Increasing machinability of grey cast iron using cubic boron nitride tools: Evaluation of wear mechanisms

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This paper presents the analysis and experimental results on the complexity of machining grey cast iron in a high production automotive industry, where surface quality, tolerances and productivity are the most specified customer requirements. The machining of a central housing of turbo charger unit in high speed turning process using polycrystalline cubic boron nitride (CBN) tools coated with titanium nitride (TiN) has been evaluated. The main limitations of machinability are appearing of burr, adhesive wear and flank wear mechanism. The cutting tool geometry and feed rate have been varied while the other parameters, such as cutting speed and depth of cut, are kept fixed. After the flank wear on the tools is monitored, it is concluded that for a certain number of work-pieces machined, the wear process on tools is less severe with using of positive tool rake insert. The machinability is additional increased with improved cutting strategy in the way of burr appearance and with rolling of formatted burr. The worn surfaces are analyzed with an electronic microscope.

Keywords: Grey cast iron, Machinability, Turning, CBN, Burr, Tool-life

In machining automotive parts, surface quality, tolerances are the most specified customer requirements where major indications of surface quality on machined parts are appearance of burr and surface roughness. Both properties are mainly results of process parameters such as tool geometry (i.e. nose radius, edge geometry, rake angle, etc.) and cutting conditions (feed rate, cutting speed, depth of cut, etc). In finish turning, tool-wear becomes an additional parameter affecting surface quality and appearance of burr of finished parts. Finish turning process can be defined as turning of semi manufacture into finished components. The greatest advantage of using finish turning is the reduced machining time and consecutiveness increase of productivity and complexity that require additional manufacturing processes to satisfied quality and geometry requirements.

Automotive part which machinability is dealt with in this work is central housing of turbo charger (Fig. 1). A grey cast iron central (bearing) housing provides locations for a fully floating bearing system for the shaft, turbine and compressor which can rotate at a few thousand rev/min. CNC machinery turns and drills specified housing faces and connections.

Besides, the particularity is that its dimensional tolerances are tight with quite high surface quality requests. Since, central housing of turbo charger is a work-piece that is not exposed to high mechanical stress, special requirements of alloy grey cast iron are not given. Consequence the hardness and strength of used grey cast iron are low, because of reduced costs of such material.

It is known that the grey cast irons are relatively soft, but very abrasive. So using of CBN cutting tools, with their high abrasion resistance is the best choice for machining grey cast iron. Another reason for choosing CBN tools is permitting grey cast iron cutting at feeds and speeds much higher than...
conventional cutting tool materials. Because CBN tools maintain a sharp cutting edge, part surface finishes are excellent, close tolerances are easy to obtain, and dramatic productivity increases can be expected. Finally, from the view of ecology in mainly cases coolants are eliminated altogether.

The problems found when machining central housings of turbo charger were the high wear rate of cutting tools and the presence of burrs. This study is, therefore, very important, since its goal is to analyze, through tests, the main mechanisms of wear when machining grey cast iron central housing of turbo charger. Thorough understanding at the phenomena implicit in this process, solutions based on scientific analysis will be proposed, in order to enhance process quality and reduce its cost.

Besides the effects of CAM processing, there are numerous machining factors that affect surface quality in turning using CBN cutting tools, but effects is hard to adequately quantify. These influences are, work-piece material microstructure, tool geometry, tool-wear, work-piece geometry, burrs and vibrations.

From the statistic research, it is known that in hard turning practice, industry chooses the correct tool geometry less than half of the time, uses proper machining parameters only about half of the time, and uses cutting tools, especially CBN, to their full life capability only one third of the time, what also happened in current research topic. This sub-optimal practices cause loss of productivity for the manufacturing industry. Improvements to the current process planning for finish turning are needed to improve cost effectiveness and productivity.

**Grey Cast Iron Machinability**

Cast iron solidifies with separation of graphite is called grey cast iron due to the fact that fracture surfaces appear grey because of the exposed free graphite. It is an alloy with 2 to 3.5% carbon and 1 to 3% silicon content, and is one of the most free machining ferrous materials. In all grey cast iron grades, free graphite is present in the form of flakes of various sizes and distributions. In grey cast iron, it is presented 1 or 2% of cementite, which is cause of fast cooling of alloy. In the opposite case, slow cooling of grey iron with a high content of carbon and silicon, will yield in a matrix with a high content of free ferrite and large flakes of graphite.

From a machinability point of view the microstructure, which is almost synonymous with hardness, is totally dominant. The hardness and strength of the grey cast iron describes: quantity, size and distribution of graphite flakes, the amount of free ferrite and lamellar pearlite. Machinability can be improved with C, Si, S and Si/Mn alloying elements. The opposite effects have elements like Mo, Mn and Cr.

Grey cast iron is widely used for engine blocks, brakes and so on, due to its low cost and excellent moldability. Carbide and ceramic cutting tools are conventionally used for machining grey cast iron that features easy to cut properties. However, due to the growing demand for high speed, high efficiency and high precision cutting and long life tools, CBN cutting tools are replacing conventional tools. In general, cutting tool-life is longer and tool cost is lower in the cutting of grey cast iron than in the machining of other ferrous materials. However, machinability of grey cast iron varies depending on their microstructures and the pearlite/ferrite ratio. Even now that the application of CBN cutting tools in machining is very common, the problems in grey cast iron machining remain unsolved. Under the circumstances, the development of cutting tools that provide stable machining quality and long tool-life for the machining of grey cast irons with a large variety of machinabilities is anticipated.

The quality and the integrity of the finish machined surfaces which are represent under term machinability, are affected by work-piece material microstructure, which is almost synonymous with the hardness. The work-piece material hardness of an unalloyed grey cast iron is between 90 and 275 HBN. It is also known that the surface roughness of grey cast iron decreases with increasing hardness. Furthermore, work-piece hardness has a profound effect on the cutting life of the CBN tools.

**Tool geometry**

On the other hand, CBN cutting tools demand prudent design of tool geometry. They have lower toughness than other common tool materials, thus chipping is more likely. Therefore, proper edge preparation is required to increase the strength of cutting edge and attain favourable surface characteristics on finished machined parts (Fig. 2). Therefore, CBN cutting tools are usually designed as feature negative rake geometry and an edge preparation.

Edge geometry of the CBN tool is an important factor affecting surface quality. The chamfered cutting edge of CBN tools results in a significant
increase of tool-life. However, the chamfer is unfavourable in terms of attainable surface finish compared to honed or sharp edges. Chou et al.\textsuperscript{10} tested three types of edge preparation for CBN in finish turning. The results indicated that the honed cutting edge has worse performance than the other two, based on tool flank wear and part surface finish. On the other hand, the tool nose radius has an inverse relationship with surface quality, but nose radius cannot be made very large. The importance on edge geometry implies additional importance to tool wear. It is important to predict, that as tool-wears, and his edge geometry may change and thus affect the part surface quality.

Performance of CBN cutting tools is highly dependent on the cutting conditions, i.e., cutting speed, feed rate and depth of cut. Especially cutting speed and depth of cut significantly influence tool-life. Change in the edge geometry, increased cutting speed and depth of cut results in increased tool stresses and tool temperatures at the cutting zone. Since CBN is a ceramic material, at elevated temperatures chemical wear becomes a leading wear mechanism and often accelerates weakening of cutting edge, resulting in premature tool failure (chipping)\textsuperscript{9}. With increasing feed rate, residual stresses change from compressive to tensile, which leads to adhesive tool-wear and edge breakage\textsuperscript{11}.

**Tool wear**

When two moving metallic surfaces are put into sliding contact, there is loss of material from both, although this effect is less damaging to the hardest one. During the chip formation process, there is a strong interaction between the cutting edge, the chip, and the machined surface (on the rake face and on the flank face, respectively). When this process happens, depending on the cutting conditions, the edge suffers high pressure and high temperature combined with the presence of cutting fluid, which encourages the occurrence of several physical processes and chemical reactions. The final result is wear on the cutting edge. The high temperature in the region of chip formation results from the rate of thermal energy generated by the shearing process, which is not fully dissipated. The capacity to dissipate the heat depends on the properties of the tool material and the work-piece material\textsuperscript{11}. Additionally, other properties, such as hardness, toughness and chemical stability at cutting temperature and the capacity to dissipate heat is also important in order to maintain a relatively low temperature at the cutting edge. The wear on the cutting edge can be attributed to some well known mechanisms\textsuperscript{12}:

**Adhesive wear**

Several layers of work-piece material are compressed against the cutting edge at high temperature. After compression, the layers adhere to themselves and to the edge and usually become hard in a manner similar to the process of strength hardening. Some pieces of these layers may break off taking parts of the edge surface away\textsuperscript{11,12}. The process can be more complex than described here, but it usually happens at relatively low cutting speeds associated with a high pressure/high temperature on the cutting edge. The adhesion can also be accelerated depending on the chemical affinity between tool and work-piece materials. A built up edge and notch wear are the more common types of wear related to this mechanism.

**Abrasive wear**

This occurs where abrasive, or hard particles, are present in the region of interaction between the cutting edge and the work-piece\textsuperscript{11,12}. The resistance to such a wear mechanism is associated with material hardness and melting point. As the cutting speed and feed rate increase, the temperature in the chip formation region also tends to rise. In such conditions, some hard carbide particles, present in the chip being formed, wear the rake face. Similarly, particles present on surface being machined, wear the flank face of the tool. Using tool materials with a high thermal conductivity may contribute to minimising the action of the abrasive wear mechanism, because the heat can then be removed rapidly from the chip formation region. Flank and crater wear are the types of wear most frequently associated with this mechanism.

**Diffusion**

This is essentially associated with the chemical affinity between the tool and work-piece materials under the high temperature and pressure occurring during the cutting process. The high temperatures
reached during the chip formation create the conditions for diffusion of some of the chemical elements present in both tool and work-piece materials. The most common is the diffusion of the carbon. Chemical wear is mainly associated with crater wear and, to a less extent, flank and notch wear.

**Fatigue wear**

This can be mainly of two kinds, mechanical and thermal fatigue. The first is due to the alternating tensile and compression stresses on the cutting edge. The second can be associated with alternating cycles of heating and cooling. Tools used in milling operations usually present this mechanism. Chipping and catastrophic failure are the main types of wear associated with the fatigue mechanism (comb cracks).

**Wear by oxidation**

This is a particular type of chemical wear, which occurs when metals and oxygen are in contact. It can be accelerated at high temperatures and/or high pressures. Notch wear is suggested to be caused mainly by this mechanism.

The change from one wear mechanism to another is highly dependent on the cutting speed, since it is responsible for changes in the temperature at the cutting edge. At relatively low cutting speeds it seems that adhesive (mainly) and abrasive wear are predominant, whereas at high speeds chemical, thermal and mechanical fatigue are more evident.

**Vibrations**

Another factor that is often ignored, but is very significant for machinability is tool vibrations. The relative distance between tool and work-piece is changing in presence of vibrations (chatter vibrations). In order to reduce tool vibrations, it is necessary to provide sufficiently rigid tool and work-piece fixtures and avoid non-stable regions of cutting process.

**Burr formation**

In many cases, burrs are accepted to be an inevitable consequence of the process and a finishing operation is used to remove the offensive defects. Generally, burrs are undesirable projection of material that results from a cutting and forming that occurs along the edge of a work-piece. The importance of burrs in manufacturing processes for automotive industry has great attention. As the demand for component tolerances and surface quality, which are in this industry more stringent in the connection with cost, the burr issues need to be addressed at the point of prevention rather than rectification. Burrs can cause serious and insidious consequences as the appendages, when loosened from the component at a later stage, can cause major damage to the device or system.

High speed spindles are progressively becoming standard specifications in machining tools. In modern high speed cutting process, at such high cutting speeds the presence of burrs on the machined components is far less prevalent.

The fundamental burr formation mechanism is found to consist of four stages: (1) initiation, (2) initial development, (3) pivoting point and (4) final development stages. The initiation stage represents the point where the plastically deformed region appears on the edge of the work-piece. In the initial development stage, significant deflection of the work-piece edge occurs. The mechanism involved in this stage is similar to bending deformation. The pivoting point stage represents the point where material instability occurs at the work-piece edge. From this stage on, bending at the work-piece edge occurs. In the final development stage, a burr is further developed with the influence of the negative deformation zone formed by a shearing process. Hence, plastic bending and shearing are the dominant mechanisms in this stage. Depending on the cutting conditions and material properties, edge breakout can occur through the negative deformation zone.

Burr size measurement is found to be a tedious task. In the process of cutting, the cause of burr is largely attributable to the use of the up-cut method in the tool feed. As the cutting tool return from

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![Fig. 3—Burr size measurement and its difficulty](image1)

![Fig. 4—The importance of feed direction in the way of burr formation (a) up-cutting and (b) down cutting](image2)
the work-piece the chip does not break cleanly off from the edge of the work-piece, resulting is the residual burr. The ductility of work-piece material is likely to reinforce this phenomenon. The problem can be resolved through the use of the down-cut tool feed (Fig. 4), but there is important to mention that with this solution we did not avoid of burr, but this burr was just removed to another work-piece edge, which is probably not so critical.

Another factor that affects the burr formation is the sharpness of the cutting tool edge. When the tool is sharp, the “pivot” point of the tool is located close to the work edge (Fig. 5). When the tool is blunt, the pivot point is located further away from the work-piece edge. That result in the formation of larger burrs. With introduction of coated tools and harder tool materials such as CBN, ceramics and diamond, have alleviated the problem substantially. These tools, with their superior temperature resistant, are particularly important in overcoming the rapid tool wear problem, associated with high-speed cutting.

While it is not always possible to avoid burses completely in machining processes, some attention taken at the planning and execution stages of technology, can provide significant reduction in the way of costs, time and effort in post-machining operations. Burrs should be kept to places, which are not critical or are easier to access for removing operations.

The magnitude of the burr problem in industry is underlined by the fact that there are many types of deburring methods. Mechanical deburring methods such as brushing/buffing and rolling are generally more cost effective. However, the risk of work-piece damage is high. As parts continue to increase in complexity and the tolerance, specifications become more demanding and deburring processes rise in the way of complexity and costs.

**Experimental Design**

The tests of tool-wear were carried out using CBN tools during the finishing turning process of grey cast moulded semi-manufacture (Fig. 6). Tool-wear was investigated on three main critical cutting operations that will be detailed presented in continuation. During tests, two CBN tools worked consecutively. They were used with the same preferences, but were from different tool makers. All tests were carried out in the machining line of the manufacturing plant.

An OKUMA LT 10–M CNC lathe was used for the carrying out of the cutting experiments in this study, the flank wear of cutting tools was measured and recorded in the experiments. The CNC lathe is used to perform dry cutting on grey cast iron.

**Work-piece material**

The central housing is cast and gets to the machining line unworked. The central housing gets there, where for example most outer diameter of ~110 mm has to be machined to 106.3 mm with turning process. Most important preference of work-piece material is its hardness. Therefore, hardness of used grey cast iron was measured and is shown in Fig. 7. Measurements
were done on two parts, belonging to two different moulding series. It can be seen that hardness on sampling place is changing with the distance from the surface. Average hardness by Vickers method is about 210 HV1.

 Mostly fast tool-wear consequence of hard particles with high hardness. In grey cast iron that particles may be free cementite or phosphoric eutectic, but in this case there is no presence of hard inclusions.

Grey cast iron has a perlitic structure with lamellar graphite. Graphite in dealing material is mostly A type, on some places (mostly on surface) can also be found graphite type B and D. In central part of cast, the grey cast structure is mostly perlitic, where density of ferrite is less than 5%. On the surfaces, the microstructure on some part is ferrite and is the same in depth, especially on the part of work-piece, with most outer diameter. Ferrite structures are located in pearlite like ice lands areas. So on such a part is concentration of ferrite more than 5 %, locally also more than 10 % to almost 100% (Fig. 8).

Chemical structure of material that is added by foundry is presented in Table 1.

![Fig. 8—Microstructure of grey cast iron near surface](image)

### Table 1—Chemical structure of grey cast iron

<table>
<thead>
<tr>
<th>DIN</th>
<th>CE (%)</th>
<th>C (%)</th>
<th>Si (%)</th>
<th>Mn (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Cr (%)</th>
<th>Sn (%)</th>
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<tbody>
<tr>
<td>GG20</td>
<td>4.060</td>
<td>3.500</td>
<td>2.200</td>
<td>0.025</td>
<td>0.050</td>
<td>0.080</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.100</td>
<td>0.010</td>
<td>0.060</td>
<td>0.012</td>
<td>0.960</td>
<td></td>
<td></td>
<td>220</td>
</tr>
</tbody>
</table>

### Table 2—Composition and properties of used CBN cutting tools

<table>
<thead>
<tr>
<th>CBN content approx. vol. (%)</th>
<th>Average starting grain size (µm)</th>
<th>Matrix /Binder</th>
<th>Format</th>
<th>Knoop's hardness (GPa)</th>
<th>Fracture toughness (mPa√m)</th>
<th>Thermal conductivity (W/m·K) (20°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>22</td>
<td>Al Ceramic</td>
<td>Solid</td>
<td>30.4</td>
<td>5.8</td>
<td>130</td>
</tr>
</tbody>
</table>

Cutting tools

Because of all advantages that are mentioned above (introduction), CBN cutting tools (Table 2) were used. For the comparison, two manufacturer of cutting tool were used, SECO and HOFER. Cutting tool geometries were negative and are compared in Fig. 9.

Because grey cast iron materials are not particularly hard, but exhibit well wear resistance characteristics making them very abrasive to cutting tool materials. Rough machining grey cast iron requires the chamfering of the cutting edge. The skin of grey cast iron is usually rough, hard and contains impurities such as sand from the casting process. These and the larger depth of cut mean much more pressure on the cutting edge. The chamfering of the insert strengthens the CBN cutting edge, thereby, ensuring consistent and maximal tool-life.

Cutting operations

One-cut and two-cut machining strategies were used. Three critical cutting operations were analysed in the way of tool-wear. All three operations are presented in Fig. 10. Cutting speed is changing with...
work-piece diameter, 4000 rev/min (up to 1382 m/min). Dry machining has been performed.

Tool T1A has rhomboid shape (CNMN 120416S), tool T2A has triangle shape (TNMN 110304S) and Tool T6B has triangle shape (TNMN 110304S). Feed rates and depths are presented in Table 3.

Results and Discussion

The cutting tool flank wear is observed with tool maker’s microscope, with an error of 0.001 mm.

Results of wear accompaniment carried out in the machining line of the manufacturing plant are presented in Fig. 10. There is presented tool-wear for T6B, which is most critical. Other tools-wear have similar mechanisms but the wear rate is slower. Every 20 work-pieces has been measured with the presented microscope. In this way, the need of at least ten flank wear measurements in forecasting the tool-life was obtained.

From these results, rapidly increasing of tool-wear can be observed at the beginning and after that, area of steady linear wear increasing state can be recognized. There is also recognized high thermal influence especially on HOFER tools, which are coated with (TiN). However, this tool coating disappears after 20-machined work-pieces. After 100 (for SECO) and 140 (for HOFER) machined work-pieces the burr was recognized by machine operating surgeon and tool edge had to be changed.

Therefore, a criterion for tool-life is burr appearance and so not directly a flank wear. Flank wear defines the cutting edge retreat and has a significant influence on the work-piece dimensional accuracy. Therefore, these criteria have been used to measure the tool wear rate and also to classify wear of different cutting tools according to tool manufacturer. The tool-wear is the loss of the cutting material chosen to measure the tool damage. Thus, the flank ware VB value is only a geometric dimension and it does not show the tool-wear rate, but it is possible to obtain the volume of tool material removed as a function of VB13:

\[ V = S \cdot h = \frac{VB^2}{2(\tan(\alpha) + \tan(90 - \beta))) \cdot h} \quad \ldots (1) \]

this lead to length (L) of the workpiece rubbing:

\[ L = \frac{\text{machined surface}}{f} \quad \ldots (2) \]

where \( \alpha \) and \( \beta \) presents rake and flake cutting angles (Fig. 11), \( h \) is the length of cutting edge, and \( f \) is cutting feed rate.

As a tool-wear measurement, Fig. 13 shows the flank ware VB as a function of machined work-pieces for two compared tools. The integration of length along the cutting edge gives the surface of the work-piece rubbed with flank surface of the tool.

From these results shown in Fig. 12, a criterion for tool-life can be classified into two distinct groups according to the place of cutting. The first group represents T6B tool, where tool-wear VB is not critical, but the burr appearance is the criterion for tool or cutting edge elimination. The second group represents cutting tools T1A and T2A, where burr is not presented. Therefore, the tool-life criterion is tool

<table>
<thead>
<tr>
<th>Operation</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1A</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>T2A</td>
<td>0.2</td>
<td>0.2</td>
<td>0.15</td>
<td>0.15</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>T6B</td>
<td>0.08</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1A</td>
<td>~2</td>
<td>~2.5</td>
<td>~1.8</td>
<td>~2</td>
<td>~2</td>
<td>~2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2A</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>~0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>2.2</td>
<td>~1</td>
</tr>
</tbody>
</table>

* ~ approximate cutting depth is given, because of moulding dependence
flank wear, which is connected with machined surface quality.

The burr on a work-piece edge appear after about 100-140 of machined work-pieces. It is not big difference between tool makers. HOFER tool behaviour is a little better, but this is due to different tool geometry (Fig. 8); HOFER tools have smaller cutting edge chamfering. Consequently, the tool flank wear at cutting edge elimination is \( VB = 180 \, \mu m \).

In second group two cutting tools are used one after another, \( T1A \) is for roughing and \( T2A \) is for finishing. Because of separated operations, the decrease in tool flank wear was expected. After 240 machined work-pieces the tool flank wear was not critical. Tool flank wear of cutting tool \( T1A \) after 240 machined work-pieces was 142 \( \mu m \) for SECO and 138 \( \mu m \) for HOFER. Tool-wear of cutting tool \( T2A \) after 240 machined work-pieces was 246 \( \mu m \) for SECO and 177 \( \mu m \) for HOFER. In addition, the difference between different tool makers is because smaller tool edge chamfering. Smaller tool edge chamfer is recognized as better behave tool geometry, what is expected because of relatively soft grey cast iron.

Second presented results (Fig. 13) show the cutting tool material removal rate in relationship with rubbing

Fig. 11—Companion of T6B tool-wear as a function of quantity of machined work-pieces

Fig. 12—Measured flank wear

Fig. 13—Flank wear for different cutting tools in three different cutting operations
Thus, each flank wear can be defined by one parameter that is the straight line slope. Higher is that slope, greater the tool-wear rate is. Also from these rates, it can be seen that the most critical cutting tool is T6B. Differences in tool makers are the same as introduced above.

The surface of the tool rake and flank plane with cutting edges shows many wear mechanisms that can be observed with the optical microscope. Picture of tool-wear for T6B cutting tool (which is critical) are shown on Fig. 14.

At early stage of cutting, initial breakdown in cutting edge with the edge rounding is observed with only a flank wear which increased rapidly. Then the flank wear becomes or it is going to be stable. From results presented in Fig. 14, it is possible to see grooves, which are formed in the cutting speed direction. Those grooves seem to be the result of extensive abrasion wear. The grooves on the flank surface appear at the beginning of machining and they never disappear.

On rake face can also be seen slight crater wear. Crater wear is usually cause of hard work-piece material particles and high cutting speed but in this case is cause of high cutting speed with present of BUE. Increase in cutting speed with presence of BUE leads to an increase in cutting temperature, which contributes to acceleration of tool-wear\(^{1,12}\). Cause of high cutting temperature and abrasive particles in using HOFER cutting tools lead to rapidly elimination of the TiN layer and the coated insert behaves like an uncoated insert.

This rapid tool-wear show the presence of free ferrite. Free ferrite content of the grey cast iron is an important factor when machining with CBN. The free ferrite content must be below 10% in order to achieve optimum performance\(^6\). Therefore, this work-piece material has to high free ferrite content. Iron with free ferrite contents above 10% lead to chemical attack of the CBN, which in turn will result in greatly reduced tool-life. Examination of the flank wear on the used tool and the presence of vertical striations on the wear scar is an indication of chemical wear as a result of free ferrite contact.

Another cause of rapidly tool-wear at critical tool T6B is to small feed rate\(^{13,14}\). Because of difference in feed rate between tools T2A (\(f=0.2\ mm/rev\)) and T6B (\(f=0.08\ mm/rev\)), which are geometrically practically identical, is tool-wear at T6B tool extremely more critical. Practically the feed rate is smaller than the tool chamfering length (0.2 or 0.1 mm), so the tool rake angle is even more negative (–26°).

It is known that increasing in the feed rate increase the tool-life\(^{14}\). Cause of this may be the instability or absence of BUE (build up edge). In order to identify the cause, it is necessary to perform instantaneous cut interruption, which is called Quick-Stop-Test.

**QSD Test**

Cutting conditions and tool geometry have effect on the cutting force, but it seems interesting to analyze the chip formation mechanisms, with aim to increase machinability. Therefore, the process has to be “frozen” during the process in the real cutting conditions and without cutting the chips from the work-piece material. For this kind of experiments it is used Quick Stop Device.

QSD tests were performed in usage of most critical cutting tool T6B. Because of very high cutting speed and limitations of QSD devices, three different QSD tests were made: (i) at 560 m/min, (ii) at 710 and (iii) at 1200 m/min. All results are presented on Fig. 15 as magnified pictures of turned grey cast iron microstructure. The observations of the cutting edges are done as the photomicrograph and etch structure of chip.

From Quick-Stop test results it is seen that Quick Stop Device was to slow for cutting speed 1200 m/min. So in results from tests at smaller cutting
speeds, it has to be included the influence of smaller cutting speed. As a result from microstructure in Fig. 16, it can be seen that machined grey cast iron structure was grey cast iron with type A graphite in a perlitic matrix. It is possible to recognize that in front of cutting tool chamfer, there is zone of high deformation of cutting material which could result in build up edge (BUE). Deformations and material flow are good seen especially from graphite flakes orientation. Built-up edge (BUE) is largely a temperature and cutting speed-related phenomenon. High deformation of machined material caused high temperature and pressure influence on cutting tool. Under these conditions, chips become gummy and tend to smear and stick to the insert flank. The workpiece material is welded onto areas of the edge where the substrate is exposed. The BUE is torn off repeatedly, leading to chipping.

Because of negative cutting tool geometry and tough grey cast material, cutting tool “push away material”, which lead to increase of cutting forces. At extreme point, where this material deformation cause very high mechanical and thermal influence on cutting tool edge, premature edge breakdown, and even catastrophic insert fracture can occur. These

Fig. 15—Tool-wear at cutting edge elimination because of burr appearances for both manufacturers (a) HOFER and (b) SECO

Fig. 16—Quick-stop test during turning of grey cast iron with negative CBN tool geometry, at three different cutting speeds: (a) \( v_c = 560 \) m/min, (b) \( v_c = 710 \) m/min and (c) \( v_c = 1200 \) m/min, and with two observations method: photomicrograph (right) and etch structure of chip (left)
kind of catastrophic insert fractures, which also happened in machining of this central housing, are shown in Fig. 17. The effect has also high influence on burr appearance and machined surface quality, because of high material deformation in cutting zone. This cutting zone with material plastification is shown in Fig. 18. Main part of plastification is presented in front of cutting tool chamfer, because of too small feed rate. Therefore, the real rake angle is even more negative (instead of -6° is -26°).

On this result, it is possible to conclude that (i) cutting tool edge chamfer must be decreased or even eliminated. In spite of that, the cutting edge still must be honed, to reach machined surface quality, or (ii) use positive cutting tool geometry.

The material immediately in front of the tool is bent upward and is compressed in a narrow zone of shear, which is shown in Fig. 18. For most analyses, this shear area can be simplified to a plane. As the tool moves forward, the material ahead of the tool passes through this shear plane. If the material is ductile, fracture will not occur and the chip will be in the form of a continuous ribbon. If the material is brittle, the chip will periodically fracture and separate chips will be formed. In this case, the material is grey cast iron but it is not so brittle. It is within the shear zone that gross deformation of the material takes place, which allows the chips to be removed. As on the stress-strain diagram of a metal, the elastic deformation is followed by plastic deformation. The material ultimately must yield in shear. As the material flows from the bulk of the work-piece to the shear area, it is violently sheared, and then continues into the chip section. Change of uncut and cut chip thickness characterize shrinkage coefficient:

\[ \lambda = \frac{h_i}{h} \]  

Value of shrinkage coefficient in this case is \( \lambda=2 \), while the share plane angle is \( \Phi=20^\circ \). Share plane angle increase if the shrinkage angle is decreased. With increasing of cutting speed and feed rate, the share plane angle is decreasing. Nevertheless, the share plane angle is also decreasing with increasing of rake angle. So important is to decrease share plane because that leads to reducing of cutting forces and temperatures in cutting zone.

**Cutting Conditions Improvement**

From experiments above, it is possible to conclude that the main reason of low productability is to high tool-wear rate. There is no escaping the fact that in one respect, tools for high production technology are just like all others. They wear out.

Crater and flank wear develop during the working life of all high production technology tools. Knowing how wears and very important burr arises and the effect will nevertheless help maximise the productivity benefits of finish turning case – grey cast iron surfaces. To increase machinability of used grey cast iron can be implemented three improvements: (i) tool geometry, (ii) cutting parameters and (iii) cutting tool path.

**Tool geometry**

From the properties (Fig. 8 and Table 1) of used grey cast iron can be seen, that the content of free ferrite is above 10%. The hardness of free ferrite is about 90 HBN, so in this case we have to deal with relatively (very) soft grey cast iron and the need of high tool toughness is not necessary and rake angle can be increased and chamfer angle of tool edge can be decreased.
Virtually all high production technology inserts have a chamfer, which is essential for controlling their performance\(^1\). In addition, a chamfered edge is less sensitive to chipping and generally performs more consistently (Fig. 19). From Ref.\(^1\), the honed tool giving a low resultant force as compared to the chamfered tool; Cutting direction stresses are higher at the tool tip and on the chip surface for the chamfered tool due to greater work-piece-tool contact area. In addition, the compressive stresses are distributed over a wide range due to larger chip-tool contact length.

Increasing of cutting rake angle, thereby increase the cutting edge shear angle and improve chip flow over the insert. This lead to lower cutting forces and thus lower levels of transferred energy. The result is lower temperature level in the cutting zone. Improvement in tool-life released through reduced flank ware, due to lower temperature and load. Reductions in both cutting temperature and load lead to a reduction in chemical attack of the cutting edge, thereby increasing tool-life. In addition, also the improvement in surface finish due to the improved chip flow can be expected. Improved cutting tool is shown in Fig. 20. From the economical point of view, the proposed geometry is better, because it is possible to manufacture positive tool geometry with grinding. Such tool configuration combines the advantage of an increased shear angle and cutting edge with economics of a multi-cutting edge solid CBN insert.

**Cutting parameters**

Second improvement in machinability could be done with improved cutting parameters. Course of high wear rate of critical cutting tool T6B is because to low feed rate \(f=0.08 \text{ mm/rev}\). From the tool manufacturer the recommended feed rate cutting depths form 0.5-4 mm are between 0.2 to 0.8 mm/rev\(^6\). Increasing of feed rate will not just increase tool-life, but also decrease burr formation possibility on work-piece edge, because it is known that higher the feed rate is, smaller is the possibility for plastically deformation of material.

**Tool path**

The third addition is to improve cutting strategy, to increase machinability due to reduce the probability of burr appearance. In cutting process planning of part, designers need to pay attention to burr formation potential on part’s edges\(^18\). Burr at certain location on the edges can affect part’s performance drastically. To the minimum, designer should be aware of the impact of edge finish on the part’s performance. The critical edge where burr formation is not allowed must be clearly specified (not as subjective filling). In above presented technology, after some tool-wear on work-piece edge burr appears. This burr has very low high (about 5 µm) and is shown on Fig. 21.

This burr appears at entrance of cutting tool T6B (backward flow). To decrease the possibility presence of that burr, the cutting strategy can be changed, as mentioned in Refs\(^19,20\). It is clear that whenever possible, the part’s edge angle should be greater than 90°, especially when burr forming is critical (Fig. 22). This same idea leads to the notation of pre chamfering part’s edge to avoid burr formation in turning.
In case of that work, the improved technology to decrease the burr appearance possibility is shown in Fig. 23.

Conclusions
As one of the most important targets and solutions of high speed manufacturing is the manifestation of an analysis approach, in which the whole value adding chain is taken into consideration. Thus, in the development process the manufacturing steps for row material must be analysed in order to calculate costs and validate the manufacturing relevant parameters (dimensions, mechanical properties, microscopic material structure, manufacturing behaviour such as abrasive reaction characteristics in chipping process).

This means also that resources and environment must be dealt with in product and process development issues. Applying this concept of sustainability to material and manufacturing process research, in addition to the economical scale, the following aspects have to be taken into consideration: (i) reference materials of specific characteristics, (ii) machining tools (mould and dies), methods and indicators (e.g. tool-wear, specific cutting force) and (iii) optimised manufacturing processes.

Manufacturing based on cutting processes covers more than 60% of the value adding chain. Especially new cutting materials and tool technologies offer increased functionality to operate by higher speeds, tool-life performance and process quality. Improvements in machine tool construction showing flexible concepts and mechanical properties with higher feed rate capabilities, stiffness and accuracy guide to innovative process application, such as high speed cutting and dry machining. Furthermore, materials research must furnish important contributions especially in the field of mechanical engineering technology for the assessment of operational strength and system reliability. Efficiency increase in mechanical engineering apart from lightweight construction aspects and the integration of information technology into mechanical engineering, this industry in terms of economic efficiency especially benefits from durable tool materials, low-cost manufacturing processes, innovative joining technologies and from so-called “intelligent materials”, which have a high potential for energy saving and performance increase in many fabrication processes.

In Automotive industry, part materials are chosen or developed to be able to operate at specific mechanical and thermal conditions encountered in service and at the same time maintain their machinability characteristic to ensure economical aspects of used material. Machining of this grey cast iron (dealt in this work) generate high temperatures at the cutting edge, which impair the performance of cutting tool materials. Commercially available cutting tool materials can only be used at moderate speed conditions. Superior tool material such as CBN is capable of producing high quality components at higher cutting speed condition. Like all tool materials their tool-life is limited by extreme temperature and/or pressure generated at the cutting interface. Since all tool materials lose their hardness at higher cutting conditions, there is a genuine need to harness technologies tailored specifically to minimising the temperature generated at the tool-work-piece and tool-chip interfaces. In machining technology optimization, machined parts customer requirements must be taken into account. In machining of automotive parts, surface quality, tolerances and productivity are the most specified customer requirements, where major indication of surface quality on machined parts are surface roughness and burr appearance.

Briefly, paper presents alternatives and chipper way of improving performance of available cutting tools as well as introducing improved cutting technology, which can markedly improve soft material machinability. Future machining of such grey cast iron at higher speed conditions can therefore be improved by a combination of appropriate tool material, machining technique and the choice of a suitable cutting tool geometry.

References