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Marker-Free Traceability in Battery Production from Continuous Electrode Foils to Cell-Specific Individual Electrode Segments

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This article presents advancements in the Track & Trace Fingerprint technology applied to lithium-ion battery production, focusing on its innovative approach to material identification using unique surface microstructures. Traditional traceability methods often compromise material integrity through physical markers or fail when continuous material (e.g., electrode or other web material) is interrupted. This technology eliminates these issues by leveraging marker-free identification, enabling reliable tracking of continuous and segmented electrode materials without altering their properties. Experimental results demonstrate the effectiveness of the technology across various materials, including aluminum, copper, graphite, lithium-iron-phosphate, and nickel-manganese-cobalt coatings, with high identification rates and robust traceability. Additionally, software enhancements have improved predictive algorithms for estimating fingerprint locations, increasing processing speed and efficiency. Future developments will focus on graphics processing unit acceleration and optimized local database management to increase the current supported feed rate from 25 m min^{-1} to 60 m min^{-1} or more to broaden applicability. The technology's versatility extends beyond battery production, with potential applications in other continuous manufacturing processes, such as paper and steel production.

1. Introduction

1.1. Traceability in Lithium-Ion Battery Production

Traceability plays a critical role in the production of lithium-ion batteries, as it ensures the quality, safety, and reliability of battery cells throughout their lifecycle. With increasing regulatory control from the EU, manufacturers are driven to provide increased transparency across the supply chain.[1] This includes not only the origin and composition of raw materials but also information related to production processes, repair or reuse options, and end-of-life solutions, such as recycling and recovery procedures. In battery production, cells are tracked after cell assembly using applied markers such as Data Matrix codes (DMC) or barcodes. Although marker-based identification methods of electrode segments have been documented in electrode strip production,[2] traceability of single cells usually takes place afterwards, as cell-specific identification using markers during coating, calendaring, and cutting cannot be achieved continuously. This limitation is due to spatial constraints on the electrode surface, the slitting of coils in the production process or the removal of electrode segments for defect management and quality control. If physical markers are used, it must ensure that at least one marker is retained.[3] Moreover, physical markers can negatively affect the material properties and pose a risk of material alteration.[4] For instance, laser-engraved identifiers may influence conductivity, while ink-based prints may introduce contaminants that interfere with the final product's functionality.[5] As the industry moves toward more automated and continuous manufacturing processes, the limitations and challenges of traditional identification techniques become increasingly apparent. Thus, indirect material tracking techniques using optical features of, for example, the electrode surface and camera-based image-matching have been studied but have not yet shown identification rates close to marker-based techniques.[6] Moreover, tracking the position by, for example, encoders or laser surface velocimeters, can become ineffective when they lose positional tracking or when continuous material like electrode or web material is cut or otherwise interrupted.

Traceability in other industry sectors that process continuous materials faces similar challenges related to identifying and tracking individual product segments. For example, in the paper or sheet metal industry, traceability is generally implemented at batch level using marker-based or wireless systems like RFID.[7]

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Factors such as the cost of identification technologies and tags or processing integration constraints often prevent comprehensive traceability at process level.

In lithium-ion battery production, traceability at process level is important as part of the quality management process and essential to ensure consistent cell quality and safety throughout the entire product lifecycle. It enables the correlation of inline process data with cell-specific product components. For example, individual electrode segments can be linked to their corresponding processing data such as electrode coating and quality parameters like coating thickness and homogeneity, mass loading, or areal capacity to promptly identify and correct defects, material inconsistencies and process deviations in the manufacturing process.[8]

Moreover, this enables a more in-depth understanding of the production process and improves product quality. High-quality data sets support data-driven production analysis to leverage data-driven approaches[9] to better understand, predict, and prevent incidents that might affect production yield and safety. Or briefly summarized: Traceability at process level increases product quality that reduces failures in the field, which in turn reduces potential critical accidents involving valuable assets or even humans.

1.2. Marker-Free Identification Technique

Track & Trace Fingerprint technology goes in a similar direction as the image-based approaches in.[6] It leverages what is already present on the material itself: Individual microstructure on their surface can be used to reliably identify objects among millions of others, just like a human fingerprint can be used to confirm someone's identity. This marker-free approach enables a direct link between a single item's surface and related data, as well as mitigating the risks associated with traditional methods.

Previously, the technology was aimed at identifying discrete parts with well-defined locations for fingerprint generation in production lines[10] or even in free fall.[11] However, recently, it was adapted for continuous electrode materials used in battery production.[8]

Two significant challenges arise when applying the Track & Trace Fingerprint technology to continuous materials: The absence of well-defined locations for fingerprint generation and the need for rapid processing speeds to keep pace with high throughput production. As the technology operates completely non-invasively, it does not mark the location where the fingerprint is generated and unlike discrete components, continuous materials lack visible landmarks that can be utilized for automatic localization (compare **Figure 1**). Consequently, the system must independently track the movement of the material and generate fingerprints at fixed spatial intervals to ensure that the material is covered over its whole length. The upside of this extensive approach is the ability to identify a section of material, regardless of whether it still belongs to a longer strip or has already been cut out. The technology is also independent of any positional information coming from external devices like rotary encoders. Additionally, the high feed rates that are characteristic for continuous production require fingerprint generation and tracing processes to operate efficiently and effectively to ensure a viable integration path into existing manufacturing workflows.

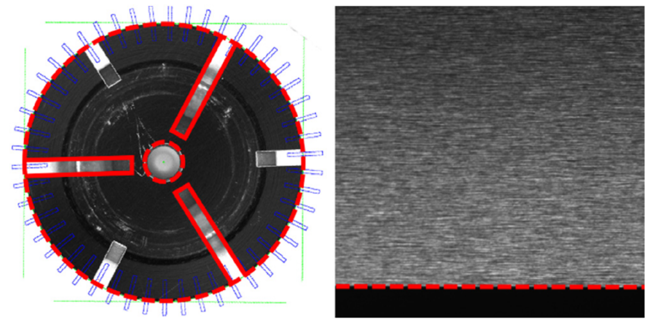

Figure 1. Comparison of a discrete part with visible landmarks (from[10] with additional markers) and a segment of continuous material (copper) with only the coating edge as orientation in the vertical direction. The landmarks (marked with red lines) enable a precise localization of the captured microstructure each time a discrete part is imaged. The continuous material lacks landmarks (in horizontal direction) needed for automatic fingerprint location, which induces challenges that need to be overcome.

1.3. Track & Trace Fingerprint Technology

The Track & Trace Fingerprint technology uses a sophisticated algorithm which can be considered as a fundamentally modified and highly optimized version of the Fourier-Mellin phase correlation presented in.[12] It is developed by Fraunhofer IPM and extracts only unique information from microstructural characteristics found on the surfaces of materials to generate a distinct bitset.[13] This bitset is called a "fingerprint" and is used to identify the surface section at a later point in time. By utilizing high-resolution imaging techniques, the system captures the intricate details of the surface non-invasively and fast. Track & Trace Fingerprint can extract fingerprints from a wide range of suitable materials such as metals, papers, plastics, and woven or unwoven structures. These fingerprints are robust against limited local changes to the surface, such as scratches, cracks, stains, and others induced by processing steps in production.[14]

Before any identification can take place, the material must be imaged once. An area of a few square millimeters is sufficient to generate the fingerprint and store the few kilobytes in a database. This process is called "adding" the fingerprint.

Adding fingerprints is only the first step of two. The other one is the identification step—also called "tracing". It is now possible to identify an arbitrary section of the material by capturing the microstructure and generating the fingerprint again. This new fingerprint will then be compared to the database, yielding a similarity value for each entry. All values are statistically analyzed to identify the correct fingerprint. This approach has several advantages: Firstly, a fingerprint does not have to be exactly the same to be identified. Secondly, instead of identifying a wrong fingerprint, the algorithm will mark it as a statistically unsafe trace when certain thresholds are not met.

There are two major advantages compared to marker-based identification: 1) Spatial requirements are low. For instance, in the case of this study, an area of around $16 \times 2\ mm^2$ was sufficient to obtain high recognition rates (compare **Figure 2**). Furthermore,

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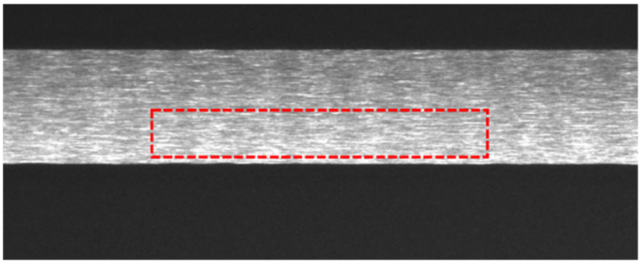

Figure 2. Detailed crop of a high-resolution image originally capturing around $60 \times 15\,mm^2$ of cathode material (aluminum with NMC coating) each frame. The dashed box ($16 \times 2\,mm^2$) depicts the area that is used to generate the bitset called "fingerprint". Due to its high information density, it is robust against local defects and surface changes.

distances between two consecutive fingerprints can almost be arbitrarily small as the creation of overlapping fingerprints is possible. As an example, most tests in this study have been carried out with 1.5 mm distance between fingerprints. 2) Fingerprints may still be identified when a part of the original microstructure has been altered or completely removed due to cutting or other process influences. As a rule of thumb, around 80% of the original microstructure should be remaining. But there have been cases when 40% to 50% was still sufficient for identification. The exact numbers are dependent on how well Track & Trace Fingerprint works with a certain material and how many fingerprints there are in the database.

Both advantages enable Track & Trace Fingerprint to be applicable in cases where the available surface area is either too small for markers (e.g., winding-based cells with narrow contact strips) or where markers are potentially cut away (e.g., sheet-based cells with conductor tabs). Basically, in most use cases, Track & Trace Fingerprint can be configured such that there is at least one identifiable fingerprint left on any material section right before cell assembly (compare **Figure 3**).

Even though partial cutting of a fingerprint can be unproblematic, it should be avoided, to keep identification rates high. As a side effect, granularity is also much better compared to approaches with larger inter-marker-distances.

Besides the mentioned advantages, there are of course challenges. One such challenge is the precision with which the images of the microstructure must be taken: Image acquisition conditions have to be as similar as possible each time a fingerprint is generated. Otherwise, similarity decreases, even before any microstructural changes are taken into account. As opposed to marker-based techniques like DMC, perspective or scale corrections are usually not feasible or even impossible. Additionally, motion blur and deviating lighting conditions may also change the appearance of the microstructure. Most of these challenges can be overcome by a thoroughly designed and configured sensor system but may still be a source of error, especially when materials show non-planar structures (e.g., wrinkles). Another smaller drawback is the inability to put information onto the material. Markers usually contain their information and reader systems can operate independently as there is no need for external data storage. Another drawback that usually affects marker-based technologies as well, are surface alterations. The more the surface changes (due to process influences, aging, damages or material removal) the lower is the similarity between fingerprints from the same area. At some point the similarity is too low and the identification fails.

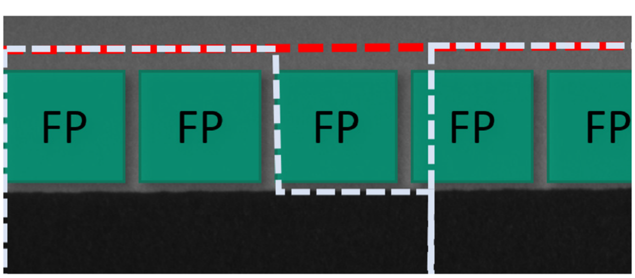

Figure 3. Visualization of fingerprint area placement to conform with slitting (red dashed line) and potential (tab) cutting (white dashed line). The fingerprint area is flexible in size and shape and is adjustable to spatial limitations. It is also possible to densely cover material, such that there is always at least one fingerprint area remaining after cutting.

1.4. Thresholds, Confidence Values, and Identification Rate

As a measure of similarity between two fingerprints their Hamming Distance d_H can be calculated. It is defined by the ratio of the count of differing bits N_{diff} and total bit count N_{total}:

$$d_H = \frac{N_{diff}}{N_{total}}$$

Due to the stochastic nature of the surface microstructure, the distribution of bits (1 s and 0 s) within a fingerprint is random. Thus, creating a bell-shaped distribution of Hamming Distances when comparing random fingerprints with each other. This curve can be approximated by a Gaussian distribution with mean μ and standard deviation σ as characteristic parameters, whereas μ is expected to be located around 0.5 if each fingerprint bit has the same chance to be 1 or 0. This curve is called distribution of *non-matches* or in mathematical terms:

$$P_n(x) = \frac{1}{\sqrt{2\pi}\sigma_n} e^{-\left(\frac{x-\mu_n}{\sqrt{2}\sigma_n}\right)^2}$$

It can be used to statistically estimate whether a Hamming Distance between two fingerprints is part of this distribution (and likely just appeared randomly) or if it is, in fact, an anomaly. These anomalies happen when the fingerprints originate from the same surface area. Naturally, they are expected to have a much higher similarity and are sufficiently well separated from all other Hamming Distances (compare **Figure 4**).

Two confidence values are calculated for the potential match. The first, CV1, is the distance to the center of the distribution. It is given in units of the distribution's standard deviation. The second, CV2, is the gap to the next lowest Hamming Distance. Both values must hit defined thresholds to prevent misidentifications due to random appearances. The probability for a *non-match* to have a CV1 above threshold t_{cv1} can be calculated by integrating $P_n(x)$ from $-\infty$ to $(\mu_n - t_{cv1}\sigma_n)$. The formula can be defined with the error-function when some variable substitutions are applied:

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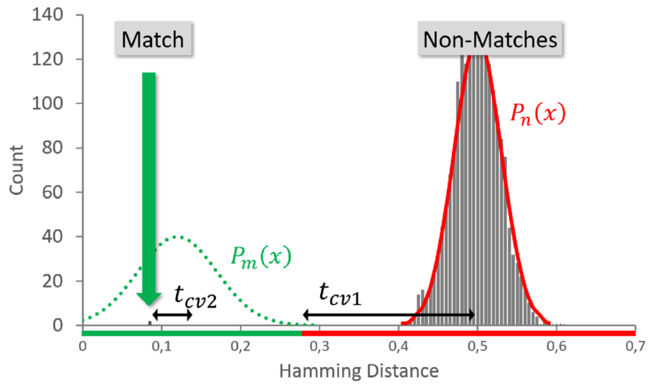

Figure 4. Schematic Hamming Distance histogram of a successful trace (based on diagram in[8]). One fingerprint from the database shows a low Hamming Distance as it was generated from the same surface area. The thresholds t_{cv1} and t_{cv2} for the confidence values CV1 and CV2 prevent any misidentifications, which are strictly forbidden in production. $P_m(x)$ and $P_n(x)$ describe the expected distribution for matches and non-matches.

$$P_n(X \leq \mu_n - t_{cv1}\sigma_n) = \frac{1}{2}\left(1 - \mathrm{erf}\left(\frac{t_{cv1}}{\sqrt{2}}\right)\right)$$

It is common that a trace consists of millions of fingerprint comparisons and t_{cv1} should be chosen such that even hundreds of traces will probably not yield a random Hamming Distance with a CV1 above it. For most use cases $t_{cv1} = 7$ is chosen. $P_n(X \leq \mu_n - 7\sigma_n) = 1.28 * 10^{-12}$ is so small that on average only one out of about 800 billion comparisons is randomly above threshold. As misidentifications in production are usually unacceptable, Track & Trace Fingerprint deploys a second threshold for CV2 to ensure the match is "uncontended". A value of $t_{cv2} = 0.05$ has been empirically proven to be adequate in most cases. A solid theoretical derivation of this value has not yet been developed and will be subject of future work.

Some materials and surfaces are better suited for Track & Trace Fingerprint than others. Some surfaces experience alterations between adding and tracing fingerprints. This can be due to processing steps or other environmental influences. The estimation of the achievable identification rate is crucial to assess the performance of Track & Trace Fingerprint. Therefore, a limited number (typically around 20 to 50 pieces) of labeled material samples is provided and analyzed by adding and tracing them to determine the distribution of the non-matches, $P_n(x)$, and of the matches, $P_m(x)$, which is assumed to be Gaussian as well (compare red solid and green dotted lines in Figure 4). With these distributions, it is now possible to find the mean probability of a successful trace by calculating the following integral (with N being the number of comparisons per trace):

$$P_{success} = \int_{-\infty}^{\mu_n - t_{cv1}\sigma_n} P_m(x) * \left(\int_{x+t_{cv2}}^{\infty} P_n(z)\,dz\right)^N dx$$

Graphically speaking, the formula goes from left to right through $P_m(x)$ until it hits the threshold location $\mu_n - t_{cv1}\sigma_n$ and calculates the probability of each value x to appear. This probability is multiplied by the chance that a non-match has a higher Hamming Distance by at least t_{cv2} to the power of N.

In an experiment, for a high number of traces the identification rate should converge toward $P_{success}$, if the distributions of matches and non-matches can indeed be approximated by a Gaussian curve. If this relation is validated, it can be used to predict the expectable identification rates for different database sizes from just a few samples, hence, simplifying and improving feasibility studies greatly. The test of this relation is part of this work.

1.5. Adaptations for Continuous Material

Historically, Track & Trace Fingerprint was aimed at tracing individual parts through production where automation and handling systems place about one object per second in front of the fingerprint sensor and trigger image acquisition. Localization of the fingerprint area is usually simple: Either the positioning is precise enough, or features in the image can be used as orientation. This is not the case for continuous material: Specific localization in feed direction is impossible. External triggering may be possible but creates unwanted dependencies on other equipment like encoders. Production speed is also much higher. To tackle these challenges, some adaptations must be made: 1) The Track & Trace Fingerprint software tracks the material surface on its own. Acquisition of overlapping images ensures measurement of the current feed via algorithms like template matching (e.g., digital image correlation) and guaranteed visibility of whole fingerprint areas. Overlap should be the size of a fingerprint area to guarantee full visibility. No external triggers are needed. 2) Batch processing and other optimizations enable adding hundreds of fingerprints per second (compared to one for discrete parts). 3) Fingerprints are automatically generated at fixed distances d to each other, ensuring a dense material coverage (compare **Figure 5**).

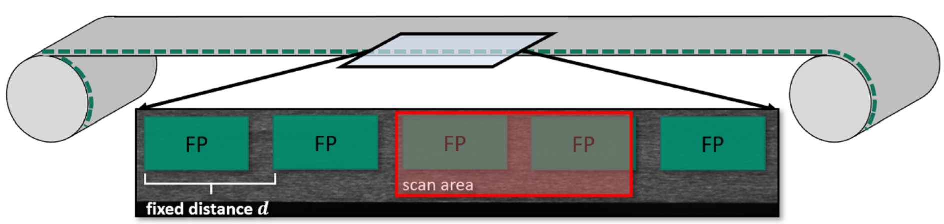

Figure 5. Fast fingerprint (FP) generation at fixed distances ensures dense coverage over the whole length of the material. Combined with the small areal footprint it is possible to have at least one identifiable fingerprint left even when most of the material is cut away in later process stages (e.g., cutting out conductor tabs). The identification algorithm does not differentiate between continuous or segmented material. A scan over the fixed distance d guarantees identification completely independent of external input. As long as at least one fingerprint area remains, identification is possible.

Due to missing landmarks on the material, the algorithm scans the distance *d* step by step during the identification stage to find the exact location of the fingerprint area. These steps increase the number of comparisons per trace, having unfavorable effects on the trace duration and possibly identification rate.

1.6. Fingerprint Sensor

The Track & Trace Fingerprint technology was successfully implemented on a coating machine at the Center for Battery Cell Manufacturing (ZDB) of Fraunhofer IPA as part of the joint project DigiBattPro 4.0.

It typically relies on a standard camera lens setup with a lateral resolution of around 30 μm/pixel. This setup lays the foundation to capture detailed images of the surface microstructure of most materials. Depending on the material, it is necessary to choose the proper illumination considering three main aspects:

First is the brightness. Higher brightness enables lower exposure times, which, in turn, reduces motion blur. Second is a homogeneous illumination in feed direction. Tests were conducted by installation of one or two fingerprint sensors into a production line at different locations in the process chain (compare **Figure 6**). For the calendering process, additional experiments have been carried out to study the impact of the calendering force on the identification rate.

The surface needs to look the same, whether in the middle or at the image's border. Third is the illumination type. Depending on the material, diffuse lighting (e.g., dome light) may have advantages compared to directional lighting (e.g., bar light), especially for non-planar materials but bar lights oriented in feed direction have shown to be advantageous for electrode material as they pronounce microstructure and enable a smaller sensor footprint (compare **Figure 7**).

The fingerprint sensor used for these studies consisted of a bar light (CCS LDL2-266/30-SW2, 42 W) oriented parallelly to the feed direction and a high-resolution camera (Allied Vision Manta G-2460B) with up to 25 megapixels paired with a high-resolution lens (Schneider APO-COMPONON 40/2.8 V2) that captures around 60 mm of material at a time at a working distance of about 260 mm. The illumination was positioned next to the camera but around 50 to 100 mm closer to the material.

The illumination angle to the surface was near 90°. The image height was reduced to cover about 30 mm of material to increase the frame rate and decrease the computational load. The camera was oriented to show the feed in horizontal direction. In total, these hardware components can be acquired off the shelf for less than 5,000 €.

Each sensor tracks a single lane of material, but they can also be combined to operate in a multi-lane configuration. This is important as the material may be separated along the feed direction in a later production step (compare **Figure 8**).

1.7. Architecture of Track & Trace Fingerprint Systems

Each fingerprint sensor is connected to a PC that runs a software called FP-Reader. It is responsible for acquiring images, tracking the material, generating fingerprints, and sending them via network to another software called FP-Management. This software runs on a high-performance computer and manages the fingerprint database together with the computation of all trace comparisons.

When new material first passes a fingerprint sensor, its fingerprints will be generated and added to the database. The material can now be identified wherever another fingerprint sensor is installed. It is important to prevent generating multiple fingerprints for the same surface area. Otherwise, they lead to unsuccessful traces as the algorithm is unable to decide which fingerprint is the correct one. Usually, it is the user's task to do this, but Track & Trace Fingerprint offers the feature to execute a trace before adding, to make sure it is not already present in the database. To perform an actual trace later in production, the sensor images the surface again, but this time, it uses the larger scan area to trace the fingerprint. The trace task is sent to the FP-Management where the fingerprint comparisons are calculated with the Hamming Distances as results. These Hamming Distances are then sent back to the original FP-Reader, which

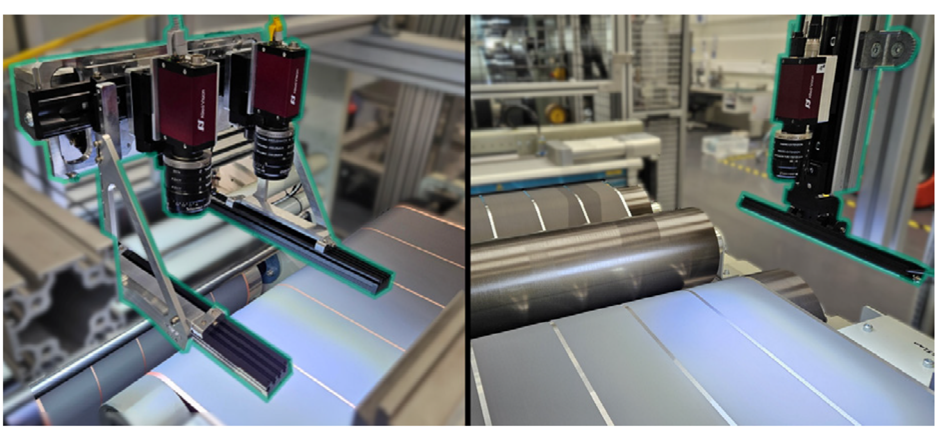

Figure 6. Left image shows the experimental dual-lane test setup of fingerprint sensors right after coating. Right image shows the experimental test setup in single-lane mode right before calendering. The highlighted outline shows the hardware belonging to the fingerprint sensor.

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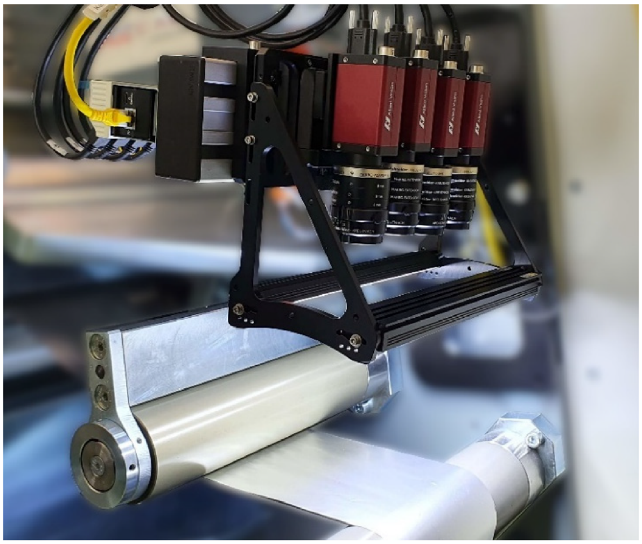

Figure 7. Fingerprint sensors in multi-lane configuration at the Center for Digitalized Battery Cell Manufacturing (ZDB) of Fraunhofer IPA, sourced from.[8] Four lanes of material can be tracked at once, ensuring full traceability even if the material is split in feed direction. The image shows bar lights perpendicular to the feed direction, which has later proven to be inferior to a parallel orientation.

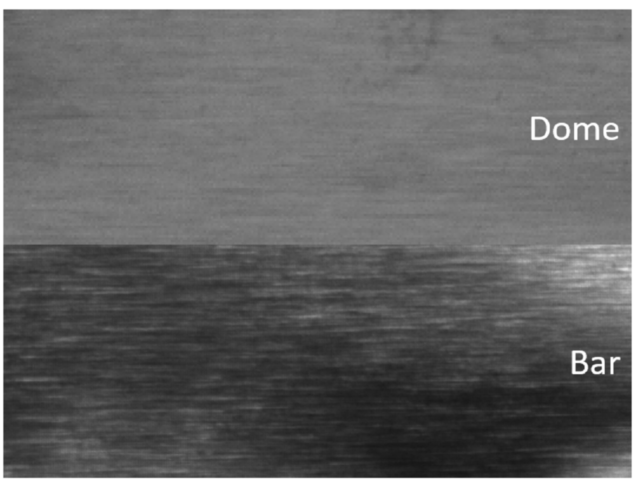

Figure 8. Comparison of the influence of a dome light (diffuse) and a bar light on the imaged microstructure. The microstructure appears very homogeneous when illuminated by the dome but shows a low contrast. The bar light is prone to inhomogeneities when the illuminated material is not planar but produces very high contrast when oriented parallelly to feed direction. The bar light configuration was used in the conducted tests due to advantages in contrast and hardware size.

decides—based on the chosen thresholds—if the identification was successful or not. Possible interfaces like TCP, Serial, OPC UA, Profinet, or others can be used to link the fingerprint to a manufacturing execution system (MES) handling the production data. Usually, a fingerprint sensor is installed anywhere where new data should be linked to the material or where existing data has to be transferred to another traceability solution.

For electrode production the latter case happens at the winding or stacking machine. All material that goes into a cell needs to be identified before its data can then be transferred to, for example, a DMC. **Table 1** shows an overview of typical fingerprint sensor locations in battery production. Marker-free traces can now go from stacking or winding all the way back toward the coating process.

Table 1. Typical locations for fingerprint sensors in battery manufacturing together with examples for the data that may be paired there. Tracking is possible as soon as the carrier material enters production. Traces can now go back from stacking or winding to the coating process.

Process	Pairable Data
Coating	Coating thickness, areal density
Calendering	Calender force
Stacking, winding	Data transfer to assembled cell

1.8. Materials, Processes, and Testing Methodology

To assess the feasibility of Track & Trace Fingerprint in battery production, a series of materials and processes were studied. Most electrode material is based on aluminum and copper as carrier material with graphite, lithium-iron-phosphate (LFP), or nickel-manganese-cobalt (NMC) as coating material. Important processes include coating, drying, calendering, slitting, cutting, and stacking or winding. Calendering was identified as the most invasive process with regard to surface changes as the rolls apply high amounts of pressure, changing the coating and possibly imprinting their own microstructure onto the carrier material or damaging it. The separation and removal of material during slitting and cutting is not harmful to the microstructure itself but must be taken into account during fingerprint generation. Slitting is not problematic as the cutting line is known in advance and fingerprint areas can be adjusted accordingly. But for segmentation and cutting, it is necessary that at least one complete fingerprint area is left for identification on each material segment. Processes after cell assembly were not considered because tracking is usually done by other means like DMC on the outer casing of the cell. However, the single segment data has to be transferred to the assembled cell, so a last trace before winding or stacking is still needed.

2. Results and Discussion

All tests were conducted with the same fingerprint settings: Fingerprints were generated from an area of around $16 \times 2\,mm^2$, creating a sequence of around 12,000 bits each. The area was located right next to the coating edge in case of the carrier material or about 2 mm away from it in case of coating material. The area size and position has been chosen such that a later slitting in feed direction does not cut apart any fingerprint areas. Thresholds of $t_{cv1} = 7.0$ and $t_{cv2} = 0.05$ were applied.

2.1. Material Tests

Two different carrier materials (aluminum and copper) and three different coatings (graphite, LFP, and NMC) have been tested for their usability for Track & Trace Fingerprint.

Figure 9 shows exemplary images of the material surfaces captured by the fingerprint sensor. Copper shows a much finer texture than aluminum. All coating materials are shown in their uncompressed form before calendering. LFP shows a much more granular structure compared to graphite and NMC, which may originate from differing coating parameters and material formulations.

The periodic structure visible in the aluminum image is the reflection of the LED array and not part of the microstructure itself. It has not negatively affected traceability compared to using a diffusor in front of the light source. If not stated otherwise, the following settings have been used for the tests: The distance between two generated fingerprints was set to 1.5 mm to show that a dense coverage of fingerprints is possible. The distance between two traces was set to 100 mm to regularly check for changes in identification rate. These values can be optimized depending on the use case. The scanning range to precisely locate the fingerprint consisted of 250 steps (50 in horizontal direction to cover the 1.5 mm gaps and 5 steps in vertical direction to compensate for inaccuracies in material positioning). The number of fingerprint comparisons (or Hamming Distances) for a single trace is the database size multiplied by the number of scanning steps. The final validation of the identifications was conducted as follows: A physical marker was manually placed to mark the beginning of the material that had passed the adding sensor. This was used to confirm when the tracing sensor should be able to identify the material. Additionally, the index of the identified fingerprints was regularly checked and confirmed to be only ascending in fixed intervals. For example, the index must increase about a value of 66 when a distance between fingerprints of 1.5 mm and a trace every 100 mm is chosen.

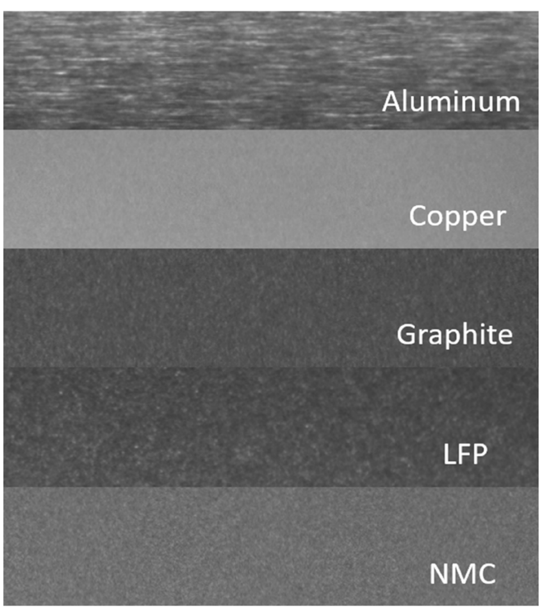

Figure 9. Exemplary overview of the material surfaces captured by the fingerprint sensors. Aluminum and copper are carrier materials, and graphite, LFP and NMC are coatings. The coatings are shown in their uncompressed form before calendering. All materials show a random microstructure ranging from LFP as the most granular to copper as the finest.

2.2. Aluminum and NMC

Two fingerprint sensors have been installed in production environment at the calendering machine. The first sensor was estimated to be roughly 7 m in front of the calendering rolls and the second one around 5 m behind them. No calender pressure was applied.

2.3. Copper and Graphite

For the tests on copper and graphite, a single fingerprint sensor has been installed in production at the coating machine after the processing right before coiling. For tracing, the coil was put through the machine again and the same sensor was used.

2.4. LFP

In exception to all other experiments, LFP was evaluated at ZDB of Fraunhofer IPA instead of an industrial production environment. Two sensors have been installed at the calendering machine about 2 m in front of the calender rolls and about 0.5 m after them. No calender pressure has been applied, to focus on the traceability of LFP alone. The scan area during tracing has been extended to 17 steps in vertical direction to account for higher positioning tolerances (total steps: 850). It is also noted that the tested sample exhibited some defects that the authors contribute to material age and suboptimal handling (compare **Figure 10**).

Table 2 shows experimental parameters and results for the conducted traceability tests. Feed rates varied depending on the machine and current test settings but showed no negative influence on the identification rates. All materials show rates of 100% except for LFP, which has a rate of 98.6%. The sample quality may have influenced the distribution of matches negatively as the observed inhomogeneities represent larger macro structures that take away some of the individuality of the microstructure. However, once LFP is tested in an industrial environment with optimized machine settings and short storage periods, it is likely that higher identification rates are achieved. Incorrect identifications (statistically safe identification of a wrong fingerprint) have not taken place in all tests. Additionally, statistical identification rates have been calculated by numerically approximating the integral of $P_{success}$ and inserting the calculated distribution values μ and σ. They are in line with the experimental results, indicating that

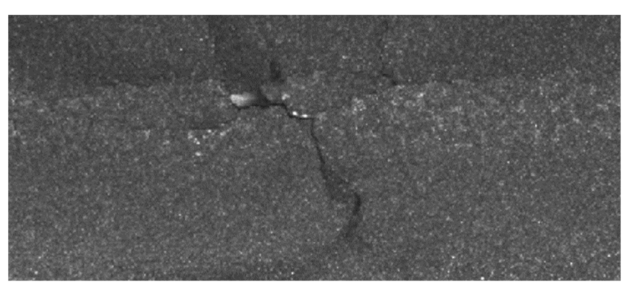

Figure 10. Detail image of an LFP sample analyzed in the laboratory. It exhibits cracks and wrinkles. The appearance is contributed to sample age and suboptimal manual handling.

Table 2. Experiment parameters and results for the traceability tests of all five material types are shown in this table. Feed rates vary depending on test settings and machines but maxed out at 25 m min^{-1}. Up to this feed rate, no motion blur or other malicious influences have been observed. Experimental identification rates have been at 100% except for LFP that showed 98.6%. LFP was the only material that had not been tested in industrial environments and probably suffered from unoptimized machine settings and sample age. Experimental results have further been used to calculate the parameters of the distributions of matches and non-matches. The statistical identification rate based on these distributions is in line with the experimental results. This underpins the theoretical considerations made at the beginning of this work. The results indicate that all materials are suitable for Track & Trace Fingerprint.

Material	Feed rate [m min^{-1}]	Added Material [m]	Added Fingerprints	Traced Material [m]	Successful/Total Traces	Ident. rate (exp.)	μ_m	σ_m	μ_n	σ_n	Ident. rate (stat.)
Aluminum	10	61.9	41,000	38.9	389/389	100.0%	0.175	0.018	0.500	0.010	>99.9%
Copper	25	125.5	83,100	22.3	216/216	100.0%	0.142	0.019	0.500	0.018	>99.9%
Graphite	25	122.0	80,700	21.5	208/208	100.0%	0.109	0.016	0.500	0.018	>99.9%
LFP	3	10.2	6,700	7.3	71/72	98.6%	0.259	0.057	0.500	0.011	99.0%
NMC	10	60.0	40,000	39.2	390/390	100.0%	0.238	0.022	0.500	0.009	>99.9%

the distributions for matches and non-matches can indeed be approximated by Gaussian curves.

2.5. Calendering Tests

The calendering process was identified as the one with the highest chance of changing the appearance of the microstructure, especially for the coatings. An overview, as given in **Figure 11**, shows that this is indeed the case. Changes due to slitting and cutting are also affecting the spatial composition of the fingerprint areas but not the microstructure itself. Usually, this is mitigated by proper placement and configuration of the fingerprints.

Experiments have been carried out with two sensors installed in the industrial production line. The first sensor is installed about 7 m before the calendering rolls and the other 5 m after them. Different calender gap forces have been applied to assess their influence on the identification rate. **Table 3** and **4** summarize all important testing parameters and obtained results for aluminum and NMC, respectively.

Both materials, aluminum and NMC, show increasing Hamming Distance values for the matches with increasing calender force, indicating an influence of the calendering process on the microstructure. However, the influence on aluminum is very moderate such that identification rates remain largely unaffected. NMC, on the contrary, is getting compressed which visually changes the microstructure even at comparatively low pressures of 50 kN or 100 kN and prohibits reliable identification. To ensure traceability over the process, it is either possible to switch to fingerprint generation on the carrier material or reduce the confidence value thresholds. The latter increases the risk of misidentification but may be feasible if only shorter material segments (e.g., below 15 m) have to be traced.

In both cases, aluminum and NMC, the statistically computed identification rate is largely in line with the observed experimental rates. There are, however, some deviations in the lower single digits especially for rates below 90%, which shows, that the modeling with the Gaussian curves is indeed just an approximation.

Figure 11. Images of the NMC microstructure captured by the fingerprint sensor after calendering with different gap forces. An immediate change in structural composition is visible even when applying a comparatively low force. The change scales with increasing force. At 200 kN and up the material shows increased reflectivity and starts to exhibit larger horizontal structures that are assumed to be calender roll imprints.

Table 3. Experiment parameters and traceability results for aluminum under the influence of different calendering forces are shown in this table. The mean value for the match distribution is increasing with growing calender force. This indicates an influence of the calendering process on the carrier material, but it is not enough to affect the identification rates in a noticeable way. As with the preceding material tests, the statistically computed identification rate is in line with the experimental results.

Gap Force [kN]	Feed Rate [m min^{-1}]	Added Material [m]	Added Fingerprints	Traced Material [m]	Successful/Total Traces	Ident. Rate (Exp.)	μ_m	σ_m	μ_n	σ_n	Ident. Rate (Stat.)
0	10	61.9	41,000	38.9	389/389	100.0%	0.175	0.018	0.500	0.010	>99.9%
50	15	19.8	13,100	11.1	110/110	100.0%	0.205	0.022	0.500	0.011	>99.9%
100	25	24.0	15,800	19.8	196/196	100.0%	0.215	0.028	0.500	0.011	>99.9%
200	25	38.8	25,600	31.7	313/313	100.0%	0.220	0.026	0.500	0.010	>99.9%
300	25	10.8	7,100	8.9	88/88	100.0%	0.212	0.023	0.500	0.010	>99.9%
435	20	42.5	28,100	41.9	416/416	100.0%	0.249	0.025	0.500	0.010	>99.9%

Table 4. Experimental parameters and traceability results for NMC under the influence of different calendering forces are shown in this table. The identification rate decreases notably with increasing calender forces. At 50 kN gap force, the identification rate is still fairly high but at 100 kN already only three out of four fingerprints are safely identified. Statistical prediction of the identification rate is deviating by low single-digit percent in some cases, indicating some differences between modeling and reality. In order to guarantee traceability through the calendering process, it is necessary to either reduce thresholds (and risking invalid identifications) or to switch to the carrier material.

Gap Force [kN]	Feed Rate [m min^{-1}]	Added Material [m]	Added Fingerprints	Traced Material [m]	Successful/Total Traces	Ident. Rate (Exp.)	μ_m	σ_m	μ_n	σ_n	Ident. Rate (Stat.)
0	10	61.9	41,000	39.2	390/390	100.0%	0.238	0.022	0.500	0.009	>99.9%
50	15	19.8	13,100	11.1	108/110	98.2%	0.373	0.013	0.500	0.009	99.1%
100	25	24.0	15,800	19.8	150/196	76.5%	0.395	0.014	0.500	0.009	72.8%
200	25	38.8	25,600	31.8	89/315	28,3%	0.410	0.011	0.500	0.009	26.5%
300	25	10.8	7,100	8.9	11/88	12.5%	0.420	0.012	0.500	0.009	11.1%
435	20	42.5	28,100	14.2	0/140	0.0%	0.431	0.006	0.500	0.010	0.0%

2.6. Performance and Optimizations

Maximum feed during the performed tests was 25 m min^{-1} due to production related constraints at the time of testing. The maximum feed witnessed (but not tested) by the authors was around 80 m min^{-1} for short intervals during winding. The fingerprint sensor's frame rate is high enough to theoretically support 95 m min^{-1} feed rate when parameterized accordingly, but motion blur currently becomes noticeable at around 40 to 50 m min^{-1}. This is mostly a matter of exposure times and it can be solved by increasing lighting power and switching to strobe operation. The more important part is the time it takes to add and trace fingerprints.

By default, Track & Trace Fingerprint for discrete parts adds one fingerprint at a time. The communication overhead between FP-Reader and FP-Management is large compared to the actual add-operation. When working with continuous material, it is beneficial to reduce the relative share of the overhead. A batched operation mode was introduced. On a system equipped with a 12-core AMD Ryzen 9 5900X it is now possible to add up to 460 fingerprints per second. This corresponds to 2–3 ms duration per fingerprint on average. The trace rate, however, is lower due to the higher compute load. While using the fingerprint settings from the conducted tests, a high-end CPU (64-core AMD Ryzen Threadripper 3990X) manages to compute close to 30 million Hamming Distances per second. The database of a 10,000 m coil then contains about 6.7 million fingerprints. In the best case (precise material positioning), the scanning range can be reduced to 50 steps, which results in 335 million computed Hamming Distances per trace and at least 11 s computation time. Which is, in fact, not really feasible when dealing with high feed rates. Before finding solutions, it is beneficial to analyze what is taking the most time during a trace. A trace essentially consists of these five steps: 1) Fingerprint creation (incl. scanning range). 2) Network transmission of the fingerprints to FP-Management. 3) Computation of all Hamming Distances. 4) Network transmission of the Hamming Distances to FP-Reader. 5) Computation of the statistical result.

Steps 1 and 3 are usually taking the most time. Both scale with scanning range size and the latter additionally scales with database size. Steps 2 and 4 consume less time but when the bandwidth between FP-Reader and FP-Management is low, they contribute substantially. Step 5 is negligible in comparison to the other steps. Effective solutions to improve the trace rate should mainly focus on steps 1 and 3. There are already methods to decrease the duration to single-digit seconds: 1) **Prediction of fingerprint location:** The Track & Trace software can predict the location of the following fingerprint based on a successful trace before. This is only viable as long as the material is still contiguous, but it can reduce the scanning range significantly, resulting in a five- to tenfold speed-up for steps 1 and 3. 2) **Smart tracing:** Fingerprints already identified before will be removed from the database and not be considered for another trace. The gain from this technique is low in the beginning and significant toward the end of the coil. Theoretically, a speedup of step 3 from 1% to 99% can be achieved.

Furthermore, other methods to speed up trace time have been identified: 3) **Sliding-window approach:** For processes where permutations of fingerprints are ruled out (e.g., when the material is guaranteed to be contiguous), method 2 can be expanded to ignore fingerprint areas that are yet to be unwound from the coil. It should be possible to narrow down Hamming Distance computation to a few hundred fingerprints. Theoretically, this should quickly translate to a tenfold speed up of step 3 depending on database size. 4) **Local database handling:** The idea is to include database handling and Hamming Distance computation into FP-Reader. Steps 2 and 4 are basically removed from the equation and up to a few hundred milliseconds are saved per trace. 5) **GPU-acceleration:** Accelerated computation of Hamming Distances by using a custom Cuda kernel and an Nvidia GTX 1650ti (mobile) has shown a five to tenfold acceleration of step 3 in a prototypical implementation.

Methods 3 to 5 are not yet implemented but offer some clear directions on how to achieve viable trace rates to support feed rates of up to 60 m min^{-1} or more.

3. Discussion

The conducted experiments showed that applying Track & Trace Fingerprint in battery production is generally very feasible. Aluminum, copper, graphite, and NMC promise over 99.9%

identification rates for coil lengths of thousands of meters. LFP has a lower identification rate of 98.6% which is probably increasable when production standards are met. The experiments also showed that a thorough fingerprint sensor design is the key to minimize potential negative influences. Track & Trace Fingerprint needs reproducible imaging conditions to maximize identification rates and guarantee reliable traceability for thousands of meters of material.

To verify that full traceability is possible throughout the production chain, the most critical process in terms of surface manipulation, calendering, was investigated. The coating material, NMC, exhibited significant changes to the surface even with comparatively low calender gap forces. Robust traceability over the calendering process using the coating is therefore not possible. In contrast to that, the results for aluminum showed only a minor impact on the identification rates, indicating that full, marker-free traceability from stacking or winding all the way back to the coating process is indeed possible. Other processes like slitting or cutting, that pose challenges to marker-based tracing techniques, are no hurdle for Track & Trace Fingerprint. It was shown that fingerprint areas can be very small, and they can be positioned very densely on the material, meaning that for most use cases at least one fingerprint area is identifiable on the remaining material after slitting and cutting. Throughout the evaluation of the experimental results, identification rates were mostly in line with the derived statistical estimation. This corroborates the assumption that the distribution of matches and non-matches can be approximated by a Gaussian distribution. In some cases, this approximation deviated a few percentage points from the experimental result, making it clear that it cannot make arbitrarily precise predictions but it can give a clear direction, which may help in future feasibility studies and experiments.

Additionally, actions have been taken to accelerate fingerprint generation and identification processes to match typical feed rates in battery production: Batched processing has shown a strong acceleration when adding fingerprints to the database. Implementing a predictive algorithm reduced the duration of a trace to just a couple of seconds when tracing through a whole database. Additional optimizations to achieve sub-second durations have been formulated to show a path on how to achieve operation at high feed rates of 60 m min^{-1} or more. These optimizations are subject to future work.

4. Conclusion

The advancements in the Track & Trace Fingerprint technology take a significant step toward achieving holistic marker-free traceability in lithium-ion battery production. This innovative approach not only promises full process traceability even after segmentation and cutting but also addresses material integrity concerns associated with traditional identification methods. By imaging unique surface microstructures, the technology leverages what is already there and provides a reliable, marker-free, and non-tactile solution that enhances product quality and safety.

4.1. Outlook and Future Work

Track & Trace Fingerprint has proven to work as a marker-free traceability solution for continuous material in battery production. The focus is now on verifying that the solution works for segmented sheets as predicted and on increasing the technology readiness level (TRL) in the battery environment. A future goal is to expand to other industries. To achieve this, supporting higher feed rates is key, and future works will revolve around reducing trace durations significantly by pursuing the outlined approaches of local database handling, the sliding-window approach, and GPU acceleration. The aim is to lay the pathway for a broader adoption of the technology in the industry.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords: battery production · DigiBattPro · digitalization · marker-free · traceability

[1] European Commission: Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020 Document 52020PC0798. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798 (accessed: June 2025).
[2] A. Sommer, S. Bazlen, H.-Y. Tran, W. Braunwarth, R. Daub, *Proc. CIRP* **2023**, *120*, 171.
[3] J. Wessel, A. Schoo, A. Kwade, C. Herrmann, *Energy Technol.* **2022**, *11*, https://doi.org/10.1002/ente.202200911.
[4] G. Riexinger, J. P. Doppler, C. Haar, M. Trierweiler, A. Buss, K. Schöbel, D. Ensling, T. Bauernhansl, *Proc. CIRP* **2020**, *93*, 125.
[5] A. Sommer, M. Leeb, S. Haghi, F. J. Günter, G. Reinhart, *Proc. CIRP* **2021**, *104*, 1011.
[6] J. Lindenblatt, J. Schneider, A. Sommer, R. Daub, *Fut. Batter.* **2025**, *5*, https://doi.org/10.1016/j.fub.2025.100049.
[7] S. Ijaz, A. Bukhari, Real Time Data Warehouse, arXiv, **2013**, https://doi.org/10.48550/arXiv.1310.5254.
[8] G. Riexinger, D. J. Regina, C. Haar, T. Schmid-Schirling, I. Landwehr, M. Seib, J. Lips, S. Fehrenbach, J. Stübing, D. Carl, A. Sauer, *Traceability in Battery Production: Cell-Specific Marker-Free Identification of Electrode Segments, Advances in Automotive Production Technology – Towards Software-Defined Manufacturing and Resilient Supply Chains, Stuttgart*

Conf. on Automotive Production, **2022**, pp. 344–353, https://doi.org/10.1007/978-3-031-27933-1_32
[9] M. Thomitzek, O. Schmidt, G. Ventura Silva, H. Karaki, M. Lippke, U. Krewer, D. Schröder, A. Kwade, C. Herrmann, *Sustainability* **2022**, *14*, https://doi.org/10.3390/su14031530.
[10] A. Förste, T. Schmid-Schirling, T. Körber, *JOT J. Oberflächentechnik*, **2022**, *62*, 40
[11] T. Deliktas, M. Liewald, P. Clauß, I. Kuntz, T. Schmid-Schirling, M. Feurer, G. Dimitropoulos, F. Wientapper, F. Räuchle, Kontrolle und Identifizierung von Pressteilen im freien Fall, wt Werkstattstechnik online Vol. 10/2023 pp. 389–394, **2023**, https://doi.org/10.37544/1436-4980-2023-10-11
[12] R. Ishiyama, T. Takahashi, K. Makino, Y. Kudo, Fast Image Matching Based on Fourier-Mellin Phase Correlation for Tag-Less Identification of Mass Produced Parts, IEEE Global SIP, **2018**, https://doi.org/10.1109/GlobalSIP.2018.8646344
[13] T. Schmid-Schirling, A. Förste, Track4Quality - Markierungsfreie Einzelteilverfolgung in anspruchsvoller Produktionsumgebung zur Prozessverbesserung und Qualitätssicherung, final report, **2018**, https://doi.org/10.2314/GBV:104651847X
[14] T. Schmid-Schirling, Track & Trace Fingerprint Inline – Marker-free component traceability at the rate of production, **2023**, https://www.ipm.fraunhofer.de/content/dam/ipm/en/PDFs/product-information/PK/IVS/Track-trace-Fingerprint-Inline-component-authentication.pdf (accessed: June 2025).

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