省段取りブロック自動加工技術による角物部品の 極少量マシニングセンター加工用CAD/CAM ソフトウェアの研究*

Afzeri[†]・星 鐵太郎[†]

CAD/CAM Software for Extremely Low Repetitive Machining Center Work of Block Like Components Using Automatic Setup Free Block Machining Technology*

Afzeri[†] and Tetsutaro HOSHI[†]

Setup-Free Block-Machining Technology has been studied in the interest of manufacturing extremely low repetitive and high variability products, in shorter throughput time and for reduced cost than using conventional machining methods. By specially designed setup-free attachment mounted on the table of a horizontal machining center, block like components, falling into a small size range, can be automatically machined from all of the six orientations in only one process without using other fixtures. To establish procedures and technologies for automatic operation of the single process block machining equipment, the Personal Computer (PC) Based CAD/CAM software, of which CAM phase generates NC program automatically, is structured. Machining Feature-based CAD concept, that is a subset of the parametric feature-based design principle but limiting the user's choice to features machinable by machining centers, is the principal methodology that makes the CAD output possible to be automatically processed in the CAM phase for generating the NC program.

1. Introduction

The ultimate goal of challenges for the factory automation of low repetitive manufacturing will be to realize automated manufacturing of products repeated as low as one.

Typical application may be fabrication of various fixtures and prototypes. The adoption of Flexible Manufacturing Systems (FMS) is a viable solution in which machining equipments are operated 24 hours a day with attendance by workers during small part of the operation hour. However, FMS is not effective for all ranges of production, but presently is economical only in the mid-volume production runs of 200 to 20,000 parts per year[2]. The reason is that substantial preparations are necessary for each machining process. The application of FMS for low repetitive production is not cost effective, for the following reasons:

1. The cost and lead-time of preparing fixtures

are substantial on single part basis. Therefore, economical sense of flexibility tends to be lost.

2. The generation of NC program needs certain human judgment. Once the NC program is developed, it should be verified prior to actual production. This verification is often found tedious and costly.

A solution to this problem has been proposed in previous articles in which block like components are machined without using a fixture[3,4]. Manually operated prototype called block-machining attachment was tested on vertical CNC Milling Machine. The article introduced a method for machining all six faces of a block like part in one process.

In order to elaborate this concept, automatic attachment is developed in the present study and performance of the attachment including accuracy of clamping mechanism, parting off error and machining accuracy are analyzed in line with use of a specially developed CAD/CAM software. Based on the result of those performance analyses[6], ma-

*原稿受付 1998年10月29日

[†]豊橋技術科学大学 Toyohashi University of Technology; 1-1 Hibarigaoka, Toyohashi city, Aichi 441-8580, JAPAN

Key Words: CAD/CAM, feature base, machining.

chining methods have been selected for inclusion in the CAM software so that a block like component can be machined by unattended operation to certain accuracies.

2. Setup Free Block Machining Attachment

2.1 Function

For block like components falling into a small size range (smaller than 80mm square in cross section and 200mm length), a specially designed setup free attachment as shown in Fig.1 is developed for a horizontal machining center. A round bar stock (120mm in diameter) is supplied through a material indexing device inside which it is clamped directly by a main clamping device. The end of the round bar is further supported by auto centering vise jaws, marked in the figure as Sub clamp, to increase the rigidity of the material and to prevent cutting vibration.

Fig. 1 Setup free block machining attachment

As illustrated in Fig.2, four circumference faces are machined by indexing the bar by 90, 180 or 270 degrees. In the actual machining, after face milling is performed on four circumference faces, as shown in the sequence (1) to (4), various machining is carried out to generate other geome-

Fig. 2 Machining operation using setup-free attachment

tries as specified by the component design on those faces, sequence (5). The next operation is parting the end off from the bar material (6). Then the fifth face, the end face of the bar, is machined after rotating the vise index by 90 degrees (7), followed by the sixth face after counter rotating the vise index by 180 degrees (8).

By the attachment mounted on the table of a horizontal machining center, a block-like component can be automatically machined from all of the six orientations in one process without using other fixtures. The operation of the setup free attachment is totally controlled by NC program using optional M codes.

2.2 Mechanism of the Attachment

For achieving the principal function of the attachment that is to fix or clamp the workpiece in the machining area with adequate clamping force, and to orientates the workpiece in 6 directions, the Block Machining Attachment is composed of the following mechanism; Material indexing device, Sub clamp, Vise index and Material pulling chuck.

Function of the material indexing device is to hold a round bar stock and index it for every 90 degrees around the longitudinal axis. Rotation of the bar, for machining the circumference faces, is programmed by optional M codes M60, M61, M62 and M63 for indexing 0, 90, 180 and 270 degrees respectively.

Sub clamp is applied at the end of the bar to increase the rigidity while circumference surfaces are first machined. In the later operations of the process after the product is parted off from the

round bar stock, the Sub clamp will be the main clamping equipment when the end and parted off surfaces are machined.

Vise index, to which the floating Sub clamp is attached, can rotate 90 degrees (counter clock-wise) and minus 90 degrees (clockwise) using codes M71 and M70 respectively and also can move along a forth U-Axis which is parallel to X-axis. Rotation of the Vise index is for orientation of the surfaces number 5 and 6 to the spindle direction. Linear movement of the Vise index along U-axis is to pull the bar material into machining area and then, after the workpiece is parted off from the bar, to escape before rotational orientation occurs by 90 or -90 degree.

For pulling the round bar into machining area, M50 is commanded by the NC program, then the material pulling chuck clamps the round bar and moves along U axis by a distance determined by the length of the workpiece including the width of parting off groove and roughing allowance. After pulling the material, material-pulling chuck is released by M51, and vise index moves back to the center of the workpiece to be made.

2.3 Auto-centering Sub clamp mechanism

The Sub clamp mechanism is designed for a capability to clamp the round bar without causing excessive bending of the bar. Different from conventional fixture system, in which the fixture never releases until a process is finished, the Sub clamp should open and close frequently during a process. By auto centering clamping mechanism, bending error caused by force imbalance between the lower and upper vise jaws can be minimized to the accuracy within $\pm 0.015\text{mm}$.

The principle of the auto-centering mechanism is a floating vise, which slides over the vertical column as shown in Fig.3. Hydraulic cylinder c1 provides the counter balancing for the floating vise and Cylinder c2 clamps the workpiece. Cylinder c1 is activated first to support the weight of the vise and then Cylinder c2 is activated to push the upper vise downward. As the upper vise jaw touches the workpiece and further pushes, the floating slider mechanism prevent the imbalance of clamping forces between upper and lower vise jaws. After satisfied clamping force is achieved, the floating slider is fixed to the vertical column using two floating slide clamps.

Fig. 3 Vise index with floating vise mechanism

3. Structure of the CAD/CAM Software System

3.1 System Environment

A Windows-base Personal Computer (PC) is connected to a Horizontal Block Machining Equipment and to a tool pre-setter using serial RS-232C cable to transfer NC program and tool dimension data respectively.

The CAD/CAM system software is coded in this research using Microsoft Visual C++ programming language, and interfaced to a commercially available CAD system, AutoCAD R13J.

3.2 CAD System

The CAD system uses commercially available AutoCAD software for performing certain functions including graphic presentations, data handling and edition of the product data for design modification.

The essential function of the CAD system developed by the present study is to capture the machining features information specified by the designer during the CAD phase and later transfer it to CAM processing.] In order to enable the AutoCAD command for modifying the data like erase, copy, move etc, machining feature parameters are stored in the database memory under management by the AutoCAD.

3.3 Design Process

In using the developed CAD system, first step for the designer is to create a component base from which necessary machining features are removed. After specifying basic sizes (length, width

Fig. 4 Available machining features for setup free block machining

and height) of the workpiece, designer specifies machining features on design surfaces. User selects a design surface, either top (1), front (2), bottom (3), back (4), left (5) or right (6) surface, then proceeds to selection of machining features from available choice as shown in Fig.4, and specify its location and dimensions. Surface (1) to (4) are on circumference faces while surface (5) and (6), on the end and the parted-off surfaces respectively. Machining features designed on the currently selected design surface are presented in solid lines, and those on other surfaces, in dashed lines of a different color for each surface. When an icon designating a machining features is clicked, machining feature dialog box appears on the screen into which numerical data, finish quality, and need of edge chamfer for the selected machining feature can be input through the keyboard and the mouse. CAD system is connected to a database from which the technical data corresponding to the specified machining feature are searched for and shown to the user while user inputs the machining feature parameters into the dialog box. For example under hole diameter for a tapped hole will automatically be searched from the database when the user inputs the tap diameter.

Complex features like contour or *polyline* pocket can be designed by drawing a *closed polyline* or by transferring a 2D contour object to a *closed polyline*. To identify the polyline, the user is to insert the name of that feature using extended entity data into *polyline* entity.

After the design process is finished, Product

Data which are the sets of parametric values converting the CAD drawing to information essential for the subsequent CAM processing are generated. The data include the name of machining features, directional cosine values of the normal to design surface, origin coordinates, parametric dimensions and finish quality and they are recruited from the entity database from the CAD system.

3.4 Automated Block CAM System

Machining a part using the Block Machining Center is completed only in one process so that process planning always has a unique solution and is not necessary.

However, the selection of cutting tool and generation of NC data for machining the component may be directly performed automatically once the design process is completed[7].

Outline of tool type selection is summarized in Table 1. Type of tool is determined for machining to finish quality specified (rough, medium or finish). For example, POCKET machining features needs two kinds of tools, octagonal insert end mill, and square end mill, to achieve medium finish quality ($> IT8$).

For enabling automated selections of operation and tool as summarized in the above, each machining features has a set of information called Operation Data. The Operation Data is a part of the Common Database shown in Fig.5, and includes tool path generation logic, type of cutting tools, optimum tool diameter and allowance to be removed by subsequent operations for producing required finish quality. According to data pre-

Table 1 Classification of tool types for machining feature specified

Qualityu \ FEATURE		Rough > IT10	Medium > IT8	Finish > IT6
FACE		Face mulling cutter	Face mulling cutter Face finish cutter	Face mulling cutter Face finish cutter
SIDE		Rough end mill	Rough end mill Square end mill	—
STEP	Round	Ball end mill	Ball end mill Square end mill	—
	Square	Oct insert end mill	Oct insert end mill Square end mill	—
POCKET		Oct insert end mill	Oct insert end mill Square end mill	—
SLOT	Square	Oct insert end mill	Oct insert end mill Ball end mill	—
	Round	Ball end mill	Square end mill	
DRILED HOLE dia < 20		Drill	—	Center drill Drill, Reamer
TAPPEND HOLE		Drill Tap	Drill, Hole chamfer Tap	Center drill, Drill Hole chamfer, Tap
BLIND BORE	dia < 60	Rough end mill	Rough end mill Square end mill	—
	dia > 60	Oct tip end mill	Oct insert end mill Square end mill	—
THRU BORE	dia < 60	Rough end mill	Rough end mill Square end mill	Rough end mill Square end mill Borer
	dia > 60	Oct insert end mill	Oct insert end mill Square end mill	Oct insert end mill Square end mill Borer
POLYLINE CONTOUR		Rough end mill	Rough end mill Square end mill	—

pared in the Operation Data, machining features in the Product Data are automatically processed to generate Machining Data.

During the CAM processing, the user is responsible to confirm and when necessary, manually change the cutting tools, tool offset (length and diameter) data, toolpath logic selected by the computer, and the operation sequence. User is also responsible for actually preparing cutting tools to be used in the succeeding fabrication stage. After necessary cutting tools are selected for each cutting operation, the CAM system will read the newest tool offset data from the tool database, calculate toolpath for machining referring to the tool path logic, and finally generate NC program.

3.5 Operation Sequence

To arrange the operation sequence for the part, the optimum planning called Operation Sequence is automatically performed as shown in a flow diagram Fig.6. The task is to optimize the sequence

of multiple machining operations for machining features specified by the designer in a product component. The machining sequence is optimized based on the orientation of the surface to be worked; the finish quality specified; and tools to be used. Operation sequence is partly accomplished when the component is designed using CAD system, by the chronological sequence in which the designer specified machining features. The CAM system rearranges the sequence by grouping operations on the same face, operations that use the same tool, and operations for multiple stepped features to minimize the machining time and improve the finish accuracy.

3.6 Tool Database

Selection of tools for machining a feature within the CAM system needs the tool selection criteria data as follow: type of tool, optimum tool diameter, maximum permissible tool diameter, minimum permissible tool diameter and minimum in-

Fig. 5 Flow chart of CAD/CAM system

Fig. 6 Flow diagram for optimization of operation sequence

sert length. Those data are calculated when Machining data are generated. The CAM system will use the tool criteria for selecting candidate tools and then select one tool from the candidate tool list.

Four databases: fixed tool database, magazine and material specific cutting condition database, machine specific tool dimension database and Tool

Class Interchangeable (TCI) database are prepared for the CAM system.

Fixed tool database contains a set of data for each of all cutting tools available, and the set consist of tool number, tool name, insert type, arbor used and name of the arbor.

Magazine tool database is a devise for user to assign a tool pot number for a tool to be installed.

Material specific cutting condition database is used to select proper cutting condition referring to the tool and workpiece material.

Tool Class Interchangeable (TCI) database as shown in Table 2 is the list of alternative tools that can be used for a specified operation, in stead of the tool type that has been defined in operation data. Purpose of the TCI database is to enable changing a tool with another if the defined tool is not permissible or not available.

Table 2 Sample of Tool Interchangeable (TCI) database

Basic Tool class	Interchangeable tool
20	160
160	50
10	20

4. Machining Accuracy Performance

The operation sequence, tools, cutting condition, rigidity and accuracy of the Block Machining attachment are factors that influence the accuracy of the machined part. Last two of the list that are related to the attachment are evaluated by the cutting test and the results are used as target accuracy values for improvement by modification of machining methods generated in the CAM system.

4.1 Accuracy Improvement of Machining a Rectangular Base

Four circumference surfaces are machined prior to machining other features. Rough machining of the first surface is the critical process because in this case, the Sub clamp is holding the round bar before it will be machined flat. In order to reduce the error, machining sequence and cutting condition have been improved as follows. Rough machining for face 1 to face 4, as shown in Fig.7 takes place after recess grooves are made by the SLOT cutting. When finish quality has been designated, the circumference surfaces are finally finished by a face-finishing cutter. Besides achieving good surface, this finishing operation also removes the burr after all of machining features on circumference faces are machined.

Fig. 7 Rough machining operation for four circumferential face

Burrs that are generated while machining some features on a product surface cause a problem when finally clamping the surface for parting off from the round bar material. Burrs between the Sub clamp vise and the part surface to be clamped can reduce the contact area and cause error in position and orientation of the workpiece after the cut off.

De-burring operation is additionally performed to remove the burr by finishing two opposite surfaces to be clamped. Operation plan of the CAM system automatically postpones the final finishing operation for de-burring the two clamping surfaces, until all of the features on surface 1 to surface 4 are machined.

4.2 Cut off Sequence

The component will be parted off from round bar stock after all machining operations on surfaces 1 to 4 are over. Residual internal stress is responsible in bending the bar when clamping by the sub clamp vise is released, as illustrated in Fig.8. Imbalance of internal stress caused by cutting on side B will bend the material if clamped end L is released as shown in a and b.

To reduce the deflection error, cut off operation is optimized as follows:

- (1) Cutting off starts by machining side A using a roughing end mill (18-mm diameter for example) at 10-mm axial depth of cut.
- (2) Rotate Work-piece around X-axis by 180° and cut side B with the axial depth of cut same as side A.

Operation (1) and (2) will be repeated until 2 mm material is left between side A and B which is machined by a last cut off operation using a smaller diameter (16 mm for example) roughing end mill.

4.3 Machining Accuracy Evaluation

Cutting tests have been conducted to evaluate the accuracy of the Setup Free Block Machining, which generally depends on cutting and clamp-

Fig. 8 Deflection of bar on parting off process caused by residual internal stress

ing forces, cutting heat, attachment misalignment, original and induced internal stress of the work-piece material, vibration, etc.

A block measuring 120-mm long and 80×80 square mm designed with 6 reamed holes is used as standard accuracy test piece. Six faces of the test piece are machined to finish quality. Rough machining is done by a 114-mm diameter face mill in 100-mm radial width of cut, 2-mm axial depth of cut and 960-mm/min radial feed rate. Three finishing paths are repeated to achieve the final surface quality using a finish-facing tool. First of the finishing path is performed by 0.1mm depth of cut and 600-mm/min radial feed rate, second and third paths by 0.03 and 0.01-mm depth of cut respectively with 2000-mm/min radial feed rate. Six holes with 8mm diameter are machined using a center drill, a drill and a reamer in the sequence.

The errors due to the characteristic procedure such as deflection errors in parting operation, limited clamping force of the Sub clamp vise in machining parted off surface, has been reduced by modifying the machining procedure and the cutting condition in CAM software.

The machining accuracy that are found achievable using the prototype attachment under current study as analyzed from the test data is exhibited in Table 3, are parallel and squareness 0.02/80 and 0.03/80 respectively. Dimensional accuracy, including the alignment of two counter-

Table 3 Test piece accuracy record machined by setup free block machining center

<p>Parallel Errors</p> <p>Top-Bottom 0.010</p> <p>Front-Back 0.010</p> <p>Left-Right 0.020</p>	<p>due to parallel error in Z between A and X axes</p>	<p>Front to Back Parallel Separation -0.060</p> <p>$a - b/2 + c/2 * 3$</p> <p>due to Y-axis offset error</p>
<p>Squareness Errors</p> <p>Front-Back (Reference: Bottom) 0.020</p> <p>Left-Right (Reference: Bottom) 0.010</p> <p>Front-Back (Reference: Top) 0.015</p> <p>Left-Right (Reference: Top) 0.020</p>		<p>Front & Back Inclination -0.030</p> <p>$b/2 + c/2$</p> <p>due to A-axis angular motion</p>
<p>Size Errors</p> <p>Top-Bottom 3 0.050</p> <p>Front-Back 0.050</p> <p>Left-right 0.070</p>	<p>due to Z-axis offset error</p>	<p>Front to Back Crossing 0.000</p> <p>$b/2 - c/2$</p> <p>due to parallel error in Y between A and X axes</p>
<p>Pin Height Errors</p> <p>Top</p> <p>Front</p> <p>Left</p> <p>Back</p> <p>Right</p> <p>Bottom</p> <p>120</p> <p>80</p> <p>c</p> <p>b</p> <p>a</p> <p>Front Face Pin Height Difference (Pin on Right is Datum) -0.030</p> <p>Front-Back Pin Height Difference (Front & Right Pin is Datum) -0.060</p> <p>Back Face Pin Height Difference -0.030</p>		

reamed holes, is ± 0.05 -mm.

5. Case Study

Various part sizes ranging from $45 \times 45 \times 65$ to $85 \times 85 \times 200$ -mm³ can be designed and made using the setup free attachment. Fig.9 shows the wire frame model of a sample part designed by the system. The toolbar menu is prepared to help the users for operation of the system starting with the selection of machining features until CAM processing.

Samples of parts fabricated by the methods are shown in Fig.10. Parts smaller than $45 \times 45 \times 65$ -mm³ is also possible to be machined in one process using cutoff methodology as illustrated by an example in Fig.11. The example part is parted off from a rectangular base. It is designed to have a slot, a drilled hole and a pocket. ontoured groove is additionally designed to cut off the part from base material in three step machining operations. Step 1 is to rough-cut the boundary of the part leaving 2-mm on the bottom side of the groove and the step 2 is to finish the side of the product to the same depth. The last step 3 is to cut the 2-mm thick bottom down to 0.15-mm thickness. Then

Fig. 9 Wire frame computer display of sample part design

the part can be removed by hand folding.

Fig. 10 Sample of machined parts

Fig. 11 Small part machined by cut off methodology

6. Conclusion

Setup free block machining technology is one solution to manufacture low repetitive and low volume product in unattended operation. Although limited to small size block-like prismatic components, low-repetitive parts may be machined continuously even if every product piece is different.

Using the CAD/CAM software developed by the study, block like components can be designed fast and easy, NC program can be automatically generated and used without prior verification. Because there is no fixture that should be prepared to machine parts, preparatory task of workpiece holding is also reduced.

Based on the result of accuracy and performance test, implementation of Setup Free Block Machining Technology in industrial application seems viable.

Depending on the part design, some machining features may not be machined because the clamp-

ing is not possible or collision occurs between the tool and the Sub clamp. To avoid those special cases, automatic evaluation and automatic modification of the cutting logic and machining sequence is a challenge for the further research.

Acknowledgemnt

The study reported is a part of the Setup Free Technology research initiated at Toyohashi University of Technology during 1986 and 1988 by the sponsorship of Industry-University Cooperative Research Program of the municipal government of Shizuoka Prefecture under a title "Development of Fixture CAD/CAM System for Discrete Part Machining".

The sponsorship has been succeeded, since 1993, by a group of industrial companies through the Setup Free Research Consortium and the Science Create Corporation which is a non-profitable organization promoting industry-university cooperation research.

Since 1996, the research is partly funded through Creative and Fundamental R&D Program for Small and Medium Enterprises titled "Multimedia CAD/CAM Setup Free Machining Center Work Technology" of the New Energy and Industrial Technology Development Organization (NEDO) administered by the Japan Small Business Corporation (JSBC).

References

- [1] F. J. A. M. Van Houten: Manufacturing interfaces; *Annals of the CIRP*, Vol. 41, No.2, pp.699-710 (1992)
- [2] T. Hanada, B. P. Bandyopadhyay and T. Hoshi: Implementation of low-volume FMS for prismatic component; *Journal of Manufacturing Systems*, Vol. 14, No.2, pp.91-108 (1995)
- [3] M. A. Latief, T. Hanada, B. P. Bandyopadhyay and T. Hoshi: Development of a fixture free machining center for machining block-like components; *Proc. Pasific Conference on Manufacturing*, Osaka Japan, pp.90-97 (Nov. 1992)
- [4] T. Hanada, B. P. Bandyopadhyay and T. Hoshi: Development of a CAD/CAM system for rapid prototyping; *Manufacturing Science and Engineering*, PED-Vol.64, pp.101-108 (1993)
- [5] Afzeri: Setup free block machining technology with personal computer based CAD/CAM software; Master thesis, Toyohashi University of Technology (1997)
- [6] Afzeri and T. Hoshi: Automatic setup free machining technology for high-product variability and extremely low repetitive block like components; *Proc. 1998 JAPAN-USA Symposium on Flexible Automation*, pp.825-832 (1998)

- [7] B. J Davies, A. Joseph and M. Kalta: An expert system to generate NC data from CAD product model; *Journal of Material Processing Technology*, Vol.24, pp.90-97 (1991)
-