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ORIGINAL ARTICLE

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Short and safe tool setting by safe space in NC machining

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Abstract The shortest tool setting is recommended to reduce the tool deflection and chatter in NC machining. However, it is not easy to shorten the overhang length because the holder can collide with the workpiece. In this paper, the safe and shortest tool-setting algorithm using a safe space is proposed and applied in NC machining. The safe space is the volume in a tool coordinate system that does not interfere with the workpiece and the holder located in the safe space never collides with the workpiece. So the tool holder assembly that has the shortest overhang length and does not interfere with a workpiece is possible using the safe space. This algorithm was implemented with C++ language and has been used by over 50 mold-machining companies for safe and short tool setting.

Keywords Overhang length · Tool setting · Holder collision · Safe space · NC machining simulation

1 Introduction

1.1 Frequent tool-holder assemble

A tool and holder setting is one of the most important parts in NC machining, since over 30 cutting tools are used to machine a cavity or core of a mold. The milling tool is separated from holders and assembled with a holder just before it is used. The overhang length of the tool and the diameter of the holder are changed each time it used because the depth and width of the model is various.

In conventional tool setting, the overhang length of a tool has been computed by the distance between the highest z-value of the workpiece and the minimum z-value of the tool path for safety. If the overhang length is longer than the depth of the pocket as shown in Fig. 1a, the holder and arbor will not collide against the workpiece but the tool deflection and chatter vibration will increase because the stiffness is low.

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1.2 Tool deflection and chatter affected by overhang

Much research has shown the relationship between the setting length of a tool and deflection and chatter. Research has detected collision between holder and workpiece model.

The horizontal portion of the cutting force deflects the tool, which can be regarded as a cylindrical cantilever beam [1–3]. The deflection of the tool is affected by the cutting force perpendicular to the tool axis, Young's modulus, tool length, and diameter as shown in Eq. (1).

$$\delta = \frac{FL^3}{3EI} = \frac{64}{3\pi}\frac{F}{E}\frac{L^3}{D^4} \tag{1}$$

δ Deflection
F Cutting force perpendicular to the tool axis
E Modulus of elasticity
I Second moment of area
L Tool length
D Tool diameter

The modulus of elasticity E depends on the tool material and the cutting force F depends on the workpiece material, feed per tooth and engagement conditions. The tool slender parameter L^3/D^4, where L is the overhang length and D is the tool diameter, the most important parameters in the static tool deflection. The overhang length should be reduced and the tool diameter should be increased to reduce deflection error.

Chatter is severe vibration between the tool and the workpiece, which is mainly caused by self-excited vibration.

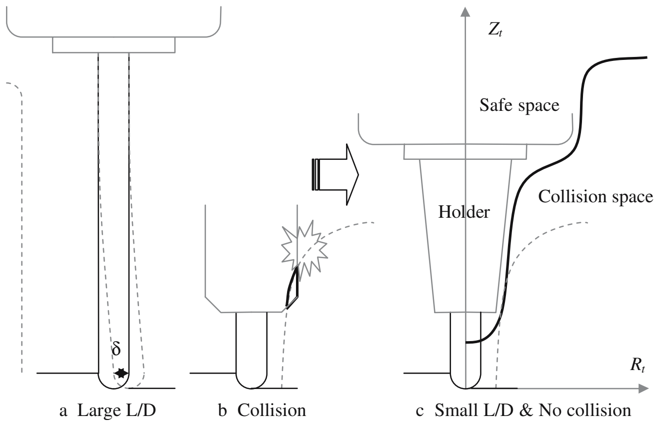


Fig. 1 Short and safe tool setting by safe space

The chatter is affected on the spindle speed, the depth of cut, and dynamic stiffness of the machine tool system [4, 5]. The dynamic stiffness of the machine tool system is affected on the overhang length and effective diameter of the tool. If dynamic stiffness is increased by reducing the overhang length and increasing the effective tool diameter, then the chatter will also be reduced [5].

1.3 Collision detection in CAM and simulation

The additional adaptor is widely used between the tool and holder to increase or to reduce overhang length of tool and increase the diameter of the shank. As the stiffness of the tool increases, the deflection and the vibration is reduced. But if the tool is fixed too shortly to reduce tool deflection and chatter vibration without a safe verification method, the holder can collide against workpiece, as shown in Fig. 1b.

The conventional CAM or virtual machining system designs a tool-holder assembly and checks if there is a collision between the assembly and the workpiece model [6–12]. The configuration space was suggested for the gouge-free and collision-free three-axis NC tool-paths generation for sculptured surface machining [6], and the configuration space and the visibility were suggested for the collision-free cutter orientation selection in five-axis machining [7, 8]. The collision of tool-holder assembly against stock or design model is checked when the tool path is generated. If collision is checked with starting stock model, it is very safe, but tool overhang will be higher than optimal length. If collision is checked by offset model of design, it is dangerous because some part of the real workpiece can be higher than the offset model. The virtual machining system checks if there is collision between tool-holder assembly and workpiece model through the NC machining simulation [9–12]. If there is collision, a more slender assembly should be designed and checked if there is interference again. This recursive tool-holder design and collision check simulation is a time-consuming process and it is difficult to get the optimal holder model and overhang length.

1.4 Tool setting by safe space

In this paper, we propose a safe tool-setting algorithm that computes collision-free space called "safe space" in the coordinate of the cutting tool by a machining simulation and selects the best holder and overhang length of tool at one time as shown in Fig. 1c. What the safe space is, how it is computed, how the holder and overhang length are selected, and how it is different is the conventional method will be explained in the following chapter. The proposed method is adopted by many companies machining middle-sized and large molds and application results will be shown.

2 Safe space

2.1 Definition of safe space

In this paper, we propose a safe and short milling tool-setting algorithm. The safe space is the space in the tool coordinate system that does not interfere with the work-piece while the tool moves along the tool path. It is used to compute the collision-free holder diameter and tool overhang length as shown in Fig. 1c.

The space in the coordinate of the tool is divided into the collision space that overlaps the workpiece while the tool moves along the tool path and the safe space that does not overlap with the workpiece. If the safe space does not have common volume with the workpiece and a holder is inside the safe space, there is no interference between the holder and workpiece by the theory of Eq. (2).

$$\text{if } \mathbf{S} \cap \mathbf{W} = \mathbf{\Phi} \;\&\; \mathbf{H} \subset \mathbf{S} \text{ then } \mathbf{H} \cap \mathbf{W} = \mathbf{\Phi} \qquad (2)$$

S Safe space
W Workpiece
H Tool holder
Φ An empty set

So the holder, additional adapter, and arbor assembled in the safe space do not collide against the workpiece if the safe space is computed correctly.

2.2 Safe space computation during cutting simulation

The safe space can be computed from the start stock or the design model. It is safe but not the optimal solution to compute the safe space from the starting stock model. The method for computing the safe space form the offset model of design is dangerous to use because some remained stock can be higher than the offset model of design. To compute the exact safe space and collision space, the removed part and remaining part of the workpiece at the current tool position should be considered.

This paper computes safe space during the material removal simulation in virtual machining system so that the remaining shape and the shape already removed by passed tool path is considered. The virtual machining system inputs a start stock model, NC code and tool geometry and outputs machined model and the safe space. The safe space and stock is expressed by the z-map, which has been widely used for three-axis machining simulation. The stock model is removed by the tool moving along the tool path block as shown in Eq. (3) and Fig. 2a. The safe space at tool coordinate is also removed by stock model reversely moving along the tool path block as shown in Eq. (4) and Fig. 2b.

$$\mathbf{W} = \mathbf{W} - (\mathbf{T} + \mathbf{p}) \quad (3)$$

$$\mathbf{S} = \mathbf{S} - (\mathbf{W} - \mathbf{p}) \quad (4)$$

$\mathbf{W}$ Workpiece model
$\mathbf{T}$ Tool model
$\mathbf{S}$ Safe space
$\mathbf{p}$ Points on tool path

The stock model is removed by the tool model at start point $\mathbf{p}_s$ and end point $\mathbf{p}_e$ and the surface swept by the tool as shown in Fig. 2a [10]. The safe space is computed by removing the safe space by the workpiece at start point $-\mathbf{p}_s$ and end point $-\mathbf{p}_e$ and the surface swept by workpiece as shown in Fig. 2b. The silhouette curve of the workpiece is the group of points where the normal vector of workpiece model is normal to the tool path direction vector as Eq. (5). The surface swept by a workpiece expressed by dot curves in Fig. 2b is extrusion of the silhouette surface along the tool path.

$$\mathbf{n}_{sp} \cdot (\mathbf{p}_s - \mathbf{p}_e) = 0 \quad (5)$$

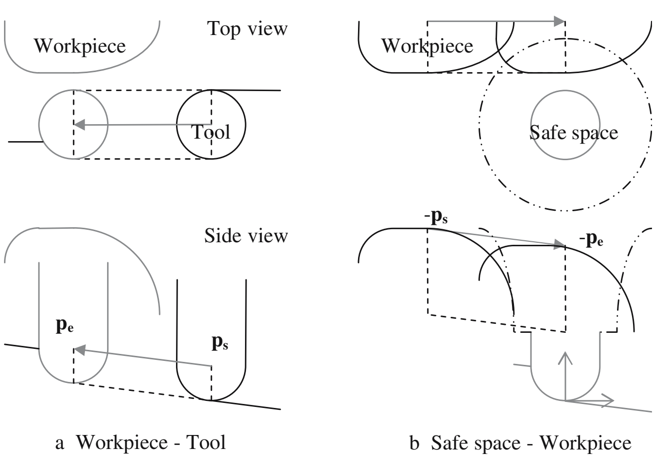


Fig. 2 Boolean operation between workpiece, tool, and safe space

$\mathbf{n}_{sp}$ Normal vector of workpiece model on the silhouette point
$\mathbf{p}_s$ Start point of a tool path block
$\mathbf{p}_e$ End point of a tool path block

2.3 Comparing the safe spaces computed by the stock, design and simulation

The safe spaces computed by the stock model, design model and cutting simulation are compared in Fig. 3. The boundary of the safe space and collision space is expressed by a curve on the cylindrical coordinate fixed on cutting tool. The diameter of the safe space was used instead of the radius of cylindrical coordinate since the shapes of the holders are usually expressed by the diameter and length. Figure 3a shows the safe space on cylindrical coordinate and the roughing simulation result by shading. The starting stock is a box shape and the cutter is rounded endmill 50 mm in diameter. Figure 3b also shows the safe space and the semi-finishing simulation result when the starting stock is the roughing result in Fig. 3a and the cutter is ball endmill 25 mm in diameter.

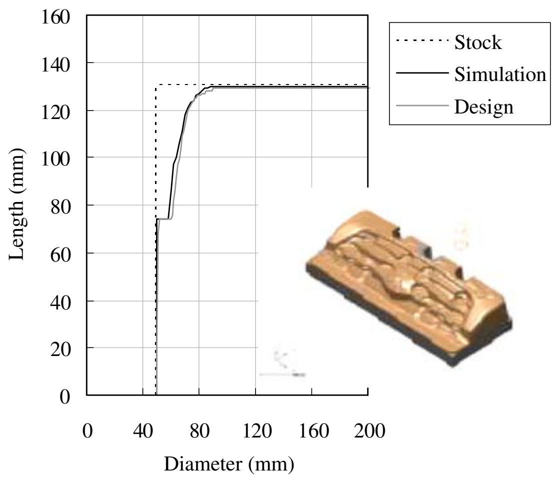
The safe space computed from starting stock model drawn by a dot curve is higher than the others because it does not consider the part already removed by the passed tool path. The safe space computed from the design model (gray curve) is dangerous to include some collision space because some part of the stock can be higher than the offset of design. The safe space computed by removing the collision space that interferes with the current workpiece model is drawn by a black solid curve. The safe space computed during cutting simulation is optimal because it does not include the collision space that interferes with the workpiece that is not yet removed and does include the part of workpiece that is already removed by the previous tool path. So the safe space of this research is computed by the cutting simulation.

3 Tool setting by safe space

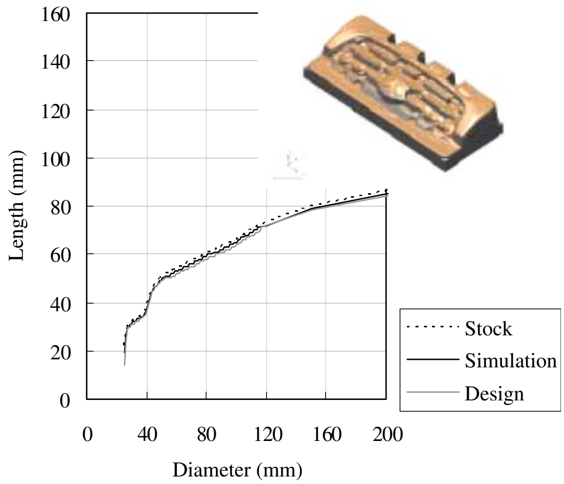
3.1 Holder and overhang length selection

The mold-machining factory has many kinds of holders that are separated from the cutter and assembled just before they need to be used. The tool deflection and chatter is affected by the holder and the overhang length. So the collision-free holder diameter selection and overhang length estimation method is needed in NC machining. This paper proposed the safe space that is the good reference for the holder diameter and the overhang length computation.

The holder database of a job shop is constructed to suggest the safest and shortest tool holder assembly automatically from the safe space computed by a virtual machining system. A holder model is expressed by outer diameter, inner diameter, and the outer shape expressed by the diameter and height. The holders that have the inner diameter the same to the tool diameter and the outer diameter the same as the arbor



a Safe space of roughing



b The safespace of zig-zag semi-finishing

Fig. 3 The safe space computed by stock model, design model, and cutting simulation

diameter can be used to fix the tool. The overhang lengths for all fixable holders are computed quickly using the safe space and the shortest overhang length and the holder with larger diameter is selected.

For example, three holders can be used to connect the cutting tool and the arbor in Fig. 4 because of fixable diameter range. It becomes obvious that the overhang length of the cutting tool is shortest when holder B or C is used by replacing each holder between the tool and arbor and lowering until it is inside the safe space. The best choice is holder C in this case because it has a larger diameter than holder B.

3.2 Comparison of the safe space and simulation

The conventional simulation system checks the collision of only one holder assembly through a cutting simulation, but

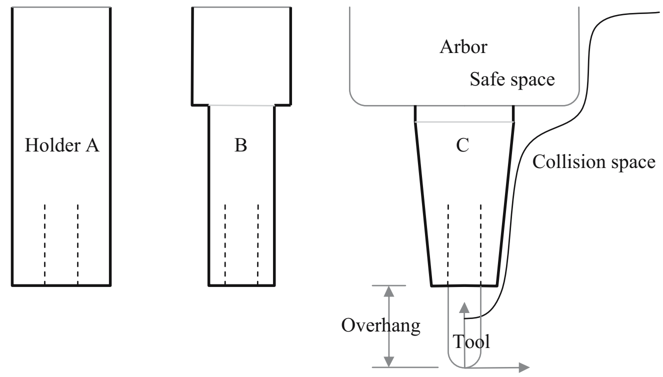


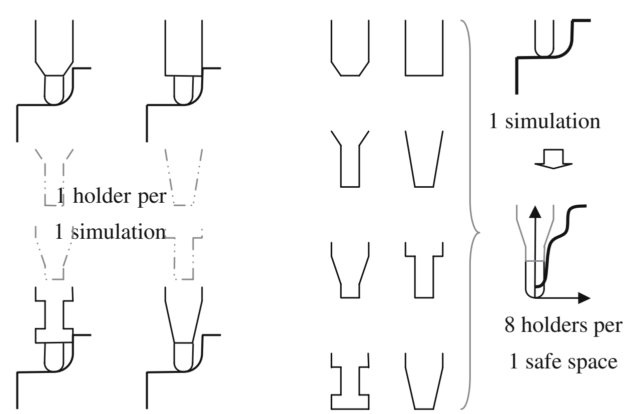
Fig. 4 Holder and overhang selection by safe space

the proposed method checks the collisions of all holders by a safe space after a cutting simulation.

In a conventional simulation system, the collision between a holder assembly with a fixed overhang length and workpiece is checked through a cutting simulation as shown in Fig. 5a. If there are eight holders that can be joined to a tool, eight machining simulations need to select a holder, and additional recursive cutting simulation should be done to get the shortest overhang length.

The new method selects the best holder by comparing the overhang lengths of all fixable holders using a safe space computed by a cutting simulation as shown in Fig. 5b. If there are eight fixable holders, only a machining simulation and a safe space computation is needed to compute the safe setting lengths of the eight holders that are used to select a holder and the shortest overhang length.

The calculation times of the previous collision simulation method and the proposed safe space-based holder and overhang length selection method were compared. The calculation time of the conventional collision simulation is proportional to the count of fixable holders as Eq. (6). It takes short if only one holder and overhang length is used



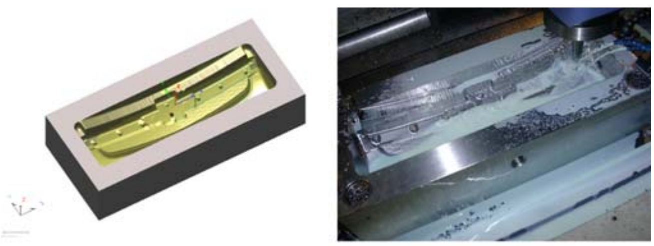
a Collision check by simulation   b Collision check by safe space

Fig. 5 Collision check by simulation vs. by safe space per tool, but takes long if many holders and overhang lengths are used per tool.

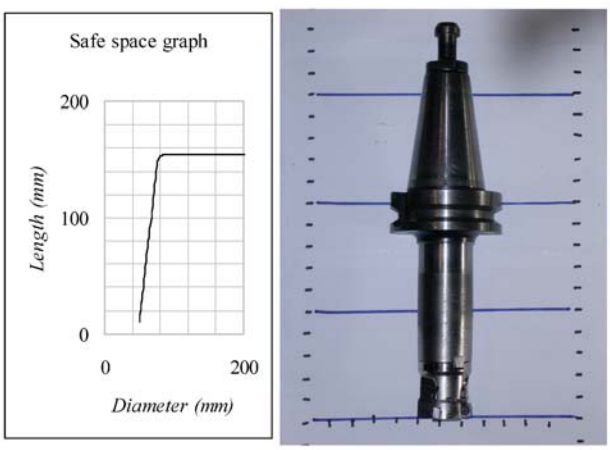
$$t = n_h(t_s + t_c) \quad (6)$$

t	Total time
n_h	Number of fixable holders per tool
t_s	Simulation time
t_c	Collision check time

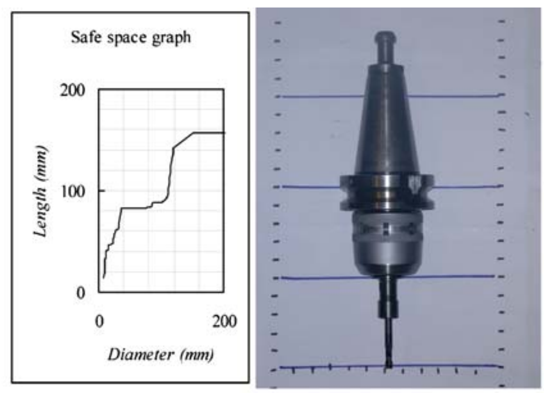
The calculation time of the proposed safe space-based holder and overhang length selection method is almost constant as Eq. (7), because simulation and safe space calculation takes a long time and the safe setting heights of holders are computed very quickly. It takes longer if only one holder and overhang length is used per tool, but takes much less time if many holders can fix a tool with various overhang lengths than the previous collision simulation method.



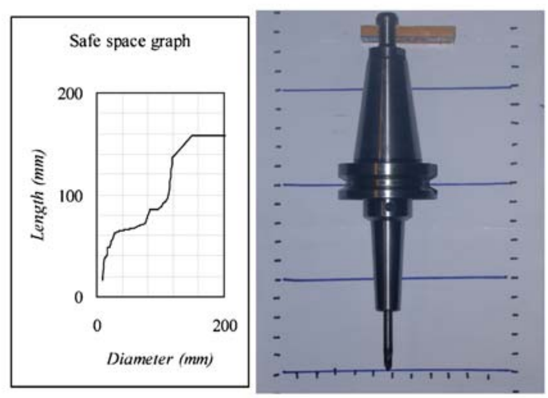
a Simulation result and real NC machining of large mold



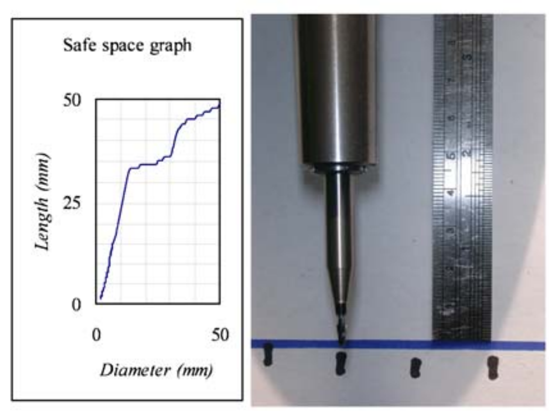
b Tool-holder assembly for roughing (Dia. 50 mm cutter, L/D 3.2)



c Tool-holder assembly for pencil (Dia. 8mm flat, L/D 20 → 7.8)



d Tool-holder assembly for finishing (Dia. 10mm ball, L/D 16 → 9)



e Taper of small tool and holder assembly for grill cutting (Dia. 2 mm ball L/D 20 → 5)

Fig. 6 Experiment of tool-holder setting method using safe space; on the *left* is the safe space graph and on the *right* is the tool holder and arbor assembly used in NC machining

Table 1 Tool setting length/diameter before and after using safe space

	(b) Roughing	(c) Pencil	(d) Finishing	(e) Grill
L/D manual	3.2	20	16	20
L/D safe space	3.2	7.8	9	5

$$t = t_s + t_{sp} + n_h t_{oh} \quad (7)$$

t_{sp} Safe space calculation time
t_{oh} Overhang length calculation time ($t_{oh} << t_s + t_s$)

The simulation time and safe space calculation time of the large mold shown in Fig. 6a were measured by a PC (Pentium 2.13 GHz CPU, 2.0 GB memory). The 32 cutting tools were used and the actual machining time was about 62 h. The total calculation time of the proposed safe space-based tool setting method was 14.5 min and does not change much as the number of holders changes. Since the pure simulation time was 9.5 min, a conventional collision simulation is shorter than the proposed method if only one holder and overhang length is used per tool. If an average of five holders can be joined to a cutting tool, the proposed safe space-based tool-setting method takes less time than the previous collision simulation method that will take over 47.5 min according to Eq. (6).

The proposed safe space-based holder diameter and tool overhang length selection method is useful for large or middle-sized mold machining that uses many tools and holders and is reassembled each time it is used. The shortest and stiffest tool setting is possible by changing the length of the tool and the diameter of the holders based on the safe space.

3.3 Experiment of tool-holder setting

The simulation system that inputs stock model, tool shape, and NC code and outputs the machined model and the safe space was implemented by C++ language. The safe space computed in the system was applied to large mold machining for the experiment of proposed algorithm.

The machining of the large mold is very difficult because slender tools should be used to cut deep and complex geometry. The tool deflection and chatter during machining can be reduced by using the various holders that reduce the overhang length of the cutting tool.

The proposed tool-setting algorithm using the safe space is applied to machining the front grill injection mold. Figure 6a shows the simulation result of virtual machining system on the left and the photo of real NC machining of plastic injection mold on the right. Figure 6b–e shows the safe space graphs computed by virtual machining and the tool setting based on the safe space that was used for the machining of the mold. The distance between the two points in the photos on the right is 20 mm. The overhang length of the cutter was reduced to as short as possible by the safe space graph as shown in Fig. 6c,d. Since a small tool of 2 mm diameter usually has the shank of 6 mm in diameter, the length of the small tool and the taper connecting the tool and shank is important for the strength of the tool and interference between the shank and the workpiece. The safe space also helps to select the best overhang length and taper geometry of the small tool as shown in Fig. 6e.

Table 1 shows the tool length diameter ratio before using safe space and after using safe space. Since the length over diameter ratio was reduced by half by using the proposed algorithm, the productivity was increased and quality was also better than before. Though the overhang length was decreased by half, there was no collision accident between the holder and the workpiece because the holder was inside of the area of the safe space.

3.4 Application in other companies

The developed virtual machining system and the new tool-setting algorithm based on the safe space have been applied at over 50 mold-machining companies and proved that it is very effective and practical at large and middle-sized mold-machining because the holder collision accident was perfectly removed and tool deflection and chatter was reduced substantially.

Figure 7a shows the sliding core of an injection mold that should be machined by rotating the stock five times. The safe and short tool setting was very difficult before the application of the safe space-based tool-setting algorithm because it was almost impossible to know the remaining workpiece shape at the CAM system. The safe space was computed exactly from the remaining workpiece model in

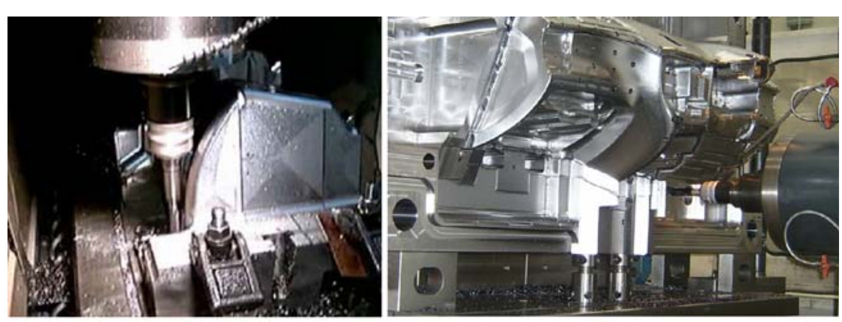


Fig. 7 Application to large mold machining

a The slide core of mold   b The mold of the automobile the virtual machining system and the tool was set safely and shortly by the help of the safe space. We can see that the holder is passing close but does not collide with the workpiece in Fig. 7a.

Figure 7b shows the large-sized mold that will be used for the mass production of the plastic part for an automobile. The interference-free holder setting is very important in large-sized mold machining because the height of the mold great compared to the tool diameter. The collision of the holder, arbor, and spindle body against the stock was the largest problem, and the tool deflection and chatter because of the overhang was the second biggest problem of the company before the application of the proposed tool-setting algorithm. After the application of the safe space-based tool-setting method, there was no collision accident between the tool spindle system and the stock and the over-cut error caused by the tool deflection and the chatter was reduced substantially. The number of companies using the proposed tool-setting system are continuously increasing and they are achieving good results.

4 Conclusions

The safest and shortest tool-setting method using a safe space was proposed and applied in NC machining. It was proved that holders never collide with a workpiece if they are inside the safe space, that is, the volume does not interfere with the workpiece while the tool moves along the tool path. It was also shown that the best safe space calculation method is the machining simulation, and the virtual machining system that inputs stock model, tool shape, and NC code and outputs the machined model and the safe space was implemented by C++ language. So the tool holder assembly with the shortest overhang length and that does not interfere with a workpiece was possible using the safe space.

The proposed method is different from the interference check of cutting simulation that checks the collision of a tool holder assembly during a simulation. In the new method, the interferences of all holders at all overhang lengths are checked quickly using the safe space computed by a cutting simulation. So the method is useful for the machining of middle- or large-sized molds that use many kinds of holders, selects a holder, and is reassembled each time it is used.

In our experiments, the tool length over diameter was reduced to 40% at pencil and 56% at finishing with the help of the proposed tool-setting algorithm. This system has been used at over 50 mold-machining companies for safe and short tool setting, and the collision accident between the holder and workpiece was greatly reduced after it was applied.

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