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Single part tracking enabled by fluorescent Polysecure tracing particles in AM parts

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Abstract

Traceability is widely recognized as a core enabler of many industry 4.0 technologies. The necessary identification of products is often realized through label-based systems, but tracing products with particular geometric constraints that prohibit the use of such systems remains an issue. A promising alternative of label based identification is the pattern based identification. This contribution portrays a novel method to utilize fluorescent particles integrated in polymer-based products and optical pattern recognition to facilitate the identification of products with specific geometric constraints. The particles are integrated into the polymer and the unique random distribution of fluorescent particles triggered by an LED flash is used to recognize individual products. To demonstrate the approach, polymer-based gear wheels were printed using ARBURG plastic freeforming and an automatic identification system was designed. The presented approach could be a reliable alternative to other surface-structure-based approaches for product identification and enable comprehensive tracing of components throughout value-chains.

Introduction

In the last decade the digitalization of production systems under the term industry 4.0 has taken hold throughout several branches of industry. One of the central building blocks of these advances is traceability, the ability to provide information regarding a product throughout its lifecycle. Traceability can enable better efficiency throughout production control, limit the consequences of production related defects, and plays a vital role fighting fraudulent products. Furthermore, traceability can enable the operation of efficient circular economy systems, a topic which has seen rapidly increasing interest. Here traceability supports the sorting and routing of products at their end-of-life (EOL).

Traceability includes both the capture and provision of information. Information capture includes the ability to automatically identify products and components and the collection and assignment of data describing the condition of the product and its environment, as well as process characteristics. Information provision describes the ability to efficiently provide this data where it is required. To identify products a wide range of technologies exists. The most commonly used ones include alphanumerical codes, data matrix codes (DMC) and Radio-Frequency Identification (RFID) tags. In some circumstances, however, these technologies are not applicable due to space limitations, security requirements or cost limitations. Alternatively, to these label-based systems, pattern-based systems can be used, for example identifying products by their surface structure, chemical compounds or other characteristic properties. While several such solutions exist, their application in practice has largely been limited to specific niches. This paper discusses a new pattern-based identification system for polymer products. This system could enable the cost-efficient instance specific identification of polymer based products throughout their lifecycle.

The solution is based on proprietary tracing particles from Polysecure, a Freiburg-based company. These fluorescent particles can be activated using a controlled lightsource. Currently the particles are applied to large scale polymer parts to identify different materials for example enabling the efficient sorting of different polymers in a recycling plant. Combinations of particles with characteristic colors are assigned to specific materials to enable them to be distinguished from each other. The particles can then be identified either by their color or their characteristic discharge time. This method allows the identification of n^2 different materials, where n is the number of available distinct colors. While this is sufficient for the distinction of polymer classes in a recycling context and can also be used to verify the origin of a product, it does not provide enough information to identify specific product instances. For this new traceability systems pattern recognition is used, identifying products based on the naturally occurring unique distribution of particles throughout the product.

A polymeric gear wheel from an electric actuator was chosen as an exemplary product to test the new particle-based traceability system. The traceability system was implemented in the learning factory global production at wbk institute of production science in Germany. The learning factory includes an assembly line for the electric actuators as well as a remanufacturing line where the actuators are disassembled, conditioned and reassembled at their EOL. This paper presents the newly developed traceability solution for polymer-based products.

State of the Art

Various existing particle and pattern-based ID solutions and their applications in industry are described below, followed by a detailed description of the Polysecure technology and its role in additive manufacturing.

Particle- and pattern-based ID solutions and their applications. A crucial component of traceability systems are identifiers. The most common ones in industry are alphanumeric codes, barcodes and RFID systems [1]. Other identification systems are based on peculiarities of surface structures or on chemical or biological markings. There are various categories into which these marks can be classified. One possibility is the classification into tamper-evident marks and auto-ID identifiers. Tamper-evident marks can be used to check whether a product corresponds to its declaration, i.e. whether it is an original part. They are forgery-proof and therefore cannot be easily copied. However, unlike auto-ID marks, these technologies cannot store any further information. The only information they can provide is whether the object is genuine or not [2]. In the case of tamper-evident markings, a distinction is made between overt and covert markings. Overt markings are visible to the human eye and are often obviously attached to the product. Concealed markings, on the other hand, are invisible and can only be checked with special equipment [3]. Table 1 shows an overview of the existing particle- and pattern-based ID technologies. In the following, some singular markers are presented that have features of the Polysecure technology, e.g. they are particle-based, pattern-based, fluorescent or use image recognition.

#Image recognition: Holograms are photographic images produced with laser light that reproduce a three-dimensional image of the original object when illuminated with similar light. The integration of complex features and structures makes it impossible for counterfeiters to copy holograms. Typical areas of application are medical products, packaging and banknotes. The decisive factor in successfully combating product counterfeiting through holograms is their exact verification and comparison with the original hologram. This comparison can be done either by machine or by an expert. [4]

Table 1: List of different particle- and pattern-based ID technologies.

Tamper-evident marks		Auto-ID identifiers
Overt marking	**Covert markings**	**Machine-readable**
Holograms	Electromagnetic features	Copy Detection Pattern (CDP)
Colour shifting inks	IR-/UV-colour pigments	Laser surface authentification (fingerprint)
Security threads	X-Ray fluorescence	DNA markers
UV inks	Photochromic colours	Organic and inorganic markers (e.g. Polysecure)
Security paper	DNA markers	
Watermarks	Bacteria markings	
Die-cuts	Digital watermarks	
Thermo-reactive and thermochromic colours	Organic and inorganic markers (e.g. Polysecure)	
Digitally printed pattern	Microscopic plastic particles	
Surface pattern	Micro-overprints	
Stampings	Marks with rare earths	
Engravings		
Colour-codes		

#Pattern-based: In die-cutting, a company logo is usually created on packaging, paper or a product. Since the pattern is visible through the embossing and can be easily felt, no ink needs to be used. Die-cuts are also used for packaging seals. The die-cuts make it impossible to peel off the packaging label without destroying it. [3]

#Fluorescence: UV ink is a type of special ink that is not visible under normal lighting conditions but fluoresces under UV light. The ink is printed onto the product or packaging using special printers. It is mainly used for discreet labelling of alcohol, tobacco, pharmaceutical, and software and music products. One advantage of UV ink is that it adheres to various substrates such as paper, glass or metal. [3]

The UV-BioTAG^{TM} Microorganisms were developed to rule out possible cross-contamination in food samples caused by unclean work in the laboratory. The marker consists of a microorganism that expresses a protein that fluoresces green under UV light. It is cultivated in the laboratory with the food sample on the same culture medium. If only green fluorescent colonies grow under UV light in the area where the UV-BioTAG^{TM} was applied, it can be concluded that there is no cross-contamination. [5]

#Off-product tracer particles: DNA markers can be used both as a covert tamper-evident marker and as an identifier in track-and-trace systems. Although the technology has only recently become commercially available, it is already being used in the food sector, the textile industry, the pharmaceutical industry and on cigarette packs, among others [6–9]. DNA molecules are linear chains whose building blocks are four different nucleotides. Since it is easy to convert quaternary code into binary code, this nucleotide sequence can be represented as binary code [10]. For example, customer-specific codes or product information can be stored in DNA sequences. Depending on the provider, these sequences are then sprayed, glued or even directly incorporated onto the product or packaging [11]. The information stored in the DNA can then be translated again via polymerase chain reaction (PCR). DNA markers have also already been used at the Pentagon to unmask counterfeit electronic products. For example, the ministry has obliged the manufacturers of certain devices to place a manufacturer-specific marker in the form of DNA sequences on their products [12]. In the course of the breast implant scandal, in which a French manufacturer of breast implants stretched them with inferior industrial silicone, a marker was developed at the Fraunhofer IAP from tomato DNA sequences. By reading the tomato DNA, it is possible to determine whether the concentration of the high-quality silicone, which is compatible with humans, has decreased in the implant. Thus, a stretching of the high-grade silicone can be detected [13].

#Native tracer particles: In the protein fingerprint method, no labelling in the classical sense is attached to a product. Instead, in a research project at the University of Hawaii, naturally occurring proteins in honey were analysed to determine its origin. It was found that the proteins of different types of honey from the same region have a very similar structure. Thus, with the help of a database, it can be checked whether the honey in question really comes from the region indicated on the packaging [14]. The procedure is reminiscent of the principle of DNA barcoding, which involves comparing the DNA sequences of animal or plant species in order to trace their degree of relationship [9].

Polysecure technologies and the particle fingerprint: The Polysecure Company has the vision of enabling an efficient and sustainable circular economy. For this purpose, they use small glass-ceramic markers, organic macromolecules or inorganic crystals as tracing particles. The latter are excited to fluorescence by lasers or LEDs and thus made detectable. Fluorescence describes the spontaneous emission of light and happens when electromagnetic radiation reaches a substance.

One of the company's main focuses is the separation of plastics by type. Nowadays, these are only separated according to the dominant main polymer, but not according to the numerous subclasses or uses. Mixing during recycling means that plastics can no longer be used for their original purpose. The plastics would have to be sorted at the end of their life cycle much more precisely and in a way that is appropriate for further cycles. With its tracer-based sorting technology, Polysecure offers a process that allows products to be sorted precisely into freely definable fractions at the end of their life cycle. The material is already marked with fluorescent markers (tracers) during the production of a plastic product. The amount of marker required per plastic is in the range of a few micrograms and does not represent a significant cost factor. The markers can be applied by incorporating them into the printing ink or into the plastic itself. Another advantage of the process is the high detection quality. Deformation, dusting or geometry of the product have no influence. Polysecure has already successfully validated a system for separating PVC flakes containing glass fibres. Further development into a pilot sorting plant for products such as packaging, textiles, shredded vehicles, white goods, insulating foams and more is under construction.

In addition to material sorting, Polysecure develops, produces and markets other solutions for tracing plastics: these are product authentication, individual product labelling and tamper-proof material verification. All these solutions can be realized by the particle fingerprint. For implementation, the tracer particles are included in the polymeric material since production and arrange themselves randomly during solidification, creating a kind of "3D starry sky". The particle pattern is identified by means of excitation, camera and the Polysecure algorithm. It compresses the image of the particle fingerprint into a binary hash that is stored and can be found again in a database. Each random pattern is unique and can thus identify each individual product inline in a forgery-proof manner. The number of different fingerprints is almost unlimited. Even extremly small products can be individually marked and identified with the particle fingerprint. The tracers can be used over several years and product life cycles, as they are durable. The benefit is a robust, non-copyable, invisible, individual fingerprint of a product, reference for a digital twin and material passport, the unique assignment to an overall product. Commercialized applications for an individual part tracking haven been realized with injection molded products but not with additively manufactured parts. This further enables tracking realizations for complex geometric forms or miniaturized individual products, to name some examplary applications.

AM parts. Besides the plastic parts that are ubiquitous in our daily lives, additively manufactured parts are also becoming more and more common. The advantages lie in the production of complex geometries, the very fast delivery of spare parts and the production of prototypes. Furthermore it is ideal for products in small batch sizes [15]. Our goal was to investigate whether the Polysecure marker particle technology is compatible with additive manufacturing processes as well and which adaptations have to be conducted.

Polymer additive manufacturing includes powder-based processes like laser sintering or binder jetting. Essential for these processes are fine polymer powders, manufacturer-specific binding fluids and high-priced components like lasers [16]. On the other hand, material extrusion of thermoplastic polymers is the most common additive manufacturing technology. FDM is a low-cost and widely used material extrusion process for rapid prototyping. A large range of different polymers can be processed in form of wire-like filaments. Commonly used polymers are for example polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and polypropylene (PP) [17]. These filaments are produced by melting granules and extruding thin strands with a constant diameter. Printers are available that can directly process the standard industrial granules. The company ARBURG offers such a 3D printer named Freeformer [18]. The printer uses a plastification unit with an extrusion screw known from injection molding. Instead of filling a mold tool, a piezo-actuated nozzle produces a droplet strand with a controlled volume. Hence economically, the Arburg Freeformer is the more suitable 3D printer, as it prints the granules directly and saves one process step compared to an FDM printer, where the filament first has to be extruded.

Material & Methods

A single-part tracking of 3D-printed polymer gears was developed as a use case. In the following, the use case is described in detail, starting with the insertion of tracer particles into the additively manufactured gear, its printing process, up to the application and integration of hardware and software for tracing. Figure 1 gives an overview of the steps carried out.

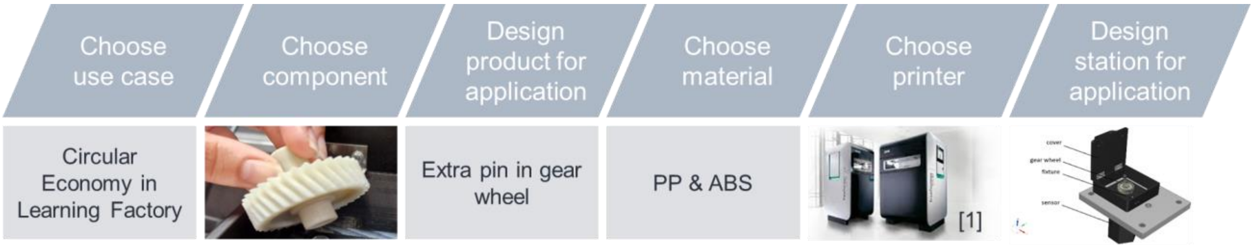


Figure 1: Overview of approach and carried out steps to realize the particle fingerprint for an individual part tracking. Picture [1] Arburg.com.

Manufacturing AM parts with tracing particles. Commercially available PP Lupolen 1800H from LyondellBasell and ABS Terluran 35 GP from BASF were selected as materials for the AM process. PP is a wide used polymer especially in food packaging applications as it is biocompatible. ABS is the most reported material used for the Arburg freeformer printer.

A masterbatch was prepared by mixing the polymer granules, adhesive oil and Polysecure tracing particles in a standard compounder. After extruding, the polymer strand was granulated. The masterbatch contained 100 ppm of the marking particles with a mean particle size distribution of approximately 120 µm. Next, a suitable printing technology had to be chosen. The first experiments were carried out with a commercial FDM printer Original Prusa i3 MK3S+. A filament with the diameter of d = 1.75 mm and a nozzle diameter of d = 0.4 mm are used. The FDM printer requires a preliminary step to produce the filament. For this purpose, an extruder (Felfil) was used. For further experiments, the Freeformer 200-3X from Arburg was employed. It prints the granules of the master batch directly, which is more resource and time efficient. Optimal printing parameters for the marked material had to be determined. In addition, the influence of the tracer particles and their size on the printing process in terms of wear was to be investigated. As a base for the printing parameters the publication of [19] was used for printing with ABS, and the publication of [20] for printing with PP. The polymers PP and ABS were delivered from Polysecure.

Hardware development: As hardware components, a proprietary sensor unit developed by Polysecure was used. This unit includes both a camera as well as an IR-Light setup. For demonstrator setup and integration in the institute's learning factory assembly line several requirements had to be defined and met:

- Requirement 1: Need of a fixture to prevent rotation of the gear and to have a defined distance for measurement. The particle pattern of each gear wheel is unique. The measuring window concerns a 1x1 cm area on the gear wheel where the particle pattern is read in. The image of a gear must always be taken at the same place so that it can always be assigned to the same gear.
- Requirement 2: Modular approach to be changeable. A modular design of the fixture and the entire Polysecure tracing particle unit is required. A modular design of the fixture allows easy replacement with another fixture for a different type of gear. A modular design of the whole unit has the advantage that it can be moved to another place in the assembly line or in the remanufacturing line.
- Requirement 3: Prevent IR light exposure endangering user's eyes.
- Requirement 4: Simple operation of the software and hardware. The number of motions should be reduced to a minimum.

Software development: The identification of parts is realized using the image captured by the camera. For this purpose, a proprietary algorithm was designed. For each image, first the brightest particles are identified. The number of selected particles can be adjusted depending on the particle density within the part. Each of the selected particles is subsequently assigned a specific position. The similarity of the sets can then be calculated. Using this method individual missing particles do not affect the identification of the part. Due to this and the ability of the sensor to detect particles up to a depth of 100 µm, surface level abrasion does not immediately affect the recognition.

Results

Manufacturing AM parts with tracing particles. The basic question of the investigations was whether the materials PP and ABS with tracer particles can be processed with the Freeformer. The influence of the tracer particles needs to be determined and the process parameters must be adjusted accordingly. In the end, the correct ratio of tracer particle and polymer must be identified for fast and simplified recognition of parts.

In principle, PP could be processed with the tracers, but PP is generally a complicated material because it is a semi-crystalline polymer. This leads to enormous volume expansion during printing when the temperature is high and to subsequent deformation due to contraction during cooling. By optimizing the printing parameters, the phenomenon could be significantly reduced. It remained unclear whether all tracer particles were extruded through the annular gap, since according to the manufacturer, the annular gap size was only 12 µm, but the tracers mixed into the master batch had an average particle size of 120 µm. Analyzing the “starry sky” pattern of the printed PP part, an average particle size of d = 25-50 µm was found. It is possible that the nozzle was subject to wear. Particles larger than 12 µm could pass the annular gap at these points of wear. Even larger tracer particles, on the other hand, were retained on the inside of the nozzle. These could lead to critical blockage in the long term. Polysecure describes the tracers as round, hard, and crystalline.

Moreover, the standard ABS Blend printing plates from Arburg proved unsuitable, as the PP material did not adhere to the plate and clumped or warped. As a result, a PP sheet was used, which significantly improved the results.

Table 2: Series of experiments to investigate the printing of PP tracer material with the Freeformer under variation of the printing parameters. Parameters kept constant: Mass pressure 330 bar; Application speed 150 mm/s; Build chamber temperature 80 °C.

	1 based on [20]	**2**	**3**	**4**
T / °C (Nozzle - Extruder Zone 2 - Extruder Zone 1)	230-220-220	230-220-190	190-180-160	230-220-190
Layer thickness / mm	0,12	0,2	0,2	0,2
Discharge number / %	40	85	85	85
Form factor	2,12	1,7	1,4-1,7	1,4-1,45-1,5-1,55-1,6-1,7
PP printing plate	no	no	yes	yes
Printing result	Probably the most promising results when using a suitable underlay of the same material. Missing PP underlay leads to displacement during printing	Deformation, see Fig. 2	Temperature too low leads to volume shrinkage, material deforms plastically after 3D printing	Deformation becomes smaller with higher form factor, material deforms plastically after 3D printing

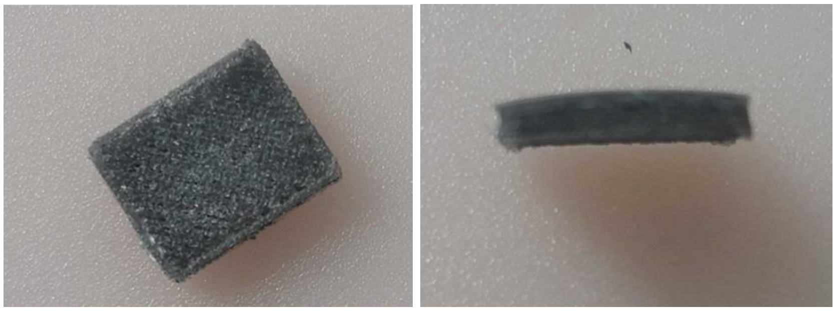


Figure 2: Experimental result no. 2, see Table 1, of PP print with Polysecure tracer particles.

However, the parts printed with PP were limited to flat cuboids. Larger structures caused warping and extruded material adhered to the nozzle clogging it. The main difficulties are refered to the polypropylen itself and are not only caused by adding the tracer particles. Further investigations have to be carried out.

To produce larger parts for industrial applications, the polymer used for the masterbatch was switched to ABS. This polymer is one of the standard materials for the Freeformer whereby better printing results were expected. The following printing parameters were used: the nozzle temperature was set to 250 °C, the build chamber was heated up to 80 °C, for a layer height of 0.15 mm the discharge number and the form factor were adjusted to 80 % and 1.6 respectively. To print components with overhangs, a support structure is required. Arburg offers a water-soluable polymer named Armat 11 for this purpose. With this support material and the second discharge unit in the Freeformer, it was possible to produce a more complex component such as a gear wheel for an electric actuator (Fig. 3).

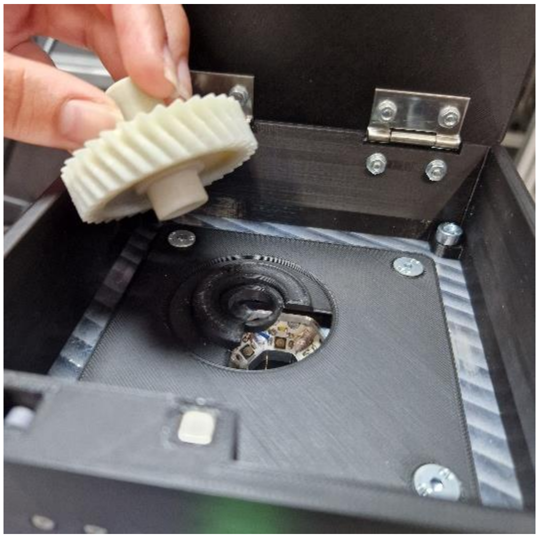


Figure 3: Printed gear wheel consisting of ABS and Polysecure tracing particles with fixture.

As shown in Figure 4, the unique distribution of particles can be captured using the setup described above. The image shows the particles within a defined area of the gear wheel. Using this image, a defined number of bright spots can be identified. The "starry sky particle pattern" was evaluated by Polysecure by measuring the particle size and counting the particle number. The biggest tracers found had a diameter of 18 μm, the number of particles found was 500 particles / cm².

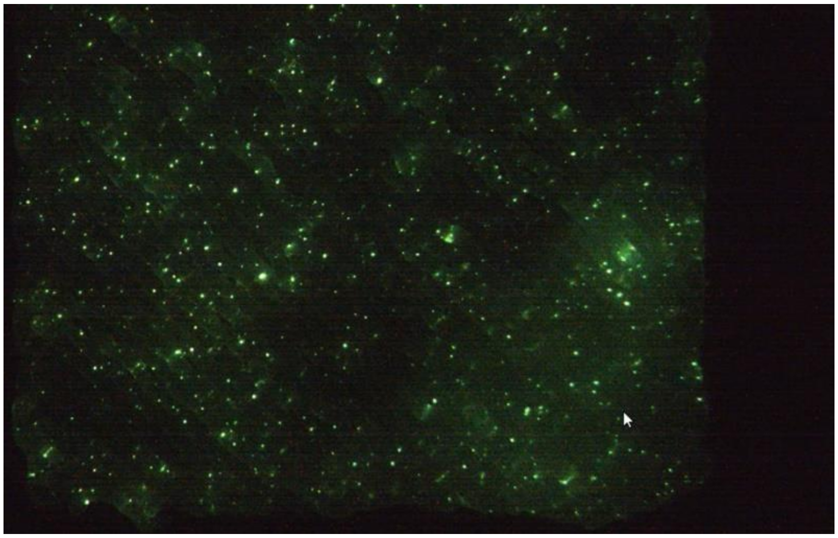


Figure 4: “Starry sky” pattern based on ABS print with fluorescent Polysecure tracing particles. Cutout 0.5x0.5 cm. 500 particles / cm² were detected.

Summing up, it was found possible to produce components with additive manufacturing methods that are filled with tracer particles. The PP masterbatch could not be processed into more complex parts. Unsatisfying inter-layer adhesion as well as deformation due to semi-crystallinity made it impossible. The ABS with tracer particles was considerably easier to process with a standard parameter set. The size of the tracer particles causes wear inside the discharge unit. The fluorescent images of printed parts showed extruded particles larger than expected as a result of their abrasive nature. Future research should investigate the impact hereof.

Hard- & software development for the use case. Solutions for the required criteria are presented in the following enabling a stable, simple, safe and changeable application of the Polysecure technology.

- Solution for requirement 1: To meet the criteria of stable measurement, the geometry of the gear wheel was slightly modified: an additional pin was integrated, which positions the gear wheel in a fixed manner in a support device (see Fig. 5). A gear wheel support device was designed. With this fixture the same defined distance between the detection plane and the camera is always guaranteed and a stable measuring process can be established. Camera parameters can be set and safed accordingly.

Figure 5: Tracer-based gear wheel. Tracing particles are not visible until excitation with IR light.

- Solution for requirement 2: Modularity was achieved by integrating the Polysecure unit into the standardized modular design according to which each learning factory station is built, with standardized geometric dimensions and the ability to be operated as a stand-alone unit (see Fig. 6 left). To achieve a quick change of the product to be measured, the support device for the product as well has to be changed (see Fig. 6 right). For this occasion the support device was designed as well as a stand-alone unit placed with 4 screws on the measurement unit. Thus, it can be switched according to plug and play mode.

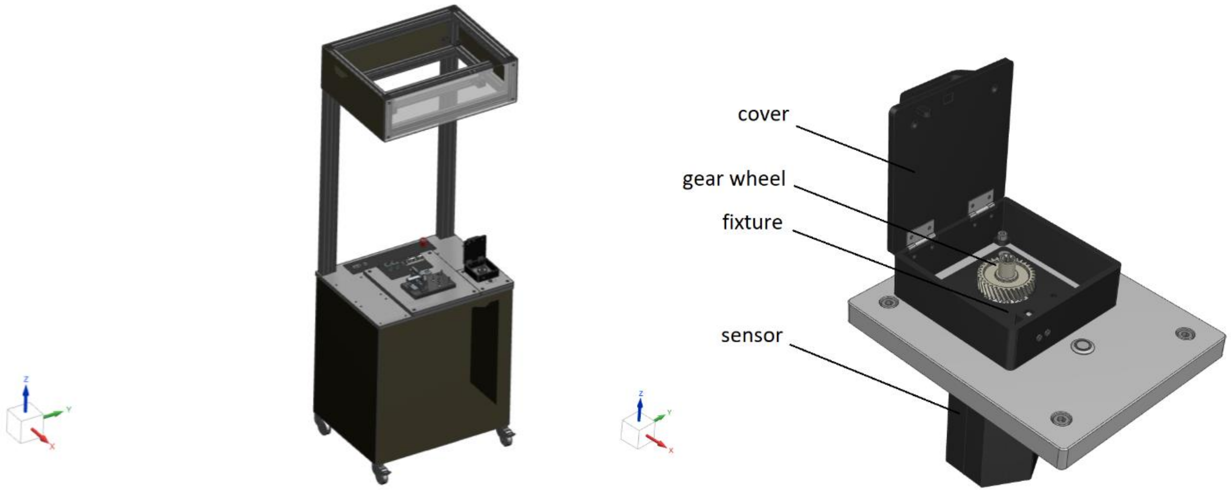


Figure 6: Integration of module in a learning factory station (left) and composition of the identification module (right).

- Solution for requirement 3: To deal with the danger prevention coming from the IR light, a cover with an integrated button was designed (see Fig. 6 right), so that a measurement only starts when the cover is closed. The closed space in the housing also prevents external light from entering (hall lighting/light at the assembly station), which is important in this case because the camera is oriented from bottom to top.

- Solution for requirement 4: Simplicity. The number of motions was reduced to four: Open cover → insert gear wheel into fixture → close cover → press button (see Fig. 7). On the software side, simplifications were made as well. A software update with reduced settings in the GUI was written. It contains two modes, the "register mode” where the product is registered and an ID is assigned, and the “matching mode”, where the product is recognized. The output shows the captured image of the particle pattern and the matched image in comparison (see Fig. 8).

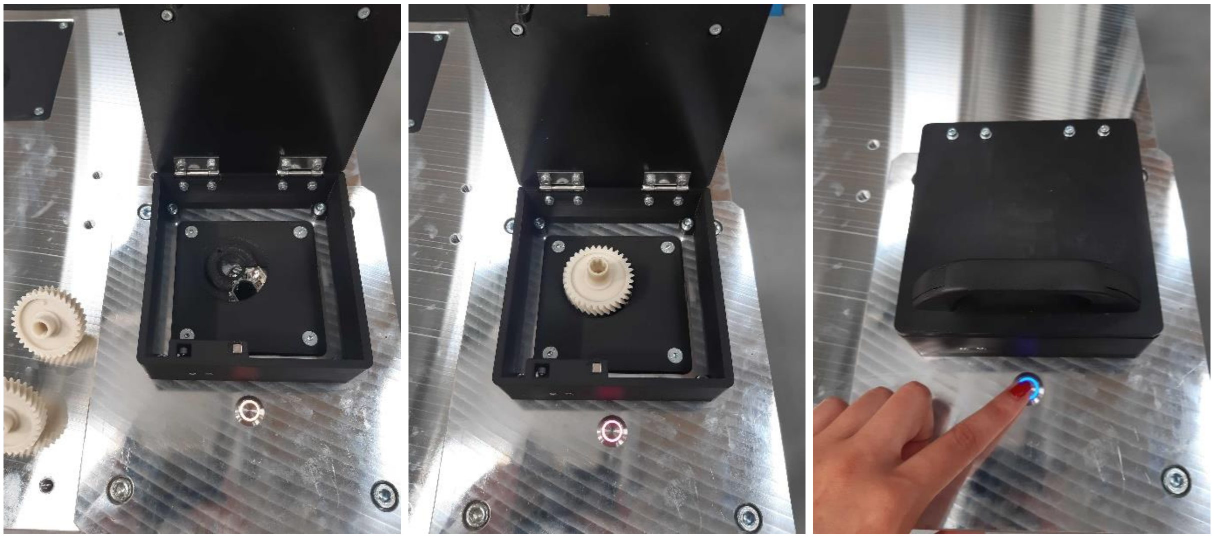
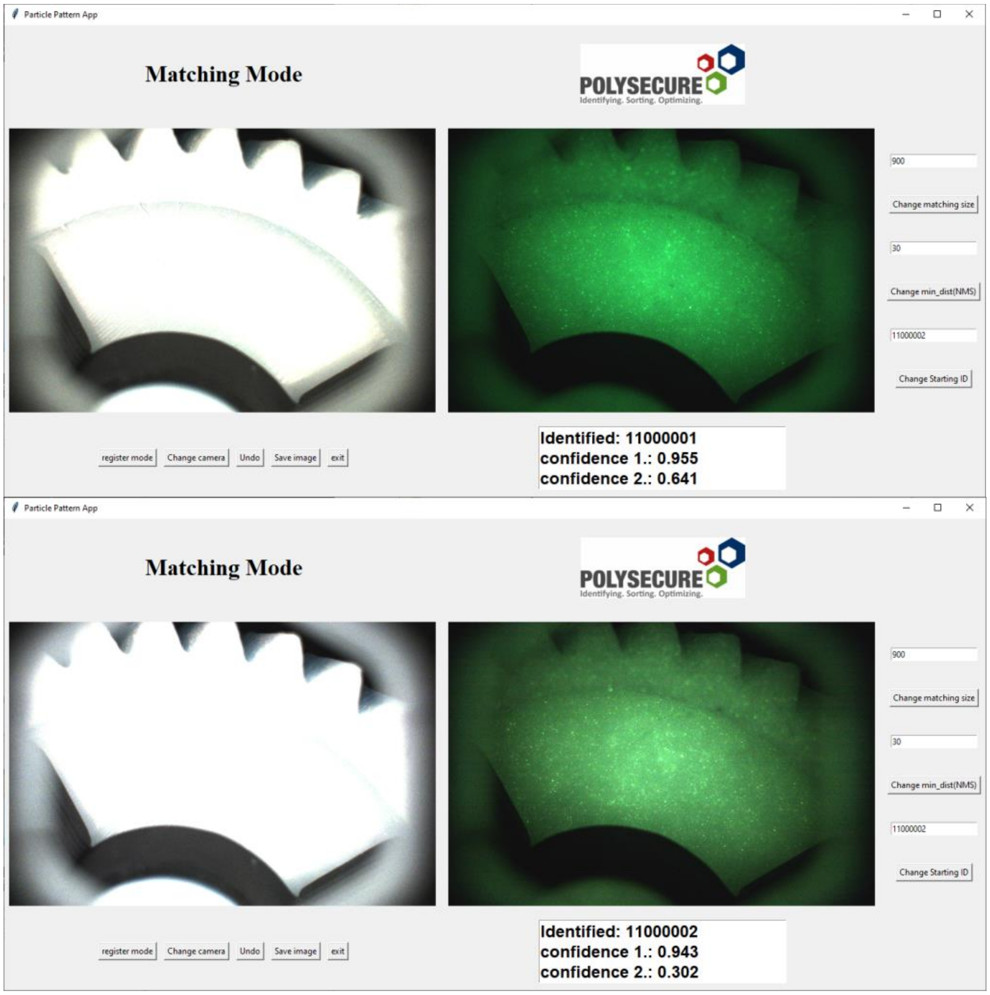


Figure 7: Handling for measurement process of tracer-based gear wheel, from left to right: Open cover → insert gear wheel into fixture → close cover → press button.



Particle Pattern App

Matching Mode

900

30

11000002

Identified: 11000001
confidence 1.: 0.955
confidence 2.: 0.641

Particle Pattern App

Matching Mode

900

30

11000002

Identified: 11000002
confidence 1.: 0.943
confidence 2.: 0.302

Figure 8: GUI shows the match of gear wheel No. 1100000-1 (top) and No. 1100000-2 (bottom). Measured and registered fingerprints are equal. Gear wheels were succesfully re-identified.

Using the above described station, the gear wheels can be individually detected. The functionality and reliability of the system was tested using three 3D printed gears. The system is able to detect up to a billion different individual gears. The test of a bigger sample size of gear wheels is currently underway.

Conclusion & Outlook

The successful integration of Polysecure tracing particles in polymeric AM parts was shown. The product-dependent and thus time-consuming fixing of the component has proven to be a disadvantage. In addition, the nozzle is worn out by the tracer particles during the printing process. Further investigations are necessary for optimisation. Clear advantages of the Polysecure tracing particle technology are the short process time for identification. This is only a few seconds, the measurement itself only takes µsec. With this technology, a unique ID can be generated and assigned for several hundred thousand different components. Even wear and tear on the surface does not limit the technology, as a 3D image of the particle pattern is created and the pattern recognition is robust, hence it works even with fewer data points. The additive insertion of the markers allows that even complex component geometries can be marked. The technology can be integrated into existing processes, and a combination with previous material sorting technologies is also possible.

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