ABSTRACT: Ceramics are remarkable for their unique hardness, also at high temperatures, their chemical stability and high wear resistance. This makes them ideally suited for high-speed and hard machining to achieve significant reductions in production time and cost. Furthermore, they are able to run dry, allowing clean machining processes with reduced environmental impact. New developed mixed-ceramics exhibit extremely fine and homogeneous grain structure with increased hardness and fracture toughness. New compositions of silicon-nitride are characterized by a reduced grain boundary phase content and offer further increased wear resistance combined with an extraordinarily high strength. Coatings on silicon-nitride based on new layer designs are extending the range of application.

KEY WORDS: Silicon Nitrides, Sub micron mixed ceramics, High speed and hard machining
Introduction

The most important new technologies are high speed and dry machining as well as dry machining of hardened.
Introducing of new machining technologies into a production line requires certain preconditions of the machine tool. High speed cutting for example needs powerful drives and high spindle speeds, good static and dynamic stiffness.
Dry machining demands new concepts for removing the heat generated in the cutting zone and removing the chips thereof. In addition the requirements to cutting tools and coatings could be different depending on workpiece design and material. A complete description of the whole system consisting of tool, machine tool, workpiece, technology and environment is necessary.
Motivating factors for dry machining are stricter legislation and regulations governing the handling and disposal of lubricants and increased costs for their use.
High speed and dry machining is used in large variety of metalcutting applications already. The increase of cutting speed is leading to higher removal rates, improved surface quality and reduces the cutting forces and process temperatures. However, increased cutting speeds are related to reduced tool life.
The continually increasing demands for improved environmental performance of passenger cars requires that fuel consumption and emissions be minimized. The reduction of weight is one of the main targets for automotive designers. New materials like different grades of gray iron with increased strength and hardness, compacted graphite iron (CGI) and nodular cast iron as alternatives within the cast iron family are leading to higher demands on the tools.

1. Current Developments in Ceramic and Silicon-Nitride Cutting Materials

The production of ceramic and silicon-nitride inserts requires expertise and continuous development of the associated process and manufacturing technology. This is particularly true for every new grade, where the development of the material and manufacturing technology have to be done in parallel. Improved production technologies and coatings are leading to new grades with advanced material properties and higher suitability for applications in chip-removal machining.

The following subjects are among the main topics of research and development in the field of ceramic cutting grades:
- mixed ceramic with sub-micron structure
- silicon nitrides and sialons
- coatings on silicon-nitrides
2. Mixed-Ceramic with Sub-micron Structure

Mixed-ceramics consisting of alumina with additions of hard materials such as titanium carbide and/or titanium nitride. They show increased hardness, hot-hardness and wear resistance compared to oxide-ceramics. Apart from that, they offer a higher resistance to thermal shock and increased cutting edge stability. The development of a very fine-grained and extremely homogeneous microstructure was reached by intensive research in materials and production technologies. The alumina/titanium-carbonitride-composite exhibits an average submicron particle size which is much smaller than that of a conventional type of mixed-ceramic. Figure 1 shows the microstructure of the new type compared with a conventional mixed-ceramic (Lightmicrographs, magnification: 1000x).

![Figure 1](image)

**Figure 1.** Sub-micron structure of a new type of mixed ceramic (right) compared with a conventional mixed ceramic (left)

This structure has greatly increased the mechanical and thermal strength of the mixed-ceramic, together with its wear resistance and edge stability. The hardness and fracture toughness of this cutting grade are significantly higher than that ones offered by classic mixed-ceramics. Combined with an advanced production technology, the sub-micron structure also allows highly precise cutting edges to be produced.

Table 1 illustrates the excellent physical and material properties of this new grade. The properties predestine it in particular for hard finish machining, e.g. finish turning of hardened workpieces rather than grinding. Precisely this application demand a high level of hardness, compressive strength and wear resistance at very high temperatures. For this is also a final machining process, strength and stability of the cutting edge, withstanding chipping or fracture, are particularly important with regard to the tight dimensional and shape tolerances and also to the high surface quality demanded.
### Properties Conventional mixed-ceramic Sub-micron mixed-ceramic

<table>
<thead>
<tr>
<th>Properties</th>
<th>Conventional mixed-ceramic</th>
<th>Sub-micron mixed-ceramic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>Al2O3+Ti(C,N)</td>
<td>Al2O3+Ti(C,N)</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>4.28</td>
<td>4.33</td>
</tr>
<tr>
<td>Grain size (µm)</td>
<td>&lt; 2</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Hardness HV10</td>
<td>2100</td>
<td>2200</td>
</tr>
<tr>
<td>Fracture toughness Kic (MPa m 1/2)</td>
<td>5.0</td>
<td>6.6</td>
</tr>
</tbody>
</table>

**Tab. 1: Comparison of properties for sub-micron and conventional type of mixed-ceramic**

The main fields of application of mixed-ceramics are finishing and fine-finishing at high cutting speeds of cast iron and finish turning of hardened steel of up to 64 HRC, preferably in continuous cutting. The hard turning of rolls made from hardened steel or chilled cast iron featuring a material hardness of up to approx. 75 Shore C is an additional application.

The improved material behavior of this new type of mixed-ceramic is leading to a fairly better performance in turning hardened steel. Figure 2 is showing a comparison in tool-life of the new sub-micron type with a conventional type of mixed-ceramic.

The targets of further developments of sub micron grain structured mixed ceramics are as follows:

- Secure manufacturing of the grade at a high level of repeatability.
- Use of those grades in hard machining even in interrupted cuts guaranteeing a high level of production security

This requires intensive work in terms of material science and manufacturing technologies e.g. grinding. First samples of a new type of mixed ceramic grade of further reduced grain size of only 4 microns and a share of 30% Ti(C,N) show very encouraging results. When tuning a gear shaft made from case hardening steel of 60 +2 HRC hardness in partly interrupted cut a dimensional accuracy IT6 was required. In actual production these parts are grinded. Using this new developed type of mixed ceramic a number of 20 workpieces could be turned dry at a cutting speed of $v_c = 80$ m/min, a feed rate of $f = 0.12$ mm and a depth of cut $a_p = 0.10$mm. Conventional mixed ceramics however failed already when machining the first workpiece. Increasing the cutting speed to $v_c = 180$ m/min and the feed rate to $f = 0.15$ mm the machining time of the workpiece could be reduced from $t_c = 1.4$ min to 0.5 min. Tool life then was 11 parts.
2.1. Dry Machining of hardened Steel with Mixed Ceramic

Hard finish turning is preferably used in the automotive industry, where case-hardened steels with a hardness of 54 – 64 HRC are machined. Typical components include gears, crown wheels, drive shafts and bushes.

Significant advantages of hard finish turning compared with grinding can be achieved if the production job, component, machine tool, clamping device, tool, grade and machining conditions are properly co-ordinated. These advantages include:

- Shorter machining time.
- Greater flexibility in the component geometries that can be machined in the same set-up.
- Less production steps from the blank to the finished part.
- Reduced investment costs for the required machine tool.
- Lower energy consumption.
- Dry machining and avoidance of grinding sludge.
- Reduced production and disposal costs.

Through the improved wear resistance and edge strength of the new sub-micron mixed-ceramic the economic advantages compared with grinding are increased even further. Compared with CBN grades, the lower price of the sub-micron mixed-ceramic offers a particularly good cost-benefit ratio. Consequently, they are recommended for machining in continuous cutting and constant depth of cut. The cutting conditions themselves – speed and feed – are specified according to the required surface quality, the geometry of the used insert and the hardness of the
workpiece material. As a rule, with hard finish turning, the cutting speed and feed for the sub-micron mixed-ceramic and for CBN are more or less the same.

2.1.1 Examples of Application

Figure 3 shows a typical workpiece suitable for hard turning. With this spur pinion, made of case-hardening steel 57 – 59 HRC, the bore, synchronizing cone and rear side are hard turned. Apart from tight dimensional, shape and positional tolerances, the high demands in terms of surface quality up to Rz = 2 µm are reliably achieved by this process. Furthermore the workpiece is machined dry in just one set-up.

Figure 3. Hard turned spur pinion

Figure 4 shows another typical example of a hard machining operation. In this case, the bore of a case-hardened drive pinion is machined with a insert TPUN 110308T. The sub-micron mixed-ceramic is used at a cutting speed \( v_c = 200 \) m/min, a feed rate \( f = 0.06 \) mm and a depth of cut \( a_p = 0.1 \) mm. The required dimensional and shape
accuracy is achieved over a tool life of 500 parts. Generally speaking, this machining operation is also performed dry.

Figure 4. Hard turned drive pinion

3. Silicon Nitride

The microstructure of silicon nitride contains needle-like silicon nitride grains which are embedded in a highly temperature resistant grain boundary phase. The needles enable mechanisms such as crack deflection, crack bridging and pull-out effects, which lead to a superior fracture toughness. The high temperature resistance of silicon nitride strongly depends on the content and composition of the grain boundary phase.

Silicon nitride is particularly suited for rough-machining of cast iron, even under unfavorable cutting conditions such as heavily interrupted cuts and varying depth of cut.

Apart from turning and boring, silicon nitride is also successfully used for milling cast iron, even with positive tool-geometries.

A new material composition based on high purity ceramic powders, optimized powder processing and sintering technique is leading to further increased high-temperature hardness and fracture toughness. The new silicon nitride grade is characterized by a reduced grain boundary phase content and a extremely homogeneous microstructure. The result is a higher bending strength and wear resistance, especially at very high temperatures combined with the high fracture toughness.
Table 2 shows the differences in the physical and material data of the new grade and a conventional silicon nitride.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Conventional Silicon nitride</th>
<th>NewType Silicon nitride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>&gt; 95% β-Si₃N₄</td>
<td>&gt; 98% β-Si₃N₄#</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>3.24</td>
<td>3.21</td>
</tr>
<tr>
<td>Hardness HV0.5</td>
<td>1850</td>
<td>1950</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>7.1</td>
<td>8.0</td>
</tr>
<tr>
<td>KIc (MPa m 1/2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending strength</td>
<td>820</td>
<td>1100</td>
</tr>
<tr>
<td>σB (MPa)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

# low substituted SiAlON with z=0.4

**Tab. 2:** Comparison of properties for a new and a conventional type of silicon nitride.

3.1. Silicon Nitrides for High Speed Machining of Cast Iron

In high performance cutting, turning, boring and milling of cast iron silicon-nitride gained meanwhile an important market share when it comes to high productivity, reliability and cost-efficiency in high volume production series, e.g. in the automotive industry and their suppliers.

The excellent physical and chemical material properties of this newly developed grade gives a definite edge over conventional types of silicon nitride. As shown in figure 5, a significant lower wear rate in high speed turning can be observed.

This new grade allows the user to increase tool-life and productivity in the workshop with excellent reliability and reduced manufacturing costs at the same time, which was confirmed by the following results in various high volume production jobs.
3.1.1. High Speed Turning

For example, when rough turning a clutch pressure plate (see figure 6) made of cast iron using a notch-type insert of this new grade under extreme cutting conditions – cutting speed $v_c = 900$ m/min, feed $f = 0.84$ mm and depth of cut $a_p = 1.2$ mm – the tool life could be enhanced to 350 components per cutting edge compared to 150 with a conventional and even coated silicon nitride grade.

![Clutch pressure plate machined with silicon nitride](image)

**Figure 5.** High speed turning of cast iron with new silicon nitride (SL500) in comparison to conventional grades (grade A and grade B)

**Figure 6.** Clutch pressure plate machined with silicon nitride
3.1.2. High Speed Boring

When it comes to rough boring of cast iron housings silicon nitrides together with powerful and fast machine tools enable high cutting speeds and feeds ($v_c > 800$ m/min; $f_z = 0.2 - 0.3$ mm) and very short machining time.

Figure 7 shows a boring operation on a motor block at a feed speed of $v_f = 2100$ mm/min and a cutting speed of $v_c = 780$ m/min allowing each bore to be rough machined in less than five seconds. Using the new type of silicon nitride tool life was increased from 1400 up to 1800 bores. Per cutting edge. On more powerful machine tools even higher spindle speeds and feed speed can be achieved reducing machining time down to less than two seconds per bore.

Figure 7. High Speed Boring of a motor block with the new silicon nitride grade
3.1.3. Milling of Cast Iron at High Speed

Milling involves high alternating mechanical and thermal load of the tool. Owing to their high fracture toughness and resistance to thermal shock, silicon nitrides are also suited for milling operations involving larger chip cross sections and positive tool geometries.

If enabled by the machine tool cutting speeds $v_c > 1000$ m/min can be achieved at feed rates per tooth $f_z = 0.10 - 0.30$ mm. First trials on high speed machining centers with linear drives with axial positive milling cutters demonstrated the potential of silicon-nitride:

At a spindle speed of $n = 15000$ rpm, cutting speed $v_c = 2400$ m/min and feed speed $v_f = 9600$ mm/min; $a_p = 2.0$ mm a tool life of 120 m could be reached.

However, such data are still the exception to the rule. Figure 8 is showing a state-of-the-art milling operation using silicon nitride in machining an engine block. A milling cutter, diameter 125 mm, eight inserts SNGN 120412T running at $v_c = 1180$ m/min, $a_p = 4$ mm and $v_f = 3600$ mm/min machined 600 components per cutting edge before tool-life criteria was reached. Compared to milling with a conventional type of silicon nitride tool life increased by 100%.

Figure 8. High Speed Milling of a motor block with new silicon nitride grade at a feed speed of 3.6 m/min
Silicon Nitride is also setting new standards in high performance cutting using milling cutters of smaller diameters in the range of 40 to 63 mm. Theoretically cutting speeds higher than 2500 m/min and feed speeds in the range of 11 to 14 m/min could be achieved. Those values are far above the ones running in actual production. Nevertheless also on existing machine tool equipment high speed milling with silicon nitride can be set.

Summerizing the experiences also on conventional machine tools with limited spindel revolutions in the range of 4000 to 6000 min\(^{-1}\) feed speeds can be multiplied by factor 2 to 3, cutting speeds by factor 3 to 4 when using silicon nitrides instead of tungsten carbides. The machining time can be reduced by 65% in average.

3.2. Milling of CGI with Silicon Nitride

The machinability of compacted graphite iron is generally not as good as of normal cast iron. But contrary to the reported experiences with silicon nitrides and CBN in high speed turning, mainly boring in smooth cut, milling at high cutting speeds of CGI can be achieved. As shown in figure 9 milling at \(v_c = 800\) m/min, feed \(f_z = 0,16\) mm and \(a_p = 2.0\) mm the wear rate depends on the perlite content of the CGI material. High perlite content (95%) of CGI leads to higher tool life than lower perlite content. Compared with cast iron GG25 the wear on the cutting edge is obviously higher. But it remains still within the limits to run production at an acceptable output also at given high cutting speeds. A drop in cutting speed from \(v_c = 800\) m/min down to 630 m/min will only slightly influence the wear rate and tool life by about 15%.

![Figure 9. Milling of CGI compared to CI with silicon nitride - Influence of material on wear rate](image)
4. Coatings on Silicon Nitride

The wear resistance and also the chemical stability of ceramic cutting tools can be increased by the application of coatings. The classical coating materials are TiN, TiC, TiCN and Al₂O₃ and various combinations thereof, which are applied using different coating techniques e.g. CVD or PVD. Especially if Al₂O₃ is contained in the layer, - for instance within a multi-layer alumina/titanium nitride coating as shown in figure 10 - the increased diffusion- and oxidation resistance leads to a benefit in application.

Figure 10. Multi layer coating on silicon nitride

The multi-layer concept is one possibility to compensate the thermal misfit between the substrate and the coating material. This concept does not only improve the grade’s wear resistance compared to the uncoated substrate, but also provides for the range of applications of silicon nitrides to be extended to turning of nodular cast iron. As shown in figure 13, a significant reduction of the wear rate will be achieved when using coated silicon nitrides as introduced above. Compared to state of the art coatings new layer design will increase wear resistance and tool life even further.
This characteristics enable the user to replace tungsten carbides by coated silicon nitrides for turning workpieces made of nodular cast iron. Typical workpieces in this range of application are fly wheels, crankshaft journals and differential housings. Higher cutting speeds and shorter machining times can be achieved resulting in decreased production costs. Dry machining instead of using coolants is also applicable, which is offering further economical advantages.

5. Future Trends and Conclusions

Ceramic cutting grades, used together with an adequate machine tool equipment, constitute an excellent contribution to a reliable and highly profitable production. High speed machining of cast iron with silicon nitride has become a state-of-the-art process already, as well as the application of mixed-ceramic in the range of hard turning operations.

A trend towards newly developed very fine grained cutting materials with homogeneous microstructures can be identified. Special designed ceramic coatings will be applied to an increasing extend. These developments are leading to further increased material properties to realize higher performance and opening up a wider range of cutting applications in the future.
New workpiece materials like compacted graphite iron CGI used for cylinder blocks or heads for instance replacing conventional gray cast iron are setting new challenges to tooling and cutting tool material especially in high speed machining. To achieve cost effective CGI machining further investigations in cutting materials, tooling and manufacturing concepts are required. The same tasks are set in the range of machining metal matrix composite workpiece materials. In this materials SiC, alumina, B_4C fibers or other are distributed in a metal matrix like aluminum, magnesia or other to increase the material's resistance against abrasion and to improve its tensile strength. The improved mechanical and physical properties of the MMC can lead to completely new component designs opening up new ranges of application especially regarding light weight concepts.

Only a tight cooperation of tool manufacturer, machine tool supplier, workpiece material manufacturer and end user will lead to successful machining solutions to match all challenges related to the increasing use of those new materials.

References