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PREFACE

Tool marks on human tissue such as cartilage and bone have been investigated since the beginning of the twentieth century and compared with possible tools used in the crime (Bosch 1963; Esser 1933; Michailow 1977; Korpássy et al. 1943; Bonte 1972, 1975; Bonte et al. 1973).

Such investigations have frequently led to the identification of the tool actually used in the crime. Nevertheless, this branch of marks analysis has not been able to assert itself sufficiently to enable it to be included in the solving of homicides involving sharp and semi-sharp force trauma. There are probably various and, in some cases, in some cases very practical reasons for this.

Firstly, the evidence has hitherto not been secured in line with any rules, neither by the police nor by forensic medicine. In many homicides there is (seemingly) no dispute as to which weapon has been used (for example, the blood-covered tool is often still present at the scene of the crime). Or perhaps the question as to whether a certain tool has caused the victim's injuries only occurs in the investigations or the main trial at a later stage, with it then generally being too late to secure evidence. At this point in time, the victim has usually been already cremated. Even in the case of a burial without cremation, evidence originally present such as that on the cartilage of the ribs may have already been destroyed by decomposition.

An additional reason for the what currently tends to be the rare investigation of tool marks on tissue may be that the potential of the method is familiar in only a few homicide squads and public prosecutor's offices, and its specific implementation is common practice in only a small number of forensic institutes. This book is therefore intended to illustrate the opportunities and limitations of tool mark examinations on human cartilage and bones and thus raise the awareness of this branch of investigation. It is therefore primarily directed at public prosecutor's offices and homicide squads.

Furthermore, this book outlines the procedure involved in the method as well as the material required. It will therefore be able to help introduce the method in forensic institutes and is therefore also directed at marks experts.

In an ideal case, all evidence of sharp and semi-sharp force trauma to bones and cartilage would generally be secured as casts. The most pragmatic solution and ideal for the quality of the secured evidence would be for the evidence to be secured directly during the post-mortem examination by the responsible staff – in a similar way to that customary for removing tissue samples. This book is therefore also intended for the institutes of forensic medicine.

CONTENTS

Figure 2:
Chemically contrasted (ninhydrin) fragment of a shoe print on paper.
[Photo: LKA NRW]

1. INTRODUCTION

The examination of tool marks on cartilage and bone is usually conducted in institutes of forensic medicine. Generally, all connecting factors and facts based on the findings from the inspection of the crime scene, a bloodstain pattern analysis if appropriate and above all the key findings from the post-mortem examination are evaluated for this purpose. This leads to key indications of the tool causing the injury. If a potential instrument of crime is present, the forensic scientists are already able to make an assessment of whether the instrument was that actually used in the crime on the basis of its shape, surface structure and mass.

A comparative examination of the marks in firm tissue using a tool with the aim of unambiguously identifying the instrument of crime on the basis of attributes in the mark is not conducted by forensic scientists. In Germany, this further type of investigation is conducted by marks specialists in the state criminal police offices. In order to explain how these examination belongs to the field of tool marks and marks in general, the following provides a detailed description of this classical area of forensic science.

In crimes such as theft or burglary, the perpetrators often employ tools. Doors and windows are frequently forced open using levering tools such as screwdrivers and crowbars. The use of these tools generally leaves marks on the objects tampered with. A classic example would be a break-in involving a detached house, in which the perpetrator has gained access by prising open a window. The window then exhibits marks from the lever on the casement and frame that can be secured by taking a silicone rubber mould.

If a potential perpetrator is then established on whom levers such as crowbars or screwdrivers are found, a comparative examination of the tool marks can then be conducted to prove that leverage marks on the window (Figure 1) have been caused by the tools found on the perpetrator.

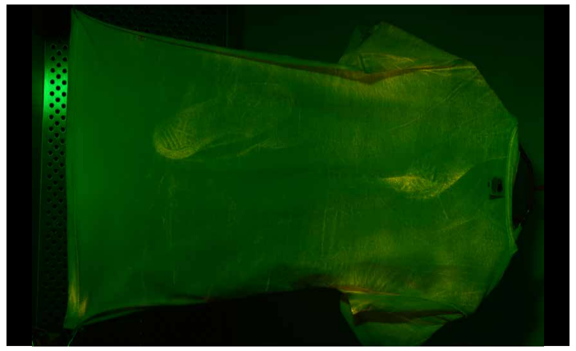
Figure 1:
Office door with lever marks at the level of the mortise lock (left: overview, right: detailed view). Casts were subsequently taken of the tool marks for examination.
[Photo: LKA NRW]

The tool mark examinations are a sub-area of marks analysis and thus belong to what are known as the classical forensic techniques, which also included disciplines such as dactyloscopy, the evaluation of handwriting and documents or even ballistics.

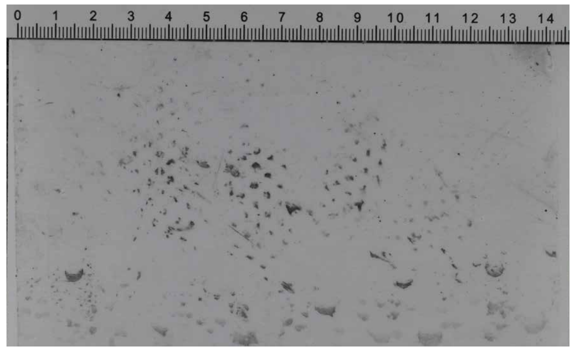
In addition to tool marks, the field of marks analysis also includes the examination of shoe, tyre and glove marks, physical match evidence, glass fragment analysis and other marks. Tool marks alongside shoe, tyre and glove marks (Figure 2, Figure 3, Figure 4, Figure 5) generally pursue the goal of unambiguously identifying or eliminating a potential source of the mark as the actual source of an evidence mark secured at the scene of the crime (Baldwin 2013).

In a physical match examination, the non-reproducible pattern of tear or breakage structures of fragments are investigated to see whether they previously formed a single unit (Figure 6, Figure 7). In this way, the adhesive tape used for restraining purposes can be matched to the roll of adhesive tape (Figure 8) found with the suspect (Weimar, Körschgen, et al. 2010; Weimar 2008). Similarly, after a hit-and-run accident, the involvement of a vehicle that fled can be demonstrated by the matching of fragments remaining at the scene of the accident, e.g. of an indicator cover, to the parts still located on the vehicle. Fragments remaining in a victim's body (Figure 9) can be matched to a weapon secured from the suspect (Weber 2020).

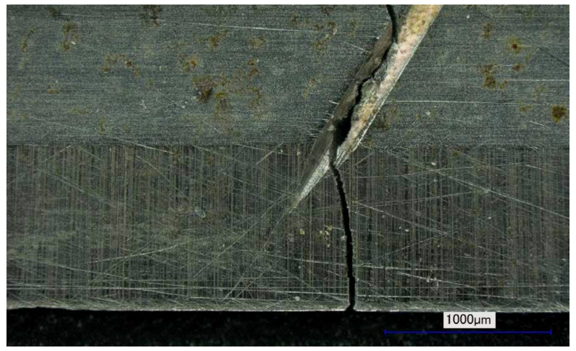
▲ **Figure 3:**
Tyre track on clothing of a victim that had been fatally run over.
[Photo: LKA NRW]



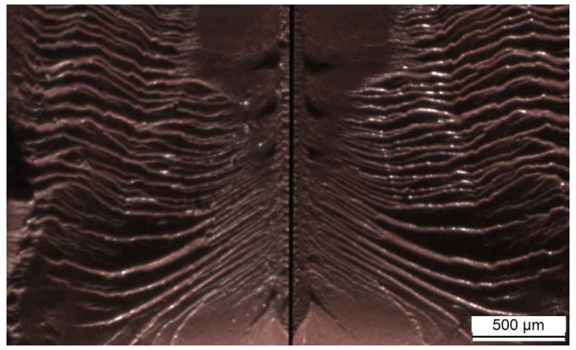
▲ **Figure 4:**
T-shirt with skin abrasion marks on the inside. The marks have resulted from kicks to the upper body. The marks were contrasted with indandione/zinc and fluoresce when illuminated appropriately. The marks allow conclusions to be drawn about the size and model of the shoe.
[Photo: LKA NRW]



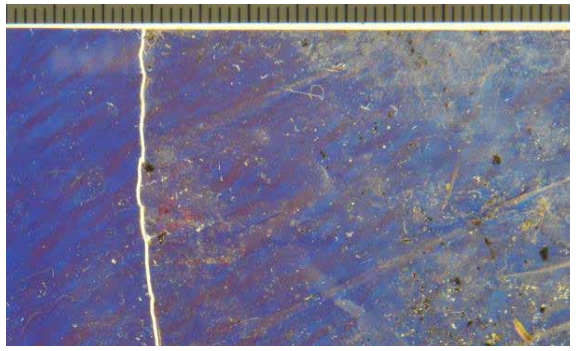
▲ **Figure 5:**
Glove print (contrasted with fingerprint powder) on a record card. The prints display the features of a studded glove.
[Photo: LKA NRW]



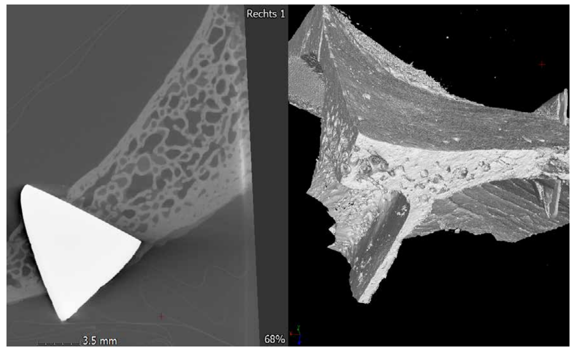
▲ **Figure 6:**
Fracture pattern on the broken blade of a utility knife.
[Photo: LKA NRW]



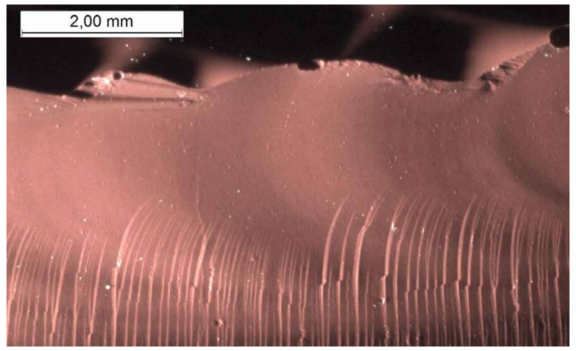
▲ **Figure 7:**
Comparison of the cast (casting material: AccuTrans AB brown®) fracture surfaces of two plastic fragments that previously formed a single unit. The surfaces are illuminated with opposed lighting and exhibit clearly inverse topographical features to each other, on the basis of which their previous existence as a single unit is proven.
[Photo: LKA NRW]



▲ **Figure 8:**
Physical match examination for a homicide. The fragment on the right was used to restrain/package the victim. The left-hand piece belongs to the roll of adhesive tape found in the suspect's possession. The examination took place with transmitted light using polarization filters. The former unity of the two fragments is proven by the matching pattern of the crack.
[Photo: LKA NRW]



▲ **Figure 9:**
CT scan of a section of a calvaria with an embedded fragment of a knife blade tip (different views).
[Photo: LKA NRW]



▲ **Figure 10:**
Fracture surface cast from a pane of glass. Hackle fractures (from the bottom to about the middle) and arched Wallner lines are clearly visible (casting compound): AccuTrans AB brown ®.
[Photo: LKA NRW]

▲ **Figure 11:**
Microscopic examination (Keyence digital microscope) of the damage on a pane of glass (laminated glass).
[Photo: LKA NRW]

▲ **Figure 12:**
Traces of manipulation in the form of fine scratches and on a cylinder pin.
[Photo: LKA NRW]

In the examination of glass breakage, the analysis of the breakage pattern and the structures on the fracture surfaces (hackle fractures, Wallner lines, Figure 10) can be used to determine the cause of breakage (throw, shot, thermal influence, material defect, Figure 11) and, if applicable, also the direction, number and sequence of the attacks (Von Kerkhof 2011). In the case of insurance fraud involving the faking of a burglary, in particular, evidence of a window being smashed from the inside and not from the outside can help to solve the crime.

Another subdivision of marks is the investigation of mechanical locking devices such as locking cylinders, padlocks, mortice locks or secure storage units. In this case, although it may also be a matter of identifying a specific tool, the tool marks in the locking devices are analysed to determine whether the locking mechanism was defeated by manipulation (Figure 12).

2. TOOL MARKS

2.1. Fundamentals of comparative tool mark analysis

2.1.1. Types of tool mark

Although this book primarily describes the investigation of tool marks on cartilage and bone, the following initially provides a general overview of tool marks and marks in general. Tool marks are surface changes (marks) on solid bodies (marked evidence) caused by tools or objects used as tools (source of marks). If, in addition to general features (shape, size), individualizing features also manifest themselves in the surface changes, the mark is suitable for comparative examination with a potential source of the mark.

The surface changes may be plastic deformations or material removal. Tool marks can be divided into impression and striation marks (Figure 13, Figure 14). If the tool tends to press statically into the marked exhibit and deforms it plastically, an impression mark is created, i.e. a negative pattern of the active surface of the tool. The surfaces of the tool that come into contact with the marked exhibit are referred to as active surfaces. When the tool is moved over the surface of a marked exhibit of lesser hardness by a relative movement and under force and material is removed or displaced, striation marks are created.

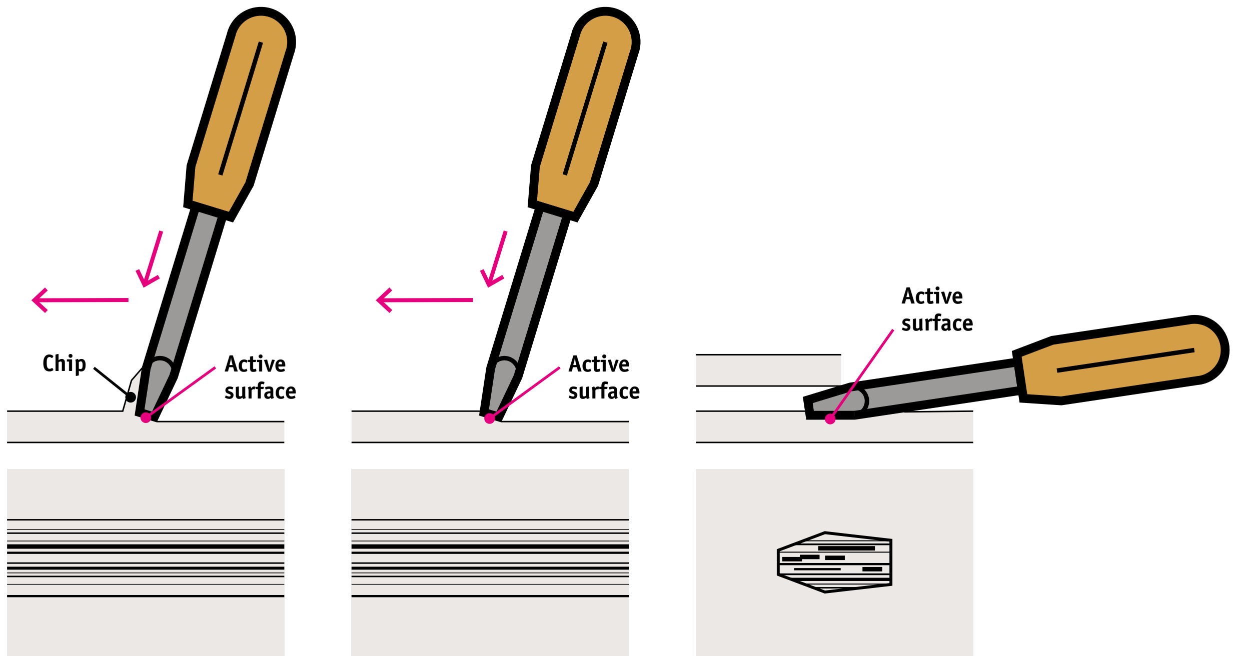
The striations in the mark present in such cases are due to the ground structure and are called grinding grooves[1]. The term striation mark is based on the fact that the marks consist of parallel striations[2]. The height profile of these grooves corresponds to the inverse height profile of the active surfaces involved in the intervention causing the marks.

In addition to the three-dimensional impression and striation marks, two dimensional marks can occur when material is transferred to a surface through contact. An example of this would be shoe print marks or glove marks made with blood. Material can also be removed by the source of the mark (Figure 15).

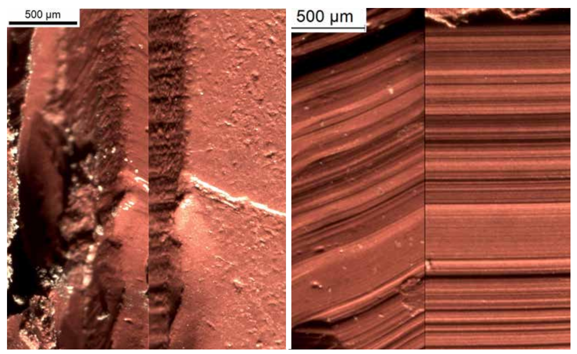
Separation marks, consisting of saw marks, cut marks, stab marks and slash marks, represent a subgroup of tool marks and play a major role in tool

[1] **Groove:**
A groove refers to a regular or irregular depression or mark on the surface caused by machining, e.g. grinding (DIN 4761).

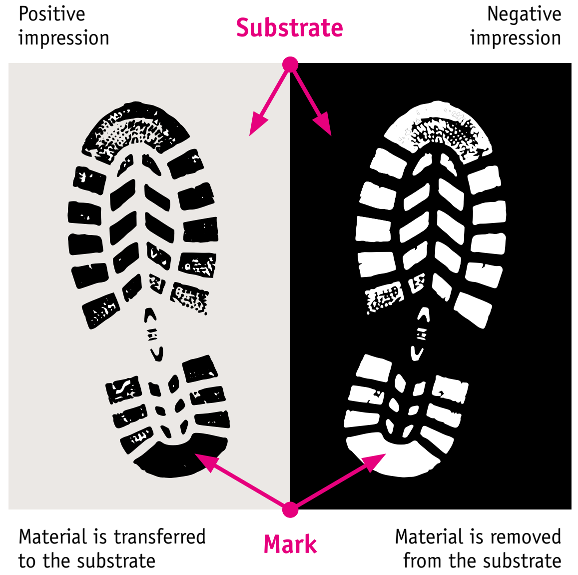
[2] **Striation:**
Surface imperfections that display linear depressions with a round or flat base (ISO 8785).



▲ **Figure 13:**
Mechanisms of formation for striation marks (left) and impression marks (right).
[Graphic: Marco Tavano]



▲ **Figure 14:**
Left: Comparison of an impression mark recovered in an over-tightened car lock cylinder (left half of the picture) with the test mark of the tool used in the crime (right half of the picture, screwdriver).
[Photo: LKA NRW]
Right: Comparison of a striation mark (left half of the picture) secured at the scene of a burglary with the test mark of the tool used in the crime (right half of the picture, screwdriver).
[Photo: LKA NRW]



▲ **Figure 15:**
Schematic representation of an impression mark (left) and a removal print (right).
[Graphic: Marco Tavano]

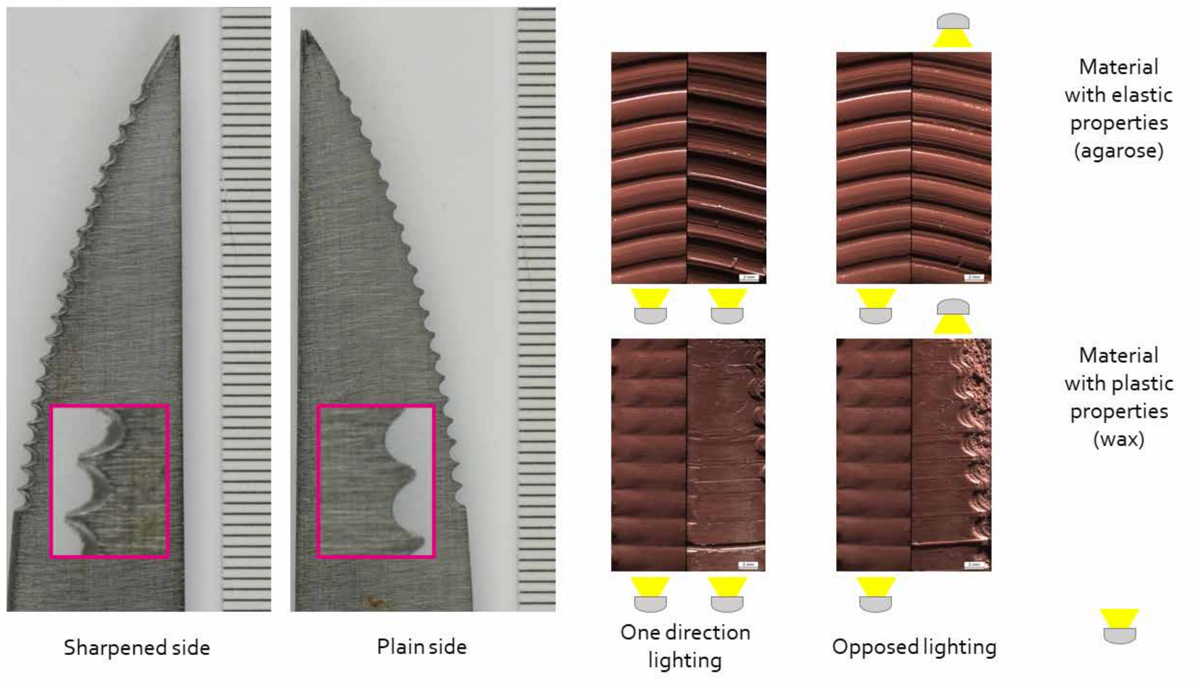


Figure 16:
The left-hand image shows the two side views of a knife blade with a serrated edge; the right-hand image shows the two marked surfaces of a marked sample cut with this knife made of material with elastic and plastic deformation properties respectively. The marks were cast with Silmark Cart casting compound and illuminated from the same and opposing sides
[Image: LKA NRW]

marks on human tissue. In addition to these, marks from angle grinders, plasma and water cutters etc. are also included among separation marks, although these marks can usually only be evaluated to a limited extent in terms of tool marks and tend to exhibit generic characteristics for the group. An examination of such marks may nevertheless be worthwhile[3] (Weimar 2019). The creation of saw marks is similar to that of striation marks due to material removal, although in the former case each individual cutting surface of the saw can be regarded as a tool causing marks.
In the case of cutting and stabbing marks, it is necessary to distinguish between material that exhibits predominantly elastic or predominantly plastic behaviour. Elastic materials are separated by the edge of the blade, with the resulting marked surfaces exhibiting inverse topographies to each other. Depressions on one marked surface are juxtaposed with raised structures on the other marked surface and vice versa. Viewed with opposed lighting, the marks can then be depicted almost identically. Marked exhibits with plastic deformation, on the other hand, are also initially separated by the edge of the blade. However, the mark is then further altered by the side surfaces of the source of the mark, so that the two surfaces of the mark may be completely different (Figure 16).

[3] Weimar, for example, was able to use the marks from an angle grinder to determine the direction of rotation of the cutting disc, which delivered important conclusions about the position of a worker at the time of a gas explosion caused by the grinding (Weimar 2019).

2.1.2. Objective of and suitability for investigation

The objective of a comparative tool mark examination is usually to prove that a certain tool has left a certain mark. For instance, in the case of a homicide caused by sharp force against the chest, the objective of the investigation is to prove (or exclude the possibility) that the knife secured from the suspect was used in separating the rib cartilage. The aim is therefore not only to prove (or exclude the possibility) that a knife such as that secured is the weapon used in the crime, but that precisely this one knife is the instrument used.

The basis for uniquely identifying a tool as the source of a mark is that the tool, i.e. the active surface of the tool, is unique or can be distinguished from all other objects.
Furthermore, a tool can only be assigned to a mark if the active surfaces of the tool have not undergone any significant changes after the mark was caused. If, for example, the cutting edge of the knife is completely sharpened after the crime, it can no longer be assigned to this mark. In addition, changes to the active surfaces can also occur if the marked exhibit is harder than the tool. If, for example, a safe made of hardened steel is attacked with a crowbar, the safe may leave marks on the crowbar rather than the other way round.

Another prerequisite for a successful comparative tool mark investigation is that the material bearing the mark should have a sufficient imaging quality. This means that both general features such as the shape and size of the active surface of the tool and the individualizing features of the source of the marks must be depicted in the material.

The comparative tool mark investigation begins with the examination of the material to be investigated. For this purpose, the marked exhibits are examined visually, with the naked eye and microscopically, with regard to their suitability. This involves checking whether the imaging quality of the marked material is sufficient for the examination. Ductile[4] materials, such as many metals and plastics, are very well suited as marked exhibits, because even comparatively fine details of the mark are transferred to them. In brittle[5] or porous materials, however, the imaging quality is comparatively low. In the case of cartilage and bone, it is often the case that the tissue depicts marks in sufficient quality. However, for both tissues this depends on various factors, which will be discussed in more detail in subsequent chapters.

[4] **Ductile** = plastic, i.e. permanently deformable.

[5] **Brittleness** = brittle materials fail (break) under load without any or with very slight plastic deformation.

2.1.3. Distinguishability

In addition to the marked exhibits, the possible sources of the mark, i.e. the tools, are also examined microscopically with regard to their suitability. This involves checking whether the active surfaces of the tool have unique features, i.e. features that can be distinguished from other objects, or whether other tools with the same surface topography may exist.

Figure 17:
Kitchen knife as an overview and detail view of the knife tip and knife edge with numerous usage features.
[Image: LKA NRW]

Since the distinguishability of the active surfaces of the tool provides the basis for the tool mark examination, it will be dealt with in detail here: individualizing features that make the tool distinguishable arise both through use and during the actual manufacturing processes. When a tool is used, the active surfaces come into contact with other objects. In the process, they can undergo changes in the surface texture. For instance, scratches, dents and impacts may occur, or material may be chipped away or coatings may flake off. The type and intensity of the changes is related to the hardness of the objects coming into contact with the active surfaces, the force or stress ratios that occur in the process, the type and manner of contact and a multitude of other, often random factors. The more intensively an active surface has been used, the more of these individualizing usage features of use it will bear. A kitchen knife (Figure 17), for example, undergoes changes to the blade through use. The cutting edge of the blade is bent over and pieces successively break out, causing scratches and deformations.

In addition to these usage features, the active surfaces of most tools already have features immediately after production that make them distinguishable (Burd et al. 1968). The production steps that play the most important role in this are those which involve machining of the tool. Most active surfaces of tools undergo material removal in one of the last machining steps with a geometrically undefined cutting edge. This includes production processes such as grinding (Monturo 2009), vibratory finishing and shot-blasting. In contrast to machining with a geometrically defined cutting edge (drilling, milling, sawing, etc.), the number, shape and position of the cutting edges responsible for the machining change in these processes. The cutting edges here are the edges of the abrasive grains consisting of irregularly shaped hard material grains. During machining, the cutting edges of the grains remove material from the workpiece.

At the same time, the hard material grains also change. The cutting edges of the abrasive grains become blunt, splinter and thus form new sharp cutting edges. In processes with bonded abrasive grit, such as in grinding with solids and abrasive belts, the abrasive grains become completely detached from the bonded surface, such as when they are blunted by machining.

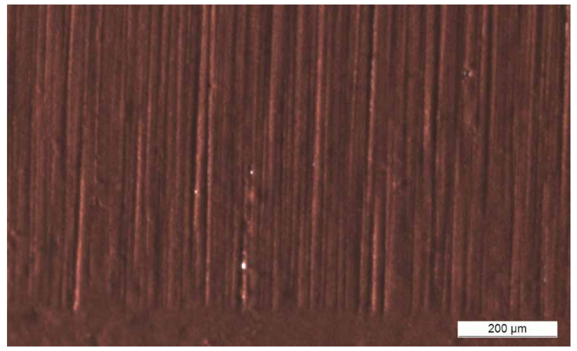


Figure 18:
Cast of a grinding pattern for an unused scalpel blade (casting compound: AccuTrans AB brown®).
[Photo: LKA NRW]

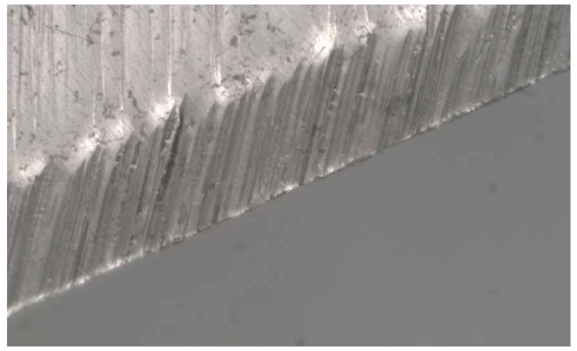
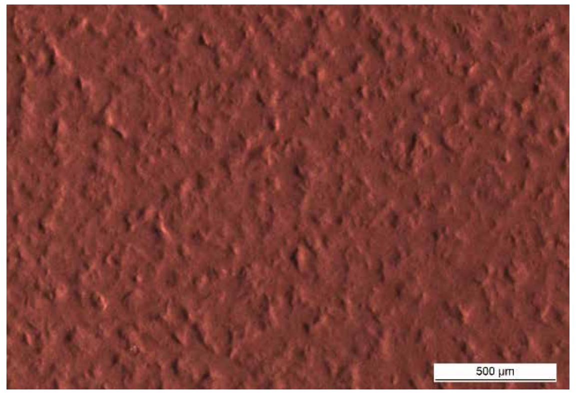


Figure 19:
Surface structure of a ground knife blade.
[Photo: LKA NRW]

The abrasive grains underneath then lie on the surface and cut into the surface of the workpiece. Grinding creates parallel grinding grooves on the surface of the workpiece. Due to the fact that the cutting-edge geometry of the hard material grains is subject to constant change, the grinding grooves also change with increasing length. They begin where a hard material grain cuts into the surface, change when the hard material grain rounds off or splinters and disappear when the hard material grain breaks away from the bonded abrasive or no longer cuts into the surface for reasons of geometry (Figure 18, Figure 19). Since the grinding tool is constantly undergoing wear and change, it is not possible to produce the same grinding structure twice or multiple times.

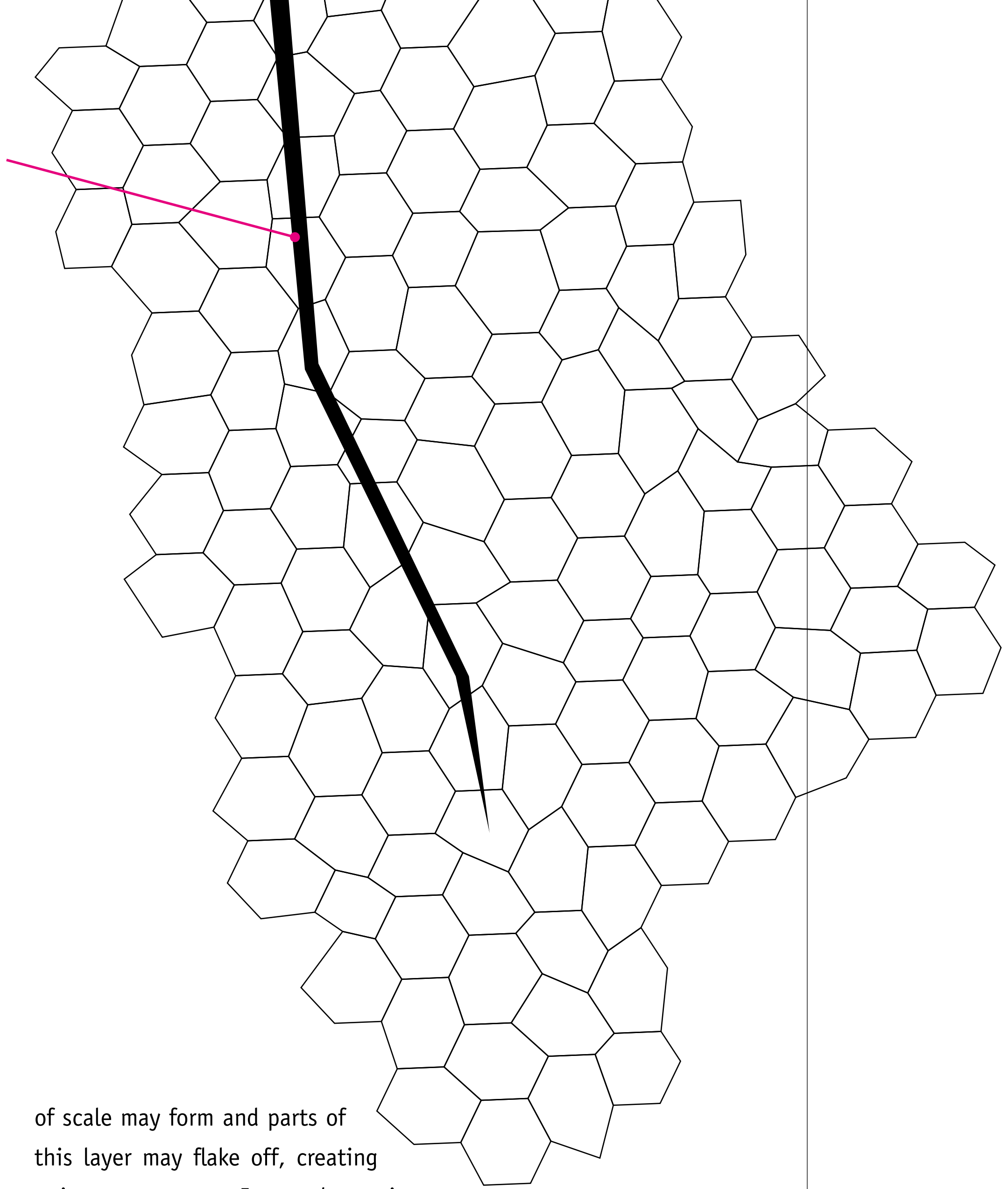
Shot-blasted surfaces (Figure 20) are also uniquely and distinguishably structured. In shot-blasting, the abrasive grains are fired onto the surface of the workpiece at high speed. It is not possible to control which of the irregularly shaped abrasive grains hits the surface and where, with which side or orientation and at what speed. This creates random and non-reproducible structures on the surface.

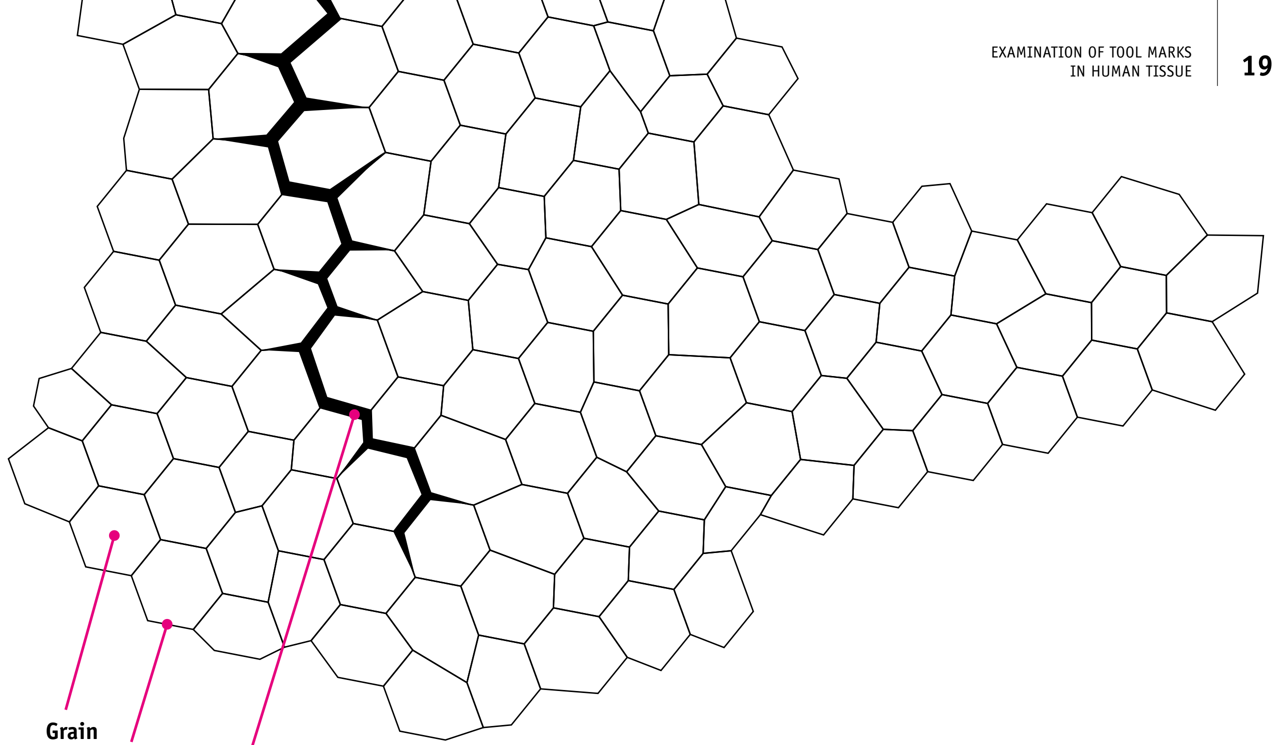


▲ **Figure 20:**
Cast surface structure of a shot-blasted screwdriver for slotted screws (casting compound: AccuTrans AB brown®).
[Photo: LKA NRW]

In addition to the machining processes mentioned, other technical processing steps also produce unique surfaces. For instance, cracks can appear during hardening, which individualize the surfaces. A layer of scale may form and parts of this layer may flake off, creating unique structures. In spark erosion, randomly distributed craters are created by melting and evaporating the material by means of an electric arc (Weimar, Balzer, et al. 2010). During the analysis of the tool and assessment of the individualizing features, it is therefore always necessary to examine the production of the surface as well.

Another fundamental aspect of the individuality of the active surfaces of tools is the influence of the material structure. Fracture mechanisms and the resulting fracture structures play a fundamental role in both production-related and use-related individualizing features. In the machining of steel, for example, cracks in the material precede the cutting edge and thus remove the chip from the material. Since most of the tools investigated in tool mark analysis are made of steel, the material structure of steels receives particular attention here. However, most of the mechanisms explained below can be applied to the common metals used as construction materials. Steel has a structure formed from an association of many crystals. A polycrystalline structure is formed during solidification of the melt. Commonly the crystals grow from particles known as nuclei until their growth is interfered and impeded by the surrounded crystals in the solidifying melt. Another name for crystals is grains. A grain is separated from the neighboring grains by the grain boundaries. The grains differ in shape and size. The orientation of the crystal lattices of the individual grains is distributed randomly. In polycrystalline materials cracks and fractures propagate in intercrystalline or transcrystalline manner (Figure 21). Intercrystalline crack propagation and fracture occurs along the grain boundaries and the fracture too. Transcrystalline crack propagation and fracture occurs through the grains. The course of crack propagation and fracture depends on the random orientation, size and chemical bounds (hardness) of the individual grains and is therefore not reproducible.





▲ **Figure 21:**
Schematic representation of transcrystalline (left) and intercrystalline crack propagation.
[Graphic: Marco Tavano]

To summarize, it may be said that most tool surfaces, if they have been ground or shot-blasted or have acquired surface characteristics through other production processes, can already be distinguished when they are still brand-new. The damage to the active surfaces that occurs during use, such as from chipping, scratching, paint flaking off or denting, provides additional individualizing features. As a rule, this also applies to the instruments used in homicides, such as knives, axes, hatchets, hammers and the like.

Tool Hammer · Type Locksmith hammer · Dimensions Length approx. 315 mm; Handle approx. 295 mm
Type of crime Homicide; blunt force against the skull bone; hole and depressed fractures
Quality of the marks Limited quality · Examination results Inconclusive

Tool Knife · Type Kitchen Knife (Ceramics) · Dimensions Length approx. 200 mm; Blade length approx. 100 mm;
Max. blade width approx. ca. 21 mm · Type of crime Homicide; Stab against the rib cage through the breastbone (sternum)
Quality of the mark Limited quality · Examination results Elimination

2.1.4. Casts

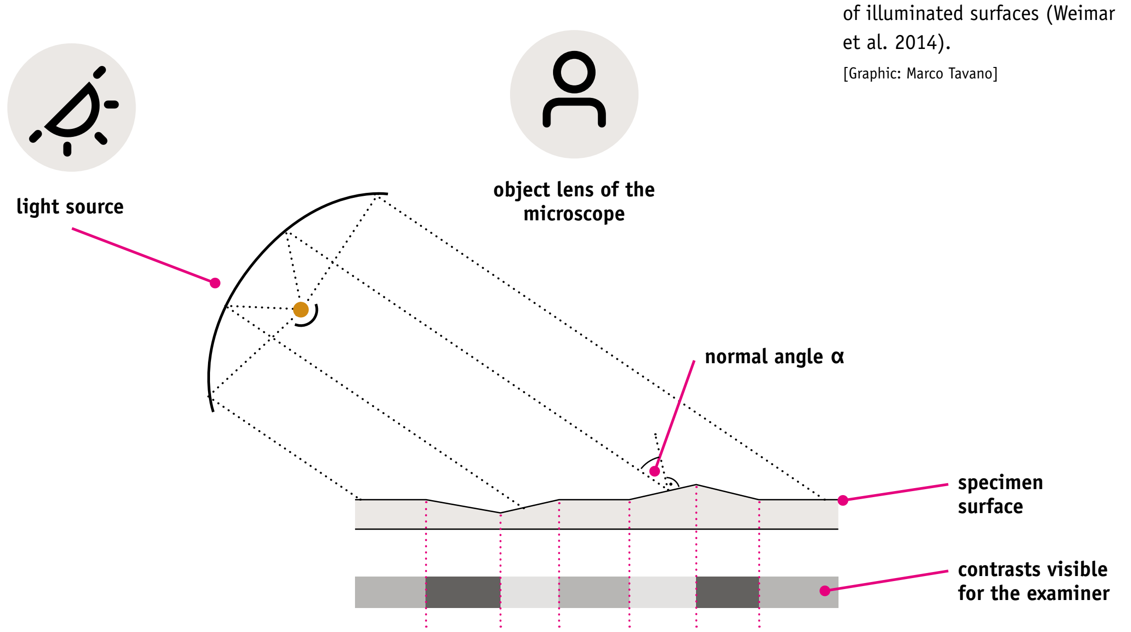


Figure 22:
Sketch of the reflection intensity of illuminated surfaces (Weimar et al. 2014).
[Graphic: Marco Tavano]

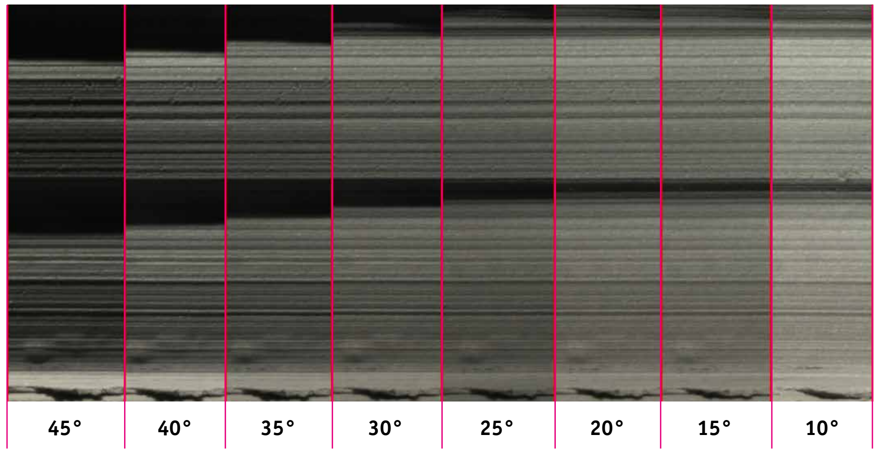


Figure 23:
Light microscopy images of the same striation mark (in grey plasticine compound) under different angles of illumination.
[Figure: LKA NRW]

Tool marks on technical surfaces can in principle be examined in the original state. In the case of some marks, such as puncture marks in car tyres, this is in fact also regular practice. In many cases, however, tool marks are secured by casting, for which there are various reasons. For example, securing evidence in the original object is not possible or only possible with unreasonable effort in the case of heavy or stationary objects such as safes, windows or doors. In these cases, the marks are recovered by using casting compound.

In the case of marks in cartilage and bone tissue, there are ethical reasons, among others, for not performing a direct examination. As these examinations are usually carried out in the forensics departments of the state criminal police offices, the casting process renders the sending of tissue samples and body parts obsolete. Another reason for securing evidence by casting, which is indispensable in many cases, is the limited suitability of the marked evidence for examination by light microscopy. Many technical surfaces, but also bones and cartilage, exhibit properties that make an examination significantly more difficult, if not impossible. The shine of metallic surfaces, for instance, interferes with optical examination. In the case of dark surfaces, there is the problem that it is extremely difficult to display any marks in them with sufficiently high contrast when light microscopy is used. In the case of cartilage and bone, it is the partial translucency and the light colouration that make direct examination of tool marks by light microscopy or scanning difficult.

Tool marks are illuminated by oblique lighting from the side, i.e. light with a very shallow angle of incidence. This allows fine details of the topography to be distinguished, which is due to the different intensity of the reflected light (brightness) of the partial surfaces of the mark that are aligned differently to the incident light. For a surface that is not specular, not translucent and homogeneously exhibits the reflection, τ, the intensity of the reflected light can be calculated as a function of the angle of incidence, α, to the normal of the surface according to the following formula (Figure 22).

$$I_{\text{reflected}} = I_{\text{incident}} \cdot |\cos\alpha| \cdot \tau$$
$$\text{for } \alpha = -90° \dots 90°$$

Light rays impinging on the surface at an angle of $\alpha = 0°$, i.e. at right angles to the surface, result in a maximum reflection intensity or brightness. If the light rays impinge parallel to (or at the rear of) the mark ($\alpha \leq -90°$ | $\alpha \geq 90°$), the minimum reflection intensity = 0 is attained. The surface is then unlit and dark. Corresponding intermediate values result for $-90° \leq \alpha \leq 90°$.

The intensity of the reflected light of the individual surfaces of the illuminated mark are therefore dependent upon the individual angle of incidence, α, which in turn depends on the angle of illumination. With a shallow angle of illumination, a mark therefore generally appears darker but with greater contrast, so that even fine structures become recognizable. In the case of a steep angle of illumination, the mark appears brighter and fewer areas are covered by shadows, but finer structures are barely visible or possibly even not visible at all (Figure 23).

The maximum possible distance between the brightest and darkest values gives the greatest possible contrast for the display of the marks. The greater this distance, the greater will be the number of brightness values that can be displayed for the eye to distinguish or in an image file. The minimum possible reflection intensity independent of the reflectance, τ, and thus independent of the colour is always 0, because $\cos(-90°) = \cos(90°) = 0$. However, the maximum reflection intensity depends on the reflectance, τ, i.e. the colour or brightness of the illuminated material ($\tau = 1$ for white surfaces, $\tau = 0$ for black surfaces). For this reason, marks in dark materials cannot appear with as much

contrast and hence as much detail as in lighter materials under the light microscope.
This might lead to the conclusion that white materials are optimally suited for light microscopy, but there are limitations to this as well. The direct illumination from the oblique lighting is reflected diffusely by the mark. This increases the brightness for all areas of the mark. The areas with a low level of lighting and those in the shade are thus additionally illuminated and appear brighter, but the areas that are already illuminated to the maximum do not appear any brighter as a result. Since the mark thus contains fewer brightness levels, it appears less detailed. This effect is of course most pronounced in white materials. In addition, white materials are often more translucent than dark materials, which means that the light shines through thin-walled areas of the mark illuminated by oblique light, and areas in the shade are additionally illuminated, which also leads to a reduction in contrast and the visibility of details. In addition, this makes the boundary of the surface to the surroundings visible with greater focus.

To compensate for these effects, marks are regularly cast on both technical surfaces and tissue. Casting compounds are available in different colours and with various methods of application. In forensic science, two-component casting compounds (casting material and hardener) intended either for mixing or for direct application by means of manual dispensers and mixing tips have become established. A previous study (Weber et al. 2021) has shown that of the casting compounds tested, brown compounds produce the most detailed image with light microscopy. In the case of the 3D tool mark scanner ToolScan[6], light-coloured casting compounds tended to lead to incorrect measurements while images with the highest contrast were obtained with black and brown materials.

The processing time and curing time of casting materials also play an important role in their suitability for the various areas of application. The processing time here means the period of time in which the compound can still be moved on the mark without impairing the imaging quality. The curing time refers to the time taken for complete hardening to occur, i.e. until the compound may be removed from the marked evidence. Any prior movement could still lead to deformation. Processing time and curing time depend on temperature. The recommended times are 1 to 2 minutes for processing and 3 to 6 minutes for curing. Special fast-curing casting compounds are available for applications on colder marked evidence, such as tissue from cold storage, or in cold environments. These compounds enable casts to be taken from tissue in a few minutes.
The casting process itself is extremely simple: the compound is applied to the area bearing the mark within the processing time specific to the material and left there until it has completely cured. The compound should be applied in such a way that no air inclusions can form. The rubber-like solid mass can then be removed. Labelling, for example, can take place by pressing a piece of paper onto the still liquid compound or by fixing the already cured cast to a piece of paper with fresh casting compound applied to the reverse side of the mark.

[6] ToolScan. Manufacturer: LIM Laboratory Imaging (Czech Republic)

2.1.5. Test marks

Test marks are produced with the tool potentially used in the crime for the comparative examination of the marks from the crime. If, for example, a mark from the crime is present as a stab mark in rib cartilage, i.e. as a striation mark, stab marks will then also be created with the tool from the crime scene. Since the angle of attack to create the crime mark is generally not known and as the pattern of the mark changes when the angle of attack is varied (Macziewski et al. 2017; Baiker et al. 2015), it is usually necessary to create a variety of test marks.

In the case of classic striation marks created by leverage, a test mark is created for approx. every 10° to 15°. It is assumed that larger angular differences are required before the mark changes to such an extent that two marks from the same tool can no longer be matched. Marks created by pushing or pulling are hardly distinguishable from each other (Figure 24), so that in principle it is sufficient to create the set of marks in only one of the two directions of motion, although, according to Baiker et. al, preference should be given to pushing (Baiker et al. 2015). Nevertheless, practice shows that when the test marks are created manually, some angles are easier to achieve by pushing and some by pulling. In the case of screwdrivers, crowbars, etc. it is advisable to produce the marks both by pushing and pulling. In addition, the marks should be produced with the shallowest possible penetration depth in order to achieve the maximum possible quality (Baiker et al. 2015).

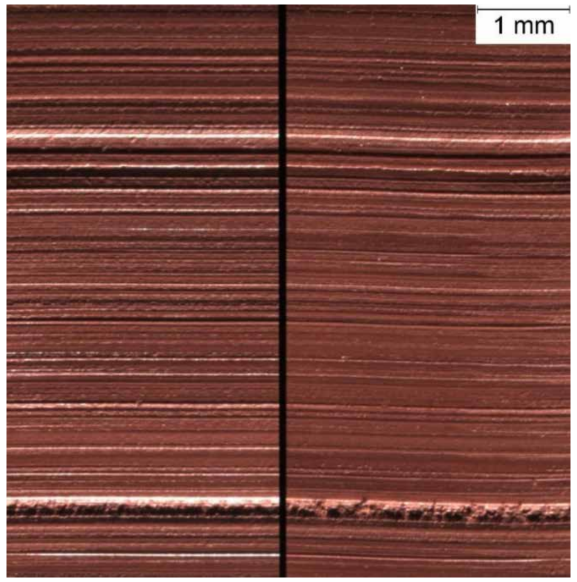
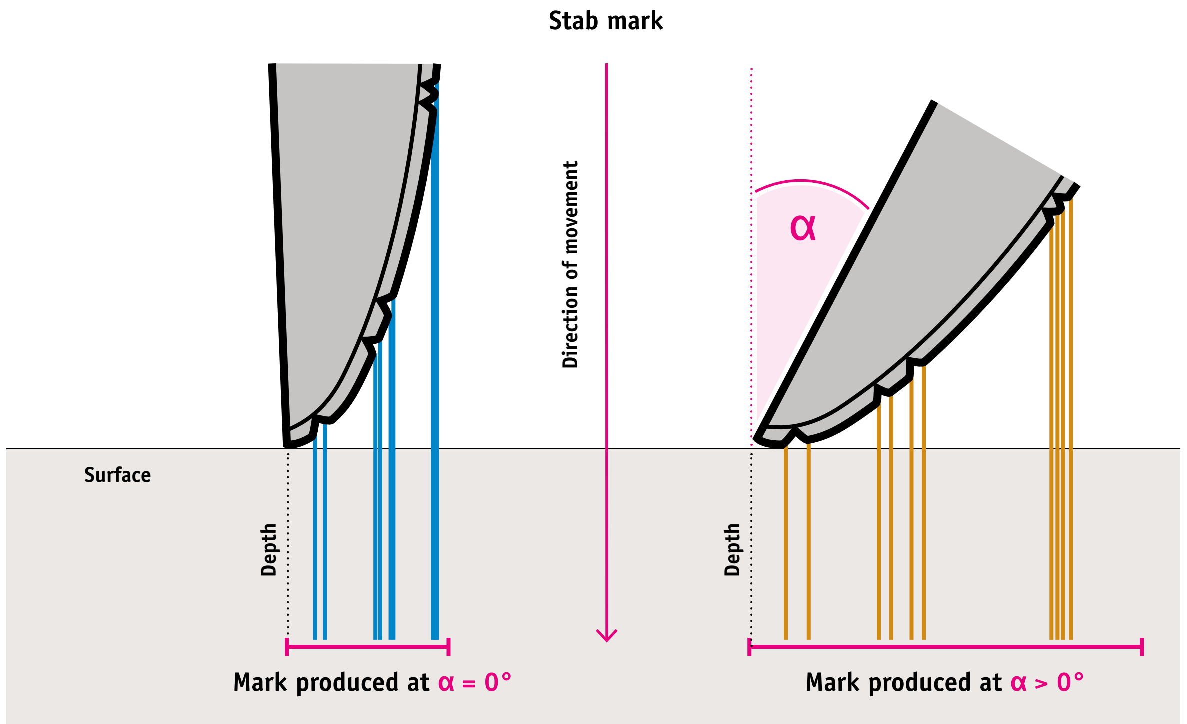


Figure 24:
Comparison of a striation mark produced by pushing a screwdriver with one produced by pulling the same tool. Both marks were created in wax and then cast (casting compound: AccuTrans AB brown®).
[Photo: LKA NRW]

In the case of cutting marks and especially stabbing marks, even a very small angular difference of a few degrees is likely to result in a complete change in the marks. A change in the angle of impact, α, causes compression or stretching of the mark (Figure 25). Depending on the angle variation and the knife, striations become wider or narrower, or previously overlapping striations are separated and divided into several individual striations. For this reason, even a slight variation in angle may mean that two marks from of the same



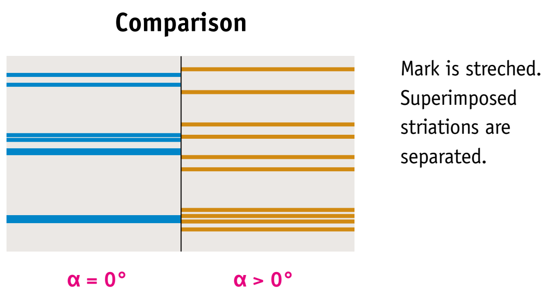


Figure 25:
Sketch showing the effect of varying the angle on the features of a stab mark. The left-hand side shows the marks made with impact angles of 0° and > 0°; the right-hand side shows a comparative display of the resulting marks with discernible stretching of the features. In addition, features lying on top of each other at 0° are discernible in isolated cases at angles > 0°.
[Graphic: Marco Tavano]

knife can no longer be matched to each other. This deserves particular attention during creation of the test marks.

In the case of impression marks, the angle of impact plays almost no role. If a mark such as this is present, an impression mark is also created as a test mark, although it is not necessary to create test marks for impression marks as a matter of principle. Depending on the evidence available, a direct comparison of a crime mark or the cast of a crime mark with the tool may also be possible. In most cases, the entire area of the active surface (in the case of the screwdriver, this would be the tool head) is cast and this cast, i.e. the negative, is filled with casting compound again to make an impression. In this way, a replica of the surface optimized for examination by light microscopy is produced from the casting compound. If the exact active surface area can be narrowed down in advance, it is also sufficient to replicate only the relevant subsection.

2.1.6. Test materials

The choice of suitable test materials is the basis for a successful comparative investigation. Test marks must be made in materials that meet the following criteria:

- They must offer sufficient resolution and image quality and be able to show fine details. As a rule, the test mark must never be of poorer quality than the mark from the crime!
- The morphology of the mark must be comparable to that of the marked evidence. Consequently, if the evidence mark consists of parallel, straight striations, the test mark should not consist of curved striations with varying distances.
- The materials must be castable. Therefore, they must not contain any substances that prevent the casting compound from hardening. In general, if materials are being used for the first time, they should be tested on a neutral spot to see if the casts harden and can be completely removed.
- Creating the test marks must not lead to any change in the source of the marks. For example, if the test material contains components that are harder than the material of the tool, any contact could change the active surface.
- In addition, the materials should of course be safe to handle and, ideally, also cost-effective.
- The test materials should be easy to procure or even easy to produce in a standardized manner.

In practice, wax plates have been used to create striation marks caused by levering or as slash marks. Other (soft) metals, wood, plastic, rubber, modelling clay and similar substrates are also used. If it is present in sufficient quantity, original material from the marked evidence can also be used to create the test marks. Elastic hydrogels such as agarose are suitable for stab marks in cartilage. Wax has proven to be effective for slashing marks on bones. Wax or lead is also often used for impression marks.

2.1.7. Comparative investigation and results

Comparison microscopes such as the Leica FS C or Projectina VisionX are generally used for tool mark examination, which allow simultaneous observation of evidence marks and test marks. The marks are located on object mountings that can be controlled independently of each other in X, Y and Z directions. The viewer sees both objects through the eyepieces and can position them for comparison. Usually, the views of the two object mountings are separated from each other in the centre of the image.

Most comparative tool mark examinations require magnifications up to a maximum of one hundred times. Comparative light microscopes are generally used for these examinations. If higher magnification ranges are required, scanning electron microscopes, confocal laser microscopes or digital microscopes may also be used.

In addition to the more classical purely optical method of comparative examination, scanning technology is increasingly finding its way into tool mark analysis. Compared to purely optical examination, scanning systems such as LIM ToolScan offer numerous software options and the possibility to export the scan data for processing into other evaluation tools (MathWorks MATLAB, Wolfram MATHEMATICA, Microsoft EXCEL). Another possibility is 3D printing of the data, for example, to produce an enlarged version of the object for presentation in court.

In the investigation, the test marks are contrasted with the crime marks and first of all the class characteristics are compared.

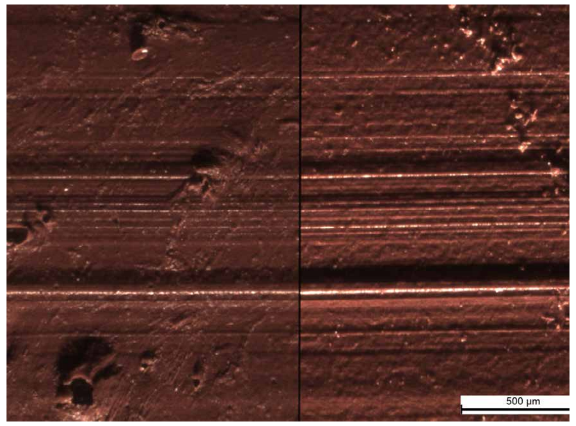


Figure 26:
Light microscopic comparison of slash marks made with a katana in a skull bone (left-hand half of picture) with test marks made in wax (right-hand half of picture) (casting compound): AccuTrans AB brown®).
[Photo: LKA NRW]

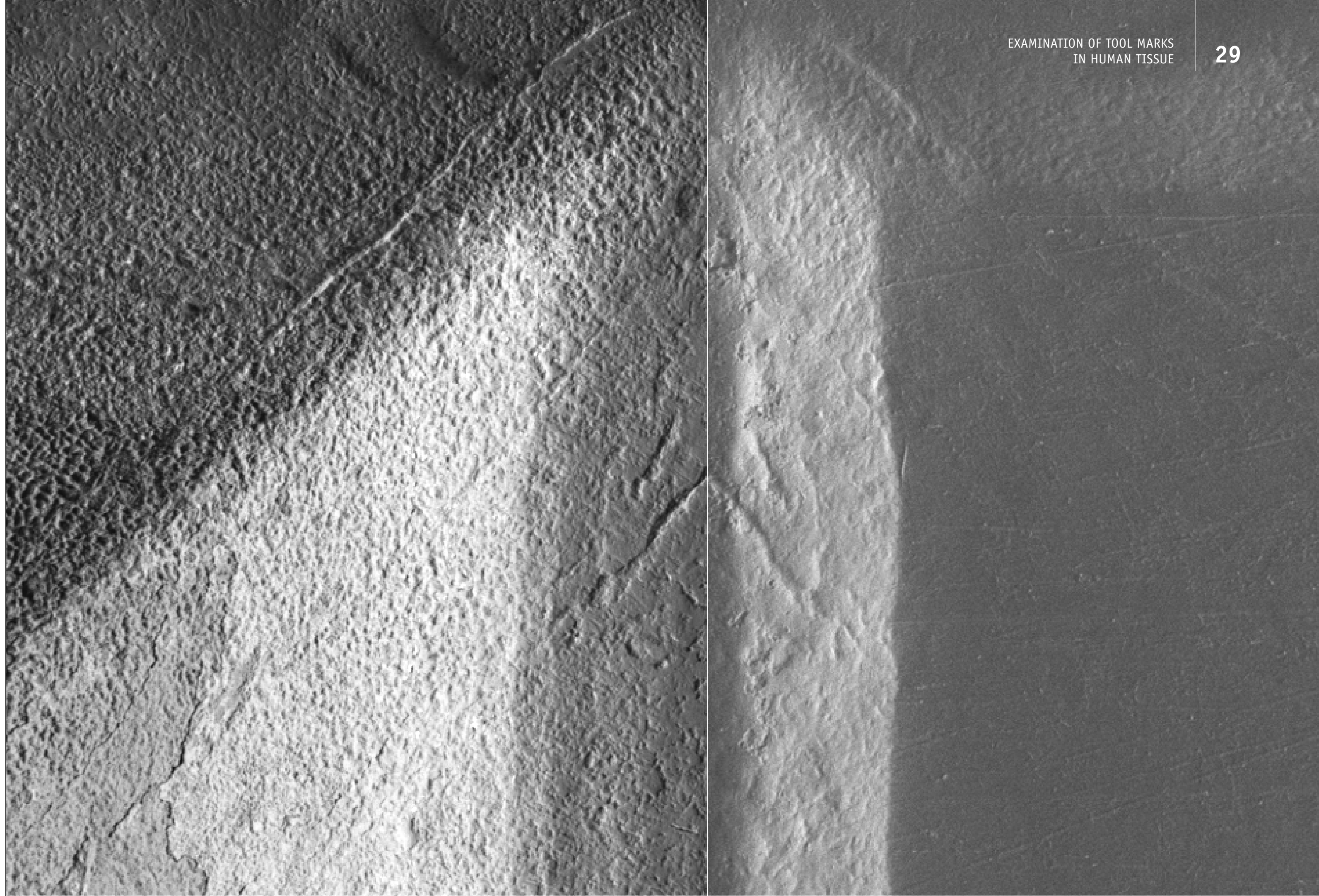


Figure 27:
Comparative scanning electron micrograph of the matching general and individualizing features of an embossed stamp (left) with the cast of a mark on an automatic pistol. For clarity, the left-hand half of the picture has been mirrored.
[Photo: BKA]

If any matches are found, the next step is to examine the individualizing characteristics. The matches between the crime mark and the test marks detected during the investigation are usually documented photographically. For documentation purposes, matching striation marks are usually represented as continuous striations of the evidence marks and test marks (Figure 26).

Impression marks are either displayed equidirectional or, for the sake of clarity, as mirror images (Figure 27). In addition, it is possible to use metrology to assist the comparison of crime mark and test mark. For instance, in the case of dot shaped mark features, which, when viewed individually, exhibit hardly any individualizing character, it is legitimate to assign them a higher degree of individualizing character by measuring the marks in the constellation in relation to each other and to the edge of the mark. A single point is therefore barely of relevance to the investigation. However, a large number of points that occur on the crime mark and test mark in the same position to each other and to the wider mark geometry may be regarded as matching individualizing features.

2.1.8. Assessment of the examination results

After the comparative examination has been carried out, the results are evaluated. In this step, the objectively described and documented matches of class and individualizing characteristics are assessed as to whether they are sufficient to prove they were created by the same object, namely the instrument of crime.

In German forensic institutes, this assessment is made subjectively. Experts decide on the basis of their experience as to which conclusions the identified matches/differences between the mark and test mark allow. In order to minimize the possibility of an incorrect assessment, a neutral second assessment usually takes place.
In the German Federal Criminal Police Office and the German state criminal police offices, the assessment of the results is carried out using a six-level conclusion scale for the findings (Katterwe et al. 2006). Level 1 is the clear identification of the tool as the source of the mark. Level 6 is the elimination of the tool. Levels 2 to 5 between are attained when the quality or quantity of the mark is limited or when the active surfaces of the tool have undergone changes after the crime.

Other scales exist and are used across the field of tool marks examination in different countries. Some scales have more or less gradations. Within the European Network of Forensic Science Institutes (ENFSI) a six level scale very similar to the scale presented here is used for collaborative excercises.

Level	Verbal form	Criteria
1	**Identification**	Unambiguous assignment (identification) of a certain object as the originator of a mark on the basis of matching criteria of an individualizing character. Quality and/or quantity of the characteristics of the objects under examination are convincing.
2	**Very strong support**	Class characteristics match. In addition, individualizing characteristics are present that do not permit identification beyond doubt due to lack of prominence and/or number. The quality and/or quantity of the objects under examination is/are limited.
3	**Moderately strong suppport**	In addition to predominantly class characteristics, particular individualizing features match, but they are of insufficient quality.
4	**Inconclusive**	Apart from predominantly class characteristics, no individualizing characteristics can be identified. Changes in the object(s) under examination also prevent identification or elimination.
5	**Limited support**	Deviations from class and/or individualizing characteristics are present. No elimination can take place due to the insufficient quality and/or quantity of the objects under examination.
6	**Elimination**	There is no doubt that the characteristics of the objects under examination do not match. Elimination of a particular object on the basis of non-matching criteria of a class and/or individualizing character.

Table 1:
Conclusion scale for findings from the Federal Government/Länder expert team "Harmonization of conclusion scales" (Katterwe et al. 2006)

2.2. History of tool marks on cartilage and bone

Hans Gross — father of criminalistics

The examination of tool marks had already been described by the Austrian judge and professor of criminal law Hans Gross[7] (Gross 1893), who is also called a "father of criminalistics"[8]. Even though the term tool mark itself receives no mention, in his "Handbuch für Untersuchungsrichter, Polizeibeamte, Gendarmen u.s.w." [Manual for Examining Magistrates, Police Officers, Gendarmes, etc.] Gross advises that any marks at burglary scenes should be examined in detail, drawn or cast, tedious though this may often be.

"Don't be put off by the effort, if the results of laborious enquiries are not needed in this particular case, they will be needed in another very important case." This is a piece of advice that still holds true today. By way of illustration, Gross described a case of a tool mark secured in a comparatively minor burglary, as a result of which it was possible to solve this and another, considerably more serious burglary, in which a lot of money was stolen from a rich grain merchant. Tool marks or impression marks were secured at both crime scenes and the tool used, a screwdriver, could be identified on the basis of matching dimensions and a distinctive missing corner of the cutting edge.

[7] **Hans Gross:**
Born 26 December 1847 in Graz (Austria), died 9 December 1915 in Graz. Judge; legal scholar, criminologist, founder of the Graz School of Criminology. [Source: http://lithes.uni-graz.at/handbuch/gross_hanns.html, last accessed January, 2021]

[8] [Source: http://d-nb.info/1098139380, last accessed February 2021]

At the beginning of the twentieth century, the coroner Richard Kockel[9] (Kockel 1900, 1903) described the examination of tool marks on felled trees in cases of vandalism “where roadside saplings have fallen victim to the high spirits of ruffians”. Kockel worked as a medical practitioner and criminologist and as such also examined bullets and marks from crime. He compared the cut marks on the wood with test marks made with a suspect’s knife and even at that time formulated the need for a homogeneous and opaque test material that is still valid today. He therefore used plasterboard panels when examining the cutting marks on the trees. In order to be able to create uniform test marks, Kockel used a microtome sledge and was able to unambiguously identify the suspect’s knife as the tool used in the crime through the results of his examination. He also took photographs back then to document his results. A similar study on a case of vandalism was presented by Bessemans (Bessemans 1957). Even though technical progress has resulted in great change, simplification and optimization, the principles of comparative tool mark analysis have remained more or less the same since Kockel’s days.

A short time later, the method of comparative examination of tool marks was applied to human tissue. Schulz (Schulz 1906; Esser 1933) examined striation marks on hatchet injuries to bony tissue. Bosch (Bosch 1963) examined stabbing marks in the cartilaginous part of the ribs. He was the first to describe the requirements for test material similar to cartilage, in other words an elastic test material. Bosch ruled out plasticine because of its plastic deformability and considered kidney and liver tissue too soft. Formalin-fixed brain tissue and hardened gelatine appeared too friable and, like yellow turnips and potatoes, unsuitable due to its low opacity. Bosch presented alginates as an extremely suitable test material and was able to produce regular striation marks on them.

Forensic pathologist Wolfgang Bonte[10] (Bonte 1972; Bonte et al. 1973; Bonte 1975) also conducted research into stab marks in human rib cartilage and used photogrammetry for comparative examination in those cases where the lack of linearity of the marks made a classical comparison difficult. In addition, Bonte also examined saw marks on bones, such as those found after the dismemberment of a corpse. A great deal of further information on saw marks has been listed in a manual by the forensic anthropologist Steven A. Symes (Symes 2010). In this work, Symes specifically addresses the examination of the marks in terms of class characteristics such as the width of the saw blade and the size and spacing of the saw teeth.

Examination of tool marks on human tissue, mainly on cartilage and bone, are now carried out in numerous institutes around the world (Rao et al. 1983; Galan 1986; Ernest 1991; Mikko et al. 1995; Clow 2005; Ostrowski 2006; Locke 2008; Weber et al. 2015; Norman et al. 2018; Weber et al. 2020) and have become a valuable part of the portfolio of the investigation of marks.

[9] **Richard Kockel:**
Born 5 January 1865 in Dresden (Germany), died 19 January 1934 in Leipzig. Professor of Forensic Medicine at the Medical Faculty of the University of Leipzig.
[Source: https://research.uni-leipzig.de/catalogus-professorum-lipsiensium/leipzig/Kockel_188/, last accessed January 2021]

[10] **Wolfgang Bonte:**
Born 22 September 1939 in Nordhausen (Germany), died 21 October 2000 in Düsseldorf. Professor of Legal Medicine at the Heinrich Heine University Düsseldorf.
[Source: https://www.gtfch.org/cms/images/stories/media/tk/tk67_3/bonte.pdf, last accessed January 2021]

3. MARKED EVIDENCE

The following section describes bone and cartilage in order to show the differences between the two tissues with regard to material behaviour and the resulting effects on tool mark examinations of these tissues. While rib cartilage, for example, exhibits stabbing marks with a comparatively fine resolution, bone usually splinters when punctured.

Unlike technical materials that can be produced homogeneously under optimized production conditions, the two tissues exhibit both inter- and intra-individual fluctuations in their material properties. For instance, bone density and strength are among the properties that depend on regular loading of the bone (Warner et al. 2002; Smathers et al. 2009). Age, nutrition, diseases and other factors also determine the material properties (Hukins et al. 1976; Kemper et al. 2007; Weber et al. 2021), which in turn can influence the ability to record tool marks. Moreover, handling tissue is fundamentally different to handling technical materials. Both bone and cartilage require techniques and preparation measures during tool mark examination that are different to those necessary for metals, wood or plastics, for example (Wong 2007; Bailey et al. 2015; Froch-Cortis et al. 2016).

The following sections will therefore take a closer look at these tissues and present the special features that relate to tool mark examinations.

3.1. Bone

3.1.1. Material

3.1.1.1. Function

The large number of bones in the human body, some of which are very different in size and shape, form the skeleton. The skeleton of an adult human comprises approximately 205 individual bones. They are part of the passive musculoskeletal system and can be differentiated according to their external shape into short, long, flat, sesamoid[11] and irregular bones.

As a whole, the bones support the body in withstanding the external forces to which it is exposed. Among other functions, they protect the organs inside. The skull bone, for example, protects the brain. The rib cage consisting of the bony ribs and those with cartilaginous parts, the sternum and the thoracic vertebrae forms a kind of protective enclosure for the lungs and heart and makes breathing possible. In addition, bones act as a lever system for transferring the forces generated by the muscles (Nigg et al. 2007). The biological function of bone is to store calcium and to form the red blood corpuscles in the bone marrow. Bone is made up of 65% minerals, 35% organic matrix, cells and water (Jee 2001).

3.1.1.2. Structure

Bone, like cartilage, belongs to the connective tissues and has various cell types that possess different functions. Osteoblasts synthesize bone by producing osteoid and influencing the mineralization of this matrix of the bone. Osteoclasts are multinucleated phagocytes and break down bone. Osteocytes regulate the activity of the osteoblasts and osteoclasts thus control bone remodelling. The osteocytes are embedded in the bone matrix and are connected with each other via cytodendrites. They are supplied with oxygen and nutrients via a separate vascular system.

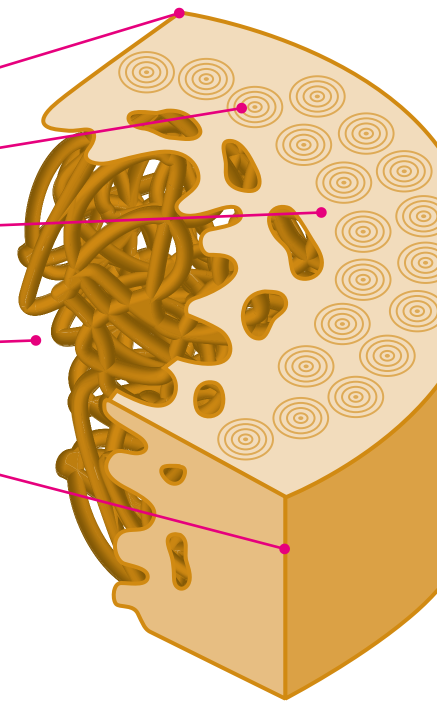
Bone in adults mainly has a lamellar structure. The lamellae are layers with a thickness of 3 to 7 µm that contain collagen fibres with a special alignment. Bone lamellae such as this are arranged concentrically around a channel (Haversian canal) with a central blood vessel and form the basic functional unit of bone, the osteon (Jee 2001). In the human skeleton the lamellar bone can be classified as a lightweight structure. In terms of morphology, a distinction can be made between cancellous and cortical bone (Figure 28). On its outer surface, bone is surround by the periosteum, a tight membrane of connective tissue containing many cells, vessels and nerves. The periosteum borders on the cortical bone, which is a firm and compact tissue that forms the outer layer of the bone. Cancellous bone describes the delicate system of bony trabeculae in a sponge-like arrangement, which is mainly found in the interior of the bone. In contrast to the long bones, the cancellous bone is called diploic bone in flat bones (skull, ribs, sternum, etc.).

The long tubular bones (e.g. femur and humerus) consist of a tubular shaft (diaphysis), made up of cortical bone and contain the bone marrow. The thickened ends of bone are called epiphyses and have cancellous bone in the interior covered with cortical bone.

The structure and arrangement of the bony trabeculae depends on the load to which the bone is subjected, i.e. it is orientated along the load lines (trajectories). Areas of bone exposed to relatively high loads therefore exhibit a denser network of cancellous bone than areas with a lower load. This effect is known under the term Wolff's law (Wolff 1995), the law of bone transformation. It describes the adaptation of bone tissue to its mechanical load. Bone bearing a light load degenerates, whereas bone tissue subjected to a heavy load increases in strength and density. This effect can be clearly seen in the X-ray images of extreme athletes in particular sports disciplines. For instance, the cortical bone of climbers' knuckles frequently has a thickening on the upper, more heavily strained side (Figure 29). Tennis players often have changes to the bone structure on their more heavily strained playing arm (Jones et al. 1977).

Macerated bone has a yellowish white colour which varies between individuals and can be influence by the choice of maceration method and the use of bleaching agent. As described previously, colouration and opacity play an important role in the investigation of tool marks.

Tool marks on light-coloured bones can therefore only be examined by a light microscope to a limited degree. However, direct examination on the mark scanner is also possible.



▲ **Figure 28:**
Schematic structure of bone tissue, illustrated by a tubular bone.
[Graphic: Marco Tavano]

▲ **Figure 29:**
X-ray image (left) and CT scan (right) of two fingers of a competitive climber; the thickened sections of the bone structure are marked as examples.
[Images: Marcus Scholz]

[11] **Sesamoid bones:**
Small bones embedded in tendons.

3.1.2. Slashing and cutting marks

Bone tissue is generally highly suitable as a substrate for marks and can also show very fine details. Nevertheless, this is restricted to the cortical bone. Owing to its spongy structure with numerous cavities, cancellous bone tends to be unsuitable for bearing tool marks to an extent that can be evaluated in sufficient quality. Furthermore, cancellous bone can lead to problems in casting as residues of the casting compound adhere to the recesses.

Blows involving sharp force, e. g. with an axe, hatchet, sword, machete or similar instrument, may result in marks in the cancellous bone that can be evaluated (Figure 30, Figure 31). Several factors play a role in this. A flat angle of impact, hence more tangential to the bone surface, results in a longer mark than a more orthogonally executed blow, in which the maximum length of the mark corresponds to the thickness of the cortical bone. However, a longer mark can contain more information than a short mark. In individual cases it is possible for an orthogonally produced mark to contain sufficient features for a successful comparative examination.

Another factor is that the firm bone material is split by the stresses occurring due to the penetration of the tool blade in an orthogonal blow and not separated by the blade. In the splitting process, a stress-induced crack precedes the blade and fracture surfaces occur with only a small proportion of tool mark striations. In a slash executed with a shallow angle, material is separated from the surface of the bone as chips, which makes splitting less likely and tends to result in marks that can be evaluated.

In addition to the angle of attack, the thickness, the cutting angle and the sharpness of the blade also play a role. A shallow cutting angle and a blunt and thick blade are more likely to result in splitting or impression fractures than a thin blade

Figure 30:
Slash mark executed with an axe in a fragment of a calvaria.
[Photo: LKA NRW]

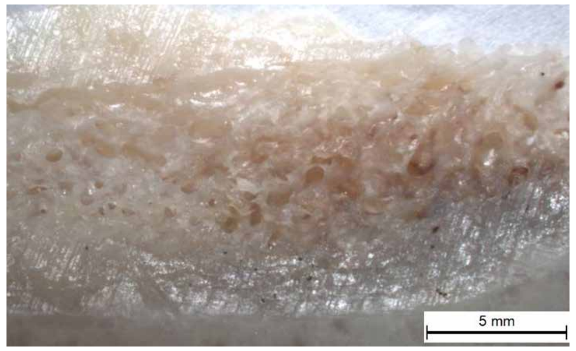


Figure 31:
Digital micrograph of a slash mark in a cranial bone suitable for evaluation (particularly the upper half of the picture).
[Photo: LKA NRW]

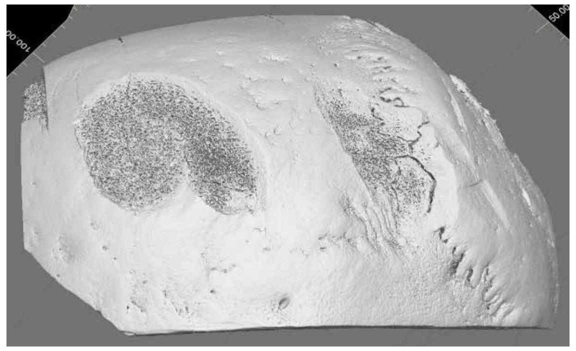


Figure 32:
CT scan of various slash marks on a fragment of a calvaria. The tool used in the crime was a katana.
[Photo: LKA NRW]

Figure 33:
Cutting and slashing marks on a human thigh bone (femur). The tools used are unknown.
[Photo: LKA NRW]

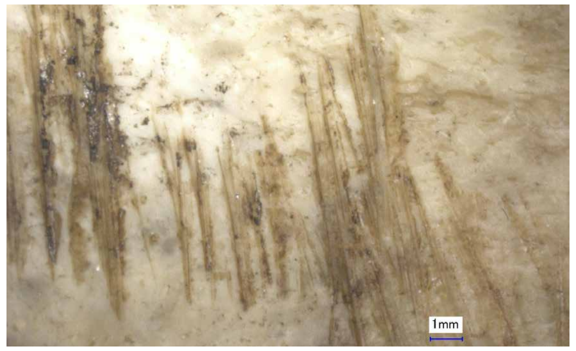
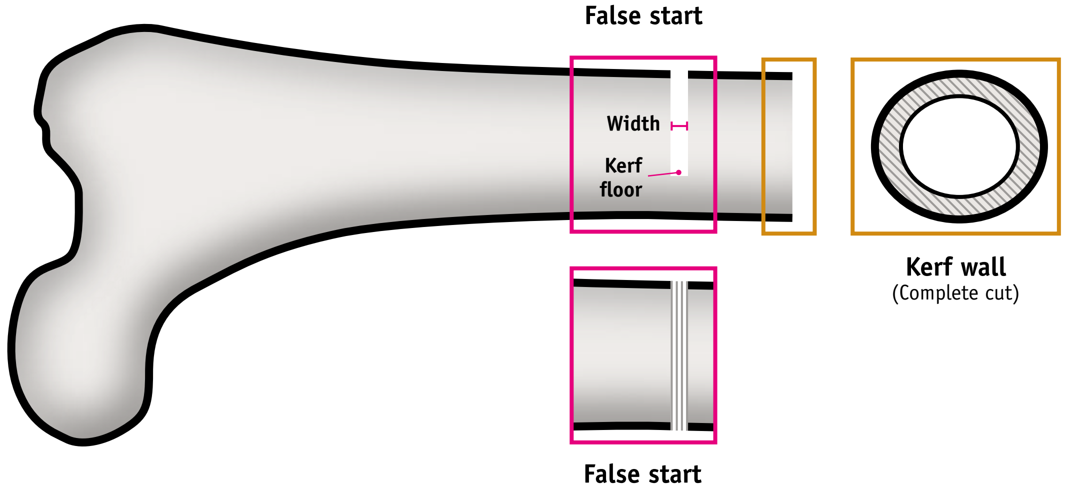


Figure 34:
Detailed image of the cutting and slashing marks on a human thigh bone (femur).
[Photo: LKA NRW]

with a pointed and sharply ground cutting angle, which tends to remove bone fragments completely (Figure 32).
Cutting marks (Figure 33, Figure 34) on the surface of the bone, i.e. marks caused by forward and backward strokes of a blade aligned in the direction of movement, are only of limited suitability in terms of tool mark analysis. It is generally not possible to identify the tool used in the crime with the aid of the marks as they do not exhibit any individualizing characteristics. However, an examination of the marks can at least yield information relating to the geometry of the cutting edge. In any case, it is worth investigating the bone as accurately as possible and also using casts and tool mark scanners as well as side illumination in the process.

3.1.3. Saw marks

Figure 35:
Schematic representation of saw marks showing walls and floor (complete cut and false start) on bone.
[Graphic: Marco Tavano]



When describing the possibilities of examining tool marks on bones, saw marks must also be mentioned. For instance, it is not uncommon for saws to be used in the dismemberment of corpses so that the opportunities for investigation will be dealt with here briefly.

Generally saw marks are less likely to be suitable for the identification the source of the mark than other tool marks. As the cutting surfaces of the saw teeth are generally very small, it is often difficult to find matches of individualizing features. In addition, a false start would have to be present of which marks suitable for evaluation could be found (Figure 35). However, the kerf wall is not suitable for identification because it does not carry individualizing features. Nevertheless, there are known cases where circular saws and chain saws have been identified as the source of marks, so this possibility cannot be disregarded. It can be assumed that as the width of the cutting-edge increases, the probability of identifying the mark also increases.

Saw marks can generally be evaluated and do deliver valuable information about the type of tool (Alsop et al. 2021; Symes 2010). The width of a cut gives an indication of the width of the saw blade. Here, the possible set of the saw blade, i.e. the lateral offset of the teeth, always has to be taken into account. The cutting pattern also allows conclusions to be drawn as to whether the saw is motorized or hand-operated. The tooth pitch can be can be narrowed down by analyzing the cut surfaces impression marks and chatter marks. In addition, it may be possible to determine or at least limit the range of diameters for a circular saw blade.

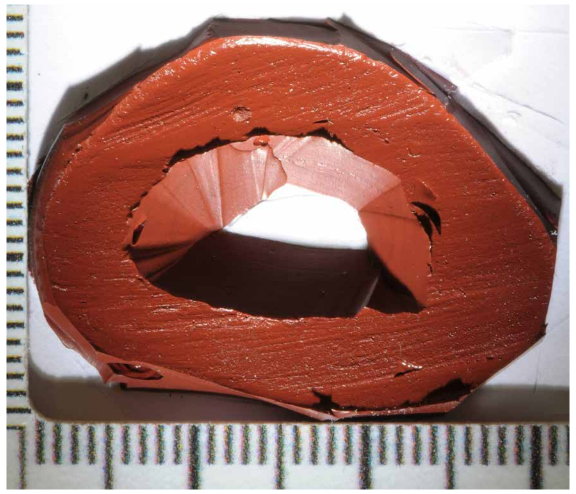


Figure 36:
Cast of the edge of a saw (casting compound: AccuTrans AB brown®) on a bone of the upper arm (humerus).
[Photo: LKA NRW]

3.1.4. Fractures

The assessment of bone fractures does not fall within the field of tool marks, so this topic is not described in detail here. Nevertheless, some basic knowledge is helpful when examining tool marks on bone tissue. For example, post-mortem or medico-legal reports are used as facts based on the findings for the assessment of tool marks. Consequently, there follows a brief discussion of the skull fractures that frequently occur due to blunt force. The interpretation of skull fractures must be carried out by medical experts and always includes the tissue and organ structures in the assessment as well.

Skull fractures occur when the force applied causes tensile and compressive stresses that exceed the elasticity limit of the bone. Blunt force with the use of a tool, which is relevant in connection with the occurrence of tool marks, usually results in fractures to the cranial vault (calvarial fractures). These can also extend into the base of the skull as well as the visceral cranium in the form of bursting fracture lines, but this is of secondary importance for considerations of tool mark analysis, which is why these structures will not be discussed further here.

Calvarial fractures are commonly classified into shaped fractures, depressed fractures and unshaped fractures. A shaped, hole fracture occurs when the cranial bone comes into contact with a small area (smaller than 4 cm x 4 cm) with sufficient energy input and a section of the calvaria is punched out.

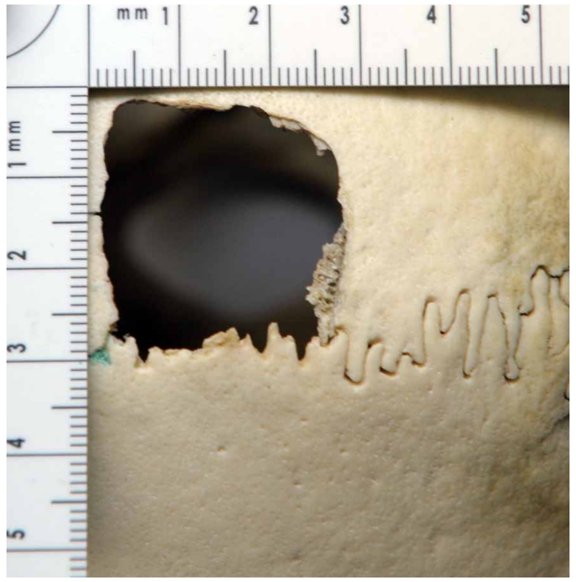


Figure 37:
Hole fracture in a cranial bone; the instrument of crime was a locksmith's hammer; the marks were made with the face of the hammer.
[Photo: LKA NRW]

A typical example in which hole fractures are caused is the powerful blow with the face or peen of a hammer. The shape of the resulting depression then corresponds to the shape and dimensions of the active surface (Figure 37, Figure 38). In the case of a hammer face larger than approx. 4 cm x 4 cm, the edges no longer exhibit a smooth pattern, but change into the next type of fracture, the depressed fracture.

In the case of depressed fracture (Figure 38) small, often parallel fragments are produced that follow a step-like or terrace-like pattern from the surface of the calvaria towards the interior of the skull.
Unshaped fractures include bending and bursting fractures. Bending fractures (Figure 39) occur when the calvaria of the skull is bent due to collision with a solid object. This deformation can lead to tensile loads on the inside of the calvaria (inner table of the skull), which in turn result in the bone tearing open. In adjacent regions, if the bending load is sufficient, it can lead to circular fracture of the outside of the bone (outer table of the skull). Injuries of this kind may occur, for example, when a stone hits the bone. If the calvaria continues to bend due to the contact, a globular fracture occurs, which consists of concentrically (bending fractures) and radially (bursting fractures) arranged fracture lines.
Bursting fractures (Figure 40) occur under extensive loading and not directly at the point of contact, but indirectly as a result of the deformation of the calvaria triggered by the load. The load creates tensile stresses orthogonal to the orientation of the applied force. The resulting fracture in turn runs parallel to the direction of the force.
According to Puppe's rule (Puppe 1914; Schüttrumpf 1966) , the temporal sequence of successive fractures of the skull bone can be determined under certain conditions. The rule is that the fracture lines of newly developed fractures never cross the fracture lines of already existing fractures, but instead terminate there. The lines of the most recently created fracture then end in those of a previously existing fracture. Another rule in connection with skull fractures is the hat brim line rule introduced by K. Walcher in 1931 (Walcher 1931), which is mentioned here for the sake of completeness, even though it is of secondary importance for tool mark analysis. The hat brim line describes the band-like area on the head above its greatest circumference, i.e. the area on which a hat would rest.

Figure 38:
Hole and depressed fractures in a calvaria; the instrument of crime was a locksmith's hammer; the marks were made with the peen of the hammer.
[Photo: LKA NRW]

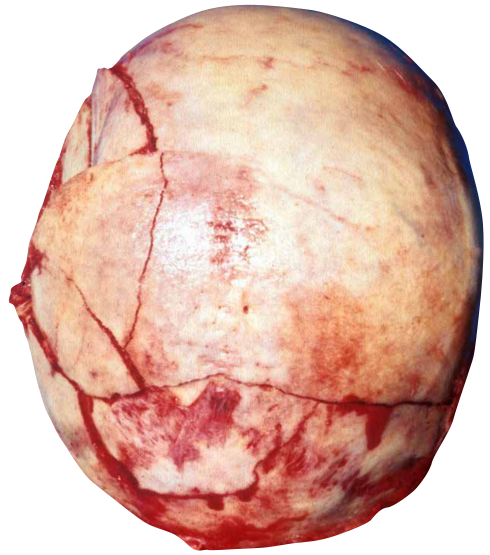


Figure 39:
Bending fracture of the calvaria in a complex fracture system. In the upper third of the picture, at the transition of the temporal bone to the parietal bone, a depressed fracture with the edge of a bending fracture forming a sill-like protrusion above the remaining level of the skull. Blows to the head with a fire extinguisher.
[Photo: Institute of Legal Medicine Cologne]

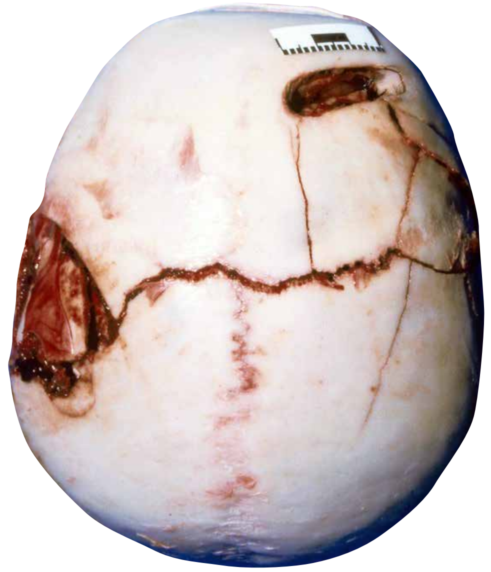


Figure 40:
Hole fracture (blow with pipe wrench) in the upper right-hand frontal area (top right in the picture) with fine burst fracture lines extending from it to the rear and the right. A further gaping burst fracture line runs across the calvaria, originating from a depressed fracture in the left-hand temporal bone.
[Photo: Institute of Legal Medicine Cologne]

According to the hat brim line rule, injuries above the hat brim line are more likely to indicate a sequence of blows while injuries at or below the hat brim line are more likely to indicate a fall. However, this rule should only be seen as a guide and only applies to the alternative of a fall from a standing position on the level without any intermediate impacts. It no longer applies in the case of fall from a height, such as when riding a bicycle, and of course a blow can also be delivered from below.

3.2. Cartilage

3.2.1. Material

Cartilaginous material has a firm consistency and behaves viscoelastically, i.e. its mechanical properties are dependent upon time, velocity and temperature. When a certain compressive force is applied, the cartilage is deformed and when the pressure is removed, the cartilage tissue does not regain its original shape spontaneously but instead over a period of time. Cartilage has one type of cell, chondrocytes, and consists of a matrix composed mainly of water, collagens and proteoglycans[12].

Like bone, cartilaginous tissue is part of the musculoskeletal system and belongs to the connective tissues. A distinction can be made between three different types of cartilage in the human body, which have different compositions and functions. Elastic cartilage gives the auricles and parts of the nose their elastic shape. As a part of the skeleton, one of the functions of elastic cartilage is to maintain the shape of the body. Fibrocartilage is the material that makes up the articular discs, such as the intervertebral discs, which are partly responsible for the mobility and stability of the spine. Furthermore, the menisci of the knee joints are made of fibrocartilage, which lie between the incongruent joint surfaces of the femur and the tibia and, among other functions, serve to distribute load evenly. The cartilage thus protects the bony skeletal parts of the joints. The ends of the bones are covered by hyaline[13] cartilage. Articular cartilage has the essential function of transmitting and distributing forces in the joint and, in a healthy state, allows the joint to move largely without friction (Nigg et al. 2007). In addition, hyaline cartilage plays a major role in bone development, as it forms the shape of the developing bones as a cartilaginous template, but is also involved in longitudinal bone growth in the growth region known as the epiphyseal or growth plate. The following describes the three types of cartilage in more detail.

3.2.1.1. Structure of the hyaline cartilage

Hyaline cartilage is the most common type of cartilage found in the human body. Hyaline cartilage includes, for example, the articular cartilage, the cartilage of the respiratory tract (e.g. nasal septum, laryngeal skeleton) or also the costal cartilage. During skeletal development, hyaline cartilage plays an important role in the bone templates and epiphyseal plates. Hyaline cartilage has a bluish-white and milky but translucent appearance.

The hyaline cartilage tissue consists of the chondrocytes[14] (cartilage cells) and the extracellular matrix. The chondrocytes are present in the tissue singly or in isogenic[15] groups. Young chondrocytes tend to be flattened in shape, the mature specimens approximately round, and older cells hypertrophic[16].

The chondrocytes are surrounded by the cartilage matrix or extracellular matrix, which is composed of approx. 60-80% water, 15% collagen and 5% proteoglycans (Mow et al. 1992). The basic substance of the cartilage matrix is amorphous and consists mainly of water, collagen type II and cross-linked

[12] **Proteoglycans:** Macromolecules are made of protein (aggrecan)

[13] **Hyaline:** glass-like, clear, transparent, translucent.

[14] **Chondrocytes:** Cartilage cells that are rich in cell organelles. Chondrocytes synthesize proteins and carbohydrates.

[15] **Isogenic group:** Cell groups of two to a maximum of eight chondrocytes that have developed from a cartilage cell by mitosis, i.e. originate from the same progenitor cell.

[16] **Hypertrophic:** enlarged.

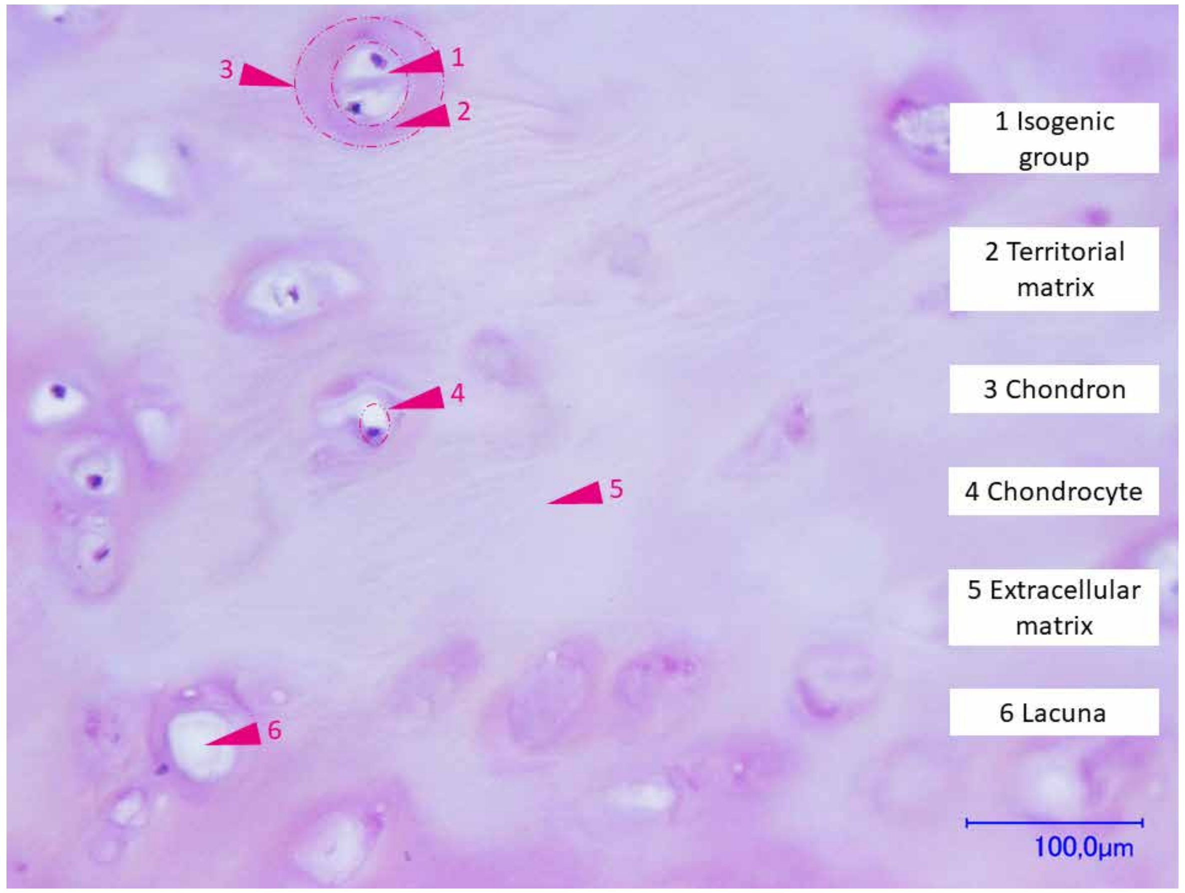


Figure 41:
Histological section of human costal cartilage with constituent parts labelled (staining: haematoxylin-eosin).
[Image: Matthias Weber]

proteoglycans. In the cartilage matrix, a distinction can be made between the pericellular, territorial and interterritorial matrix. The matrix that lies directly around a cell is the pericellular matrix. The cartilage cells sitting in their cavities called lacunae, the capsule surrounding the lacunae and the territorial matrix form the chondron[17]. The term interterritorial matrix is used to distinguish the area between the various lacunae (Shrive et al. 2007).

Collagen fibrils consist of long collagen molecules (protein chains). The fibrils are often in arch-shaped and are characterized by a high tensile and tearing strength. They form a trajectory-based functional system that is adapted to the respective load conditions. In general, the fibrils in hyaline cartilage are offset from each other. In the tracheal cartilage[18], some of the fibres are S-shaped; in the articular and epiphyseal plate cartilage[19], they tend to be arch-shaped. However, the fibres are always compacted under the cartilage surface and parallel to the surface, so that the compressive and tensile stresses that occur during load can be transmitted and distributed. Type II collagen is mainly present in articular cartilage.

[17] **Chondron:** Functional unit in cartilage tissue consisting of one or more chondrocytes, which are present in the lacuna enclosed by the cartilage capsule.

[18] **Trachea:** windpipe.

[19] **Epiphyseal plate:** growth region of the long bones.

The proteoglycans, which are also present in the extracellular matrix, consist of a protein (hyaluronic acid) and one or more covalently bonded carbohydrate groups (glycosaminoglycans). These glycosaminoglycan chains (GAGs) consist of repeating disaccharide units. At least one carbohydrate in the disaccharide has a negatively charged carboxylate or sulphate group. The GAGs attract water due to their numerous negative charges (Kuettner et al. 1985).

An essential constituent of hyaline cartilage is the proteoglycan aggrecan[20], which forms aggregates with hyaluronic acid. Hyaluronic acid is a very long, unbranched macromolecule and acts as a molecular backbone to which the aggrecan molecules attach via linking molecules. Up to 140 aggrecan molecules can bind to one hyaluronan chain. Aggrecan consists of the two macromolecules keratan sulphate and chondroitin sulphate. The compaction of the sulphate groups with negative charge within the aggrecan when the articular cartilage under mechanical stress leads to mutual electrostatic repulsion of the side chains (Mörgelin et al. 1994). This intramolecular interaction is responsible for the compression resistance of cartilage.

Cartilage cavities is the term used to describe the spaces that form when cartilage cells shrink due to poor tissue preservation or when the tissue is dehydrated during histological dissection of the cartilage. These cartilage cavities do not exist in living tissue.
Structurally, articular cartilage is heterogeneous and can be divided into four zones. The superficial zone is the thinnest and lies on the surface. The chondrocytes here are flat and spindle-shaped. The collagen fibres here are densely packed and aligned parallel to the surface. This is followed by the middle or transition zone, which makes up about 40% - 60% of the total thickness of the cartilage. The cartilage cells here are spherical and the collagen fibres are randomly oriented. In the lower or deep zone, the chondrocytes are hypertrophic and the collagen fibres are oriented perpendicular to the cartilage surface. The proteoglycan content is highest here. The calcified zone characterizes the transition from articular cartilage to the subchondral bone (Shrive et al. 2007).
With the exception of articular cartilage, hyaline cartilage is covered with a cartilaginous membrane, the perichondrium. The perichondrium is a firm connective tissue sheath consisting of two layers. An inner (near the cartilage[21]), cell-rich layer (chondrogenic layer) containing undifferentiated mesenchymal[22] cells that can develop into chondroblasts[23] and can assist in regeneration of the cartilage to a limited extent. In addition, the perichondrium consists of the outer (remote from the cartilage[24]) fibrous layer (stratum fibrosum), which is formed from relatively tight connective tissue (with fibroblasts) of densely layered collagen fibrils. The fibrous layer can absorb the tensile forces that occur under a bending load.
Hyaline cartilage is usually avascular, which means it contains neither blood nor lymph vessels, and is therefore bradytrophic[25]. The vessels penetrate into the cartilage from outside only as far as the perichondrium (see below). The cartilage and the cartilage cells (chondrocytes) are therefore supplied from the perichondrium via diffusion through the extracellular matrix. Articular cartilage is mainly supplied by the synovial fluid. Articular cartilage has no nerves either.

The cartilage grows on the one hand through mitotic division of the cartilage cells in the cartilage capsules, and on the other hand through increased synthesis and deposition of the extracellular matrix. between the chondrocytes. In addition, the cartilage expands via appositional growth (surface growth) of the cells of the inner layer of the perichondrium (chondrogenic layer).

[20] **Aggrecan:** Protein, which accounts for about 10% of the weight of hyaline cartilage.
[21] **Chondrogenic layer:** Inner layer of the perichondrium (near the cartilage).
[22] **Mesenchyme:** Embryonic tissue type that has the ability of pluripotent stem cells to differentiate into almost all cell types of the three germ layers. In mechanical terms, the mesenchyme can approximately be considered as a fluid.
[23] **Chondroblasts:** Divisible progenitor cells of the non-divisible chondrocytes. They also secrete (~produce) the extracellular matrix.

3.2.1.2. Structure of elastic cartilage

Elastic cartilages include, for example, the auricle, Eustachian tube, cartilaginous parts of the external auditory canal, the small laryngeal cartilages and also the smaller bronchi.

Elastic cartilage is similar in principle to hyaline cartilage. Both types of cartilage have comparable chondrons. In elastic cartilage, however, they are smaller and less rich in cells than in hyaline cartilage.

The extracellular matrix of elastic cartilage is also basically analogous to that of hyaline cartilage. In addition, however, the matrix of elastic cartilage has extensive networks of elastic fibres that determine the material behaviour and give the cartilage its characteristic yellowish colour. These elastic fibres consist of the protein fibrillin, which is associated with the protein elastin.
In addition to compression elasticity, this structure means that elastic cartilage exhibits better bending elasticity than hyaline cartilage.

3.2.1.3. Structure of fibrocartilage

Examples of fibrocartilages include the menisci and the intervertebral discs. The composition of the extracellular matrix of fibrocartilage is similar to that of hyaline cartilage and both are relatively poor in cells.

However, fibrocartilage has a comparatively high content of collagen type I fibres. Formed into tight bundles, they occur irregularly and are clearly evident in comparison to the small number of chondrocytes.

Because of the orientation of the collagen type I fibres, fibrocartilage is tight and pressure-resistant and can remain resilient even when subjected to substantial forces and high deformation.

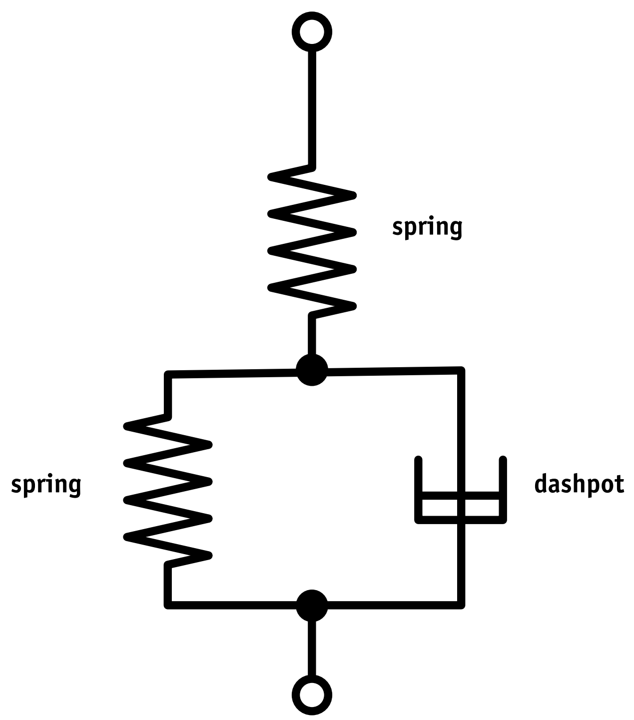
3.2.1.4. Biomechanics of the cartilage

Cartilage tissue can undergo compression spontaneously when subjected to pressure, exhibiting an elastic component and additional a plastic component depending on how long the pressure is applied.

When decompressed, the tissue first spontaneously regains its shape by the amount of the elastic component and, after a sufficient passage of time, the deformation due to the plastic component returns to its original state. Materials that undergo deformation that is dependent on time and velocity yet completely reversible are called viscoelastic.

Viscoelastic material behaviour can be explained clearly in a spring and dashpot model (Figure 42).

[24] **Fibrous layer:** Outer layer of the perichondrium (remote from the cartilage).
[25] **Bradytrophic:** Tissue with slow metabolism. The bradytrophic cartilage tissue is mainly supplied by diffusion from the surrounding fluid.

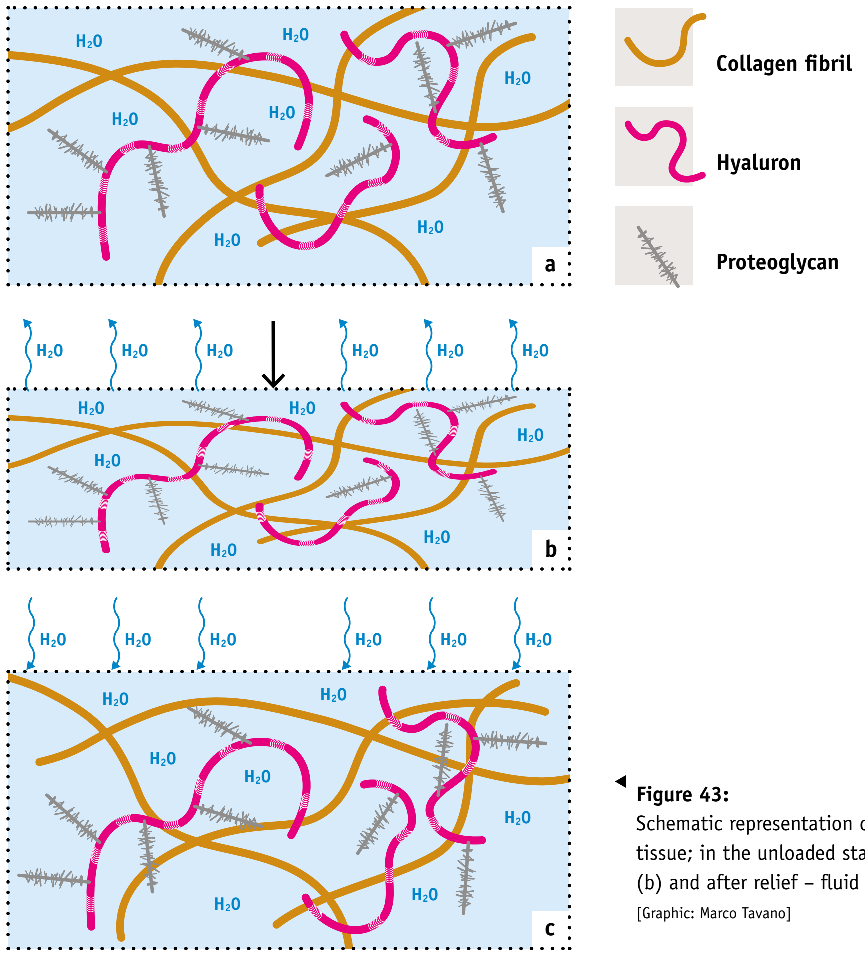


▲ **Figure 42:**
Spring and dashpot model (Menges et al. 1990) for viscoelastic material behaviour.
[Graphic: Marco Tavano]

Here, ideally elastic material characteristics are symbolized by a spring, ideally plastic characteristics by a dashpot. Viscoelastic behaviour can be represented as a series connection of a purely elastic component (immediate recovery after removal of the load) with a parallel connection of spring and damper (time-delayed full recovery).

The reversible compressibility of cartilage tissue can be explained by the properties of the extracellular matrix. The hydrophilic proteoglycans are present in the extracellular matrix and connected to the high tensile-strength collagen fibrils in the compressed[26] state (Figure 43). Here the collagen fibrils prevent further water absorption and the resulting expansion of the proteoglycans. The cartilage tissue is therefore under osmotic pressure. The state of this molecular construction is comparable to that of a spring under tension.
If the cartilage is now subjected to a pressure that is higher than the swelling potential of the proteoglycans, the tissue can initially be compressed up to a certain limit. In this process, the compressive load forces the (incompressible) interstitially stored water out through the mesh of the extracellular matrix. The maximum degree of compression is achieved when the mesh of the matrix is so compacted as to be impenetrable for the water molecules, and no further water can escape (Shrive et al. 2007).
If the compressive load is removed from the cartilage tissue, it expands due to the previously described swelling potential of the proteoglycans with the water that has previously escaped being reabsorbed. The cartilage tissue ceases to expand when the collagen fibrils have attained their maximum length.

[26] Compressed to approx. 1/5 of its normal volume.



◄ **Figure 43:**
Schematic representation of the processes in the cartilage tissue; in the unloaded state (a), under load – fluid escapes (b) and after relief – fluid flows back into the tissue (c).
[Graphic: Marco Tavano]

Due to the low thickness of cartilage tissue in joints, the role of articular cartilage in buffering impacts is comparatively small. The muscles in particular take on this protective function.
Cartilage adapts functionally to changing conditions. Hyaline articular cartilage is a particularly illustrative example because it is relatively sensitive to changes in mechanical loading. During movement, articular cartilage undergoes intermittent deformations, on the one hand, and is in a state of hydrostatic tension, on the other. This is the case when the same level of pressure acts from all sides and therefore cannot cause any deformation. Intermittent deformation of the articular cartilage occurs, for example, during relevant physical activity. With a balanced relationship between hydrostatic stress and intermittently acting deformation ("kneading"), the cartilage remains in its original state. If the cartilage tissue is deformed excessively and frequently, this causes a proliferation of the collagen fibres extending as far as a transformation of the cartilage tissue into connective tissue. If, on the other hand, the cartilage tissue is deformed to an excessively small extent, this eventually leads to chondral ossification[27], hence the complete replacement of the cartilage tissue by bone.

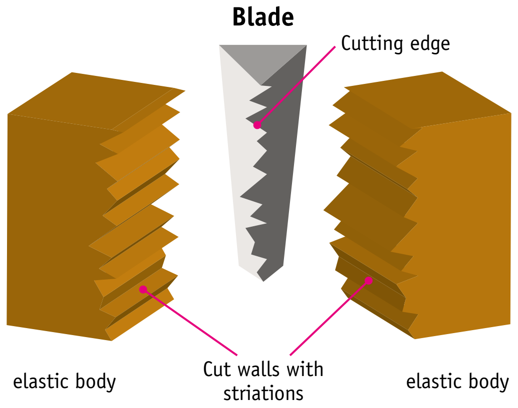
[27] **Ossification:** Formation of bone tissue.

Weapon Sword · **Type** Katana · **Dimensions** Length approx. 1020 mm; Length of the blade approx. 720 mm; Max. blade width approx. 31 mm · **Type of crime** Homicide; Multiple blows against the skull bone **Quality of the mark** Sufficient · **Examination results** Identification

Tool Knife · **Type** Swiss Army Knife · **Dimensions** Length approx. 198 mm; Blade length approx. 79 mm; Max. blade width approx. 15 mm · **Type of crime** Homicide; Stab into the rib cage; severed costal cartilage **Quality of the mark** Sufficient Quality · **Examination results** Identification

3.2.2. Stabbing and cutting marks

If cartilage tissue is cut or pierced, the cutting edge of the blade divides the elastic or viscoelastic tissue into two surfaces bearing marks that are the inverse of each other (Figure 44, Figure 45). During this process fine striations may also be displayed in the tissue, which can be used to identify the blade.

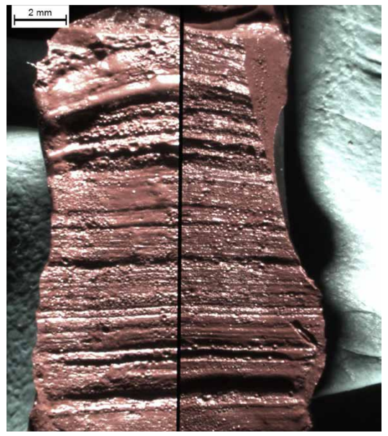


▲ **Figure 44:**
Sketch of the surfaces of the marks caused by a blade cutting through an elastic body. The cutting edge of the blade creates the striations of the mark present on the surfaces in an inverse relation to each other.
[Graphic: Marco Tavano]

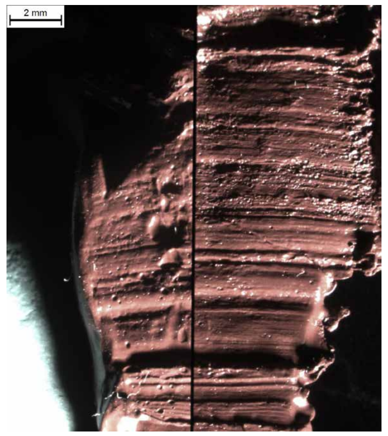
A stab refers to a cut made with the tip first and along the main axis of the stabbing instrument. In forensic medicine, the term stab wound is used if the ratio of the length of the external open skin wound to the maximum depth that can be measured is less than 1.
An incision occurs when the movement performed to separate the tissue is carried out with the cutting edge first. In forensic medicine, the term incised wound is used if the ratio of the length of the external open skin wound to the maximum depth that can be measured is greater than 1. Of course, there can also be a combination of both movements which are called stab-and-slash wounds.

As already described, the angle of impact, α, plays a decisive role in the pattern of stab and slash marks. A change in the angle of impact causes compression or stretching of the mark (Figure 25, Figure 46). The difference in angle beyond which a complete change in the mark can be anticipated is currently the subject of research and is likely to depend on the blade geometry, among other factors.

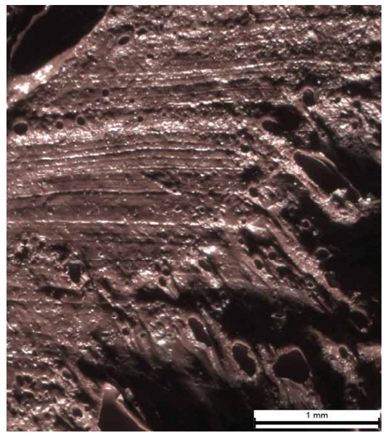
Intact cartilage tissue has a whitish colour and exhibits very little opacity. Examination of the cartilage tissue with regard to whether the marks it bears are suitable for evaluation is therefore only possible on the basis of casts. Direct examination of the



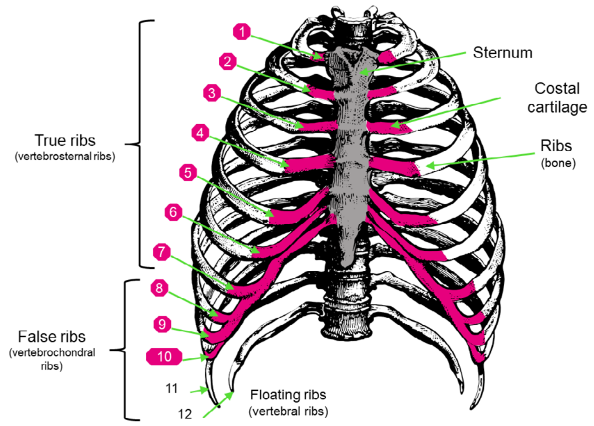
▲ **Figure 45:**
Casts (casting compound: AccuTrans AB brown®) of the mutually inverse mark surfaces of a stab mark in human costal cartilage.
[Photo: LKA NRW]



▲ **Figure 46:**
Casts (casting compound: AccuTrans AB brown®) of stab marks made at different angles of attack in human costal cartilage caused by the same stabbing tool.
[Photo: LKA NRW]



▲ **Figure 49:**
Cast of a stab mark in human costal cartilage with numerous dots. (casting compound: AccuTrans AB brown®).
[Photo: LKA NRW]



▲ **Figure 47:**
Schematic representation of the skeletal rib cage. The cartilaginous part of the ribs is marked in red. The numbering of the ribs is shown.
[Graphic: pixabay.com, Matthias Weber]

cartilage tissue by light microscopy or scanning of the cartilage tissue does not yield evaluable results. A large proportion of the cartilage examined in tool mark analysis is rib cartilage (costal cartilage). The twelve pairs of ribs are numbered from the head downwards. The upper ten pairs of ribs are connected directly (true ribs) or indirectly (false ribs) to the sternum through the costal cartilage (Figure 47). The eleventh and twelfth rib pairs are not connected to the sternum (floating ribs).

Case work with costal cartilage has shown that the quality of stab and incised marks varies across the cross-section of costal cartilage. Frequently it can be observed that the area close to the perichondrium exhibits comparatively clearly defined striations, whereas the central area often has no evaluable mark.
In addition, interindividual differences in the cartilage can be detected and play a role in the pattern of the mark. Signs of ageing such as calcification[28] and ossification of the cartilage change, for example, the colouring – the cartilage takes on a yellowish to brownish colour (Figure 48) – and also the material properties, which significantly reduces the cuttability of the tissue. While comparatively young cartilage tissue may exhibit fine striation structures, heavily calcified cartilage is more likely to split and does not exhibit any evaluable mark pattern, but frayed fracture structures instead.

When casts are made of the surfaces of cuts in cartilage tissue, small mound like grains of sand appear at regular intervals on the casts (“dots”, Figure 49), which are probably due the negative impressions caused by the cartilage cavities (Weber et al. 2021). These features may interfere with the comparative examination, but cannot be avoided.

▲ **Figure 48:**
Cartilage samples in different colours from donated bodies of different ages.
[Photo: Matthias Weber]

[28] **Calcification:** Deposition of calcium salts in cartilage tissue.

4. SECURING MARKS IN TISSUE

4.1. Photographic documentation

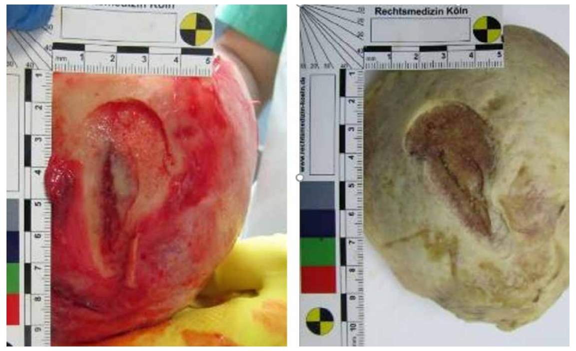
Comprehensive photographic documentation of wound patterns and positions of the marks is a useful aid in the investigation of tool marks. As a rule, all injuries are documented by forensic medicine and are then available, for example, as an image folder with the post-mortem report as well as in digital form.

In addition to overview photographs, which are also needed for subsequent guidance, detail photos of the individual injuries also have to be taken. Often the injuries to the skin provide additional information regarding the type of tool, which may be relevant for the comparative examination. The interpretation of injuries to the skin should be performed by experts in forensic medicine. Skin exhibits special features such as Langer's lines of skin tension (also called cleavage lines) and is elastic, which affects the pattern of the mark and means that is difficult to compare with damage caused by stabbing in technical materials such as textiles or rubber. In general, the photographic documentation of injuries should be carried out in line with the standards that usually apply in forensic medicine and science. Photographs should always be taken against a scale and in a parallel plane to the scale. Sufficient lighting is important so that photographs can be taken with a low ISO number (< 400) and using a small aperture with sufficient depth of focus and quality. If possible, a tripod should be used to avoid camera shake. In addition to the photographic documentation, marks can also be entered on a body pattern in order to collate information of assistance in evaluating the marks.

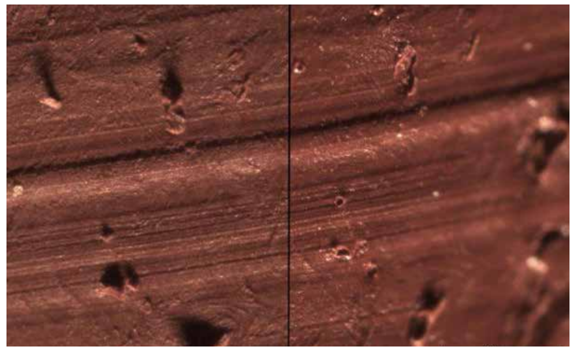
4.2. Securing evidence on bone

4.2.1. Maceration

▲ **Figure 50:**
Skull bone with decayed tissue remains.
[Photos: Institute of Legal Medicine Cologne]



▲ **Figure 51:**
Slash mark in calvaria during post-mortem (left) and after maceration (right).
[Photos: Institute of Legal Medicine Cologne]



▲ **Figure 52:**
Cast of slash mark made with a katana sword on bone (casting compound: AccuTrans AB brown®). Comparison of the casts made before (left) and after (right) maceration on the basis of the striation marks. There is no discernible qualitative difference between the marks.
[Photos: LKA NRW]

Tool mark examinations on bones can be carried out on dry, macerated[29] samples as well as on non-macerated samples (Figure 50). However, no tissue should cover the areas bearing the marks.

In the case of untreated bones, the marks should be gently freed from larger tissue remnants using customary post-mortem instruments such as forceps and scalpel, without creating any misleading marks. Any remaining soft parts are then removed from the bone by means of maceration.

If the bone is macerated in advance, the method chosen should have the lowest possible impact. The more fragile the bone becomes due to maceration, the higher will be the risk that marks can be altered or destroyed during the investigation. Maceration with hot water and heavy-duty liquid detergent, for example, is gentle on the bone structure (Figure 51, Figure 52) as long as the temperature of the maceration bath does not exceed 75 °C. Subsequent bleaching is not necessary for the examination of tool marks and is more likely to damage the bone structure of the specimen and hence the marks as well.

[29] **Mazeration:** Removal of the soft tissue from bone.

4.2.2. Reconstruction of bone fragments

▲ **Figure 53:**
Cranial bone before (left) and after reconstruction (here with plasticine compound) of all existing fragments.
[Photos: LKA NRW]

▲ **Figure 54:**
Cranial bone before (left) and after reconstruction (with glue) of all existing fragments.
[Photos: LKA NRW]

Depending on the intensity of the force used against the cranial bone, it may break into fragments. In order to detect, secure and subsequently interpret potential tool marks, it is often necessary to assemble the fragments into their former unit. The reconstruction of bones is in fact a core task of forensic medicine and one of those in which post-mortem and dissection assistants undergo training. Against the background of issues relating to the examination of marked evidence, however, it should take place in close consultation with and, if appropriate, together with the forensic science experts, according to the questions to be answered and the case in hand.

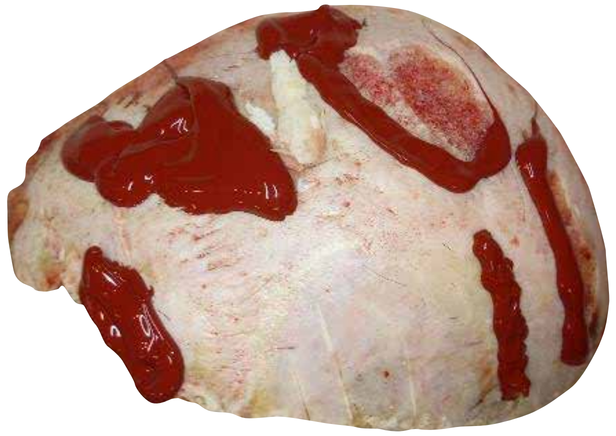
The macerated fragments are assembled on the basis of their fracture lines. Since bones break in a brittle manner and without plastic deformation, the fragments often fit together very well at the edges of the break. If only a few fragments have to be assembled, they can, for example, be held together with plasticine compound (e.g. type cleaner for typewriters) (Figure 53). After photographic documentation and examination of the marks, the plasticine compound can be removed almost without residue.
If the fragments are large in number and small in size, the adhesive force of the plasticine is often not sufficient to enable a stable reconstruction. In this case, the parts can be cemented together using commercially available PVA glue (Figure 54). Since the glue does not set immediately, the cemented fragments have to be held in place using plasticine compound until the glue sets. Once the compound has set, the next fragments can be cemented in place. One advantage of this method is the high stability of the cemented fracture surfaces. However, care must be taken not to allow any glue to come onto areas bearing marks. A further advantage is that the (PVA) glue can be removed afterwards at temperatures in excess of 70 °C.

One problem that occasionally arises in the investigation is that of missing bone fragments (e.g. due to animals carrying them off when corpses are found outdoors or in a body of water). If not all the relevant fragments are available for examination, a full reconstruction cannot be carried out, which may also reduce the significance of the subsequent examination.

4.2.3. Securing of evidence marks

Before any evidence is secured, the bone should be examined closely for tool marks from all sides using oblique light. Marks made on bone with a shallow angle of attack are often difficult to detect.

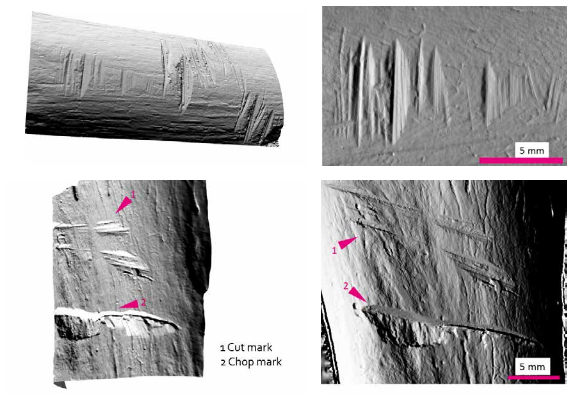
In contrast to cartilage tissue, tool marks in bone can be secured very well using tool mark scanners. Due to the matte texture of the surface of the bone, even fine details can be scanned in sufficient quality (Figure 55, Figure 56). This option should therefore always be considered.



▲ **Figure 57:**
Cast of slash marks on a fragment of a calvaria. The weapon used in the crime was a katana.
[Photos: LKA NRW]

The usual method of securing marks by casting (Figure 57, Figure 58) is also possible for bones without additional measures. However, care should be taken to prevent any casting compound from penetrating into the cancellous bone if possible. Once it has penetrated and hardened there, the casting compound can usually no longer be completely removed from the bone. The use of narrow application tips makes it possible to make very precisely targeted casts, thus avoiding such problems.

After curing, each cast must be inspected for defects and any adhesions using optical aids, repeatedly if necessary. Furthermore, three casts should be taken of each mark as a general rule. This reduces the risk of not recording any details of the mark that may be relevant for the investigation at a later stage.



▲ **Figure 55/56:**
Surface scan (ToolScan) of cutting and slashing marks on a human thigh bone (femur). The tool used is unknown.
[Photos: LKA NRW]

▲ **Figure 58:**
Cut marks on finger bones (top) and procedure for casting the marks. The weapon used in the crime was a pair of garden shears.
[Photos: LKA NRW]

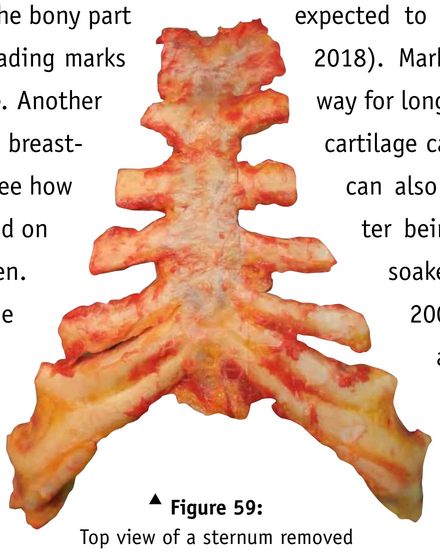
4.3. Securing marks on cartilage

4.3.1. Preparation

In order to be able to secure the marks on cartilage independently of and, at best, parallel to the forensic examinations, it is advisable to remove the marked tissue and examine it separately. Experts in forensic medicine must carry out the proper removal, ideally as part of the post-mortem examination.

In the case of stab marks in costal cartilage, practice has shown that removing the entire breastplate, i.e. the sternum and ribs (Figure 59), is very effective. Usually, the ribs are separated in the bony part for this purpose, so that no misleading marks are created on the cartilage tissue. Another advantage of removing the entire breastplate is that it is still possible to see how the marked evidence was positioned on the body when the cast is then taken. Consequently, it will then also be possible to determine from which side the stab came, how the mark is aligned in relation to the axes of the body in which rib the mark is located. This information is no longer available or very difficult to obtain, if only a sample of cartilage has been removed. If the marks are not in the costal cartilage, but in other cartilaginous tissues, such as the trachea or the thyroid cartilage, the same procedure should be adopted, i.e. the area removed should be as large as possible. In this process, it is always important to weigh the steps necessary for the forensic investigation against ethical aspects.

If it is not possible to take a cast of the injured cartilage close to the time of the post-mortem, the exhibit can be stored in the refrigerator, wrapped in gauze or a towel soaked in saline solution (NaCl 0.9%), for several days between the time of removal and the examination. As the storage time increases, the degree of deterioration of the marks can be expected to increase as well (Stanley et al. 2018). Marks should not be stored in this way for longer than a few days. If the marked cartilage cannot be secured in good time, it can also be frozen (approx. - 20 °C) after being wrapped in gauze or a towel soaked in 0.9 % NaCl solution (Wong 2007) and then further wrapped in aluminium foil . This can also lead to a reduction in quality of the marks.

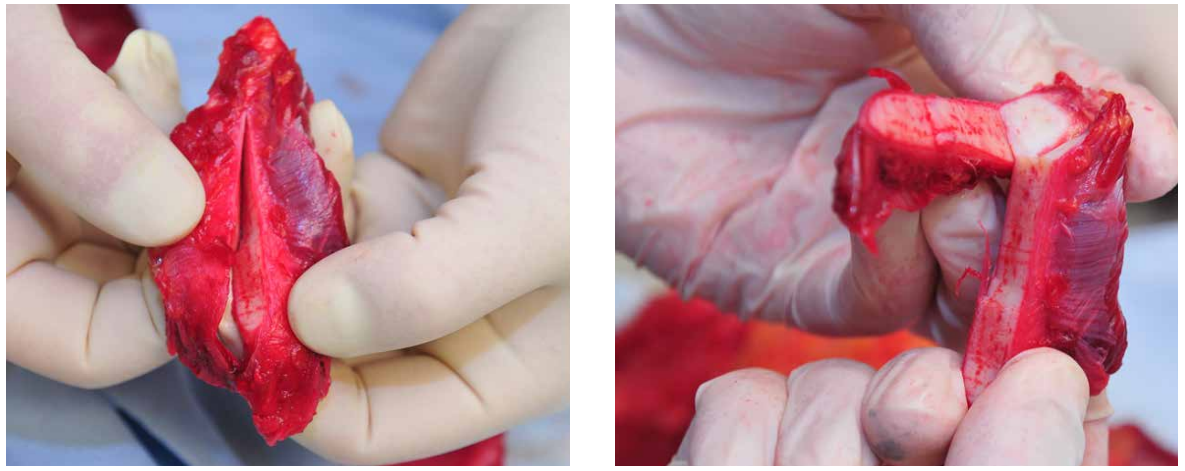


▲ **Figure 59:**
Top view of a sternum removed during the post-mortem with cartilaginous parts of the ribs. The attached soft tissues were mostly removed by dissection; the soft tissue still present does not have any effect on securing the tool marks.
[Photo: Legal Medicine Cologne]

For the documentation of the mark pattern and further examination, it may additionally be necessary to free the cartilaginous tissue from any interfering soft tissue. The tissue can usually be separated with little effort by using conventional dissection tools such as forceps and scalpel.

In order to secure the marks, it is necessary to separate the surfaces of the cut or stab marks. Incisions can be folded open for this purpose and then separated using a scalpel (Figure 60). In order to avoid misleading marks, the cuts should be made orthogonally to the marks of the crime and the cuts made in preparing the samples should be marked, for example, in colour. ▬

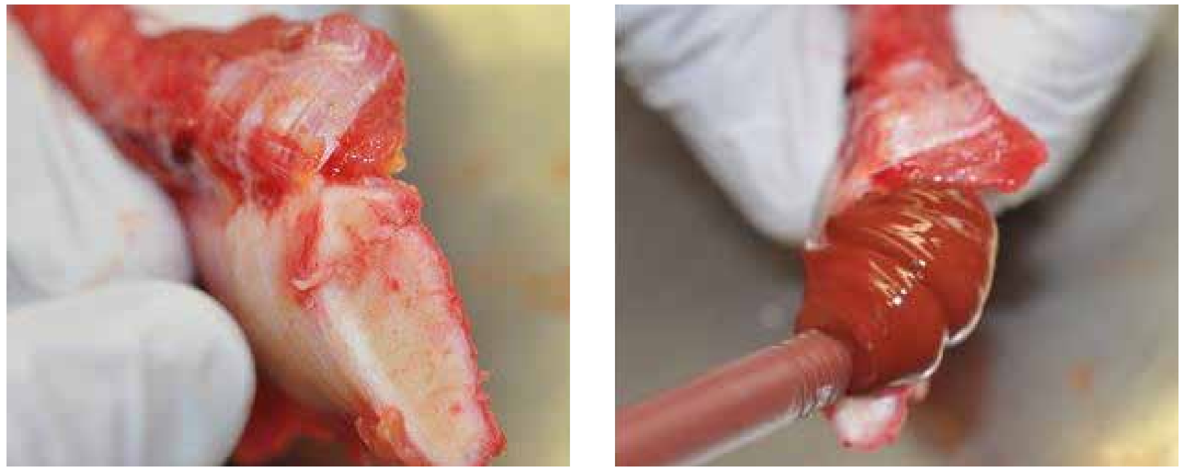
▼ **Figure 60:**
Separation of a stab mark or notch in a costal cartilage. To preserve the marks during dissection, the tissue was cut from the side furthest away from the marks.
[Photos: LKA NRW]



4.3.2. Securing marks

Stab and cut marks on the cartilage may contain tissue remnants such as fats and blood. The best way to clean the areas bearing marks is to make multiple casts of the marked surfaces (Figure 61).

Any obstructing parts will adhere to the casting compound after it has cured and will be removed when the cast is lifted off. Several casts should always be made for cleaning purposes. After curing, the last cast must be inspected for defects and any adhesions using optical aids and repeated if necessary. As a general rule, three good-quality casts should also be present for marks in cartilage. Since cartilage tissue has a relatively high heat capacity due to its high water content, the use of fast-curing casting compounds speeds up the preparation of samples in the case of exhibits that have been refrigerated during storage. ▬



▲ **Figure 61:**
Cut mark surface on a costal cartilage separated with a knife (left) with adhering soft tissue; cast of the mark (right).
[Photos: Francois Truffier]

5. SOURCES OF MARKS

5.1. Tools of sharp and blunt force

Sharp force is the term used for the effect of sharp cutting, semi-sharp or pointed objects against the body. They include knives, glass shards, scissors, axes, swords, machetes etc.. Blunt force describes the mechanical effect of a flat structure against the body.

It is therefore primarily a general term for any mechanical contact of the body with an object that does not pierce or cut. In terms of the forensic issues, it is above all frequently a matter of distinguishing whether the injuries resulting from the blunt force were caused by a blow or a fall (or a combination of both). For example, blows inflicted with tools and objects such as clubs, baseball bats, metal pipes or hammers count as blunt force.

5.2. Suitability

From the viewpoint of marks analysis, the use of tools of sharp force on cartilage and bone produces marks suitable for evaluation. Blunt force rarely results in the formation of specific marking patterns on the bone that can be used to identify the instrument of the crime. As a rule, blunt force does not create evaluable marks unless plastic deformation results in an impression being created on the marked evidence. Bone[30] and cartilage[31], however, do not undergo (permanent) plastic deformation.

In the case of semi-sharp force, on the other hand, such as in the case of marks left by axes, swords or other sharp-edged objects, marks regularly appear on bones and cartilage that make it possible to identify the tool. The basis for identification, namely the presence of individualizing features on the active surfaces of the tool, is almost always present in the case of tools used in acts involving semi-sharp force. All of the above tools bear ground cutting edges and are therefore suitable for investigations involving comparative mark analysis.

The same applies to the tools of sharp force with ground cutting edges. Yet glass shards should also produce identifiable marks on the basis of their "cutting edges", which can be distinguished by their Wallner lines and lanceolate fractures; however, there are no known cases in this connection. One of the reasons for this is that the edges of the broken glass are damaged when they come into contact with bones during the process of causing the injury, which in turn changes them. However, forensic identification of the glass edge causing the injury should always be attempted in appropriate cases.

[30] Compression of bone tissue is not plastic deformation in the technical sense but, instead, brittle fracturing of the material.

[31] Strictly speaking, cartilage does undergo plastic deformation because it is a viscoelastic material. However, since plastic deformation of the cartilage tissue requires a certain time to take effect, which is practically never attained during assaults on the human body, it does not play any role in this context.

6. COMPARATIVE EXAMINATION OF MARKS IN CARTILAGE AND BONE TISSUE

6.1. Preliminary examination and suitability

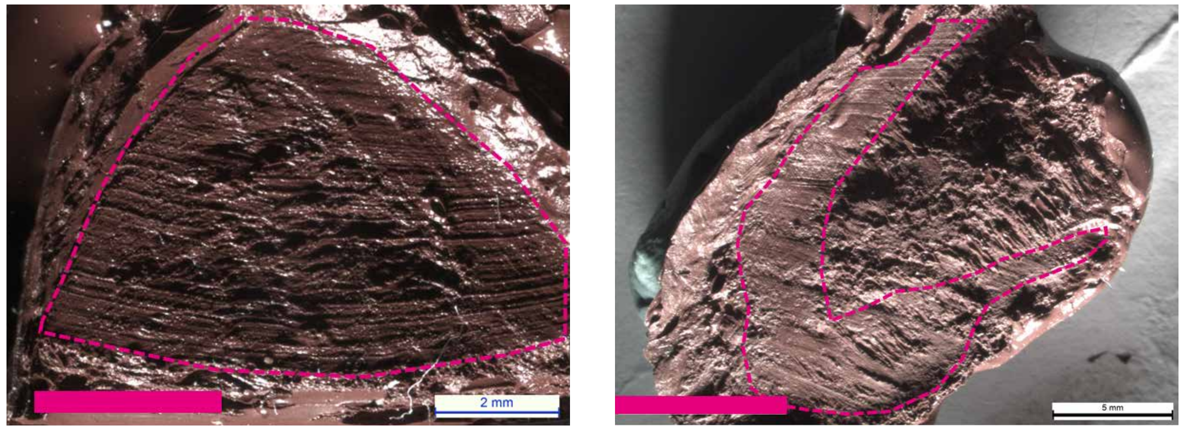


Figure 62:
Surfaces of two cutting marks in costal cartilage. The regions of the mark on which evaluable striations can be detected have been identified. [Photos: LKA NRW]

After the evidence has been secured by casting or scanning, the first microscopic inspection of the marks takes place. This involves assessing whether general and individualizing features can be found in the marks that may be used to identify the instrument of crime in the subsequent comparative examination. In a comparative tool mark examination of this kind, marks are produced in a test material with the tool under investigation and these marks are compared with those from the crime using light microscopy.

The suitability of marks on cartilage tissue is assessed on the basis of any detectable mark striations. If striations are visible on the casts or the scans, further examination is then recommended (Figure 62). It is impossible to determine whether the marks are of sufficient quality and quantity for a comparative study on the basis of a single mark. In the case of these marks, the suitability usually only becomes apparent in a comparison with test marks.

If several marks are present, they can first be compared with each other for an initial assessment of their suitability. If the marks can be matched to each other, they are suitable for a comparative examination.
If the marks are unsuitable for identification due to their insufficient prominence, they may nevertheless often still be used to eliminate certain weapons or tools.

A similar approach applies to marks in bone. If not only fracture structures but also defined striation marks can be recognized, further examination is recommended.

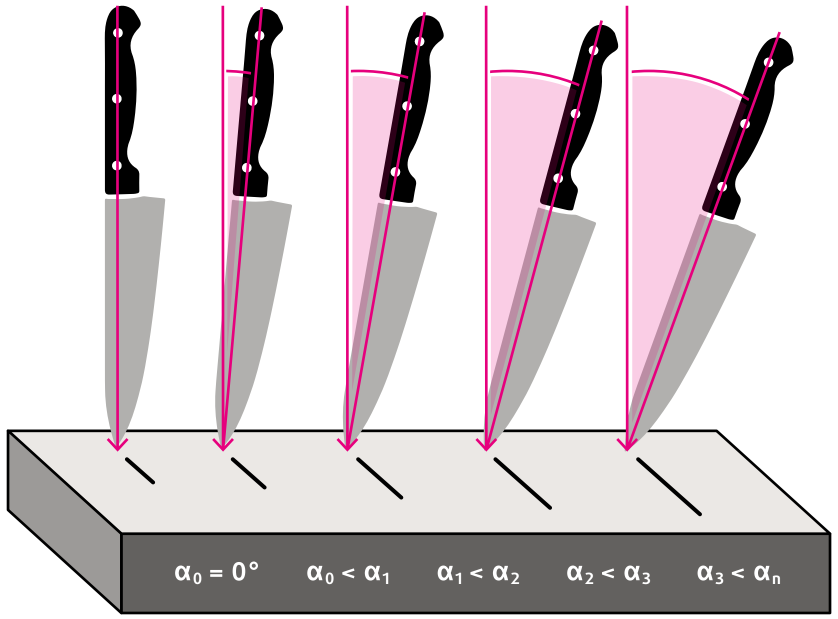


Figure 63:
Schematic representation of test mark creation with varying angles of impact.
[Graphic: Marco Tavano]

6.2. Test marks

6.2.1. Comparison marks for stabbing and cutting marks in cartilage

Dip-Pak® and ballistic gelatine are often cited in the literature for stabbing and cutting marks on cartilage. At first, an obvious approach would be to create the test marks in cartilage. However, animal cartilage is too inhomogeneous and available in such limited dimensions that it is virtually impossible to use it for producing complete sets of marks. Results from our own current research (Weber et al. 2021) lead us to recommend the hydrogel agarose.

Agarose is normally used in gel electrophoresis[32] and is produced with a relatively low concentration and strength for this purpose. The test material recommended here for stabbing marks in cartilage is 7% agarose (Weber et al. 2021) (see Appendix for recipe). At this concentration, the material is relatively firm and exhibits marks with a very fine resolution. Due to its water content, agarose is very easy to cut, which minimizes the risk of injury. Furthermore, it is non-toxic and can be cast with commonly used compounds.
The material can be cast as a plate of a few millimetres in thickness. The area should be selected so that test marks of sufficient quantity and length (depending on the length of the knife and the stabbing angle) can be made in the material. Plates of approx. 25 cm x 15 cm are recommended for common kitchen knives.

Where stabbing marks are concerned, the angle of attack plays a crucial role in the mark pattern (see above). A change in the angle always causes contraction or stretching of the mark. In the case of contraction, this can lead to striations that had previously appeared separately in the mark becoming superimposed. In the case of stretching, the opposite effect may occur. There is currently no study available on which variation in angle results in a situation in which it becomes no longer possible to match two stab marks from the same knife.

[32] Gel electrophoresis is an analytical method used in molecular biology and chemistry to separate different types of molecules.

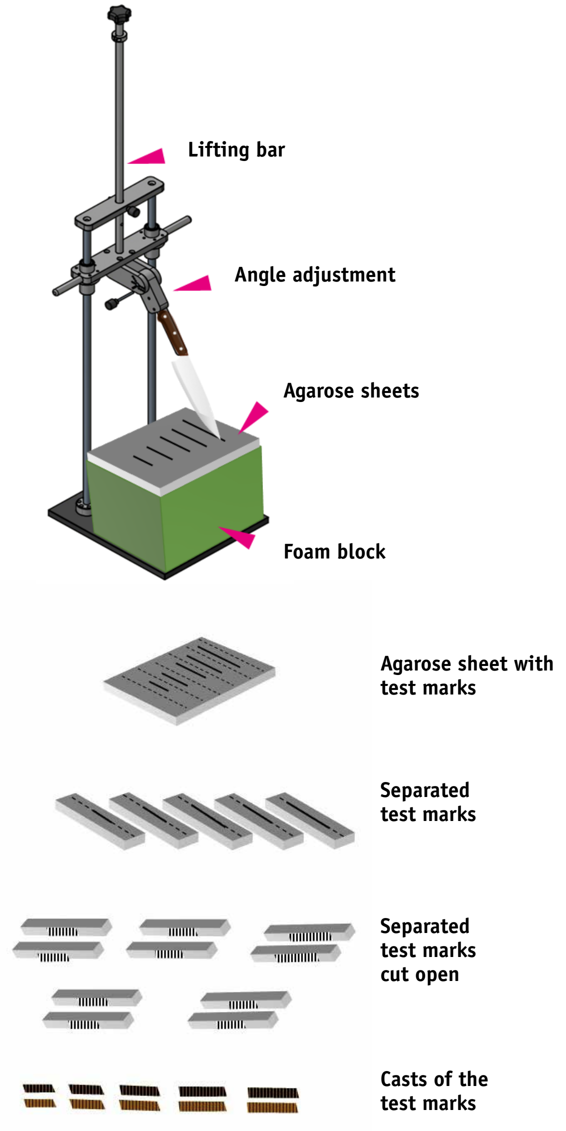


Figure 64:
Schematic representation of the production of a set of stabbing marks in agarose plates.
[Graphic: Matthias Weber]

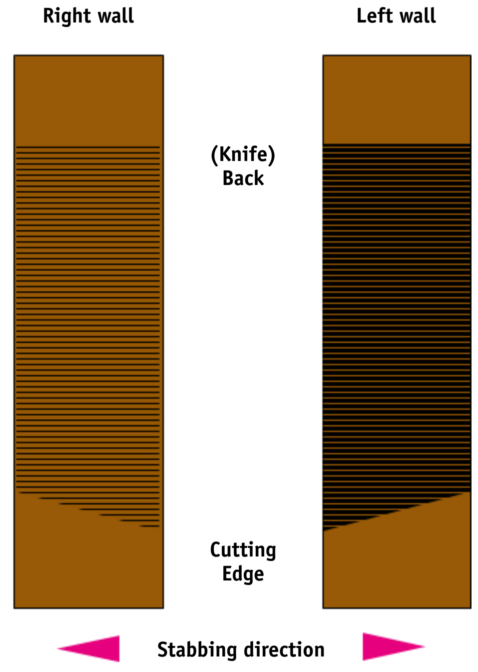


Figure 65:
Schematic representation for labelling the cast of the right-hand (as viewed from the back of the knife) and left-hand surfaces of the mark, indicating the orientation of the knife and stabbing direction.
[Graphic: LKA NRW]

In addition, there is usually no information available on the angle of attack, so that test marks have to be created with different angles (Figure 63). In the authors' experience, stabbings in homicides are usually carried out at impact angles close to 0°, so it makes sense to create more test marks close to 0°, rather than at greater angles. The authors recommend creating sets of marks starting at 0° in a delta from 1° to +/- 5° for single-edged knives and from then in a delta from 5° to 25° (to -25° for double-edged knives). The number and angle of the test marks may vary from case to case.
A specially designed[33] stabbing/cutting device (Figure 64) with an adjustable angle has proven to be useful for producing comparative stab marks. The device can be used to create stabbing and cutting marks at different angles. A block of foam block serves as a readily penetrable base so that the knife does not undergo any changes. The marks are then cut out of the plate.
The stabbing marks are then separated and each is cut open so that casts can be made of the individual mark surfaces. The direction of the stab and the orientation of the knife, i.e. the position of the back of the knife and the cutting edge together with the respective angle of attack, as well as the side of the mark, i.e. viewed from the right or left of the back of the knife (in the case of single-edged knives), should be recorded on the paper on the back of the casts during the process (Figure 65).

[33] The prototype of the device was developed and built by Jürgen Geiermann, Development Workshop/Precision Engineering of the Institute of Biomechanics and Orthopaedics, German Sport University Cologne.

6.2.2. Test marks in tool mark investigations on bone

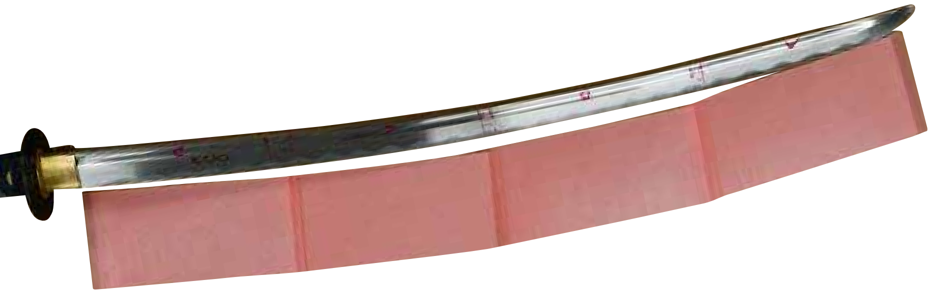


Figure 66:
Test slash marks created segmentally in wax plates with a katana.
[Photo: LKA NRW]

Various materials can be used when tool marks are present on bone. The choice depends on the location of the marks.

In the case of slash marks on bone, the test marks can be produced in wax plates (modelling wax) (Weber et al. 2020; Weber et al. 2015), which is available in different degrees of hardness. Relatively hard wax plates are recommended to avoid any smearing of the marks. The plates can be stored in the refrigerator in order to adjust the consistency of the wax and harden the material if necessary. As an alternative to wax, test marks can also be created in non-hardening clay (e.g. Roma Plastilina) (Petraco 2011).

The sets of marks are then created with shallow slashes into the wax plates (Figure 66, Figure 67). It is important here to make sure that the underlying surface is soft enough (e.g. wood) to protect the active surfaces of the tool against changes. Variation of the angle often plays a subordinate role in slash marks, since slashing tools and weapons such as axes or machetes are barely guided during impact or penetration due to their flat geometry (hardly any lateral variation in the angle) and generally strike the surface orthogonally (hardly any axial variation of the angle). Consequently, even just a few test marks are often sufficient and effective.
In the case of saw marks, plastic material properties similar to bone, such as Synbone® generic plates or comparable materials can be used. Alternatively, if the saw dimensions permit, mammalian bones of corresponding anatomical topography can also be used.

Production of the test marks always depends on the marked evidence. If a cross-section is present, in other words merely the surfaces of the cut, it is usually only possible to recognize class characteristics and the test marks are similarly produced as cross-sections. If an incision is present and striations of a quality and quantity suitable for evaluation are visible, test marks are made individually with each saw tooth. The teeth must be marked individually before the examination.

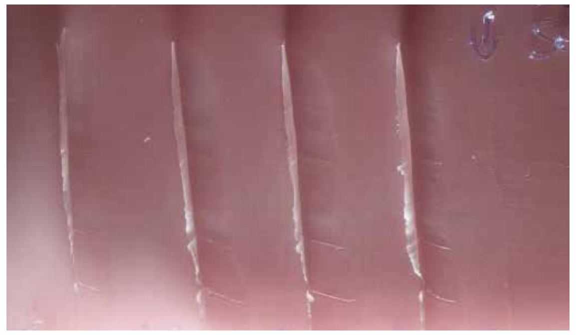


Figure 67:
Test slash marks made in wax plates with a hatchet.
[Photo: LKA NRW]

6.3. Comparative examination with light microscopy

For examination by means of light microscopy, the test marks are cast with brown silicone rubber mass in the same way as the marks from the crime scene.

First, the marks from the crime scene are mounted on one of the two object stages of the comparison light microscope and then examined. To gain an overview, the mark is viewed under low magnification and with flat oblique light. The direction of illumination is rotated through 360° around the mark so that all striations in the mark can be detected. The mark is then aligned so that the striations are perpendicular to the dividing line of the comparison microscope. The illumination is flat and orthogonal to the striations. If there is any interference from reflections (glare), the azimuth angle can be varied by a few degrees.
The test mark is mounted and illuminated on the second object stage in a similar manner, and both marks can then be compared with respect to their class and individual characteristics (Figure 68, Figure 69).

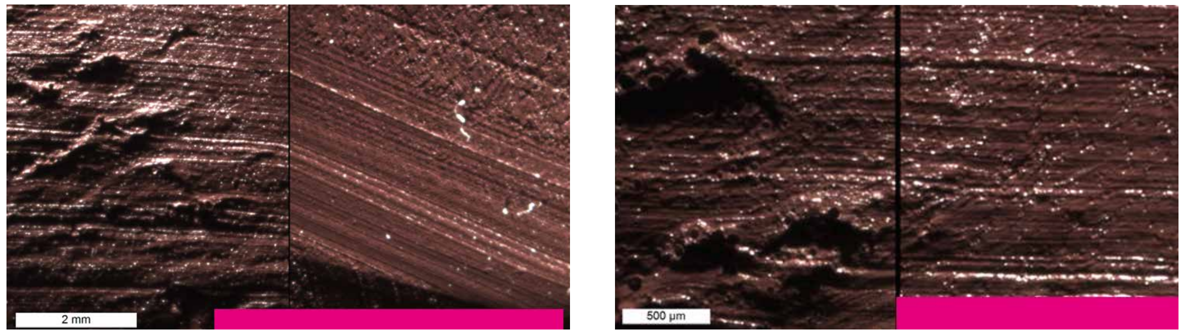


Figure 68:
Comparative pictures of a stabbing mark in the cartilaginous part of a human rib (left-hand half of each image) and the test stabbing mark made with the knife from the crime scene (on the right in each case) as casts (casting compound): AccuTrans AB brown®). It was possible to identify the tool used in the crime on the basis of the matching individual characteristics.
[Photos: LKA NRW]

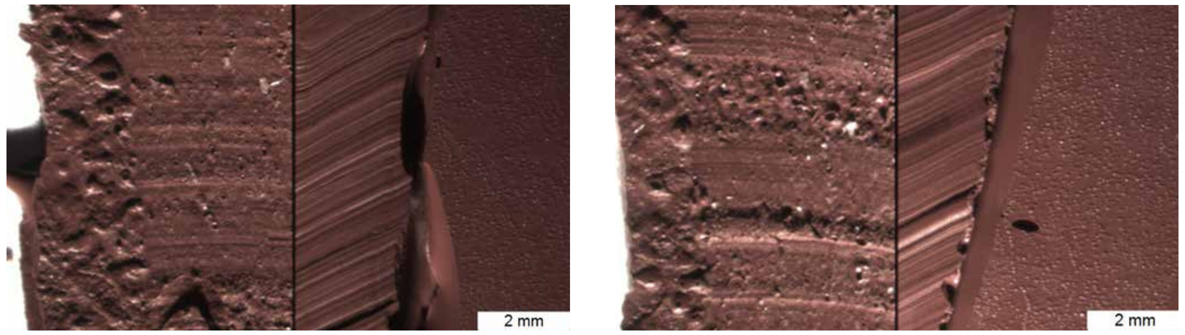


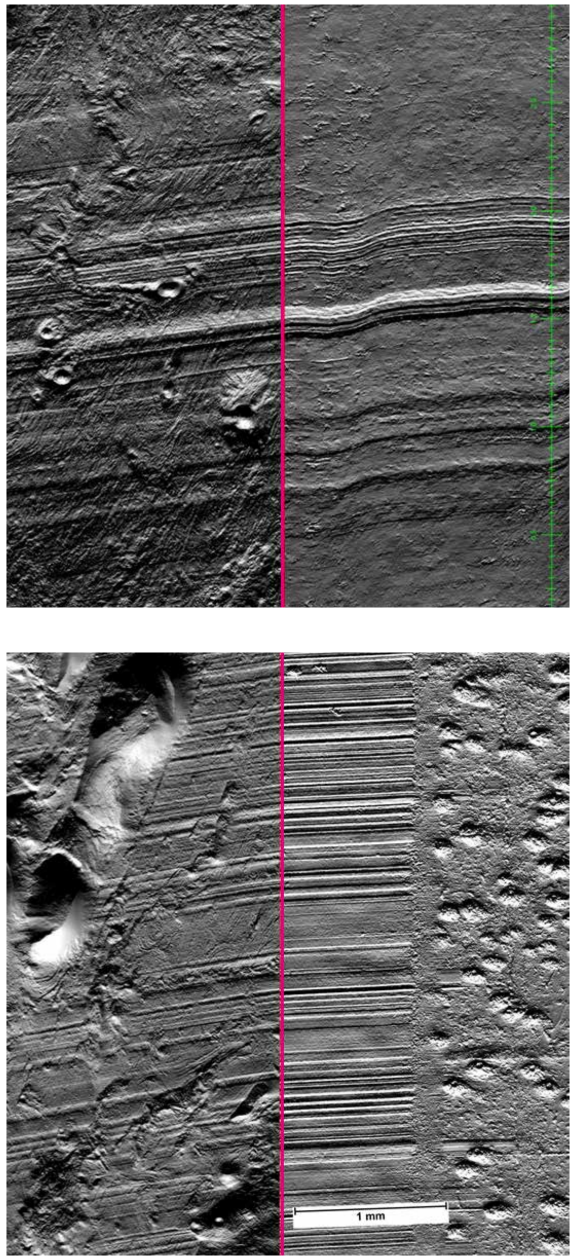
Figure 69:
Comparative pictures of a stabbing mark in the cortical part of a human skull (left-hand half of each image) and the test stabbing mark made with the tool from the crime scene (axe, on the right in each case) as casts (casting compound): AccuTrans AB brown®). The tool used in the crime was identified on the basis of the matching individual characteristics.
[Photos: LKA NRW]

6.4. 3D scan comparison

Tool marks are regularly examined with the aid of light microscopy. Viewing the casts created with light microscopy is less time-consuming than scanning, as objects are viewed directly.

One disadvantage of the light microscope, however, is that the depth of focus decreases with increasing magnification. Scanning a tool mark, on the other hand, can take from several minutes to several hours, depending on its size. Nevertheless, the scan has the advantage that, firstly, the mark is displayed with full depth definition. Secondly, the surface is available as a 3D data record and can undergo virtual examination. With this technique, appropriate software is able to compensate for interfering factors such as waves on the surface. In addition, protruding peripheral areas, which cause interference in the form of shadows when the lighting on the microscope is from a flat beam on the side, can be removed from the data record. Furthermore, the surface can then be illuminated optimally from a shallow angle, and even fine details of the mark become visible.

The best results are obtained with the ToolScan mark scanner when test marks are cast with a black silicone rubber compound. Bone is sufficiently opaque for scanning (not for light microscopy) and can be scanned in directly. Casts should also be made of cartilage with black compound, as the low opacity may lead to incorrect measurements. The comparison of the scan data can then be carried out in a similar manner to that using light microscopy (Figure 70).

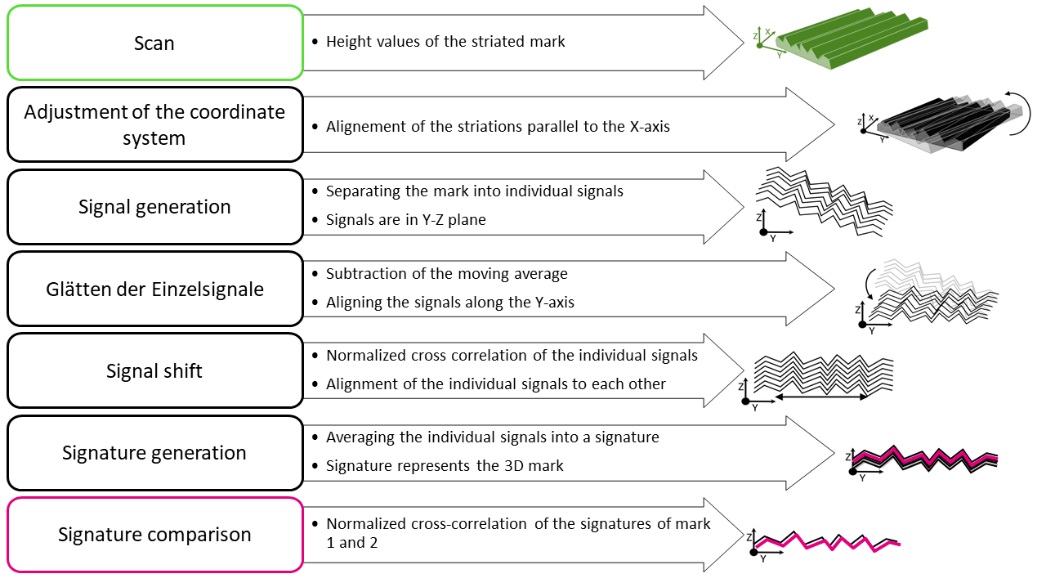


▲ **Figure 70:**
Comparative images based on a 3D scan of slash marks made with a katana in a skull bone (left half of each picture) with test marks made in wax (right half of each picture).
[Photos: LKA NRW]

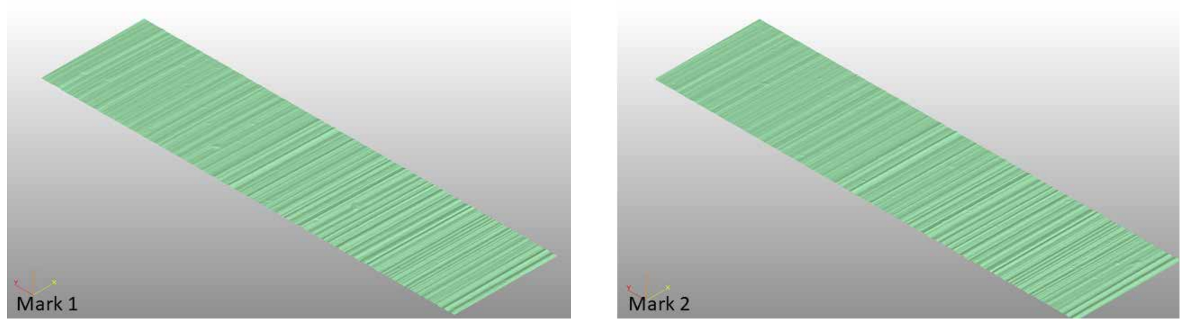
6.5. Numerical comparison

One method that is currently the subject of research is the comparison of striation marks by calculating their cross-correlation, which can be performed in various ways with different scanning methods, use of filters, etc. (Baiker et al. 2014; Baiker et al. 2015; Vorburger et al. 2016). One of the numerical methods of comparison is presented here as an example (Figure 71) .

In the first step, the individual marks (e.g. evidence mark and test mark) are first scanned to obtain the height values of the striations (Figure 72).



▲ **Figure 71:**
Schematic representation of the comparison of two marks 1 and 2 by means of normalized cross-correlation as an example.
[Graphic: LKA NRW]



▲ **Figure 72:**
3D representation of the scan data of two marks (1 and 2).
[Figure: LKA NRW]

In preprocessing, the coordinate system can then initially be aligned so that the striations are aligned to the x-axis. The x-axis thus follows the direction in which the mark was produced, the y-axis crosses the width of the mark, and the height values are displayed in the z-direction.
In the next step, the mark is then divided into individual signals orthogonally to the direction in which they were caused, i.e. parallel to the y-axis. The individual signals are then each smoothed out horizontally along the y-axis by subtracting the moving average (Figure 73).

These signals are then aligned with each other on the basis of their normalized cross-correlation (Figure 74).

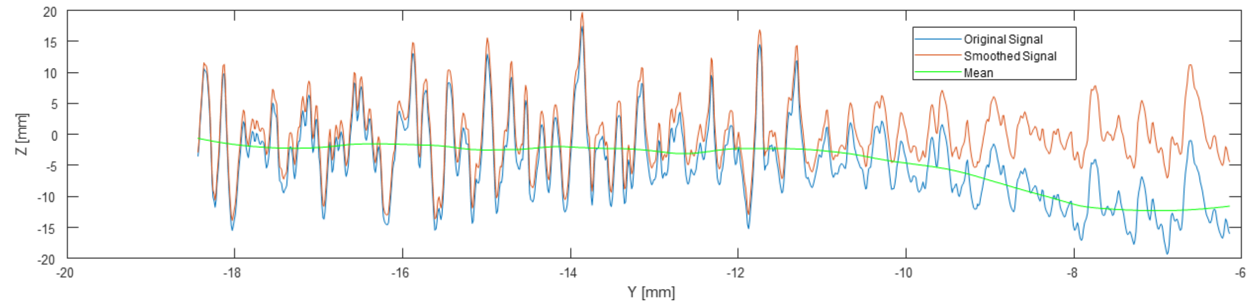


Figure 73:
Representation of smoothing a signal by subtracting the moving average.
[Figure: LKA NRW]

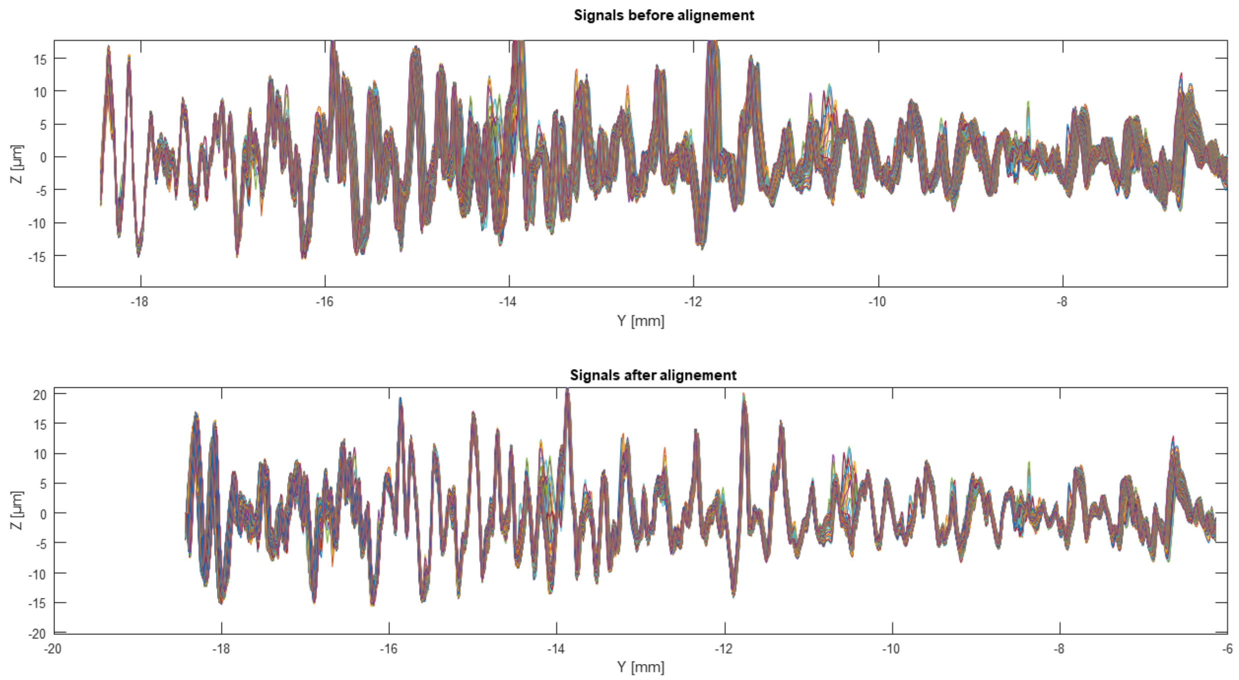


Figure 74:
Representation of 260 signals of a mark before (top) and after alignment using their normalized cross-correlation.
[Figure: LKA NRW]

The normalized cross-correlation determines the displacement, L, at which two discrete signals, S1 and S2, are most similar to each other. The cross-correlation coefficient X is calculated as a measure of similarity (Eq. 1).

$$X\{L\} = \frac{\sum_{i=1}^{p} S_1[i] \cdot S_2[i+L]}{\sqrt{\sum_{i=1}^{p}(S_1[i])^2 \cdot \sum_{i=1}^{p}(S_2[i+L])^2}} = \frac{\textit{Cross Correlation}}{\textit{Normalization}}$$

Here, p is the number of discrete data points and L is the displacement of the signals with relation to each other. The basis of the calculation is therefore a multiplication of the individual height values at a given displacement and subsequent summation of these values. The result is normalized for better comparability, so that for two identical signals without any displacement, X = 1. Two inverse signals would lead to a value of X = -1. No matches result in a value of X close to 0. In this way, cross-correlation can be used to determine the displacement at which the best match is obtained for two signals and the level (from -1 to 1) of the measure of agreement.

After aligning the individual signals with each other, they are averaged into one signal. This one signal then represents the original mark and is called its signature.

The test mark is similarly converted into a signature by preprocessing. Subsequently, the two signatures of the mark and test mark can be compared by cross-correlation (Figure 75).

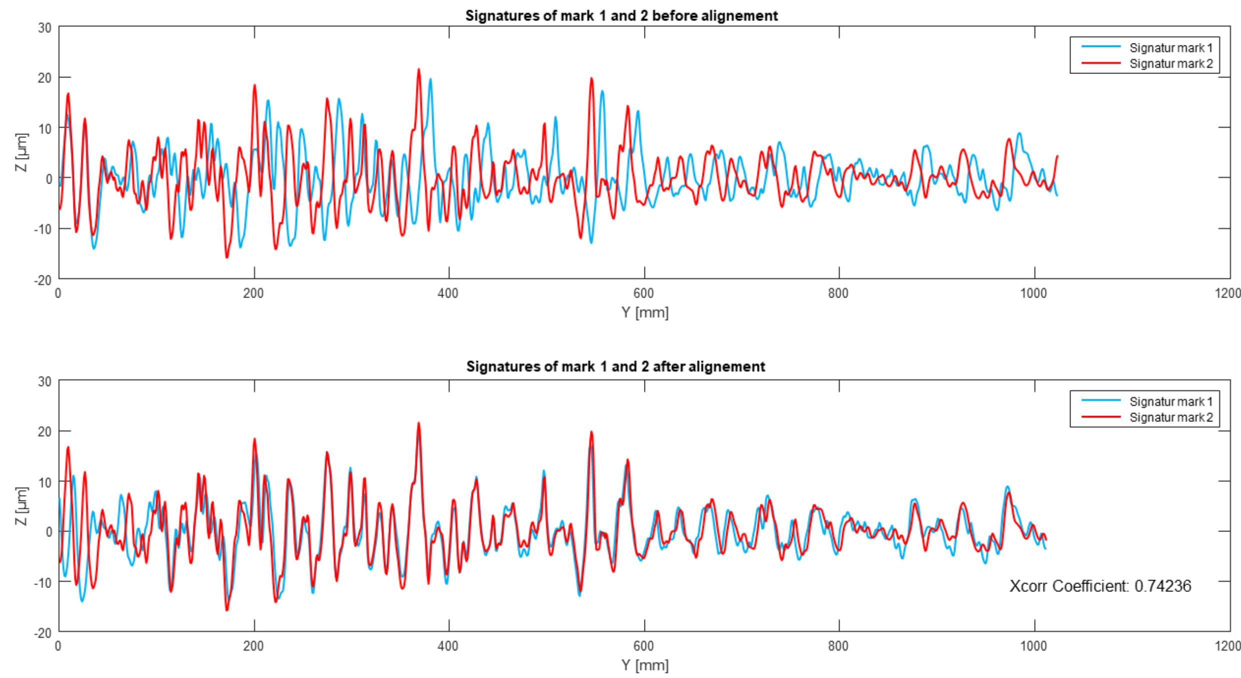


Figure 75:
Sample representation of the signatures of two marks 1 and 2 (stabbing marks in agarose; made with the same knife) before (top) and after (bottom) alignment based on their normalized cross-correlation. In this example, a cross-correlation coefficient of 0.74 was calculated.
[Figure: LKA NRW]

6.6. Consecutive Matching Striae

As the name indicates, the Consecutive Matching Striae (CMS) method involves counting consecutive striae on the mark and test mark.

CMS was proposed in an article by Biasotti published in the Journal of Forensic Sciences in 1959 (Biasotti 1959). In an extensive analysis of 720 known non-match comparisons of land and groove impressions in fired bullets Biasotti found no case in which the CMS exceeded four. In 1997, on this basis, Biasotti and Murdock jointly published their quantitative criteria for identification as expressed in terms of CMS.

In three-dimensional marks, identification of the weapon as the source of the marks can be justified when at least two different groups of at least three consecutive matching striae appear or a group of six consecutive matching striae. In the case of two-dimensional marks, there must be at least two groups of at least five consecutive matching striae or one group of at least eight consecutive matching striae (Figure 76). However, the striae must be exclusively individualizing characteristics.

To date, the CMS method has not managed to establish itself in Germany, particularly since the issue of whether it can be applied to tool marks in general has yet to be resolved. Nevertheless, it is a practical and easy-to-apply method and a more objective approach than the mere assessment of the examining expert.

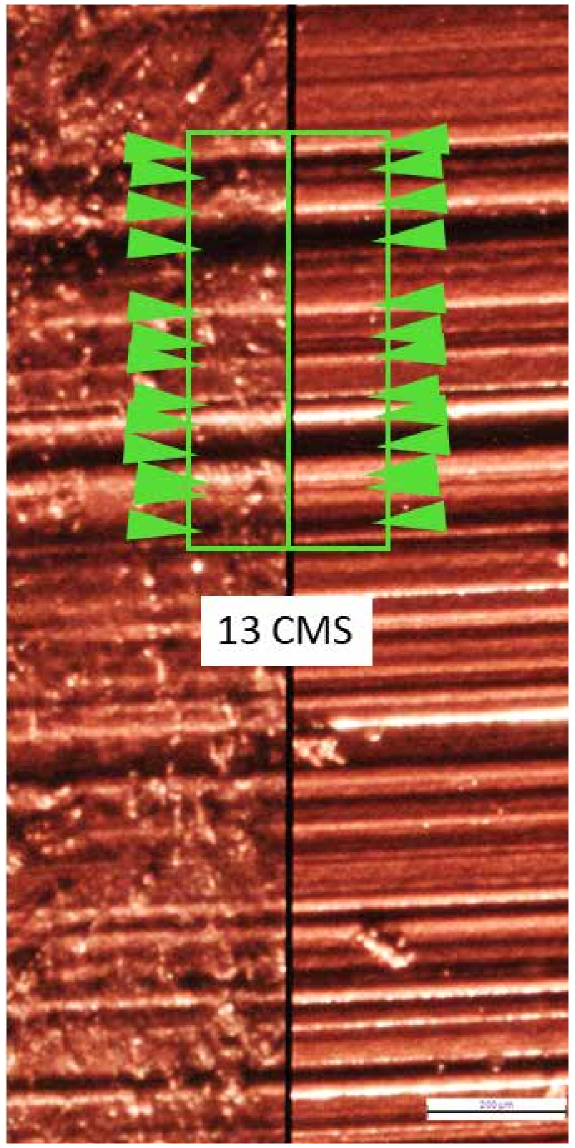


Figure 76:
An example of the CMS method applied. The figure compares two casts of striated marks (AccuTrans AB brown® casting compound) are compared at one point, at which 13 CMS can be counted. According to the method, this corresponds to an identification, since 13 > 8.
[Figure: LKA NRW]

6.7. Calculation of the possible alignment combinations

The evidential value of a mark can also be estimated by calculating the possible alignment combinations of distinguishable mark features that have undoubtedly been caused by individualizing characteristics of the source of the mark.

N distinguishable features can be arranged in N! (N factorial) different ways. For example, the four distinguishable letters of the term “WORD”” can be arranged in 4! (4 x 3 x 2 x 1) = 24 distinguishable sequences, e.g. “ROWD””. Due to the rapid growth of the factorial, if there are already 10 distinguishable features present, there will be 10! = 3,628,800 possible arrangement combinations. The arrangement possibilities are a measure of the probability that the features detectable in the mark appear in the order found purely by chance.
In the example shown in Figure 77,10 distinguishable characteristics are determined, which give rise to 3,628,800 possible arrangements possibilities and which match in both the evidence mark and the test mark, i.e. they are all present and in the same arrangement. This makes it easy to justify the identification of the crime tool as the source of the marks.
The decision as to what is accepted as a distinguishable mark characteristic is also made by the investigator in this method. Since only the sequence, but not the exact location, orientation and shape (assumed here to be matching) is taken into account, the evidential value of a mark te nds to be underestimated. Consequently, this is a conservative model.

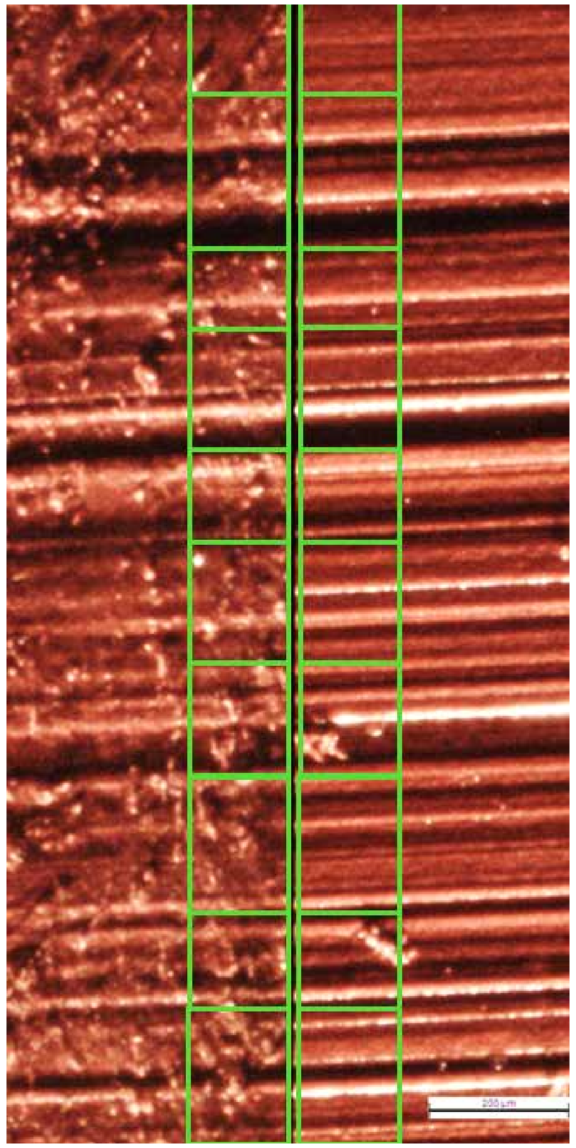


Figure 77:
Example of the comparison of two marks (slash mark in cranial bone, cast with AccuTrans AB brown®) on the basis of the possible arrangements of distinguishable mark characteristics.
[Figure: Bert Weimar]

6.8. Results and evaluation

In principle, the results of a comparative examination of tool marks on tissue are evaluated in a similar way to other tool mark examinations.

However, biological material and especially cartilage reacts more intensely to external conditions such as temperature and moisture and special attention must be paid here to possible changes in the marks. Specifically, this means that if there are deviations in the characteristics between the evidence mark and test mark, any possible changes to the evidence mark are always taken into consideration as well.

7. EXPERT REPORTS ON MARKS IN TISSUE

7.1. Facts based on the expert's findings

The acquisition of facts based on the expert's findings plays a significant role in the assessment of tool marks in cartilage and bone tissue.

This includes the photographic documentation of the crime scene, in which, for example, blood stain patterns may already yield clues as to the tool used. The crime scene can also provide information about the direction in which the instrument used in the crime was moved, which can considerably simplify and shorten the investigation.

The image folder on the crime scene work can be requested via the public prosecutor's office or the criminal investigation officer.

In addition to the crime scene documentation, the post-mortem report (including photographic documentation) and further forensic medical reports (e.g. on analysis of blood spatter pattern) are the most important sources of information. It is possible to obtain the exact locations and morphology of the injuries from this documentation. Also contained within the documentation is the forensic medical interpretation of the injuries with regard to the tool used and its direction of attack and orientation.

7.2. Expert report

The examination to identify the instrument of crime is usually commissioned by the police clerical officer, the public prosecutor's office or by an order of the court to take evidence. Following this, the investigation process as well as the determination and evaluation of the results are carried out by a forensics expert and recorded in the form of an official report. In the state criminal police offices and the Federal Criminal Police Office, the investigations are carried out by forensic experts, i.e. forensic scientists with a background in the natural sciences, engineers or police officers with appropriate additional training, and the expert reports are represented in court if required.

Since an expert report is usually addressed to parties involved in the trial who mostly have no or little knowledge of natural sciences, it should be formulated in a way that is self-explanatory and understandable to the layperson. The expert report names the party commissioning the report as well as the exact investigative objective and lists all objects of investigation and the equipment used. The methodology of tool mark examination should also be explained. For this purpose, it is advisable to include sketches in the expert report for clarification.

This is followed by a critical appraisal of the material, in other words the description of the objects under investigation, their origin and suitability for comparative examination. This section should therefore include the history of marked evidence and the condition of the material when it was collected so that these aspects can be discussed later in the expert report. In particular, if the corpse had been lying for a long time or exhibited a high level of decomposition, this may have a negative influence on the quality of the marks. The age of the person killed also plays a role because, as previously described, changes in cartilage tissue that progress with age can reduce its suitability as evidence.

The description of the marks and their localization should be guided by the formulations in the forensic medical reports. This makes it easier for parties involved in the trial to understand and evaluate the forensic report and the results and interpretations it contains.

To enable the suitability of the marks for a comparative examination to be assessed, the marks on tissue have to undergo the previously described preparation steps. These steps should also be listed in the expert report.

The next part of the report describes the examination procedure and specifies the results. This includes the preparation of the test marks and the actual comparative examination as well as a detailed description and documentation (e.g. by means of micrographs) of the detected matches or differences in the evidence marks and test marks. Any changes to the stored exhibits caused by the examination should be noted.

The results are then evaluated, taking into account all the facts based on the findings and – where known – the connecting factors. There should always be a precise distinction and division between the purely objective description of the findings and the subjective assessment by the expert. The results are usually evaluated on the basis of the six-level conclusion scale (Table 1, p. 30).

In conclusion, details are provided on the location of the stored exhibits. By signing the report, the expert assumes responsibility for the correctness of the form and content of the report, taking into account the current state of the art in science and technology.

8. ADDENDUM: MICROTRACE ANALYSIS

By: Dr. Pia Rosendahl (Landeskriminalamt Nordrhein-Westfalen, Forensic Institute, TD. 53.1 – Forensic Textile Analysis, Botany, Material, Hair and Soil Evidence)

When a tool comes into contact with a surface intensely enough to create a tool mark, material can be transferred from the tool to the marked evidence and vice versa. Active surfaces of a tool with a painted finish often leave deposits of paint on the marked evidence.

For this reason, the departments of tool marks and microtrace analysis in the state criminal police offices often work closely together Tool marks on solid tissue, and especially on bone, can also result in the transfer of microtraces to the tissue. For this reason, we will include a brief description of this topic.

Similar to a burglary, in which, for example, a door has been prised open with a painted object and there is an expectation that material adhering during the tool used in the crime will have been transferred to the door, comparative examinations of material in homicides may be able to connect potential tools of the crime with the injured victim.

8.1. Securing microtraces

After homicides involving blunt, semi-sharp or sharp force trauma, transfers of microtraces of material from the object used can be expected at relevant areas.

The collection of microtraces from the injured persons can be carried out in different ways, with a distinction being made between the recovery of traces of material transferred to the surface and those adhering to damaged bones, etc. (Vermeij et al. 2012; De Wael et al. 2016; Palazzo et al. 2018; Weber et al. 2020).

Variant a) Obviously visible material traces are secured with forceps (e.g. splinters of paint, metal or glass).
Variant b) Material can be secured by tape-lifting from the corpse and relevant areas.
Variant c) Collection of evidence in the original state (e.g. dissected[34] or macerated[35] piece of bone).

If a potential crime tool is present in its original state, material samples should be taken from this tool for purposes of comparison.

[34] Bone has been freed from the epidermis.
[35] Bone has completely freed of soft tissue and dried.

8.2. The forensic microtrace examination

The examination material submitted, auxiliary traces (lifter tapes, *collection of evidence variant b*) or original marked evidence (e.g. bones, *collection of evidence variant c*), is examined for foreign microtraces adhering to it of potential relevance for the crime.

Cut and fracture edges on bone, cartilage and other tissues are of particular interest in original evidence samples and may exhibit microtraces[36] from the impacting object (Figure 78 and Figure 79) (Vermeij et al. 2012; Palazzo et al. 2018).

The foreign microtraces, individually separated microtraces (collection of evidence variant a, e.g. Figure 80) and potential crime tools then undergo a comparative examination. Fundamentally, the optical, physical and chemical properties examined represent class characteristics, with individuality increasing through the combination of different material microtraces. If the tool used for the crime is unknown, forensic examination of foreign microtraces can provide clues as to the tool used or the type of tool (Ryland et al. 2006; Vermeij et al. 2012; Palazzo et al. 2018).

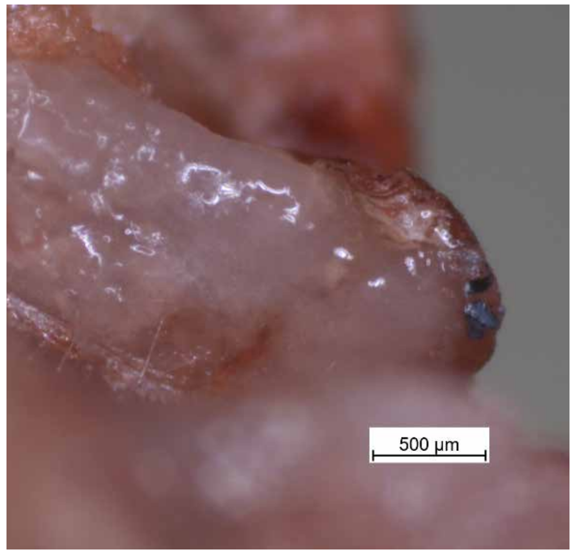


Figure 79:
Metal particles on the tissue in the fracture area of a dissected bone.
[Photo: LKA NRW]

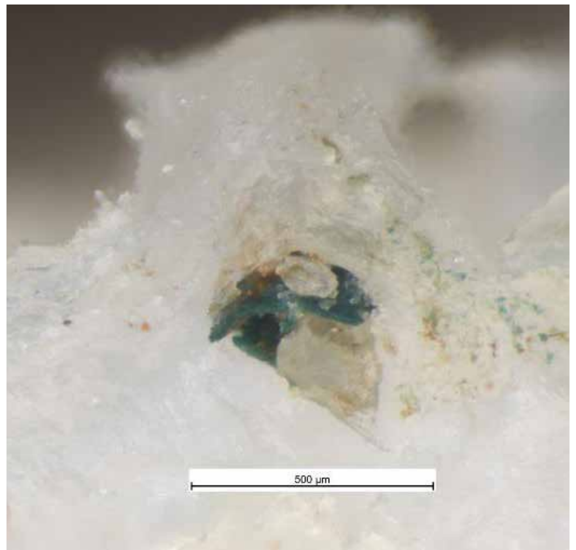


Figure 78:
Coloured paint particle and metal abrasion in the fracture area of a macerated bone.
[Photo: LKA NRW]

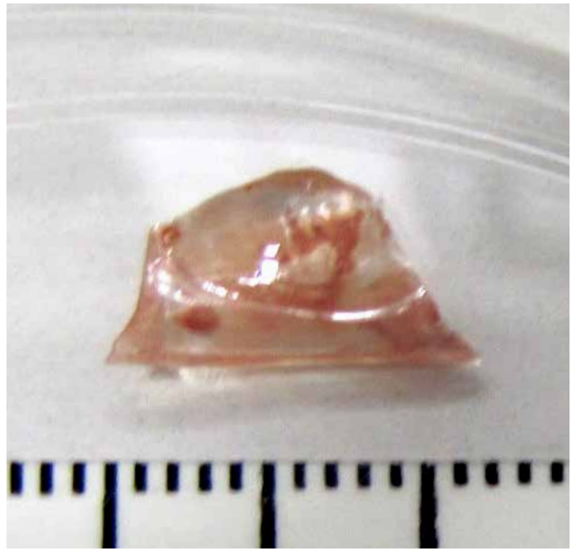


Figure 80:
Blood-contaminated glass fragment secured from the wound area of an injured person.
[Photo: LKA NRW]

[36] This means particle sizes in the microtrace range (< 1 mm).

8.3. summary

The forensic examination of microtraces on injured bone, cartilage or other tissue, on lifter tapes from corpses, or on separately secured microtraces from wounds can provide important information about the instrument used in the crime **and thus make a valuable contribution to clarifying the circumstances of the crime.**

Tool Axe · Type Hatchet · Dimensions Length approx. 345 mm
Type of crime Homicide; Blow against the Skullbone; complex skull fracture · Quality of the mark Insufficient quality

Tool Axe · Type Hatchet · Dimensions Length approx. 460 mm
Type of crime Homicide; Blow against the Skullbone · Quality of the mark Sufficient · Examination results Identification

9. GLOSSARY

Active surface
Area of the tool surface that comes into contact with the exhibit.

Bone
Bone is an especially hard form of the connective and supporting tissue. The bones form the skeleton.

Cartilage
Cartilage consists of specialized cells (chondrocytes) and extracellular matrix and is one of the connective and supporting tissues.

Cast
Impression of a surface taken with a casting compound.

Casting compound
Viscous material, often consisting of polyvinyl-siloxane, which, due to its reflective properties and low light transmission, is used as a brown, gray or black brown, gray or black mass to secure tool marks.

Class characteristics
General features such as size and geometry that allow the type of tool to be narrowed down to the exact model, but without being sufficient for identification alone.

Deformation, elastic
Deformation that completely recedes after the exertion of force ceases.

Deformation, plastic
Deformation that does not recede after the exertion of force ceases.

Grooves
Regular or irregular depression or mark on the surface caused by machining, e.g. grinding.

Identification
Clear and unambiguous assignment of an object as the source of a mark on the basis of matching individualizing features that are manifested both in the evidence mark and on the tool or its test mark.

Impression mark
Plastic deformation of the surface of the evidence usually caused by static content with the source of the mark.

Individual characteristics
Unique features that make the source of marks unambiguously distinguishable from all other objects.

Intercrystalline crack
Fissure in a metal that runs between the grains of the structure and is oriented to the grain boundaries.

Manufacturing feature
Individualizing features that are already created on the active surfaces of the source of the mark during production which make them distinguishable and can also be found in the marks. Examples of such features are grinding grooves and hardening cracks.

Nicks
Defect in a cutting edge.

Opacity
Impermeability to light.

Pattern evidence
Generic term for a mark produced on an exhibit, in which the pattern of the surface(s) of the source is manifested. Pattern evidence includes tool marks as well as shoe, tyre and glove prints and all other pattern marks.

Reflectance intensity
Intensity, here brightness, with which a surface reflects incident light. The reflectance intensity depends on the angle of the incident light.

Striations
Surface imperfections running in parallel, which represent linear depressions with a round or flat base.

Striation mark
Scoring in the exhibit caused by the source of the mark.

Source of mark
Tool or object that has produced a permanent change (mark) on the exhibit.

Test mark
Mark made with the tool used in the crime in a test material and used for comparison with the marks secured in evidence.

Test mark
Tool marks are marks created by tools on an exhibit in which the shape of pattern of the active surfaces of the tool is manifested. Tool marks are a subdivision of pattern evidence.

Test material
Substrate in which marks with the nature of those in the crime can be made with the tool under investigation. The test material exhibits similar properties to the original material in terms of mark generation.

Transcrystalline crack
Fissure in a metal that runs through the grains of the structure and is not oriented to the grain boundaries.

Usage feature
Individualizing features created by the use (in addition to the manufacturing features) on the active surfaces of the source of the mark. Frequently occurring usage features are scratches, deformations, chips and flakes.

Viscoelasticity
Viscoelastic behaviour describes spontaneous elastic material characteristics with an additional time-dependent plastic behaviour.

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11. FIGURES

12. APPENDIX

A: Recipe for agarose plates

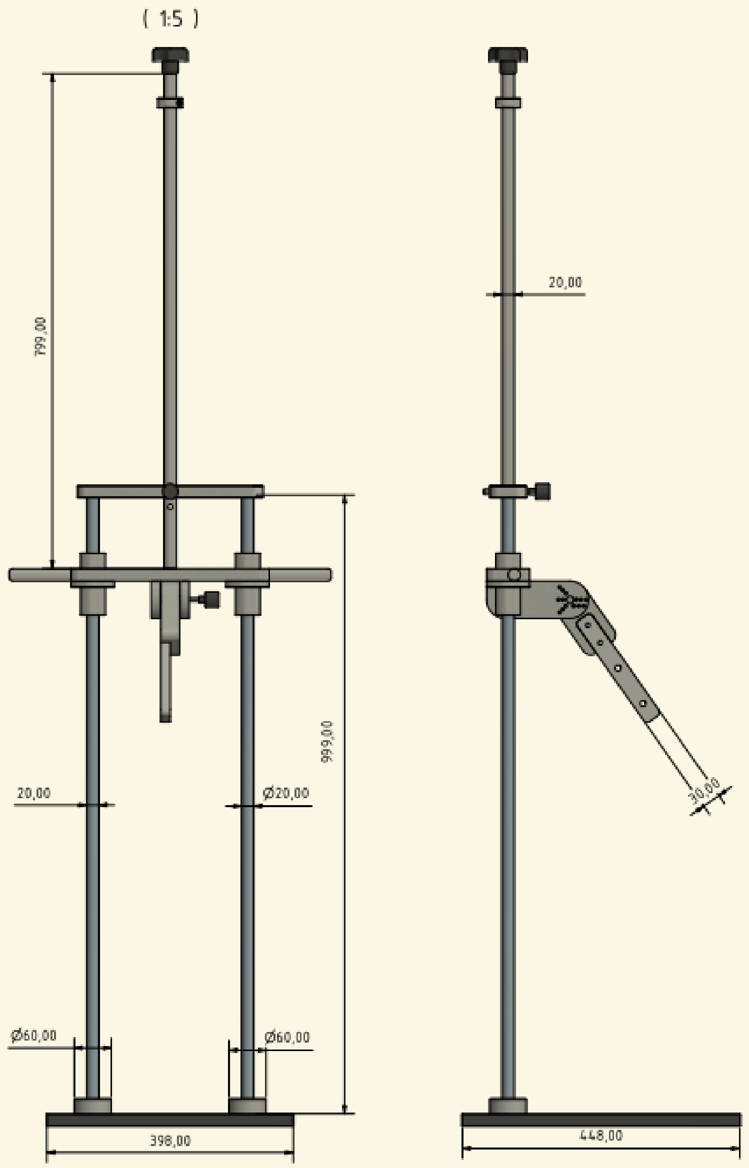
The following are required for approx. 600 ml of 7% agarose plates: 600 ml distilled water, 2.5 ml antifoam[37] (Medical Antifoam C Emulsion), 42 g agarose powder (Agarose Standard supplied by Roth).
Heat 600 ml of distilled water to approx. 90 °C. Then stir 2.5 ml of antifoam into the water (using a stirring bar). Slowly sprinkle in 42 g of agarose powder while stirring constantly with the stirring bar.
The material gradually thickens and may become lumpy. If the stirring bar no longer functions because of the increased viscosity, remove it and stir in the remaining agarose powder with an immersion blender. Continue using the immersion blender until an homogeneous mass has formed. Heat the agarose compound in a microwave and bring it to the boil. Stop the process as soon as the first signs of boiling occur and stir the compound with the immersion blender. Bring the compound to the boil again and then repeat the stirring with the immersion blender. Pour the finished mixture into a mould and leave it there for approx. 1 hour for cross-linking to reach completion and the compound to cool down. After cooling, the agarose is polymerized and firm with a clear appearance. Some inclusion of air bubbles in the material is unavoidable. Only if there are too many air inclusions, should you reduce the concentration of agarose as appropriate.

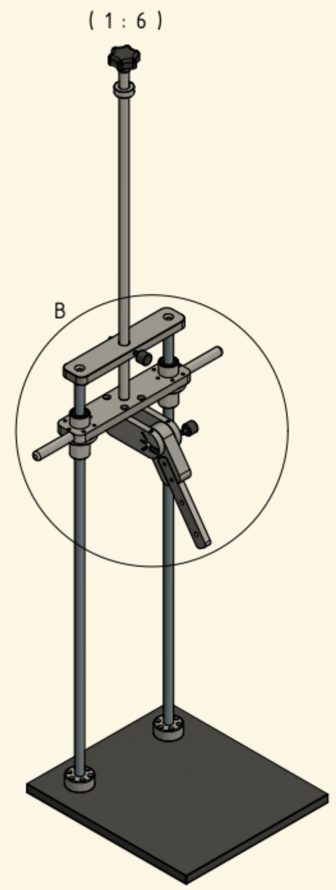
Note: Agarose plates dry relatively quickly (minutes - hours) in air and should be stored in foil (cool) in order to delay shrinkage. The plates cannot be frozen without damage occurring.

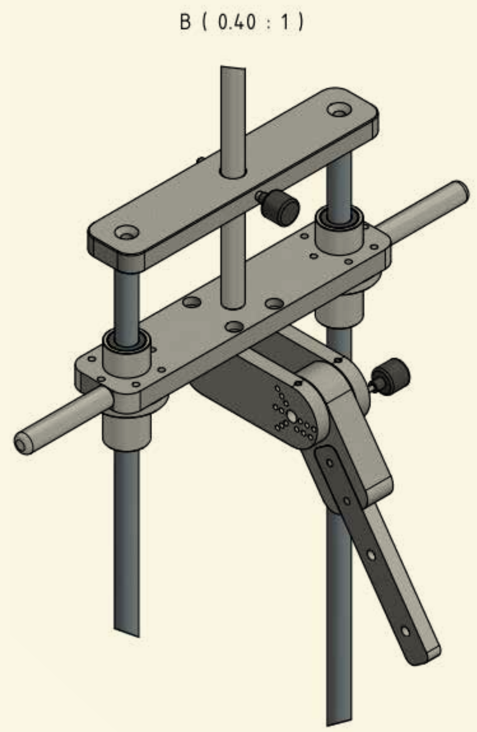
[37] Dow Corning® Medical Antifoam C

B: Design drawing of a stabbing/cutting device

Developed by Jürgen Geiermann, Development Workshop/Precision Engineering of the Institute of Biomechanics and Orthopaedics, German Sport University Cologne.







C: OP for "Casting"

Extracts from "Work Instruction for Methods (SOP): Production of silicone casts by means of AccuTrans® casting technique on cartilage and bone" of the Institute of Legal Medicine Cologne.

Introduction

Injuries to cartilage and bone tissue are not infrequently caused by the effect of a sharp or semi-sharp tool, e.g. in the context of wounds from stabbing and cutting or slahing by means of a knife, hatchet or hammer. Tools such as this exhibit individual features due to their manufacture or usage that may leave specific individual marks behind above all by penetrating the cartilage tissue so that an unambiguous assignment of the tool causing the injury can be made.

In cooperation with the department for tool marks and other pattern evidence of the State Criminal Police Office in North-Rhine/Westphalia (LKA NRW) in Düsseldorf, tool marks in cartilage following stabbing, cutting or slashing wounds are secured by means of AccuTrans® ICE casting compound in the Institute of Legal Medicine of the University Hospital Cologne. Together with the instrument of crime under discussion, these casts are then sent to the LKA NRW in Düsseldorf by the clerical staff of the police for comparative examination using mark examination techniques.

The procedure is particularly well suited to use on costal cartilage and all bones in the cortical bone area. It is almost impossible to take casts of of tool marks in the cancellous bone.

An impression of tool marks created by means of the AccuTrans® casting compound serves the purposes of permanent preservation, documentation and subsequent comparative examination of the instrument of crime under dispute using tool mark analysis in the LKA NRW in Düsseldorf. The aims of the examination are to eliminate or identify potential instruments of crime as the cause of the marks. In addition to this, if there is no suspected instrument of crime, the analysis is not least able to supply information on the tool used (type, shape and quality of the blade).

A tool can then be identified from a tool mark if the active surfaces of the tool exhibit individual attributes that uniquely characterize the tool and which can be unambiguously assigned to the specific pattern of the crime mark. These attributes occur both through certain production processes (grinding, tempering, sandblasting, etc.) and during usage (e.g. due to damage, scratches, flaking off of coatings, etc.). Consequently, brand-new tools can generate distinguishable marks. Owing to their optical properties, original marked exhibits (bone and cartilage) are unsuitable for direct comparative examination using light microscopy in tool mark analysis.

Properties and benefits of the AccuTrans® casting compound and AccuTrans® casts (marks)

- Casting material made of polyvinyl siloxane.
- Odourless material.
- No harmful ingredients (no irritants).
- No transfer of colour from the material to the exhibit.
- Tear-resistant, not sensitive to stretching, flexible material.
- Homogeneous mixing of the casting compound without any air inclusions due to application using a dispenser and mixing tips; elimination of mixing errors as no manual mixing of the casting compound is necessary.
- Short drying time of the casting compound.
- Fast, easy-to-manage application.
- Casts are possible without removal or retention of the marked evidence.
- Can be use on curved surfaces as well as flat, horizontal or vertical planes.
- Cartridges and mixing tips can be changed cleanly and quickly during the working procedure.
- he silicone can be lifted with practically no residue.
- Casting compound is available in various colours:
  - suitable: brown and dark grey casting compounds for light microscopy
  - suitable: black casting compounds for scanning
  - unsuitable: white and transparent casting compounds.
- Presentable casts without any change to the mark.
- No change in the pattern of the marks in cold conditions.
- High opacity and excellent legibility when illuminated from the side or when the mark is viewed under a stereo microscope (without unwanted light reflexes).
- High stability of the mark during storage.
- Possibility for mobile use: dispensing gun and accessories are compact, lightweight, unbreakable and stable.

Responsibility

Whether it is necessary to perform the casting is the decision of the first pathologist. Any decision as to whether it is meaningful to take castings in the case of bone marks should always take place on an individual basis (if appropriate in consultation with the police officer responsible for the case). In case of doubt, evidence should generally be secured by casting.

The corresponding post-mortem assistants are responsible for the casting being carried out properly.

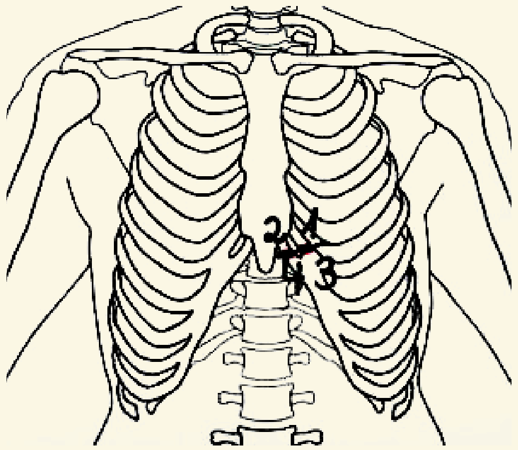
Responsibility for all AccuTrans® casts, including the administration and correspondence with clerical staff of the police, lies with the scientific assistant.

Execution

Casts from cartilage and bone, if appropriate, are taken after all other evidence such as molecular biological evidence, fibres and gunshot residues has been collected. It is recommended that areas bearing marks should separated during the post-mortem examination. Casts can also be taken from the affected section in situ if necessary.
Securing of tool marks should be conducted in a timely manner in order to avoid a deterioration of the mark due to storage. For practical purposes, casts are taken immediately after the post-mortem examination. If organizational reasons prevent this, the separated cartilage/bone tissue can be kept cool for the short term in a towel moistened with 0.9% NaCl solution. For longer-term storage, gauze soaked in 0.9% NaCl solution and aluminium foil on the outside should be used to wrap the tissue, which is then frozen at -20 °C. For subsequent casting the tissue is thawed at room temperature in a bath containing 0.9% NaCl solution.

Prior to preparing the casts

Notes should be taken on any conclusions drawn from the injuries relating to the orientation of the tool used in the crime within the body (position of the back or blade of the knife; angle of entry in relation to body axis, insertion direction, etc.). This is of relevance for LKA NRW when preparing optimum test marks and reduces the length of the investigation.
In addition, the relevant localizations of the stab wounds on the cartilage (or bone) should be drawn on a body diagram form as a legend and numbered (Fig. 1). The details of localization are required for the exact assignment of the casts to the corresponding cuts in the cartilage.



1.-6. Rib cranial; 2.-7. Rib cranial
3.-6. Rib distal; 4.-7. Rib distal

▲ **Fig. 1:**
Example of a body diagram including a legend referencing the localization of the mark.
[Photo: Institute of Legal Medicine Cologne]

Case No XX-xxxx Deceased: X.Y. Location 1 Cast 1/3	Case No XX-xxxx Deceased: X.Y. Location 1 Cast 2/3	Case No XX-xxxx Deceased: X.Y. Location 1 Cast 3/3	
Case No XX-xxxx Deceased: X.Y. Location 2 Cast 1/4	Case No XX-xxxx Deceased: X.Y. Location 2 Cast 2/4	Case No XX-xxxx Deceased: X.Y. Location 2 Cast 3/4	Case No XX-xxxx Deceased: X.Y. Location 2 Cast 4/4

▲ **Fig. 2:**
Information supplied on the adhesive label.
[Photo: Institute of Legal Medicine Cologne]

For this purpose, adhesive labels that allow a cast to be assigned exactly to a mark are affixed to the tickets (Fig. 2) , which in turn are attached to the casts. These tickets will be described in greater detail later. The adhesive labels bear the case number of our institute the initials of the deceased (First name, surname, X.Y), the localization (cast position as per legend) and the consecutive number of the AccuTrans® cast produced (see Fig. 2).
Maceration and bleaching can destroy the tool marks on cartilage and diminish the quality of the marks on bone. An especially careful maceration is therefore necessary. Bleaching with hydrogen peroxide must be avoided.

Producing the casts

A minimum of three casts are taken from each mark. The repeated casting carefully removes any tissue residues that may interfere with the mark.
At the start, any loose (tissue) matter adhering to the areas bearing the marks is removed and the incisions rinsed with 0.9% NaCl solution if necessary. Casts are then taken of the relevant mark. The casts are inspected visually. If the third cast exhibits any adhering tissue, further casts are made until a cast has been produced without any defects.
If there is no complete cut through the cartilage tissue but instead a notch, a cast should initially be taken before separating the cartilage tissue. Afterwards, the area bearing the marks is carefully separated. For this purpose, an incision can be made into the tissue from the side of the cartilage that has no notch. During this recovery process, the direction of incision should be at right angles to the direction of the mark to avoid any misleading marks. The incision made during recovery should be identified. The surfaces of the cut can now be cast – as described above – under visual control. Misleading marks should be avoided in this process. If a relevant area has obviously been impaired with the scalpel, the instrument used is sent to the LKA in the Quatropak so that a test mark can be produced there.

A total of at least three runs are performed for each mark:

- **Run 0:** If necessary: prior to separating the cartilage tissue (for notches, etc.)
- **Run 1-2:** Cleansing casts
- **Run 3:** Securing the mark
- **Run 4:** If necessary: repeat casting if any defects can be detected on the third cast.

The tool marks are secured with AccuTrans® ICE casting compound. It is especially designed for low temperatures and cures quickly (in less than 5 minutes at 0 °C). This means that the mixing tip has to be changed for every run. If visible air inclusions or other defects occur in relevant areas of the cast, a new cast of the mark must be made. All casts, even those containing defects, must be handed over to the investigation.
After the object has been prepared and the mixing tip has been affixed to the dispenser, the lever is pressed to automatically mix the two components in the correct ratio and the compound is applied to the target area of the mark. In areas that are difficult to access, it is advisable to attach thin application tips to the mixing tip, which can then penetrate deeper into the channel and thus allow the silicone compound to be applied with greater precision.
It should be noted that immediately after the casting compound has been applied (before the casting material has cured) a label (evidence card) with the localization details is affixed to the side of the casting material away from the mark. Generally, provided the label is affixed before the casting compound has set, it should adhere to the casting compound automatically. Finally, the cured cast together with the ticket can be detached from the area bearing the mark like a cap. As an alternative to the label the cast can also be packaged individually in a labelled parchment paper bag.
The evidence card/parchment paper bag bears a note of the localization in accordance with the legend on the previously prepared body pattern. If available, information on the orientation and direction of motion of the crime tool (position of back and blade of knife, direction of stabbing) can also be noted on the card or bag. If, after drying out, the cast does not remain stuck to the ticket, an area of the cast that does not bear any marks can be stapled to the ticket – if possible.

After preparing the casts

The casts are packed in envelopes that are sealed with a printed label. One envelope is taken for each localization, in which all associated casts are placed. The cartilaginous material separated from the corpse is placed in 4% formalin solution and, along with the other tissue samples removed during the post-mortem examination, stored in the institute and disposed of after expiry of the retention period unless the public prosecutor's office or the court has decreed otherwise. Bone material is not macerated.

Documentation

An overview photo should be prepared of all casts. The photos are stored in the photo archive in the respective section folder for the job number under a separate folder with the name "AccuTrans".
The tissues separated for casting during the post-mortem examination (generally rib cartilage) are entered in WinLims under "Exhibits" – "Laboratory area: Maceration – Material (e.g. rib cartilage)". The list of casting cases is held by the medical officer in charge.

Sample storage

The packaged casts are handed over in a container to the responsible medical office who then hands this over to the clerical staff of the police.

Required materials and order numbers

- Camera (documentation)
- Instruments (for preparation)
- Envelopes (one per localization)
- Brown paper bag (supplied by Brinkmann; one per body)
- Parchment paper bags (one per mark)
- Labels
- Notepad
- Ballpoint pen/pencil
- Magnifying glass (quality control)
- Ampoule of distilled water or 0.9% NaCl
- Towel (for keeping marks moist)
- Dispenser for Accutrans
- Accutrans brown ICE cartridge
- Mixing tips yellow
- Application tips (notches, incision channels)
- Quatropak with sleeve (for storing the tool from the crime scene)

Disruptive factors/Sources of error

- Defective impression on excessively moist or dry (incorrect/long storage) object.
- Premature removal of the cast from the object (in the case of casts of non-ICE cartridges).
- Maceration and bleaching (destroy the tool marks in cartilage).
- Reduced quality of marks on bone.

Tool Knife · Type Pocket Knife · Dimensions Length approx. 210 mm; Blade length approx. 85 mm; Max. blade width approx. 25 mm · Type of crime Homicide; Stab into the rib cage; severed costal cartilage Quality of the mark Sufficient Quality · Examination results Identification

Tool Knife · Type Kitchen Knife · Dimensions Length approx. 255 mm; Blade length approx. 130 mm; Max. blade width approx. ca. 35 mm · Type of crime Suicide; Stab into the rib cage; severed costal cartilage Quality of the mark Sufficient · Examination results Identification

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IMPRESSUM

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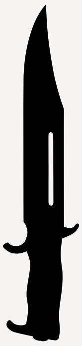

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