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Comparison of the measurement performance of high precision multi-axis metal cutting machine tools

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Abstract

High precision manufacturers continuously seek out disruptive technologies to improve the quality, cost, and delivery of their products. With the advancement of machine tool and measurement technology many companies are ready to capitalise on the opportunity of on-machine measurement (OMM). Coupled with business case, manufacturing engineers are now questioning whether OMM can soon eliminate the need for post-process inspection systems. Metrologists will however argue that the machining environment is too hostile and that there are numerous process variables which need consideration before traceable measurement on-the-machine can be achieved. In this paper we test the measurement capability of five new multi-axis machine tools enabled as OMM systems via on-machine probing. All systems are tested under various operating conditions in order to better understand the effects of potentially significant variables. This investigation has found that key process variables such as machine tool warm-up and tool-change cycles can have an effect on machine tool measurement repeatability. New data presented here is important to many manufacturers whom are considering utilising their high precision multi-axis machine tools for both the creation and verification of their products.

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1. Introduction

The synergy between manufacturing and measurement is absolute. Without capability in measurement there cannot be capability in the manufactured product. Classically, measurement within a manufacturing environment is associated to realisation of a manufactured product against its design specification. Modern high precision manufacturing is characterised by low batch, high variety, tight tolerance, and high value products [1]. Capable dimensional measurement is integral for the successful achievement of these requirements [2]. Coordinate-measurement-machines (CMMs) are utilised to perform dimensional measurements due to their metrological capability and flexibility [3]. On-machine probing (OMP) is used frequently as part of the machining cycle effectively replacing the need for manual gauging [4]. These systems are most often used to set machine-workpiece datums and alignments. However there is a now a strong trend to use such systems for on-machine product verification (OMV) purposes [5], driven by an ambition to bring measurement closer to the machining process.

Historically manufacturing organisations ensure quality through product measurement only [6]. This 'gate-keeping' approach does not directly improve or guarantee quality, as it is based on a strategy of defect detection, not prevention. Many therefore argue that measurement of final product attributes after a machining process is too late. Good measurement practice however dictates that measurement systems are independent of manufacturing systems for metrological reasons. For high-precision monolithic products CMMs are the only measurement systems capable to perform with an acceptable level of uncertainty [7]. Manufacturing

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engineers are often frustrated by CMMs as they are a major source of process bottlenecking and inefficiency [5], [8]. As the need for more adaptive and data driven manufacturing increases the feedback delay from the CMM to the machine tool is generally regarded as unacceptable. A reduction in the reliance of CMMs is likely to result in benefits associated to cost and time saving, pro-active process control, elimination of non-value adding tasks and agile manufacturing, as indicated by Table 1.

Table 1 - Benefits associated to on-machine inspection [1],[5],[8]

Benefit	Through
Cost and Time Saving	• Decreasing lead-time required for gauges and fixtures • Minimising need for design fabrication, maintenance of hard gauges, fixtures & equipment • Reducing inspection queue time and inspection time • Reducing part set-ups • Reducing CMM part queuing • Eliminating rework of non-conforming product
Reactive Inspection to Pro-active Control	• Integrating quality control into the product realisation process • Characterised and qualified processes to increase product reliability • Focusing resources on prevention of defects instead of detection in the end (proactive intervention) • Generating real-time process knowledge and control for product quality improvement • Enhancing small batch acceptance capability
Elimination of non-value adding activities	• Reduced final-inspection • Data-driven sampling plans • Part waiting and measurement gate bottlenecking • Design, fabrication and maintenance of hard gauges • Reworking of non-conforming parts
Agile Machining	• Quick responses to product design changes • Rapid integration of new and existing technologies such as probing strategy, error compensation, data analysis software • Fixture design technology can be integrated into the OMI system • Machine health monitoring

2. Theory

On-machine gauging (OMG) has been present on the shop-floor for over 20 years [9]. Today most multi-axis machine tools utilise spindle mounted touch-trigger probing to set-up and adjust co-ordinate and tool offsets. Such systems replace the need for manual gauging necessary for workpiece alignment, tool length calculation, datum setting and in the case of +5-axis systems tool rotation-centre point control [10]. OMP systems can also be used to monitor the size of the features being machined, to validate the part movement, distortion, and feature dimensions [8].

Where used, on-machine process verification (OMV) via OMP is typically used at the end of a machining cycle whilst the part is still constrained and in the machining environment. This form of OMV can be used to verify that a machining process has performed as expected and produced the correct part geometry. Advantageously, non-conformance can be detected closer to the point of feature creation, and if necessary reworked, in-situ.

The measurements taken by machine tools can be easily affected by errors introduced before and during the measurement process. The sources of such measurement uncertainty is often due to: 1) Errors due to machine tool, 2) Errors due to environment, 3) Probing strategy, 4) Workpiece, 5) Data evaluation strategies and 6) Probing Systems. As illustrated by Figure 1, these sources of error are synonymous with CMM equipment. However the nature in which such errors manifest themselves or are controlled on a machine tool can vary dramatically.

Substantial research programmes have been carried out by academic, national, and international institutes, as well as industrial companies, leading to a number of different methods and technologies aimed at improving the measurement capability of machine tools. Such methods and technology include rapid machine tool calibration and verification techniques, OMM probing systems development, machine tool design and controller optimisation, and off-line OMP design, execution, data processing and analysis software [1], [4]–[6], [8], [11]–[18].

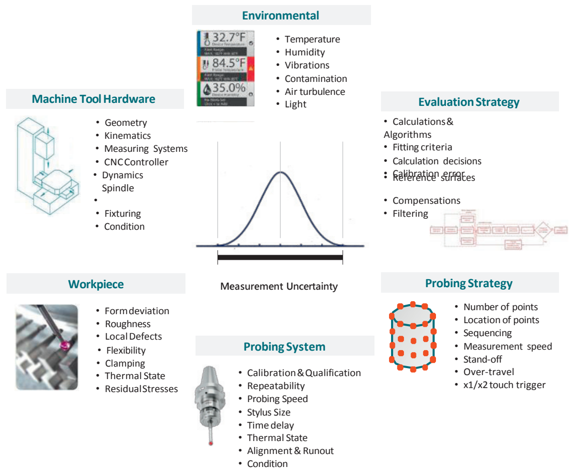

Fig. 1. Measurement uncertainty contributors for machine tools

2.1. Standardised methods for machine tool capability evaluation

Standardised methods to evaluate the performance of multi-axis machine tools have been prepared and published by ISO committee TC39/SC2. Their recent ISO 230:10:2011 standard defines the testing procedures required to evaluate the measurement performance of machine tool contacting probing systems [18]. The standard does not include non-contact probing systems or scanning probes. The standard is also not intended to distinguish between the various causes of measurement error, rather the combined influences of machine probing process variables. The standard however remarks that the main influences on machine tool probing performance are: 1) Repeatability of the machine tool, 2)

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