Although there is a broad range of alternative construction materials, natural stone is still preferred by architects, construction engineers and end users for floors, staircases and pavements or the sheathing of facades. Due to their excellent technical and aesthetic properties, the demand for high quality construction and decoration material made of natural stone is constantly increasing. Since 1986, the global production has increased by over 300%. Up to 2025, the production is expected to increase by 7.7% each year. Consequently in 2025, the global production of raw material will amount to 300 million tons compared to 80 million tons in 2005. Furthermore, it is expected that the demand for end products of natural stone will increase by 100% up to 2015 and by 400% up to 2025. Presently, alone in Europe goods of a value of 20 billion Euro are produced each year by 60,000 companies with about 500,000 employees (eg, Paspallaris, 2005). Besides the mining and preparation of blocks within the quarries, the machining of slabs and tiles is a major factor within the process chain. These slabs and tiles are usually...

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Process and tool design for high speed cutting of granite

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IN THIS PAPER IT WILL BE DEMONSTRATED THAT THE WIDTH OF CUTTING DISKS USED FOR THE PRODUCTION OF SLABS CAN BE REDUCED CONSIDERABLY BY MEANS OF A SYSTEMATIC TOOL DESIGN AND ADJUSTED PROCESS PARAMETERS. THIS RESULTS IN BOTH ECONOMICAL AND ECOLOGICAL ADVANTAGES.
The stone sawing machine used to conduct the experiments described in the report.

machine by means of multi-blade disk saws. The abrasive cut-off disks used within this process feature diamond cutting segments. A major disadvantage of this technology is the high rate of work piece material removed, which especially applies for thin slabs. Depending on the slab width, the removal volume (i.e. ratio of the removed material and the slab volume) amounts to over 60% (Figure 1). Besides the waste of raw material, the high removal rate causes high tool and energy costs. Therefore it is reasonable to reduce the material rate removed by a considerable reduction in the kerf width, both from the ecologic and the economic point of view (e.g. Glatzel, 2004). This can be achieved by the development of new tools which enable the machining of adequate kerfs by a reduced tool width.

Still, an adequate slab quality has to be maintained as decisive deviations in the slab width increase the costs for the following treatment. Thus, the use of thinner abrasive cut-off disks would become uneconomical due to an inprocess deflection of the tool within both the horizontal and vertical direction. The aim of the process and tool design described in the following is to reduce the removal volume in the natural stone production by a reduction in the steel blade and segment width. The resulting reduction in the tool rigidity is to be compensated by higher rotation per minute values of the saw blade, i.e. higher cutting speeds. For a
Figure 1. Potential of a tool width reduction in the cut-off grinding of granite.

Figure 2. Influence of the cutting speed on the tool deflection for different base body geometries.

tool data:
- $E = 210000 \text{ N/mm}^2$
- $v = 0.3$
- isotropic material
- $d_b = 1000 \text{ mm}$
- $d_f = 335 \text{ mm}$
- $W_d = 2.7 - 5 \text{ mm}$

FEM simulation:
- software: ANSYS WB
- $F_B = 50 \text{ N}$
- $v_C = 0 - 80 \text{ m/s}$
- rigid restraint
- at flange
- no tensioning
systematic tool design, FE simulations will be carried out with different geometries of the base body. Furthermore, the relationship between the cutting speed and the deflection of the steel blades will be examined during these simulations. The limiting factors on the maximum cutting speed will be determined by machining experiments. For the examination of the process design, an apparatus has been developed which delivers the cooling water tangentially into the kerf with cutting speed. The effects on the process forces and the tool wear will be analysed.

1. TOOL DEVELOPMENT
1.1 Steel core geometry
FE simulations for the calculation of the deflection due to an axial force will be carried out starting from a standard base body with a diameter of \( d_1 = 1000 \text{ mm} \) and a width of \( w_0 = 5 \text{ mm} \). The dimensions will be varied throughout the different simulations. Additionally, conical base bodies will be used, which are usually applied in the machining of wood. The results are presented in Figure 2.

As expected, the reduction in the tool width leads to a higher deflection at a given axial force \( F_a \). With a thinner, conical steel blade of \( w_0 = 3.0 - 3.3 \text{ mm} \), the deflection in the static state at an axial force \( F_a = 50 \text{ N} \) is only slightly higher (\( \Delta w = 0.25 \text{ mm} \)) than it is with a parallel blade of \( w_0 = 3.5 \text{ mm} \).

The advantage of the conical blade is that the width of the cutting segments can be decreased considerably. The comparison of a conical blade and a parallel blade of \( w_0 = 3.0 \text{ mm} \) for identical segment widths shows that the deflection can be reduced by \( \Delta w = 0.5 \text{ mm} \) when using a conical shape in the static state.

Besides the width and the geometry of the tool the cutting speed has a significant influence on the deflection of the steel blade. The tool rigidity increases considerably at a high rotational speed. If the cutting speed of a conical blade (\( v_c = 3.0 - 3.3 \text{ mm} \)) is increased from \( v_c = 30 \text{ m/s} \) (which is the standard value for conventional processes) to \( v_c = 50 \text{ m/s} \), the deflection is reduced by \( \Delta w = 0.4 \text{ mm} \). If the cutting speed is set at \( v_c = 80 \text{ m/s} \), the deflection is below one millimetre and the required slab quality is assured for an axial force of \( F_a = 50 \text{ N} \). What can be deducted from these examinations is the fact that the reduced rigidity of the conical base body prototypes can partly be compensated by higher cutting speeds. Still, with respect to the market requirements on the quality of natural stone raw products, the dimensions of these base bodies have to be adjusted to realistic machining parameters (compare Figure 2). This is why for further examinations a base body with a core thickness of \( w_0 = 3 - 3.3 \text{ mm} \) is chosen.

1.2 Design of the cutting segments
Two factors are decisive in the design of diamond cutting segments. Besides a low tool wear and a resulting long tool life, low grinding forces are important for the process results, especially if thin steel blades are applied. Therefore, it is important to adjust the combination of bonding and diamond abrasives to the workpiece material and the respective process. Recent developments concern the substitution of cobalt by alternative materials which comply with the requirements of high speed machining regarding grain adhesion and
wear resistance. In this case, it is important to guarantee the self-sharpening of the tool. If the cutting speed is increased while the other parameters are kept constant, the bonding is not as strongly displaced as required and an increased amount of diamonds is flattened due to the decreasing single grain chip thickness $h_{c}$. At the same time, the grain protrusion decreases and the tool becomes tarnished. As a consequence, the process forces increase considerably, the cutting quality decreases and a higher drive power is required.

The new bonding type used for the cutting segments is based on a pre-alloyed bonding powder of the type MX 2480 with a reduced cobalt content of only 20%. This powder is cost-saving compared to other bonding powders, can be applied at lower sintering temperatures and provides a higher grain protrusion due to a better grain adhesion.

The new cutting segments are arranged in a sandwich structure, which offers another opportunity to enhance the axial guidance of the saw blades during the machining process. For the tools used in the investigations, different bond hardnesses and diamond concentrations C were applied for the segment flanks and the segment core (Figure 3). This structure is to ensure that the tool wear is higher on the segment core than on the segment flanks. Thus, a kerf-like cavity is produced in the middle of the cutting film.
Figure 3. Different base body geometries (left) and wear structure of conventional and sandwich cutting segments (right).

parallel steel core with standard segment geometry

- Flange
- \( w_3 \) at outer rim: 3.0 mm
- \( w_3 \) at flange: 3.0 mm
- \( w_4 \) at bottom of segment: 4.0 mm
- \( w_5 \) at top of segment: 5.0 mm
- Consistent diamond concentration
- Uniform wear behaviour

conical steel core

- Flange
- \( w_3 \) at outer rim: 3.0 mm
- \( w_3 \) at flange: 3.3 mm
- \( w_4 \) at bottom of segment: 3.8 mm
- \( w_5 \) at top of segment: 4.2 mm

Figure 4. Comparison of the tool data of a conventional cutting disk and the advanced conical cutting disk.

standard cutting disk

- \( h_1 = 20 \) mm
- Tooth height: 70 segments, \( D = 1000 \) mm

<table>
<thead>
<tr>
<th>tool specification:</th>
</tr>
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<tbody>
<tr>
<td>core: steel 75Cr1, tension 90°</td>
</tr>
<tr>
<td>tooth geometry: ( h_1 = 20 ) mm, ( l_1 = 24 ) mm</td>
</tr>
<tr>
<td>bond: standard cobalt bond</td>
</tr>
<tr>
<td>abrasives: MBS 950, 30/40,40/50 Mesh</td>
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<tr>
<td>concentration: C25</td>
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</table>

<table>
<thead>
<tr>
<th>cutting parameter:</th>
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<tbody>
<tr>
<td>cutting speed: ( v_c = 32 ) m/s</td>
</tr>
<tr>
<td>feed rate: ( v_f = 4 ) m/min</td>
</tr>
<tr>
<td>cutting depth: ( a_d = 10 ) mm</td>
</tr>
<tr>
<td>removal rate: ( Q_w = 400 ) cm²/min</td>
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</tbody>
</table>

advanced conical cutting disk

- \( h_1 = 10 \) mm
- Tooth height: 70 segments, \( D = 1000 \) mm

<table>
<thead>
<tr>
<th>tool specification:</th>
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<tbody>
<tr>
<td>core: steel 74NiCr2, tension 100°</td>
</tr>
<tr>
<td>tooth geometry: ( h_1 = 10 ) mm, ( l_1 = 24 ) mm</td>
</tr>
<tr>
<td>bond: prealloyed MX 2480</td>
</tr>
<tr>
<td>abrasives: MBS 960, 30/40,40/50 Mesh</td>
</tr>
<tr>
<td>concentration: C25</td>
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<table>
<thead>
<tr>
<th>cutting parameter:</th>
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</thead>
<tbody>
<tr>
<td>cutting speed: ( v_c = 50 - 60 ) m/s</td>
</tr>
<tr>
<td>feed rate: ( v_f = 13 ) m/min</td>
</tr>
<tr>
<td>cutting depth: ( a_d = 4 ) mm</td>
</tr>
<tr>
<td>removal rate: ( Q_w = 520 ) cm²/min</td>
</tr>
</tbody>
</table>
Figure 5. Process forces for the conventional cut-off grinding process and the newly developed process with different coolant supply strategies.

Figure 6. Tool life for the conventional cut-off grinding process and the newly developed process with different coolant supply strategies.
The newly developed tools proved the possibility of attaining the requested cutting quality with a considerably reduced steel blade width.

which provides guidance for the segment within the kerf. The depth of the cavity relating to the segment flanks should be between 0.2 mm minimum and 0.8 mm maximum (e.g. Glatzel, 2004).

Figure 4 summarizes the specifications of the newly developed, conical cut-off grinding wheel for the machining of granite. The additional depiction of the data of a conventional cutting disk allows the comparison between the standard cut-off grinding process and the newly designed process.

2. CUTTING EXPERIMENTS WITH CONICAL TOOLS AND A NEW WATER SUPPLY

The process suitability of the newly developed conical saw blade has been examined in cutting experiments. According to a fundamental process design with different cutting parameters, a newly developed tangential water supply has been applied. The results of the experiments are presented in the following: "Rosa Sardo", a class 3 granite, was used as body material. During the experiments, the process forces and the radial wear of the tool have been determined. Afterwards, the cutting quality has been evaluated by measuring the slab and the kerf widths.

2.1 Process forces

The objective of the process design for the high speed machining of granite with thin tools is a reduction in the machining forces.

Reduced process forces lead to a decreased tool deflection due to a reduced bending moment. This can be achieved by a lower contact length between tool and work piece, which especially decreases the process forces in the normal direction. Still, it has to be mentioned that this principle is opposed to the subgoal of increasing the cutting rate for a reduced processing time and a higher efficiency of the process.

The usual field of conventional processes of \( \alpha_s = 10 \text{ mm} \) was reduced to a cutting depth of \( \alpha_s = 4 \text{ mm} \). At the same time, the feed rate was increased from the usual \( v_n = 4 \text{ m/min} \) to \( v_n = 13 \text{ m/min} \). This leads to an area cut per time unit of \( Q_{\nu} = 520 \text{ cm}^2/\text{min} \), exceeding the usual value of \( Q_{\nu} = 400 \text{ cm}^2/\text{min} \) by 30%. The process forces for a normalised segment width of one millimetre are presented in Figure 5. The process forces were considerably lower than those used in conventional processes with a standard tool. This is mainly due to the reduced contact length. The new water supply strategy has only a minor influence on the forces, as shown in Figure 5. An analysis of the absolute figures of the normal process forces (which are not presented in Figure 5) shows that the absolute force level decreases from \( F_{\text{max,cov}} = 1400 \text{ N} \) to about \( F_{\text{max,cov}} = 400 \text{ N} \).

2.2 Tool wear

A considerable influence of the coolant supply strategy on the macroscopic wear can be observed (Figure 6). For each supply strategy
the radial wear of the segments has been evaluated. The tool cut area presented is the average of five measurements and refers to a segment height $h_s = 10$ mm.

While the cut area is about $A_{wt} = 88$ m$^2$ with a conventional water fork and a cooling supply to the side of the blade core, it can be increased considerably by use of a tangential supply. If the water is supplied at cutting speed ($v_w = v_c$), the cut area is about $A_{wt} = 112$ m$^2$, which exceeds the cut area achieved with a conventional water fork by 25%. The fact that the cut area is reduced by $\Delta A_{wt} = 12$ m$^2$ compared to the value achieved with a conventional tool is due to the cutting rate, which is increased by 30%.

2.3 Cutting quality
For an adequate industrial use of the newly developed tools, the maximum cutting deviation and slab quality is decisive. The cutting deviation should be within the valid quality requirements for a cutting length of $L = 1$ m and a total depth of cut of $t_{cut} = 300$ mm, i.e. below $w_p = 1$ mm.

The results of the slab width measurement after the cutting experiments are presented in Figure 7. In each case, 10 slabs have been measured.

The quality requirements demanded on the markets are not met by all cutting conditions examined. The deviation in the slab width is below the requested $w_p = 1$ mm both for the standard tool and the new tool at water supply speeds of $v_w = 45$ m/s and $v_w = 50$ m/s. The lowest variations in the slab thickness are achieved at a water supply speed of $v_w = 50$ m/s. The average value of the width deviation is at about $w_p = 0.6$ mm for all values of the water supply speed, but
there is a considerable difference between the minimum and maximum deviation. This is why some slabs do not meet the quality requirement, especially with the new tool, coolant supply with a water fork and a tangential supply at \( v_w = 55 \, \text{m/s} \). These variations resp. deflections of the saw blade, which are due to axial forces, can only be explained in part. Schulze (eg. Schulze, 1980) puts these forces down to the axial component of the single grain forces which do not add up to zero because of inhomogeneities.

3. EVALUATION OF THE PROFITABILITY
The results presented above show that processes with thin, conical saw blades can meet the cutting quality requirements. This results in both economical and ecological advantages. Due to the thinner kerf, the removal volume \( V_w \) is reduced by about 40%. Accordingly, the amount of slabs and tiles produced out of one granite bloom increases by about 20%. Furthermore, the amount of abrasive slurry produced is also reduced by 40%, which means the disposal costs can be reduced considerably. Thus, this new tool generation contributes much to the protection of natural resources and to the reduction of waste.

Additionally, the tool costs decrease because less diamonds and bonding powder are needed for the thinner segments. In addition, pre-alloyed bonding powders like MX2480 are about 30% cheaper than conventional cobalt base powders. Compared to conventional body materials, the costs for the conical steel blade are increased by 25%. High-precision machine tools and machining processes are required.
TABLE 1. COMPARISON OF THE PROFITABILITY OF THE CONVENTIONAL CUT-OFF GRINDING PROCESS AND THE NEWLY DEVELOPED PROCESS

<table>
<thead>
<tr>
<th></th>
<th>conventional process</th>
<th>new process</th>
<th>new process with identical tool wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>machine and tooling</td>
<td>100.0%</td>
<td>92.5%</td>
<td>72.5%</td>
</tr>
<tr>
<td>work piece costs</td>
<td>100.0%</td>
<td>84.0%</td>
<td>84.0%</td>
</tr>
<tr>
<td>total costs</td>
<td>100.0%</td>
<td>-11.3%</td>
<td>-22.2%</td>
</tr>
</tbody>
</table>

- Production time as a cost for work piece disposal by 20%
- Production based on 20 production orders

for the production of those blades, like truing, clamping and conical grinding, but thinner steel sheets can be used, which leads to high potential savings. Furthermore, the fact that the cut area

is increased by 30% leads to reduced processing times, which results in labour and machine expense savings. Additionally, the grinding energy and the power input are reduced considerably.

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72 world of mammomachine
With the new tool generation the costs of the production of slabs and tiles, especially those of expensive natural stone, can be reduced because of the lower removal volume. Table 1 summarizes the economical and ecological benefit of the newly developed cut-off grinding process. The calculation presented in Table 1 is based on 20 production orders, each order with an area to be cut of 100 m². In this calculation the conventional process reaches an area cut per time unit of $Q'_{w} = 400$ cm³/min just like the new process with identical load factor. In the new process an area cut per time unit of $Q'_{w} = 520$ cm³/min is reached.

4. CONCLUSION
The FE calculations and the results of the examinations give evidence of the potential of the high speed machining of granite with thin tools. By a modification in the geometry of the abrasive cut-off wheel and the machining parameters, remarkably improved removal rates can be achieved at a good cutting quality and at an only slightly increased wear. The test series with the newly developed tools proved the possibility of attaining the requested cutting quality with a considerably reduced steel blade width. High cutting speeds contribute to the rigidity of the thin saw blades. At the same time, the material removal rate was increased significantly by increased feed rates. If high cutting speeds are applied, the technological conditions regarding the natural frequency of the tool and the vibration characteristics of the steel blades have to be considered. A tangential water supply at cutting speed leads to considerably increased tool cut areas. The new tool generation provides high economic potential. The costs of the production of slabs and tiles, especially those of expensive natural stone, can thus be reduced articulately.

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