

An Application of Finished Test Piece Methods for Evaluating the Performance of Computer Numerical Control Machining and Turning Centers

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ABSTRACT

Currently, many mechanical parts are produced from computer numerical control (CNC) machines including CNC machining centers and CNC turning centers. In order to keep production costs as low as possible, workpieces have to be rejected at the minimum rate. This can be done, but it depends on many parameters. One important parameter is adequate machine performance to produce the workpiece. In this research, a new technique was introduced to evaluate the performance of both CNC machining and turning centers. The first benefit of this technique is that manufacturers can evaluate a machine's performance themselves (no expert is required). The second benefit is that the approximate workpiece dimensions can be predicted in advance. In addition, using the standard test piece, experimental results confirmed that this new technique can be used in industry.

Keywords: finished test piece, machining centre, performance, turning centre

INTRODUCTION

Presently, computer numerical control (CNC) performance testing can be classified into two categories—direct measurement methods and indirect measurement methods.

With direct measurement methods, testers usually employ the ISO 230 series (International Organization for Standardization, 2012) and ISO 10791 series (International Organization for Standardization, 1998) as testing standards. For CNC turning centers, the popular testing standards are the ISO 230 series (International Organization for Standardization, 2012) and ISO 13041 series (International Organization for Standardization, 2005). Major equipment for these test methods

includes laser interferometers, ball-bars and/or dial-gauges (Figure 1). The results from this testing can be used for several machine adjustments. Since most testing results are based on quasi-static errors, manufacturers are notable to determine the extent of the difference between the true product geometry and its design geometry.

For indirect measurement methods, testers usually use International Organization for Standardization. (1998) to evaluate the performance of CNC machining centers, and employ International Organization for Standardization (2005) to evaluate the performance of CNC turning centers (Reference). These tests use finished test pieces to evaluate the CNC machine performance (a piece either complies or does not comply).

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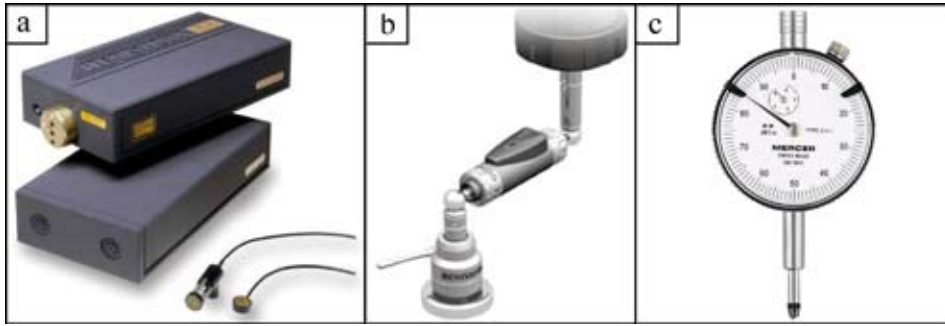


Figure 1 Examples of testing instruments: (a) Laser interferometer; (b) Ball-bar; (c) Dial gauge. (Sourced from: <http://mtsandtg.com>, <http://www.renishaw.com>; and <http://www.rotagriponline.com>; 20 May 2013).

Unfortunately, both methods (direct and indirect) cannot tell whether or not the machine can produce finished workpieces that follow the geometrical product specifications (GPS) because normally, the testing results are employed to adjust the CNC machine tools (Chean and Geddam, 1997; Liu and Venuvinod, 1999; Raksiri and Parnichkun, 2004; Zhu *et al.*, 2012;).

Hence, in this research, a new technique to evaluate the performance of both CNC machining and turning centers was introduced based on modifications to International Organization for Standardization (1998) and International Organization for Standardization (2005). This technique involves a shorter testing time and a lower testing cost compared with other techniques. Additionally, this new technique can predict whether or not the machine can produce finished workpieces following the geometrical product specifications (GPS).

Relevant theory

The important relevant theories are: 1) ISO 10791-7 and 2) ISO 13041-6 (International Organization for Standardization, 1998, 2005).

ISO 10791-7

ISO 10791-7 tests conditions for machining centers and in part 7 covers the accuracy of a finished test piece with regard to

the ISO standard which details information as broadly and comprehensively as possible on the tests which can be carried out for comparison, acceptance, maintenance or any other purpose. It can be used for numerically controlled milling and boring machines.

There are two types of test piece. The first is a positioning and contouring test piece. The second is a face milling test piece. Examples of both types of test piece are shown in Figures 2 and 3.

Tooling and cutting parameters (cutting speed, feed rate and depth of cut), blank and preliminary operations need to be done in accordance with the standard. A coordinate measuring machine (CMM) must be used as the major measuring instrument.

Both types of test piece can provide some useful information for evaluating machine performance. This information includes: 1) cylindricity of the holes—this is the tolerance zone of holes created by two imaginary cylinders; 2) straightness of the hole axis and the reference—this is a form tolerance to control the hole axis and the reference by using two imaginary parallel lines; 3) straightness of the sides—this is the straightness of the sides of the test piece 4) squareness of the sides—this shows variation from a 90-degree angle; 5) parallelism—this indicates the relation of the inspected feature to another datum plane;

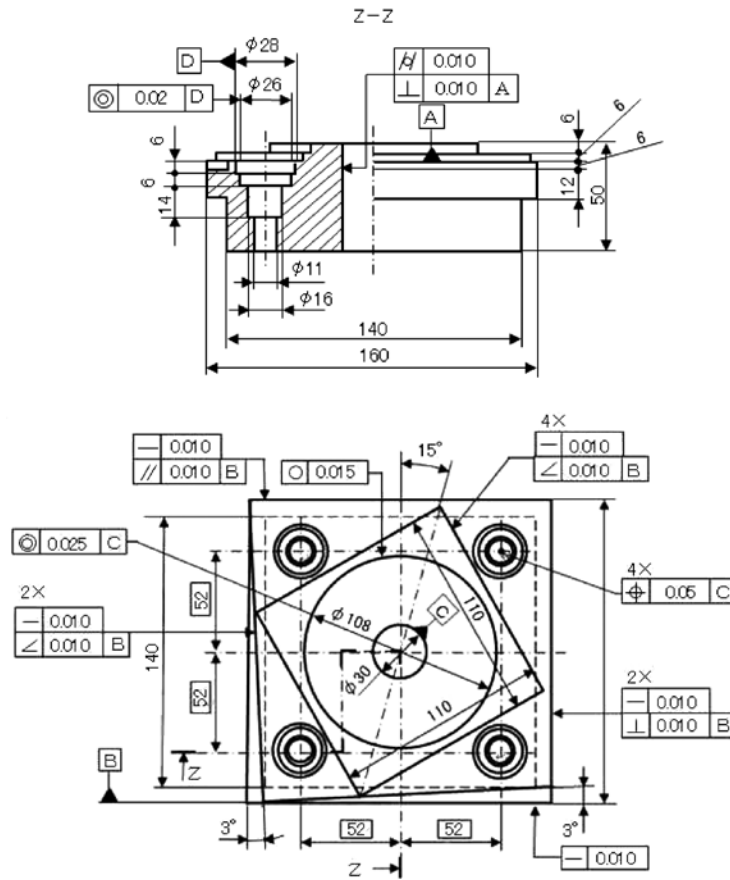


Figure 2 Example of small-sized positioning and contouring test piece. (Sourced: International Organization for Standardization, 1998).

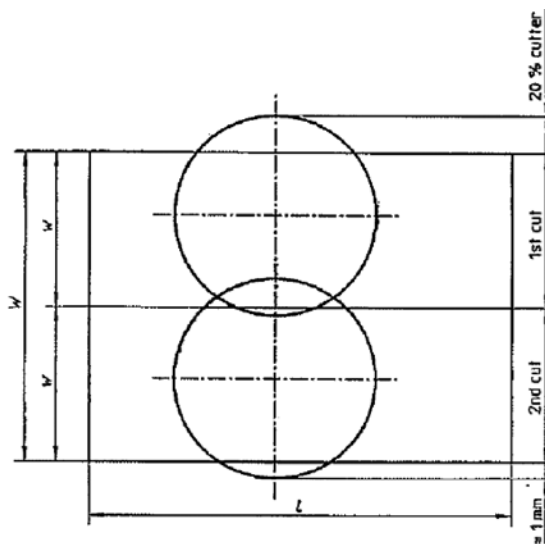


Figure 3 Example of a pattern in a face milling test (Sourced: International Organization for Standardization, 1998).

6) circularity—this defines the roundness between two concentric circles; 7) concentricity—this is used to compare two or more cylinders and to ensure that they share a common center-axis; 8) straightness of the faces—this is the straightness of the faces of a test piece; 9) accuracy of the angles—this is the variation in the specified angle between a related datum and the angled feature; and 10) flatness—this is the variation in the surface of the part which is limited by the two, imaginary, perfectly flat planes.

ISO 13041-6

ISO 13041-6 tests the conditions for numerically controlled turning machines and turning centers and in part 6 covers the accuracy of a finished test piece with regard to the ISO standard which details information as broadly and comprehensively as possible on tests which can be carried out for comparison, acceptance, maintenance or any other purpose. It can be used for both numerically controlled turning machines and turning centers.

In order to apply ISO 13041-6, reference is made to ISO 230-1, especially for the installation of the machine before testing, warming up of the machine, description of measuring methods and evaluation and presentation of the results.

There are four types of test piece. The first is a cylindrical test piece. The second is the flatness of a surface test piece. The third is a test piece machined under different kinematic conditions. The last is a circular test piece. Some examples of these test pieces are shown in Figure 4.

Tooling and cutting parameters (cutting speed, feed rate and depth of cut), and a pre-machined blank need to be done in accordance with the standard. A CMM must be used as the major measuring instrument.

Using this ISO standard, test pieces can provide some useful information for evaluating the performance of a turning center. This information includes cylindricity, consistency of machined

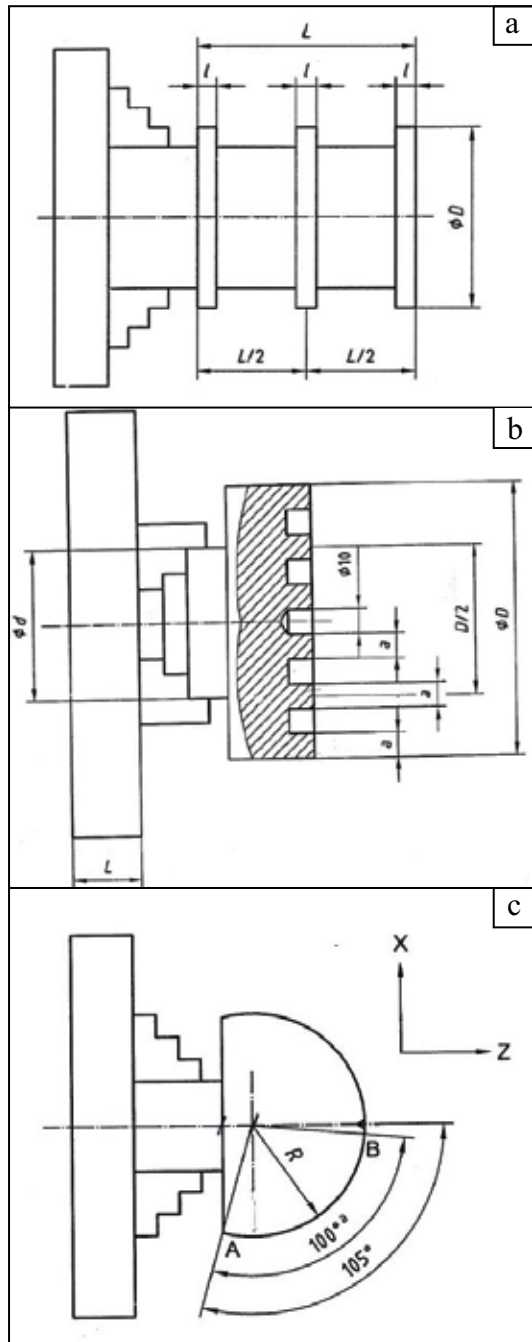


Figure 4 Three finished test pieces shown in International Organization for Standardization (2005): (a) Cylindrical test piece; (b) Flatness of surface test piece; (c) Circular test piece.

diameters, flatness, circular deviation, squareness, parallelism, straightness, accuracy of the angles, true position of holes and concentricity of outer holes to inner holes, as defined in the previous section.

A new technique for computer numerical control machining and turning center performance evaluation

The original idea for this new concept was first introduced in 2013 (Chungchoo, 2013a, 2013b). It can be used for evaluating the performance of both CNC machining and turning centers. The concept involves converting the tolerance values of the test piece to a tolerance per unit length of each tolerance type (as shown in Figure 5). Additionally, the uncertainty of measuring equipment is relevant to this concept.

For CNC machining centers, the test piece is prepared following the ISO 10791-7 standard. However, the test piece for CNC turning centers is made under the recommendations of ISO 13041-6.

In a working length, there is variation in the machine performance. For example, in CNC machining centers, the straightness of the Y-axis on the left hand side is not the same as on the right hand side. Normally, the usual working zone has the lowest machine performance. If the

tested piece is located in this zone, the reported performance is the minimum performance of the machine. Manufacturers need to use this worst value to predict whether or not the machine can produce finished workpieces following the GPS. The recommended testing position is at the center of the table for CNC machining centers and at the zone between the chuck to one quarter of the working length in the z axis for CNC turning centers.

MATERIALS AND METHODS

Experimentation

Equipment and materials for computer numerical control machining center

Test pieces (according to International Organization for Standardization, 1998) were prepared using a CNC machining center (model MCV1165; Micro-Tech; Tamil Nadu, India) which employed two cutting tools. These cutting tools were a flat end mill with a diameter of 30 mm (four flutes) and a face mill with a diameter of 63 mm (six flutes). The geometric dimensioning and tolerancing (GD&T) values of these test pieces were measured using the CMM machine (model 910; Mitutoyo; Kawasaki, Japan). The test piece material was aluminum alloy #5083.

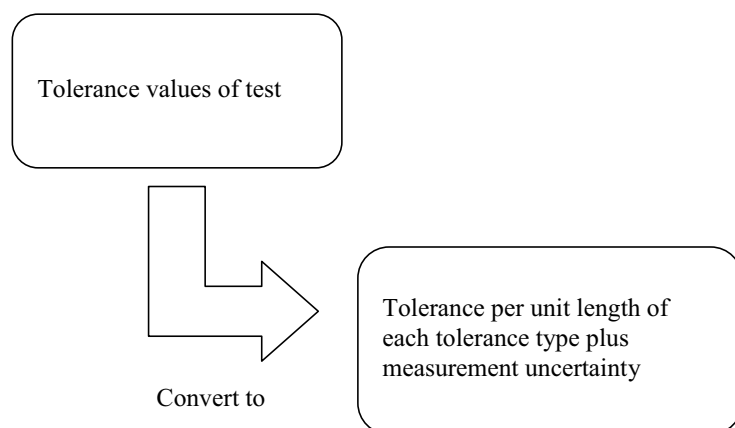


Figure 5 A new technique for computer numerical control machining and turning center performance evaluation.

Equipment and material for a computer numerical control turning center

Test pieces (according to International Organization for Standardization, 2005) were made by employing a CNC turning center (model: ST10; Hass; Tainan, Taiwan) which used two tool inserts. These inserts were WNMG080404MA (for endface and roughness) and TNMG160404R2G (for finishing). The GD&T values of these test pieces were measured using a CMM machine (model PMM-C700; Brown & Sharpe; North Kingstown, RI, USA). The test piece material was stainless steel SUS304.

Experimental set-up

Experiment for computer numerical control machining centers

In this research, a small-sized contouring test piece according to the International Organization for Standardization (1988) standard was used as a standard test piece. The method for preparing the blank, including the selection of the cutting parameters, was done by following the recommendations mentioned in the ISO standard.

When the machining process was finished, the test piece was assessed for its measured tolerance values using the CMM machine. The 13 tolerance measurements (mentioned in International Organization for Standardization, 1998) were recorded. Then, these tolerance values were converted to the tolerance per unit length of each tolerance type plus the measurement uncertainty.

The design shown in Figure 6 was used as a case study to test the concept of the new technique for evaluating the performance of a CNC machining center. Before production, the calculated tolerance was used to predict the dimension of the workpiece. After the machining process was complete, the real and the predicted dimensions were compared.

It should be noted that the number of contact points required for CMM measurement followed the recommendations shown in Table 1.

Experiment for computer numerical control turning centers

A cylindrical test piece, the flatness of surface test piece and a circular test piece of the ISO 13041-6 standard with sizing in category 1 were used as standard test pieces. The method for preparing the blank, including the selection of the cutting parameters, followed the recommendations mentioned in the ISO standard.

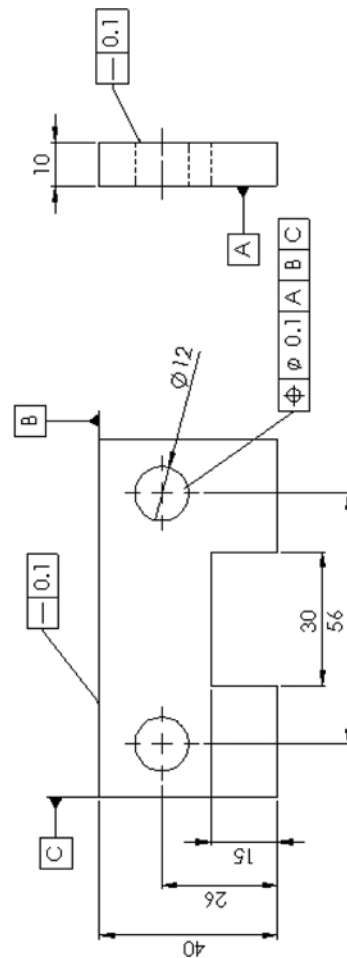


Figure 6 Case study for workpiece produced by the machining center.

As in the above section, when the machining process was finished, the CMM machine was used to measure the tolerance values of each test piece. The four objects of tolerance (mentioned in International Organization for Standardization, 2005) were recorded. Then, these tolerance values were converted to the tolerance per unit length of each tolerance type plus the measurement uncertainty.

The design shown in Figure 7 was used as a case study to test the concept of the new technique to evaluate the performance of the CNC turning center. Before production, the calculated tolerance was used to predict the dimensions of the workpiece. After the machining process was finished, the actual and the predicted dimensions were compared.

RESULTS AND DISCUSSION

Testing of computer numerical control machining center performance

The performance of the CNC machining center was assessed by following International

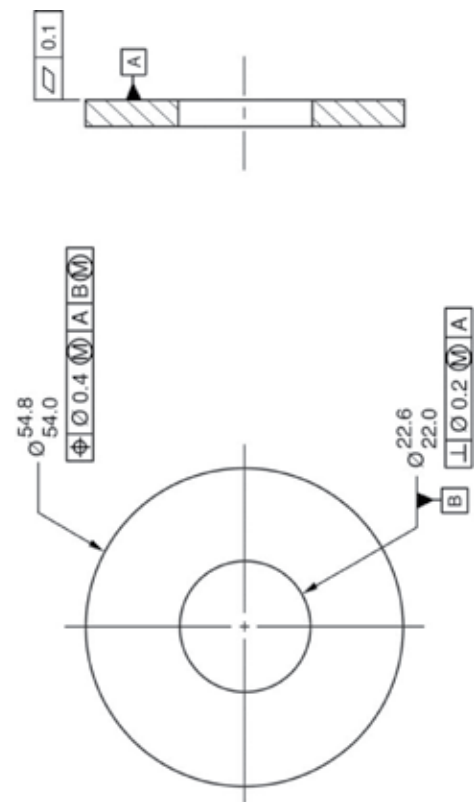


Figure 7 Case study for workpiece produced by the turning center.

Table 1 Recommended contact point for coordinate measuring machine measurement (Flack, 2001).

Geometric feature	Mathematical minimum	Recommended amounts
Straight line	2	5
Plane	3	9 (approximately three lines of three)
Circle	3	7 (to detect up to six lobes)
Sphere	4	9 (approximately three circles of three in three parallel planes)
Cone	6	12 (circles in four parallel planes for information on straightness) 15 (five points on each circle for information on roundness)
Ellipse	4	12
Cylinder	5	12 (circles in four parallel planes for information on straightness) 15 (five points on each circle for information on roundness)
Cube	6	18 (at least three per face)

Organization for Standardization (1998). In this work, a small-sized contouring test was used (Figure 8). Using the CMM machine, the test results were recorded and are shown in Table 2. Considering Table 3 of International Organization for Standardization (1998), it was found that there are some tolerance objects which did not meet the accepted criteria. These were the squareness of the adjacent sides to basis B, the accuracy of the 75°

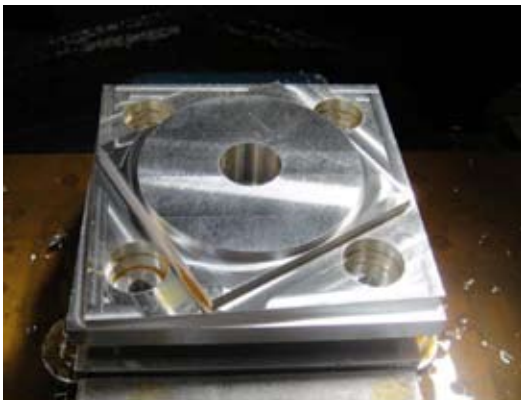


Figure 8 Example of a small-sized contouring test piece.

angle to basis B, the circularity, the accuracy of angles 93° and 3° to basis B and the concentricity of the inner hole to the outer hole D. Although this machine can be used for producing low accuracy workpieces, the owner needs to refurbish as soon as possible.

As stated earlier, the test results following International Organization for Standardization (1998) need to be converted to the tolerance per unit length with uncertainty. The uncertainty value can be determined from: 1) the actual uncertainty of the CMM machine that is reported in the certificate of calibration, or 2) the permissible error of the CMM machine calculated following International Organization for Standardization (2009).

In this research, the uncertainty value was taken from the permissible error of the CMM machine (International Organization for Standardization, 2009). This value can be calculated from $\Delta U = \pm (3.9 + 4 L / 1,000) \mu\text{m}$. Since the unit length that was used in this research was 100 mm, the uncertainty is $\pm 4.3 \mu\text{m}$.

Table 2 Small-sized contouring test piece.

Object	Measuring value (μm)	Measuring value per unit length with uncertainty (μm)
Cylindricity	8	$2.9 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Squareness between the hole axis and the basis A	7	$6.7 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Straightness of the side	10	$6.3 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Squareness of the adjacent sides to basis B	15	$9.4 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Parallelism of the opposite site to basis B	5	$3.1 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Straightness of the side	6	$3.8 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Accuracy of 75° angles to basis B	10	$8.3 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Circularity	20	$18.5 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Concentricity of the external circle and the internal borehole C	23	$76 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Straightness of the faces	4	$2.5 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Accuracy of angles 93° and 3° angles to basis B	4	$2.5 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Position of the holes with respect to internal bored hole C	11	$21.2 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$
Concentricity of inner hole to outer hole D	25	$82.5 \mu\text{m} / 100 \text{ mm} \pm 4.3 \mu\text{m}$

Predicting milling workpiece dimension using the introduced concept

Employing the case study shown in Figure 6, the predicted tolerance values were calculated as shown in Table 2. Compared with the real tolerance values measured by the CMM machine (Figure 9), it was found that the new concept, introduced in this research work, can be used to predict the workpiece dimensions (Table 4).

For the case study, it should be noted that only two objects (straightness and center to center of two holes) were investigated as shown in Figure 6.

Testing of computer numerical control turning centre performance

Before machining these test pieces, pre-machine blanks (Figure 10) were prepared as recommended by International Organization for Standardization (2005). Employing the cutting parameters specified in International Organization for Standardization (2005), three test pieces were made. Employing the CMM

machine to measure the test pieces (Figure 11), the test results were recorded and are shown in Table 5. Considering Tables M1, M2 and M4 in International Organization for Standardization (2005), it was found that there were some tolerance objects which could not pass the accepted criteria,



Figure 9 Measurement of the case study using the coordinate measuring machine.

Table 3 Small-sized contouring test piece (all dimensions in millimeters).

Object	Tolerance Nominal Size		Measuring instrument
	320	160	
Central hole			
a) Cylindricity	0.015	0.010	CMM
b) Squareness between the hole axis and the basis A	0.015	0.010	CMM
Square			
c) Straightness of the sides	0.015	0.010	CMM or straightedge and dial gauge
d) Squareness of the adjacent sides to basis B	0.020	0.010	CMM or square and dial gauge
e) Parallelism of the opposite side to basis B	0.020	0.010	CMM or height gauge or dial gauge

CMM = coordinate measuring machine

Table 4 Case study for concept testing.

Object	Predicted Value (μm)	Real Value (μm)	Error (%)
Straightness of the side (40 mm length)	1.52 ± 1.3	2.21 ± 1.24	31.22 ± 0.64
Center to center of two holes	11.9 ± 1.8	9.83 ± 1.24	17.39 ± 0.43

being the consistency of machined diameters and the flatness. From these results, the owner needs to refurbish this machine as soon as possible although it can be used for making low accuracy workpieces.

The uncertainty value was taken from the permissible error of the CMM machine (International Organization for Standardization, 2009). This value can be calculated from $\Delta U =$



Figure 10 Example of pre-machined blank of a flatness-of-surface test piece.

$\pm (3.9 + 4 L / 1,000) \mu\text{m}$. Since the unit length that was used in this research was 100 mm, the uncertainty is $\pm 4.3 \mu\text{m}$.

The following steps show an example of the calculation. Supposing, the flatness needs to be converted into the form of tolerance per unit length with uncertainty. As shown in Table 1, the measuring value is 15 μm for 132 mm length (radius). For a length of 100 mm, the tolerance value per unit length (100 mm) is $(15 \times 100 / 132) = 11.4 \mu\text{m} / 100 \text{ mm (radius)} \pm 4.3 \mu\text{m}$. The rest of the converted values are shown in Table 5.

Predicting turning workpiece dimension using the introduced concept

Three of four test pieces were used in the experiment. Hence, only four tolerance objects (cylindricity, consistency of machined diameters, flatness and circular deviation of a 100°) can be estimated in terms of the tolerance value per unit length (shown in Table 4).

The results of the case study shown in Figure 7 showed that there are three GD&T predictions of concern. However, only the flatness



Figure 11 Measurement of test pieces using the coordinate measuring machine: (a) Cylindrical test piece; (b) Flatness-of-surface test piece; (c) Circular test piece.

Table 5 Cylindrical, flatness-of-surface and a circular test pieces

Object	Measuring value (μm)	Measuring value per unit length with uncertainty (μm)
Cylindricity	5	12.6 $\mu\text{m} / 100 \text{ mm (radius)} \pm 4.3 \mu\text{m}$
Consistency of machined diameters	15	37.9 $\mu\text{m} / 100 \text{ mm (radius)} \pm 4.3 \mu\text{m}$
Flatness	15	11.4 $\mu\text{m} / 100 \text{ mm (radius)} \pm 4.3 \mu\text{m}$
Circular deviation of a 100°	25	50 $\mu\text{m} / 100 \text{ mm (radius)} \pm 4.3 \mu\text{m}$

can be predicted before machining because the other GD&T values need to be predicted from a test piece machined under different kinematic conditions which was not done in this research.

Using information in Table 4, the predicted flatness was calculated. The value is about $6.2 \mu\text{m} \pm 4.3 \mu\text{m}$ (calculated using linear approximation). Compared with the real tolerance values measured by the CMM machine ($5.3 \mu\text{m} \pm 0.8 \mu\text{m}$), the result showed that the new concept introduced in this research work, can be used to predict the workpiece dimensions.

Limitation of the introduced method

The important limitation of the method is that in this state, the proposed technique cannot be applied in some cases such as: 1) the cutting conditions of the test piece differ from the cutting conditions of the workpiece; and 2) the material properties of the test piece differ from the material properties of the workpiece.

CONCLUSION

The standard test piece was used as a case study and the experimental results indicated that the proposed technique can be used to evaluate the performance of both CNC machining and turning centers. In addition, by applying this technique, machined part manufacturers can approximate the geometric error of their product in advance. However, with the machining center, the difference between the predicted value and the real value is quite substantial (Table 4). Similar results were observed in the case of the turning center. Therefore, this technique needs to be improved in order to enhance its accuracy for approximating the geometric error of a product in advance

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