Analysis of the material removing mechanism for an automated chiselling approach

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ABSTRACT:
The European stone industry was exposed to great competition during the last years. However the European market is still the most important one for natural stone products. Especially traditional artistic processing techniques are very expensive due to the high personnel requirement. Thus automation becomes interesting for economic reasons. To process individually designed stone products it is planned to use a robot mounted tool.
One of the issues to achieve this goal is the analysis of the material removal to get repeatable results. We analysed different manual techniques used for sandstone surfaces in a first step and measured the movement of the chisel with a high speed camera system. We chose two techniques for further analysis and designed a first mechanical testbed to achieve repeatable kinetic energies. The material removal was analysed with the camera. Thus we are able to see the movement of the chisel and the flow of the removed material.
With this knowledge the analysis of relevant material and process properties will be shown as well. Furthermore, this paper discusses the relevant result parameters which define the optical quality of the surface. Combining these data it is possible to analyse the working parameters of an automated system which is able to process various sandstones with individual surface geometries.

KEYWORDS

Artistic Stone Production; Traditional Stone Processing Techniques; Analysis of Handcraft; Material Removal with chisel

INTRODUCTION

The European Stone market has the highest per capita consumption of stone products. However the European industry has seen bigger competition over the last years. High personnel costs drive companies to apply more automation to their processes. Especially the application of industrial robots with their flexibility and large workspace are promising for the stone industry. Yet surface finishing with traditional techniques is still mainly manually applied. They are physically demanding, require training and skills and the process is slow. Thus the personnel costs make large surfaces expensive. Other technologies are used to finish stone products or imitate traditional techniques such as milling [1] and waterjet-cutting [2], [3].
The approach to imitate traditional techniques with other tools has not the same optical quality then the original techniques. Therefore, an application to tasks such as restauration is not yet done. The approach of the research presented in this paper is to analyse traditional processing techniques and design a robot mounted tool based on these to produce surface qualities that are similar to original techniques. However, many parameters have to be estimated. There is a high amount of different techniques which developed in centuries. They differ in applied tools, tool handling, required skill of the mason and the applicability to different stones.

Different stones show different material behaviour for the techniques. Stone manufacturers usually use many different stones. Thus, the combination of techniques and stones changes often. The masons adapts to different stones both by experience and controlling his results visually. Sometimes masons make even trial hits to adjust to a stone. This is not possible in automated process. Therefore, it is necessary to analyse the material removal behaviour of traditional techniques to apply the right amount of hitting energy for each stone.
There are analyses of scratching tests for estimating the compressive strength [4], analysis of the brittleness of stones [5] or the application of Schmidt hammers which do not have a sharp tip [6]. But the combination of an energy impulse to a chisel tool and its material removal in a stone has not been analysed to our knowledge. In the literature only anthropological analysis of manual techniques can be found [7]. [4] shows furthermore that there is a ductile and a brittle mode of material removal in stones. Both modes can be seen in our results and will be further described.
In this paper we describe a first selection of analysed techniques (section 1), the description of the quality aspects of traditional stone surfaces (section 2), the design of a preliminary testbed and the analysis of the material removal mechanism (section 3) and the analysis of process parameters which are relevant for the process (section 4).

1. TRADITIONAL STONE PROCESSING TECHNIQUES

Traditional artistic stone processing techniques evolved over a long period of time. Thus many different techniques and patterns of techniques can be found especially on historic buildings but also in new applications. Masons use traditional elements to finish surfaces and create individual stone products. Furthermore, there are local deviations in some techniques and the combination with different natural stones results in a high amount of different techniques and variations for different materials.
Therefore, we did a preliminary selection of techniques, which were both promising to automation and economic usage. We chose four techniques which are tooling, aligned tooling, punching and bush hammering. All these techniques are typically applied to sandstone. Because of this all presented analysis are only made with sandstones. We will give a short description of the techniques, and explain how the tool interacts with the stone. A detailed analysis of the automation of these techniques can be found in [8].
We first analysed the manual techniques using a high speed camera system GOM Pontos HS Figure 1. With this System, we were able to analyse the movement of the tools and the velocity of the hammer right before the impact and thus estimate the kinetic energy applied to the tool for the different techniques.

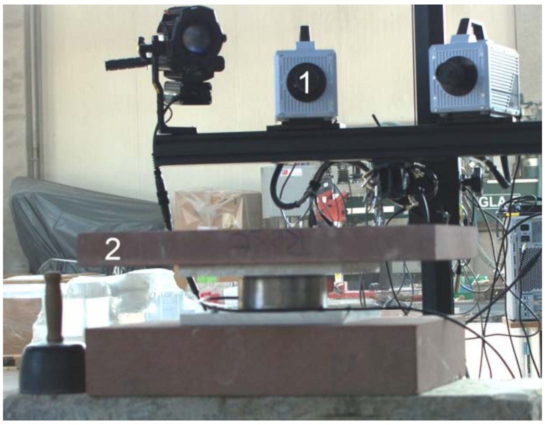

Figure 1: High speed camera system GOM Pontos HS (1) and stone specimen (2)

Tooling:

Tooling is a common technique for traditional surface processing. A drove chisel and a mallet are used for making a groove pattern. The breadth of the drove chisel can be up to 200 mm. The mason positions the chisel on the surface at an angle of about 45° and hits it with the mallet but gives the chisel a rotation that the chisel edge leaves the material after the hit. This results in rounded grooves which are characteristic for this technique (Figure 2). The automation of the movement is challenging but manageable. The material removal for the manual technique is in the ductile mode since only fine grain is removed from the stone. The estimated energy from the manual experiments was 19.46 J for a 76.2 mm chisel on *Röttbacher Sandstein.*

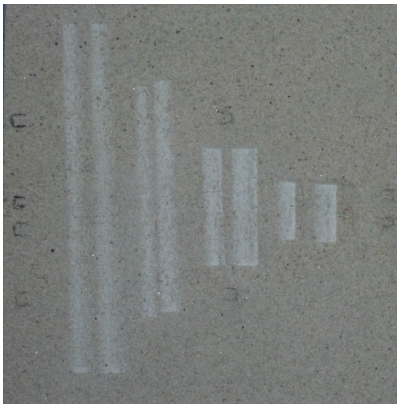

Figure 2: Examples of tooling (left four hits) and aligned tooling (right four hits)

Aligned tooling:

This technique is a variation of the normal tooling. The main difference is that the chisel does not leave the material after the hit. It moves down in a straight line with only little rotation of the chisel and results in triangular formed grooves (Figure 2). This variation is applied when there is not much space and the chisel cannot leave the stone. The material is removed in the ductile mode for small grooves. When the grooves are deeper it is also possible that chips start to break out of the edge of the groove. The removal of this technique will be shown in detail in section 3. The energy level is similar to normal tooling.

Punching:

The punching we analysed was performed with a hammer and a punch. There are different possibilities to apply this technique. One characteristic is if there is only one singular hit or if there are consecutive hits (Figure 3). The first is called point punching and the second is called line punching. Furthermore, regarding to the force applied to the punch one can distinguish between fine punching and rough punching. The energy was estimated with 23.99 J for rough punching.

When performing line punching the first chisel hit drives the punch in the material with a steep angle and the consecutive hits use a flatter angle and drive the punch sideways. Thus a line pattern is achieved. The material breaks out in rough chips in the brittle mode. Therefore, the predictability of the material removal is very low. Thus, consecutive hits are not possible to automate since the positioning of the chisel for the single hits is not manageable without scanning the results each time. This is not reasonable for economic reasons. Only point punching with one hit can be an option for automation since the chisel has to be positioned on the surface once and individual formed surfaces making use of the unpredictable material behaviour are acceptable in artistic stone processing.

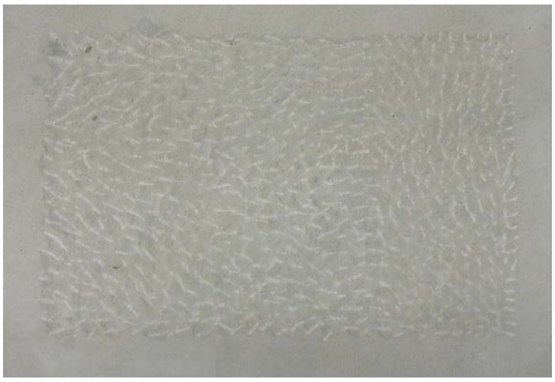

Figure 3: Line punching on a sandstone surface

<u>Bush hammering:</u>
The Bush hammering tool has a head with a pattern of tips. The number and size of these tips can vary. A number of 9 to 36 tips in a square pattern are normal sizes. The tool head can be mounted at a normal hand held hammer or to a pneumatic hammering tool. The movement is perpendicular to the stone surface. Since the kinetic energy is low compared to the other techniques (1.14 J) and there are a number of tips, the penetration of the stone is only shallow. The energy was estimated for a pneumatic tool. The surface is processed by moving over the surface and roughing it (Figure 4).

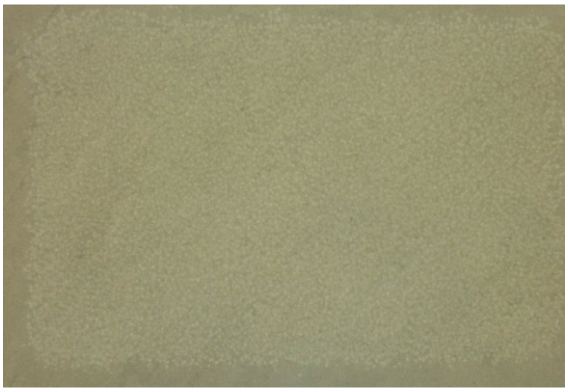

Figure 4: Bush hammered surface on sandstone

For the further automation we chose tooling since the results achieved on this way can be adapted to automate other techniques. However, for getting a general idea of the process of material removal, the simple movement of aligned tooling was analysed first to apply the results to regular tooling. In this paper the results regarding aligned tooling will be shown.

2. QUALITY ASPECTS OF TRADITIONAL STONE TECHNIQUES

The techniques described above are all used to produce decorative surfaces. They do not achieve any further technical function. Therefore, the optical appearance is the main criteria a surface is assessed with. As described above we first analysed tooling and aligned tooling in the project. The main characteristics of a aligned tooling groove are the width, the breadth and the depth. The breadth of the groove is the same as the chisel breadth. The depth and the width are both defined by the material behaviour, the applied energy, the angle of the chisel edge and the angle the tool is set on the surface.

However, the visual appearance is most defined by the width and the breadth since the depth is not so easy to estimate for the human eye. Only large differences can be directly be seen in the depth, where changes in the width are much more visible. Furthermore, the changes can be easier estimated than the absolute value of the width. Thus, the repeatability of results is more interesting than absolute precision.
As described above in aligned tooling at distinct depth there is a transition from ductile to brittle mode in the material removal. When the brittle mode appears larger chips break out of the edge of a tooled groove. This behaviour is a problem when surfaces with a close groove patter should be processed. For other surfaces the mason or designer has to decide whether this is desired optical effect or not.
Another possible defect in surface processing appearing in automated processing is an oblique groove (Figure 5). In the manual process the mason adjusts the chisel edge with the feeling of his hand to the stone surface. An imitation of this behaviour with a force torque sensor would be very expensive. Furthermore, the stones used in this process are previously milled. But there can be variations from the planned part and the resulting product. Therefore the robot path planning is programmed on scanned mesh files of the stone. Furthermore, a previously developed approach for measuring the position of the stone product is applied in the project [9].

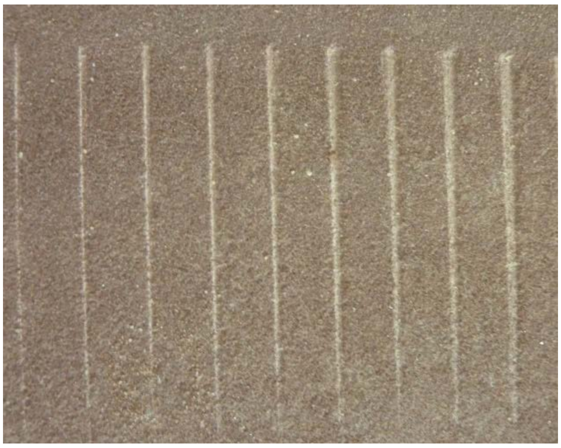

Figure 5: Oblique chisel grooves resulting from misalignment of chisel and stone surface

3. DESIGN OF PERLIMINARY TESTBED AND VIDEO ANALYSIS OF MATERIAL REMOVAL

When performing the manual experiments, we realised that the different hits of the masons had different energy levels and also the starting angle of the chisel may vary. But for an efficient design of experiments a higher repeatability and a precise adjustable angle of the tool is required. Since the robot mounted tool was designed parallel to the first experiments we designed a simple mechanical mechanism (Figure 6). Two springs can be compressed to a distinct level and a sledge with a hammer plate can be released with a pneumatic cylinder. The mechanism is robot mounted and can thus be positioned and oriented on the surface for different experiments. By knowing the mass of the sledge and its velocity we know the kinetic energy applied to the chisel. The velocity in respect to the spring compression was calibrated with the GOM camera system. Thus, effects like friction of the bearings are accounted for.
To get an idea of the material behaviour in the stone we positioned the chisel on the edge of the stone and filmed the process of hitting the chisel with the high speed camera. We measured aligned tooling with an angle of 45°. In the left part of Figure 6 is a picture of the chisel in the material. One can see that the materiel is removed in a stream of grain in the ductile mode. When

the chisel reaches a certain depth the edge of the groove start to break out and the removal or the material changes to the brittle mode.

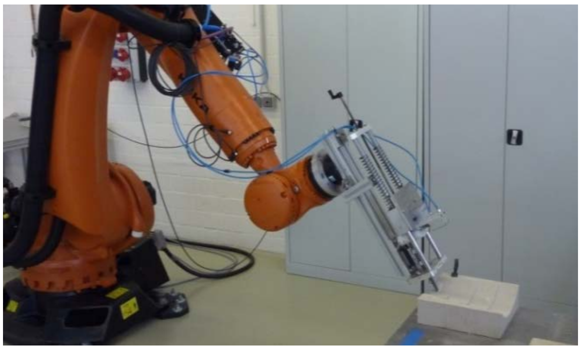

Figure 6: Test mechanism for repeatable hitting energy mounted on a robot for positioning

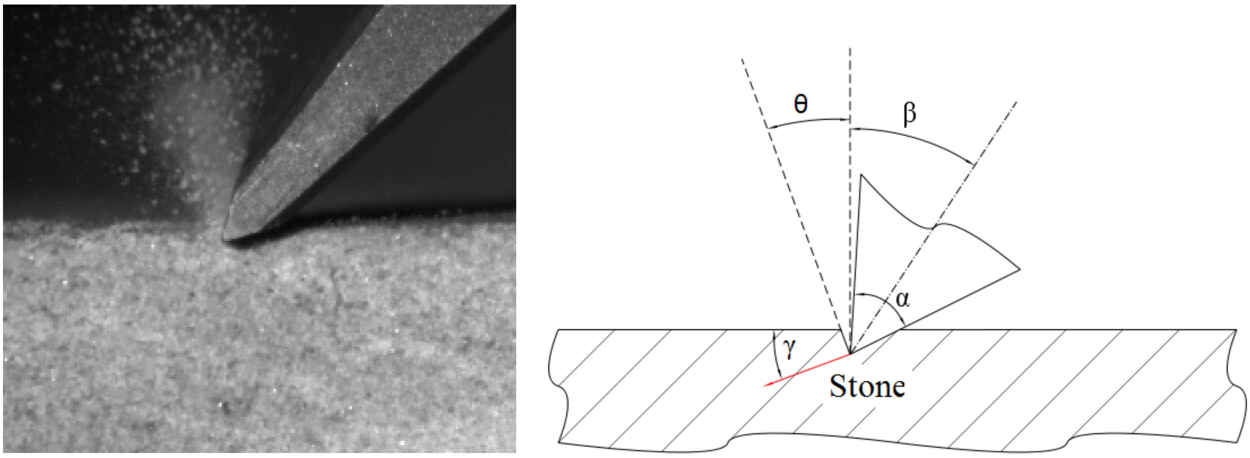

Figure 7: Highspeed camera picture of the chisel in stone (left) and relevant angles of tooling (right)

The geometric parameters that can be altered are the angle of the chisel edge α and the angle of the tool in respect to the surface β. This results in the angle

$$\gamma = 180\,° - \beta - \frac{\alpha}{2} \tag{1}$$

of the groove in the material. The material is removed through a channel in front of the chisel. This channel results in the angle *θ*. This seems to be a material specific value, but has not yet been analysed in detail. The first analysed values are the depth *d* and the width *b* of the groove which are shown in Figure 7. Resulting from this is also the Volume *V* of the removed material with

$$\mathrm{V} = \mathrm{l}\frac{\mathrm{bd}}{2} \tag{2}$$

with *l* the breadth of the chisel. These values were further analysed and the results are shown in the next section.

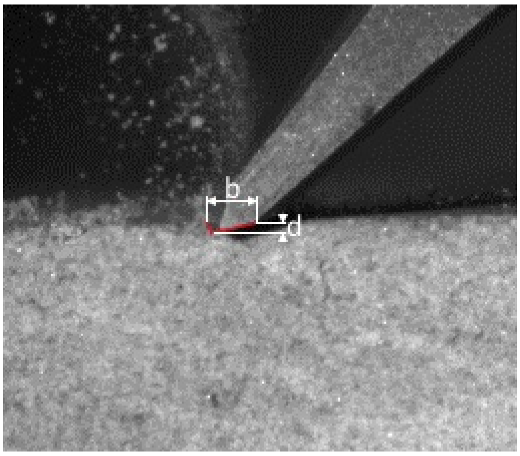

Figure 8: Depth *d* and width *b* of a chisel groove

4. RELEVANT PROCESS PARAMETERS OF THE TECHNIQUES

To analyse the relevant parameters of the process in respect to their results we performed two different experiment series. The tools which were used had a breadth of l = 25.4 mm and an angle of α = 62.5°. The other chisel had a breadth l = 50.8 mm and an angle of α = 64°. The angle β was chosen with 45° according to the manual technique. For each tool a test series with ten different kinetic energy levels was done. For each level three punches were performed.
For the tests a set of different sandstones were used. The data of the different sandstones we used for the experiments presented in this publications are given in Table 1. The compressive strengths reach from 49.5 MPa to 100.4 MPa so the experiment behaviour in respect to the compressive strength can be analysed. All experiment series were performed on each stone.

Table 1: Material data for the analysed stone types

Stone Type	Compressive Strength [MPa]	Porosity [%]	Mean grain size [mm]
Leistädter Sandstein	49,5	19,8	0,1 – 0,3
Steigerwald Quarzit	96,8	12,2	0,2 – 0,3
Neckartäler Hartsandstein	100,4	14,6	< 0,3
Udelfanger Schilfsandstein	55	Not available	Not available
Sander Schilfsandstein	57.3	18.1	0.18 – 0.3
Mainsandstein weiß grau	78.3	15.5	0.2 – 0.6

In Figure 8 the results of the chisel with l = 25.4 mm and α = 62.5° can be seen on *Mainsandstein weiß grau*. One can see that beginning at the third series of hits the breakout of bigger chips starts to emerge. The grooves of the single experiments were measured with a coordinate measurement machine (Wenzel LH 54). We measured each groove with 3 different measurement lanes. Figure 9 shows an example of a measured groove. There are differences in the single lanes. Thus, a mean value was reckoned for all single hits.

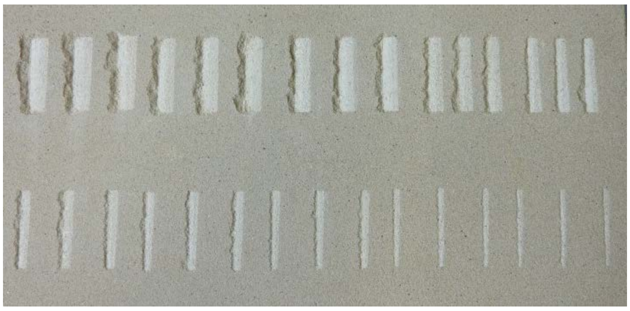

Figure 9: Resulting grooves Mainsandstein weiß grau with *l* = 25.4 mm, *α* = 62.5° and *β* = 45°

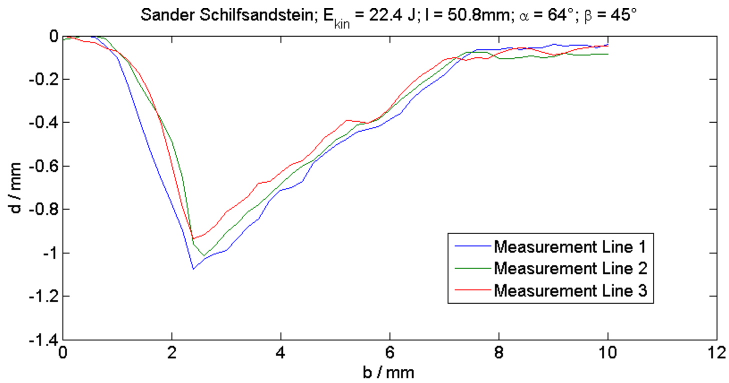

Figure 10: Three measuring curves of a groove

One can see that the relevant process data cannot be directly extracted from these measurements. Therefore, the curves were flattened. First the values of the surface were corrected to a mean value. When the depth value falls under a certain value the edge of the groove is detected. The threshold value depends on the stone since the pore size is different for the stones. However, the error of this flattening is small compared to the overall depth.

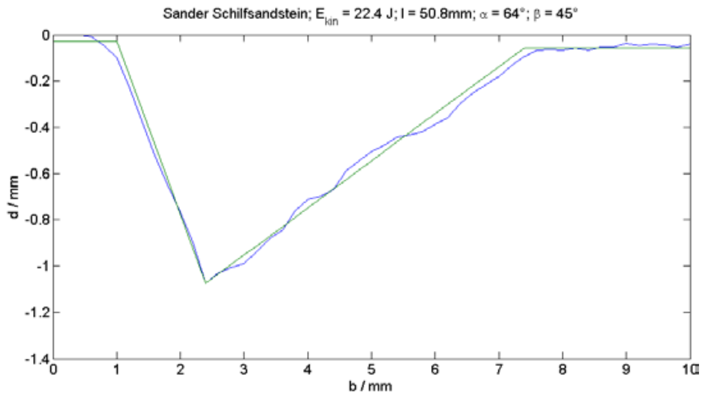

Figure 11: Comparison of original measured curve and flattened curve

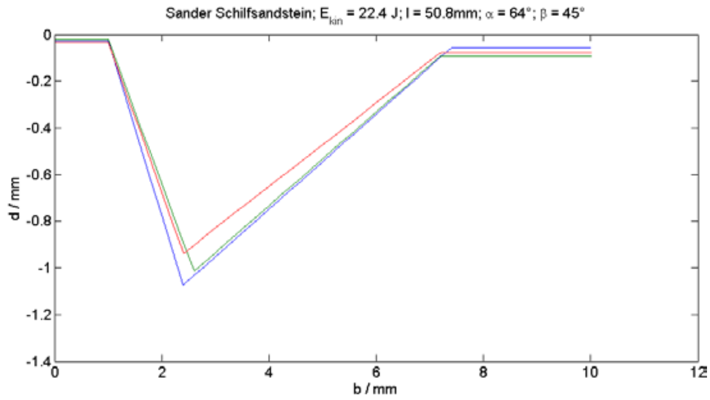

Figure 12: Flattened curves of Figure 9

From these curves the values of *d* and *b* were extracted. The depth *d* was reckoned from the deepest value to the mean value of both surface ends. Each single stroke was combined to mean value. It has to be noted that not all the values could be extracted since in the brittle mode in some experiments too much of the edge broke out and the original size of the groove could not be measured. When it was possible the size of the groove was also estimated in the brittle mode. Figure 12 to Figure 14 show the values of *d, b* and *V* in respect to E_{kin} of the chisel hit.

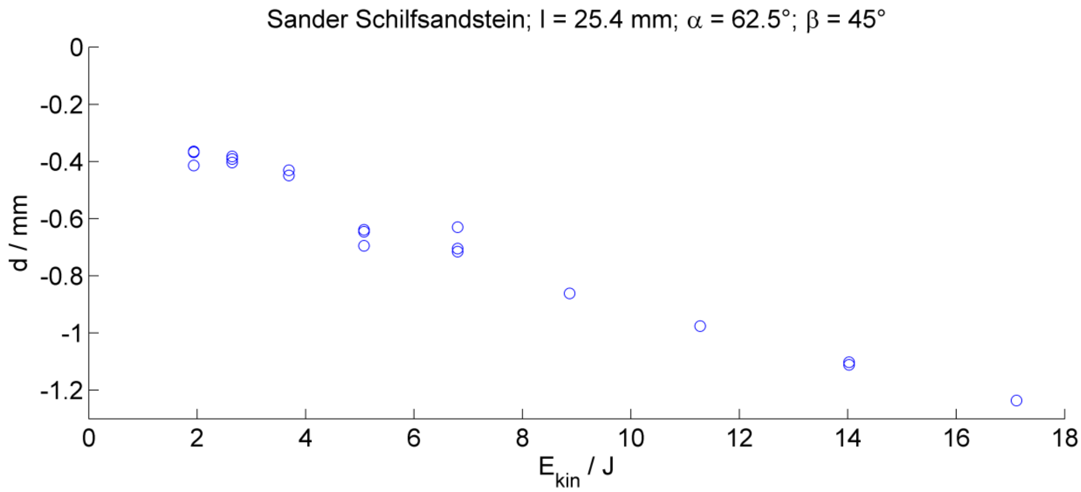

Figure 13: Values of *d* over the E_{kin}

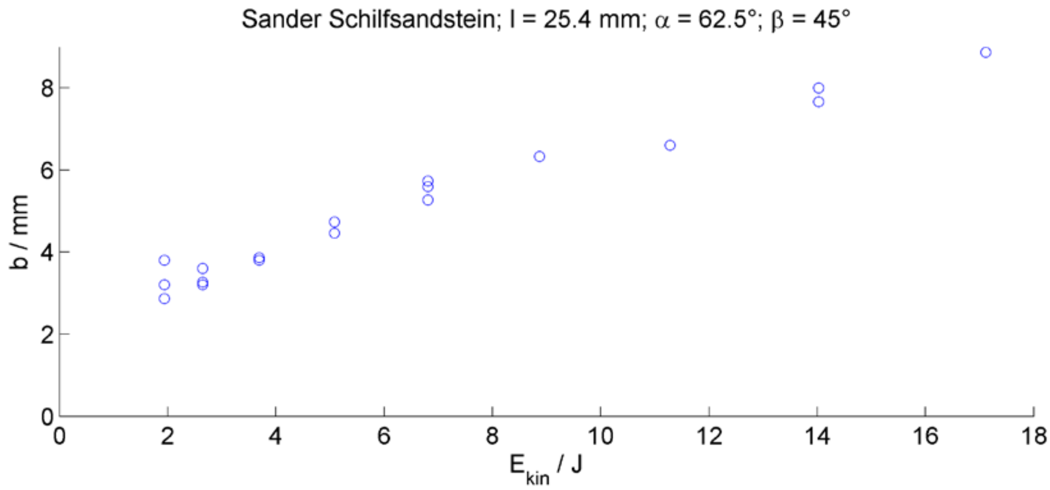

Figure 14: Values of *b* over the E_{kin}

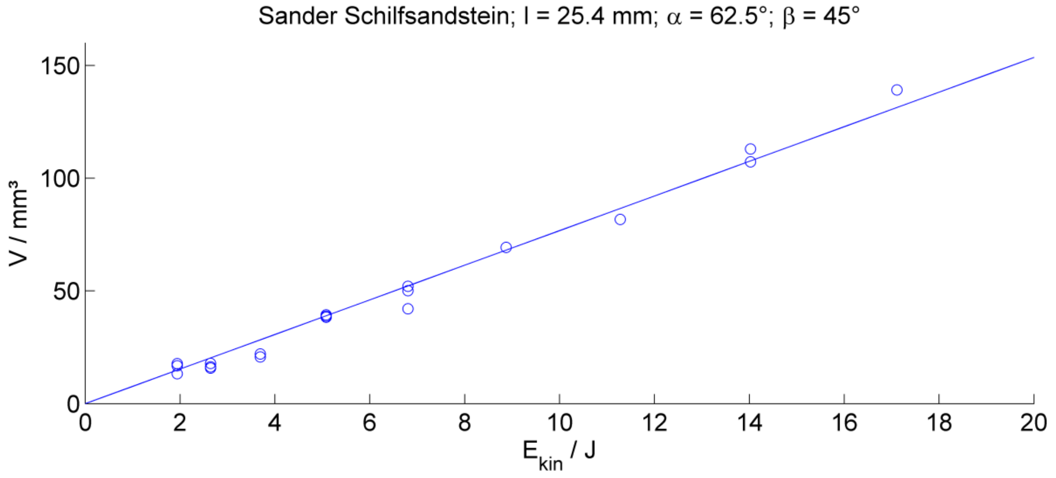

Figure 15: Values of *V* over the E_{kin}

Figure 14 shows that there is a linear correlation between the Volume of removed stone *V* and the kinetic energy E_{kin} applied to the chisel. The inverse gradient can be given as the specific kinetic energy necessary for removing material. Table 2 shows this value for each experiment series. One can see that the values differ from the compressive strength of the stone and are higher than that value. This is because the friction of the chisel in the stone could not be measured directly and some of the kinetic energy dissipates during the hit. Also one can notice that the values for the large chisel are all higher than the values for the small chisel. The reason for this is not yet estimated. The values for *Neckartäler Sandstein* are much higher compared to the other values. For chiselling of stones also the ductility of stones has an effect. Thus, not only the compressive strength is a relevant parameter. The relevant stone properties have further to be investigated.

Table 2: Analysed Material Values for different stones and chisel experiments

Stone Type	Compressive Strength [MPa]	Intrinsic energy measured with α =45° β= 62.5° and l=25.4 mm [MPA]	Intrinsic energy measured with α =45° β= 64° and l=50.8 mm [MPA]
Leistädter Sandstein	49.5	157.9	192.2
Steigerwald Quarzit	96.8	258.1	375.5
Neckartäler Hartsandstein	100.4	696.4	722.3
Udelfanger Schilfsandstein	55	145.0	199.3
Sander Schilfsandstein	57.3	129.6	170.5
Mainsandstein weiß grau	78.3	261.7	385.1

5. CONCLUSION

We presented different traditional stone processing techniques. We build a preliminary testbed to apply repeatable energy levels to a chisel and analysed the material removal for a selected technique with a highspeed camera. Furthermore, the correlation of applied kinetic energy and the Volume of the removed material was analysed and a material parameter for the different kind of stones and chisels estimated. However, it differs for the different chisel sizes and the values are not directly comparable to the compressive strength.

There is yet no analysis of energy dissipation during the hit and friction of the chisel in the material. All these parameters are still part in the material value. Therefore, the transferability of the results

to other mechanisms has to be analysed. Also the material properties besides the compressive strength like the ductility of stones can be further investigated. Furthermore, the influence of the angle β should be analysed. The angle θ can also be further detailed but is at the moment not considered relevant to the process.
The next step will be the analysis of a mechanism which allows the imitation or the regular tooling. The implementation of an automated tool will furthermore allow performing more experiments in a shorter time.

6. ACKNOWLEDGEMENT

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