Design of multi-purpose carbide end mill

H Ku and W C Chia

Faculty of Engineering and Surveying,
University of Southern Queensland, Australia.

Corresponding Author:

Title	: Dr.
Name	: Harry Siu-lung Ku
Affiliation	: Faculty of Engineering and Surveying, University of Southern Queensland.
Tel. No.	: (07) 46 31-2919
Fax. No.	: (07) 4631-2526
E-mail	: ku@usq.edu.au
Address	: Faculty of Engineering and Surveying, University of Southern Queensland, West Street, Toowoomba, 4350, Australia.

Abstract

End mills are multiple-tooth cutters designed for cutting materials by feeding the work piece to a rotating cutter. They have cutting edges on the face end as well as on the periphery, and may be single or double end construction. The company in which one of the authors works has been constantly improving and developing innovative and high performances end mills cutters to constantly support the various aspect of engineering industries by providing them with the latest technologies, tooling solutions and high performances end mill cutters.

This paper reports the design and development of a multi-purpose carbide end mill (MP-CE) to suit all kinds of cutting processes which will uncover the background information on different kinds of end mill structures, tool materials and various surface treatments on the cutter. The MP-CE was a successful design; it helps in reducing production cost, production time, tooling cost, labour cost and speeds up the manufacturing processes; it will also contribute a generous profit margin to the company making it.

Keywords: end mills, carbide tools, tool life and metal cutting industry.

Introduction

In metal cutting industry, end mill cutter plays an important role in cutting metal to obtain the various required shapes and sizes. End mills are the most commonly and widely used type of milling cutters (Rakowski, 1980). Figures 1 and 2 show a straight shank end mill and a taper shank end mill. The terminology of an end mill is depicted in figure 3. Table 1 explains the terminology of an end mill. It is also an essential cutting tool for the engineering production in the various aspects of engineering industries, e.g. automobile, aerospace, precision engineering, metal stamping and plastic molding industries. The increasing competition in the market spurs the various manufacturers to constantly develop many new high performances end mill cutters to cater the huge demand in the various aspects of engineering industries, which can speed up the production time, processes and also reduce the production and labour cost.

Some of the common problems faced in using end mill cutters are (ASME, 1985):

- Chipping and breakage of the end mill cutters due to wrong selection of tools, inappropriate tool materials.
- Unsatisfactory finishing of the work materials due to uneven hardness distribution on the work materials.
- Chattering marks on the work materials due to distortion and vibration of the end mill cutters.

Analysis and troubleshooting on the common problems faced by different types of end mill cutters during manufacturing processes will also be studied by conducting cutting tests on various work materials to justify its cutting performances and cutting conditions. Upon achieving all these technical information, design and construction of MP-CE will start.

The objective of this research project is to design a multi-purpose carbide end mill to operate at high speeds and feeds and at the same time extend the tool life of the end mill, and to reduce the deflection of the tool while machining a deep wall cavity. Another objective of the end mill is to perform complex machining tasks such as deep pocket milling, helical drilling and so on.

Once the MP-CE prototype is produced, test cut of the end mill will be conducted to evaluate its cutting performance and condition on various work materials. Lastly, test results on cutting performances, cutting conditions and tool life of the MP-CE and conventional end mills will be analyzed and compared.

Characteristics of end mills

When an end mill is viewed from the shank side as depicted in figure 4, the end mill having cutting edge facing right is the RIGHT HAND cutter, and that having cutting edge facing left is the LEFT HAND cutter.

The material and shape of work piece will determine the hand direction and helix selection; in general, type (a) is used. The milling with types (a) & (b) end mills are smooth as chips come up along the flutes; (c) & (d) of figure 4 are the front views of types (a) and (b) respectively. The number of flutes of end mills used should be determined by the materials machined, dimensions of work piece and milling conditions. Generally speaking, an end mill having smaller number of flutes will have a big chip room and is used for roughing cut; end mills with a large number of flutes is used for finishing cut. Figure 5 shows the differences between 2, 3, 4 and 6 flutes end mill. When the end mill has fewer flutes, the chip room is bigger and will result in better chip ejection; end mill having more flutes is more rigid and will have lesser deflection and breakage [1, 2].

The feature of 2 flutes end mill is designed with wide chip space, which is good for chips ejection and high-speed milling. It is normally used on conventional application, such as slotting, drilling and roughing purposes. Multiple flutes end mills have several types of design and features; the different number of flutes on the end mill cutters is catered for different cutting operations. By and large, multiple flutes end mill is more rigid than 2 flutes end mill therefore it is normally used for side milling and finishing operations [3, 4].

End mills consist of center cut type and center hole type. The latter cannot be used for drilling but is convenient for being re-ground; the former can be used in any operation. End mill style is divided into square end, ball end, corner radius, corner chamfer, corner round and drill nose as shown in figure 6. The last four types can be achieved by modification during regrinding, or by special order. Ball nose end mill is used for profiling and finishing operation of corner radius. This end mill is especially effective when milling curved surfaces and the lesser the ball runs out tolerance, the better the surface finishing of work materials will be [5, 6].

Tool Material

The recent advancement in work materials are very remarkable; the recently developed materials are hard chromium-molybdenum steels, tool steels and heat resisting alloys which are used for parts of aircraft and engines. On the other hand, there have been big developments in machine tools as well, making operations more productive and economical. These machines include high-speed full automatic profiling machines, computer numerical control milling machines and machining centers. In order to meet the demand of milling difficult to machine materials, the improvement of tool materials is indispensable. The proper selection of cutting tool material will increase productivity improve quality and ultimately reduce costs. The factors that affect the selection of tool materials include [2]:

- Hardness and condition of the work piece material;
- Rigidity of the tool, the machine and the work piece;
- Production requirements;
- Operating conditions such as cutting force, temperature and lubrication;
- Tool cost per part machined (including initial tool cost, grinding cost, tool life and labour cost).

There are three important properties that must be considered when manufacturing end mills [7]:

- Hardness

  Hardness is the ability of a material to resist stresses and maintain hardness and cut efficiency at elevated temperatures.

- Wear Resistance

  Wear is the most common point of failure for cutting tools. Flank wear is directly related to speed and feed of cutting. As the speed and feed are increased, rate of wear also increases.

- Toughness and Strength

  Toughness is the ability of a material to absorb energy and withstand plastic deformation without fracturing under a compressive load.

The classification of tool materials is shown in figure 7. End mills can be manufactured from high speed steel (HSS), powder metallurgy high speed steel and carbide materials.

- High speed steel (HSS)

  High speed steel has high toughness rating and is relatively cheap. HSS with cobalt is a premium HSS and is used for higher cutting speeds. High vanadium and high cobalt HSS cutters are used for difficult to machine materials.

- Powder metallurgy high speed steel

  These are higher grade HSS. These types of tool materials have better quality and make the manufacture of high vanadium super HSS end mills possible. This material is much more expensive than HSS and is used for milling hard materials.

- Carbide material

  There are various types of carbide materials in the market and the two most common types are the tungsten carbide (TC) and micro grain carbide (MG).

Tungsten carbide provides higher wear resistance and is generally used for insert type end mills and turning tools. There are four groups of it and all groups have cobalt content [1]:

.

- Group P is for milling steels. If the work material produces longer chips, the tool must have high heat resistance. Tantal carbide (TaC) or titanium carbide (TiC) is added to it to provide heat resistance.
- Group K is for milling cast iron. Chips come out like fine powder.
- Group M performance is between P and K groups
- Group Z is for micro-grain tools. It is recommended for small size milling to prevent chipping or breakage, and to provide higher toughness.

Micro grain carbide has great toughness as well as wear-resistance and rigidity, which resembles normal carbides. Its transverse rupture strength is 4000 N/mm^2, this is almost the same as high speed steel. Micro grain carbide (MG) is recommended for improving metal removal rate and tool life for milling high speed steels for the conditions where carbide with normal strength would chip or break. The high edge strength of micro grain carbide allows the use of tool geometry similar to that used in high speed steel; the speed can also be as low as those used in high speed steels.

Features of micro grain carbide end mills include:

- Provision of sharp cutting edge with a special flute and being best for cutting steel (hardened and high alloy steel);
- Tolerances of both two-flute and four-flute types of end mills are standard to minus range. Thus, there is no necessity to make adjustment of dimensions after replacing the tools;
- The total length and shank diameter are provided; this is particularly important for numerical control machining because no measurement is required at each tool replacement;
- The size of the carbide grain
- In addition to the features of excellent wear resistance and high rigidity, the micro-grain has higher toughness;
- Displaying a full ability to cut cast iron and aluminum.

Cutting fluids and surface treatments

Metal cutting tools are often given surface treatments to improve tool performance and longevity. As cutting tools cut on material, they will generate heat which will weld chips onto them; this will cause friction and wear on the tools. Therefore appropriate types of coating are required to prevent these problems to happen. Figure 8 is the FEM analysis of heat generated when cutting tools cut on materials. It is found that the highest temperature (631.57^{o}C) reached is at the tool chip interface.

Cutting conditions

The factors determining cutting condition are:

- Material to be milled;
- Surface finish required;
- Depth of cut;
- Tool life

The combination of these factors determines the number of revolutions of the cutting tool and the feed of the work table. As the number of revolutions and the depth of cut are mutual dependence, the change of one makes the change of the other and the relationship between the three cutting conditions is given in figure 9.

The *number of revolutions per minute* of the end mill is the most important factor in determining the tool life. Generally, it depends on the material to be milled. For milling with long length of cut, lower milling speed is recommended as it is subjected to deflection and chatter. The number of revolutions per minute of the cutting tool should vary with the different tool materials; this is especially true in carbide end mills and it must therefore be carefully selected.

Feed is the most important factor for productivity. The selection of feed rate is affected by the material to be milled, tool material and depth of cut, all of which will affect the tool life. Feed per tooth should be altered according to tool materials. It is very important to select the feed not to cause chipping, particularly in milling hard materials (over HRC 40). Historical data indicates the tool life varies markedly when the feed is changed in both carbide and powder metallurgy HSS end mills. Feed per tooth should also vary with the change of depth of cut [8].

In slotting operation, the recommended depth of cut is ½ D (a half diameter of the mill). If it is increased to 1D, the feed has to be decreased by 50%. When the depth of cut is decreased to ¼ D, the feed must not be doubled; a 30% increase will be the maximum because there is limit to the strength of the cutting edge and chipping may result. To get higher productivity, select end mills with larger number of flutes (Rakowski, 1980). In side cutting, the recommended depth of cut is 1.5D (axial depth) x 0.1 D (radial depth). If the radial depth is changed to 0.3D, the feed should be decreased to 50%. If the radial depth is under 0.05D, it becomes a finishing operation [8].

Machining problems in conventional end mills

When operators use conventional end mills to perform certain milling jobs, they will face some common problems [5, 6]:

- Using different end mills for different applications will result in higher tooling cost, longer machining time and cost;

- Improper selection of end mills will bring about poor quality milling and damaged work material as well as tool breakage which will also affect milling machine capacity;
- Unable to achieve high speed milling and cutting process because of not using high speed CNC machining centre.

Concept of developing multi purpose carbide end mill

The concept of developing MP-CE is to provide a possible solution to problems faced in milling jobs, which will in turn, improves the machining time and cost. The MP-CE can also be used to perform complex multi-task applications, which will help to save the tooling costs. One of the features of this MP-CE is that it is very effective for side milling on deep wall cavity due to its unique design.

In making of this MP-CE, the carbide material selected is group Z of micro grain carbide, which has great toughness as well as wear resistance and rigidity. With TiALN coating on the end mill flute surface, the surface finish and productivity of this MP-CE mill is much better than conventional end mills. Due to the above mentioned factors on the carbide material and TiALN coating, the MP-CE is able to perform high speed milling and cutting processes and at the same time maintaining the excellent surface finish of the work material. Figure 10 illustrates the schematic diagram of the MP-CE mill. The details of the specifications are not shown because of commercial reasons.

Features of MP-CE (multi purpose carbide end mills)

The features of this MP-CE mill are unique in its flute form and reduced shank. The helix angle is 40 degrees. There are corner radiuses on four cutting edges. Figure 11 shows that there are only two points that come into contact with the work piece at any time. The unique design allows it to perform complex multi-task applications as well as highly precise and efficient side milling of deep wall area, which cannot be done by most of the general end mills due to their conventional design, which will cause the end mill to deflect against the deep wall and this results in damaging the end mill and being unable to obtain satisfactory finishing on the work piece. Figure 12 shows the difference between MP-CE mill and the general end mill on performing side milling operation on a deep wall cavity. The MP-CE mill can generate straight side [8, 9].

When the conventional end mill performs side milling operation on deep wall cavity, it will deflect as it has to mill the side wall with the whole flute length, while the MP-CE mill does not deflect as much as its rival because of the reduced shank design, which is necessary in performing step milling operation. The design of the long slim shank of the MP-CE also has other advantages over the conventional type end mill because the over-hang length of the former end mill can be adjusted to perform various types of milling applications. The milling applications it can perform include (figure 13):

- Step finishing for deep wall side milling;
- Deep pocket milling;
- Helical drilling;

- Ramping process;
- Deep portion milling with corner radius;
- Contour process.

In the past, it is necessary to use different types of end mills to perform these various applications but now the MP-CE can perform all these various applications at high speed milling.

Risks in using MP-CE

Some risks that are to be observed in the design and use of MP-CE to avoid injuries to the operators while using them are given below [10]:

- Handling of the end mill cutter

  Problem: **-** The cutting edge of the end mill cutter is very sharp and if the operators do not handle it with care or without safety protection, e.g. wearing safety gloves, their hands will be hurt easily.

  Solution: **-** Add corner protection chamfering at the tip of the cutting edge, this will minimize the chance for operators to have their hands cut accidentally and the end mill will still be sharp enough to mill an excellent surface finishing. On top of that, operators must also always remember to put on safety gloves.

- Work material chips produced by end mill cutter

Problem: - Normal work material chips produced by conventional end mill cutters are long and curly, which can get tangled in the spindle or the work material. Operators will have to remove it manually by hands.

Solution: - The unique design of the MP-CE is able to produce short and broken chips. This feature improves automated milling operation as operators do not need to be beside the machine to manage chip ejection and the risk of getting their hands hurt is reduced.

- Distortion and vibration of the end mill cutter.

  Problem: - While using MP-CE cutter, it can cause vibration and distortion of the milling machine, which will spoil the work material and also cause injuries to the operators.

  Solution: - Operators using the MP-CE will need to have proper technical guidance on how to use it by being informed accurately on the cutting speed and feed rate. Suitable tool chuck holder should also be introduced to hold the end mill cutter tightly and rigidly, in order to prevent distortion or vibration and unnecessary injuries to the operators.

Results of MP-CE tests

Figure 14 illustrates the comparison between the MP-CE mill and general powder metallurgy end mill with TiCN coating on cutting speed, feed and machining time. The work material was an alloy steel (35HRC); the other cutting tools were micro grain carbide cutters; the coolant was water soluble; the depth of cut was 0.5mm and the machine used was Makino V750 CNC milling machine. The cutting speed and feed used on the MP-CE mill were150 m/minute (8000rpm) and 800 mm/minute (0.05 mm/t) respectively, while those on the general end mill were 40 m/minute (2100rpm) and 210 mm/minute (0.1mm/t) respectively. From the results obtained, it can be found that the machining time of the MP-CE mill was almost 2 times faster than the general end mill. This proves that MPC end mill is able to perform at high speed milling better than general end mill.

Figure 15 illustrates the comparison between the MP-CE mill and the general micro grain carbide end mill coated with TiALN on the tool life. The cutting conditions applied on both cutters were the same and the work material was stainless steel (SUS 304); the coolant was water soluble; the depth of cut was 0.3mm and the machine used was Makino V750 CNC milling machine. It was found that the tool life of MP-CE was 14 hours while that of micro grain carbide end mill was 8 hours, i.e. the tool life of MP-CE was 1.7 times that of micro grain carbide end mill. This is because the unique design of the flute form of the MP-CE is much better than that of its rival.

Figure 16 explains the comparison of the MP-CE mill with various general end mills on the deflection rate. The MP-CE performed three times step-milling operation, while the other general end mills performed only one time milling operation. The results showed that the MP-CE had the lowest deflection rate as compare to the other three general end mills, when they were cutting at the same speed [6, 11].

Table 2 shows the results obtained while putting MPC end mill and the general long series end mill on a series of tests. It can be found that the MPC end mill had a much better quality than the general long series end mill in various aspect; with the same radial depth of cutting, MP-CE was operating at higher feed and speed. The deflection rate and axial roughness of MP-CE was tremendously better than the general long series one; the cycle time was also reduced by 40%.

Conclusion

Based on various tests on the MP-CE and the conventional end mills, it can be argued that the newly developed MP-CE is much better in many aspects than the conventional end mill. The MP-CE can also be operated at high speeds and feeds and at the same time, its tool life is also much longer than conventional end mills. In side milling on deep wall cavity, the deflection rate of MP-CE is also less than its counterpart. It had also been proved that this MP-CE was able to perform multi complex applications (figure 13), which could not be achieved using conventional end mills. With the success of developing this MP-CE, it will definitely help the metal cutting industry to solve the common machining problems in using different types of conventional end mills. Generally, it will help in reducing production cost, cycle time, tooling cost, labour cost and speed up the milling operations. It can be anticipated that the MP-CE will be welcomed by the metal cutting industries [10, 11].

References

1. Bever, M, B (1990) Mechanical Behaviors of Materials, McGraw Hill International Edition, USA.

2. Degarmo, E P, Black J T and Koshers R A (2003), Materials and Processes in manufacturing, Wiley, 9th edition, U.S.A. pp. 515-545.

3. Rakowski, L R (1980), Tips on choosing/using end mills, Machine and tool blue book, Vol. 75, No. 1, pp. 60-72.

4. AMME (American Society of Mechanical Engineers) (1985), Milling cutter and end mill, United Engineering Centre, ANSI/ASME B94.19.

5. Kitaura, S (1994), Cutting characteristics of carbide end mills, Kobelco Technology Review, No. 17, April, pp. 16-19.

6. Matsubara, T, Yamamoto, H and Mizumoto, H (1984), Proceedings of the 5th international conference on production engineering, Tokyo, Japan Society of Precision Engineering, pp. 155 – 160.

7. OSG, MFG Company and Corporation (1992), OSG end mills technical guide, Toyokawa, Japan.

8. Oberg, E, Jones, F D, Horton, H L and Ryffel, H H (1992), Machinery's Handbook, Industrial Press, U.K.

9. Semba, T, Sakuma, K, Taguchi, K and Uchiyama, K (1989), Development and evaluation of finishing end mill with high rigidity, Nippon Kikai Gakkai Ronbunshu, C Hen, Transactions of the Japan Society of Mechanical Engineers, Vol. 55, No. 511, March, pp. 787-791.

10. Chia, W C (2004), Research and development of multi purpose carbide end mill, BEng thesis, University of Southern Queensland, Australia.

11. Kato, H, Shintani, K Iwata, K and Sugita, H (2004), A study on the high-speed milling using small-diameter end tool mill, Progress of Machining Technology, Proceedings of the 7th international conference on progress machining technology, ICPMT'2004, pp. 436-441.

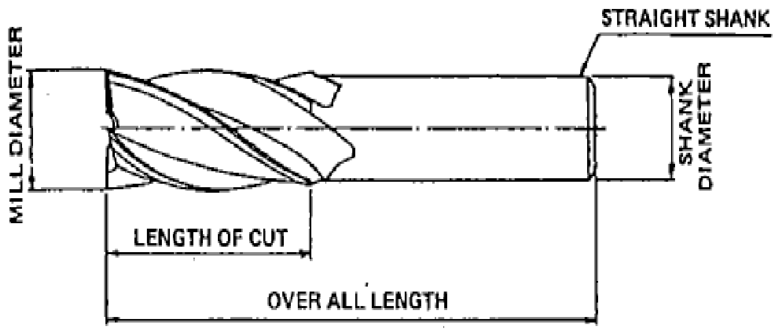


Figure 1: Straight Shank End mill

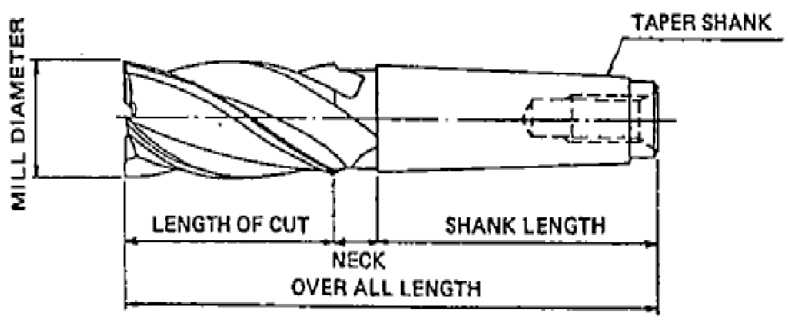


Figure 2: Taper Shank End mill

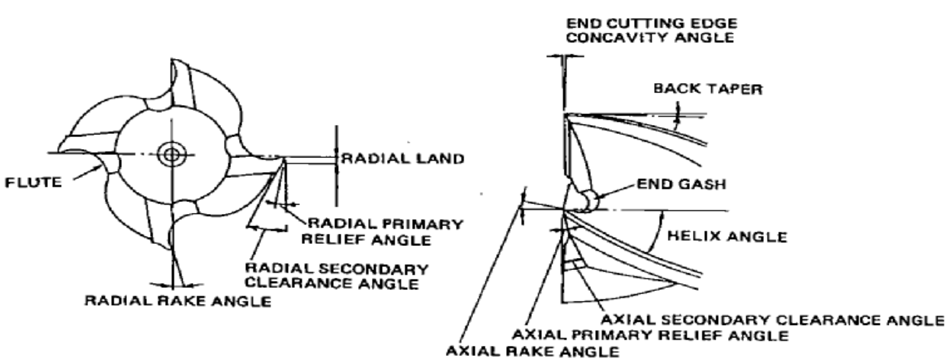
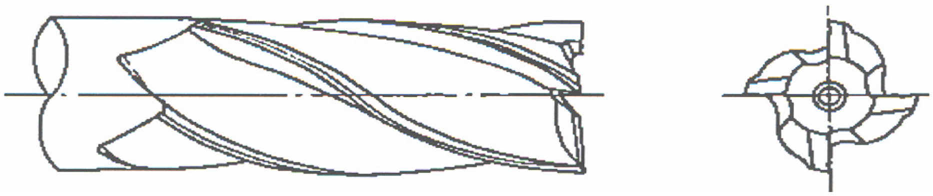
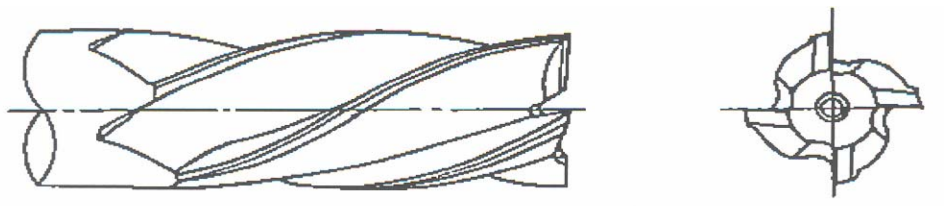


Figure 3: Terminology of an end mill



(a) Right-hand helix **(c) Right-hand cut**



(b) Left-hand helix **(d) Left hand cut**

Figure 4: Helix of End Mill

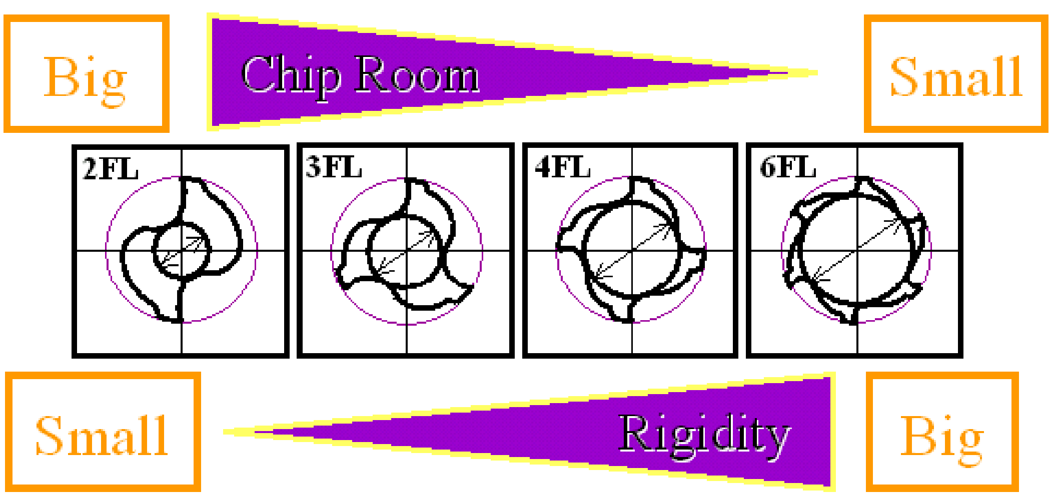


Figure 5: Chip Room and Rigidity of End Mills

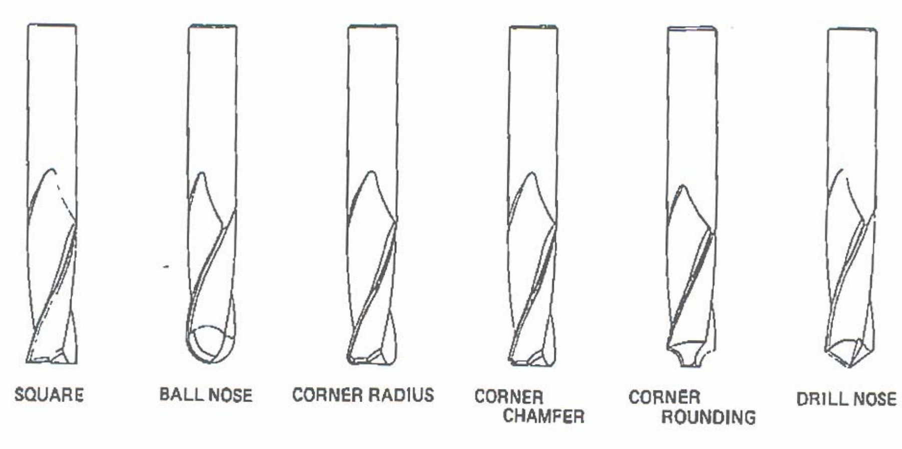


Figure 6: Various types of end profile in end mills

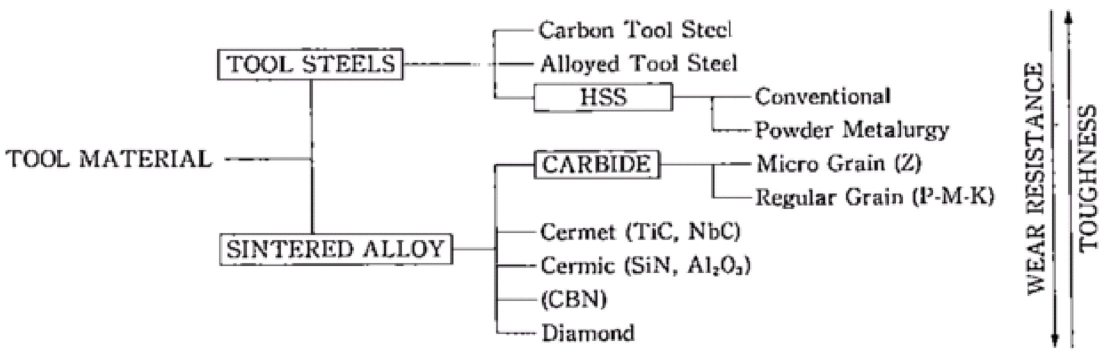


Figure 7: Various types of tool materials

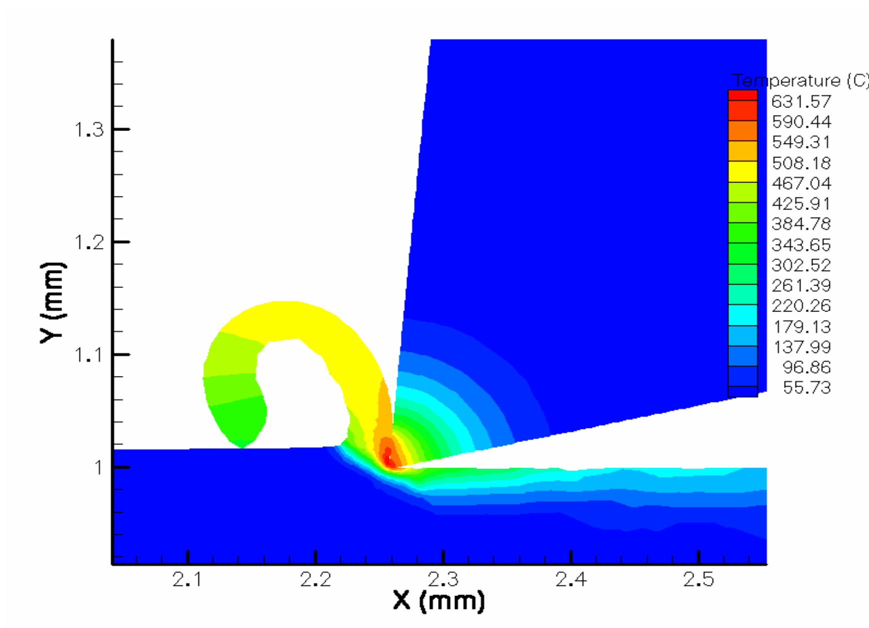


Figure 8: FEM analysis of heat generated during material cutting

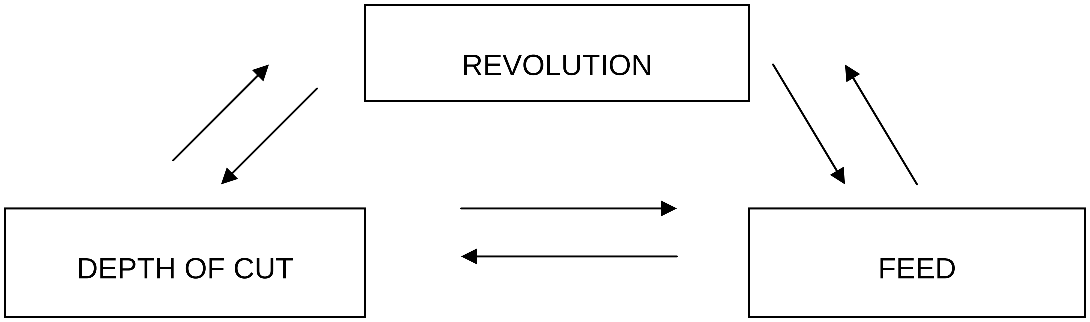


Figure 9:Inter-relationship between the three factors

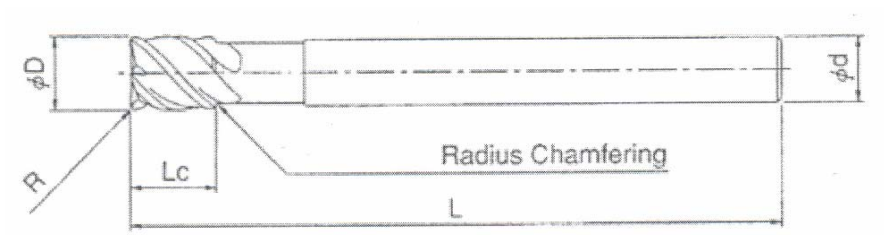


Figure 10: The schematic diagram of the MP-CE

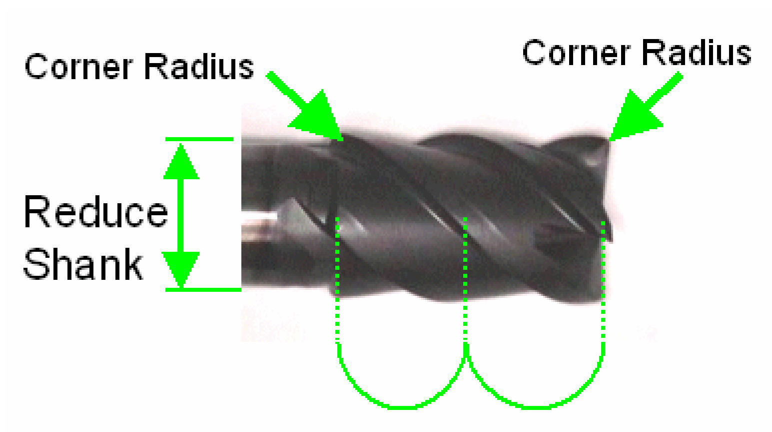


Figure 11: The magnified diagram of the MPC end mills

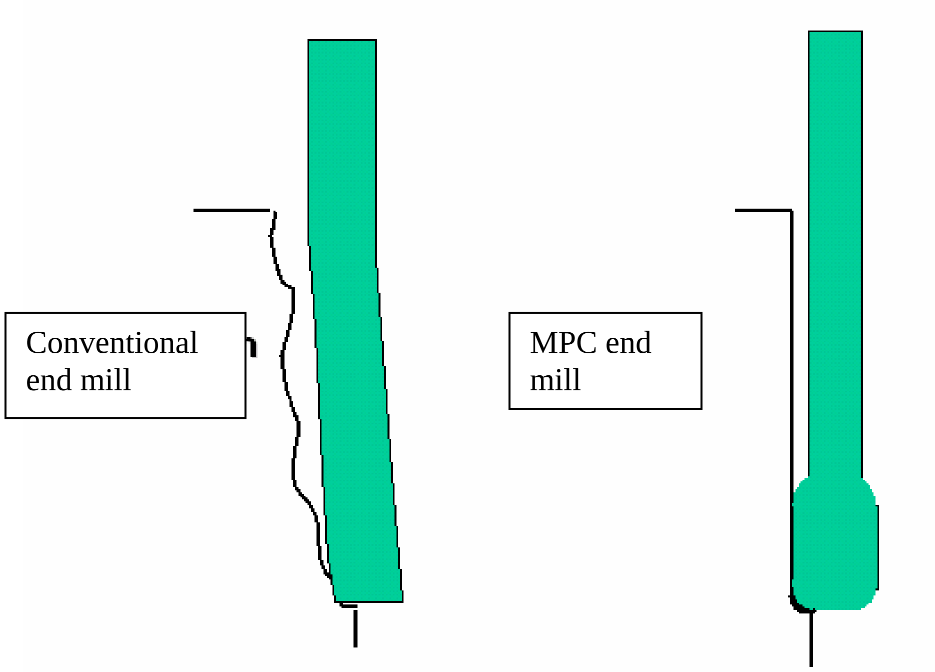


Figure 12: Comparison between MPC and conventional end mills

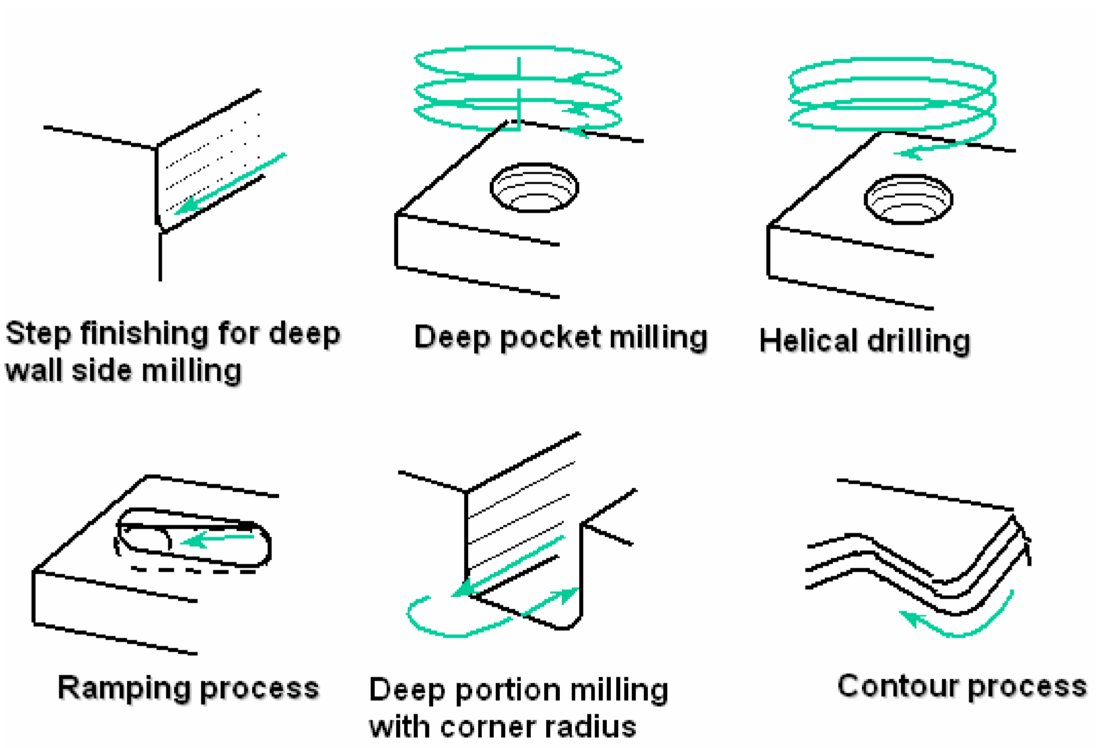


Figure 13: Various applications of MPC end mill

Company:	Author's	Company B
End Mill:	**MP-CE**	HSS-CPM + TiCN
Size:	**Ø 6**	Ø 6
Speed:	**150m/min (8,000/rpm)**	40m/min (2,100/rpm)
Feed:	**800mm/min (0.05mm/t)**	210mm/min (0.1mm/t)
Machining Time:	**60mins.**	126mins.

Work Material:	Alloy Steel (35HRC)
Coolant:	Water Soluble
Machine:	Makino V750 (V)
Depth of Cut:	0.5mm
Others:	2D milling

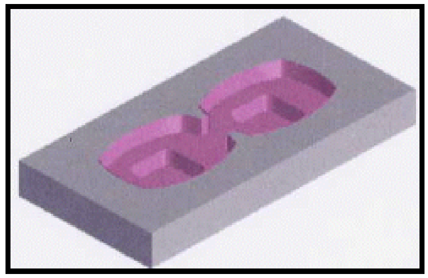


Figure 14: Test Data 1: Comparison of Performance between MPC end mill with general powder metallurgy end mill

Company:	Author's	Company C
End Mill:	**MP-CE**	Micro-Grain + TiALN
Size:	**Ø 6**	Ø 6
Speed:	**470m/min (15,000/rpm)**	470m/min (15,000/rpm)
Feed:	**6,000mm/min (0.2mm/t)**	5,500mm/min (0.18mm/t)
Tool life:	**14hrs.**	8hrs.

Work Material:	Stainless Steel (SUS 304)
Coolant:	Water Soluble
Machine:	Makino V750 (V)
Depth of Cut:	0.3mm
Others:	3D milling

Figure 15: Comparison of performance between MP-CE mill with general micro grain carbide TiALN coated end mill

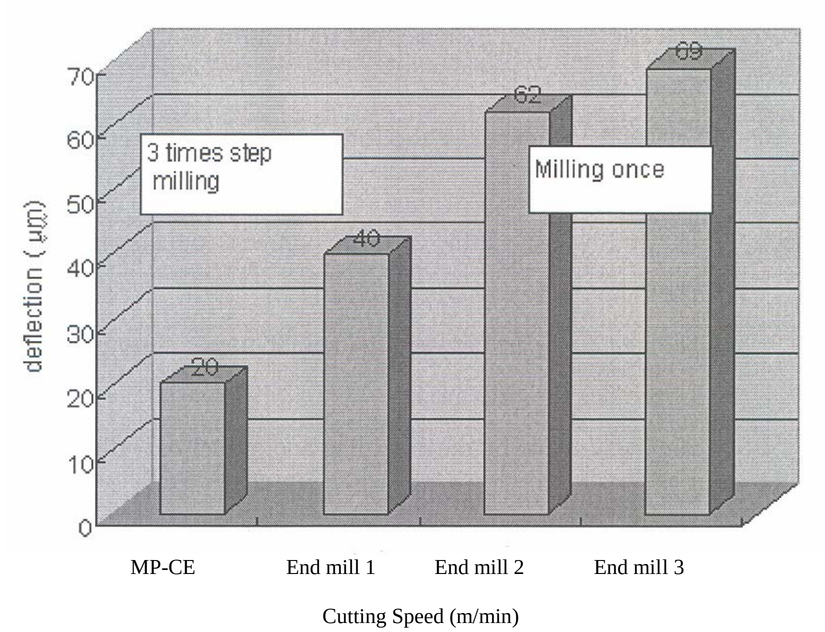


Figure 16: Comparison of the deflection

Table 1: Explanations of terminology of an end mill

Clearance angle	The angle, which indicates the inclination of the flank relative to the finish surface.
Cutting edge	One of the elements of the cutting part. It is the intersecting line of the face and flank.
End cutting edge	The cutting edge at the end face opposite to the shank.
End gash	The flute of the end cutting edge.
Flute	The indented part between the neighbouring cutting edge and the heel. It becomes the chip space.
Helix angle	The angle made by the axial line and the helix cutting edge.
Length of cut	The length of the cutting part.
Neck	The necked part between the shank and the cutting part.
Overall length	The overall length (including length of cut and shank) measured parallel to the axis.
Primary relief	The part directly behind the cutting edge.
Radial Rake angle	The angle made by the inclination of the face relative to the reference plane.
Relief angle	The removal or absence of tool material behind the cutting edge.
Shank	The part of the tool held by the milling machine.
Shank diameter	The diameter of the straight shank.
Shank length	The length of the shank measured in parallel to axis.
Straight shank	The circular cylindrical shank.
Taper shank	The circular cone shank.

Table 2: Cycle time reduction

Endmil	Long Series End mill		MP-CE	
deflection				
deflection(μ m)	49	17	18	10
Axial roughness(μ mRy)	6.72	4.1	3.56	3.68
Milling speed (m/min)	20	←	200	←
Feed (mm/min)	127	←	1061	←
Radial depth (mm)	0.05	←	0.05	←
Zero cutting (times)	0	3	0	1
Time proportion	1	4	0.6	1.2