High-speed milling strategies in mould manufacturing

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High-speed milling strategies in mould manufacturing

High-speed cutting is one of the key issues in mould manufacturing. But to apply high-speed milling to mould manufacturing, unlike conventional milling, it is necessary to define specific cutting parameters. This article aims to define the influence of milling strategies and cutting parameters, such as cutting speed, feeding speed, cutting tool tilting angle, on the process stability.

Long tool life and cutting strategy have a major influence on the results of machining hardened steel. Machining with drawing cut and down-cutting in copper and with drawing cut and up-cutting in hardened steel gave the best results with respect to tool wear and surface quality. Tool approach across the feeding direction results in heavy impact loads on the tool which lead to heavy tool wear and substantial dimensional deviations.

Good surface quality is achieved in machining of a work piece of 2363 steel (X100CrMoV51) hardened to 60 HRC, using the strategy of up-cutting with drawing cut and a tool approach with a tilting angle of 15 degrees. While up-cutting allows for achieving better surface quality, down-cutting provides longer tool life than up-cutting for all angles of approach.

Keywords: Ball-end milling; High-speed milling/cutting; Mould manufacturing

1. Introduction

Manufacturing of small moulds by High-Speed Milling (HSM) plays a significant role in the design and manufacturing chain, from the conceptual to the mass production stage, because reduced cost, larger diversity, and shorter product lead time are required in order to overcome the global competition pressure. To decrease product cycle time, increase product variety, and cope with pressure due to international competition, mould-manufacturing firms need to develop themselves from the technological and organizational perspectives at all stages of production chain.

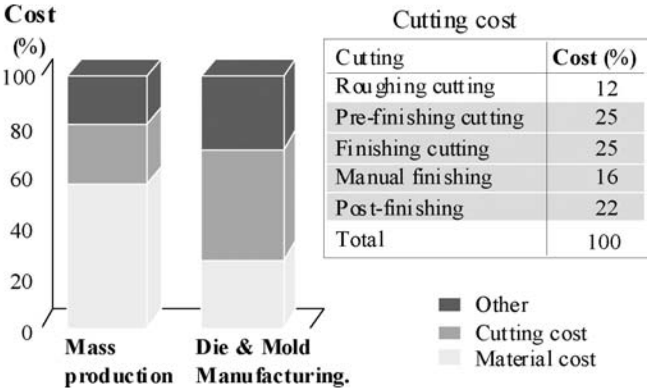
Manufacturing strategies are extremely important to the production of moulds. Schützer et al. experimentally researched the relationship between cutting strategies, machining time and surface quality of a part [1]. The manual finishing process is a vital part in mould manufacturing but it is undesirable, and it defines the smoothness of the mould. Lee et al. established a systematic finishing process model to minimize the finishing time by introducing critical surface roughness and removal volume [2]. Tansel et al. proposed a genetically optimized neural network system to select optimal cutting conditions from the experimental data to minimize the machining time while keeping the surface roughness at a desired level [3]. Major advantages of HSM are high material removal rates, shortening of product lead times, low cutting forces, dissipation of heat with chip removal, increased dimensional accuracy, and excellent surface finish. However, disadvantages of HSM are excessive tool wear and the need for advanced cutting tools and for high-speed machine tools [4, 5]. Fallböhmer et al. experimentally and theoretically studied tool failure and tool life in HSM and prediction of chip flow, stresses, and temperature in the cutting tool [4]. Defining manufacturing technologies in mould manufacturing often relies on personal experience, which sometimes may lead to nonoptimal solutions. Kuzman and Nardin made a brief study of this subject and presented a determination model to decide between two main manufacturing technologies, Electrical Discharge Machining (EDM) and High Speed Cutting (HSC), in mould manufacturing [6].

In recent years, CAD/CAM technologies have been used for the manufacturing of free-form surface moulds. Some researchers have even attempted to develop a geometric algorithm for reconfiguration of previously manufactured moulds for free-form objects to meet user requirements [7]. Using CAD/CAM manufacturing chain is a prerequisite for high-speed milling of free-form surfaces.

2. Application of high-speed cutting in manufacturing of free-form surfaces

In the mould manufacturing industry, functional surfaces occupy more places in proportion to free-form surfaces. These convex and/or concave curvature surfaces can be cut in three-axis milling using a ball-end tool without damaging the contour. Five-axis milling is not appropriate for small-form geometries. The surfaces cannot be generated exactly and can only be approached by a groove profile. This groove profile must be smoothed to obtain the desired finish surface and to remove dimensional deviations. Although several researchers studied the automation of the finishing process using honing tools [8, 9], presently this process has been generally carried out manually. Manual finishing, which is cost intensive and also creates a bottleneck in small-mould manufacturing, requires personnel [10–12].

The cost structure in mould manufacturing substantially differs from the cost structure of mass production. Cutting cost occupies a major share in small-mould manufacturing, if the manufacture of only a single product is involved (see Fig. 1).



Cutting	Cost (%)
Roughing cutting	12
Pre-finishing cutting	25
Finishing cutting	25
Manual finishing	16
Post-finishing	22
Total	100

Fig. 1. Cost structures of mass production and die and mould manufacturing [10, 12].

Manual finishing, such as groove smoothing, requires high cost and high time consumption. The cost of the manual finishing is decisively determined by how the desired contour can be approached. Figure 2 shows that the surface roughness is determined by the stepover and the diameter of ball-end cutting tool.

Use of HSC in mould manufacturing reduces the manufacturing time. Meanwhile, high-speed cutting can be used for two fundamentally different goals in finishing process of steel and copper in small-mould manufacturing [13]:

(i) Keep the manufacturing time constant, improve the surface quality:
The use of HSC cannot reduce the manufacturing time. However, it offers the possibility of increasing the stepover within the same machining time because the feed rates that are employed can be increased by 5 to 10 times. This results in closer approximation to the final contour and leads to substantial reduction in the finishing time and improvement of the surface quality. Inaccuracies involved with the manual processes are also reduced.

(ii) Keep the surface quality same, reduce the manufacturing time:
When this option is selected, HSC reduces the manufacturing time. This means that the stepover is kept constant as compared with the conventional machining. The machining time is reduced due to increased feed rate.

The development of cutting tool materials of better quality promoted the wider use of HSC. However, in the cutting of steel in particular, the limited life of cutting tools represents a problem. Reducing total cutting time and improving surface quality with increasing cutting speed can compensate for increasing tool costs. In addition, changing the tool always causes a mark on the contour. Thermal load of the cutting tool is lower when cutting depths are small. Therefore, longer tool life can be achieved in steel cutting [14, 15].

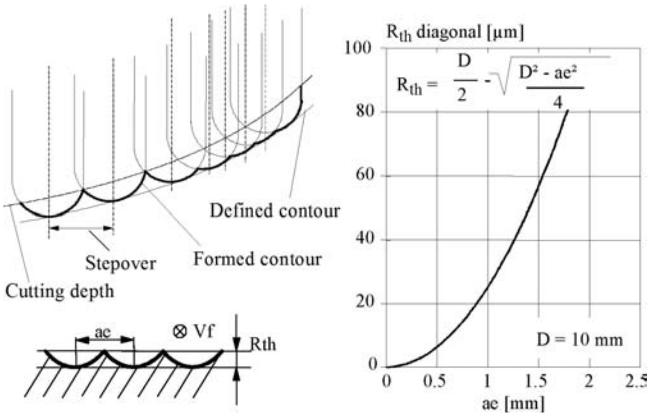


Fig. 2. Influence of stepover on surface quality [16].

Table 1. Advantages of HSC [11].

High chip volume	-shorter cutting time -shorter cycle time
High surface quality	-less manual finishing
Lower cutting force	-cutting of thin-walled work pieces possible

The use of HSC tools, which are made of steel, in die and mould manufacturing is meaningful only for pre-finish and finish cutting. The use of high-speed milling for finish cutting produces better surface for manual finishing. Basically, the rough cutting of steel should take place at normal cutting speeds. This is only possible with the development of better high-tech cutting tool materials. In many cases, milling of the form directly into the hardened steel can alleviate the need for eroding process [17].

The technological advantages of high speed cutting summarized in Table 1 [11].

3. Technological principles

Figure 3 shows the cutting geometry and cutting parameters in three-axis milling using a ball-end cutting tool. A double comma formed chip emerges in milling using ball-end cutting tool. The curvature of the chip lies along the direction of the circumference and also along the cutting edge of the tool. Each single cutting-edge-point has different loadings because the conditions over the cutting edge keep changing. In three-axis milling, chip thickness at the centre of the cutter, where no cutting speed is available, is null. This means that the cutting tool tip is exposed to extreme friction and crushing.

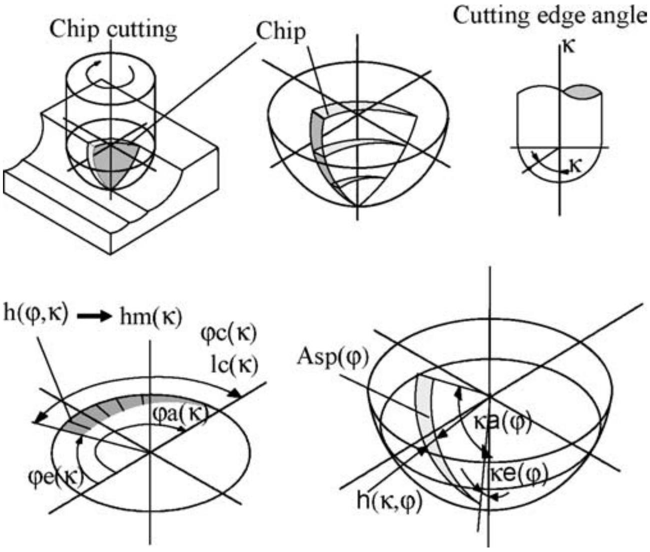


Fig. 3. Process and chip parameters in milling using ball-end cutter [16].

The shape of the chip, which is independent of the tool tilting, is always representative of the segments of a sphere. During each cut, chips of the same geometry are removed. However, the path of the cutting edge of the tool in chip removal and the contact conditions of the cutting edge change. Employed tool tilting in the cutting process with ball end cutting tools can change the contact conditions such as the path of the cutting edge. This means that tool wearing, surface quality, dimensional accuracy, and process stability can be affected from the cutting tool tilting (see Fig. 3).

The tool tilting angle, the angle between the tool axis and the surface normal, corresponds to the surface inclination in three-axis milling. The state of milling direction with respect to surface inclination gives the tool tilting angle along or diagonal to the feed direction (see Fig. 4) [18].

The cutting parameters of chip change with surface inclination and/or the workpiece contour. Figure 5 shows the changes in the cross-section of a chip with different surface inclinations and milling strategies (down cutting and up cutting) in drawing cut and drilling cut. The maximum cross-section of the chip decreases with increasing surface inclination, and chips of smaller angles are formed.

The cutting force must decrease with increasing surface inclination, according to the Force Law of Victor–Kienzle. No constant cutting speed can be realized at the cutting edge in milling with ball-end cutting tool. Therefore, it is meaningful to use the mean cutting speed rather than the cutting speeds of the cutting points of the cutting edge. The mean cutting speed can be calculated from the minimum and maximum values of the diameter of cutting-edge section, which cuts the workpiece.

When the tilting angles of the tool are small, a large cutting speed gradient arises at the cutting edge. This causes a major deviation from the optimum cutting speed and creates problems, especially at the centre of the cutting tool. In Cermets and cubic boron nitride (CBN) tool materials, this often causes breaks off the tip of cutter and results in a decrease in tool life. It can be assessed that non-uniform cutting conditions can be realized in three-axis milling of the form contour. The objective of the technological optimisation is the acquisition of a suitable milling strategy and the avoidance of frequent cutting using the centre of the cutter tip.

4. Technology and milling strategy for the HSC in mould manufacturing

4.1. Influence of tool movements on tool life

Experiments were made using work pieces of 2363 steel (X100CrMoV51) hardened to HRC 60 and 2311 steel (40CrMnMo7). The tool life in the case of different tilting angles of the tool in down cutting for the work pieces 2363 steel and 2311 steel are shown in Fig. 6a and b, respectively. It can be seen that the longest tool life can be achieved by using a tilting angle of tool of 15°. The cutting tip of the tool is broken off when the tilting angles of the tool are smaller ($-5° < \beta f < 5°$).

The cross-section of the chip increases slightly at the beginning of cutting and decreases suddenly at the end of cutting in dawn cutting in drawing cut. Whereas the cross-section of the chip suddenly increases at the beginning of cutting and decreases steadily at the end of cutting (see

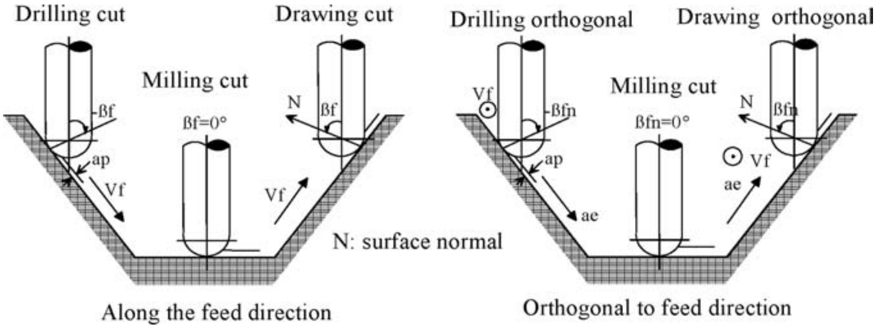


Fig. 4. Possible feed directions.

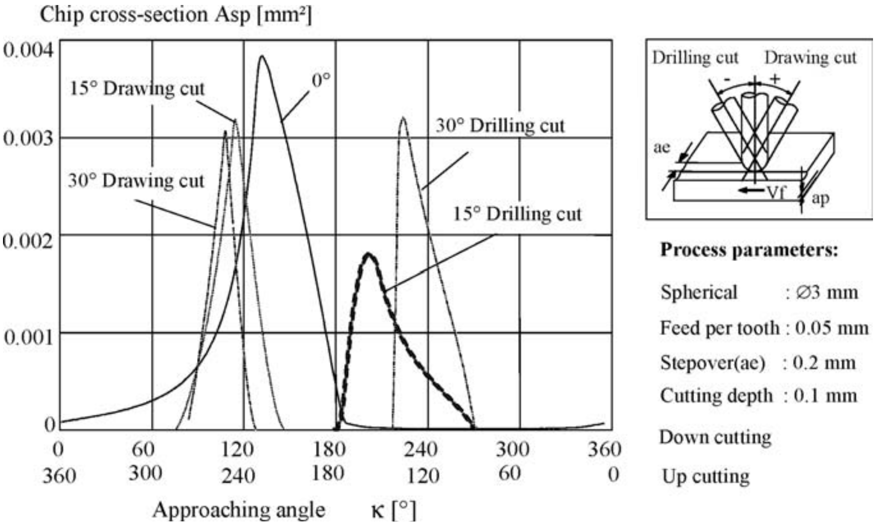


Fig. 5. Cross-section of chip cross-section for different surface inclinations and cutting strategies [16].

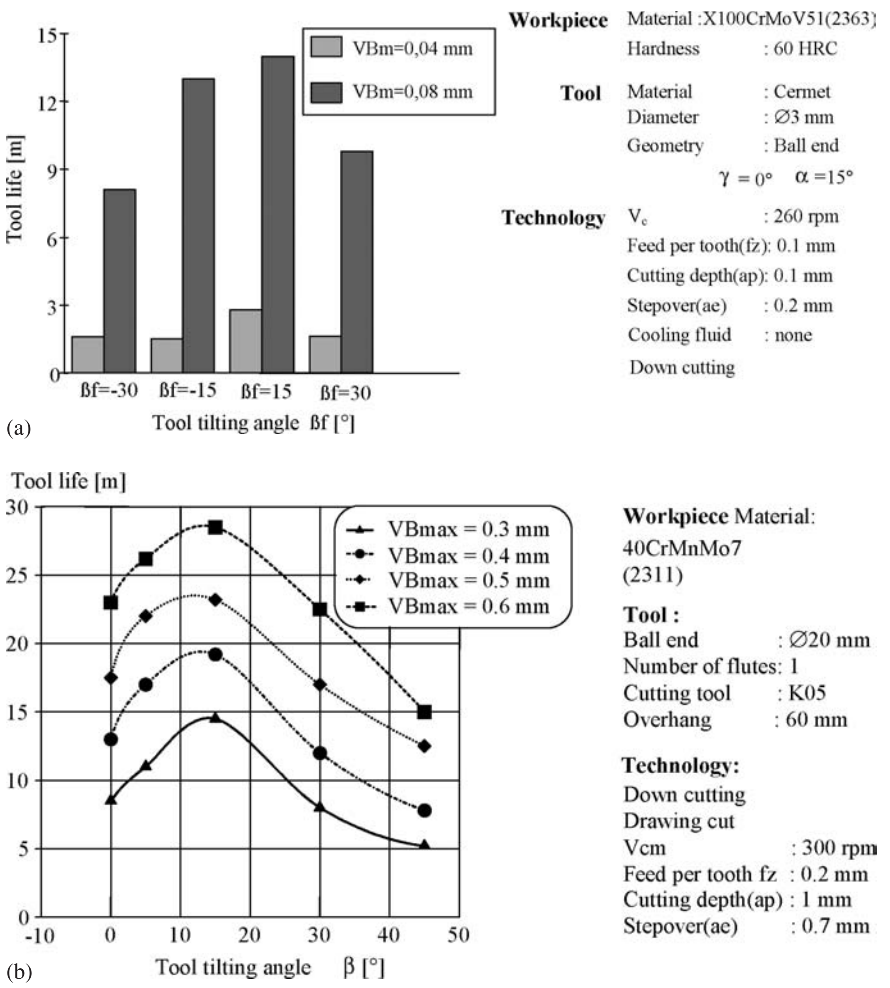


Fig. 6. (a) Tool life for different tilting angles of the tool for the work piece X100CrMoV51. (b) Tool life for different tilting angles of the tool for the work piece 40CrMnMo7 [16].

Fig. 5). Instantaneous loading at the entrance of the cutting tool into the workpiece leads to increased tool wear (see Fig. 7a and b). From the point of tool wear, softer insertion of the cutting tool into the workpiece is more favourable.

The tool life is longer in drawing cut than in drilling cut at all tilting angles of the tool. The shortest tool life is observed at zero tilting angle of the tool ($\beta f = 0$). When the tilting angle of the tool is zero, very poor surface quality and vibration of the tool are observed.

4.2. Down/up cutting in milling of steel 2363 (X100CrMoV51) hardened to HRC 60

A milling attempt has been carried out using down and up cutting. Meanwhile drawing cut has been used as optimal milling strategy. Tool tilting (drilling or drawing cut) and milling strategy (down or up cut) combinations play an important role in the milling of steel 2363 (X100CrMoV51) hardened to HRC 60. Experiments have shown that the increase in the cross-section of the chip has a decisive influence on the wear behaviour. In both combinations, down cutting–drawing cut and up cutting–drilling cut, tool insertion into the workpiece is soft, which favours tool wear. The above combinations resulted in lesser tool wear than the combinations of down cutting–drilling cut and up cutting–drawing cut, which cause a sudden increase in the cross-section of the chip [18].

Whereas the opposite effect can be observed for the surface quality because soft insertion of the tool causes crushing of the chip between the cutting edge and the workpiece. Thus, surface quality worsens and the chip sticks to the cutter. In contrast, cross-section of the chip increases suddenly and no friction and chip crushing occurs in up cutting–drawing cut and down cutting–drilling cut. This means that down cutting–drawing cut in milling is more favourable from the point of tool wear [19]. However, it is not possible to obtain adequate surface quality using this strategy because of chip crushing. Therefore, it is possible to obtain adequate tool life and surface quality in steel milling using up cutting–drawing cut with some compromise (see Fig. 8).

5. Technological data

A flat surface milled by straight milling paths is used to assess tool wearing behaviour of different cutting tool materials, using up cutting–drawing cut strategy and tilting angle of 15°. Herein, the aim is to optimise the cutting speed and feeding for all cutting tool materials with respect to tool life. Figure 9 shows the maximum tool life of different cutting tool materials, accompanied by optimised technological cutting parameters. The longest tool life is attained when CBN tool material is used. The tool life for CBN is 220 m for the wearing width VBm = 0.15 mm. Good results are also obtained with TiN-coated hard metal tool material.

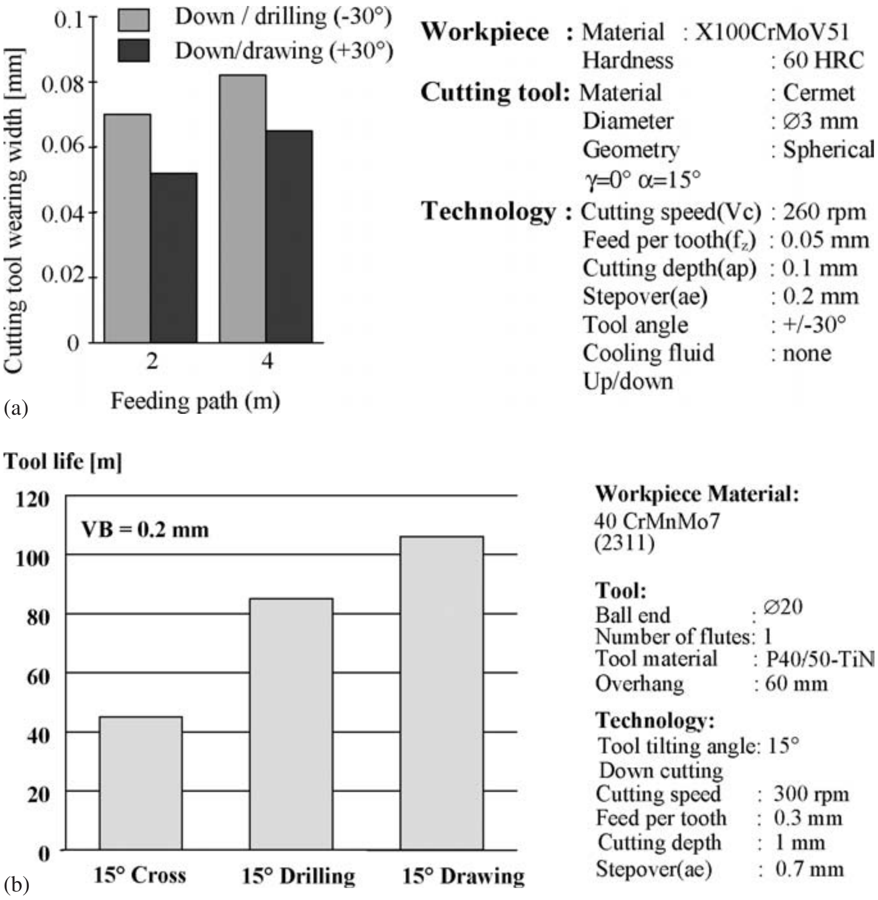


Fig. 7. (a) Tool life for different milling strategies and tilting angle combinations for the work piece X100CrMoV51. (b) Tool life for different milling strategies and tilting angle combinations for the work piece 40CrMnMo7 [16].

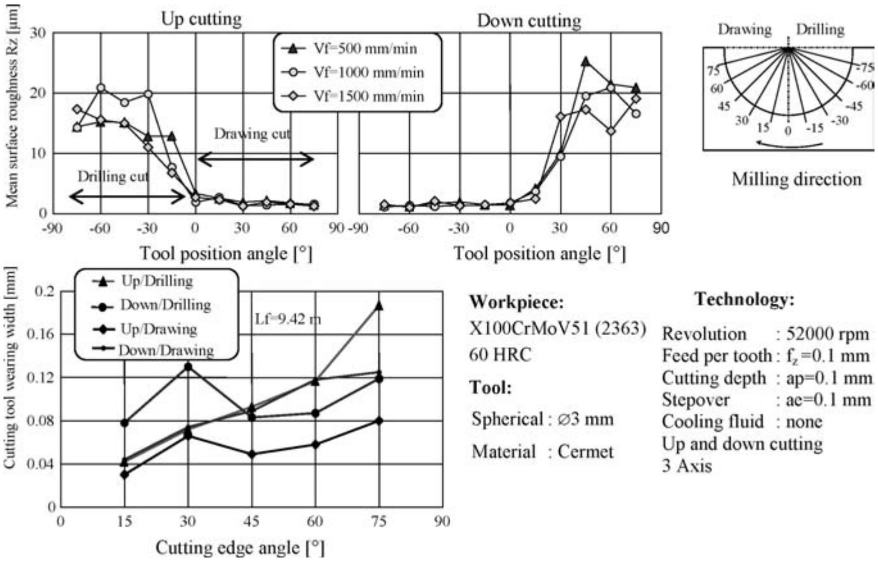
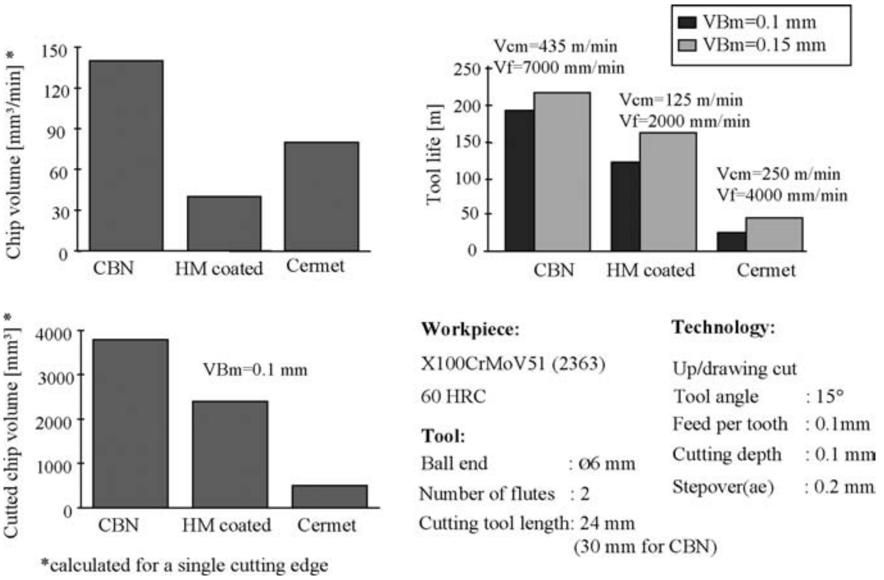


Fig. 8. Surface quality and tool wearing for different cutting strategies in the use of Cermets.

The tool life was 160 m for the wearing width VBm = 0.15 mm. The tool life was 24 m for Cermet for the wearing width VBm = 0.15 mm. Therefore, Cermet is not suitable for cutting of hardened steel 2363 (X100CrMoV51). Herein, it should be noted that the optimal cutting parameters differed with tools. The feeding speeds dependent on the adjusted cutting speed are different, although the feed (fz = 0.1 mm) is identical in all the tools. Thus, the chip volume for each cutting tool differed (see Table 2). It may be seen from Fig. 9 that chip volume formed per unit time with Cermet tool is twice as much that formed with HM-coated tool because of higher cutting speed.

Table 2. Optimum cutting parameters for different tool materials.

	CBN	HM TiN-coated	Cermet
Mean cutting speed (m min^{-1})	435	125	250
Feed (mm)	0.1	0.1	0.1
Feeding speed (mm min^{-1})	7000	2000	4000
Chip volume (mm^3 min^{-1})	140	40	80

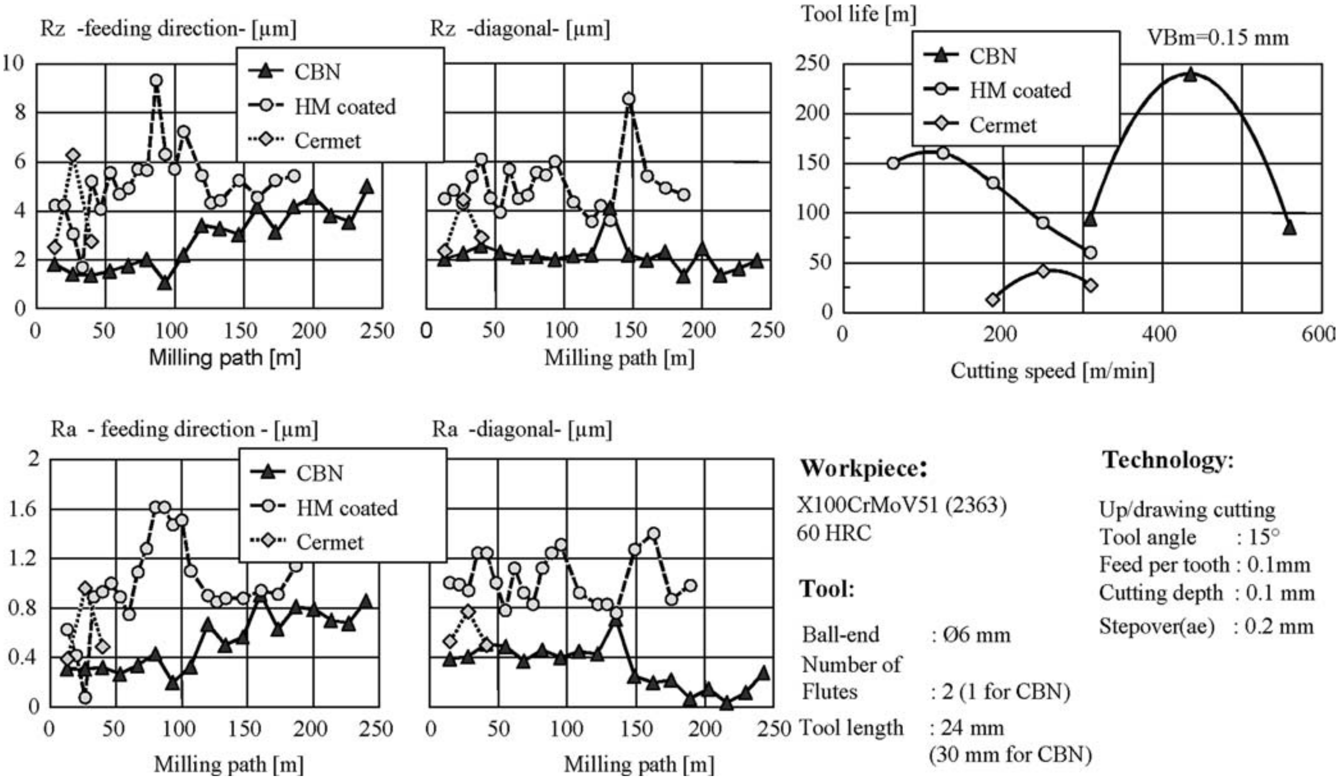


Workpiece:
X100CrMoV51 (2363)
60 HRC

Tool:
Ball end : Ø6 mm
Number of flutes : 2
Cutting tool length: 24 mm
(30 mm for CBN)

Technology:
Up/drawing cut
Tool angle : 15°
Feed per tooth : 0.1mm
Cutting depth : 0.1 mm
Stepover(ae) : 0.2 mm

Fig. 9. Tool life and chip volume for different cutting tools in milling of 100CrMoV51.



Workpiece:
X100CrMoV51 (2363)
60 HRC

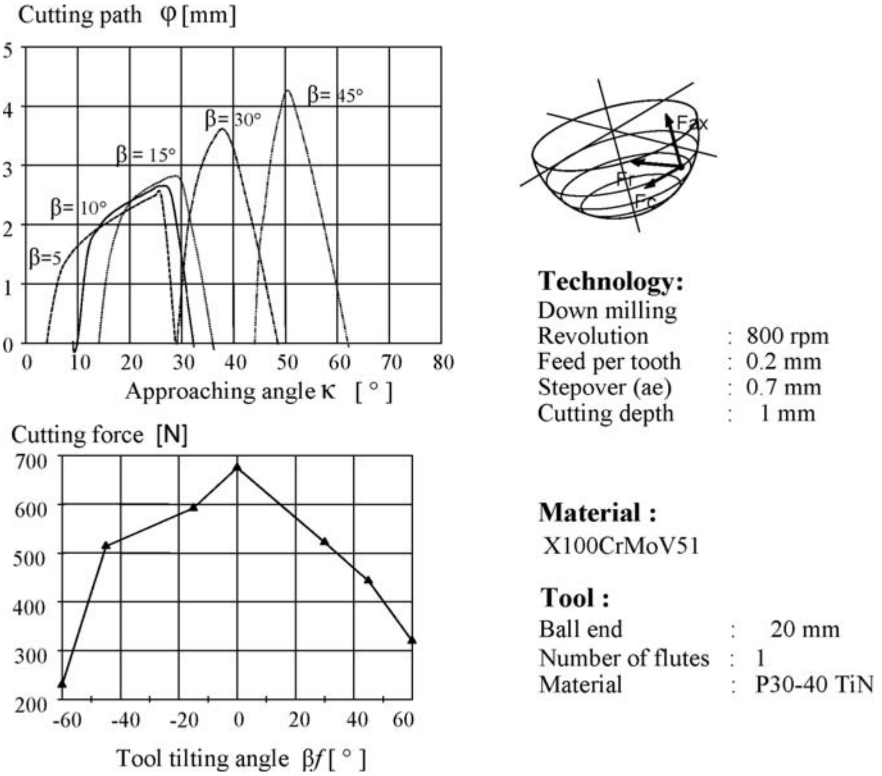
Tool:
Ball-end : Ø6 mm
Number of Flutes : 2 (1 for CBN)
Tool length : 24 mm
(30 mm for CBN)

Technology:
Up/drawing cutting
Tool angle : 15°
Feed per tooth : 0.1mm
Cutting depth : 0.1 mm
Stepover(ae) : 0.2 mm

Fig. 10. Surface quality obtained using different cutting tool materials.

Figure 10 gives an overview of the surface qualities obtained with each cutting tool material. In Fig. 10, R_z and R_a values recorded during the whole milling process are also depicted. The roughness values remain relatively constant over the total milling process. From the results of surface quality, the tool made of CBN delivers the best results. The roughness values for CBN material lie between 1 and 2 µm along the feed direction. These values increase up to 5 µm when the tool is worn out. The roughness values orthogonal to the feed direction remain between 1 and 2 µm till the tool life is diminished. This value also corresponds to the calculated theoretical roughness value of 1.6 µm. The roughness values along the feed direction lie between 4 and 7 µm and those orthogonal to the feed direction lie between 4 and 5 µm for TiN-coated hard-metal tool materials.

The effect of tilting angle of the tool on the cutting force is shown in Fig. 11. As seen in the diagram, cutting force decreased with increasing tilting angle of the tool. This decrease can be explained by the fact that the maximum cross-sectional area of the chip decreases when tilting angle of the tool increases. When $\beta f = 0$, the cutting force is maximum, which is attributed not only to the friction between workpiece and the tool tip (no cutting occurs under this cutting condition) but also to the maximum force that is applied, which is due to the maximum cross-sectional area of the chip.



Technology:
Down milling
Revolution : 800 rpm
Feed per tooth : 0.2 mm
Stepover (ae) : 0.7 mm
Cutting depth : 1 mm

Material :
X100CrMoV51

Tool :
Ball end : 20 mm
Number of flutes : 1
Material : P30-40 TiN

Fig. 11. Change in cutting force relative to tilting angle of the tool.

6. Conclusions

In the manufacturing of small moulds, functional surfaces occupy more places in proportion to free-form surfaces. These surfaces having convex and/or concave curvatures can be milled in three axes, without damaging the contours, by using a ball-end cutter. Machining in five axes is generally not possible or at least very difficult due to the small-form geometries. In this case, the surface is not reproduced exactly but only by approximation in a grooved profile which, as a rule, must be smoothed to obtain the specified finished roughness as well as to eliminate dimensional deviations. This finishing requires manual labour, which is cost intensive and often causes a bottleneck in mould making.

For technological reasons, application of high-speed milling in die and mould manufacturing is reasonable only for finishing and prefinishing of steel. Thus, high speed milling is used in finishing operations to generate surfaces that are better prepared for manual finishing.

The best results are given by steel with respect to tool wear and surface quality. In small-mould manufacturing, it is not always possible to set the tilting angle of the tool and the path of milling that should always be chosen so as to ensure machining with a drawing cut. Tables 2 and 3 show optimum cutting parameters and optimum milling strategies of milling of steel 2363 (X100CrMoV51) hardened to HRC 60, respectively.

Depending on the type and direction of tool approach, different mechanisms can be selected and eventually different surface quality and tool wear can be obtained. When cutting is performed using the centre of the cutter tip, the cutting speed at the cutting edge becomes uneven. At excessively low cutting speeds, chipping occurs in the area of the centre of the edge when hardened steel is machined. With increasing of inclination, the load on the cutting edge of the ball-end tool increases as a consequence of the longer path covered by the cutting edge within the material. If the tool approach is along the feeding direction, the load on the cutting edge is higher for a drilling cut than for a drawing cut, and the tool tends to vibrate when tool wear occurs. If the tool approach is across to the direction of feed, tooth contact is in the form of shocks, thereby leading to breaking off of the edge of high-quality cutting materials in particular.

Table 3. Appropriate milling strategies.

Steel 2363		drawing/ down	drawing/ up	drilling/ drawing	drilling/ up
	Tool life	+	o	o	o
	Surface Quality	–	+	o	–

+: good o: suitable –: unsuitable

Long tool life and cutting strategy have a major influence on the results of machining hardened steel. Machining with drawing cut and down-cutting in copper and with drawing cut and up-cutting in hardened steel gave the best results with respect to tool wear and surface quality. Tool approach across the feeding direction results in heavy impact loads on the tool which leads to heavy tool wear and substantial dimensional deviations. It should, therefore, be avoided.

Good surface quality is achieved in machining of work pieces of 2363 steel hardened to 60 HRC, using the strategy of up-cutting with drawing cut and a tool approach with a tilting angle of 15 degrees. While up-cutting allows for achieving better surface quality, down-cutting provides longer tool life than up-cutting for all angles of approach.

Experimental studies related with this research have been realised in Production Management, Technology and Tool Machines department of Mechanical Engineering Faculty of Darmstadt Technical University.

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