer by layer until the 3-dimensional parts' geometry is reached. On the one hand this is a barrier because for critical application the material has to be qualified and reproducible propertied have to be reached. On the other hand this a chance as well because the material properties can be modified very locally in one single part so that the material can be designed just like the geometry to meet the requirements and to enhance the functionality.

Individualization becomes possible in a very economical way as a result of the first elementary potential shown in *Figure 3*. As there is no need for tooling a lot of consequential potentials like flexible production, small batch sizes and even single piece production can be stated out as potentials. Thus business models focusing on mass customization and individualized products arise due to these capabilities. As mentioned above a unique (authentication) or at least serial (identification) marking is just a kind of product individualization and can be integrated in or on a product directly during the manufacturing process without increasing production costs. The other elementary potential “additive manufacturing from 1D over 2D to 3D” offers the different technological opportunities to implement markings geometrically or by local manipulations of materials properties. The test set-up explained in the following section is limited to three kinds of implementation exploiting this technological potential.

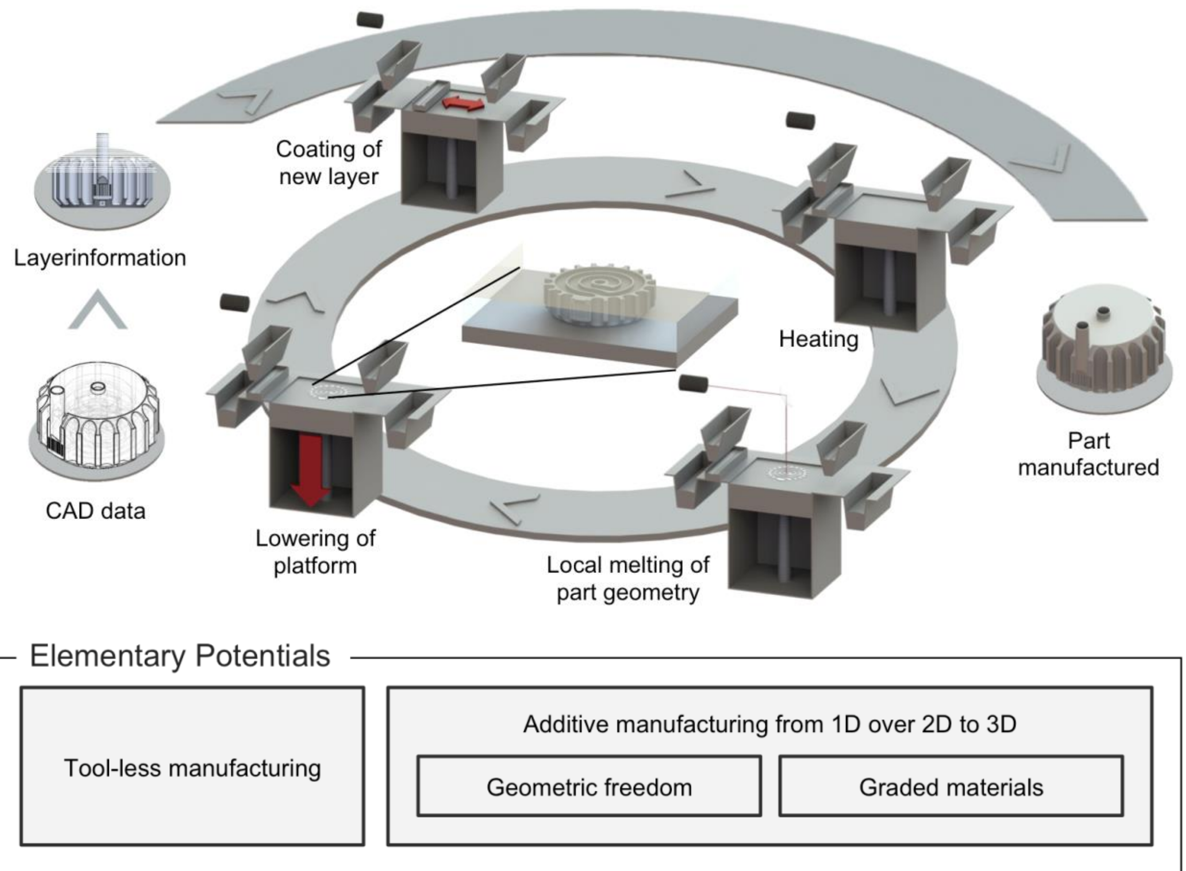

Figure 3: top: Laser Sintering Process | bottom: Elementary Potentials of Additive Manufacturing

The three alternatives discussed in this paper are based on manipulation of STL-files (Standard Triangulation/Tessellation Language) as the most used file format for AM. A STL-file consists of several planes that define the whole surface of a part. It is possible to set a marking “onto” a plane, to stamp it “into” a plane or even to set it under a plane. All of these ways have different requirements and come along with different problems.

- *Set marking onto a plane:* In this case the marking is an extrusion out of the plane. Of course It can have different sizes in X and Y direction and extrusion heights in Z direction.
    - *Advantage:* Nearly no changes to the flow of forces in the manufactured part will occur. Therefore there will be no sharp notches on which cracks canform.
    - *Disadvantage:* The extrusion can be bothersome because it changes the shape and interface areas of the part.

- *Set marking into a plane:* In this case the code is an intrusion into the plane. It can also have different size and intrusion depth. Here for every pixel is built by a recess on the surface of the build part.

- *Advantage:* There is no extrusion on the plane that might be bothersome in any way.
- *Disadvantage:* there might also be a change to the flow of force and sharp notches on which cracks can grow. Thus it should already be considered when designing the part.

- *Set marking under a plane:* In this case the marking is completely inside the part. This becomes possible by defining cavities for every voxel of the marking. In this inclusions the powder will not be melted during manufacturing.

  - *Advantage:* The marking is not bothersome in any way, because it does not change the surface. Depending on the thickness of surface the marking is not mandatory visible, which can also be an advantage. For example for applications where only the producer should know where to find the marking. It also can be added much more easily to a part with no plane surfaces but a complex or freeform geometry.
  - *Disadvantage:* The marking is naturally not visible caused by the fact that it is under the surface. So there are special tools needed to measure or read it. It also has the same problem as the intrusion, there might be a change to the flow of force and sharp notches on which cracks can form. Thus it should already be considered when designing the part.

It is also possible to combine two or all of the strategies with one or more markings at once. This allows to individualize a part and increase the complexity of a marking as needed. To set a marking under a surface can also be used to build 3-dimensional structures inside a part which maximize the ability to individualize a part. So there is the possibility to set in markings, which contains different information based on from which side it is read.

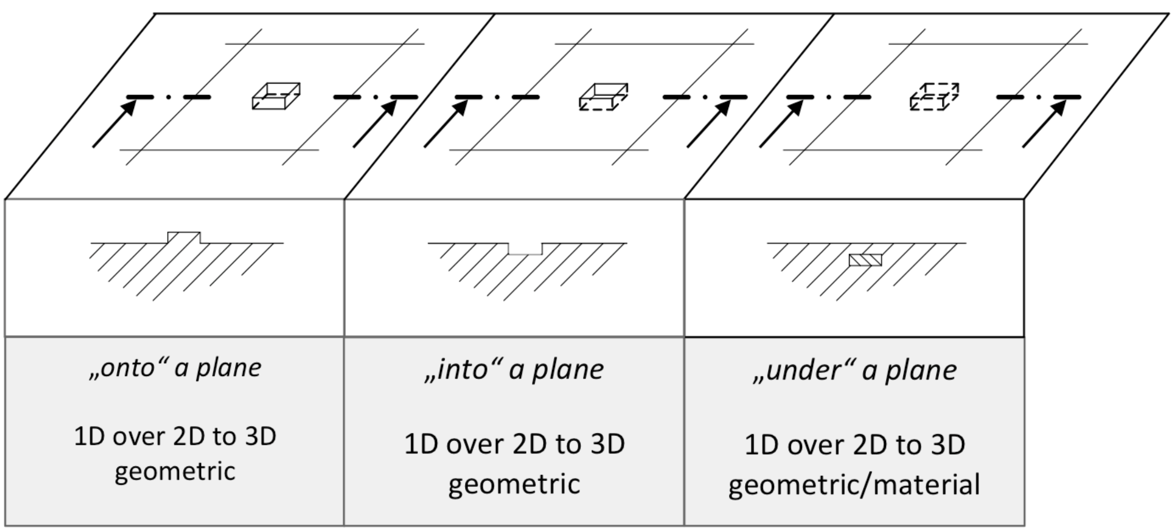

Figure 4: Geometric Alternatives for direct implementation of voxel-based markings

Derivation of specification for robust marking on the example of LS

This sections aims at giving a methodological approach of how to derive specifications for robust markings. In this paper a promising selection of sizes and orientations are used in the Laser Sintering process. It only shows the methodological approach and results for this composition of geometry, machine and parameters but can easily adapted to further powderbed based AM process like Laser Melting.

Requirements of markings have been mentioned above, the test set-up is designed to allow declarations in which setting (size and orientation) markings are robustly measurable:

As the codes specified and administrated by Global Standards 1 (GS1) are wide spread all over the world the GS1-Datamatrix with a size of 18x18 pixel is focused. [GS1SP]. Usually these codes are printed on paper or labels. Therefore a generic test specimen have been designed that can be clamped for assessing the measurability in defined positions. With this part shown in *Figure **5*** it is easily possible to light through to get a maximum of contrast for reading the code. Of course it is not very similar to real parts but it minimizes geometrical influencing factors and allows an evaluation easy methods and without special equipment. Following factors which can influence the quality of the marking were defined:

- Size of the code/marking: In the test set-up sizes of 2mm x 2mm x 1mm, 1mm x 1mm x 1mm and 0.5mm x 0.5mm x 1mm millimeters per voxel are considered. The result were a 36mm x 36mm x 1mm, an 18mm x 18mm x 1mm and a 9mm x 9mm x 1mm GS1-Datamatrix.

- Orientation of the part itself: Here the marked plane is oriented in 9 alternatives:
  90 degrees, 60, 45, 30 and 0 degrees once with code on the upper side and once with marking on the down side. The code inside the build part has been printed only in 5 different part orientations, because in this case there was no need to differentiate between up- and downside. So the inside code needed to be produced with 90°, 60°, 30° and 0° angle only.

Figure 5 shows the different complexities and orientations of test set-up. In total 84 parts have been manufactured to be analyzed. For the robust traceability of specimen to its orientation and build job a simple binary code was used.

Of course for this procedure for marking neither the machine settings nor the type of machine itself is fix. It is absolutely possible to produce marked parts, or the parts created here, on other types of machines with other AM-processes and materials. It is planned to produce the same test set-up on other machines later on to generate more information and robustness parameters.

To assess the measurability a widespread smartphone-app has been chosen for scanning the specimens: The Barcode Scanner App from manatee works. This one works with algorithms also used in industrial devices. For the rating of the measurability of each printed part it was necessary to create comparable conditions for each test. Especially the lightening conditions had to be the same each time. Most of the marked test specimens were directly readable. Each code gets a rating of how readable it has been: Factors in that test were time and distance to the part.

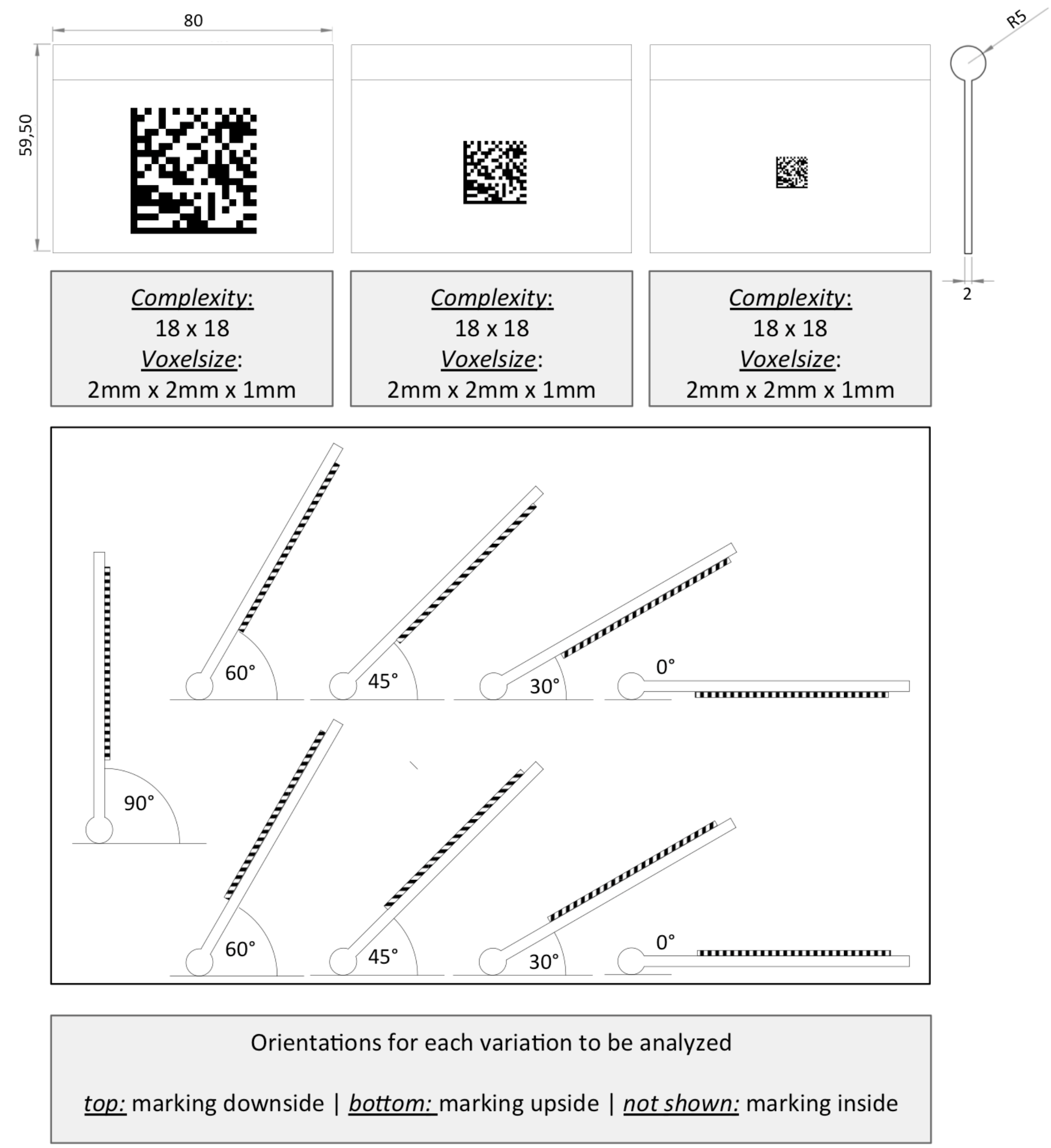

Figure 5: Test set-up of specimens; variations in size and build orientation

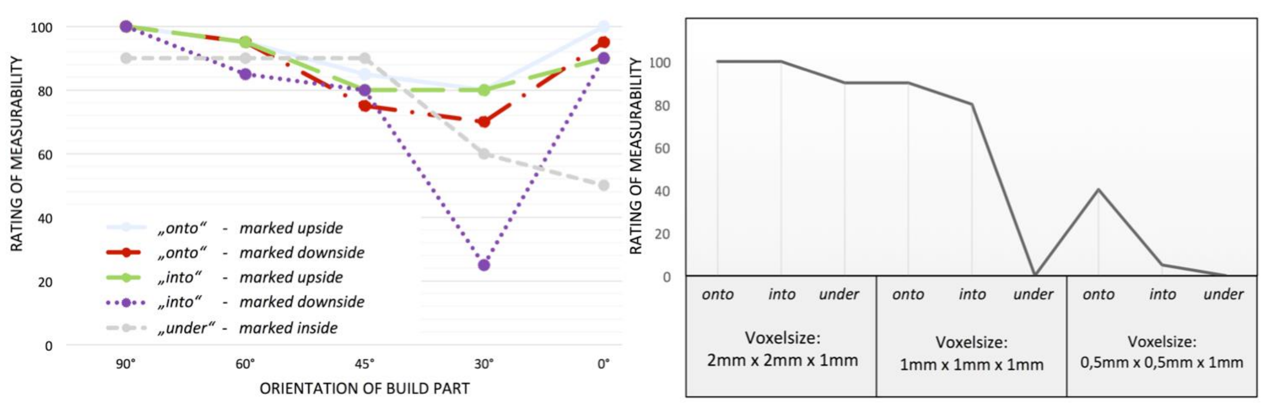

Figure 6: Analysis of test results
<u>left</u>: Relation of measurability and build orientation for voxelsize 2mm x 2mm x 1mm
<u>right:</u> Measurability depending on voxelsize and geometric alternatives “onto”, “into” and “under” with fixed build orientation of 90°

Figure 6 shows on the left side a rating of the measurability of specimens with markings manufactured in different orientations. The measurability assessed in terms of time and distance decreases in the angles of 60°, 45° and more extreme with an angle of 30°. The test specimens build in 90° and 0° have better quality. Only markings that have been "printed" under the surface have a decreasing measurability from 90° to 0°. As a best practice producing the marking vertically to the layers can be derived. On the left side only the biggest voxelsizes are anaylzed.

The trend that is shown in *Figure 6* is obviously visible. The quality of the markings in terms of measurability decreases with decreasing voxelsizes. The markings under the surface are only readable in the biggest size that was tried here. The first conclusion is about the size, bigger markings lead to better quality. Smaller markings can also be readable but take much longer with the used equipment. Further tests have to evaluate if better equipment can absorb worse quality due to smaller sizes.

Process definition for automated marking integration

One risk for the acceptance and therefore for the broad application of production integrated markings for AM is the manual effort. If it will be necessary to touch each part of a ready designed part class just to integrate a marking even if several instances of a part class should be manufactured, the fewest companies will decide for a holistic marking of their products.

Therefore at the Paderborn University a software solution has been developed demonstrating an approach for automated product marking to lower the hurdle of application in reality. *Figure 7* shows phases of the process from a digital parts design to a physical marked part that is ready for traceability. The description of the single phases will show that there is minimal manual effort necessary to achieve a production integrated marking.

Phase 1: Digital representation of part

The most common digital representation of a part is the format STL. It contains the information about all planes which defines the part. Therefore it is a plane-model of the part. STLs can contain the possibility to put two or more STLs together in one STL very easy. So it becomes possible to create a STL-Model of a code to mark the STL-model of the part and merge them together. Experiments showed that it is possible to merge STLs to a printable new STL.

Phase 2: Initial definition position for marking for each part type

Instead of marking each part with a new code it is possible to define a marking pattern for a part class with type of marking (e.g. according to the specification of GS1), a position and an orientation for the marking. Thus it becomes possible to code parts automated by software algorithms. All information needed can be put as code into the pattern and then a new STL will be generated automatically. For new markings it is possible to generate a new STL-representation of the code on the right position and orientation and merge it with the digital representation of a part class. Thus the desired number of parts to be printed can be marked without manual effort.

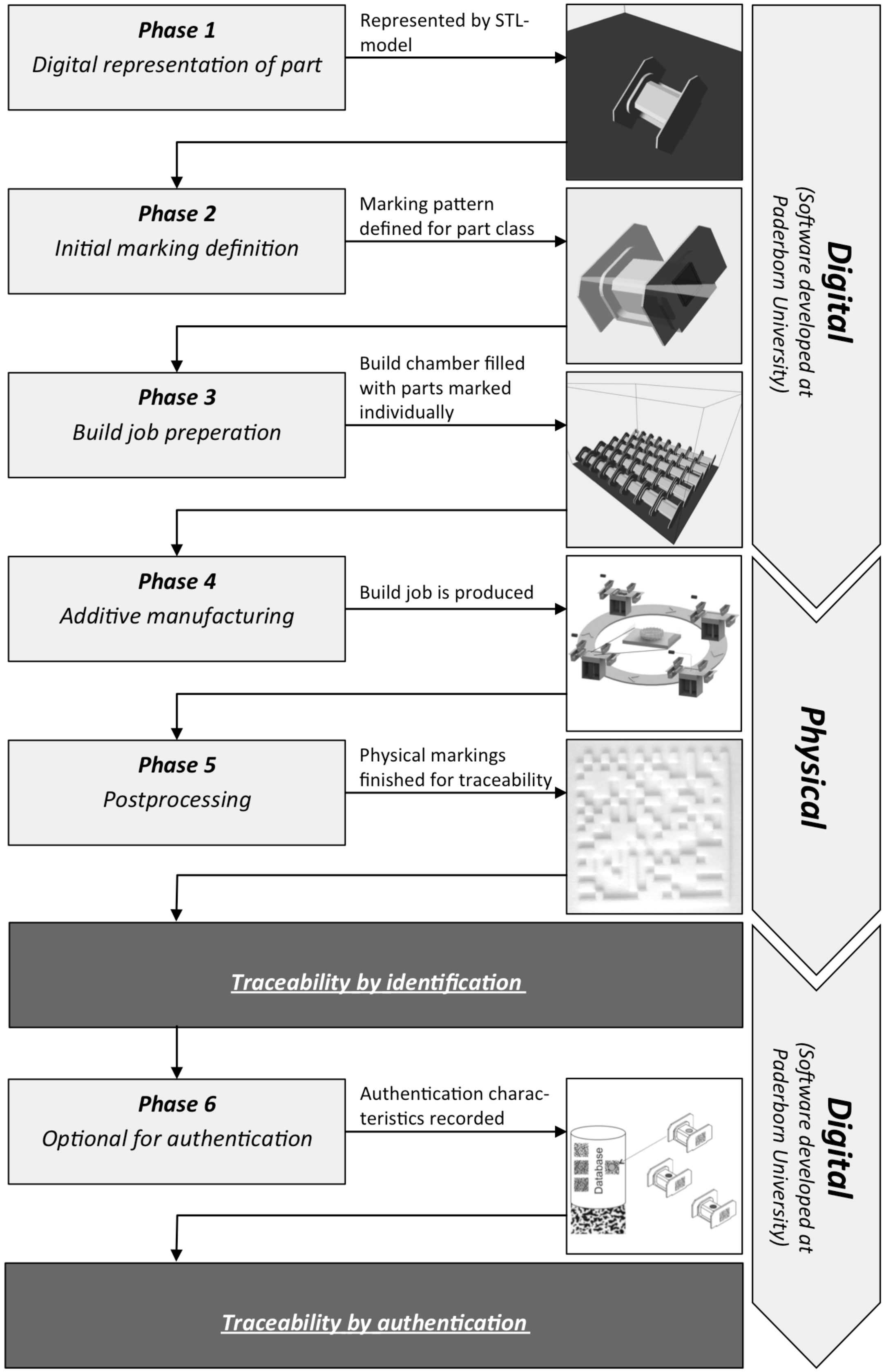

Figure 7: Process definition for automated marking integration in digital and physical phases

Phase 3: Build job preparation

The definitions and possibilities which were described in Phase 2 are now useable to mark entire build jobs. After the positioning and orientation of all parts they can be replaced by marked instances of their own. While position and orientation are also known, this information can be put into the marking too. This allows a very good traceability and quality assurance. Due to algorithms it is easy to automate this once the rules and specifications are determined.

Phase 4: Additive manufacturing

The marked build job is now ready to be printed. The difference in production costs and time to manufacture the parts with or without marking is roughly not existing. There might be a minimum of material needed more or less but this deviation is very small. This might be the biggest advantage for marking parts manufactured additively: The production of integrated marking itself is for free.

Phase 5: Postprocessing

After the build job is finished a post-processing is needed as always. Beside the normal process it is possible to include a automated quality check of marking here to ensure the traceability.

Phase 6: Optional for authentication markings

If a code or a specific geometry has been added to the part it can optionally be checked for process specific defects and errors that are not reproducible or will at least result in different defects. Those specific errors are very similar to biometric characteristics and can be used to authenticate a part. Therefore the characteristics have be stored in the database for a comparison later on. In the case of guarantee and/or live time quality it is possible to trace exactly when and where the build part was produced.

Approach for authentication markings:
Several test have been performed using Laser Sintering of the test specimen not equipped with markings but with various geometries to analyze with kind of geometrical detail is supposed to be produced with defects. This is a similar approach like to derive design rules but just the other way around. Geometries that cannot be produced by the machine correctly will create very unique structures that can be compared with a fingerprint. To determine promising geometries it is necessary to manufacture a stochastic representative number of parts in multiple build job with exactly same parameters and conditions like powder material etc. It has to be ensured that post-processing, in particular when blasting is used, is done in the very same intensity. An example is given in *Figure 8*. The test specimen has been manufactured two times with the same orientation and the same positioning in the same machine with same parameters and material. Different geometries like radii and angles etc. have been implemented in different sizes to this specimen in same three alternatives as tested for marking described above: onto, into and under.
Both parts have been photographed under same light conditions to achieve a comparability. By a detailed inspection a couple of defects and differences can be detected with the eye but thus it is hard to quantify the degree of difference. Using software tools and algorithms there is no doubt that those defects can explicitly distinguish parts produced under same conditions. But to achieve a authenticating traceability over lifetime geometries under surface are more promising due to wear and abrasion on the surface.

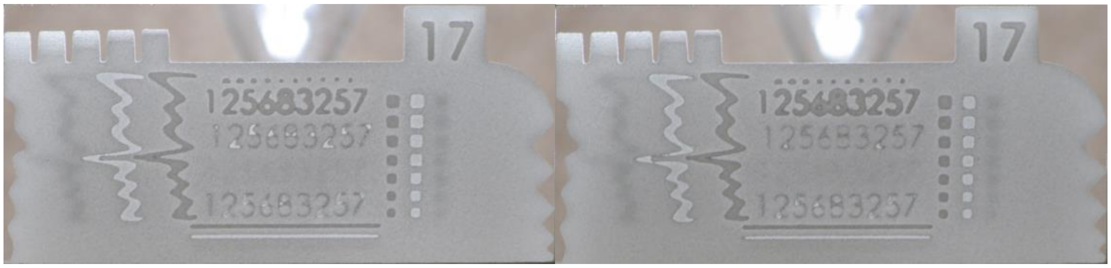

Figure 8: Test specimens for derivation of authenticating characteristics

Conclusion and outlook

Using AM costs for production of integrated product marking are not increased as there is no need for tools or assembly after production. Therefore there is no reason for not marking parts directly using AM. Also without the need of automation of production or aiming at the vision of industry 4.0 a marking helps at least in the field of product piracy and quality management. The only cost driver for integrated marking arise due to the effort of data preparation in particular when done manually. The software solution developed at Paderborn University demonstrates that automated marking decreased the effort for markings by far. But in the best case it requires an integration already in the product development process so that marking patterns are defined already by designers that know about the functionality of the part.

The methodological approach for derivation of best practices and specification of for robust markings has been proofed. More tests and build jobs under same conditions are now necessary to confirm the results.

As shown in *Figure 1* it was always technological innovation acting like a game changer from revolution to revolution and the time intervals decrease from time to time: When will we expect the next revolution?

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