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Forensics in motion - Historic vehicles, genuine or fake?

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ABSTRACT

In-depth forensic investigation and analysis of historic vehicles is a relatively new field of research. However, such examinations are becoming an important tool in the face of rising market values and the associated increase of manipulations and forgeries. We review various forensic approaches used in our interdisciplinary work in this field, including vehicle specialists, metallurgists, restorers, and archaeometry laboratories. The related investigations cover a general examination of the vehicle including detailed analysis of its materials and construction techniques, which are cross-referenced with the techniques and materials used in period. We illustrate our theoretical and analytical approach with practical examples from our work on collector vehicles. Finally, we consider methods and approaches currently under development.

1. Introduction

Until recently, historic vehicles were not examined with forensic methods. But if we look at developments in the last two decades, we see that similar methods are used for special models and individual pieces in the art trade and with other collector's items (see for example Fig. 1). Documented results of historic vehicle auctions show this high-priced segment had a yearly turnover of about $824 million in 2019[1] [1]. Consequently, their increasing values warrant this type of examination.

Vehicles classified as "historic", "monetarily valuable" and "worthy of collection" (like for example the Bugatti T57 in Fig. 1.) usually refer to specific models built between 1886 and the late 1970s. Initially manufactured and used as utilitarian objects and means of transportation, it was standard practice to repair and replace components to keep them functional, or to upgrade or rebuild them as desired in their phase of normal use. Most of them later were ultimately scrapped, but some were just decommissioned and forgotten in a remote garage or barn, after finishing their "service life". At that moment, no one expected that this kind of vehicle "scrap" would some 40–50 years later be considered exclusive again and often traded at higher prices than when it was brand new.

Even when the first enthusiasts began to take an interest in "veteran cars" in the 1950s and 60s, the standard practice remained: to preserve or even enhance the value, the body would be rebuilt, or upgraded with a more fashionable type, a more powerful drivetrain installed, a new paint job or a completely refurbished interior would complete the process. In most cases, the techniques and materials applied at that time were those at hand for normal used-car repair. This often also involved a lot of undocumented "mix-and-match" work, where identities, chassis, and components were swapped between different vehicles, or historic fragments of different origins were combined to create a road-ready example.

It was only in the last 15–20 years that this approach began to change. Connoisseurs with exquisite collections began to specifically search for vehicles of undisputed provenance (i.e., a proven genuine identity and chain of ownership) and rare surviving high-class models in historically preserved, "unrestored" condition. Today, these fetch significantly higher bids than specimens with unclear identities or those that have, like it is called in the collector's idiom, already been "restored to death" [2].

As a result of significantly rising market prices, an emerging field for manipulations and forgeries developed in art objects, watches by famous watchmakers, and antique wines. In the same way this also emerged for rare historic vehicles [3]. Still, looking at the usual appraisal and sales behavior, an examination going beyond just visual inspection or opinions from individual experts is still relatively rare in this profitable, but

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[1] Reflecting the market without the effects of the pandemic in the following two years.

[2] Put in relation to refurbished examples with similar technical configuration and unique design at that time, the price for this specimen was about 1/3 higher because of its extraordinary historically preserved condition.

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Fig. 1. This 1939 Bugatti T57C with one-off Vanvooren coachwork and in so called unrestored, historically preserved state is a good example for recent developments in the field of valuable collection vehicles. 2013 it changed ownership in a private sale for about $3 million.[2]

generally very secretive market. However, scientific methods can play a decisive role here, especially in the ongoing race between appraisers and more and more sophisticated “deceivers".

In-depth examinations carried out in recent years revealed a relevant number of collector vehicles (unknowingly or deliberately) falsely identified, presented, or appraised in misleading ways. It must therefore be assumed that the number of unreported cases is quite considerable, be it for sales by private owners, professional dealers, or auction houses [4].

Methods for closer examination in this field relate to techniques used for determining authenticity in works of the visual arts [5], the forensic examination of firearms [6], modern vehicles, and also archaeological research [7]. These of course must be adjusted to the materials and production techniques common for vehicle construction in different periods and by different makes.

At the beginning, it was not easy to find professional partners for this special kind of research, as some renowned institutions dealing with material analysis in the field of art showed little interest in historic vehicles. Laboratories routinely involved in the forensic examination of modern vehicles stated they did not have applicable reference data for pre-1980 models.

Therefore, cwork in progress in our self-funded research network, which includes the Privates Institut für Automotive Forensik GmbH (IfAF GmbH) [8], Cappel Stahl Consulting GmbH (CSC GmbH) [9], Omnia Restaurierung [10], Curt-Engelhorn-Zentrum für Archäometrie GmbH (CEZA GmbH) [11], and the Microanalytisches Labor Jägers GbR [12].

Important reference samples and archival materials also were provided by private collections, museums and partners in the vehicle industry, like for example Porsche AG and the Cité de l’ Automobile Collection Schlumpf [13].

In-depth material investigations on vehicles have been mostly commissioned by private collectors and museums, but in the meantime corresponding expert opinions are also requested by law firms, auction houses and automobile manufacturers.

The vehicles considered in this article usually consist of individually hand-crafted components, but also contain parts which have been industrially produced in larger quantities. Numerous different materials and processes have been used in their make and manufacture. At the same time, as described above, repairs, alterations and restorations from later periods of the individual vehicle’s life must also be considered. Therefore, the evidence created by measurement data always will have to be put in context with documents and archival materials preserved for the object, its period, and the related manufacturer. Cooperation with specialized historians and archives is indispensable in order to obtain a conclusive overall picture and make a holistic evaluation of the results. In the following, we illustrate the most important questions and examination methods.

2. The legal identity: vehicles have numbers

Within the scope of this article, it is not possible to explain in detail the sometimes highly complex historical marking systems for technical components in vehicle construction, some of which differed significantly from region to region and from manufacturer to manufacturer. However, since these are an essential part of the market value of collector’s items, as well as the production of forgeries, it is important to understand these numbering systems, to make a distinction between genuine and counterfeit. For this reason, a short overview will be given in the following section.

Already in the production of horse carriages and later also for motor vehicles, manufacturers applied production numbers and other markings to enable their individual identification. Traditionally, the legal identity of a motor vehicle would be either determined by markings on the chassis, which is the main structural component of the vehicle (see Fig. 2a), or, less frequently, by the engine number (see Fig. 2b). This identity number is, so to speak, the “signature of the manufacturer” and proof of authenticity.

Alphanumeric combinations were stamped not only into the frame/chassis, but also to the engine, body, the axles and other components. However, the bodies and upholstery, which often were made by outside

Fig. 2. Numbers stamped on technical components that can identify a vehicle. (a) Original chassis number on a 1938 Lancia Aprilia. (b) Original engine number on a 1933 Rolls-Royce Phantom II.

manufacturers, frequently carried their own numbering systems. These practices allowed the assignment of the components to the specimen for which they had been manufactured. As the components were often hand-built, they were not freely interchangeable between individual vehicles.

The process of marking components was maintained, usually in simplified form, as industrial mass production of vehicles increased. At the same time, there were significant differences from country to country in the legal classification to determine which markings actually defined the identity of a vehicle. This only changed when the so-called "Vehicle Identification Number" (VIN) was established as a worldwide standard in the 1970s [14]. Since then, this regulation defines the chassis or frame (or in the case of modern cars, the inner body structure) and the related number as the component which determines the identity of every individual vehicle.

Consequently, vehicle collectors today consider it to be a particular sign of unmolested historical authenticity, if not only the chassis number, but also the markings on the other main components still match those documented for the vehicle in its time of delivery. A corresponding configuration is then referred to as "matching numbers" [15] and its market value is increased accordingly.

Vehicles identified to have special original technical specifications, as well as specimens with prominent previous owners and other unique historic features, can also fetch significantly higher sales prices than their "siblings" from the same year and production without such characteristics. This also applies to examples built as individual one-offs, competition models with racing history or prototypes. Clear and undisputed identification therefore is a key question. And, of course, it is very tempting for counterfeiters to alter existing markings and features to feign the identity of a more valuable specimen, or to transfer the identity number of a long-destroyed or lost famous car to a newly-made copy.

In some cases, even archival materials and registration documents have been manipulated or created, to substantiate the falsely claimed identity and history. This in turn connects the historic vehicle world with the relatively new problems of digital forgeries. In the enthusiast community, historic images are still considered the "gold standard" for proving the origin or historic configuration of a vehicle. However, manipulation is a growing problem here, especially since collectors and appraisers today access and exchange archival materials almost exclusively in digital formats.

In the course of an upcoming auction in October 2021 [16] for example, the "original" picture of a 1969 Ford Mustang Mach I was presented to "prove" the car's provenance as being from the estate of actor Steve McQueen and the car being in an "unchanged state" since he owned it (see Fig. 3a). The photo was claimed to have been taken by his wife Barbara Minty in 1979. However, a closer look reveals that a 1972 film still from McQueen's movie "Junior Bonner" was merged with a photo of the car in its current state (see Fig. 3b.). Of course, the way this picture was made up is not very convincing, but the seller obviously tried to put an obscure car in the context of the Ford Mustang GT driven by McQueen in the movie "Bullitt", which was auctioned for $3.74 million in 2020 [17].

Practices like those described above have led to a considerable number of "doublets" with two or even more vehicles claiming the same historic identity. This not only directly affects collectors and the trade, but according to current law, copies and counterfeits cannot be legally registered and insured for road traffic in many countries. As collector vehicles usually are not kept just as static museum objects but are in active use, this often results in further legal consequences.

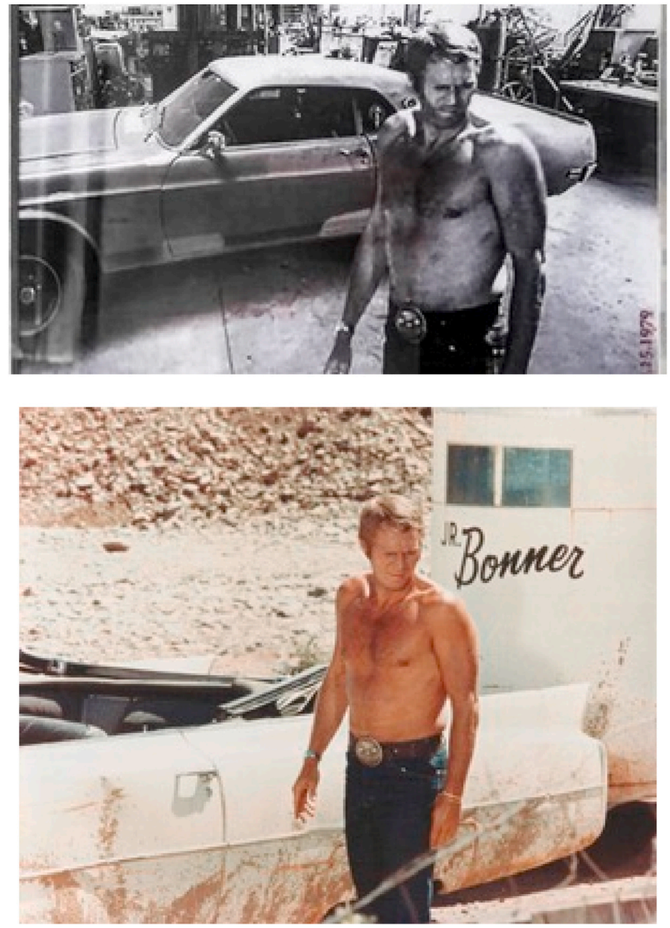

Fig. 3. Manipulations of photo material in the context of collector vehicles. (a) Alleged "proof"-photo for a car claimed to be owned by Steve McQueen, published by BILD online and other media in August 2, 021.[3] (b) Original film still photo from the movie "Junior Bonner", featuring Steve McQueen in 1972.

Repairs, replacement of components, or restorations have added at least as much to today's confusion. These usually were not carried out with falsifying intentions, but in a quite pragmatic way to keep the vehicles in running condition. Until recently, this was often done without comprehensible documentation and all too often with little regard to the historical coherence of the components.

In summary, despite, or even because of, the marking systems historically used, it can be challenging to prove the historical genuineness of a vehicle and the coherence of its technical components. For this reason, forensic procedures can be very helpful in their examination and more accurate assignment.

3. Forensic examination of steel substrates in historic vehicles

3.1. a. the crucial points and first steps of examination

As in the world of fine arts, counterfeiters use different techniques to manipulate the identity of a historic vehicle or even copies and pass them off as a „collector's object of desire".

For example, the genuine identity of an existing historic vehicle, and the component that provides it can be manipulated. Typically, this is done by grinding off the existing markings on the chassis or frame and a new identification number is stamped in place. When doing so, the counterfeiters often use stamping tools that are very similar to those initially used and try to get as close as possible to the appearance of genuine markings. As a result, and like for many art forgeries, the actual parts might be historic, but the assignment of the object is changed.

[3] Bild Online August 16, 2021, - the fake photo was removed from the BILD online article on Sep. 14, 2021, and the complete article taken down from the BILD website a week later, after the case became public.The picture manipulation then was subsequently made public in print in Auto Bild Klassik 11/2021.

Another approach used by counterfeiters is to replicate or reproduce the part defining the identity (e. g. chassis, structural frame or engine). This part is fitted with other newly made and/or historic parts, to make a functional vehicle. It is then stamped with a supposedly historical identification, often derived from a genuine specimen, or related to original historic documents.

In other cases, a complete copy of a historic vehicle is manufactured from scratch. Here too, a historic identity, illegitimately taken from an original vehicle may be added, or even completely new identities may be invented, building on the manufacturer's historic marking system.

The first step of an in-depth investigation is the visual examination of the vehicle itself and its technical characteristics, as well as identifying historic markings. In addition, the documents and archival materials relating to it will have to be reviewed and, depending on the case, checked for their authenticity.

Therefore, a central question is: Can the vehicle's history and provenance be verified in the available corresponding paperwork? Undocumented or poorly recorded restorations, as well as times when its existence or whereabouts cannot be proven, are particularly critical. Of course, supporting cross-checks for authenticity and plausibility must be carried out regarding the documentation and the historic markings, including the vehicle's current configuration. Sometimes this requires consulting designated experts for the model in question. In many cases, professional databases, archives, and information provided by vehicle manufacturers, as well as specialized literature, can complete the picture.

Parallel to this research, scientific examinations and analysis are carried out to compare the materials found on the vehicle with the results of the historical investigation on period materials and typical construction techniques.

3.2. b. Material analysis with mobile optical emission spectrometry (OES)

With few exceptions, the chassis and frames of historic vehicles were made of forged steel or steel sheet metal. However, steel manufacturers, as suppliers to the automotive industry, repeatedly developed and refined new processes for smelting ores, which ultimately affected the composition of the materials they provided. In general, the Siemens-Martin process or the "Thomasbirne" were state-of-the-art from the 1920s until the 1970s and the Linz-Donawitz process was increasingly used from the 1950s onwards. In parallel, some advanced steel manufacturers already produced so-called "electric steel" in the most advanced plants in the 1950s. In addition, the basic manufacturing processes were constantly refined. For example, special degassing and deoxidation processes made it possible to reduce gases in the steel by adding aluminium. There were also special vacuum treatment processes that affected the material. The addition of recycled steel scrap increased as well over the years. As a result, the purity and consistent qualities of steels were continuously evolving. At the same time methods for steel production which were already regarded as "outdated" were still used in less industrialized countries, while more modern processes already had been widely introduced elsewhere. These developments are well summarized in two articles published in 2017 and 2018 by Lauri Holappa, which describe the different historical steelmaking processes [18].

Analysis of the materials can reveal clear characteristics of the processes used and assign them to corresponding, typical epochs. Steels from old processes and their typical composition could only be faked if the related original manufacturing processes were to be completely reconstructed and replicated. Even the frequently repeated claim that reforged historic railroad rails or fragments of old tankers make the faking of vehicle parts untraceable can be clearly refuted through our research. The necessary thermal re-processing of historic materials inevitably will cause changes in their composition, which can also be detected analytically.

Our joint studies with Cappel Stahl Consulting GmbH/Dr. Jürgen Cappel have shown that mobile OES devices can provide good results for determining the composition and age of steel materials. Comparative measurements also have shown that the precision of mobile OES devices today is quite comparable to stationary laboratory equipment.

The measurements can be carried out directly on site, so it is not necessary to transport the vehicle to be examined. Meticulous preparation of the measuring points is indispensable for correct results. This means coatings and corrosion must be removed and the substrate sanded down to bare metal in an area of approximately 3×3cm. For this reason, the process is not completely non-destructive, but it avoids weakening the stability of structural parts by cutting out drill cores, which is required by some other methods [19].

Usually, several measurements will have to be taken from each measuring point, to exclude misinterpretations due to possible irregularities in the structure of the material (see Fig. 4.).

Alternately, in the case of very narrow diagnostic situations or small and very sensitive objects to be examined, small chips can be extracted from the metal substrate to be used as samples. These must then be examined later with a stationary measuring device. A clean metallic surface is necessary to avoid contamination and incorrect measurements due to corrosion or coating residues. This method often is difficult to implement in practice, as the processing times in the few specialized laboratories usually are significantly longer than for direct measurements. It can be challenging to synchronize the processing times with the often relatively short-term schedules of upcoming auctions or sales.

Early attempts to date historic vehicle steels mainly focused on their carbon concentration and the proportions of phosphorus and sulfur they incorporated. These attempts used Mobile X-ray fluorescence (XRF) devices, built for industrial applications or designed for sorting scrap metals in raw material recycling [20].

But even with up-to date XRF equipment, no serious chronological assessments can be made. The detection limits here are in the range of about 100 ppm, and in some cases even considerably higher. This is especially true for light elements such as aluminum, phosphorus, sulfur, and other trace elements typical for certain historical manufacturing processes. Quantification of these trace elements is critical for the precise chronological classification of the material, and XRF is not capable of determining these items sufficiently [21]. Even more important, carbon cannot be detected at all using XRF, although it is one of the most relevant elements in the identification and dating process.

Modern OES equipment today allows very precise measurements by recording a large number of elements and trace elements much more accurately. When using an accurately calibrated mobile optical emission spectrometer (OES), detection limits of 10 ppm, and in some cases as low as 1 ppm, can be achieved for the relevant elements. While the standard calibration of these devices is not sufficient for distinguishing the relevant vehicle steel compositions and their typical side elements, the devices can be individually configured to detect the elements in question [22]. During the measuring process, the new OES data can be compared to data archived from other vehicles our extensive internal reference database compiled in the last 10 years, as well as employing digitally supported "machine learning". The tailor-made algorithm learns continuously and makes suggestions for interpreting the measurements, as a support for the examining expert. Detail information like that must be handled carefully and confidentially, since in the wrong hands it could be used to "improve" counterfeits.

Blind tests have shown that it is possible to make statements with an accuracy of about 1–2 years in some cases [23]. Of course, this is only realistic with a high data coverage for the respective period and vehicle type. Typically, assignments can be made with an accuracy of about 5 years. Still, even a 5-year range can clearly unmask replicas or fakes, which are commonly produced only after a longer time interval. With a growing number of measurements and their processing by the algorithm, the accuracy will only increase in the coming years.

Remarkable improvements in the field of rapid prototyping, including 3D laser scanning and 3D printing, raise the question whether components replicated this way may be more difficult to identify. Tests

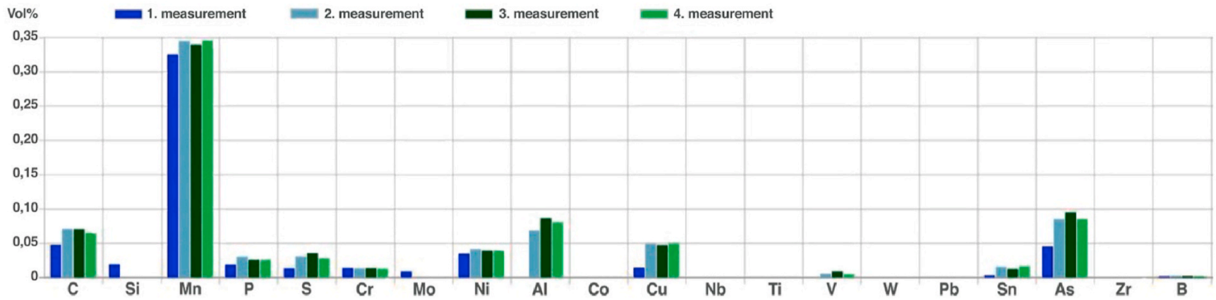

Fig. 4. Material profile of a steel part produced in the early 60s, including four measurements carried out at the corresponding measuring point and relating to 20 different elements.

carried out together with the Institut für Werkzeuglose Fertigung GmbH (IWF, AN-Institut der Universität Duisburg-Essen) and Fachhochschule Aachen – University of Applied Sciences in 2012 demonstrated that metal components produced with 3D printing can be easily identified [24]. Steel powders available for 3D printing contain far less impurities than historic steels and are clearly detectable with OES. Moreover, the layered grain structure derived from the printing process is visible with X-ray imaging.

In addition to a chronological classification of steels, OES examination can also help to evaluate the quality of repairs and vehicle restorations. All too often, material specifications originally chosen by the manufacturers are no longer known today. This is especially relevant when it comes to structural and statically important components. The wrong choice of alloys used for repairs or even the replacement of entire body frames today therefore can, in the worst case, have safety-related consequences. A good example of this is the Mercedes-Benz 300SL "Gullwing" car of the 1950s and early 60s, which is highly sought after by collectors. Its inner body frame was made from a special chrome-molybdenum steel, whose elasticity is important for the overall stability and driving properties of the car. However, measurements taken on later repairs or fully rebuilt frames reveal that the materials used does not match the properties of the alloy used by the factory [25].

3.3. c. Magneto-optical resonance examination of stamped markings

A detailed examination of the markings determining the identity of the vehicle is an essential part of the forensic investigation.

In the case of punched markings made with embossing tools, such as those used on vehicle parts and for applying the identification numbers, the material is deformed not only on the surface, but it is also compressed in deeper layers of the substrate. This means that even if an existing punch marking is mechanically removed, corresponding traces remain in the material underneath and can be made visible again (see Fig. 5.).

The magneto-optical resonance method is a simple, quick-to-use method that provides a detailed look beneath the surface. Currently, we use a mobile device developed by Regula GmbH [26].

When examining firearms, as well as other metal objects, possible manipulations of punch markings have been traditionally investigated using different etching methods [27].

These require exposing, smoothing, and polishing the metal surface of the related area, in order to obtain a clear and high-contrast image. Then, in the next step, an acidic solution is applied, and the color changes of the surface are observed under the microscope. After the examination, any acidic residues must be neutralized and removed. With these procedures, micro- and macrostructures of the surface like phases, grain structures or cold deformations, but also segregations and enrichments will become visible.

But, of course, this technique will not work well on parts that are difficult to access on a fully assembled vehicle. Instead, magneto-optical imaging offers a non-destructive method, which in most cases can be used also on hard-to-reach areas without damaging coating layers and metal surfaces.

The handheld magneto-optical device introduces a strong magnetic field into the substrate. This field penetrates up to 2 mm into the metallic material and is deflected by compacted or inhomogeneous areas in the material. These can be defects in the casting, weld seams or even removed punch markings that are not visible to the bare eye (see Fig. 6 a + b). The digital image generated by the magnetic field measurement not only can visualize extinguished or manipulated original markings, but also allows to match and precisely measure their shape and size.

The magneto optical method was originally developed for the identification of stolen or tampered firearms. A more advanced version of the device can be used not only for ferrous metals but also for aluminum materials [28].

Extensive testing together with Zetos GmbH have shown that related devices can also be applied to historical vehicles. They enable fast and non-destructive verification of the chassis or engine numbers even on painted components. The use of this technique is limited only by the

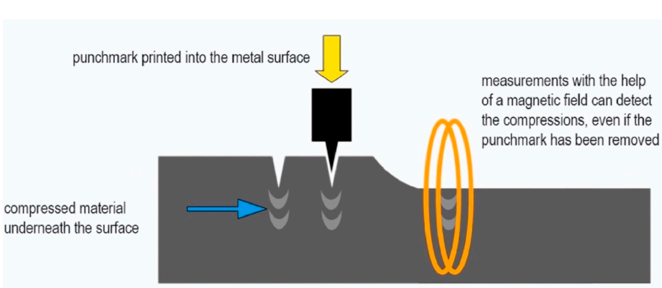

Fig. 5. Scanning a removed punchmark with the help of a magnetic field.

Fig. 6. Using magneto-optical imaging to examine stamped markings in metal substrates. (a) Magneto-optical image of manipulated digits on one of our test-panels: "3" (second left) was sanded out and restamped with "0". "6" (4. left) was cut out, the cut segment turned by 180° and re-inserted to make it a "9". "4" (far right) was stamped over to make it a "5". (b) Magneto-optical image of manipulated digits in an original vehicle identification number (see red darts):. "6" (far right) was changed to "8". "1" (4. right) was restamped to make it look like "4". . (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

physical accessibility of the areas to be examined and the relatively low penetration depth of the magnetic field [29].

3.4. d. Examination using X-ray techniques

X-ray examinations allow further forensic material examination and can provide important information on the chassis or frame.

For historic vehicles, mobile computed radiography (CR) and digital radiography (DR) X-ray systems are employed. They can be used directly on site in private collections or restoration workshops. The related procedures can be carried out both on the fully assembled vehicle and on individual demounted components. However, their application requires special professional training and observation of complex work safety procedures.

X-ray examination makes it possible to detect, document and examine hidden markings and punch numbers and reveals manipulations of existing numbers and metal components. It also helps to identify welds, even if invisible to the naked eye, and to verify if their weld pattern corresponds to the typical working techniques used in the period and on the part in question.

In the case of aluminum alloys, cast parts or porous materials, this kind of examination will deliver only diffuse images due to a significant spread of the radiation. Therefore, it will not give satisfactory results. The same applies to very thick components such as engine blocks, for which the radiation power of the mobile devices will not provide sufficient penetration.

In contrast to magneto-optical resonance methods (see below), X-ray examination allows controlled levels of penetration into the material, as well as a full view of the entire object under examination.

The analog CR system uses a flexible imaging plate, allowing access and screening of very difficult to reach and narrow locations [30]. Modern digital DR radiography systems can also be operated by remote control. However, their digital detector, which consists of a rigid unit, cannot be employed in all situations and conditions on vehicles [31].

Using mobile DR radiography, a chassis allegedly belonging to a valuable Bugatti was examined and several weld seams became visible on all associated parts. These weld seams indicate that the U-shape chassis rails, which are central to the identity of the car, were not drop-forged in one piece as it was typical for Bugatti's production. Instead, the rails were welded together from cutout flat steel parts (see Fig. 7a).

Assembly of a chassis with the welding method does not require the industrial equipment and stamping tools used by the manufacturer in period. Instead, the welding method is frequently used in later reproductions. In addition, other indicators that were found on this particular chassis, such as its material composition pointing to the 1960s, confirmed that it was not an original Bugatti component [32].

Other manipulations, like changes made to the chassis number of an Alfa Romeo SZ (see Fig. 7b) can be detected by using a small dental X-ray imaging device. In this case one of the digits was filled with liquid tin and then stamped over. When it was subsequently painted over, it was not visible with the naked eye.

Visible and invisible welding marks also can give significant evidence, when an original chassis number has been cut out and a new piece of metal inserted, which then was stamped with a new ("more valuable") identification.

In a different case, the examination of a famous Porsche racing car from the 1970s has shown the potential of X-ray examinations beyond just looking on the chassis/frame. It is documented that this vehicle underwent various modifications during its life, which included special parts added onto the roof. The large-scale X-ray of the roof, which today appears smooth and seamless, revealed no traces of earlier equipment that had been mounted nor traces that the mounting holes had been covered later. Together with other inconsistencies regarding the materials used and the existing identification markings, this led to the clear conclusion that this car was not the original racing car [33].

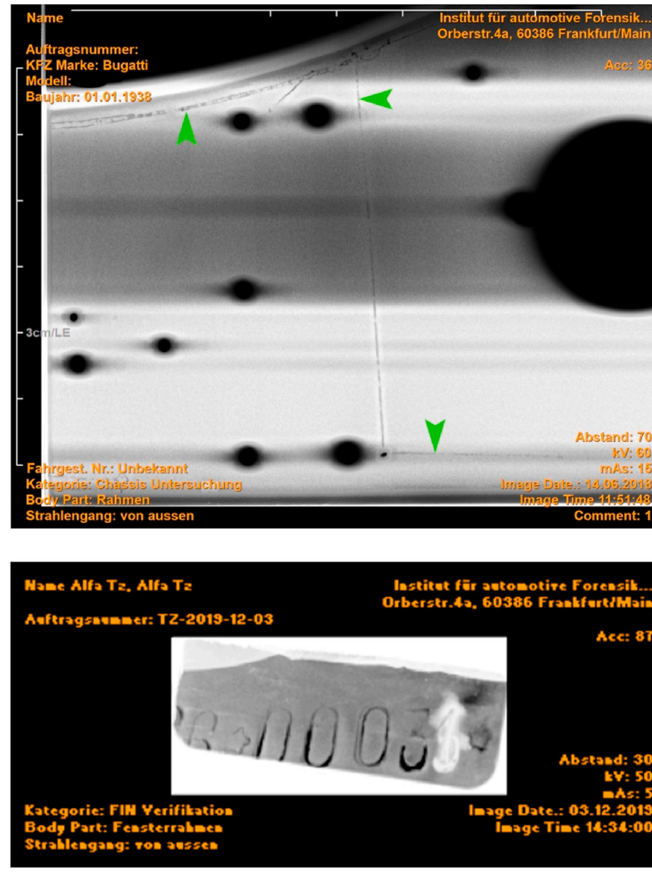

Fig. 7. Manipulations made visible using X-ray imaging. (a) X-ray image of an allegedly original Bugatti chassis, which clearly reveals welding seams (see green darts). This proves the chassis has not been made using the production processes used by the factory. (b) Manipulation on an Alfa Romeo SZ. The "1" in the chassis number (far right) was filled with tin and stamped over with "5". . (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Forensic examination of non-metallic materials in historic vehicles

4.1. a. the crucial points and first steps of examination

Going beyond questions of identity or "matching numbers", in historically preserved vehicles requires an examination of the coachwork, body paint, upholstery and interior trim. Both structures and equipment belonging to the time of delivery, as well as adjustments relating to important events in the vehicle's history, can play an important role in creating and enhancing its monetary value. All too often there is no documentation to show whether these components had been refurbished by an early collector and then developed signs of use and aging once again. In other cases, a lot of effort is put into deliberate forgery, to make replaced components and finishes appear "old" and "original".

A particularly astonishing example of such a manipulation came to light in 2011 during the examination of the body paint on a 1956 Mercedes 300SC, that was claimed to date from its time of delivery. The entire body showed a silver-metallic one-coat finish without a final clear coat, which is typical for the related period and corresponded with the car's delivery documents. Upon closer inspection and material analysis via infrared spectroscopy however, it became obvious that the paint material present was a crosslinking, styrene-modified polymethylmethacrylate, which has only been used for vehicle painting since the 1980s [34]. The final clear coat, which was a necessary part of the painting process when using metallic shades with this system, had been meticulously sanded and polished down to the silver layer over the entire body. Only under the rear license plate holder, had small remnants of the clear coat and corresponding sanding traces survived.

For sought-after marques like Mercedes, Bugatti, Ferrari or Porsche, one-off specimens designed by famous coachbuilders or vehicles with a special history, being in an untouched historic state can mean a difference of about 30–50% in sales value [35]. This explains why it was worthwhile for counterfeiters to use such a painstaking manipulation on the 300SC. Equally, a potential buyer may benefit from such an exact scientific investigation.

The central question in a forensic examination in this field is: do the materials date from the time of manufacture, or from the "historic service life" of the vehicle? Or were they added later, that is, during a restoration of the collection phase? Later changes are not held in the same esteem by potential buyers. On vehicles that obviously have been restored in one or the other way, it still can be worthwhile to look for even microscopic fragments of the initial paint job or interior trim. An exact determination of material and color can then serve as a basis for a more accurate subsequent restoration. Authentic reworking in the collection phase, being faithful to the original, usually will also have positive effects in regard of a vehicle's "prestige" and its market value. This means of course, a wide range of materials must be examined, including coating materials formulated with different binders, pigments and dyes; leather and imitation leathers of different makes; textiles, filaments and padding materials from natural and man-made fibers; wooden components and veneers; or Linoleum, natural and man-made molded polymer materials.

Investigation about the material originality of historic body paintwork and interior trim also begins with a detailed visual examination of the vehicle. This includes documenting any significant tool marks or work traces and any surviving markings, lettering or badges, that were applied by coachbuilders or in the manufacturing of the upholstery (see Fig. 8 a + b).

In the best case, there may even be historical photographs of the car that show earlier painting phases or the original design of the interior. Although such images are mostly available as black-and-white photos, they can still provide valuable initial information. Details of the type and make of the upholstery, the color of the body or special decorative accessories is often included in the order and delivery documents or historical invoices.

The initial inspection often reveals important hints of earlier modifications and refurbishing, such as modern staples, fasteners, springs or screws, or paint running over rubber window seals and into cracks in the deeper layers. Further insight can be obtained by using a head loupe or a stereo microscope and different light sources, like UV radiation or grazing light. As with the examination of paintings, paint repairs (see Fig. 9a) as well as partial replacements or repairs to seat covers, carpets and other parts of the interior can be identified in this way. In many cases, UV radiation can even help reveal runs, and fine brush and wipe marks, in the seemingly venerable "patina" of a surface, which indicate that it was artificially created (see Fig. 9b).

Investigations like described above can be carried out without damaging the fabric of the vehicle. However, for deeper insights into the material composition and a chronological classification, small samples must be extracted.

4.2. b. Analytical methods used for coatings and other organic materials

The most common method used by appraisers to determine the originality of a vehicle's finish employs measuring devices that are placed on the surface and measure the overall thickness of the coating. This practice of course has considerable limitations and rarely provides reliable information. The main reason is that no validated basic data on coating thicknesses applied in period have been documented. Coating materials used until the 1970s generally had to be processed in significantly thinner layers than high-solid two-component materials common today. Consequently, early production-era coatings that have already been overpainted one or two times still may measure "thinner" than a standard factory coating today.

Fig. 8. Historical markings can help to clarify the local and chronological context of elements and materials preserved on a vehicle. (a) Body number 2090 of a 1931 Delage D8L, applied by the upholsterer during the production process with blue wax crayon on the back of a wooden interior trim panel. Such markings, both how they were applied, and their location can give clues to the manufacturer of the body, its upholstery and interior trim, as well as to their initial affiliation with the vehicle in question. (b) A coach builder's plaque on a 1900 Renault type C, relating to body modifications commissioned by the first owner located in Spain. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Because of this, only material samples can provide detailed information about the composition and a chronological classification of the materials. It is essential in collecting the samples to keep damages to the historic fabric as minimal as possible, and to properly document the sampling locations in order to provide a clear chain of evidence.

In collaboration with the Microanalytical Laboratory Jägers and CEZA, various analytical methods, which are well-proven for works of art, can be employed for the in-depth examination of the sampled materials. The principles of the corresponding research methods are described in the publication by Mauro Matteini and Arcangelo Moles, complemented by recent literature, such as the 2018 book edited by David M. Bastidas and Emilio Cano [36].

Typically, a macroscopic and microscopic examination of the samples and their cross sections is performed. Depending on the case, reflected light, transmitted light, polarization microscopy and UV fluorescence microscopy can be used. The findings directly visible in the cross-sections, such as the sequence of layers, characteristic coatings and grain structures or distinctive UV fluorescence, are recorded in writing and documented photographically (see Fig. 10 a + b).

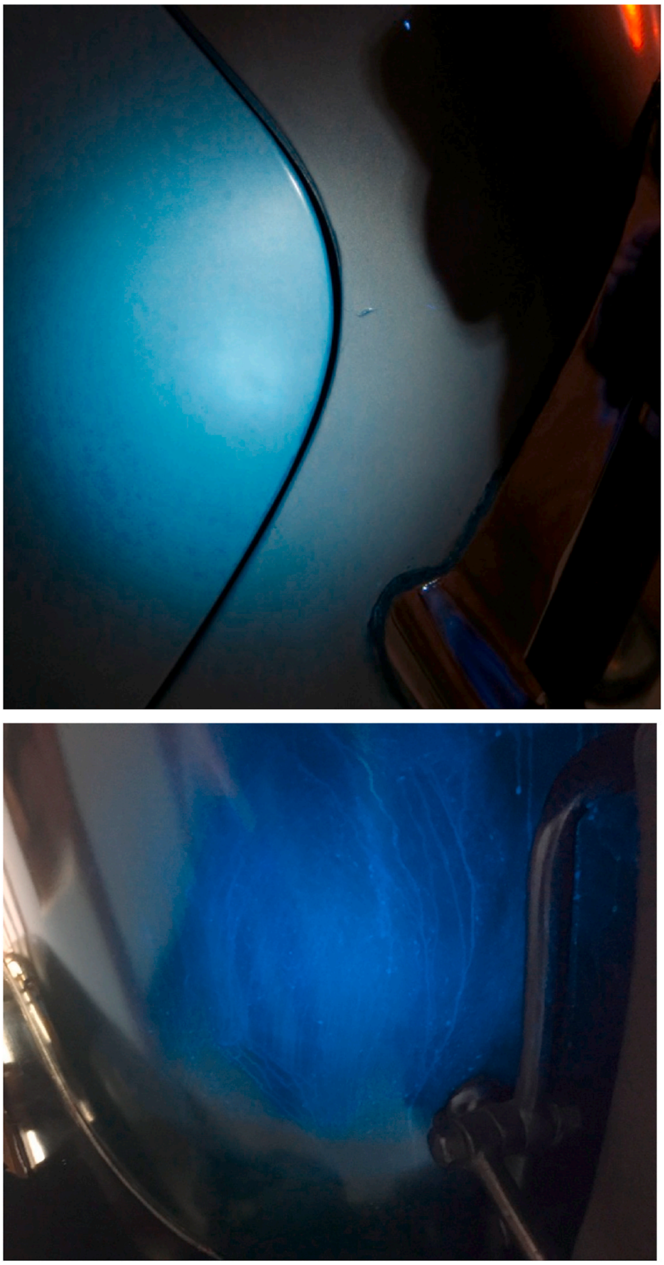

Fig. 9. With the help of UV radiation, repairs and other treatments to the vehicle paint, interior trim and other surfaces can be made visible. (a) Deviating fluorescence under UV radiation reveals the hood (left area on the picture) of a Jaguar E Type has been repainted. (b) UV radiation shows sags and brush marks in the "patina" of a Rolls-Royce Silver Ghost, indicating that its dark, supposed "antique" surface has been intentionally applied.

Energy dispersive X-Ray Fluorescence analysis (XRF, including μXray analytical microscopy) provides information about the elements of inorganic components like pigments and fillers.

Using Attenuated Total Reflection combined with Fourier Transform Infrared Spectroscopy [37] (ATR-FITR, including micro beam condenser and diamond cell technique), we can identify molecular structures in inorganic pigments and organic materials like natural and synthetic binding media, varnishes and coatings or natural and synthetic pigments and dyes.

To further determine organic binding media and additives, as well as natural or synthetic polymers and fibers, microscope-based Raman spectroscopy (Thermo Scientific-Nicolet, iS-50 FT-IR including micro beam condenser and diamond cell Thermo Nicolet) will be used.

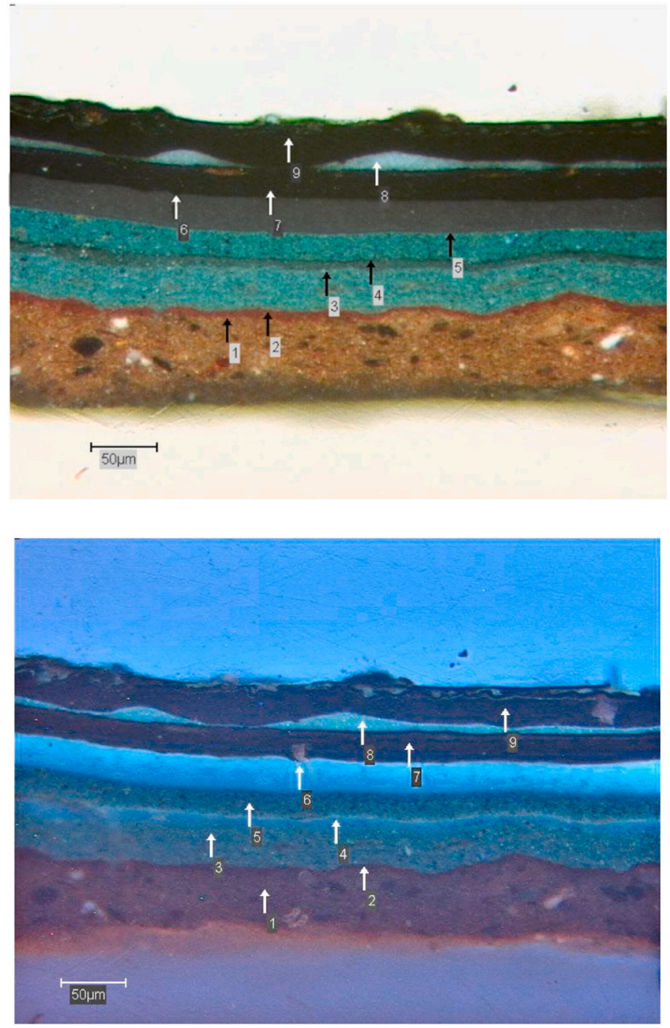

Fig. 10. Microscopic cross-section of the first, fishsilver-green paint scheme on a 1934 Mercedes 500 K (layers 1–6), - this first paint phase later was overpainted twice in black (layers 7–9). (a) The coating layers in the visible light spectrum. (b) Looking at the cross section using UV radiation (wavelength 365–380 nm), which can make details more clearly visible. . (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

With these techniques, which are well proven for the identification of related materials in the examination and analysis of works of art, craft objects and archaeological artifacts, each layer in the microscopic cross-section of a sample can be addressed, measured, and evaluated separately.

As a basis for an identification of individual ingredients we use the in-house database built up in cooperation with the laboratory of Drs. Jägers, including analytical details on a broad variety of 20th century artist and industrial materials. Over the past 15 years we expanded the data set by analyzing validated reference samples from vehicles built between 1896 and 1981. In addition to that, archival and literature research on the manufacture and composition of materials used in different eras of vehicle production plays an important role. It expands our knowledge about how these were typically processed in crafts-based and industrial vehicle production, which sometimes may have varied significantly in different regions and workshops.

It must be considered of course that certain pigments and binders have been used in vehicle coatings and other materials over a longer period. Knowledge about the earliest possible availability of an ingredient may provide only a rough framework for dating the material.

Therefore, it is particularly important to consider all the evidence and parameters in historical context. If, for example, a polyester filler is found under a topcoat formulated with cellulose nitrate binder and pigments that were used already in the 1930s, it clearly indicates the surface paint cannot have been applied in the period before World War II, but the earliest in the 1960s.

The same applies to the overall the sequence of layers, possibly containing several subsequent refinishing phases. In certain cases, this may even provide clues to the identity of the vehicle. If, for example, it is reliably documented a race car was initially painted red, shortly thereafter had been repainted blue and subsequently in a copper-metallic tone, corresponding layers still found on the body and frame must be regarded as important evidence for this car's genuine identity.

In addition to the methods described above, the age of natural organic materials like wood, natural latex polymers, leather or plant and animal fibers can also be determined by using radiocarbon dating [38].

Changes in the natural carbon cycle during the late 50's to late 60's relating to the nuclear bomb tests performed by the USA and Russia produced significant, year-related fingerprints of C-14 (relating to the so called „bomb peak" or „bomb pulse"), which is also traceable in organic materials originating from that period of time [39]. Hence, reliable results for these periods can be obtained for our investigations.

It is also very helpful that extensive restorations, as well as treatments with the intent of falsification, on pre-1950 vehicles, almost exclusively have been carried out since the 1960s together with their incipient appreciation as collectors' pieces. Conversely, this means that original materials from vehicles of the so-called pre-war period (built up to the end of WWII) can also be classified, since their C14 values can be significantly differentiated from those of their imitations, which were usually produced well after 1945. CEZA's extensive internal database provides an excellent basis for the evaluation and interpretation of the measurements.

Very small sample sizes of only a few milligrams, processed in a small particle accelerator, make this method very suitable for vehicle forensics. C-14 dating, unlike some other methods, provides a direct chronological evaluation in absolute calendar years without comparison to previously submitted reference samples of the same historic material.

In some cases, this method even can be used for components made with petroleum-based materials (like man-made "plastic" polymers). Normally, these materials cannot be dated with this method since petroleum is entirely void of C-14. But, for example, artificial leather seatcovers or piping made from polyvinyl chloride were often sewn together with natural cotton threads that can be dated very well with this method. Leatherette may be chronologically classified using this workaround.

Determining the chronological assignment of woods, be it for the supporting inner body structure or decorative parts of a historic vehicle, may not necessarily give exact results. This applies to dendrochronological methods which are based on counting, measuring, and comparing the tree-rings of wood [40], as well as C-14 dating. Since the wood used usually is obtained from the so-called heartwood (the inner parts of a tree trunk) and is dried and aged over time before processing, it usually does not reflect the actual date of manufacture of the vehicle. Furthermore, non-destructive dendrochronological dating is rarely possible because the end-grain sections of the wood components are rarely accessible. Paintings on wood panels or wooden sculptures have been dated non-destructively by visualizing tree-rings using X-ray computer tomography [41], which also may sometimes be applicable for vehicle-related wooden components. At this time, a clear statement on the originality of wooden vehicle parts can only be made for samples with annual rings clearly "too young" in relation to the period in question. Nevertheless, a microscopic determination of the type of wood and looking at the way it was processed can give clues about the period of manufacture, geographical assignments, regional craft traditions or sometimes even certain workshops.

5. Conclusion

In recent years, forensic examination methods have helped to verify and classify the identity, as well as the historical and material originality, of collector vehicles in many cases. Scientific examination methods and customized measuring equipment enable reliable detection of forgeries, which are unfortunately becoming increasingly common in the area of high-priced historic vehicles. A joint effort including specialized natural scientists, historians and vehicle experts is crucial in order to understand and evaluate the complex issues involved.

Further dissemination and application of such methods will hopefully have a deterrent effect on potential forgers, whose approach will at least be made much more difficult. Of course, it will be important to examine further methods and procedures to keep pace with the inevitable refinement of counterfeiting methods. That will certainly take place in the future and offers great possibilities for interdisciplinary work.

6. Outlook

While materials analysis and chronological evaluation of historic steels, pigments and other organic materials already yield reliable results, detailed knowledge on historic aluminum materials still is quite limited. However, related materials, which were used in the construction of the structural and body parts of historic competition cars, are characterized by a much smaller number of side elements and a manufacturing process that has remained relatively uniform throughout the entire period of production. This of course makes their chronological classification much more difficult.

Reference samples currently are being collected and evaluated. With a future database derived from these samples, specially calibrated measuring probes and a customized AI, it should become possible to date components made from corresponding alloys.

Infrared reflectography and other thermographic techniques also may offer interesting possibilities to reveal overpainted lettering and other markings on vehicle parts in a non-destructive manner. Similar to the examination of underdrawings on panel paintings, markings like starting numbers on race cars or military identifications could be verified under coatings that were applied later [42]. Corresponding test trials are currently in preparation.

The change in the view of originality and authenticity of vehicles has also led to the growing use of authentic materials in restorations, many of them reproduced according to historical formulations. For historic vehicles, exemptions have been granted to legalize authentic materials, even if they do not comply with today's environmental specifications. For example, waivers have been given despite the current regulations for example restricting the use of solvent-based paint formulations [43] for modern everyday vehicles.

As with the preservation of works of art, treatments like paint repairs should remain distinguishable from original surfaces and interiors in the long term. Thorough written and photographic documentation of all processing is critical to ensure that repairs can be distinguished from original. At the same time, various additives and pigments that are particularly harmful to health have now been completely banned from paints, artificial leathers, and other materials. They must therefore be replaced by modern substitutes in "updated" authentic formulations. Formulations like that will be analytically detectable, but not without damage to the fabric.

One very elegant way to proactively prevent misinterpretation of authentic paint repairs is to include newly developed, long-term stable UV marker pigments into these materials. Small amounts of these marker pigments do not disturb the allover color impression of a paint. At the same time, the pigments can be detected using a probe emitting UV radiation and measuring their typical fluorescence in the coating. Adding this new kind of long-term stable pigments to paints and other materials already in the production process can permanently identify repaints and other additions in a non-destructive way. In cooperation with Tailorlux GmbH, the developers of the corresponding pigments, related test series are currently being performed [44].

Using a scanning electron microscope to examine stamped and engraved markings on metal parts may be another method that should be further explored and adapted to the questions around historic vehicles. Markings that have been punched into aged, already embrittled metal components could have a different impression pattern than marks that have been applied into new metal already in the manufacturing process of a vehicle. But this technique needs to be investigated for different metal substrates in more detail.

In the face of these challenges, our research group welcomes building further synergies with experts from other areas of forensic science and practice.

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