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ORIGINAL ARTICLE

Calibration of the cutting process and compensation of the compliance error by using on-machine probing

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Abstract This paper addresses the compensation of cutting process related errors in order to improve the accuracy of manufactured parts. The compensation is a modification of the tool dimension and the tool path using on-machine probing data. A cutting depth distribution-based approach is proposed to calibrate the cutting process according to the on-machine probed error model. This approach is investigated in cases of both rigid and compliant parts. The calibration offset is estimated for the actual cutting conditions with and without a fitting process. In the case study, the offset varies from 12 to 17 μm for down milling at 6000 rpm spindle speed. The impact of the cutting speed is investigated. A rectangular profile was machined with and without compensation in down and up milling mode. The results show that the proposed approach is effective. The error is reduced from a maximum of 25 μm for down milling and 10 μm for up milling to 4 μm in both cases.

Keywords On-machine measurement · Accuracy · Error compensation · Calibration · Error model

1 Introduction

Machine tools play a key role in mechanical part production. Following the production process, the part is inspected to verify conformity to technical specifications such as dimensional tolerances. Because of fierce competition, machine tool design and use are subject to continuous improvements. The goal is to produce a part with high accuracy.

In order to improve the accuracy in the traditional manufacturing process, the machine and the cutting parameters are adjusted manually by an operator based on the observed deviation and experience. This takes time and is prone to errors.

Today, most machine tools are fitted with inspection devices such as a touch probe. This allows performing on-machine measurement of the part geometry before machining to establish the cutting starting point, and after a number of operations to verify dimensions while the part remains clamped. This can help to improve production quality by immediate deviation feedback. Using the on-machine measurement, it is hoped to replace the human observation/correction by an automated process of adjustment such as the intermittent measurement and compensation [1].

In order to investigate the dimensional and geometric inaccuracy sources of machined parts, some researchers studies the machine tools structures and motions [2–5] while others study the cutting process [6, 7]. The deviation from the desired dimension is due to the combined effects of many error sources which complicate its prediction.

The geometric errors of machine tools and their propagation on the part have been extensively studied [8, 9, 5]. Researchers use different tools to measure the deviation of the tool position with respect to the workpiece. The circular test using a ball bar is relatively simple and informative [2, 10]. Laser interferometer system is used on-machine to investigate the error of a single axis. In this process, many error sources and measurement setups [11] can manifest. On-machine probing an artifact either calibrated [12] or uncalibrated [13] is used to investigate the measurement capability and the volumetric errors of the machine tools. Periodic check of the effect of position-dependent geometric errors of rotary axis can be performed using the on-machine probing [14, 15].

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The machine tool needs to be compensated for its systematic geometric and kinematic errors before using it to cut or to inspect. The on-machine probing will not see the machine inaccuracy which is present, and similar, during machining and probing. However, during probing, the process-related errors are not present and so they can be detected.

The error sources can be from the machine tool, such as the geometric error, and from the machining process, such as the cutting forces and vibration. In order to compensate these errors by tool path modification, they must be quantified and then used as an input data to the compensation model. The global error can be reduced by applying elementary compensations. Each error component propagates according to its nature. A cutting tool deflection model is used in [16] to compensate the tool deflection. A part deflection model is used in [17].

The compensation of the on-machine probed error (OMPE) was the subject of research in [7]. The mirror technique was used to improve the dimensional part accuracy according to the mirror approach (error-to-cancel-error strategy). For errors dominated by the deflection phenomena, a mathematical model was developed in [18] to estimate the correction based on the error evolution in a multi-cut process. The cutting compliance coefficient (CCC) was introduced which relay solely the measured error and measured cutting depths.

This paper proposes a calibration procedure of the cutting process to eliminate the tool offset error (TOE) estimated for the actual cutting condition. This calibration is performed by automatic adjustment of the tool dimension on the controller. The compliance compensation model is used to eliminate the compliance error (CE) using probing data of the unclamped machined part.

The advantages are that the tool offsets are validated for the finishing cut to prevent accidental deviation due to erroneous tool offsets. The on-machine probing of the part before the finishing cut allows anticipating the expected error for the current part contrary to the standard inspection process of the final part. This improves productivity by avoiding producing non conformities. The calibration is performed automatically on the actual part without human intervention and complicated mathematical processing thus avoiding machine interruptions and potential errors.

The contribution is the answer to the following question: how to evaluate the cutting tool-related error from the on-machine measured profile? The new main idea is the implementation of the error control concept. The presented investigation results show that in order to cancel the tool-related error, it is possible to find the effective tool offset from on-machine measurement data. The separation strategy of the tool offset error from the total measured error which includes the deflection of the system (machine, tool, part) is presented as a new method which can be easily integrated in the manufacturing process. According to the error model, the tool offset error is the measured error when there is no system deflection.

2 Milling process calibration

2.1 Modeling of on-machine probed error

The OMPE is defined as the deviation vector of the probed point with respect to the design profile. To avoid the loss of part reference relative to the machine, the part remains clamped after the cut and the touch probe simply replaces the cutter.

Figure 1 illustrates the part, the tool path, and the on-machine probing. The tool path is extracted from the machining codes (G-code) or from CAM program (before post-processing). It is the successive points which are the trace of the tool center. In order to render these points numerically explicit, compact machining codes such as circular and interpolation-based spline are converted to linear interpolation points along the path [19]. The path produced by the connection of these points using straight lines must be as close as possible to the original tool path within a given tolerance.

The deviation vector, $\boldsymbol{h}_i$ of the measured point M_i, from the programmed tool path is the distance between the measured point and its normal projection on the tool center trace, M_{pi}. It can be expressed as

$$\boldsymbol{h}_i = \left(M_i M_{pi}\right)\cdot \boldsymbol{n}_i \tag{1}$$

where $\boldsymbol{n}_i$ is the normal projection unit vector of the measured point on the tool center trace. This is computed for each measured point. This is one of the three axis of the local coordinate system (LCS) which is chosen from the cross product of the feed direction, $\boldsymbol{f}_i$, and the cutter axis direction, $\boldsymbol{z}_i$, when tool is at the position M_{pi}:

$$\boldsymbol{n}_i = \boldsymbol{f}_i \times \boldsymbol{z}_i \tag{2}$$

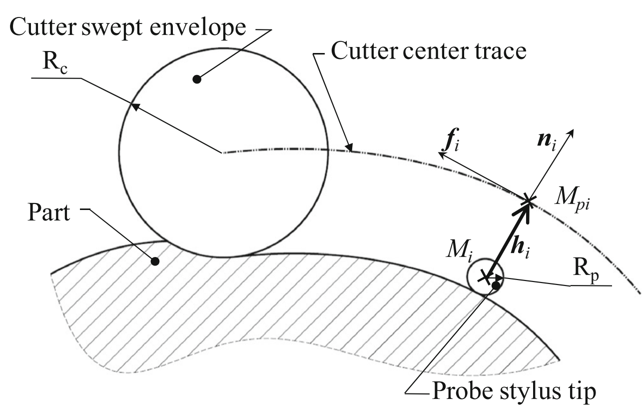


Fig. 1 On-machine probing

In the nominal case, the vector offset, $\boldsymbol{h}_i$, becomes $\boldsymbol{h}_{in}$ and can be expressed as

$$\boldsymbol{h}_{in} = \left(R_c - R_p\right)\cdot\boldsymbol{n}_i \tag{4}$$

where R_c and R_p are the programmed radius of the cutting tool and the effective (calibrated) radius of the probe stylus tip, respectively. In this case, this vector offset is constant along the tool path.

In the actual case, machining error deviates the vector offset from the nominal to the actual. This error is expressed as

$$\boldsymbol{e}_i = \boldsymbol{h}_i - \boldsymbol{h}_{in} \tag{5}$$

Experiment shows that the OMPE is dominated by the TOE and the overall system deflection [18]. The evolution of the OMPE in multi-cut process can be predicted at the finishing cut by extrapolating the results from the previous cuts.

According to the model developed in [18], the error can be expressed as a vector sum:

$$\boldsymbol{e}_i = \boldsymbol{e}_{to} + \boldsymbol{e}_{ri} \tag{6}$$

$$= (e_{to} + e_{ri})\cdot\boldsymbol{n}_i \tag{7}$$

where e_{to} is the TOE and e_{ri} is the compliance induced error. e_{to} can be caused by the tool wear, runout, eccentricity, and vibration. This error is independent of both cutting forces and part characteristic. So, it is assumed constant along the tool path.

However, e_{ri} is the error resulting from the overall system deflection phenomenon. This error depends on the cutting loads. It varies according to the cutting depth, the compliance of the machine, the tool, and the part. For the same cutting force, the local deflection magnitude of the part can change from one location to another. So, the magnitude of the error can change along the tool path. For the tool location i, the compliance error CE can be expressed as

$$\boldsymbol{e}_{ri} = \rho_i\cdot d_i\cdot\boldsymbol{n}_i \tag{8}$$

where ρ_i is the cutting compliance coefficient that characterize the compliance of the machining system [18] and d_i is the cutting depth measured at the location i.

In a milling process, the choice of cutting mode (up or down-milling) as shown in Fig. 2, is constrained by the cutting quality and other requirements. In down-milling, the cutting forces tend to separate the tool from the part and to move the part in the feed direction. In this case, the CE which is normal to the feed direction causes an undercut. However, in up-milling mode, the cutting forces tend to move the part in a direction opposite to the feed direction. In this case, the CE can cause an overcut [15].

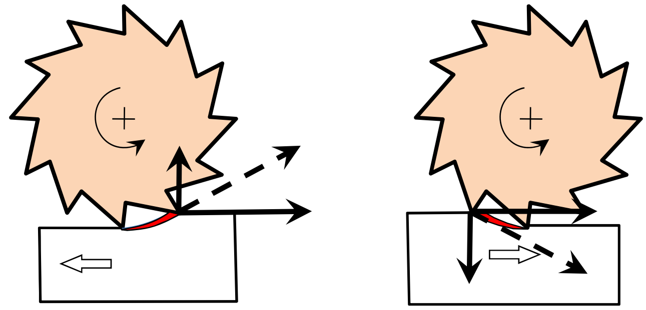


Fig. 2 Direction of the cutting forces in up and down milling

2.2 Calibration concept

2.2.1 Probe calibration

The calibration process known in the measurement task is to associate the reading to the dimension. The inscribed dimension of the master is compared to the measured one as illustrated in Fig. 3.

The deviation of the measured dimension, L_{meas}, from the calibrated one, L_{ref} is taken as a correction value, Correction = $-(L_{\mathrm{meas}} - L_{\mathrm{ref}})$. When probing with a touch probe, the correction is associated with the nominal stylus tip radius. Any future part measurement uses this compensation tip radius.

To reduce the probe measurement error sources, the conditions of the probe calibration are the same for both calibration and measurement such as part and master location, measurement speed, and directions.

2.2.2 Cutter calibration

In a similar way to the probe calibration, the proposed approach is to calibrate the cutter according to the on-machine probed error model [18]. The correction (calibration result) is added to the nominal cutting tool offset, such as the radius in end-milling. The main idea of the cutter calibration process is to separate the TOE from the total OMPE. According to the error model [18], the OMPE becomes the TOE when the cutting depth is tends to zero. In practice, in order to keep the machining process viable, the cutting depth can be reduced to an acceptable value and then OMPE is extrapolated to zero cutting depth [19]. The compliance effect is related to the cutting forces and it is negligible if the cutting depth is close to zero. In this case, the OMPE becomes, in principle, the constant TOE in dynamic mode for the corresponding cutting speed. Figure 3 illustrates the design of the calibration-cut and the associated actual cut results. The TOE is estimated from the on-machine probing data and added to the nominal tool offset as a constant correction of the tool dimension in actual cutting and dynamic conditions. Under the same cutting

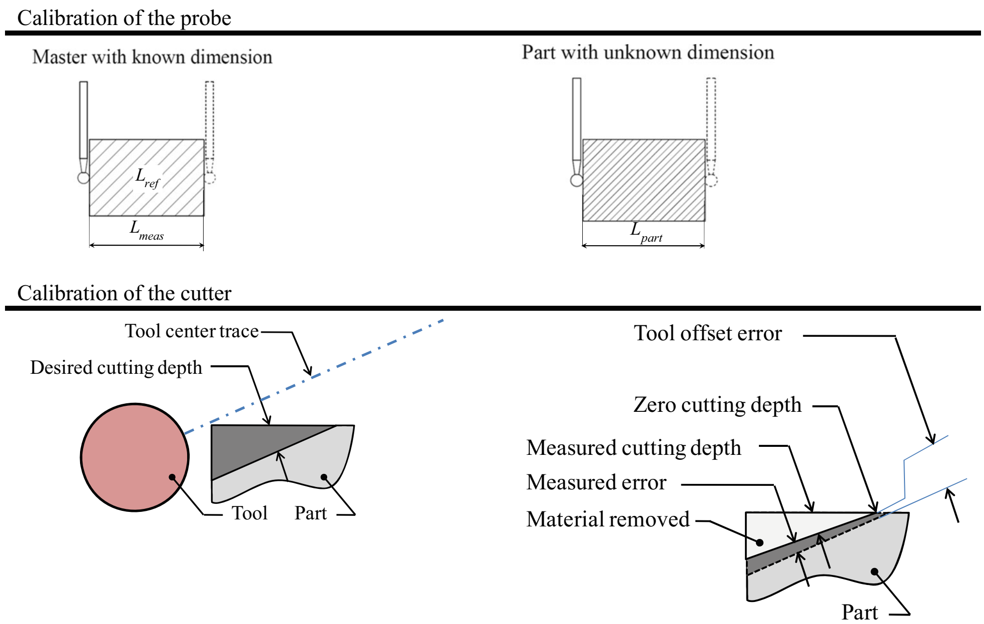


Fig. 3 Calibration of the cutter compared to the calibration of the probe

conditions as for the calibration cut, it is expected that the OMPE will be reduced to the CE and the TOE will be canceled if the next cut is calibrated. The calibration cut can be performed during the cutting process for the actual part [18, 19], and the tool diameter can be automatically updated without human intervention if the machine controller can read and write tool offset data in the part-program.

The cutter calibration process cannot eliminate the effect of all the cutting error sources because the deflection is related to the part geometry and stiffness along the profile. The calibration eliminates a constant offset error attributable to the tool geometry in dynamic conditions.

2.3 Compensation model of the on-machine probed error

The compensation model of the CE is briefly described in [18] and briefly here. The error is only compensated at the finishing cut using the cutting depth and error history at the semi-finishing cuts from the probing data. The error model for the expected error at the finishing cut, $\boldsymbol{e}_{rif}$, is written for the position i as

$$\boldsymbol{e}_{rif} = \rho_{if} \cdot d_{if} \cdot \boldsymbol{n}_{if} \quad (9)$$

where ρ_{if} is the cutting compliance coefficient estimated for the finishing cut at the position i. The linear estimation of the final cutting compliance coefficient is computed as [19]

$$\rho_{if} = \rho_{if-1} + \frac{\rho_{if-2} - \rho_{if-1}}{d_{if-1}} \cdot d_{if} \quad (10)$$

where

$$d_{if} = d_{ifn} + e_{rif-1} \quad (11)$$

is the cutting depth at the finishing cut which is the nominal depth (without compensation), d_{ifn}, plus the error probed at the last semi-finishing cut, e_{rif-1}. The "f," "f-1," and "f-2" associated with ρ indicates the final cut, the semi-finishing cut, and the cut before, respectively.

The practical model for the CE compensation for three successive cuts [18] is

$$\boldsymbol{c}_{rif} = -\rho_{if} \cdot d_{if} \cdot \boldsymbol{n}_{if}$$

$$\boldsymbol{c}_{rif} = -\left(\frac{d_{if}}{d_2} \cdot e_{ri-1} + \left(\frac{d_{if}}{d_2} \right)^2 \cdot (e_{ri-2} - e_{ri-1}) \right) \cdot \boldsymbol{n}_{if}$$

3 Experiment

The experiment's CNC machine is a five axis machine tool from Huron fitted with a Renishaw touch trigger probe. The machine tool normally need to be calibrated, aligned, and compensated before using it to cut or to inspect a mechanical part. In this paper, the systematic geometric and kinematic deviations are not the subject of the study. They are neglected, and the coordinate measuring machine (CMM) is chosen as a reference to verify the on-machine measurement capability.

The CMM measurement is the common tool to validate the conformity of the part dimension. The deviation from the target dimension and shape is computed according to standard algorithms. In the case of on-machine measurement, it is noted that the error is the deviation of the measured position compared to the programmed path. This deviation is caused by the

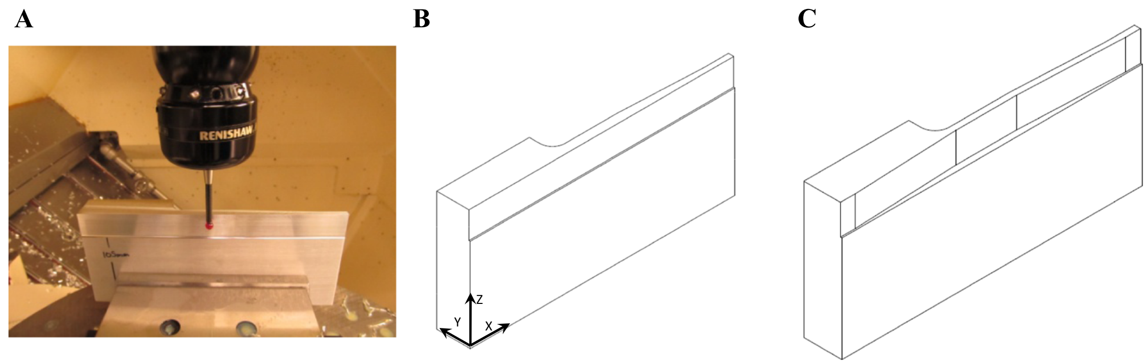
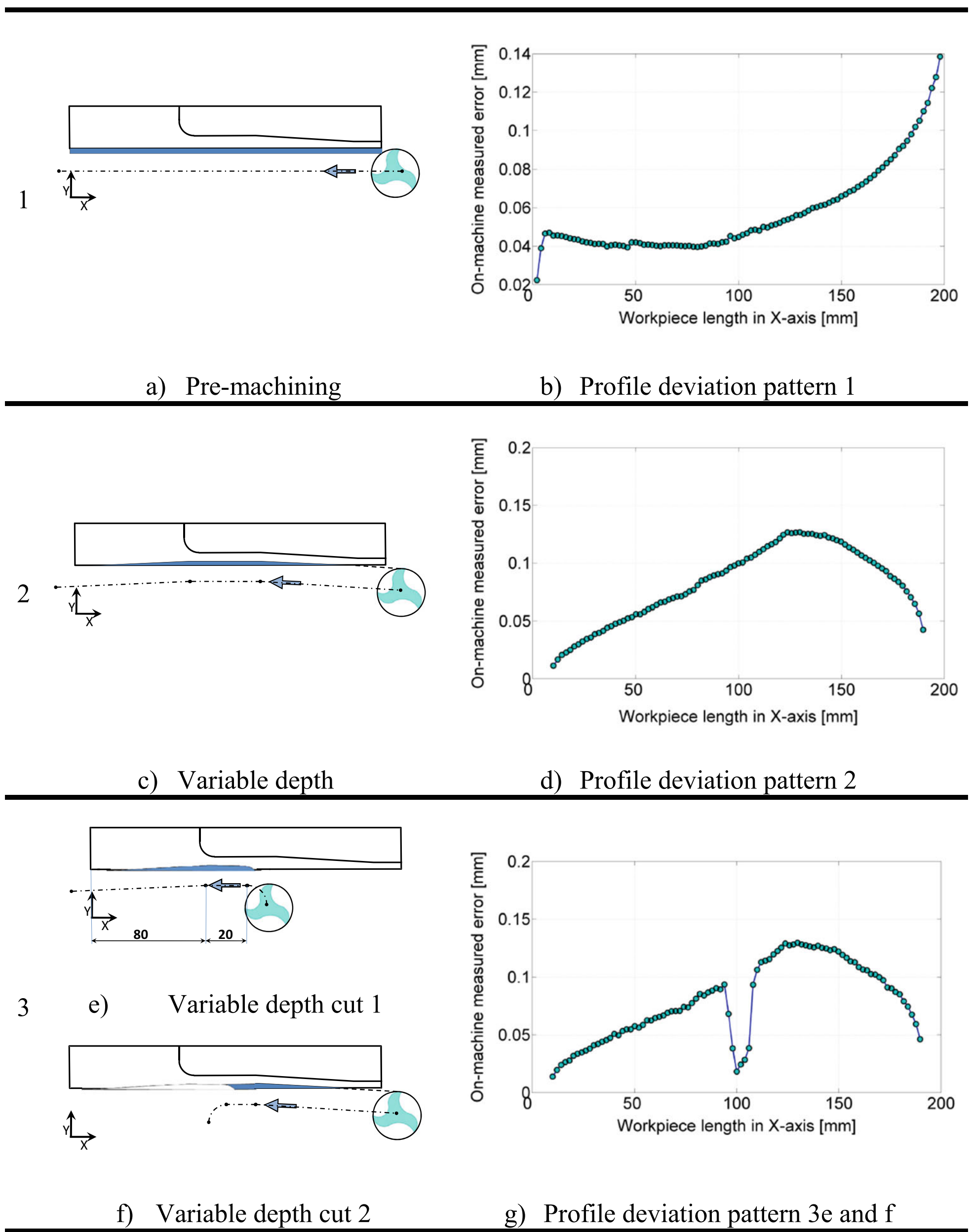


Fig. 4 Test-part 1. **a** On-machine probing. **b** Design of the pre-machined and inspected profile. **c** Design of the final machined and inspected profile

Fig. 5 Machining patterns and the corresponding profile deviation. **a** Pre-machining. **b** Profile deviation pattern 1. **c** Variable depth. **d** Profile deviation pattern 2. **e** Variable depth cut 1. **f** Variable depth cut 2. **g** Profile deviation pattern 3e and f



tool offset error including the wear and the system deflection which can be canceled by compensating the tool path. The geometric and kinematic deviation of the machine tool cannot be detected by on-machine measurement of machined part.

The machine tool error can change depending to the thermal status of the machine structure. This is not treated in this paper. However, the delay between the cutting operation and the inspection operation is relatively short. So, it is assumed that the machine thermal status remain stable. Consequently, the motion error of the machine tool axis, due to the thermal distortion and the geometric error, is assumed the same during the cutting and during the probing. Then, the error detected by probing a machined part is the process error which is the tool offset error and the deflection.

In order to verify the measurement capability of the machine tool, a ring gage is inspected by on machine measurement in the workspace of the cutting and measuring tests and on a CMM.

Figure 4 shows the workpiece clamped on the machine and its measurement by touch probing is being. The drawings show the pre-machined straight profile and the final machined geometry.

The pre-machined has variable thickness to create stiffness changes which cause a variable deflection in the *Y*-direction along the *X*-direction.

The part is made of aluminum and has approximate dimensions (mm) of X×Y×Z=200×20×100.

The sequence of machining and inspection operations illustrated in Fig. 5 is as follows

1. The part is clamped and pre-machined according to machining pattern 1.
2. The part is machined and measured according to machining pattern 2.
3. The part is pre-machined again to reproduce the pre-machined shape according to machining pattern 1.
4. The part is machined and inspected according to machining pattern 3.

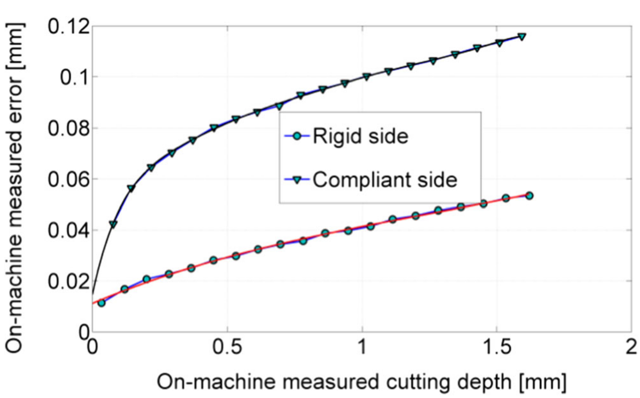


Fig. 6 On-machine probed error versus cutting depth from machining pattern 2

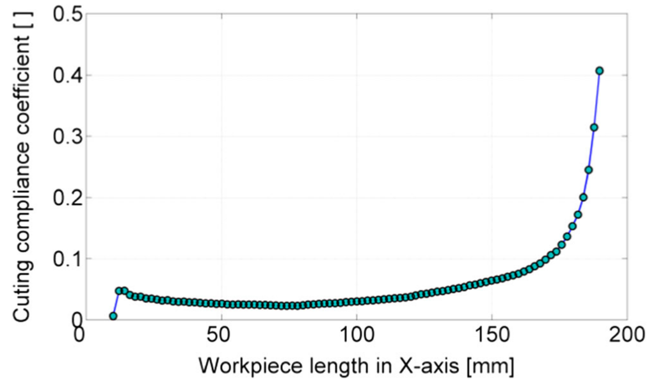


Fig. 7 Cutting compliance coefficient values along the machined and inspected profile-machining pattern 2

The machining pattern 1, Fig. 5a, is the first cut and uses a constant programmed depth. The deviation of the resulting profile relative to the desired profile is shown in Fig. 5b.

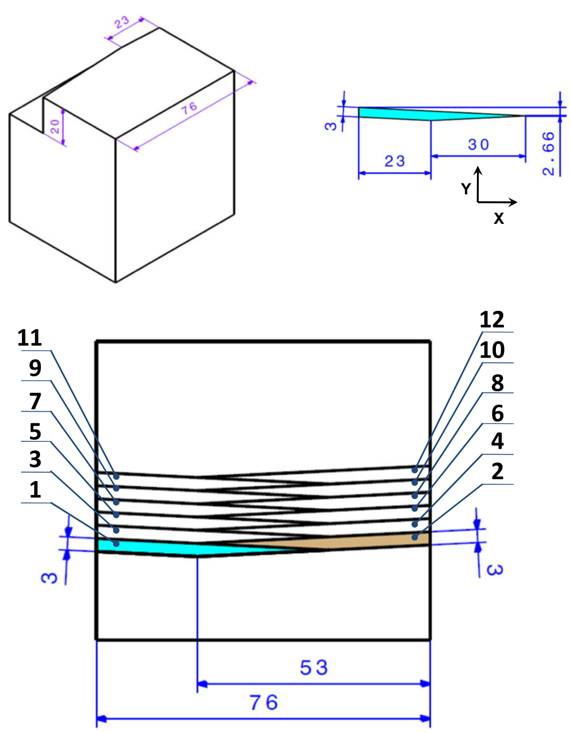
The machining pattern 2, Fig. 5c, is the next cut with variable cutting depth from 0 to 3 mm. The resulting deviation differs from that for machining pattern 1. With decreasing cutting depth, the OMPE decrease. The results show that the magnitude of the OMPE is related to the cutting depth magnitude [18]. In Fig. 5g (pattern 3), at X=100, the error is sharply drops. This is attributed to the change in the cutting depth due to the change in the cutting tool path. The variation of the cutting depth is shown in the pattern e and f (Fig. 5).

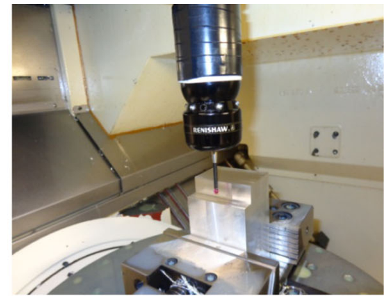
Figure 6 shows the evolution of OMPE versus the cutting depth. The error is higher for more compliant features for similar cutting depth magnitude. For both the rigid and compliant sides, the TOE normally should be theoretically the same. In order to estimate the TOE using the error model of Eq. 6, the data in Fig. 6 is extrapolated using polynomial fitting to estimate the error when the depth of cut is zero. The TOE estimated from measurement data of the rigid side is not affected significantly by changing the polynomial degree. However, for the compliant side, the estimated value can change significantly by changing the polynomial degree. On the rigid side, the behavior of the error map is close to linear. On the compliant side, the evolution of OMPE versus the cutting depth around the zero cutting depth is non-linear. The accuracy and the numerical stability of the estimated value of the TOE may depend on the fitting process and the distribution of the on-machine probed points. The cutting compliance coefficient, shown in Fig. 7, is relatively constant along the profile on the rigid side (X<100). It is may be

Table 1 Tool offset error estimation

Value (μm)	Description
12	Extrapolated with line fitting
17	Extrapolated with 8° polynomial
15	Measured value: OMPE pattern 3 at X=100

Fig. 8 Machining pattern for TOE measurement under various milling mode and cutting speed



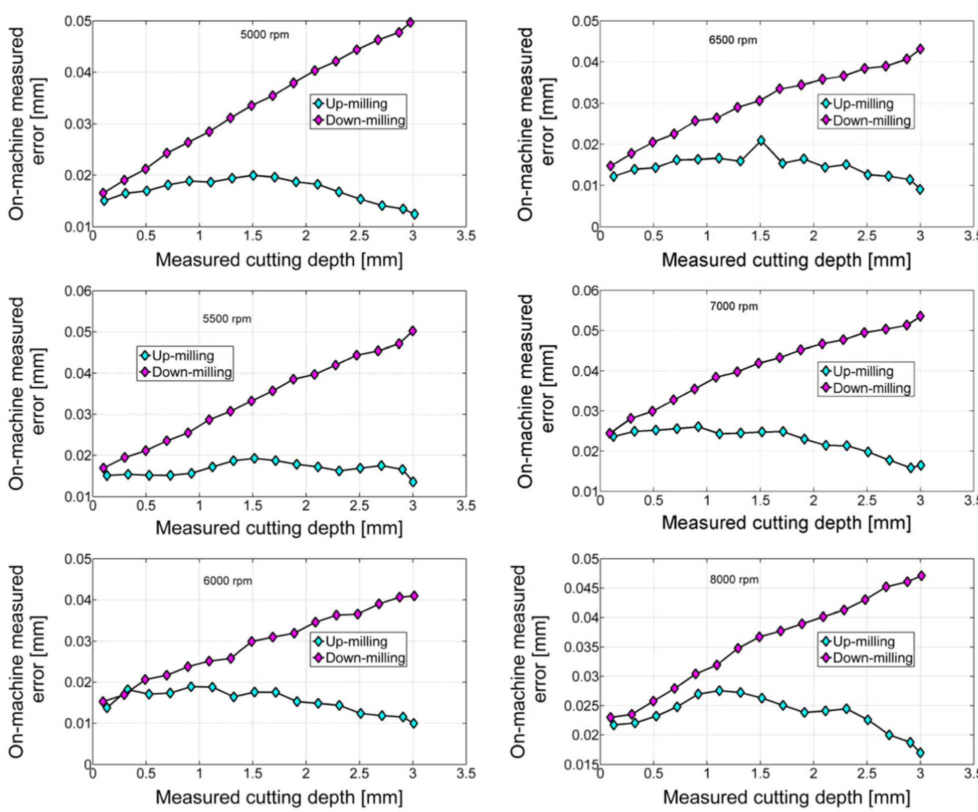


Cut No	Milling mode	Cutting speed
1	DOWN	5500
2	UP	6000
3	DOWN	6500
4	UP	7000
5	DOWN	7500
6	UP	8000
7	UP	5500
8	DOWN	6000
9	UP	6500
10	DOWN	7000
11	UP	7500
12	DOWN	8000

recommended to avoid fitting process in on-line TOE estimation. Because of the fitting process instability, an erroneous TOE can be estimated which can cause a damage on the part.

Table 1 shows the TOE correction estimated for the same tool with different methods. The 1st two values correspond to the ordinate of the curves shown in

Fig. 9 OMPE vs the cutting depth of the test described on the Fig. 8



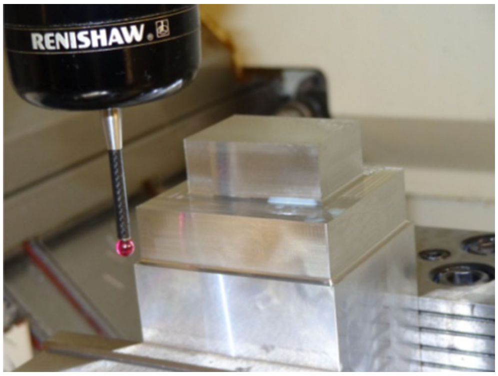


Fig. 10 Milling and inspection of a rectangular profile

Fig. 6. The last one is the TOE is estimated without fitting process. It is supposed equal to the OMPE when the cutting depth is programmed zero. In the case study, it correspond to the OMPE for $X=100$ mm after cuts with machining pattern 3. Figure 8 shows the machining pattern to investigate the TOE under various cutting speed for both up and down milling. After each cut, the resulting profile is measured. The distribution of the cutting depth magnitude along the cut is the same for all twelve cuts. The cut starts with 3 mm and finishes with 0 mm. The cutting speed, the milling mode, and the design for each cut are shown in Fig. 8.

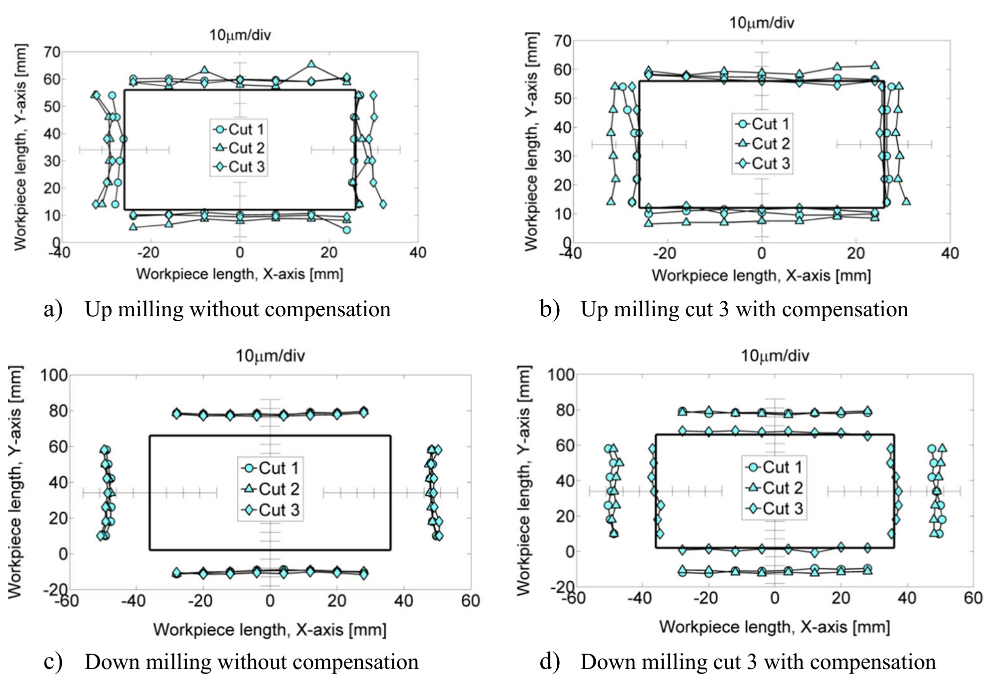
Figure 9 shows the OMPE for the machining pattern shown in Fig. 8. The error magnitude for the down milling is higher than for the up milling. This can be justified by the cutting forces direction for down/up milling mode, as illustrated in Fig. 2 and discussed above. Here, the error is the CE plus the TOE. From the experiments shown in Fig. 9, the measured value of the TOE varies from 12 to 23 μm.

Usually, the tool is changed before the final cut. The cutting calibration process concerns the finishing cut. For roughing, it is not necessary to obtain high accuracy of the part so no calibration is needed. The finishing cut can be performed in one or more cuts. The calibration (probing and tool offset correction) is performed for the cutting tool used to finish the part.

The test part shown in Fig. 4 is re-used to perform the machining test of rectangular profiles shown in Fig. 10. The cutting speed used for all the cutting profiles is 6500 rpm. The corresponding OMPE results are shown in Fig. 11.

In order to improve the accuracy of the final part, the compensation of the tool path at the finishing cut is computed using the OMPE at the semi-finishing cuts and the compensation model. Identical profiles are machined with and without compensation for up and down milling. In down milling mode, the OMPE is an under cut of about 25 μm for both the semi-finishing and the finishing cut. The TOE is estimated as 13 μm from machining result shown in Fig. 9. Consequently, the CE can be obtained as 25–13=12 μm (Eq. 6). This error is relatively constant along the profile. For up milling mode, the error is less than 10 μm. The same value (13 μm) of TOE is used. So the CE is negative (Eq. 6). As shown above, the part is attracted by the tool in up-milling mode. Finally, the OMPE is reduced by the compensation process for both up and down milling mode at the finishing cuts. It is reduced from 25 μm (down milling) and 10 μm (up milling) to less than ±4 μm. The residual error includes vibration which is

Fig. 11 Deviation of actual profile from programmed one measured by on-machine probing



difficult to compensate by the tool path modification because it is not repeated and it is not included on the error model.

4 Conclusion

An experimental study is presented to investigate an approach to calibrate the cutting process. The tool offset error in the actual cutting conditions is identified according to the on-machine probed error model for the current used tool. Decreasing the compliance error by an adaptive cutting depth distribution is the adopted approach to separate the tool offset error from the total measured error. Compliant and rigid features are used to test the proposed approach on the same part. A fitting process is used to extrapolate the data in order to estimate the correction of the tool geometry from experimental results. It was observed that for the compliant side of the test piece, the estimated value can change significantly by changing the polynomial degree. To avoid the fitting process in a production context, it is shown that a direct value of the tool offset error can be taken approximately as the OMPE when the cutting depth is planned to be zero for the actual machining conditions. This can be recommended in on-line automatic tool offset error measurement and calibration using probing.

In the proposed method, the tool offset error including the wear is corrected by a constant value. This value is measured before the finishing cut. The tool wear which appear during the finishing cut is not considered and it is supposed negligible. The results will be affected if the wear is important during this cut. It is relevant to strictly respect the tool life value to minimize this effect.

The tool offset error is evaluated, for this test at between 12 and 17 μm at three different locations for linear, nonlinear fitting, and for a direct measurement. The impact of the cutting speed and the milling mode on the tool offset error estimation is investigated. The compliance error compensation model and the calibration process are applied to produce a rectangular profile. The result shows the effectiveness of the approach for both milling modes. The maximum on-machine probed error in the case study is reduced from 25 to ±4 μm.

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