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Determining the Accuracy of Measurement on a CNC Milling Machine

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Abstract

This article describes the difference between coordinate measurement results obtained on a coordinate measuring machine and on a CNC milling machine. It also includes the raw materials used for measurement, the geometry of the workpiece used, the tools used, the principles used to evaluate the measurement and the measurement results. In terms of measurement results, machine measurement has been shown to be more accurate. For flatness, the deviation between the two measurements averaged 4 µm, for circularity 4 µm, for single-interpolation machining with one axis 3 µm, their parallelism 5 µm, for machining two ten-slots together 2 µm, their parallelism 5 µm. The difference between the errors proves that milling and measuring machine measurement do not differ to such an extent as to require investment in a measuring machine, if circumstances do not require it.

Keywords*: metrology, coordinate measurement, CNC milling machine, accuracy.*

1. Introduction

An important principle of manufacturing is to achieve dimensional accuracy and precision by means of a tool. These tools can be any of the machines used in manufacturing technology, whether driven by human power, heat, electricity, or any energy source discovered since our existence on earth. One of the most important problems we face has always been and will always be to achieve the necessary precision.

In the world of Industry 4.0 and automation, metrology has also become part of the equation, which has increased the frequency with which measuring machines are integrated into production. Both in-production and post-production measurements are an important way to improve accuracy. Two systems have become widely used in industry: on-machine measurement (OMM) and coordinate machine measurement (CMM).

OMM is a process that allows machine tools to measure and evaluate the dimensions and geometric properties of workpieces immediately after the manufacturing process and is also used for in-process measurements. As a result, the OMM system allows manufacturers to get real-time feedback on the accuracy of production and to apply corrections immediately if necessary. In this way, OMM can help to increase manufacturing efficiency and improve quality.

The term CMM stands for coordinate measuring machine. A coordinate measuring machine is a device used during and after the manufacturing process to measure and check the dimensions and geometric properties of workpieces. The CMM is a high-precision CNC-controlled system capable of accurately measuring the X, Y and Z coordinates of objects. CMMs allow manufacturers to check workpieces against design specifications and evaluate the accuracy and quality of the production process. However, the cost of such a measuring machine is very different from the tools used in the OMM process mentioned above, and its use is regulated by more stringent and binding standards. It also requires a specialist to operate the measuring machine, which adds to the cost of producing the parts.

Within the framework of Industry 4.0, it is possible to use automated systems. For OMM tools that are integrated into the system, it is important to assess the degree of reliability and accuracy of the tool and to consider whether the cost reduction is worthwhile. In contrast, in additive manufacturing, OMM is the preferred application where a hybrid machine is available that can perform both additive manufacturing and machining. In such cases, it is not practical to take the part out of the machine, so OMM should be used, further reducing the number of defects introduced.

The aim of this study is to compare the accuracy of OMM and CMM measurements.

In manufacturing and its inspection, there has always been the question of whether an expensive but accurate coordinate measuring machine is needed, or whether we should settle for the now common and relatively cheap probing units that can be installed in the machine tool. When OMM systems are used, the vast majority of companies use touch probes only for zero-point measurement, and a small percentage try to integrate them into production to a level where they can determine the size compensation value after machining. This gives them an accurate value more quickly to make the correction than after the operators have measured. The paper also discusses how the problem is to be investigated and what tools are to be used to carry out the exercise.

The following chapters will further elaborate on the specifications of the materials used and the measurement methods and guidelines used.

2. Measurement evaluation methods

The evaluation method also differed between the two machines used in the measurement. For the Renishaw gauge head used in the CNC machine, we did not use the evaluation methods offered by the manufacturer and therefore used the Excel program for the OMM. The evaluation of the measurement on the coordinate measuring machine was carried out using the Mitutoyo program (Geopak v2.3 R10). In both cases the same points were measured, and the results were calculated using the same method.

There are several methods for evaluating the points obtained during the measurement. We used the method of fitting, the Gaussian least squares method, which is also used in industry. To apply this method, we had to use the following basic equations for the different geometric elements:

Plane: $$Ax+By+C=0 \quad (1)$$

Linear: $$Ax+By+Cz+D=0 \quad (2)$$

Circle: $$Ax^2+Ay^2+Cx+Dy+E=0 \quad (3)$$

where A, B, C, D, E are the normal vector components and x, y, z are the coordinates of the given point (1), (2), (3) [1].

2.1. The gaussian curve fitting

In nature (because of the central limiting distribution theorem), measurable quantities usually have a Gaussian distribution, i.e., if the expected / theoretical value of a measurable quantity is μ, then the distribution of measured values will follow a Gaussian curve around μ, the width of which is proportional to the error of the measurement.

However, if we are not testing a single measurement in a sequentially repeatable manner, but pairs of data, that is a quantity according to a given function, then we use a modified χ^2 test (4).

$$\chi^2=\sum_{i=1}^{N}\left(\frac{f_i-f(x_i)}{\Delta f_i}\right)^2 \quad (4)$$

The theoretical function that we take as a basis is $f(x_i)$ and x_i is the value of the function at that point. The formula can be used to examine the probability that, given the given theoretical function, the measurement points obtained in practice will be obtained. The value of χ^2 gives the probability and has two parameters. One is the theoretical function itself and the other is the number of measurement points, that is, the number of degrees of freedom. If the value of the probability is less than 0.1 % then the theory is not correct and can be rejected, but otherwise it undermines the hypothesis.

The Gaussian fit we use is the inverse of this relationship. In the case where we are looking for a function by varying the parameters, we are looking for the minimum value of χ^2 (minimizing it), so we obtain the optimal parameters. This is called fitting [2].

2.2. The gaussian linear fitting

For the Gaussian fit of OMM, we used the Excel Solver numerical algorithm. Where the points were located along each line, a line was fitted to the measured points using Excel. In this case the relation of the quantity to be minimized is (5):

$$\chi^2(a,b)=\sum_{i=1}^{N}\left(\frac{f_i-ax_i-b}{\Delta f_i}\right)^2 \quad (5)$$

To check the minimalisation, we also calculated the optimal parameters using other methods. Using the equation of the line by a non-numerical method. Equation of the line is (6):

$$Y=ax+b \quad (6)$$

where a slope, b the point where the line intersects the Y-axis. To determine the slope, perform the following operation. Here, the coordinates x and y of the measured points and their mean ($\bar{x}$) are calculated (7).

$$a = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sum(x-\bar{x})^2} \tag{7}$$

The value b is solved by the following equation. The idea is that the line must pass through the points $\bar{x}$ and $\bar{y}$, so we will substitute this into the equation of the line. Then we sort the equation and get the intercept of the y-axis (8).

$$\bar{y} = a\bar{x} + b \rightarrow b = \bar{y} - a\bar{x} \tag{8}$$

Both methods gave the same result when written out to 4 decimal places, so the evaluation method can be considered correct.

The straightness of the geometric element under consideration was defined as the difference between the maximum and minimum of the measured points.

2.3. The gaussian circle fitting

We also used minimization for the circle but changed other parameters and approximated to obtain the optimal values.

For the calculation we used 24 measurement points defined by x and y coordinates.

The Pythagorean theorem was used to calculate the value of R_i (radius associated with x and y)) as a function of the measurement points (9). The centre of the circle is indexed x_0 and y_0 in the calculation and has a default value of 0.

$$R_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} \tag{9}$$

We also needed the value of ΔR which is the difference between the nominal value of R and R_i (10).

$$\Delta R = R - R_\mathrm{i} \tag{10}$$

It was also necessary to sumsquare the ΔR.

In the minimization, x_0, y_0 and R were varied as a function of $\sum \Delta R$. The circularity was given by the difference between the maximum and minimum of ΔR_i.

3. The applied tools

3.1. The NASA-test

The accuracy of machining is greatly influenced by the elements of the workpiece-machine-device-tool (WMDT) system. The US National Aeronautics and Space Administration (NASA) has developed a test piece to determine the accuracy of this system. The test piece contains surfaces and dimensions that can be used to measure the accuracy of the machine during machining. The test piece is based on a square with a circle on the base and a square rotated 45° on the circle. The test piece is shown in **Figure 1**.

The square machining of the first level from the bottom allows the longitudinal and transverse rake of the table to be measured. With the circle above it, the errors of circular interpolation can be measured, and the errors of axes flattening, and direction change due to circularity errors can be evaluated. The rotated square at the top of the piece gives the errors of the straight-line interpolation. The terraces define the positioning accuracy along the Z axis **[3, 4]**.

The workpiece material was Necuron 651 (artificial wood), which is a polyurethane foam. This material was chosen because it requires little cutting force to machine it, so errors due to cutting parameters are negligible. It also has a better coefficient of thermal expansion than steel, which was necessary because the two machines under test were not located in an air-conditioned room and were also in a different room.

Main features of Necuron 651:
- Cutting force ($kc_{1.1}$ = 120 N/mm^2);
- Easy chip handling;
- Compressive strength (25 N/mm^2);
- Coefficient of thermal expansion ($40 \cdot 10^{-6}$ K^{-1}).

3.2. Renishaw probing unit

Both the OMM (Renishaw OMP40-2) and CMM (Renishaw MH20i) probing units used in the measurement are of the switch type. They are the most widely used in the industry due to their commodity and simple principle of operation, which is why they were chosen to perform the

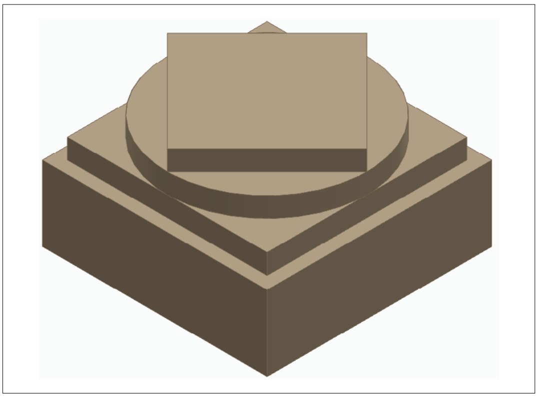

Fig. 1. *NASA test (workpiece).*

measurements. The manufacturer uses the term kinematic probe. They are measuring devices based on resistance variation and operate on the following principle.

In the probe head shown in Figure 2, three equally spaced rods rest on six hardened carbide balls, providing six contact points in the circuit. An electrical circuit is created through these connection points Figure 2 (a). The structure is preloaded by a spring, so the circuit is closed. Due to the spring load, interfaces are created through which the voltage flows Figure 2 (b). At the moment of probing, the reaction force in the opposite direction to the working force in the probing structure leads to a reduction of the interface Figure 2(c), resulting in an increase in resistance at that point Figure 2 (d). The variable force on the interface is measured as the change in the circuit. When the change in resistance reaches a limit, the output of the probe signals and sends a „tap" signal to the PLC-controller [5, 6].

In the case of the OMM, the touch probe communicates with the controller by optical signal transmission, whereas the coordinate measuring machine is directly connected to the controller.

The probe is made of industrial ruby.

3.3. The HAAS CNC milling machine

For the OMM measurement, a Haas Mini Mill Edu type 3-axis machining centre was used. The machine tool is a milling machine designed for educational purposes. Machine choice was based on the fact that the machine is equipped with a measuring system capable of optical signal transmission for OMM measurement, and the milling machine is a newly manufactured model, so possible wear errors can be neglected. The main spindle can be indexed in only one position. The machine is shown in Figure 3 [7].

The probing unit we use is the Renishaw OMP40-2, which has a repeatability of 1 μm. The length of the probe is 50 mm [8].

3.4. Coordinate measuring machine

The coordinate measuring machine was selected according to our capabilities. A Mitutoyo Crysta Plus M574 was chosen (Figure 4).

The measuring machine is equipped with an air bearing on all axes and a measuring gauge to ensure accuracy. The working space is 500×700×400 mm. The accuracy of the measuring machine is $E = 3.5 + 4.5L/100$ μm, and the resolution is 0.5 μm [9].

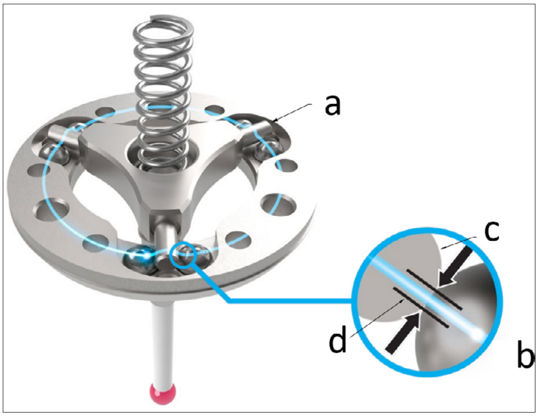

Fig. 2. *Switch type probe operating principle.* [5]

Fig. 3. *Haas Mini Mill Edu milling machine centre.*

Fig. 4. *Mitutoyo Crysta Plus M574 measuring machine.*

In the coordinate measuring machine Renishaw MH20i type probe unit was used. The size of the ruby sphere was 3 mm. The repeatability of the probe is 1.5 μm [10].

3.5. Control of probing units

In the case of the coordinate measuring machine, the program was created by teaching the points to be touched. For both OMM and CMM measurements, we used the same strategy and alignment length to ensure that any positioning inaccuracies or machine errors would affect the measurement under the same conditions (e.g., misalignment, etc.). During the measurements, the workpiece zero-point was centred in the upper plane of the workpiece.

For the CNC machine, we used G-code programming to create the point cloud. The G-codes that we used were called from Renishaw's own subroutines using G65, a simple macro call [11].

Renishaw subprogram:
– P9832 – Probe unit start;
– P9810 – Protected movement;
– P9811 – Simple surface measurement;
– P9821 – Simple surface angle measurement.

4. Results

During the measurement, several measurements were taken, and the average of these measurements is summarised in the tables.

4.1. OMM and CMM measurement results

To evaluate the OMM measurements, we used an Excel extension, Solver. The correctness of the obtained values (uniformity, parallelism) was also checked by elementary calculations.

Flatness was measured in the upper plane of the workpiece, the value of which is entered in Table 1. The number of measuring points was 9 in both cases (Table 1.).

Figure 5 shows the measurement points of the square island rotated by 45° and the regression line fitted to the points and describes the equation of the lines. From the measurement it can be seen that the CNC machine axes are not yet worn out to a level that can be detected by such a measurement. The axes move together with high precision. This can be seen from the slope of the regression lines. The difference in slope is only 0.0001 for the E3 line. For the other lines the deviation is smaller. In the equation of the line, the constant value differs from the nominal value (40 mm), the reason being that the milling tool used for the machining was not accurately dimensioned, so the diameter of the milling tool differed from the value given in the correction table [12].

Table. 1. *Upper plane measurement results*

Parameter	OMM value (mm)	CMM value (mm)
Flatness	0.0033	0.0070
Max	–0.0159	0.0050
Min	–0.0192	–0.0020

Table. 2. *The square shape rotated by 45° measurement results*

Linearity and parallelism		
Line	OMM value (mm)	CMM value (mm)
E1 (–X; –Y)	0.0028	0.0060
E2 (X; Y)	0.0030	0.0043
E3 (–X; Y)	0.0038	0.0038
E4 (X; –Y)	0.0027	0.0035
E1×E2	0.0031	0.0113
E3×E4	0.0034	0.0069

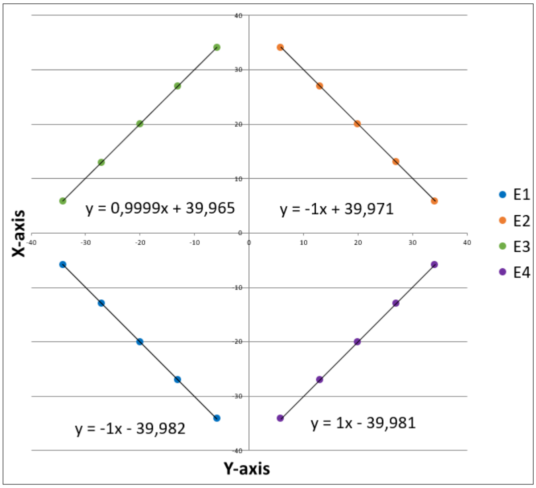

Fig. 5. *OMM measurement result of a square rotated by 45°.*

Table 2 compares the OMM and CMM measurement results.

The circular island was measured with 24 points 15° apart. A Gaussian fitting method was applied to the measurement results. The probed diameter was 80 (mm). Figure 6 shows the point cloud used for the circular shape measurement.

The parameters of the measured circle were defined, where x_0 y_0 are the coordinates of the

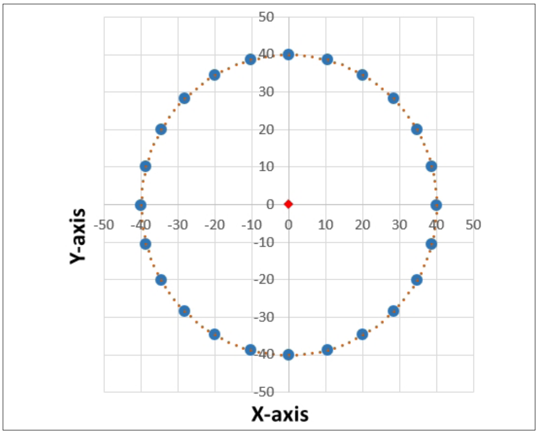

Fig. 6. *OMM measurement of the round shape with 24 points.*

Table. 3. *Round shape measurement results*

Circle parameters	OMM value (mm)	CMM value (mm)
x_0	–0.0014	0.0020
y_0	–0.0035	0.0040
R	39.9772	39.9860
D	79.9544	79.9720
Min	0.0020	–0.0050
Max	–0.0047	0.0050
RND	0.0067	0.0110

Table. 4. *The square shape measurement results*

Linearity and parallelism		
Line	**OMM value (mm)**	**CMM value (mm)**
E1 (X+)	0.0030	0.0069
E2 (X–)	0.0036	0.0068
E3 (Y+)	0.0050	0.0066
E4 (Y–)	0.0047	0.0073
E1×E2	0.0067	0.0207
E3×E4	0.0058	0.0103

centre of the circle, *R* is the radius of the circle, *D* is the diameter of the circle, *Min* is the minimum deviation from the Gaussian circle and *Max* is the maximum deviation, and *RND* is the circularity error (**Table 3.**).

When milling a square shape, the axes moved independently of each other so that displacement occurred along only one axis (**Table 4.**).

The surface of the circle shape was also checked for flatness. We recorded 3 points per quadrant on the surface, giving 12 measurement points. A plane was fitted to the measured points and the evaluation is shown in the following table (**Table 5.**).

We also measured flatness at the lowest Z level out of 4 points. In this case, the plane fitted to the points was also evaluated (**Table 6.**).

5. Conclusion

When comparing the data, the coordinate measurement on the measuring machine always more differs from the nominal value (max. 0.004 mm) than the results measured on the CNC machine (max. 0.003 mm), which depends on the accuracy of the measurement. The CMM measurement has a higher resolution due to the size of the ruby ball (Chapter 3.3 and Chapter 3.4), as it is smaller and therefore more sensitive to deviations, and therefore the deviation will be larger. In the case of the CNC, the deviation may also be caused by the difference in resolution due to the rotary encoder of the machine, as the measuring machine is equipped with a measuring gauge, therefore the higher resolution also leads to the higher sensitivity.

The same trend is observed for the flatness and its maximum and minimum values, with CMM measurements having a larger error (7 μm) than OMM measurements (4 μm).

The measurement results are relevant for industrial applications as the cost of coordinate measurements varies according to the equipment used. The CNC machine used and the Renishaw

Table. 5. *The circular shape upper plane measurement results*

Circular shape upper plane		
Parameters	**OMM value (mm)**	**CMM value (mm)**
Flatness	0.0047	0.0070
Max	–8.0034	–8.0040
Min	–7.9986	–7.9970

Table. 6. *The square shape upper plane measurement results*

Square shape plane		
Parameters	**OMM value (mm)**	**CMM value (mm)**
Flatness	0.0037	0.0000
Max	–16.0055	–16.0000
Min	–16.0018	–16.0000

OMP40-2 measuring device mounted on it allow measurements to be made more economically with sufficient accuracy.

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