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ScienceDirect

Procedia CIRP 46 (2016) 23 – 26

www.elsevier.com/locate/procedia

7th HPC 2016 – CIRP Conference on High Performance Cutting

Design of a measurement setup and first experiments on the influence of CO_2-cooling on the thermal displacements on a machine tool

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Abstract

The paper investigates the thermal influences of CO_2- and oil-cooling on the precision of a machine tool. If CO_2 is used for process cooling instead of oil, a different temperature distribution in the machine is observed. Different temperature distributions lead to different tool center point (TCP)-displacements. To measure TCP-displacements under real process conditions with CO_2 and oil, a special measurement setup is designed, built and applied. A representative process for the machine is chosen to compare the different process coolings. The results show that the choice of coolant has a crucial influence on the TCP-displacements. It is shown that the thermally induced displacements can be reduced by 15 µm in y-direction, but increase about 4 µm in x-direction, when the coolant is changed from oil to CO_2.

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Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair Prof. Matthias Putz

Keywords: Cooling, Thermal displacement; Measurement; Machine Tool

1. Introduction

For many manufacturing processes, oil cooling is the commonly used technique to prevent thermally induced damage of the tool and the workpiece. This is often done by flood cooling, which leads to high amounts of oil required for that process. Furthermore, oil has a lot of negative environmental impacts, due to additives for achieving higher performance and more areas of application. This is the reason, why there is a lot of research to reduce the amount of oil for several processes. One alternative is the cooling with CO_2 instead of oil or minimum quantity lubrication cooling with a small amount of oil only.

There are several publications that compare the influence of CO_2 instead of oil on the machining process. But the change of the cooling medium not only causes a different behavior of the process, it furthermore has an effect on the whole temperature distribution in the machine. This paper shows that a change of the cooling medium from oil to CO_2 results in a change of the precision of the investigated machine tool.

To analyze the effect of CO_2 a special measurement setup is designed, built and applied. This measurement setup can measure TCP-displacements under real process conditions, what means under oil or CO_2. To compare the two cooling media, a representative process on a machine tool is chosen and the heating up phase of the machine was measured after every two manufacturing steps.

In order to simplify the assignment of causes to their effects no workpieces is produced and only the movements of the axes and the rotation of the spindle is analyzed. This leads to the special case that this paper is able to present the effect of changing the cooling medium on the thermally induced TCP-displacements due to the movement of the axes and spindle only.

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doi:10.1016/j.procir.2016.04.075

2. State of the art

2.1. Measurement of thermal caused errors in machine tools

Thermally caused errors are estimated to contribute an amount between 40% and 80% of all geometric errors induced on TCP-displacements [1-5]. As Mayr et al. comment, thermal errors are either caused by the environment or by internal heat sources [6]. Internal heat sources can be for example drives, pumps or the cooling medium, when it has a higher temperature than the environment.

A common measurement device to compare thermally induced errors on machine tools is the R-Test, as applied by Mayr, Ibaraki and Hong or Gebhardt [7-9]. In these publications the setup is used with the machine's cooling medium turned off. Furthermore the investigated machine has not been analyzed under real process conditions yet. More precisely either the spindle was turned on or one axis moved over a longer period of time. These special test conditions lead to a special heat input, which does not occur under real process conditions because the heat input was just caused by the movement of one component.

2.2. Measurement of displacements under process conditions

2.2.1. Double Ballbar

The standard ISO 230-4 [11] describes the measurement of circular paths on machine tools. The double ballbar is usually used within a three dimensional hemisphere with predefined test paths at moderate speed. The double ballbar consists of two precision spheres that are connected with a length variable bar with an integrated measurement system. The moderate speed makes sure that dynamic effects do not affect the measurement results. This measurement setup is a good possibility to measure in 3D, but its disadvantages are its sensitivity to environmental contamination and that it cannot be used in a stand-alone automated manner.

2.2.2. Grid plate

By using a grid plate a two dimensional measurement of position accuracy and repeatability in one working plane can be performed, just as described in the standard ISO 230-2 [12]. Therefore straight-lined or freeform test paths can be used to measure position errors across and along the moving direction. The grid plate is mostly used to detect dynamic effects on machine tools. The main advantage is the contact free measurement eliminating friction which could influence the measurement results. The disadvantage is that it is an optical system and therefore not usable under oily conditions.

2.2.3. R-Test

The R-Test is a measurement setup presented by Weikert in 2004 [10]. For this setup three incremental measurement sensors and a precision ball made out of ceramics or hard metal are used. The setup enables to measure simultaneously 3D displacements within a range of ± 3 mm. The standard measurement setup with probes having IP50 protection class cannot be used under flushing conditions, due to the sensors that would need a special protection and a higher protection class.

2.2.4. Laser interferometer

The Laser interferometer is a further possibility to measure the positioning accuracy of machine tools following ISO 230-6 [13]. This measurement system can detect combined displacements of one or more machine axis depending on its configuration. Due to the issue with its exposed optical measurement principle as with the grid plate, it is also very sensitive for environmental contamination and therefore not well-suited under process conditions.

3. Measurement setup

3.1. Requirements

To use a measurement setup under real process conditions, the following requirements have to be fulfilled:

- non-sensitive against oil and CO_2
- enable measurement of translational displacements in x-, y- and z-direction
- modular build-up for re-use
- quick installation and removal of the system

To fulfill the stated requirements the measurement principle of the R-Test was adapted and a setup with sensors that persists under real process conditions was designed.

3.2. Sensors under use

Sensors are specified by their degree of protection. For the use under oil- or CO_2-cooling, sensors with a protection class of IP67 or even better like IP68 (permanent submersible) are necessary. Furthermore the sensors should have a measurement range of at least $\pm 1\ mm$. To capture the displacements of the machine tool, a sensor resolution of at least 0.25 µm combined with a high linearity is required.

The sensor used is the LVDT (linear variable differential transformer) sensor, T301F from the Peter Hirt GmbH, Nänikon. It has a protection class of IP67, a measurement range of 2 mm and a measurement resolution of 0.06 µm. The linearity over the measurement range is 8 µm and the repeatability is stated to be 0.01 µm. The sensors are readout with a recording and interpolation system from IBR Messtechnik GmbH & Co. KG, Haunetal.

3.3. Measurement concept

To use the measurement concept of the R-Test three LVDT sensors with flat probing tips, placed orthogonally towards each other, measure the displacement of a precision sphere. The R-Test concept is adapted to fit the machine tool under investigation, as shown in Fig. 1. The precision sphere is made of ceramics. To reduce thermal errors due to the measurement setup the bar is made out of Invar® steel.

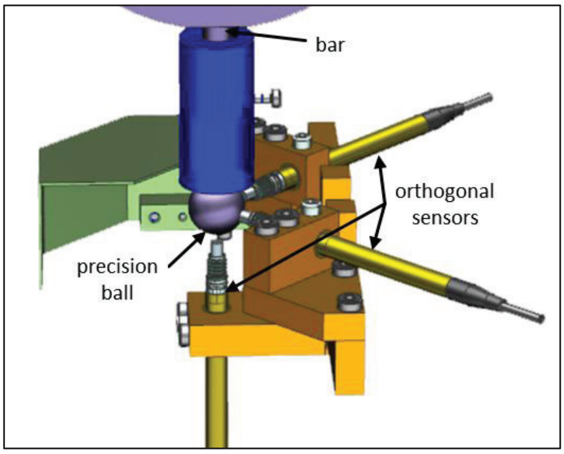

Fig. 1. measurement setup of the three sensors on the investigated manufacturing machine.

For the measurement setup three sensors are placed orthogonally to each other. Due to the available space it is not possible to align the sensors in the direction of the machine axes. This makes a transformation from the sensor coordinates to the machine coordinates necessary. The principle is illustrated in Fig. 2. For the y-displacement no specific transformation is necessary, due to the sensor's parallel mount in direction of the y-axis of the machine tool.

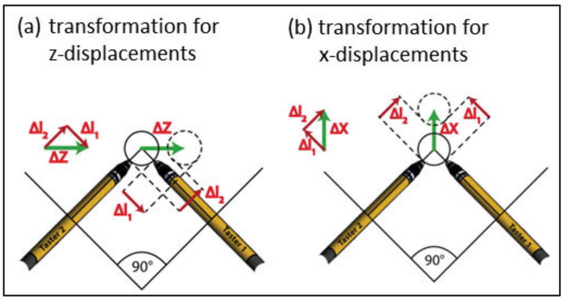

Fig. 2. (a) transformation for displacements in z-direction; (b) transformation for displacements in x-direction.

The sensors measure the displacements $\Delta l_{j,i}$ with the index j as the number of the sensor and the index i as the number of the measurement value. With the transformation matrix, shown (1), the displacements of the machine in x-, y- and z-direction can be calculated as

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \begin{bmatrix} \frac{-\sqrt{2}}{2} & \frac{-\sqrt{2}}{2} & 0 \\ 0 & 0 & -1 \\ \frac{\sqrt{2}}{2} & \frac{-\sqrt{2}}{2} & 0 \end{bmatrix} \cdot \begin{bmatrix} \Delta l_{1,i} \\ \Delta l_{2,i} \\ \Delta l_{3,i} \end{bmatrix} \qquad (1).$$

3.4. Protection of sensors and precision sphere against chips and other impairments

The measurement setup is designed in a way that it can be used during the process. The sensors are not sensitive against oil or CO_2, but their flat probing tips have to be protected against chips and other impairments. Furthermore the precision sphere has to be protected as well. Therefore a protection cover for the sensors and a protection shell for the precision ball is designed, as illustrated in Fig. 3. With the aid of Bowden cables the protections are automatically opened for performing the measurement. The movement control is done by the NC-code of the machine tool and a pneumatic actuator. Once a measurement cycle is done, the cover and the shell are automatically shut with the aid of springs.

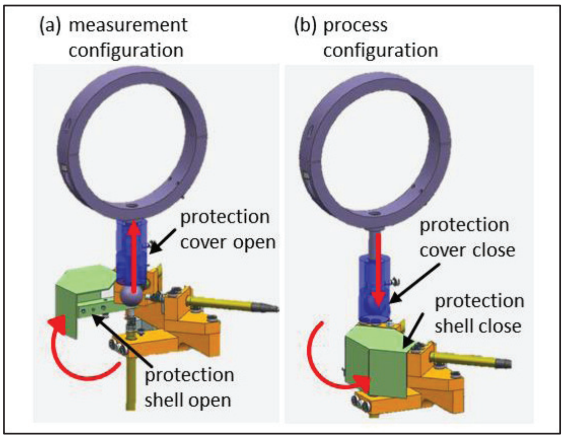

Fig. 3. (a) measurement setup with protection cover and shell opened in the measurement configuration; (b) measurement setup with protection cover and shell closed during the use of oil and CO_2.

4. Measurement scenario

To get a better understanding of the influence of CO_2-cooling on the thermal displacements in a machine tool, the NC-code of a representative manufacturing process lasting 2 minutes is used. In this process three axes are interpolating and therefore lead to thermal displacements due to the heat brought into the system. The actual thermal field is further influenced by the cooling medium, either oil or CO_2. The influence of the process itself is not analyzed as already discussed. That is why the measurements took place without producing workpieces. The measurement on the machine is started from the cold state, directly beginning the representative process runs. Every two runs the machine is stopped, is moved to the measurement position and the displacements are measured. The alternating measurements and process runs is repeated for three hours.

5. Results and discussion

The results of the measurement with oil- and CO_2-cooling are shown in Fig. 4. It is obvious that the influence in y-direction is the largest. The thermally induced displacements can be reduced here by 15 µm when CO_2 is used instead of oil. In x-direction the effect goes in the opposite direction. The change from oil to CO_2 affects an increase of about 4 µm in x-direction. The displacements in z-direction are nearly not affected by changing the cooling medium.

For the x- and the z-direction the machine reaches the steady state after about one hour, while in the y-direction this is not even the case after three hours. This is due to the unsymmetrical buildup of this machine tool and further increased by different heat sources nearby the y-axis.

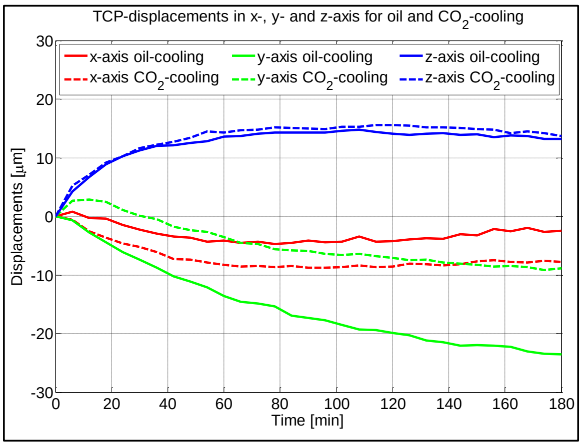

Fig. 4. measurement of the thermal displacements in x-, y- and z-direction over time as a function of the cooling medium oil or CO_2

The machine shows the largest structural dimensions in y-direction. On the tool side the part holding, the z-axis and on the workpiece side the y-axis itself. The cooling medium, in particular the oil, directly contacts them. Furthermore these components have a low wall thickness and are therefore not thermally inert. This leads to the high sensitivity of the machine tool in y-direction to the cooling medium. In x-direction the thermal displacements become bigger with the change to CO_2. There is no satisfying explanation for this effect available at this point of research. Therefore these results underline the importance of these measurements and the need of further research on this topic.

6. Conclusions

This paper presented the design, building and application of a new measurement setup. The setup allows measurements under real process conditions with cooling medium and even measurements during workpiece production are possible. Therefore the measurement setup is non-sensitive against media thanks to protection covers and shells that protect the setup against chips and other impairments.

In its first application the new measurement setup is used to measure the influence of oil and CO_2-cooling on the thermal displacements of a machine tool. It is shown that there is a huge influence (up to 15 µm differences) by the cooling medium when CO_2 is used instead of oil. However the results show not only positive influences of CO_2 on the thermal displacements. It may lead to both, increasing and decreasing thermal displacements. This shows the importance of measuring under real process conditions to get more information about the influence of cooling media on thermal displacements. In further research it is now possible to even run the process with different cooling media.

Acknowledgements

The authors would like to thank the Swiss National Science Foundation (SNF) for supporting the project “Model Reduction Methodologies for Heat Flux Simulation in Complex Mechatronic Systems”. Furthermore the authors would like to thank the Machine Tool Technologies Research Foundation (MTTRF) for their support.

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