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A study of On-Machine Measurement for PC-NC system

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ABSTRACT

The purpose of this paper is to establish an effective inspection system by using OMM (On-Machine Measurement) system based PC-NC. This system can reduce manufacturing lead time because a workpiece is inspected at every machining process and the manufacturing system which includes inspection faculty is able to realize on-line process on CNC machining center. The proposed OMM system is composed of a few algorithms for determination of inspection parameters. It is accomplished by determining the number of measuring points, their location, measuring path using fuzzy logic, Hammersley's method, TSP (Traveling Salesperson Problem) algorithm. The inspection feature applied to this system is based on machining feature. This method is tested by simulation and experiment that are analyzed measuring data and geometry tolerance.

Key Words: OMM (On-Machine Measurement), CMM (Coordinate Measurement Machine), PC-NC, Inspection, Geometry tolerance

1. Introduction

In general mechanical manufacturing, tool paths of rough cutting and fine cutting are determined by feature data which is generated after executing the modeling of product using CAD/CAM software. Machining of wanted products is carried out along these tool-paths and then the geometric error of product is determined by using inspection equipment of contact or non-contact type, at this time, errors can be caused by their equipment but most of errors are still caused by mechanical machining. Besides, nobody knows the current machining is content with the range of tolerance using the current offline system of manufacturing because inspection process of offline system is done after the cutting is finished. If a machine operator can know the information about error of each machining process in processing, a working time and a economic loss can be reduced because the operator can decide whether the following process will be executed or not with the advance of error, so in halfway the work, operator can deal with error actively. Generally, a CMM (Coordinate Measuring Machine), touch -type equipment, guarantees excellent precision whereas it is impossible to carry out inspection in machining and the inspection time is long. Besides, the error due to coordinate change must be considered because the workpiece is moved from a machine tool to a measuring machine. On the other hand, the proposed OMM (On-Machine Measurement) system can measure the error of each machining process in machining. In this study, an OMM operating system that a user can operate easily and measure the error of manufacturing during machining is developed. In the OMM study of Cho., it is presented the inspection method based on the integration of CAD/CAM/CAI for eliciting the condition of inspection efficiently based on the data of CAD.[1, 2] The research of modeling of geometric and thermal deformation errors of a machine tool have been progressed actively.[3,4,5] In fields of the machine manufacturing headed by the production of

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mold, there is requested a greater necessity of OMM which is able to inspect objects on machine. With this necessity, the system of OMM on PC-NC (Personal Computer based Numerical Control) which is oncoming generation numerical control system is made. Because PC-NC can contain CAD/CAM software unlike the current machine tool, software and module which can be operated online are under development. In this study, it was constructed the system that can run the simulation of machining and inspection through the interface and DPROM (dialog CAM program) of the PC-NC operating systems developed by HYUNDAI Motors CO., LTD. The existing CAD feature must be adjusted for carrying out the inspection. However, the CAD/CAM/CAI integrated system is built by the classification of inspection feature. The developed system is verified by the simulation and experiment.

2. The interface of DPROM and OMM module

PC-NC system, which is package control of the machine tool using PC (Personal Computer), is more improved than the existing machine in network, storage, and operating system. Because it is possible to have the software of CAD/CAM within the system, the PC-NC system has advantages to execute the 3-D simulation of machining and to execute the machining. The DPROM used in this study can model general features, simulate machining, create the tool-path and generate G-code. The developed system can conduct manufacturing and inspection on one system by linking the OMM-module with the AFFA (Advanced Fast File Access) of DPROM. Fig. 1 shows the mutually connective structure between DPROM and OMM module. The data of CAD/CAM are interfaced to OMM-module for owning geometric information. In Fig.2, the section of user interface of OMM-module is shown. It is possible to select function of the machining and inspection of each feature. In Fig.3, the structure of OMM module is shown. The OMM module can execute automatic measuring system considering the geometric feature of CAD/CAM. It is possible to generate G-code for touch-probe moving and to perform the simulated inspection. The developed program is applicable for the existing system and the other functions except the function of joining the geometric feature information are made independently.

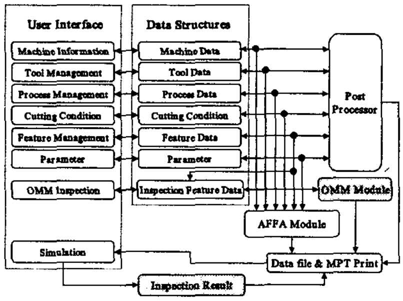


Fig. 1 The structure of In/Out data in DPROM & OMM module

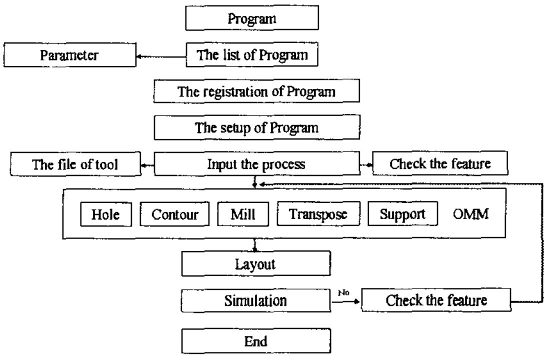


Fig. 2 The user interface OMM module in DPROM

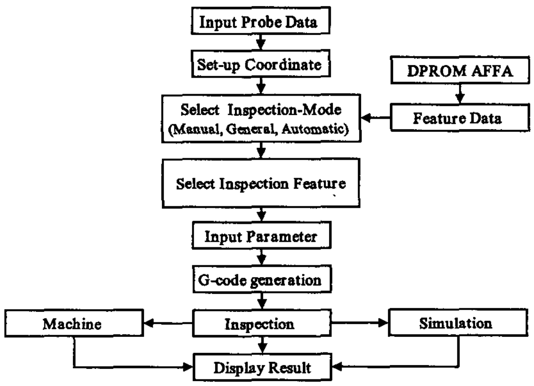


Fig. 3 The structure of OMM module

3. The OMM module

The existing OMM operating methods are of two types. One is programming probe path at machine tool directly, the other is the type where a user distribute measuring points in a feature using CAD data manually. But these methods can not measure machining features automatically. In this study, there are machining features decomposed into 3D surface and we call it inspection feature. The inspection variables were determined according to geometric characteristics of inspection features. On the occasion of the inspection of the same feature(Fig.5), the OMM-module recognizes the geometric information of CAD/CAM as in Fig.4, and can inspect the workpiece using three modes, such as Manual mode, General mode and Automatic mode after changing the compound feature of workpiece into the inspection feature. The Manual Mode requires the inputs regarding the information of position to be inspected. The input variables are the information of inspecting position (P_2) and the position of recession of probe (P_1) in the Manual mode.(Fig.5(a)) The General Mode is suitable for the inspection of an analytic features(feature based surface) and the input variables are the number of sections to be inspected(NP) and the number of inspection points for each section.[6][7][8](Fig.5(b)) The Automatic Mode achieves the inspection by classifying the feature of CAD/CAM into the proposed inspection feature. (Fig.5(c)) The input variables are the repeatability of machine tool, the leading resolution value for OMM and the area of inspection feature. In addition, the information and safety distance of probe can be inputted. Fig. 6 shows the algorithm that determines the inspection variables (the number of measuring points, their location, probe path) for automatic mode. The number of measuring points is determined by Fuzzy logic. The location of measuring points is determined by Hammersley's algorithm and the probe path is decided by 2~3 guide points and TSP (Traveling Salesperson Problem) algorithm. Because the inspection variables of the Manual and General modes are inputted by an operator, their inspection is performed without applying the algorithms described previously.

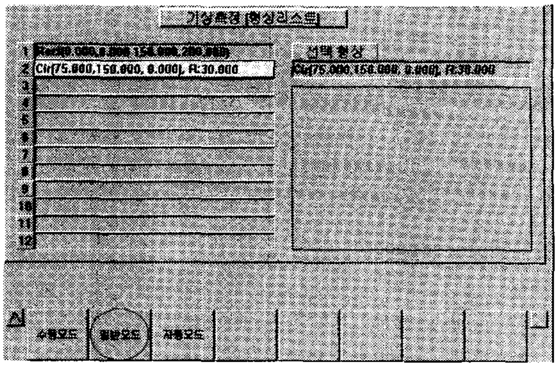
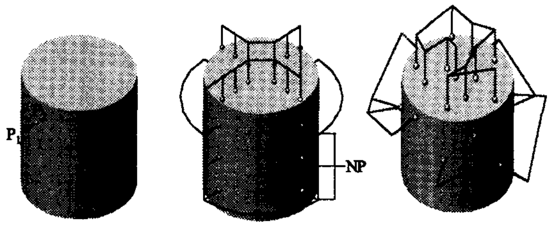


Fig.4 The selection of inspection mode in OMM module



(a) Manual (b) General (c) Automatic

Fig.5 The distribution of measuring point each mode

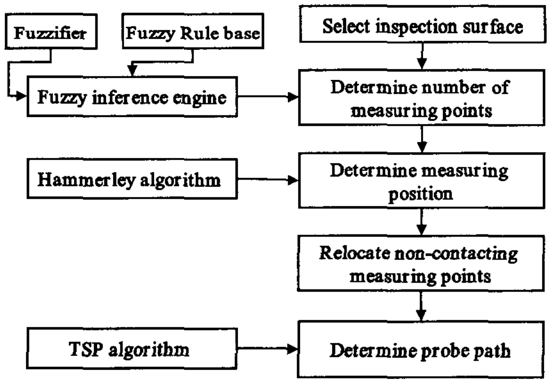


Fig.6 The procedures for determination of inspection parameters

3.1 Determination the number of measuring points using Fuzzy-algorithm

For measuring the subject, the measuring points are spread on inspection feature. At this time, the number of measuring points is determined first of all. It is the most influential factor of all the inspection variables to inspection resolution. If there is a lot of measuring points, inspection time increases. Generally, for reduction of the number of measuring points and the measuring time about various inspection subjects, the number of measured points are as follows : 3~5 points for a straight line, 4~9 points for a plane, 5~9 points for a sphere, 6~12 points for a cylinder and 7~12 points for a cone. Because it is the minimum number of measuring points which can define the inspection feature about subject simply, it is the number of measuring points ruled out the repeatability of a machine or the size of an inspection surface. Consequently, when the geometric tolerance is appraised or the result of inspection is represented using the minimum measuring points, it is not to be trusted. In this research, the repeatability of a machine tool and the size of inspection feature are added as a factor to decide the number of measuring points. Fig.7 shows the algorithm to determine the number of measuring points using Fuzzy logic. The minimum number of measuring points which is leaded by using Fuzzy logic agrees with the number of measuring points to evaluate the geometric tolerance. It is possible to input the maximum number of measuring points. The input variables are the area of inspection feature, the resolution to lead the result of inspection and the repeatability of the machine tool.[9] The measuring points are altered actively by the value of input variables.

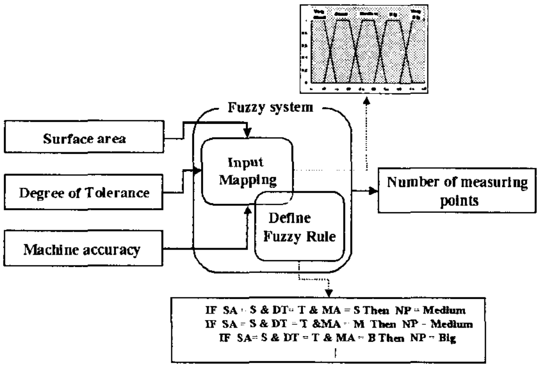


Fig. 7 The fuzzy logic for measuring points

3.2 Determination of the location of measuring points using Hammersley's algorithm

The location of measuring points to be applied to OMM module is determined by grid type and Hammersley's algorithm. The grid type method which uses the equi-interval mesh divides the range of object into definite intervals for x-, y- directions. As this mesh is applied to object, the uniform grid is made in the range of inspection object and then the intersections of x-, y-axis are decided on the inspection positions. This method is applied to the General Mode. The method using Hammersley's algorithm establishes (s, t) axis as Hammersley's coordinate in object. If 2D-section is a rectangle, a rectangular coordinate is used. If 2D-section is a circle, a polar coordinate is used. Table.1 shows the Hammersley's function for various features. In this table, the values of s, t are larger than 0 and smaller than 1. This method is applied to the Automatic Mode. Fig.8 shows the inspection positions in case of 10 measuring points.

Table 1 Hammersley's function for various features

Rectangular	$s_i = \frac{i}{N}$, $t_i = \sum_{j=0}^{k-1}\left(\left[\frac{i}{2^j}\right] Mod2\right)\times 2^{-j-1}$
Circular	$s_i' = t_i^{\frac{1}{2}} \times R$, $t_i' = s_i \times 360°$
Cone	$s_i' = t_i^{\frac{1}{2}} \times R$, $t_i' = s_i \times 360°$, $w_i' = -s_i' \times h$
Hemisphere	$s_i' = \sqrt{R^2-(-R-w_i')^2} = \sqrt{1^2-(1-t_i)^2}\times R$ $t_i' = s_i \times 360°$, $w_i' = -t_i \times R$

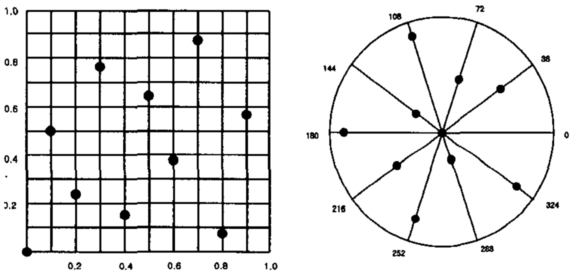


Fig. 8 The distribution of ten Hammersley points on rectangular and circular surface

3.3 Determination of the probe path using Traveling Salesperson Problem

In On-Machine Measurement, the path of probe must satisfy two conditions; generating the minimum moving distance and determining sequence of measuring points.[10] The guide point minimizes the measuring error and plays a role in collision avoidance. To determine the order of measuring points is to minimize the measuring time. Generally, the number of guide points is 2 or 3. The reason is to minimize the inspection error and to move the probe for normal direction. For the collision of probe, to use the three guide points is lucrative, but for the measuring time, to use the two guide points is favorable. In this study, the entering direction of probe is decided by two guide points. (Fig.9(a)) There are external guide points(P_i) and internal guide points(P_t).

$$Pt_i(x,y,z) = P_i - \Delta g \cdot N_i(x,y,z) \quad (1)$$

$$Pi_i(x,y,z) = P_i + \Delta g \cdot N_i(x,y,z) \quad (2)$$

In the above, Δg represents the distance from the measuring point to the guide point. The measuring order of inspection points is applied to TSP-algorithm to decrease the total measuring time. (Fig.9(b)) Eq.(3) shows the objective function.

$$E = \sum_{i=1}^{n} \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2 + (z_i + z_{i+1})^2} \quad (3)$$

(n: Number of measuring points)

Where n is the total number of measuring points, (x_i, y_i, z_i) is the coordinate of measuring point and E is the total moving distance of probe. If the sequence of measuring points is determined for minimizing E, the probe path is determined accordingly.

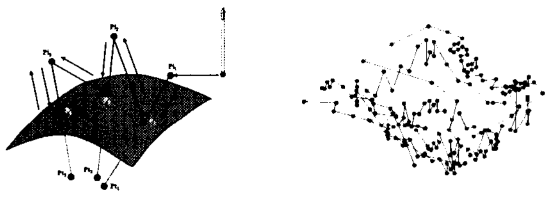


Fig.9 The probe path determination ((a) Probe path using two guide points, (b) Measuring sequence by minimum distance calculation)

4. Inspection Feature

4.1 The classification of inspection feature

Generally, the geometric information of CAD or the characteristic feature which is possible to be divided in manufacturing step is used as the inspection feature.[11][12][13] When the inspection is executed using touch-type inspection equipment such as CMM or OMM , the inspection method by feature-unit has not proposed yet except the method of position error discrimination to measure the classified feature by points-unit. Although the inspection object has the single feature of CAD/CAM, the inspection feature is separated into the surface information for measuring in more detail. Because the direction or range which is impossible to measure could exist in characteristic of touch-type inspection equipment, the feature may be not separated into the surface information. There is not easy to cope with this situation. Therefore, in this research, the inspection feature is assorted and organized as in Fig.10. At first, the inspection object is divided into analytic geometries and free-form geometries. The analytic geometries are separated no more and left the single surface. In other words, the general characteristic feature could be constituted by several single inspection features and classified. In occasion of inspecting the single surface, it is gotten the result of inspection corresponding to six geometric tolerances. In case of inspecting two or more single geometry which is integrated geometries, it is gotten the result of inspection corresponding to four geometric tolerances related to each other.

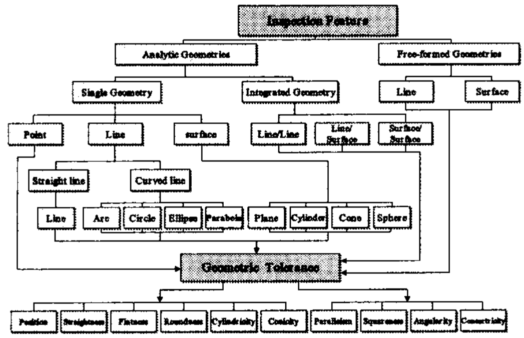


Fig.10 Geometric feature classification for inspection

4.2 OMM using inspection features

It is decided the workpiece to represent the process of determination measuring points by the classification of feature in Automatic Mode and it agrees with the object to perform the inspection in experiment. Fig.11 shows the result of feature classification for workpiece. In STEP 1, there are separated features by the classification for machining feature. In other words, there are structured the characteristic features as Island 1(F_1), Pocket 1(F_2) and Slot 1(F_3). In STEP 2, the object is divided into the inspection feature again. S_1~S_5 are determined by the approaching direction of probe and there are features which are not made by the method of machining feature classification but they exist surely in the object after machining. These features are needed certainly when the inspection is performed. Fig.12 shows the inspection feature by the method of inspection feature classification for F_2 (feature 2 in Fig.11). F2 has nine inspection single features; Side Plane 2(4 EA), Side Quarter Cylinder 2(4 EA) and Bottom Plane 2(1 EA). The number of measuring points and their location for each inspection feature are determined by the OMM algorithm, so the decision of measuring points for one characteristic feature is completed. Fig.13 shows the determination of measuring points which is applied to Fuzzy algorithm and Hammersley's method for the representative inspection features of F_2. Fig.14 shows the number of measuring points, their location and probe path. SP_{2a}, SP_{2b}, SC_{2a}, BP_{2a} are composed with 7, 7, 5, 7 measuring points, so the total number of measuring points is 26 in F_2.

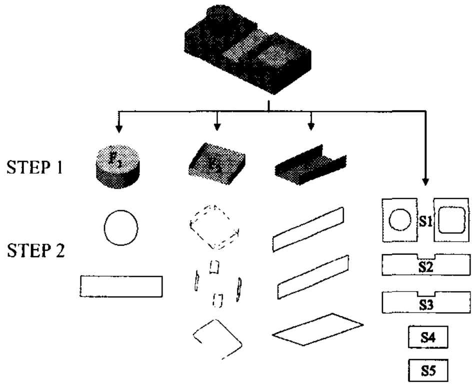


Fig.11 Feature classification for part

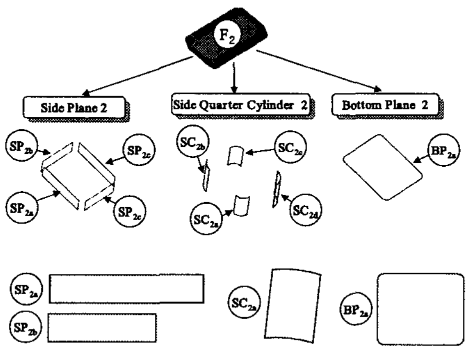


Fig.12 Inspection feature classification for F_2

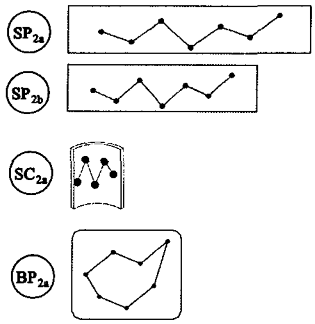


Fig.13 Distribution of inspection points for Typical Feature of F_2

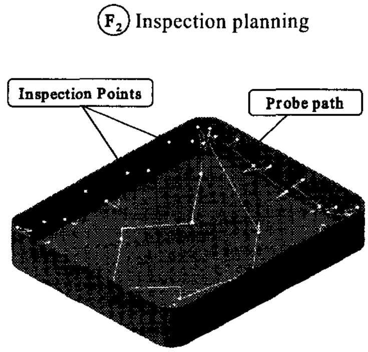
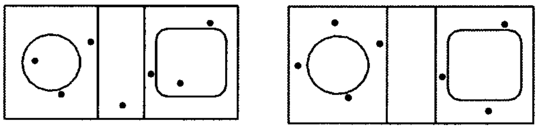


Fig.14 Distribution of inspection points for F_2

4.3 Determination of Non-contact point

The measuring points of F_1, F_3 which are machining features are determined by the same method to be applied to F_2. If S_1~S_5 are applied to Hammersley's algorithm, however, non-contact point could be generated as in Fig. 15(a). Most of S-group has non-contact points. In this case, the positions of non-contact points are determined again. In this study, for the inspection feature which has non-contact points, the locations of measuring points are determined again by the rectangle mesh. Fig.16 shows the partition of S_1. The method of location decision, at first, detects whether the measuring points exist or not in each rectangle mesh and locates the measuring points individually on mesh-center again as many as the number of non-contact points from the largest mesh to the smallest mesh which doesn't have the measuring point. If the number of non-contact points is more than the number of rectangle mesh, the divided surfaces are regenerated using the measuring points of each rectangle mesh and the measuring points are located again in order of large area. Besides, if the range between the surface and the rectangle mesh is larger than two-third of the minimum range, there is possible to be distributed the measuring points, otherwise, it is impossible. The real S_l has three non-contact points and the position of measuring point is decided again in large area order; M_{la1}, M_{lb2}, and M_{la3}. The result is showed in Fig. 15(b). [13][14]



(a) Before (b) After

Fig.15 Relocation of non-contacting measuring points for S_l

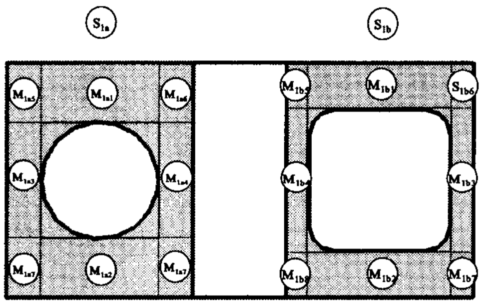


Fig.16 Rectangular mesh generation

5. Simulation & Experiment

The OMM program was made of Visual C++ ver. 6.0 based on the proposed inspection method. This program was loaded into DPROM which is the dialog based program of PC-NC, and the machining simulation and inspection were executed. The workpiece was designed and the machining simulation was executed for testing the developed OMM-Module.(Fig. 17) The workpiece material is an MC(Methylene Chloride). The real machining and the OMM were performed in a CNC M/C(V100, HYUNDAI).(Fig. 18) The results were obtained by performing the above inspection method. The number of measuring points is 60 and the time which is required for inspection is 10 min. 50 sec. Fig. 19 shows the moving path of the probe and the location of measuring points based on the inspection plan. Table.2 and Table.3 show the analytic result of geometric tolerance after inspecting the machined object. Table.2 shows the position tolerance of inspection surface. SC_{1a}, the side surface of F_2, was estimated the worst machining state and TC_{1a}, the upper surface of Island (cylinder), was estimated the best machining state. Table.3 shows the estimated results of geometric tolerances except for that. In case of performing the inspection mode, the precision of machine tool is an input variable. The purpose is to improve the precision of a machine tool, so the geometric tolerance of a machine tool was measured by laser interferometer and applied to this system. The pre-traveling error which is generated by contacts of probe was gained by the experiment and the result of inspection was calibrated by this error. [15]~[19]

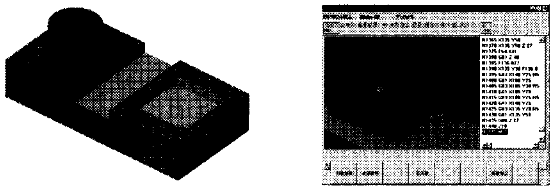


Fig.17 Part drawing and simulation

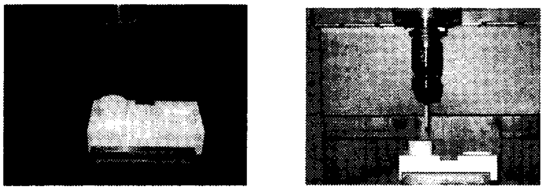


Fig.18 Machining & Inspection using OMM system

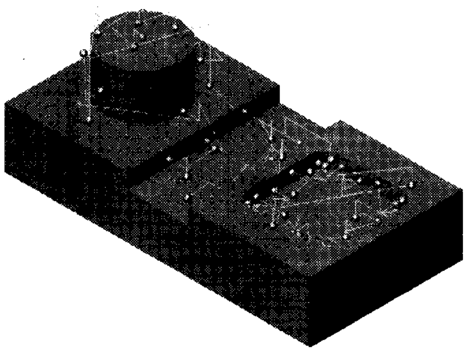


Fig.19 Distribution of measuring points for Part

6. Conclusion

The OMM using a machine tool does not require the machined object to be moved from a machine tool to a CMM for measurement. Therefore, it is possible to check the machining error on each process. Because of this advantage, the operator can cope with each process actively. This research proposes the method to execute the OMM efficiently for the object which is composed of analytic geometries, thus the results of this study are as follows:

(a) The inspection features were classified systematically for the CAD/CAM feature.
(b) The OMM was performed using the classified inspection feature.
(c) Input variables as the number of measuring points, position and the inspection path were decided automatically for the inspection feature by the respective decision algorithms.
(d) The OMM-Module was connected with DPROM, the operating system of PC-NC.
(e) The feature–based operating module of OMM was developed.

Table 2 Inspection result(position error, mm)

	Min	Max	Tolerance
S_1	-0.0851	0.0669	0.1520
TC_{1a}	-0.0038	0.0034	0.0072
SC_{1a}	-0.0766	0.0763	0.1529
SP_{2a}	-0.0450	0.0784	0.1234
SP_{2b}	-0.0132	0.0422	0.0554
SP_{2c}	-0.0450	0.0718	0.1268
SP_{2d}	-0.0131	0.0462	0.0593
SC_{2a}	-0.0685	0.0547	0.1232
SC_{2b}	-0.0589	0.0623	0.1212
SC_{2c}	-0.0653	0.0537	0.1190
SC_{2d}	-0.0583	0.0610	0.1193
BP_{2a}	-0.0143	0.0290	0.0433
SP_{3a}	-0.0113	0.0246	0.0359
SP_{3b}	-0.0114	0.0259	0.0373
BP_{3a}	-0.0351	0.0368	0.0719

Table 3 Geometry Tolerance(mm, rad)

	Flatness	Roundness	Cylindricity
S_1	0.0561		
TC_{1a}	0.0031		
SC_{1a}		0.0437	0.0438
SP_{2a}	0.0489		
SP_{2b}	0.0250		
SP_{2c}	0.0456		
SP_{2d}	0.0274		
SC_{2a}			0.0105
SC_{2b}			0.0201
SC_{2c}			0.0153
SC_{2d}			0.0198
BP_{2a}	0.0158		
SP_{3a}	0.0155		
SP_{3b}	0.0163		
BP_{3a}	0.0125		

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