High Speed Cutting of Grey Cast Iron

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ABSTRACT
High Speed Cutting (HSC) is recognised as one of the key manufacturing technologies for higher productivity and throughput. This report describes the application of High Speed Milling (HSM) to end milling of grey cast iron with polycrystalline cubic boron nitride (PCBN) and Cermet (HT) cutting tools in terms of performance and wear behaviour of these tools. The calculation of cutting forces by the use of an active magnetic bearing spindle (AMB) is dealt with as well as the resulting surface roughness depending on the tool geometry and wear behaviour.

INTRODUCTION
The expression high speed refers to cutting speeds v_c and mostly to spindle rotational speeds n which are substantially higher than for common applications. The range of cutting speeds for high speed milling depends on the workpiece material [1]. In case of high speed machining of grey cast iron the cutting speed should be more than 900 m/min. The upper limit in cutting speed is 5000 m/min. In order to machine aluminium alloy the cutting speed for HSC ranges from 2500 up to 7500 m/min [2].
The major objectives of high speed machining research are the technological and kinematical conditions of the process. In comparison to conventional machining the reduction of cutting forces is the most important technological advantage. Lower chip thickness ratio with respect to the kinematical conditions leads to higher contact length. Due to these conditions high speed cutting offers several advantages over conventional cutting (Fig. 1). High material removal rates and high surface quality accompanied with high shape and form accuracy are the most common advantages. Apart from increased productivity and throughput, high speed cutting offers the following objectives:

- reduced burr formation,
- less damage of surface integrity,
- possibility of machining of thin webs,
- higher stability in cutting due to less vibrations.

For this reasons HSM has been widely applied in the aerospace industry for end milling of thin walled and pocketed aluminium shapes. Commercial aircraft structures show webs of typical 50 mm height, 5 mm thickness which were machined with end mills less than 38 mm diameter, up to 120 mm length. A quantity of metal removal of approximately 90% of the bulk material is typical for these machining operations. On the other hand high removal rate milling HSM is more and more used for fine finishing processes like milling of scrolls in turbo chargers or compressors in air conditioning systems. End mills of 6 to 12 mm diameter with length 50 - 100 mm are used. Also milling of fan or impeller blades for jet engines and milling of hardened dies are application areas involving mostly ball nose end mills in a range from 2 up to 32 mm in diameter.

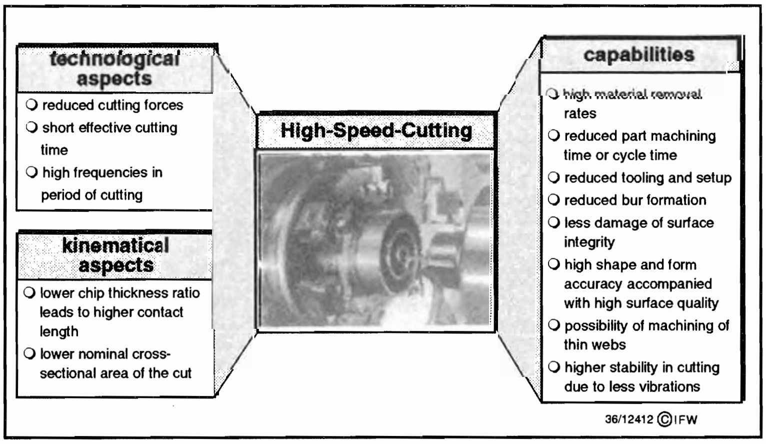

FIGURE 1: Conditions and advantages of high speed machining

EXPERIMENTAL DETAILS
High speed milling experiments with end mills were carried out to investigate the performance and wear behaviour of the tools. The investigations were realised by testing two different cutting tool materials; polycrystalline cubic boron nitride (PCBN) and Cermet (HT). In contrast to the Cermet tool, which has a helical angle of 30°, the cutting edges of the PCBN tool show an inclination angle of 2-3°. The diameter of both tools was 7mm. In all experiments the depth of cut was constant (a_p=18mm).
The used workpiece material in the investigations was grey cast iron (GG-25, corresponding to AISI A48-40B). Concerning the influence on the tribological system of the machining process workpiece material is

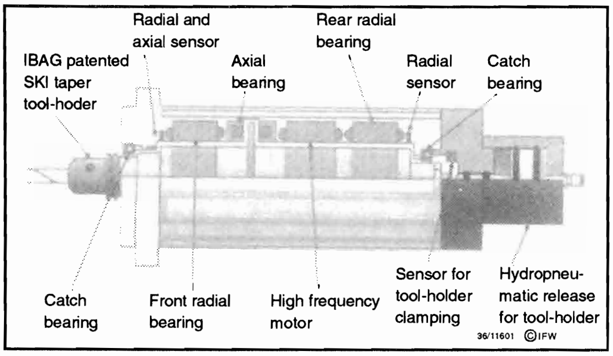

FIGURE 2: High-frequency-spindle [3]

important in many cases. The different specific properties of the material leads to significant influence on the tool load and tool wear.

The workpiece material GG-25 shows a homogeneous structure of a pearlitic matrix with embedded graphite fins. Classified by ASTM standards the material consists of graphite in the order of A. The content of free ferrite is less than 5%. The specimen were in an annealed state. The workpieces were bars of grey cast iron GG-25, with a length of 300mm, 60mm width of cut and hardness HB 187-241.

The experiments were carried out with a CNC vertical milling machine Heller PFV 1. The nominal power of the machine is P_n=30kW. The maximum number of revolutions is limited to n_{max}=5.000 rpm. The feed speed can be varied in the range of v_f=1-10.000 mm/min.

In order to obtain the necessary spindle speed the machine was equipped with an IBAG AMB-spindle HF120MA80A. The construction of this spindle is shown in Fig. 2, the technological data are listed in Tab. 1. Besides higher power and spindle speed these AMB-spindle offers a stiffness 10 times higher compared to spindles with ball bearings. These advantages go hand in hand with increasing costs up to the power of two to three. In this context life time has to be taken into consideration. Life time of spindles with ball bearings is about 2.000 h while guaranteed life time of AMB-spindles is 6.000 h [3].

Spindle	IBAG HF 120MA80A	
speed rpm	30.000 - 70.000	24.000 - 60.000
bearings	AMB	ceramic
power: permanent	7 kW	3,5 kW
peak	10 kW	7,5 kW
taper size	SKI 25	1 : 8 ∅ 17
max. Load: rad.	500 N	
axial	400 N	
stat. stiffness: rad	500 N/µm	50 N/µm
axial	400 N/µm	45 N/µm
dyn. stiffness: rad	800Hz>40N/µm	
axial	800Hz>40N/µm	
costs	220.000 DM	85.000 DM

TABLE 1: Technological data

Milling experiments under various conditions of cutting speed and feed rate proved the performance of these tool materials. The resultant surface roughness depending on both the cutting speed and feed rate is dealt with as well as the wear pattern and behaviour of the tools. Further objects of these investigations are to obtain basic data like cutting force calculated from the current and the displacement signals of the spindle, surface roughness and wear behaviour of the tools depending on the cutting length.

WEAR IN MILLING

Cutting tools are subjected to a complex load spectrum, consisting of mechanical, thermal and chemical components. The amount of these loadings respectively their temporal and local behaviour determines the wear of cutting tools. The machining process high-speed-milling is associated with regular chip discontinuity leading to non-steady-state cyclic conditions on the cutting edge. When a tooth engages the workpiece, it receives a strong shock followed by a varying forces. During the cutting part of the cycle the cutting edge is stressed and heated, followed by a period of time when it is unstressed and allowed to cool. The entering shock is detrimental to tool life, while the cooling period is usually beneficial, unless the tool material is sensitive to thermal shock. In HSM cutting times are fractions of milliseconds, involving both thermal and mechanical fatigue of the tool.

In order to improve the surface roughness high-speed-

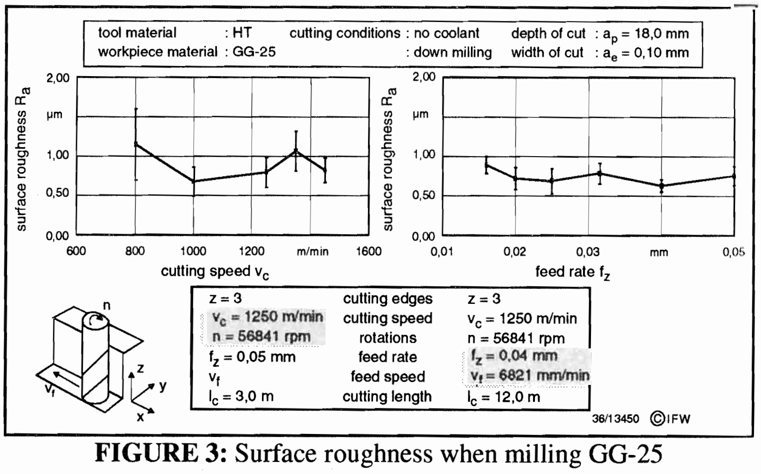

FIGURE 3: Surface roughness when milling GG-25 with a Cermet tool

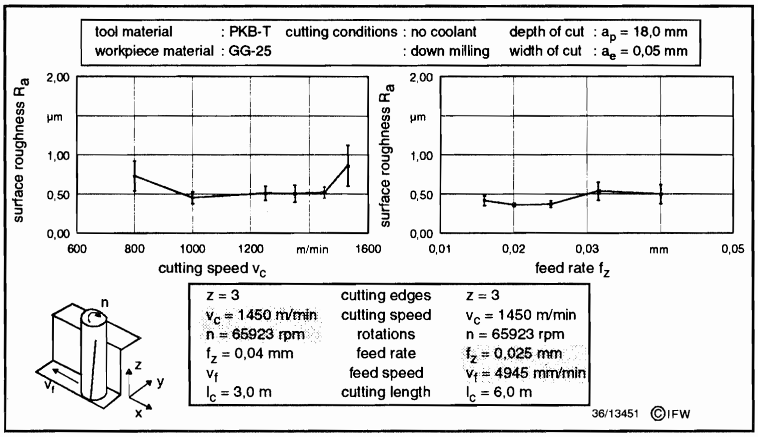

FIGURE 4: Surface roughness when machining GG-25 with PCBN

milling experiments under various conditions of cutting speed and feed rate were done. The resultant surface roughness for the Cermet tools is shown in Fig. 3, the results for the PCBN-tool are described in Fig. 4. For

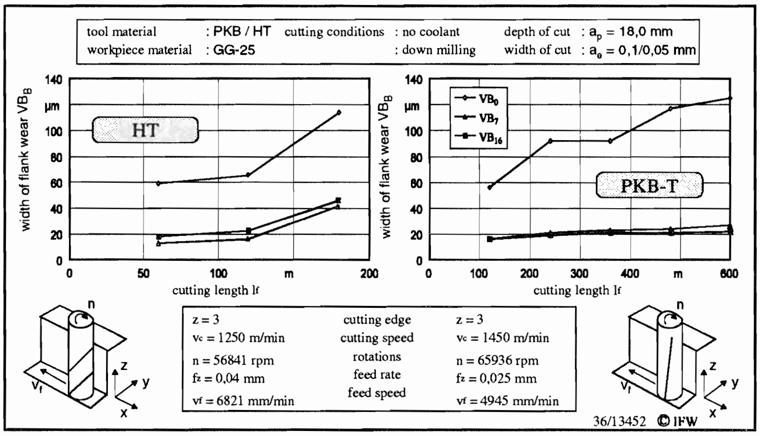

FIGURE 5: Width of flank wear land verus feed length

all conditions better results were achieved for the PCBN-tool. The smaller corner radius of these tool leads to a stable process in chip formation which reduces vibrations and results in higher surface quality. Due to the lower toughness of the PCBN-tool the mechanical load was reduced by lower feed rates and lower width of cut compared to the Cermet tool. The cutting conditions for HSM-tests were based on these results. The selected conditions are marked by a grey pattern.

In this special case of application, the surface roughness depends less on cutting speed and feed rate compared to conventional machining. The results are also influenced by the performance of the tool and spindle in the cutting process. In general, the surface roughness in not influenced by increasing cutting speed. This means that the received results from both tools show effects of the balance of the tool and the automatic balancy system of the spindle. Concerning the influence of the feed rate, the higher corner radius of the Cermet tool effecting the surface quality has to be taken into account.

The progress of wear (Fig. 5) shows differences in the performance of the tools. Life time criteria for both tools was a defined value for the surface quality or a width of flank wear of more than VB_B=100µm. The life time of both tools was limited failure in form of tool breakage. In fact of this matter the cutting length of the Cermet tool was limited to l_f=216m; the PCBN-tool was damaged after l_f=720m. The width of flank wear was measured at three distances from the top of the tool; direct at the top, 7 and 16 mm away from the top (depth of cut=18.0mm).

For common increasing cutting speed decreases the tool life distance due to higher thermal load whereas a rising feed rate accompanied with higher mechanical load increase that value [4]. These effects are less dominant compared to the properties of the different tool materials like shown in Fig. 5. Highest thermal tool load is located at the top due to the cutting process by machining the side walls and the bottom. Here flank wear developed quickly after engagement for both tools. Far from the top the progress of wear is more regular at the given cutting conditions.

A cutting edge of the Cermet tool worn by HSM of grey cast iron (Fig. 6) is characterised by non uniform wear. At the top of the tool occurs crater wear without cracks. 0.5 mm away from the top the cutting edge is rounded and no crater wear characterised the rake face. The clearence plane is

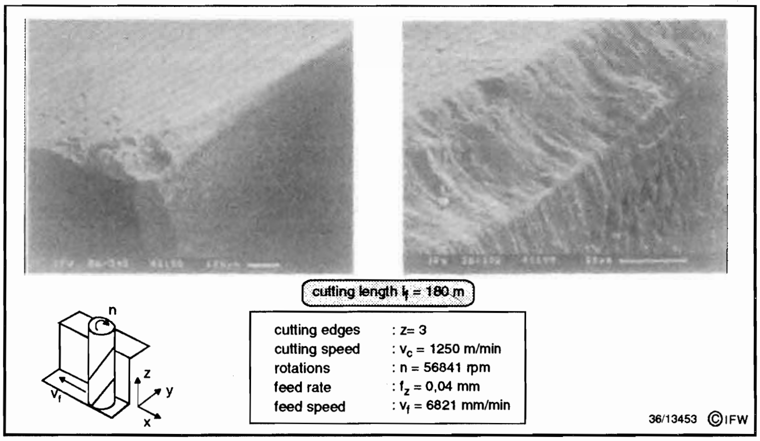

FIGURE 6: Cermet tool worn by HSM GG-25

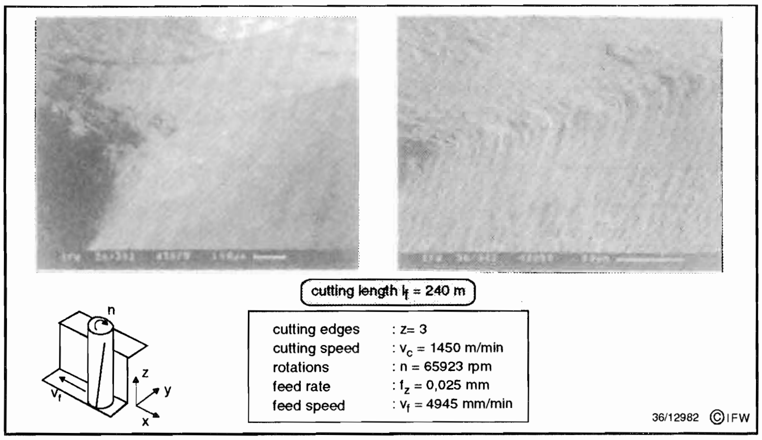

FIGURE 7: PCBN-tool worn by HSM of GG-25 after l_f=240m cutting length

performed by abrasice flank wear. Material deposits can be recognised over the complete area of contact between tool, chip and workpiece.

The wear behaviour of PCBN it totally different, com-

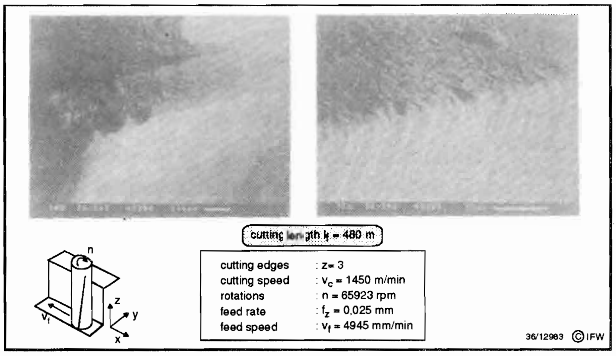

FIGURE 8: PCBN-tool worn by HSM of GG-25 after l_f=480m cutting length

pared with Cermet. After a cutting length of l_f=240m in the direction of feed motion the cutting edge shows cracks on the rake face, as shown in Fig. 7. Even on the clearance plane a small shadow line give hints to cracks that will occur.

Apart from these behaviour similar wear mechanisms could be recognised like crater wear at the top of the tool or material depositions at the contact areas. Based on the higher abrasive wear resistance of PCBN the area of crater wear is about 60% smaller (0.2mm) than the crater wear at the Cermet tool (0.5mm).

The enlargement in the upper right side of Fig. 7 shows that the corner radius of the tool is up to 5-7µm, the corner radius of the Cermet tool was measure to 15µm.

The different manufacturing technique of the tools is the reason for these properties. The Cermet tool was gound completely from bulk material. Finishing of the PCBN-tools can be divided into two parts: machining of the shaft and grinding of the cutting edges made of PCBN. Finally the tool is finished by brazing the edges inside the shaft. Based on these technology really sharp cutting edges could be received for PCBN-tools.

Fig. 8 shows the same cutting edge after l_f=480m cutting length. Although the cutting length is more than twice as long, the wear proceeded little. The area of crater wear on the top of the tool is little grown up. Far away from this area, no significant modification in the wear behaviour can be recognised, like shown in Fig. 5 in a earlier state. The most important point is the now visible crack on the clearance plane of the tool. Compared to the earlier state in Fig. 7 this crack is now really in existence while the crack on the rake face of the tool has not grown larger. Based on these cracks, the top of the cutting edge is more and more grown weak. While continuing the test, the tool was totally damaged by tool breakage after a cutting length of l_f=720m.

With respect to the obtained results we expect small parts of the cutting edges broken out leading to tool breakage. The wear behaviour of the PCBN-tool proves, that the chosen type of PCBN is too brittle for these experiments. Due to the strong shock followed by varying forces, when the cutting edge engages the workpiece, cracks occur to these type of PCBN. So the mechanical impact is responsible for tool life of the PCBN-tool.

CUTTING FORCES

An option of the spindle is to check the present position of the rotor and the effective currents in the magnetic bearings by BNC connectors for in-process measurements. An on-line control of the machining process is possible by using the collected signals. Besides, the effective force components at the cutter can be calculated referring to the different signals stored during idling and machining. The corresponding calculation formular results in:

$$F = k_{Di} \cdot X_i \cdot U_{Di} + k_{Ci} \cdot C_i \cdot U_{Ci}$$

with i as an index for the bearings (i = A,B,Z; A: rear bearing, B: front bearing, Z: thrust bearing). With regard to the constants the equations for the bearing forces in the co-ordinates i=x respectively y results as follows:

$$F_{Ai} = 10{,}21 \cdot (U_{DiN} - U_{DiM}) + 28{,}88 \cdot (U_{CiN} - U_{CiM})$$
$$F_{Bi} = 20{,}29 \cdot (U_{DiN} - U_{DiM}) + 53{,}76 \cdot (U_{CiN} - U_{CiM})$$
$$F_Z = 3{,}53 \cdot (U_{DN} - U_{DM}) + 9{,}20 \cdot (U_{CN} - U_{CM})$$

Finally the calculated 5 forces can be expressed in 3 forces acting on the tool:

$$F_x = - F_{Ax} + F_{Bx}$$
$$F_y = F_{Ay} - F_{By}$$
$$F_p = F_z$$

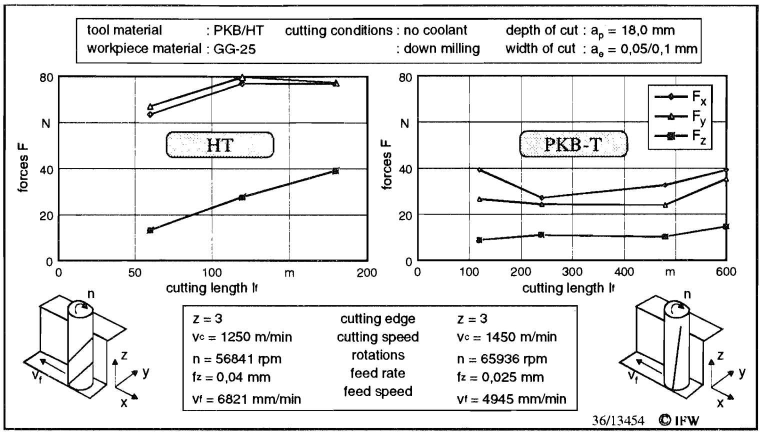

FIGURE 9: Cutting forces verus cutting length

The results received depending on the machine path for both tools are shown in Fig. 9. We can summarise that the curves for x- and y-forces have approximately the similar behaviour versus the cutting length. Compared to these two force components the force in axial direction is lower. The increase in force is influenced by the tool wear, which can be distinctly shown in the behaviour of the passive force for the Cermet tool. With forthgoing of the machining length the cutting force increases. Corresponding to lower progress of wear the PCBN-tool (Fig. 5) the increase of forces is much smaller.

The force components in x- and y-direction of the Cermet-tool have a value twice as large as the force of the PCBN-tool. These results are discussed with respect to the calculation of cutting forces and the geometry of the tools. As described the cutting force components at the cutter can be calculated referring to the different mean value signals stored during idling and machining. When using a tool with spiral cutting edges like the used Cermet-tool, the actual period of cutting versus one rotation of the endmill is longer in comparison to a tool with straight cutting edges like the used PCBN-tool. The straight cutting edges leads to high impact loads like shown on the right part of Fig. 10. Based on actual forces depending on the geometry, the mean value - which was calculated for determination of the steady-state cutting forces - for a tool with spiral cutting edges is higher, in comparison to a tool with straight cutting edges.

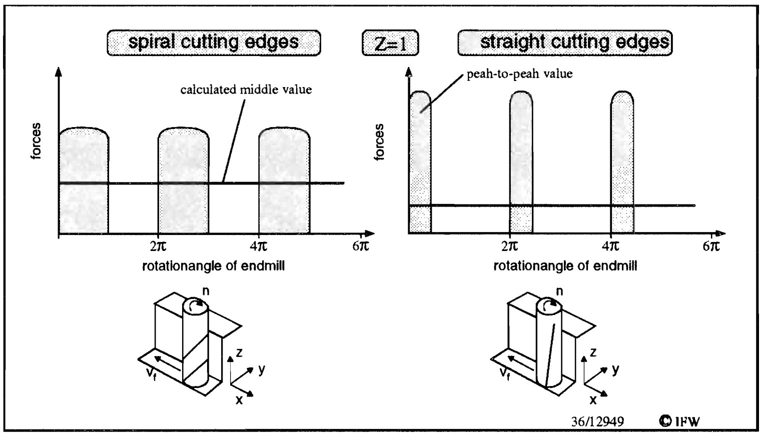

FIGURE 10: Calculated cutting forces

SURFACE QUALITY

A capability of finishing process in the area of High-Speed-Cutting is to obtain a high shape and form accuracy accompanied with high surface roughness [5]. These results, especially the resulting surface quality, depends on the performance of the cutting tool material which actually is influenced by their specific properties. Fig. 11 shows the development of surface roughness measured on the bottom of the machined path which is machined by the top of the tool (R_{aB}) and at the side walls (R_{aW}).

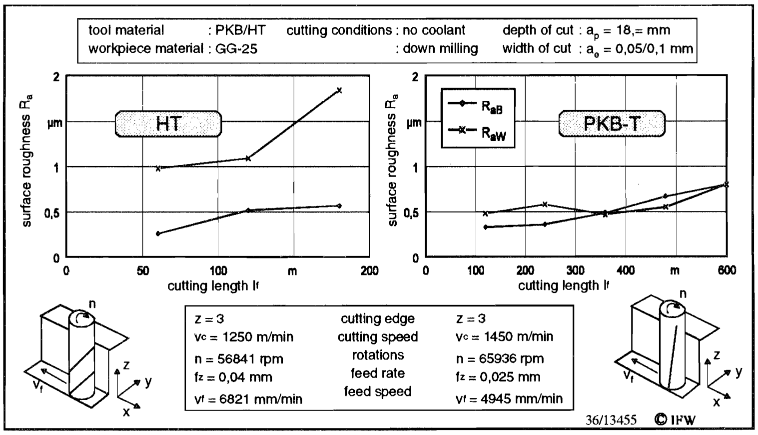

FIGURE 11: Surface quality at the bottom and at the wall versus cutting length

In agreement with progressing tool wear (Fig. 5) the surface roughness increase with forthgoing of cutting length. In order to higher tool wear of the Cermet tool the resulting surface roughness is higher compared to the PCBN-tool with straight cutting edges. Especially, the high value of the mean value deviation of the profile R_{aW} for the Cermet tool is strange and could not only be attributed to the tool wear. The surface quality is additionally effected by vibrations like shown in Fig. 12. After cutting length of l_f=216m the Cermet-tool failed by tool breakage.

The resulting surface after these tool failure shows, that during the cutting process two cutting edges are actually formatting a chip. In common understanding tools with spiral cutting edges show a smoother machining than a tool with straight cutting edges. The reason is that straight cutting edges lead to a step-by-step machining which general involves vibrations in the process.

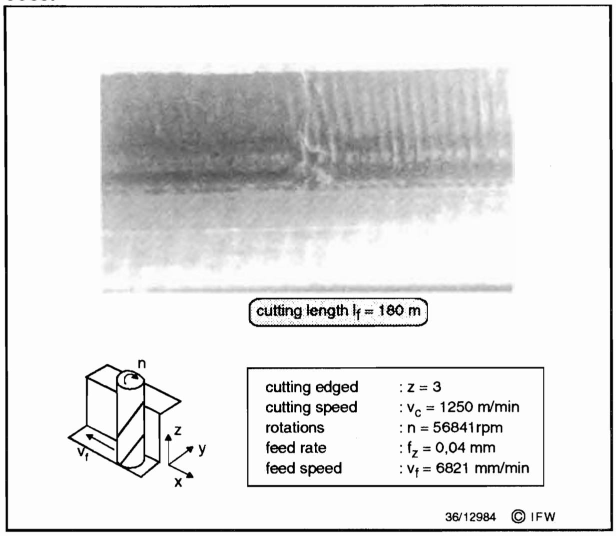

FIGURE 12: Surface topography of the workpiece when using a tool with spiral cutting edges

CONCLUSIONS AND OUTLOOK

Investigations of wear pattern in high-speed-milling revealed that Cermet and PCBN cutting tools perform different, in dependance on their specific properties and on tool geometry. It is shown that the Cermet tool is less resistant to abrasive wear in a milling process, so that the resultant tool life is short. In comparison, polycrystalline cubic boron nitride (PCBN) offer longer tool life but the costs for these tools are up to the power of 15 to 20.

The experiments have shown, that vibrations don't occur when using the PCBN-tool with straight cutting edges. These behaviour, the cutting process with the Cermet-tool is mainly influenced by vibration which lead to tool failure.

The application of an AMB-spindle for calculation of cutting forces, referring to the different signals of the current and the displacement recorded during idling and machining, has shown a good opportunity for measuring forces in HSC without additional equipment. The influence of tool geometry on the received results have to be taken into account when discussing results.

The present work has shown that High Speed Milling with PCBN-tools is suitable for end milling of grey cast iron in order to reach reduced part machining time and high surface quality. Further work is needed on improving wear behaviour of the tools by variation of different typed of PCBN materials, like kind of boundary phase or grain size. Further research is needed in order to separate the influence of the spindle behaviour and the tool due to the vibrations in the cutting operation.

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