KES Transactions on Sustainable Design and Manufacturing II
Sustainable Design and Manufacturing 2015 : pp.528-537 : Paper sdm15-075

Implementation of a machine tool performance measurement and diagnostic system and its impact on parts verification

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Abstract *Five axis machine tools are increasing and becoming more popular as customers demand more complex machined parts. In high value manufacturing, the importance of machine tools in producing high accuracy products is essential. High accuracy manufacturing requires producing parts in a repeatable manner and precision in compliance to the defined design specifications. The performance of the machine tools is often affected by geometrical errors due to a variety of causes including incorrect tool offsets, errors in the centres of rotation and thermal growth. As a consequence, it can be difficult to produce highly accurate parts consistently. It is, therefore, essential to ensure that machine tools are verified in terms of their geometric and positioning accuracy. When machine tools are verified in terms of their accuracy, the resulting numerical values of positional accuracy and process capability can be used to define design for verification rules and algorithms so that machined parts can be easily produced without scrap and little or no after process measurement. In this paper the benefits of machine tool verification are listed and a case study is used to demonstrate the implementation of robust machine tool performance measurement and diagnostics using a ballbar system.*

Keywords: machine tool verification, process control for sustainable manufacturing

1. Introduction

The fundamental part of any CNC machine is the positioning of the tool. The accuracy and quality of the final product depends upon the accuracy of the machine tool. Like any mechanical device the precision of the machine reduces with time and this affects the parts which are produced. Therefore it is very important to ensure the machine tool is monitored or checked at specific time intervals and as a result machines are capable to manufacture parts with minimum variations. Kwon et al. [1] argued that positioning of the machine tool has a direct impact on in-process inspection using a touch probe; therefore instead of relying only on the touch probe measurements for part quality assurance, machine tool accuracy and capability analysis need to be taken into account. This issue is considered redundant or counts as a less important issue for SMEs. The process of verifying machine tools is often seen as an additional cost and a non-productive activity that costs money and reduces profit. Regular machine tool verification can reduce the cost of non-conformant products and increases the OEE (overall equipment effectiveness), resulting in increased profitability and greater customer satisfaction. Today, this issue is addressed by machine tool maintenance providers. A diagnostic test can be performed on the machine identifying any error in the machine tools and finally adjusting readings. Unfortunately, due to the lack of resources and also understanding of the importance of the machine errors this issue is seen as troubleshooting not as a preventive action. Regular verification of machine tools brings confidence to companies and ensures that the equipment is performing within its accuracy specification. ISO 9001 also quotes in Quality Management: Guidelines [2]:

"The supplier shall identify and plan the production, installation and servicing processes which directly affect quality and shall ensure that these processes are carried out under controlled conditions which shall include the following:

Suitable maintenance of equipment to ensure continuing capability is maintained."

2. Project brief and objective

It is proposed that LIMA BTC (Laboratory for Integrated Metrology Applications Business Technology Centre) will assist and provide knowledge and training to help the case study project (Helander Precision Engineering) to develop a long term programme that identifies and controls the capability of their current machine tools. The company has invested in machine tools; tool setting probes and spindle probe verification equipment, which it is believed are not used to full capacity. Helander Precision will provide an overall project manager who will drive and implement the processes and procedures with conjunction of LIMA BTC. The proposal will be complemented by an existing plan within 'Bristol and Bath Science Park Engineering' to service all machines once per annum to ensure smooth running and operation of the machine tools. The LIMA BTC's supported project will identify control limits for each entity tested on the machine tool and set accordingly. It is also planned that each machine could be entered onto the gauge register to ensure that a determined regular check is carried out to monitor the capability and performance of the machine tool. This will potentially reduce the maintenance costs and increases the productivity by reducing downtime and producing conformance products.

The aim to run the project at Helander is to develop a learning plan for company's staff in order to understand the importance of measuring machine tool performance and to maintain the machine tool performance within agreed specified limits. On-going monitoring is planned to ensure the accuracy of machined components is maintained and "surprise machine tool breakdowns" are reduced to a minimum or eliminated. Furthermore, to maintain the machine tools accuracy it is suggested a measured and qualified process capability control for each machine tool at Helander Company should be produced

In order to understand machine tool behaviour and error sources within machine tools; the benefits to each department are explained in detail, discussing why there is a need to monitor machine tool performance. Based on the second law of thermodynamics no process is ever in a perfect a state of control. Hence, the monitoring of the machine tools needs to be understood by staff at different levels of manufacturing and production departments. Figure 1 shows key causes of the machine errors.

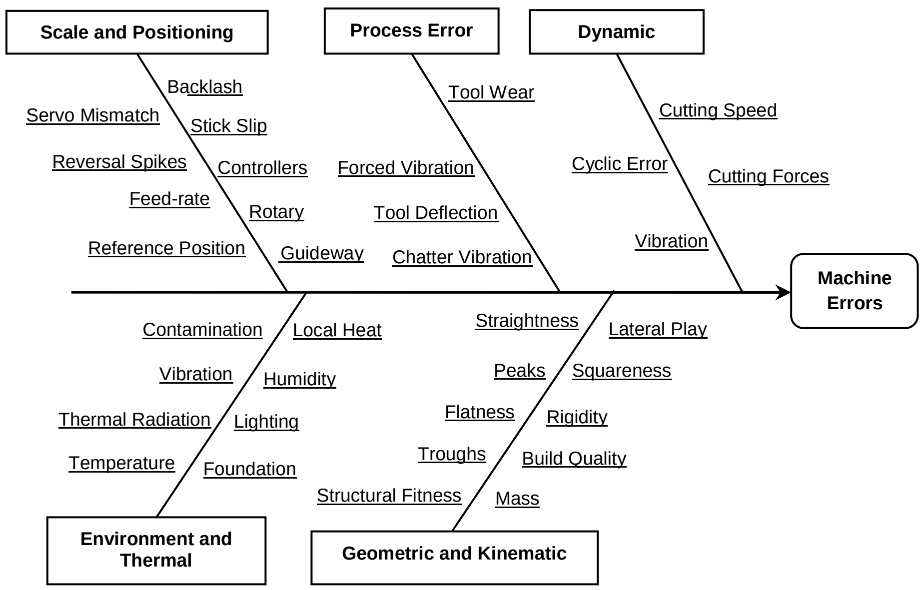

Figure 1 – Typical factors can affect machine performance [3]

The impact of these errors on each other and consequently on machine tool positioning along with the kinematic chain of the machine, can produce excessive positional errors at the tool position causing non-conformities in production [3]. Environmental factors will affect the machine and can cause considerable errors in positioning. Examples of environmental effects can be thermal expansion of machine tool components due to changes in operating temperature. As a result of temperature fluctuations different geometric positions on the machine become distorted [4].

In the next stage the use of equipment and training as well as testing standard milling machines and lathes are discussed. Then, ways to obtain valid results for analysis and identifying the adjustments required to improve machine tool performance is clarified. Regular testing helps to predict machine failure and eliminate downtime. According to Shen et al. [5] the volumetric positioning accuracy of CNC machine tool is the main element in machine precision. Advanced machine tool testing discussed in various methods incorporating Z axis checks with good house-keeping practices while testing. The Z axis testing introduced and set about performing three checks on a VMC (Vertical Machining Centre) machine, XY axis, XZ axis and ZY axis. After obtaining all three sets of results it is possible to use the software to produce a full volumetric check on the machine tool. Graphical results are shown for each plane with their individual circularity results [6]. As shown in Figure 2 data is displayed graphically combined with the numeric format to support diagnosing errors in each plane. The plane circularity errors which are generated during the operation of the multi-axis machine tool directly affect the machining precision. According to Pahk and Kim [7] assessing the 3-d volumetric errors in such machine tools is a prerequisite for accuracy enhancement and quality assurance. These errors can be monitored over time to produce a history for comparison purposes and tolerances can be set based on captured data. This approach is perfect to verify multi-axis machine tool performance. As shown the minimum and maximum deviation on each plane illustrates the sphericity error in volumetric diagnosis. Reviewing these errors over time can show how the machine performance degrades over time, therefore corrective actions can put in place to minimise the potential modifications that can be caused. It is prudent to have a part programme for the machine tool ready and loaded into the controller which reduces the production downtime considerably and enables a machine to be tested within 15 minutes, prior to resuming production.

Once tools, methods and the importance of machine tool calibration have been discussed a full explanation of error sources and the consequences on machined components can be given. The corrective actions that should be taken to reduce and eliminate the errors and an overview of additional equipment used to improve machine tool accuracy is shown. Help files in the software is a great tool to understand what each error source is and how to investigate and correct them. A reliable way to do the correction is to test errors on a machine with a known part (test piece) and adjusting parameters to see what effects corrections could be made to improve a machine tool [8].

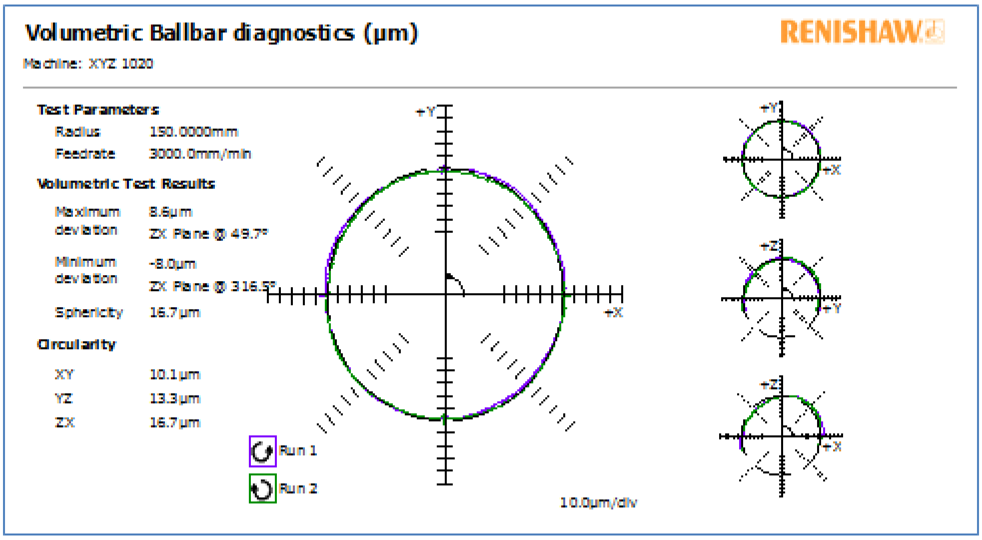

Figure 2 – A sample of a volumetric test result

Furthermore identifying control limits for each error source within machine tools and setting control limits in the testing software is explained in detail. This is useful for determining the frequency of checks to maintain accurate machine tool performance along with predicting when a machine may fail. For instance, monitoring wear within specific parts of the machine tool and knowing when to repair the machine tool before it fails. Some of these machine failures are due to the weight of moving parts within the machine. By the time the weight of the work piece can cause a repeatable displacement of the machine structure that can impact and manipulate the link between the guide-ways and machine tool position and ultimately machine accuracy [4].

The next step is tailoring the software and setting control limits for each machine tool and individual tests. This will enable the test to develop to a full test procedure to comply with AS9100 and SC21[1].The aim is to develop a balanced testing programme to ensure each machine tool is tested within specified time intervals. Finally assistance is given in developing “in-house” test processes and procedures to cover the control of testing, due dates etc. The monitoring process will be

[1] SC21 is a change programme designed to accelerate the competitiveness of the aerospace & defence industry by raising the performance of its supply chains.

followed by LIMA BTC visits to validate that the procedures and testing programme are being followed and all points that have been taught and implemented are examined. A review will be done later to re-train staff to ensure the project is successful.

3. Monitoring process

At the end of the project each machine tool will have its own set of control limits and individual testing programme / procedure to maintain accuracy and predict failure modes. Staff will be trained to use the testing equipment and interpretation of test results whilst developing a matrix of machine tool controller parameters that can be adjusted to improve and maintain machine accuracy.

The measure of success would be in the form of reduced machine tool breakdowns and reduced non-conformance (scrap) which will also assist in increasing machine tool efficiency and overall OEE. Data would need to be collected prior to the start of the project so an accurate measure of success can be identified. A simple calculation sheet can be provided to identify “machine tool break down” time and the costs *along with the cost of non-conformance.*

The company will register the machine tools on the current gauge register (Gagetrak) and the frequency of checking / verification will be set to every three months (Figure 3). This has been staggered so that three machines per week are verified and this will minimise the downtime to production requirements. These steps should be followed for calibration of machine tools based on current study at the case study company:

- Calibration frequency of machine tools is to be stated in Gagetrak
- All machine tools shall be allocated a unique asset number as well as their own machine tool name and machine type
- Circularity test results are to be printed and retained as proof of testing
- If a machine tool crashes the tests shall be repeated
- All machine tools shall be treated in the same way as any other item of measuring equipment
- The periodic verification carried out on the machine tools will not negate the routine servicing or maintenance carried out by the service providers
- A list of all machine tools with imminent certification expiration shall be given to the team leaders at the beginning of the each month

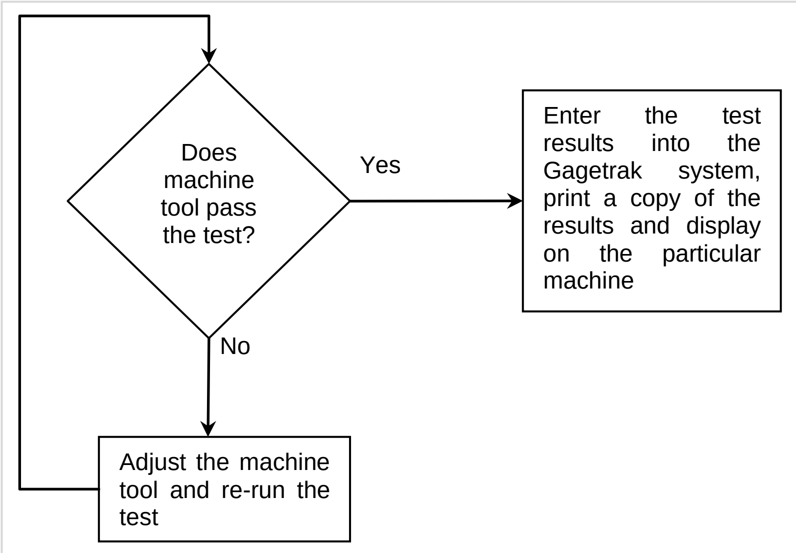

Figure 3 - Periodic verification on machine tools

The process is sound and auditable with individual control limits for each machine and the process has been added to the companies ISO 9001 manual. This will also be audited yearly by the independent ISO 9001 auditor.

4. Benefits of regular machine check

Regular machine checks will help improve the overall equipment efficiency and reduce waste with commensurate cost saving. Some of the main benefits and savings in regular machine tool verification are as follows:

- Machine's capability for producing parts to tolerance is understood.
- Scrap / rework caused by machine errors are greatly reduced.
- Prior 'value added' activities are safeguarded by choosing accurate machines for further machining.
- The touch probes for job set up tasks are utilised.
- Production schedules are more accurate based on performance capabilities.
- Throughput is increased by optimising feed rate performance.
- It is now possible to evaluate one machine against another (existing machines, or machines, the user is thinking of buying).
- Investment in new or used machine tools can now be 'signed off' after the equipment has been checked.

- Profit increased by keeping maintenance downtime to a minimum.
- Confidently demonstrated machine's accuracy to be accepted by companies who are choosing subcontractors.
- By removing uncertainties about the performance of machines, conflict between production, quality and maintenance departments is minimised.
- Getting the best out of existing machines means they will be accurate for longer. It is likely to postpone the need for expensive new machines.
- Check performance before blaming the machine and automatically calling maintenance and sub-contractor (It may not be needed at all).
- An essential process / pre-requisite when implementing a preventative maintenance programme with minimal manpower.
- Help to examine performance trends, helping to predict (and thus prevent) major machine tool breakdowns.
- Results can be archived to provide a traceable history of the performance of each machine.
- Management can make better informed decisions regarding which machines require priority attention and those that need replacement.
- The information helps to reduce the number of breakdowns, therefore reduces pressure on machine tool maintenance resources.
- Get the best possible performance out of machines, irrespective of age or condition.
- Reduce inspection failures by improving the processes.
- Prove the capability of the process without the need for lengthy investigations.
- Deterioration in performance over time can be detected by history review and use for schedule maintenance work prior to machine breakdown.

This list is indicative of the considerable benefits arising from machine tool verification and regular machine tool monitoring. These benefits need to be considered by industry in the process of prioritising these activities alongside production tasks, to achieve the optimal level of productivity and quality.

5. Conclusions

The importance and methodologies for machine tool verification and condition monitoring have been presented. In case Study Company, machine tool repeatability is verified by using a series of target points that were measured by laser interferometers and by comparing the results it is possible to find errors in straightness, parallelism and concentricity. The challenge is that the accuracy and repeatability values can differ significantly depending on the measurement procedures. For instance, the accuracy is different when fewer control points are measured. This difference in results makes it very difficult to compare the performance of different machine brands [3].

A project of verifying machine tools is used as an example and the steps towards controlling the verification method are explained. The use of ballbar diagnostic not only makes the accurate conclusive proof that servicing or re-calibration work is needed but also enables the verification process to be carried out faster. Among the benefits of using the ballbar system for verification are that the machine tool errors will automatically be diagnosed, causes and remedies are quickly identified and machine tool capability is quickly determined. The identification of the machine tool capability is a vital aspect of design for verification, as it allows design rules to be formulated that link the engineering specifications, such as tolerances and surface roughness, to the process capability, thus allowing the superior and cost effective verification of products. This is vital to SMEs, as the verified machine tool will return to the production loop in a short period of time, depending on corrective actions. Finally, the benefits of regular machine checks are listed to show the importance of machine accuracy.

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