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Current Status and Issues for Future in Cutting Technologies

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1. Introduction

Cutting has advantages over other processing methods in terms of controllability of machining shape, cost and material removal rate. Therefore, the cutting has been applied to manufacture many products since long time ago. In recent years, although electric discharge machining or other processing techniques such as laser machining have been advancing, the cutting is the major process in the aircraft industry and others. Then, the research and development of cutting has many issues with sophistication of machine tools, diversification of the materials, the complexity of the product shapes. Recent trends include the cutting operations on the high speed and multi-axis machine tool, the cuttings of difficult-to-cut, composite and brittle materials, and micro cutting of miniaturized products and surface texturing. In this paper, we review the cutting technologies and issues for the future manufacturing.

2. Cutting technologies on resent machine tools

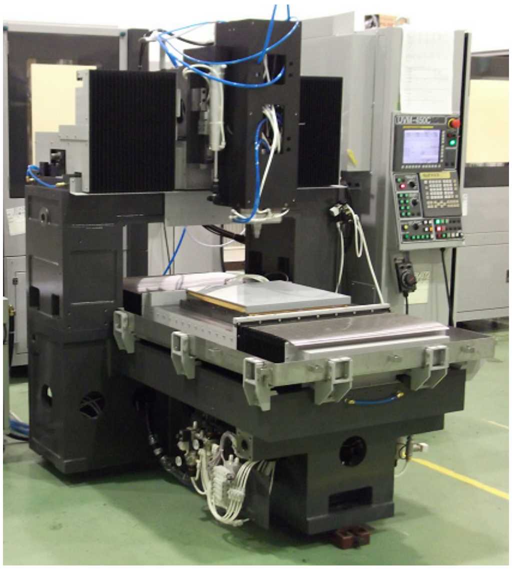
2.1 High speed cutting

High efficiency and low cost are the eternal challenges in the manufacturing processes. Therefore, the high speed cutting has been implemented on the machine tools with high speed spindles since 1990s. The high efficient cuttings with suppressing the tool wear progresses have been realized in small removal volumes at high feed rates. Then, the feed driving systems such as linear motors have been developed to achieve the high speed motions with positioning controls. Recently, as an interesting technology, carbon fiber reinforced plastics have been applied to the machine tables. A lightweight machine table, as shown in Fig. 1, promotes acceleration in the table motions with reduction of inertia and saves the energy consumption.

In high speed cutting, thermal deformation of the spindle and the table induces machining error because heat generation becomes large with energy consumption. Therefore, many technologies have also been developed to compensate for the thermal deformation of the machine tool elements and control the heat generations.

In terms of the high speed cutting, the tool material development has been done to control the tool wear. The cutting temperature increases with the cutting speed; and the tool wear rate becomes high. In the typical high speed cutting on the machining center, the cutting temperature is not so high under a small removal volume at a high spindle speed and a high feed rate because the contact time of the tool with the workpiece is short. In addition, the thermal conductivity ratio into the tool is low at a high cutting speed. As a result, the tool wear progress could be suppressed in the high speed cutting on the machining center. However, in turning, the above thermal reduction effect is not large under the steady contact of the tool with the

(a) CFRP X-Y table mounted on a machine tool (Sodick Co., Ltd.)



(b) CFRP Z-axis mounted on a machine tool (Toshiba Machine Co., Ltd.)

Fig. 1 CFRP table and axes on machine tools

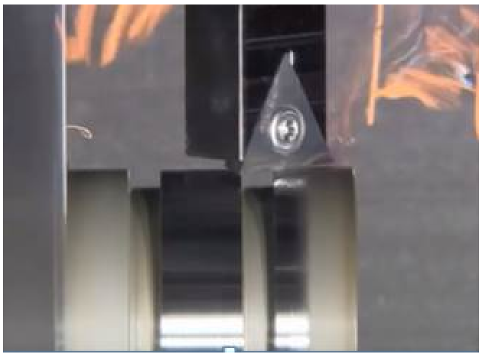
workpiece. Therefore, the high wear resistance of the tool material is strongly required for the high speed turning.

2.2 Multi-axis cutting

The turning and machining centers with many controlled axes have recently used for the machinings of the complex shapes. The multi-tasking machines have been widely applied to perform not only cutting but also the other processings such as laser machining and grinding. Furthermore, in metal laminate additive manufacturing, the metal deposition or sintering is conducted with the cutting.

In order to use the high-end machine tools well, computer aided manufacturing (CAM) systems are required to control the cutter path with the cutter axis inclination considering collision of the tool-shank systems. CAM software is commercially available to generate NC codes for multi-axis and multi-tasking cuttings.

New applications have recently been proposed on the multi-axis machine tools. Hard skiving, as shown in Fig. 2, finishes smooth surfaces on the cylinder with moving the cutting point on the turning center. The tool life is also improved with changing the cutting points during the cutter feed.



(a) Hard skiving (Sumitomo Electric Hardmetel Corp.)

(b) Rotary cutting
(YAMAZAKI MAZAK CORPORATION
Sasahara Lab, Tokyo University of Agriculture and Technology)
Fig. 2 Cutting in multi-axis machine tools

Rotary cutting is applied to suppress the tool wear with changing the cutting points during rotation of the insert tool. The changing the cutting point leads to low cutting temperature. The notched wear, which occurs in the boundary between the cutting and the non-cutting areas, sometimes a critical trouble in cutting of the materials with high work hardening properties such as stainless steel and Inconel (Nickel based super alloy). The rotary cutting is effective in suppress of the notched wear with moving the cutting area boundary during the insert rotation.

3. Cutting technology of recent materials

The high strength materials such as stainless steel, titanium alloy and Inconel have been used in the aircrafts, the implants and the energy industries. The applications of the composite materials represented by carbon fiber reinforced plastics also increases in terms of the energy saving with lightweight. In the information and communication industries, the demand of the optical or electrical devices made of brittle materials such as glass and ceramics has been increased. The cutting technologies are required for manufacturing of those products at high efficiencies and low costs.

3.1 Cutting of difficult-to-cut metal materials

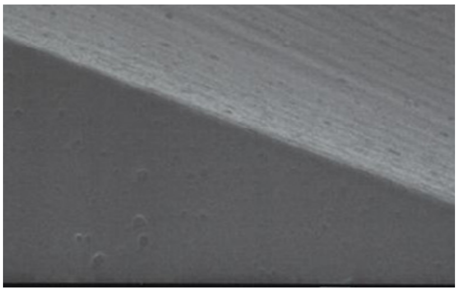
New tool materials are strongly required for cutting of difficult-to cut materials in terms of the tool wear, especially thermal dependent wear. The hard materials and their coating processes have been developed to deposit thin layers on the tool surfaces. The issues of the coating technology are:

(1) High hardness of coating material at high temperatures

(2) High thermal diffusion in coating and substrate
(3) Low friction on coating material
(4) Large bonding force of coating material on substrate

Many coating materials have been developed with the material research progress in terms of Issue (1). Issue (2) is requirements in terms of heat transfer; and thermal diffusion suppresses the cutting temperature rise on the tool surface with high thermal conductivity. Issue (3) reduces the heat generation induced by the friction energy on the tool surface. The friction reduction has been made in terms of the material physical properties and the surface smoothness. Issue (4) is sustainability of the coating function for a long time in terms of interfacial properties. When the tools are manufactured, delamination of the thin layers occurs due to large differences in the thermal expansion of the coating and that of the substrate. Therefore, the material combination should be considered in terms of thermal expansions. The coating with strong bonding force is a critical issue in the stable manufacturing process.

Chatter vibration sometimes occurs under large cutting forces in machining of the difficult-cut-materials Variable lead and pitch end mills have been developed to avoid periodicity of the change in the cutting force, as shown in Fig. 4. The cutting process becomes stable by those end mills; and thus, the material removal rate increases. However, the tool wear management of the variable lead and pitch end mills is complicated because the wear rates of edges of an end mill are different.



(a) Smoothed coating

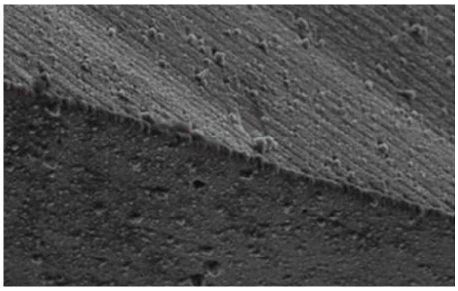


Fig. 3 Friction reduction with smoothing on tool surface
(Mitsubishi Materials Corporation)

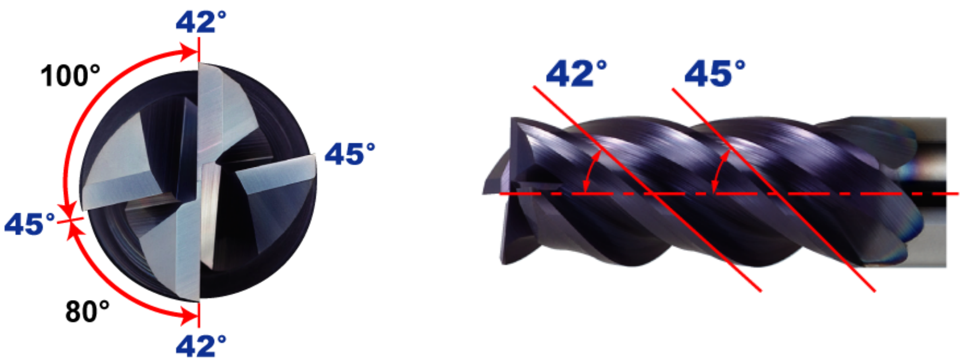


Fig. 4 Variable lead end mill (Mitsubishi Materials Corporation)

The cutting operations of the difficult-to-cut materials accompanied by high cutting temperature rises are performed with some coolant technologies. The high pressure technology supplies coolant to the cutting point well. MQL (Minimum Quantity Lubrication) promotes lubrication at small volumes of cutting oil. In cryogenic machining, liquid nitrogen is supplied at extremely low temperatures of the coolant.

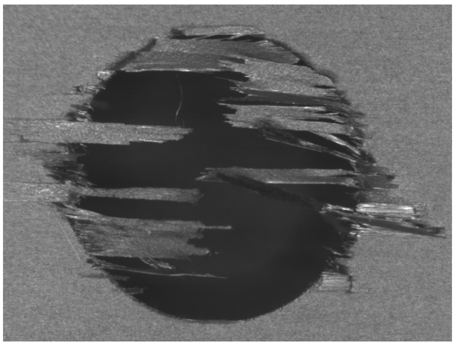
In the high pressure coolant cutting, the coolant can be supplied at pressures of 7-20 MPa[1)]. The coolant effect depends on the supply direction and the cooling position on the tool surface. When the coolant is supplied onto the rake face, the chip flow and its breaking are controlled. The tool surface is cooled to promote the thermal diffusion of the tool. When the coolant is supplied between the flank face and the workpiece surface, the coolant reaches the tool tip to promote the cooling effect directly. Then, the temperature rise is suppressed at the tool and the chip.

MQL has been applied to reduce the supply volume of the cutting oil in terms of the environmental impact. The oil mist is supplied onto the cutting point at the minimum liquid volumes enough to work for lubrication and coolant. Because MQL makes a contribution to reduce the waste oil cost, many machine shops are currently using MQL technology.

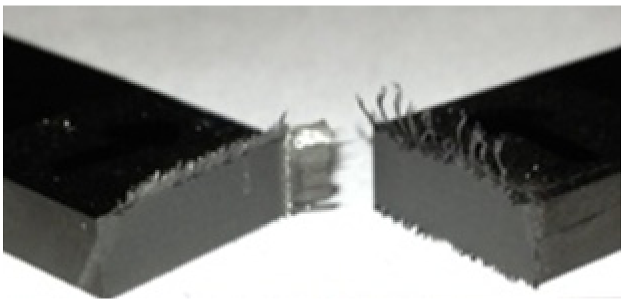
The cryogenic machining, in which liquid nitrogen or carbon dioxide is supplied to the cutting point, has recently progressed with the supply equipment. The technology is effective in control of the affected layer with reduction of the cutting temperature[2)].

3.2 Cutting of composite materials

The demand of carbon fiber reinforced plastics (CFRP) has been increasing to reduce the weight in several manufacturing fields such as the airplane industry in terms of lightweight structures of the products. Because CFRPs are made by piling up the fiber layers with the different orientations in polymers, delamination occurs in drilling, as shown in Fig. 5(a); and uncut fibers are left in milling, as shown in Fig. 5(b). Many cutting tool such as double angle drills and herringbone end mills, as shown in Fig. 6, have been developed for CFRP cuttings. The cutting operations of CFRP and titanium alloy or aluminum alloy stacks are also performed in manufacturing of some aircraft parts. The cutting parameters and the tool materials should be optimized for those different cutting properties.



(a) Delamination in drilling



(b) Uncut fibers in milling

Fig. 5 Finishing surface in cutting of CFRP

(a) Double angle drill

(b) Herringbone end mill

Fig. 6 Drill and end mill for cutting of CFRP (OSG Corporation)

Glass-plastic laminated material has also been developed for the lightweight cover glass of the mobile terminal, as shown in Fig. 7. Because the applicable edge shapes are different for brittle and viscoelastic materials, the sophisticated tool manufacturing technology is required to form the complicated edge shapes for the simultaneous cutting. Furthermore, the bonding material between the glass and the plastic layers promote adhesion of the chip. The chip evacuation should be considered in the tool design.

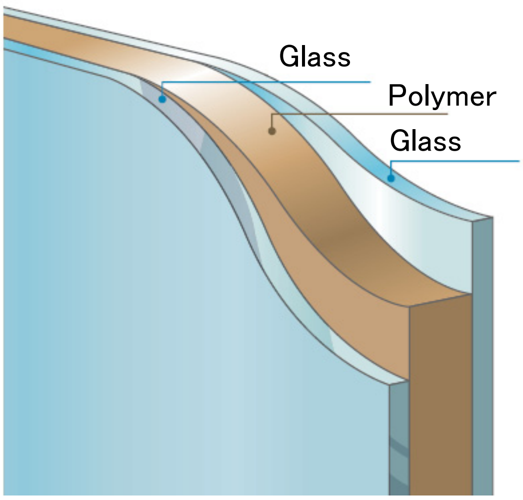
The composite and the laminated materials are increasing for multi-functional and lightweight products. The cutting technologies for optimization of the cutting parameters and the tool should be established corresponding to such combinations of the materials.

3.3. Cutting of brittle materials

The glass and the ceramic devices have been increased in the information and the bio industries. The cutting process is expected to manufacture those devices at high production rates. For example, glass micro total analysis systems (μ-TASs), in which micro channels and holes are fabricated to flow samples in small liquid volumes, have manufactured in chemical wet etching with mask-making process so far. However, in terms of environmental impact and flexibility in manufacturing, alternative processes is strongly required. A glass fabrication process has been proposed in the numerical controlled milling[3)], which reduces the environmental impact and the cost for the mask-making process and etching accompanied by hydrofluoric acid. The same cutting manner can be applied to sapphire milling[4)].

Cutting of brittle materials should be performed to finish crack-free surfaces in a ductile manner. Because the removal volume allowed in a ductile manner is in the order of micrometers or sub-micrometers, the efficient cutting should be desired at high removal rates.

(a) Glass thin plate



(b) Laminated material

Fig. 7　Glass-polymer laminated material (Nippon Electric Glass Co., Ltd.)

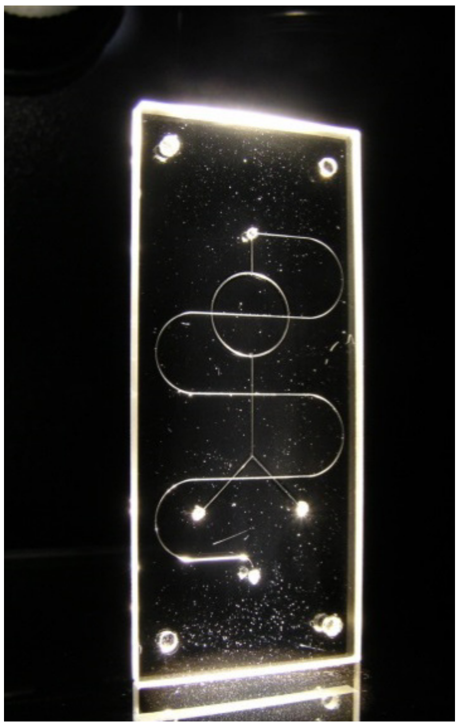
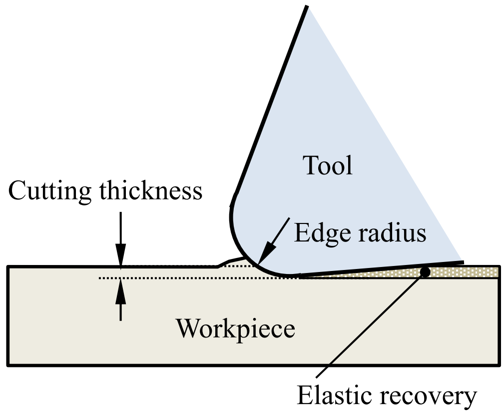
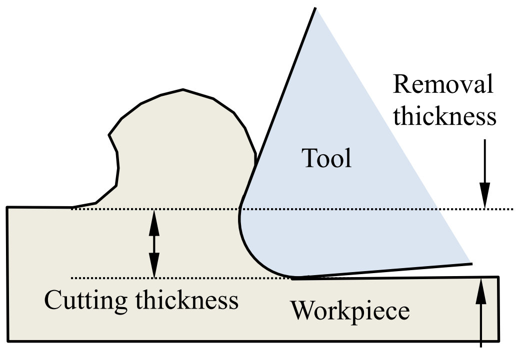


Fig. 8 Micro channels manufactured in glass milling



(a) Ploughing



(b) Shearing

Fig. 9 Cutting modes

4. Micro machining

The target of cutting has been reduced with the miniaturized cutting tool in the progress of the tool manufacturing technologies. The sizes of coating particles and the uniformities of the tool edges are critical in the tool manufacturing processes. In the micro cutting, the cutting mode changes from ploughing to shearing[5)]. Therefore, the non-cutting zone in micro milling becomes large, as shown in Fig. 10. Then, the surface profile should be controlled by the material removal model including ploughing[6)]. Indentation force loaded on the edge is also relatively large to shearing force. Then, the displacement of the end mill induces large machining error even though the removal volume is small. The crystal grain in the workpiece has an influence on the machining error because the micro cutting process depends on the distribution in the grain size and the crystal orientations. Fine grain materials have recently been developed to improve the strengths of materials. In the micro cutting, the fine grain materials are expected to control the machining accuracy well.

Deburring in micro cutting is more difficult than the normal size cutting. For example, the nearly same size burrs as the machining size are formed in milling of aluminum alloy, as shown in Fig. 11(a). Because burrs cannot be removed in cutting, the post processes such as polishing are required for deburring. Fig. 11(b) shows a micro-scale structure in the post processes, which the tops of the pillars are finished in polishing and burrs on their sides are removed in water jet process[7)].

5. Conclusions

Innovation of the cutting technology has been made by the material developments and the product

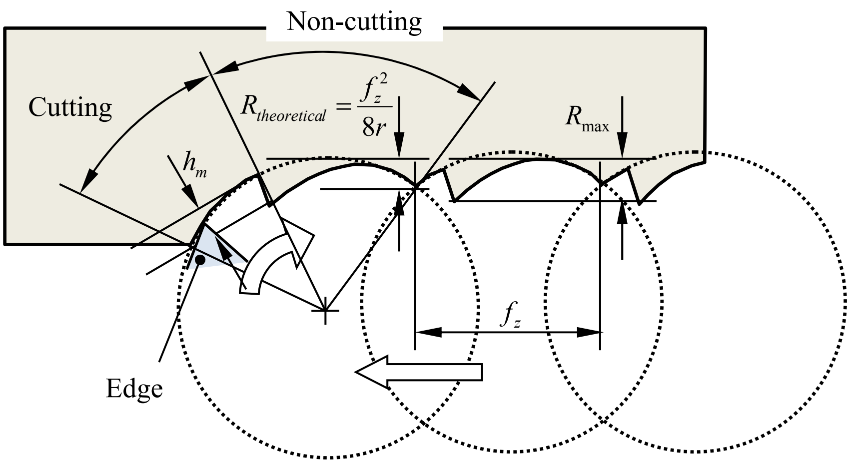
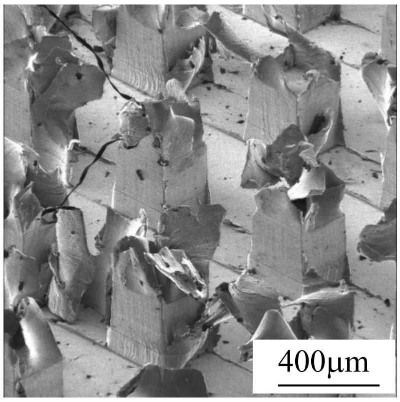
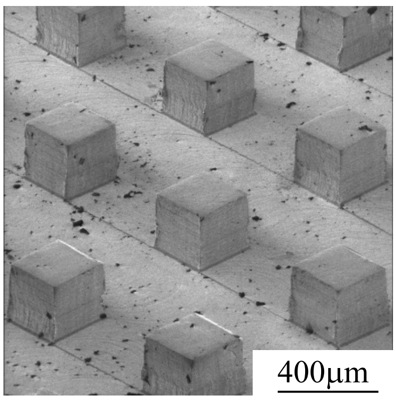


Fig. 10 Surface profile model in micro milling



(a) Burr formation in micro milling



(b) Surface structure finished in polishing and water jet process

Fig. 11 Micro fabrication in cutting and deburring of aluminum alloy

requirements. The composite materials would be diversified as the functional requirements. Many difficult-to-cut materials would be developed to improve the strengths of materials. New tool materials or coating materials should be developed in terms of the material to be cut.

From the point of the product requirement, the usage of the multi-axis and the multi-tasking machine tools is essential to manufacture the complex and the sophisticated devices. Although many CAMs are commercially available, simulation software is required for prediction or evaluation of the cutting force, temperature and tool wear. The simulation software would reduce trial and error to determine or optimize the cutting parameters and the tool.

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