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Original Citation

Willoughby, P, Verma, M, Longstaff, Andrew P. and Fletcher, Simon (2010) A Holistic Approach to Quantifying and Controlling the Accuracy, Performance and Availability of Machine Tools. In: Proceedings of the 36th International MATADOR Conference. Springer, London, UK, pp. 313-316. ISBN 978-1-84996-431-9

Paper No: 1549 – 36th MATADOR Conference

A Holistic Approach to Quantifying and Controlling the Accuracy, Performance and Availability of Machine Tools

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Abstract

With today's ever increasing demand for improved accuracy and faster material removal rates, CNC machine tool manufacturers and users are under pressure to supply and maintain machinery with a high degree of accuracy and performance. Although some machine tool users have their machines "checked", there is no formal method of establishing the capability of a machine tool as an overall measure of its performance, accuracy and availability.

This paper identifies the key performance indicators for modern CNC machines and highlights the technical difficulties in understanding machine tool capability. To solve the problem, a novel method of measuring, analysing and controlling the overall capability is presented. The philosophy and process of machine performance evaluation, optimisation and monitoring (MPEOM) is explained.

The paper also illustrates how conventional "Lean" techniques can be utilised to simplify the complex area of machine tool metrology allowing for the integration of the process into modern manufacturing systems.

Keywords: Lean manufacturing, Metrology and measurement, Sustainable manufacturing, Precision machining, Condition monitoring.

1.0 Introduction

Many high precision manufacturers are aware of the problematic areas within their processes and the impact they have on the cost and ability to remain competitive. Although quality, performance and availability levels might be measured in some form, the data only represents the symptoms of underlying problems within the manufacturing process. As a result, manufacturers usually engage in process improvement where 'Lean' strategies such as Kanban, Kaizen, TPM and Six Sigma are implemented to improve organisational efficiency and overall equipment effectiveness (OEE), Gibbons [1]. Unfortunately this process improvement will often stop at the machine tool level due to the complexity of machine tool systems and a skills shortage throughout the industry. ISO DIS 263003-1(E) Machine Tools – Reliability, availability and capability provides an indirect measurement of capability by evaluating the machining process. This methodology was developed in the automotive industry and is particularly suited to large batch manufacturing due to its use of statistical process control (SPC). The short term capability of a specific process can be evaluated, however should the process be changed or a different area of the machine be required then capability of the asset is no longer known.

1.1 Machine tool complexity

CNC machine tools are continuously increasing in flexibility and functionality, but the added complexity leaves many end-users struggling to keep up with the technology. When the capability of the machine tool is in question, not only is it often unknown, but methods of establishing it are also unclear. This leads to a situation where assumptions, based on non-factual or untraceable information, are made and proliferate among all relevant departments. As a result, the equipment is isolated from organisational quality systems. Fig. 1.0 illustrates a typical manufacturing system where all other processes are managed by some kind of auditable or "Lean" system. The interface of the machine tool into this system is often disregarded.

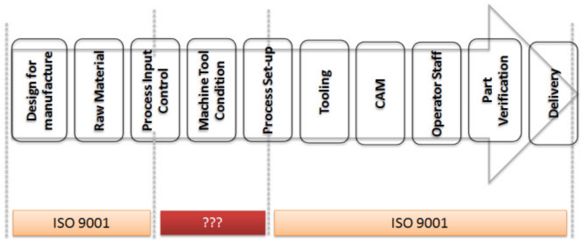

Fig. 1.0. Managing the manufacturing process

In many cases the machine tool will be 'maintained' by performing scheduled service and calibration activities, as recommended by the original equipment manufacturer (OEM) or a quality system. However, the value added by these actions is often unknown and potentially minimal. An OEM might not wish to highlight failings in their machine that indicate non-reliability and any end-user generated system requires a high level of knowledge to provide a comprehensive study.

Take for example, a company who has the linear accuracy of their machine regularly recalibrated to ISO 230-1. This gives a piece of information, but what is it's worth in isolation from the required component output? If linear compensations mean it passes the calibration, does this mean the machine has been corrected for its inherent angular or straightness errors? If these are not mechanically maintained then the machine will eventually fail to produce the correct parts, even with a certificate proving its "capability".

As a result, the machine tool is often not optimised and its problems only addressed once a failure event occurs which requires urgent attention, such as a breakdown or loss of product quality. In these cases it is common that the cause cannot be confidently identified and that "patches" are applied to 'fire fight' the machine back into production. Examples or such practice are commonly seen through the re-working of parts via offsets being applied into part programs or unnecessary replacement of entire machine tool components such as ballscrew systems. In both cases the root cause is never identified and so remains unresolved, making recurrence inevitable.

The following section illustrates how a machine tool can be categorised and its capability can be holistically analysed.

1.2 Machine tool characteristics

A machine tool can be broken down into three general characteristics which will govern its overall capability:

- Mechanical Characteristics
- Electrical / Electronic Characteristics
- Metrology Characteristics

The characteristics above are typically treated in isolation from one another. Historically, these three functions have been dealt with by different machine design departments and different end-user maintenance departments. The effect of these characteristics has a direct impact on the performance characteristics of a machine tool:

- Power
- Speed
- Accuracy & Reliability

When investigating the relationship between these characteristics (Fig. 2.0) it becomes apparent that to improve OEE these performance characteristics cannot be treated in isolation.

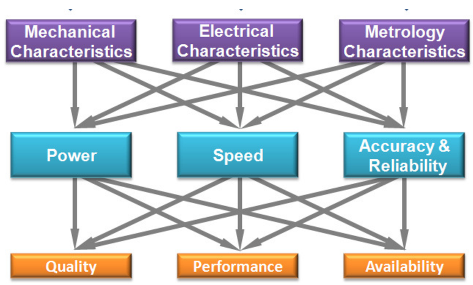

Fig. 2.0. Machine Tool – OEE Matrix

This matrix can be used to help identify key areas of non-conformance, through utilising techniques such as fish bone root-cause analysis as specified by Ishikawa [2]. Once all critical sources of non-conformance are identified we then need a method of addressing and controlling them.

1.3 Total productive maintenance (TPM) and Six Sigma

The concept of total preventative maintenance was presented over twenty years ago by Nakajima [3]. It was recognised that the effective application of modern technology can only be achieved through people, starting with the operators and maintainers of that technology and not through systems alone. TPM is now considered as a 'Lean' improvement method established as an enabling tool to capitalize on true operational effectiveness.

Six sigma is a business management strategy originally developed by Motorola (USA) in the 1980s [4]. It has the aim of improving the quality of manufacturing processes, product and services through a set of methods including statistical process control, business improvement methodologies and management systems.

Both TPM and Six Sigma have similar aims and frameworks for improving OEE on a shop floor and organisational perspective, however the way in which these techniques can be implemented to today's machine tools is still unclear. An attempt to address this problem has been made by Saunders [5]. Here a typical manufacturing process has been broken down into gated processes using a hierarchical pyramid system. At the centre of Six Sigma methodology is the DMAIC (Define, Measure, Analyse, Improve, Control) model, where project teams are created to tackle specific problems to reach Six Sigma levels of performance. On the other hand

TPM can be seen to be implemented in a multitude of ways but with no formally defined approach that can be considered as an industry standard for implementation on high precision machine tools. It is argued [4] that although TPM and Six Sigma have very close links in terms of strategy the former focuses primarily upon quality issues and the latter on reliability.

Through employing techniques used in both TPM and Six Sigma we can propose a methodology for establishing and continuously improving machine tool capability. The following section introduces this in the implementation of such a system via a machine tool service and calibration based organisation.

It has been seen from industrial experience of others that the separate implementation of 'classic' lean approaches regularly fail due to large financial, human and technical requirements which end-users are unlikely to be able to justify or provide. A strategy has consequently been developed that requires a simple yet effective system to facilitate an approach to any manufacturing cell irrespective of size, location and complexity. This system, called MPEOM, has been applied to a full spectrum of machine tools ranging from small manual lathes to very large multi-axis gantry machines and is presented in the following section.

3.0 The MPEOM™ Framework

MPEOM™ (Machine Performance Evaluation Optimise Monitor) is a six stage continuous improvement process with can be used to evaluate, optimise and monitor the condition of machine tool systems. It is a 'lean' tool that can be used to pull the machine into a quality system and creates the structure of TPM. The cycle can be seen as shown in Fig. 3.0.

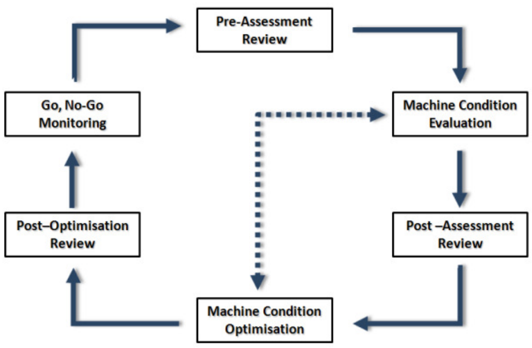

Fig. 3.0. The MPEOM cycle

The system picks up on a lean strategy often used in TPM and Six Sigma. It is an evolution of a Plan, Do, Check, Act cycle and can also be compared to the five stage DMAIC process. Each stage of the MPEOM™ process will be explained in the following section of this paper.

3.1 Pre-assessment review

The pre-assessment review brings together manufacturing engineers, production, maintenance and machine tool specialists. During this review the part or range of parts produced on a selected machine and the machining process key performance variables (KPVs) are analysed and formalised. The results of the meeting include:

- classification of the machine as reliability or accuracy biased
- a clarification of machine performance requirements
- identification where part/process specific auditing/measurement actions are required
- a metrology index based on machine configuration
- measurement equipment requirements

3.2 Machine condition evaluation

Once objectives have been set for the machine, it is then audited. During this audit critical mechanical, electrical/electronic and metrological characteristics of the machine are investigated. This includes assessment of:

- all main mechanical components
- all main electrical and electronic components
- the machines axial geometry to ISO 230 – 1 and OEM specifications
- the machines structural geometry to ISO 230-1 and OEM specifications
- the machine's measuring systems in accordance to ISO 230 - 2
- the machine's dynamic capability in accordance to ISO – 4
- artefact accuracy

During this evaluation non-intrusive tasks can be carried out also, which can include cleaning of the machine, adjustments and optimisations to any minor machine faults and its geometry and measuring systems.

3.3 Post-assessment review

The data collected on the machine is presented to the representatives from the maintenance and production departments through comprehensive reporting and charting. All machine issues or out of tolerance metrology items that could not be rectified during the evaluation stage are flagged. Concessions are negotiated, based on budget and time available for optimisation and the level of performance that is required from the machine. Once an agreement has been reached by the team, plans are formulated for any rectification and optimisation work on the machine.

3.4 Machine condition optimisation

The optimisation of the machine is a sub-cycle within the MPEOM process, consisting of four levels. Level 1 involves optimisation which can be carried out non-intrusively such as adjusting machine geometry using conventional mechanical alignment techniques, adjustment of CNC controller setting and general servicing actions. Should it be agreed that this would be insufficient a Level 2 optimisation is subsequently used. This would consist of a partial rebuild of the machine using the machine and process requirements as the specification guideline. Such corrective action could include removal of critical machine components for repair and/or re-engineering. A Level 3 optimisation option is also offered normally for high accuracy applications or for situations where time and cost restraints are prohibitive. This would involve the use of hardware and software utilising a volumetric compensation system (VCS) to compensate the geometric and positioning errors of the machine to remove up to 70% of errors left after the other levels of correction were ineffective Postlethwaite [6].

Level 4 is only used when it can be shown that all previous levels of correction would not meet requirements for the machine tool accuracy and reliability specification. In this case, a decision would be made to rebuild, redesign or replace the machine. Here the information from previous stages in the MPEOM process would be used as part of the specification and acceptance of new machinery or validation of correct redesign, retrofit and rebuild of the machine.

3.5 Post optimisation review

During optimisation new data will have been collected on the mechanical, electrical and metrological condition of the machine. This data along with any collected from the initial audit will represent the machine capability 'benchmark' condition. The data is reviewed and a preventative maintenance schedule is agreed between all concerned, again based on part and performance requirements. This will involve the implementation of a Go, No-Go / sustainment program.

3.6 Go, No-Go system

A "Go, No-go" system is set up for the machine operators and maintenance staff to use to ensure that non-conforming parts on the machine are not produced and that regular failure points are monitored to predict breakdown. The system is based on the benchmark data collected and relevant KPVs identified earlier on in the process. Data is collected from the machine and can include but not limited to circularity Ballbar, vibration analysis, oil condition monitoring, artefact probing. These tests are carried out non-intrusively and on a defined schedule, where tolerance bands are set to flag and predict when intervention is next required.

4.0 Conclusion

Although machine tools are complex systems, problems of accuracy and reliability can be addressed by breaking them down into their key characteristics. By adopting "lean" manufacturing philosophies it is possible to involve all departments across a manufacturing plant to make targeted decisions on the key performance variables for machine tool performance, accuracy and availability.

This paper presents such a strategy, which has already been successfully applied to a wide range of manual and CNC machine tools.

The MPEOM system presented in the paper provides a conduit for defining, establishing and maintaining a machine's required characteristics according to the rigours of the production requirement. It acts as best practice, but with the constant review process enabling efficient adoption of new technology as it becomes available.

At this stage only the static rigid body errors are addressed. There is scope in the future to analyse the non-rigid body errors associated to thermal displacement, load, deflection etc.

At present there is no clear ISO guideline for Machine Tool Capability across the full industrial spectrum. This continuing research exercise will contribute to redressing this shortfall.

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