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HIGH-SPEED MILLING - A NEW MANUFACTURING TECHNOLOGY

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Abstract: *High-speed milling (HSM) is becoming industrial practice instead of only laboratory use. Still it is generally considered a new manufacturing technology. The high-speed milling method has many benefits compared to conventional milling. Very often high-speed milling is considered just a way to improve productivity resulting from faster cutting speeds than those used conventionally. Seldom is it emphasised that the product quality can be improved as a consequence of increased accuracy and better surface finish.*

This report is based on the results of several Finnish projects on high-speed milling for testing the suitability of high-speed milling for different kinds of materials. In this paper the following topics are discussed: milling tools in high-speed machining and high-speed milling of different materials. The materials machined were steels, aluminium alloys, graphites and polymer matrix composites. The conclusion drawn is that most of the materials can be machined by high-speed milling. A good result is obtained by careful selection of cutting parameters. In high-speed milling, the tool life with a goal-oriented milling tool - material machined - cutting parameter combination is acceptable and the machining result is sufficient. When tools are not selected goal-orientedly, the rate of tool wear is rapid.
Key words: cutting, high-speed cutting, high-speed machining, high-speed milling, tool wear

1. HIGH-SPEED MILLING

Some benefits of the high-speed milling method compared to conventional milling can be listed as follows: The increase in cutting speed, cutting feed and chip volume, the improved surface quality, the decrease in cutting forces resulting in better accuracy due to the lower level of loads of the tool and the machine tool and the heat from the cutting zone is transferred mainly into chips, leaving the workpiece temperature relatively low and a decrease in machining time and machining costs. Very often HSM is considered just a way to improve productivity resulting from faster cutting speeds than used conventionally. Seldom is it emphasised that the product quality can be improved as a consequence of increased accuracy and better surface finish.

The main objective of the research performed by Helsinki University of Technology HUT and Technical Research Centre of Finland VTT has been to test the suitability of high-speed cutting for different kind of materials and products. Results are based on the collaborative investigation performed by HUT and VTT in close cooperation with Finnish industry. The tests have been carried out with a vertical-type machining centre Modig MD 7200, Fig. 1. Its spindle is fitted with ceramic ball bearings and can achieve a maximum speed of 45000 rpm at 5/7 kW. The maximum feeds are 24 m/min on the X and Y-axes and 20 m/min on the Z-axis. The numerical control chosen is Heidenhain TNC 415.

Fig. 1. The vertical-type machining centre Modig MD 7200 in the laboratory of HUT.

2. MILLING TOOLS IN HIGH-SPEED MACHINING

The wear of the tool material is considered to be the most important factor limiting the cutting speed. High-speed steels and coated high-speed steels were left out of our research tests because of their low wear resistance. The tool life of carbide tools with high cutting speeds is known to be short. However, they can be applied for machining soft materials. Cermets are offered for the finishing of steels. Super hard tool materials like CBN and PCD are naturally considered as belonging to the group of HSM tool materials.

The cutting tools applicable in high-speed milling can be divided into solid mills and multipart mills, Fig2. In our fields of activities our laboratory has also included the manufacturing of complex workpieces, for example the manufacture of dies. In that field, solid end mills are mainly applied. According to our experience, most standard cutting tool geometries work in high-speed machining.

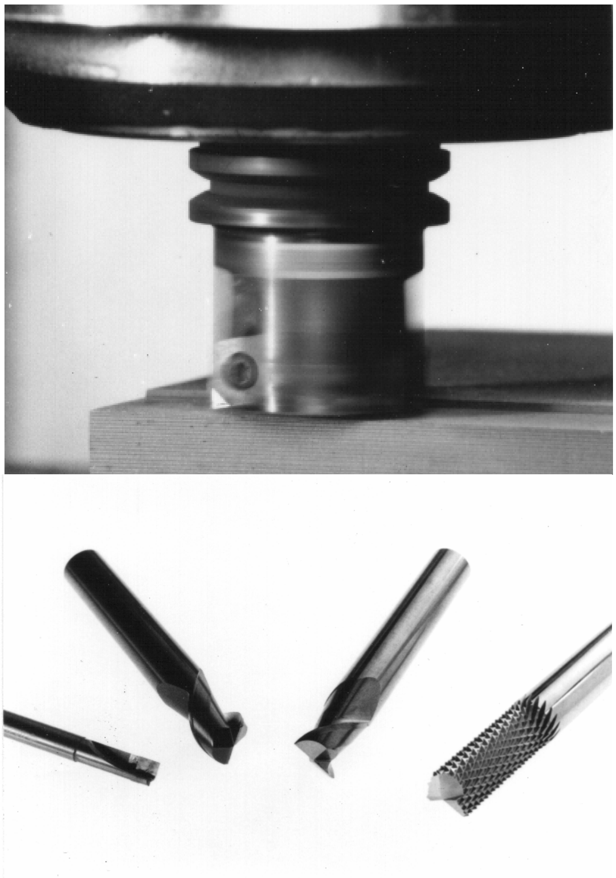

Fig. 2. Tools applied in high-speed milling. Upper figure shows an ø 32 mm PCD face mill. Lower figure ø 6 mm PCD end mill, ø 12 mm aluminium oxide end mill, ø 12 mm cermet end mill and ø 12 mm glass-fibre router with special geometry.

3. HIGH-SPEED MILLING OF DIFFERENT MATERIALS

3.1 High-speed milling of steels

The most interesting field of high-speed milling is the machining of steels, because they are the most widely used materials in engineering applications. There are a lot of steels, especially cold work, hot work and plastic mould tool steels to be finished at hardened state. High-speed milling can also be used in the machining of hardened steels. It is often used instead of electric discharge operations in finishing of die or mould cavities. CBN tools are often used, due to their many advantages, such as it gives an alternative to carbides.

The problem related to the high-speed milling of steels has been the insufficient wear resistance of the tools as well as lack of the knowledge concerning the cutting parameters for hard materials. The development of the tool materials and tool geometries has made it possible to perform investigations into the high-speed milling of different steels, even high-alloyed tool steels in tempered condition.

The wear resistance of the silicon nitride tools as well as alumina tools with yttrium oxide proved quite insufficient when tool steels were machined. In most cases tool failure was caused by breakage of the cutting edge of the tool. Excellent and promising results were achieved with cubic boron nitride ball-nose end mills when machining hardened (60 HRC) tool-steel materials. No tool wear was observed when using cutting parameters which were about 10 times higher than those recommended by the tool manufacturer. The surface roughness values are better than those of a ground surface.

Some cutting tests were carried out by face milling steel surfaces with end mills. The tested tools were solid carbide (grade K10 TiN-coated) end mills ø 8 and 10 mm, cermet end mills ø 6.8 and 10 mm, ceramic (Al2O3+Y2O3 and Si2N3+Y2O3) end mills ø 5.6 and 12 and a cubic boron nitride ball end mill ø 10 mm. The tested workpiece materials were carbon steel, cold-work steel, hot-work steel, tool steel. An emulsion was used as cutting fluid in the tests. Cutting fluid cannot be used when ceramic or cermet tools are used in the milling of steels because their poor resistance to thermal shocks. CBN tools were also used without cutting fluid.

High cutting speeds and feed rates could be used with TiN-coated cemented carbide and cermet tools, when quenched and tempered steels are machined. The cutting speeds varied from 180 m/min to 1400 m/min and the feed per tooth from 0.015 mm/tooth to 0.11 mm/tooth (from 0.2 m/min to 10 m/min).

The geometry of the end mills used in most of the cutting tests is not suitable for the high-speed milling of steels. Cutting forces directed to the cutting edge are so high when finishing with high cutting speeds and using a small axial depth of cut that the sharp and brittle nose of the edge cannot bear the resulting stress. A lot of experimental work is required to optimise the tool geometry for the high-speed milling of steels.

When ball end mills were used in the experiments, very promising results were achieved. All tool materials, i.e. coated cemented carbides, cermets and especially cubic boron nitride indicate excellent wear resistance and the surface finish of the workpiece was better than expected.

3.2 High-speed milling of aluminium alloys

The machinability of aluminium alloys is relatively high. Milling aluminium materials with conventional cutting parameters is easy. Cutting forces are low and tool wear relatively small. Tool wear rates of the cutting tools do not normally play a significant role in the machining of aluminium alloys.

Our cutting tests were performed to determine the behaviour of some commercially available tools in the HMS of different aluminium alloys. It is noted by Coleman that the most suitable aluminium and magnesium alloys have no material-removal-rate limitations (Coleman, 1992). Our results confirm this.

Cutting tests were performed according to the following procedure: Up milling was applied. Reference tool and tool for comparison tests were solid carbide (grade M20/M30) drilling end mills ø 10 mm, 2-fluted. Other tools were: solid carbide (grade K10) drilling end mills ø 6...12, 2-fluted and carbide (grade K10-K20) inserts type face mills ø 20 and 32 mm, 2-fluted. Workpiece materials were AlMgSi, AlZn5Mg and AlZnMgCu1,5.

Cutting parameters:	end milling:	face milling:
cutting speeds m/min	1400	2820 or 4500
feed rates	0.1 mm/tooth	1 - 12 m/min
axial depth of cut mm	3	0.5 or 1
radial depth of cut mm	2 or 5 mm	12 or 25 mm
cutting fluid	not used	used or not used

High-speed milling of the aluminium alloys used in these tests showed that cutting time can be shortened by using higher cutting speeds and feeds. The shortened cutting time for our sample workpiece was about 70 % of the cutting time of the comparative machining centre with a cutter of ø 16 mm. More savings could be achieved using a spindle with more spindle power thus making higher feed rate values possible.

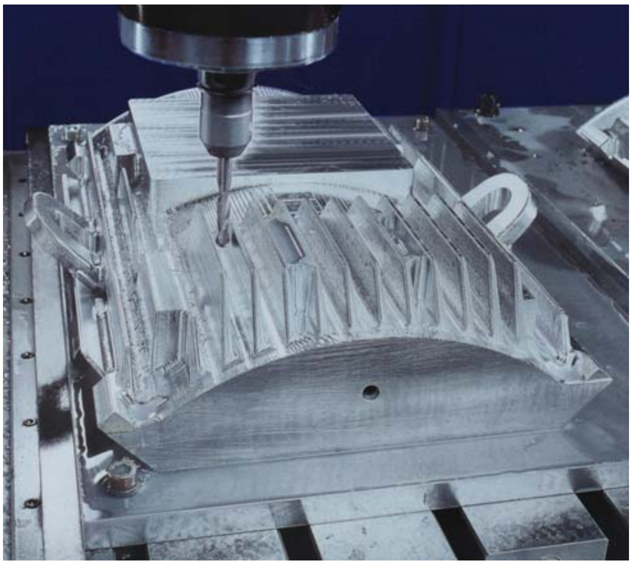

Fig. 3. High-speed milling of an aluminium part /Mikromat/.

3.3 High-speed milling of graphites

Graphites are the most widely used electrode material in EDM operations, Fig 4. Because of the material properties of graphite, higher cutting speeds and feed rates can be used as compared to the machining of metal materials. Differences in hardness, toughness, microstructure and friction characteristics require a modified approach to the selection of tool materials, tool geometries and cutting parameters.

Cutting tests were performed for determining the behaviour of some commercially available tools in high-speed milling operations with graphite. Pocket milling was used as a cutting method, down milling being mainly applied. Semi synthetic emulsion without any EP additives to prevent graphite dust spreading to the environment was used. Cutting tests were performed according to the following procedure: Reference tool was solid carbide (grade K10, micro grain) end mill ø 10 mm, 2-fluted. Other tools were 4 types of solid carbide (TiN-coated also) drilling end mills ø 10 mm, 2-fluted. Workpiece materials were four different graphite types. Cutting parameters: cutting speeds 850 or 1400 m/min, feed rates 0.08 (4.3) or 0.20 (10.8) mm/tooth (m/min) and axial depth of cut 6 mm, radial depth of cut 3 mm.

The curves of flank wear of end mills as a function of time or chip volume are different from those in metal cutting. No stable stage can be observed after the initial wear, but the width of flank wear increases almost linearly for different tool materials, and are quite small. The values of tool wear scatters between individual test repetitions are very small. Differences in the wear resistance between different end mills may result from differences in tool geometry.

High chip removal volumes can be obtained using relatively small tool diameters. In the experiments performed the value of 2.5 litres/min could be achieved with economical and reasonable tool life for the ø 10 mm end mill.

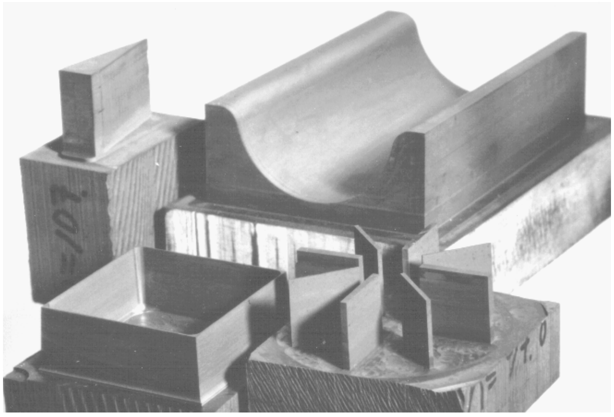

Fig. 4. Sample parts in the high-speed milling tests of graphite.

3.4 High-speed milling of polymer matrix composites

Advanced polymer matrix composites, PMC, typically combine reinforced fibres (glass, aramid, carbon) with a vinyl ester, epoxy, phenolic or thermoplastic resin matrix. Glass fibre is the most commonly used PMC material. Carbon and aramid (Kevlar) are also notable fibre materials that are used commercially. Milling PMC materials using conventional cutting parameters results in many serious problems that can be eliminated by using high-speed milling.

Cutting test was performed to find out the behaviour of some commercially available tools in high-speed milling operations of PMC materials. The following conclusions can be drawn:

- The wear resistance of conventional solid carbide end mills is insufficient for the finishing of polymer matrix composite plates.
- A special type of router with many small cutting edges seems to be very suitable for end milling glass fibre as well as carbon fibre plates.
- Chip dimensions are an important factor affecting tool wear rate when glass fibre is machined with a special router.
- Feed rate does not influence the wear rate of the special router in the milling of carbon fibre.
- When machining carbon fibre with end mills made of Al2O3+Y2O3, wear rates were approximately similar to those with special carbide router.
- Machining holes in a sandwich structure consisting of two carbon fibre plates and the aramid-fibre-based (Kevlar) honeycomb was successfully performed with a special drilling carbide router.
- Diamond tools were the only suitable material for face milling of carbon fibre blocks.

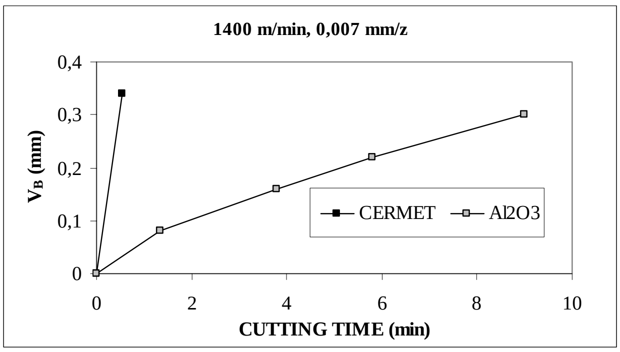

Fig. 5. Flank wear curves in the high-speed milling of glass-fibre.

4. CONCLUSIONS

Significant advantages can be achieved by using high-speed milling in manufacturing of the products made of advanced materials. Very often high-speed machining is considered just a way to improve productivity resulted from faster cutting speeds than used conventionally. Seldom is emphasized that the product quality can be improved as a consequence of increased accuracy and better surface finish. Advantages of HSM can be reached only if interactions between the workpiece and the tool are taken into consideration, the machine tool have been selected in a right way, NC programs have been made correctly, right cutting parameters are used and, the last but not least, the safety aspects have been considered.

Most of the materials can be machined by high-speed milling. A good result is obtained by the appropriate selection of cutting parameters. The empirical selection of cutting parameters is seldom possible in industrial production, therefore results derived from laboratory experiments are needed. In this presentation the high-speed milling of steels, aluminium alloys, graphite and polymer-matrix composites is discussed. The tools applied in high-speed milling are solid end mills and multipart mills. Owing to high spindle speeds, the tool holder and the tool must be dynamically balanced at a sufficient level.

Polymer-matrix composites such as carbon and glass-fibre have been high-speed milled by using advanced carbide and diamond tools. The most interesting application field of high-speed milling is the finishing operations of tool steels. Products made of hardened tool steel and comprising three-dimensional surfaces are successfully milled with CBN end mills without any significant tool wear.

The high-speed milling of materials with low machinability is a tool material selection dependent question. With the appearance of super hard tools, the possibility of high speed machining has significantly widened. Sometimes classic CBN and PCD have their status in the machining of such kinds of workpiece materials causing rapid tool wear. When machining with these tools, the optimal choice of cutting process parameters is important, as the requirements concerning the parts can often only be satisfied by cutting under extreme conditions - small chip cross-section and high cutting speed.

The conclusion obtained is that in high-speed milling the tool life with a goal-oriented milling tool - material machined - cutting parameter combination is acceptable and the machining result is satisfactory. When tools are not selected goal-orientedly, the rate of tool wear is rapid.

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