Abstract

A major issue in micro milling is the setting up of the origins of the Machine Working Coordinate Systems (MWCS). The existing methods for carrying out this operation have an unacceptably high error along the Z axis, due to the spindle thermal enlargement, and are effective only when the machining is “relative” to other surfaces milled with one cutting tool within one operation. Therefore, more efficient technical solutions are required for setting up MWCS and to reduce further uncertainties associated with micro-milling operations.

This paper describes a new cost-effective method for setting up MWCS that applies a new technical solution for detecting the contact between the cutting tool and the workpiece. A prototype system was used to validate experimentally the accuracy and repeatability of the proposed method. The results obtained showed that the sensitivity of the system is sufficient to detect accurately the contact between the cutting tool and the workpiece, and thus to set up the MWCS origins. It was concluded that by applying this method it would be possible to minimise uncertainties introduced by the spindle thermal enlargement and touch probe run-outs in setting up micro machining operations. Also, the tests undertaken showed that the prototype system is reliable and convenient for use by machine operators.

Keywords: micro-milling, on-line measuring systems, tool–workpiece coordinate system setting

1. Introduction

Recent developments in machining technology and machine tool design, especially in micro-milling and a growing demand for product miniaturisation reflect the constantly increasing requirements towards the accuracy of the produced components. This leads to continuous reduction of feature sizes and correspondingly the diameter of the cutters employed for their machining. In particular, the applications that “push” the micro-milling technology to its limits are the manufacture of micro parts for watches, keyhole surgery, housings for micro-engines, tooling inserts for micro injection moulding and hot embossing, and housings and packaging solutions for micro-optical and micro fluidics devices. A common challenge across all these application areas is the machining of micro features with dimensions smaller than 100 µm.

Many researchers have contributed to the creation of the currently available process knowledge about conventional milling. Unfortunately, the size effects are dominant in micro-milling, and therefore it is not possible to benefit directly from this rich knowledge repository. To advance this technology it is necessary to study systematically the factors that affect the process reliability when it is employed for machining components incorporating micro features.

Micro machining using conventional technologies, such as milling, present unique challenges. When the machining is performed with a micro cutter, diameter smaller than 200 µm, cutting forces and tool pressures present a whole new realm of problems. Tool pressure appears when the tool channels are filled with workpiece material, e.g. burrs and chips, especially during drilling operations. Under such conditions, any “drastic” changes of the cutting forces and their directions may lead to tool breakages. The spindle must be dynamically stable in order to minimise its thermal enlargement, tool change variations, and vibrations. In particular, any vibrations or run-outs at the tool tip may have adverse effects on the surface finish and accuracy of the machined micro features.

To reduce these negative effects it is necessary to control as tightly as possible the whole set of machining variables, associated with different components of the Machine tool-Fixture-cutting Tool-Workpiece System (MFTWS) and the surrounding environment, and thus minimise their overall effect on part quality. In the context of part dimensions and feature sizes, relative accuracy (tolerance to feature size ratio) in micro machining brings new challenges [1]. In particular, the absolute accuracy achievable in milling micro features can be considered comparable to that in ultra-precision engineering; however their relative accuracy may not be acceptable for a range of applications. Although in conventional ultra-precision manufacturing a relative accuracy of $10^{-4}$ can be attained, in micro-machining it does not exceed $10^{-2} - 10^{-3}$. For example, to achieve a relative accuracy of $10^{-5}$ or better the absolute accuracy of a 100 µm groove has to be in the sub-micron range. Hence, it becomes necessary to re-think the meaning of precision in micro machining.

There are solutions that minimise the uncertainty in MFTWS when performing micro-milling. Examples of such solutions are Tool Condition Monitoring Systems (TCMS) that improve the effectiveness of micro-milling operations. In particular, direct and indirect methods are developed for controlling the machining variables associated with the cutting tools. The direct methods are employed for detecting the actual tool status relying on optical sensing [2], while indirect ones monitor the tools through the existing relationships between their parameters [3].

There are several key areas of concern in regard to MFTWS when machining features at micro scale:

1. Environmental changes that impact on the resulting machining accuracy, in particular process predictability and repeatability;
2. Vibrations (Internal and External); 
3. The MFTWS management; 
4. The use of cutting fluids and their dynamics.

Therefore, machine resolution, control, construction, and auxiliary tools all become much more critical to the success in micro machining operations. Some of the main problems associated with the setting-up of micro milling operations are:

- **The accuracy of the measurement performed with a touch probe.** The use of a probe to carry out microstructures with relatively high material removal rates is especially the case when machining complex 3D parts, and ultimately reduce production costs. This is achieved by utilising cutting tools with diameters less than 200 µm [5]. In particular, a major problem is the big difference between the Z-levels set up using a touch probe at a spindle temperature of around 25-26°C and those measured at higher temperatures, e.g. 36-38°C at a rotary speed in excess of 20.000 rpm, resulting in 20 to 30 µm difference in Z.

Unfortunately, this negative effect cannot be avoided even by operating micro-milling machines in a temperature controlled environment. Furthermore, the existing methods for setting up the origins of MWCS for micro-milling have an unacceptably high error along the Z axis and are effective only when the machining is "relative" to other surfaces milled with the same tool within one operation. Therefore, more efficient technical solutions are required for setting up MWCS within the machine coordinate system, and thus reducing further uncertainty associated with micro-milling operations. Such solutions have to be reliable and at the same time inexpensive in order to satisfy the current requirements. One possible way to achieve this is to adopt solutions already developed for TCMS.

This paper describes a cost-effective method for setting up MWCS that adopts a new technique for detecting the contact between the cutting tool and the workpiece within MFTWS. The feasibility of this approach is verified experimentally. Conclusions are drawn about the advantages and disadvantages of this solution.

### 2. Setting up of MWCS with a cutting tool

In this research, a method for setting up MWCS is proposed that employs an existing technical solution for reducing uncertainty in MFTWS. In particular, the Tool-Workpiece Voltage Monitoring System (TWVMS) developed for detecting a tool breakage during micro-milling and drilling described in [5] is adopted for performing this setting up operation. Figure 1 depicts the general principles of this system. By creating a close electrical circuit between the spindle and the workpiece, abrupt voltage variations during the cutting process can be detected with a specially designed sensor. This sensor allows the alternating voltage to be measured. The measurements taken are converted into a digital signal and are sent to the CNC controller.

![Figure 1 Tool-Workpiece Voltage Monitoring System](image)

Figure 1 Tool-Workpiece Voltage Monitoring System

In the proposed method for setting up MWCS, the same technique is employed to detect the contact between the cutting tool and the workpiece, and thus set up the machine origins along the X, Y, and Z axes. In particular, when the cutting tool is in contact with the workpiece voltage changes are detected and used to set up the MWCS origins in the machine coordinate system. By applying this technique it is possible to avoid any additional errors from tool run-outs, $E_{r-o}$ or spindle thermal enlargement, $E_{t-e}$, which are major sources of uncertainty in MFTWS.

The setting-up of MWCS for each cutting tool includes the following four steps:

- **The run-out of the cutter-holder assembly.** This leads to changes of the cutting forces during the machining, which have a detrimental effect on tool life, achievable accuracy, and surface finish. One solution that is widely employed to minimise this problem is the use of direct tool-changing type spindles. By eliminating tool holders, it is possible to reduce the total run-out and thus to eliminate stack-up implications in micro machining.

- **The temperature variations during the machining due to thermodynamic stability of the MFTWS system.** There are two types of temperature variations; one is associated with the temperature build-up during the machine operation while the second one is linked to spindle temperature variations once the machine reaches its “steady state” after some initial period of time. It is not possible to eliminate such variations completely and there will be always some permissible temperature deviations in the MFTWS. One of the main side effects of this is the varying tool enlargement that is a major factor affecting the resulting part accuracy [4]. To minimise this enlargement the spindle must be thermodynamically stable and also special methods for its cooling and lubrication have to be employed. Another possible solution is the use of new hybrid Automatic Tool Length Measurement (ATLM) systems that combine the capabilities of contact and non-contact methods for measuring the tool tip position with sub-micron accuracy regardless of spindle thermal expansion.

- **Limitations of laser tool measurement systems.** In particular, these systems have shown certain limitations when measuring cutting tools with diameters below 50 µm. This is associated with the beam spot size used to carry out these measurements. For example, in the case of the BLUM laser system, the spot size is approximately 50 µm and 80% of it should be covered by the cutters during the measurement in order to calculate their dimensions.

- **The chips attached to micro cutters.** This can introduce errors in measuring the tools and thus lead to erroneous setting-up values. As a result the machining accuracy is compromised. To minimise such errors special techniques for cleaning the tools before performing any setting-up operation should be introduced.

All these problems place new requirements on the applied techniques for setting up Machine Working Coordinate Systems (MWCS) as a means to increase machining productivity, improve the precision and quality of the parts, and ultimately reduce production costs. This is especially the case when machining complex 3D microstructures with relatively high material removal rates.
1. Selection of appropriate locations on the workpiece to carry out the setting up operation with cutting tools. It is preferable to select them on surfaces that will be machined later on in all three axes. The positions of these spots along the X, Y, and Z axes, X_{set}, Y_{set} and Z_{set} respectively, should be measured with the touch probe and recorded for further use.

2. Installation in the spindle of the cutting tool for which MWCS should be set up. Next, the tool should be left running at its normal cutting speed until the spindle reaches its working temperature. For example, for a 100 μm diameter cutter running at 40 000 rpm, 10 to 11 min are required in order for the spindle temperature to stabilise at approximately 36°C. Only then can the fine setting up start. It is worth stressing that all steps for setting up MWCS should be performed in a temperature controlled environment.

3. The cutting tool is measured using BLUM laser system utilising standard cycles for calculating the effective tool radius, and length. In this way, it is possible to minimise uncertainties introduced by the tool-holder run-out and the spindle thermal enlargement.

4. Fine setting up of the origins of the X, Y, and Z axes employing the set up is shown in Figure 1. Sequentially, at a fast speed, the cutting tool approaches the positions X_{set}, Y_{set} and Z_{set} recorded in Step 2 and at a safe distance before reaching those switches to a low feed rate for detecting accurately the contacts with the workpiece. This distance is usually in the range of 10 to 20 mm in order to avoid any collisions. In this way, the origins along the X, Y, and Z axes are set up and thus MWCS is fully defined for carrying out machining using this particular cutting tool. If the tool is changed, the steps from 1 to 4 have to be repeated.

This four step procedure has to be executed accurately in order to assure the required repeatability and overall accuracy.

A source of uncertainty in the proposed approach for setting up MVCS is the delay with which the system is triggered when the tool contacts the workpiece. For most CNC controllers this is within 1 ms. It is possible to reduce this time by employing special input connectors [6], though the cutting tools will always "over-shoot" before the latched position is reached. This so called E_{ot}, though the cutting tools will always "over-shoot" before the latched position is reached. This so called E_{ot} << E_{ro} in the X-Y plane and E_{ot} << E_{te} in the Z direction. Another important consideration in determining this feed rate is the avoidance of tool breakage before the system is triggered.

3. Experimental Set-up

The experimental validation of the proposed approach for setting up MWCS was carried out on a micro-milling centre, KERN HSPC 2216 – a machine tool with a polymer concrete mono-block frame specially designed for improved static and dynamic rigidity, and for vibration absorption. Thus, the validation of the system was conducted in machining conditions typical for micro-cutting operations, in particular the existence of high frequency vibrations, high spindle speeds, and very low cutting forces. The centre has an integrated BLUM laser system for measuring the cutting tools. The system allows cutting tools with diameters down to 30 μm to be measured with a repetition accuracy of ±1 μm.

The experimental set-up was developed following the principles outlined in Section 2. A prototype TWVMS was fixed on the spindle and connected directly to the CNC machine controller as described in [6]. To monitor the setting up operation on-line a digital oscilloscope with a sampling interval of 1 μs was connected in parallel to the sensor as shown in Figure 1. Before commencing the experiments, the oscilloscope was calibrated for registering accurately the contact between the tool and the workpiece.

A set of experiments was conducted to assess the sensitivity and repeatability of the prototype system. The four steps of the proposed approach for setting up MWCS were performed as follows:

- **Step 1.** The initial position along the X, Y, and Z axes, X_{set}, Y_{set} and Z_{set}, were measured with a touch probe and saved for further use.
- **Step 2.** All cutting tools were left running at their normal cutting speed for 10 min until the spindle reached its normal operating temperature.
- **Step 3.** The cutting tools are measured with the BLUM system employing the standard CNC cycles for calculating tool radius, R_t, and length, L_t.
- **Step 4.** The set-up in Figure 1 is employed to detect the contact between the cutting tool and the workpiece. The initial speed of the tool was 2000 mm/min and 10 mm before reaching X_{set}, Y_{set} or Z_{set} and the feed rate was then lowered to 60 mm/min to detect the contact with the workpiece. This feed rate was selected based on the existing recommendation for conducting measurements with contact probes [6]. In addition, it is worth mentioning that the off-set distance of 10 mm was more than sufficient for the machine to decelerate to its measuring speed of 60 mm/min.

Finally, to assess the accuracy and repeatability of the proposed approach square pins were machined with tungsten carbide end mills. MWCS was set up in the centre of the pins employing the proposed four step procedure. The deviations of the milled pins in the X-Y plane were measured on the machine with an optical microscope installed in the spindle, while in the Z direction a white light profilng microscope was used.

4. The experimental results

The capabilities of the proposed method for setting up MWCS were tested on machining a brass workpiece. Two sets of five square pins with nominal dimensions 100 μm x 100 μm x 100 μm were machined with a 100 μm and 200 μm end mills, respectively. Before the milling of each pin the cutting tool was changed and the proposed four step procedure was followed to set up MWCS in the centre of the pins. The machining parameters for the two cutters were S=40000 [rpm] and F=100 [mm/min], and S=30000 [rpm] and F=120 [mm/min], respectively. The deviations of the pins’ side walls from the MWCS origins in the X-Y plane and their heights in Z were measured as shown in Figure 2. The results of these measurements are provided in Table 1.

![Figure 2 Pin measurements](image-url)
The trials undertaken provide an indication about the accuracy and repeatability of the proposed system for setting up MWCS. The error in \( Z \) would be much bigger due to the temperature enlargement of the spindle, \( E_{\text{te}} \). In particular, \( E_{\text{te}} \) of the cutting tools after each change was measured using the BLUM system and in all the cases it was in excess of 20 \( \mu \text{m} \). As already stated, \( E_{\text{te}} \) is dependent on the selected spindle speed and therefore it would be difficult to compensate fully. In addition, the errors associated with the use of the BLUM system should be taken into account when analysing the accuracy of the machined sets of pins.

<table>
<thead>
<tr>
<th>Pin</th>
<th>Tool</th>
<th>(-x)</th>
<th>+x</th>
<th>(-y)</th>
<th>+y</th>
<th>(z)</th>
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<tbody>
<tr>
<td>1</td>
<td>100µm</td>
<td>1.8</td>
<td>1.7</td>
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<td>2</td>
<td>200µm</td>
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<td>3</td>
<td>100µm</td>
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<td>1.2</td>
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<td>4</td>
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<td>5</td>
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<td>1.8</td>
<td>1.2</td>
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<td>6</td>
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\((x = |a - 50|, +x = |b - 50|, -y = |c - 50|, +y = |d - 50| and z = |e - 100|)\) in [\(\mu\text{m}\)].

For comparison, in Table 2 the accuracy data achievable in setting up MWCS with a touch probe and the BLUM system is provided (by their manufacturer www.mh-inprocess.com/eng/taster/pb3810_06_uk.pdf, www.blum-novotest.com/pdf/LasCont_NT_UK.pdf). In particular, if the conventional method for setting up MWCS was employed the accuracy of the machined pins would have been affected by uncertainties introduced by both the touch probe and the cutting tools measurements using integrated BLUM system.

<table>
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Note: \(-x = |a - 50|, +x = |b - 50|, -y = |c - 50|, +y = |d - 50| and z = |e - 100|\) in [\(\mu\text{m}\)].

In addition, the trials undertaken show that the proposed method can be used reliably for setting up WMCS, in particular there was no tool breakage during the trials.

### 5. Conclusion and future work

A method was proposed for setting up the origins of MWCS in micro machining operations. A prototype system was used to validate experimentally its accuracy and repeatability. The trial undertaken demonstrated the feasibility of the proposed new method. Based on the results obtained the following conclusions can be made.

- The sensitivity of the system is sufficient to detect accurately the contact between the cutting tool and the workpiece. By applying the proposed method it is possible to minimise uncertainties that the spindle thermal enlargement and touch probe run-outs introduce. The tests undertaken showed that the system is reliable and convenient for use by machine operators.
- The method does not introduce any constraints in regards to the cutting tool movements and workpiece/part overall shape. In particular, it is possible to apply it for machining complex 3D cavities, and deep pockets and grooves.
- The proposed method can be applied only when conductive materials are machined. However, this limitation can be overcome by covering the workpiece with a thin metallic film the thickness of which is known in advance.

The results of this research will be used to develop an integrated system that can be used simultaneously for setting up MWCS and also for tool breakage detection. Such a solution promises to improve the precision and the quality of the machined components, and ultimately to reduce the machining costs in micro manufacturing.

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### References