THERMAL-DEFORMATION BEHAVIOR OF THE COMPOSITE MATERIAL BED

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The thermal stability of the machining centers plays a major role in ensuring the production repeatability. All machine tools producers take various steps to ensure it. One of the ways to permanently maintain and stabilize the behavior of the machine tool is the use of active cooling and the choice of appropriate material of which the individual parts of the supporting system are made. In most cases, manufacturers of the machining centers use traditional metallic materials (steel, cast iron) for construction of the machine supporting system. However, these materials have some physical limitations. These materials can be replaced by or combined with unconventional materials to improve the thermal stability of the machine. The hybrid composite supporting structures are formed this way.
The authors of this article examine the impact of steel-concrete composite material on thermal-deformation behavior of the bed in a vertical turning machining center for medium-heavy workpieces. The composite consists of the steel weld, filled with high-strength concrete.

KEYWORDS

machine tool, machine tool bed, thermal deformation, steel-concrete composite

1 INTRODUCTION

Each machine tool in the production process must have certain required parameters. Accuracy and productivity are the most important criteria to determine the machine value. The accuracy is related to the dimensional deviation of the machine part from the theoretical dimension in the drawing of the machined surface. Just as important is to achieve high productivity of the machine while maintaining the reliability and efficiency of machining.

There are errors that occur on the machine tools, causing the deviations between the theoretical required dimensions and the real measured dimensions on the workpiece after machining. The inaccuracy of production and assembling of the part of the machine, the impact of dynamic or static forces, errors in the control system, and others can be source of the deviations. The machine tools are also exposed to several heat sources during their operation. Depending on the load and time, these sources influence the temperature changes of the individual machine junctions, particularly the parts of the supporting structure. The temperature gradients cause unwanted deformations which have a negative impact on the working accuracy of the machine tool.

The share of individual components of errors in the resulting accuracy projected on the tool is different for each machine and depends on various factors. The experience and the performed research show that the deviation caused by thermal expansion is dominant compared to other errors. [Weck 1995] states that up to 50% of the total error projected to the final workpiece consists of thermal expansion. The authors in [Mayr 2012] actually state up to 75%. The author [Holub 2019a] describes the influence of temperature changes on the quality of measuring the volumetric accuracy of machine tools. In the presented case study, a change in temperature of 3.6 ° C on the machine frame increased the volumetric accuracy error by 8 %. These effects can be eliminated either by a thermally stable machine design or by more time-efficient measurements of geometric errors. With a suitably designed measurement strategy, it is possible to reduce the time required for measurement by up to 55 % [Holub 2014]. Slow processes, including thermal expansion, are referred to as quasi-static errors. Experiment results indicate that the proposed quasi-online compensation method using the Ballbar system is suitable for dealing with the squareness and scaling error [Marek 2018]. Types of accuracy of machine tool and evaluation geometrical and volumetric errors machining centers is described in [Holub 2019b].

The authors have been working in the area of the machine tools development and production for many years, and moreover, they have many references and data from the machine users themselves, thus they are able to present the estimation of the share of the individual errors in the resulting working accuracy. The resulting accuracy of the final workpiece is affected by the following influences:

- temperature gradients across the structure
- the technology and machining strategy selected
- design and dynamic properties
- the method of the measurement of the final workpiece accuracy
- the volumetric accuracy
- the geometric accuracy of the machine
- the machine operator
- the workpiece material

From experience and based on research, the changes of the temperature fields inside the machine itself have the largest share in the accuracy of the future workpiece. That is why this issue should be given an appropriate attention in order to ensure a long-term stability of the machine operation and therefore to meet the customers requirements for the accurate machine.

The structure material used for the machining center supporting system may have significant impact on the thermal-deformation characteristics of the machine tool. [Mohring 2015] provides an overview of the current research in the field of various materials and design solutions for machine tools supporting systems. The most commonly used are traditional metallic materials – various types of steel and cast iron. Their main advantage is the affordable price and well-mastered production technology. However, there has been an increased interest in alternative materials on the basis of composite, concrete, natural granite, etc. recently.

2 THE IMPACT OF THE TEMPERATURE GRADIENTS ON THE MACHINE TOOL OPERATION

The disturbing influences having an impact on the thermal stability of the machine tools can be divided into two main groups:

- external influences
- internal influences

The heat sources positioned in the machine area can be considered as external disturbing influences. This group includes the circulated air in the production hall, where the temperature of the air changes throughout the day or in relation to the current season. The energy transfer is realized by convection. The heat transfer by the radiation causes the wall in the production hall, direct solar radiation or other local heat sources to have a significant impact on the thermal-deformation behavior of the machine.

The internal disturbing influences are related to the energy losses in the drive systems, lines, bearings and transmissions. The machining process is also the significant heat source. The heat transfer in this group of influences is realized mostly by conduction.

All influences mentioned above can act simultaneously with various share of the individual components of this thermal system. The temperature gradients changes rarely occur linearly but change depending on the machining conditions changes. Logically the highest increase of the temperature occurs in the first working phase of the machine operation after startup. More details on the issue of the thermal errors in the machine tools can be found in [Weck 1995], [Mayr 2012], [Marek 2016]

A number of papers dealing with the research in the field of suppression of undesirable impacts caused by the thermal load was published in recent years. These four measures can help improve the machine's resistance to the changes in temperature distribution in the structure of the machine [Mayr 2012]:

- the construction measures (the use of the higher efficiency elements, thermally symmetric structure, part of the sources placed outside the machine)
- the heat transfer (cooling, continuous chip transfer)
- the compensation (the active CNC compensation, the use of unconventional materials, active tempering (warming) of the part of the machine)
- the air conditioning (maintaining the constant temperature in the hall, shading the radiation heat sources)

The optimization of machine tools in terms of thermal-deformation is not related only with the suppression of undesired deformations and errors. Another aspect is optimization due to the energy efficiency of the machine. Description of this issue is in [Denkena 2020].

3 THE STEEL-CONCRETE COMPOSITE BED OF THE VERTICAL TURNING CENTER

The machine bed is designed for the machine marked with VTL. It is a vertical turning center designed specifically for machining of difficult-to-machine materials. The whole machine was designed as a unique prototype, which is why the process of designing was performed systematically with using the virtual prototyping.

The final optimized part is designed as suitably ribbed steel weld filled with high-strength special concrete.

Concrete suitable for steel-concrete parts construction for accurate machine tools belongs to category of so-called high-strength concrete (HSC). Compound steel profiles or welds filled with concrete were introduced to be used in construction for various supporting structures approximately 15 years ago and became known as steel-concrete composites. They always consist of the steel profile (a tube, a profile I, U, or T or the weld of various shapes) filled with high-strength concrete which adds stiffness to the whole steel structure.

The combination of the steel and concrete has been used for decades in the form of so-called reinforced concrete. This combination works quite well thanks to practically the same thermal expansion ratio of concrete and steel, thanks to which this composite does not cause any problems in case of temperature changes. In terms of durability, another excellent property of concrete is a low pH value (12.0 through 12.5), which allows so-called steel passivation and thus avoids its corrosion even in the moist conditions.

The general requirements on mechanical properties of high-strength concrete suitable for steel welds filling are following:

- minimum compression strength: 80 MPa
- minimum tensile strength in bending: 6 MPa
- minimum static elastic modulus: 37 GPa
- minimalization of volume negative changes, that means the shrinkage of concrete must not exceed 0.5 mm / m

Figure 1. Steel-concrete bed being filled with high-strength concrete

Figure 2. The bed after machining

4 THERMAL DEFORMATION PROPERTIES OF THE STEEL-CONCRETE BED

FEM analysis was used to optimize the structure of the composite bed. The bed is optimized to the high stiffness while maintaining favorable weight parameters of the steel weld, which has the largest price share concerning the economic aspect. At the same time, the structure was designed in such a way that it would be more resistant to temperature influences. In this type of machine, interactions of significant heat sources with the bed during the working cycle cause movements of the clamping plate axis along all three geometrical axes.

The Figure 3 shows the CAD model of a part of a vertical turning machine. Main part is the bed made of steel-concrete composite material. Rotary table is connected to the bed by means of a bearing, which is cooled and lubricated with oil. Pair of drives, planetary gearboxes and bevel gearboxes drive the table.

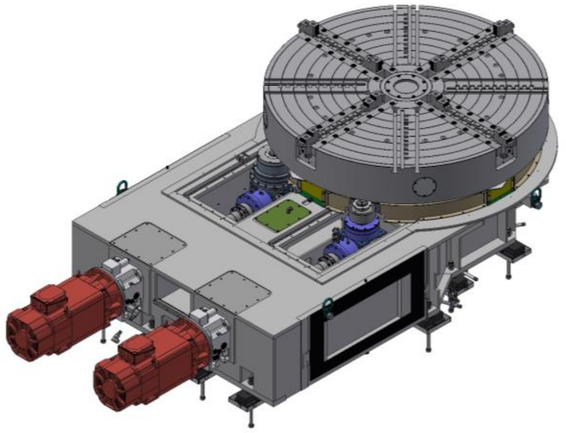

Figure 3. CAD model of the bed

For the purpose of the calculation analysis, we considered the input of three different sources of heat, Which have the major effect on the change in temperature distribution in the bed:

- bearing oil
- planetary gearboxes
- bevel gearboxes

The boundary conditions for the thermal transient analysis were obtained from an experiment with a machine of identical kinematics and dimensions. During the experiment, the machine run without load (without workpiece and machining). Tab. 1 shows the power input of main drives depending on time. Main drives have power input 58 kW. During the test the temperature of the components and the oil was measured by temperature probes.

Time	120 [min]	60 [min]	60 [min]	90 [min]	90 [min]	60 [min]	20 [min]
Drives power	70%	90%	30%	0%	70%	10%	100%

Table 1. Percentage of drive power during the test

However, exact input data is not necessary. The result of the analysis will be an assessment of deformation trends and not absolute values of deformations.
Boundary conditions were entered as the first-type boundary condition (Dirichlet) in the form of temperature per area in relation to time. Ambient temperature was considered as constant 22 °C during the whole period of time.

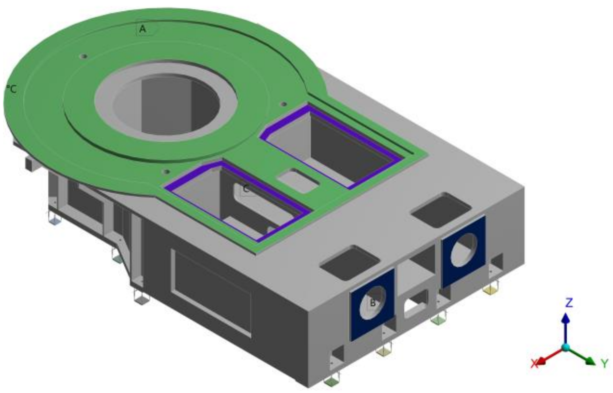

Figure 4. Boundary conditions – bearing oil (green colour), planetary gearboxes (blue colour), bevel gearboxes (violet colour)

The output of the analysis is the temperature field of the machine in relation to time. The result of the thermal simulation then serves as a boundary condition for the structural task.

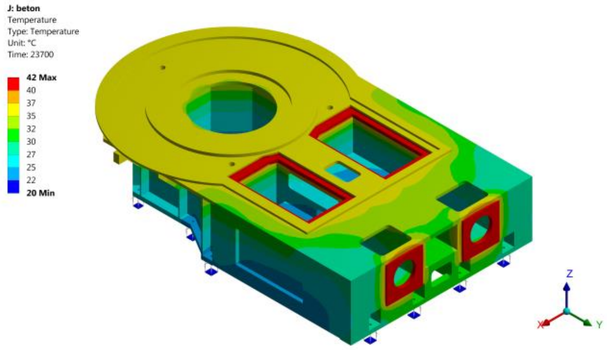

Figure 5. Temperature distribution at time t = 23700 s

Due to high time consumption, the structural task was not solved as transient and the deformations were determined at discrete moments of time that were interlinked to provide a good picture of the trends in deformation behaviour of the machine´s bed. In the calculation model, the bed was placed on flexible supports substituting for the adjustable feet of the machine.

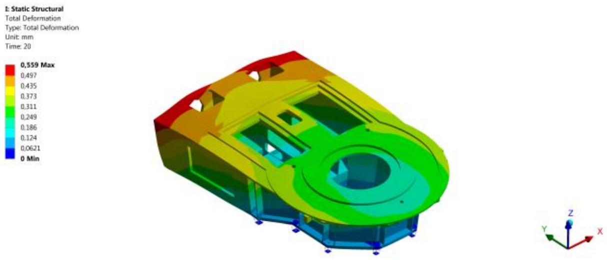

Figure 6. Thermal deformations at time t = 23700 s

Deformations along all axes were monitored and the results obtained in the steel weldment design were compared with those of the composite design.

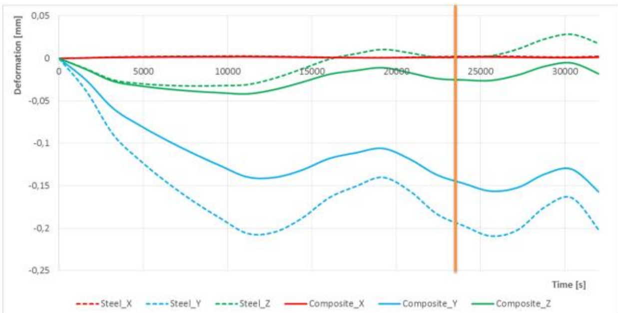

Figure 7. Obtained results – deformation along the axis

The graph shows that in Y and Z axes, deformation is lower in the steel-concrete composite bed. It is also evident that more significant temperature change does not lead to significant change of deformation, therefore, we can see higher temperature stability and resistance to sudden changes of thermal conditions. The curves are flatter. It means that the machine bed has better thermal stability and resistance to thermal shocks. Compared to traditional materials (steel, gray cast iron) specific heat of concrete is higher and thermal conductivity is lower. It leads to better temperature stability of the steel-concrete components.

Deformation along the X axis is negligible as in this direction the structure is symmetric. However, irregular warming up of the transmissions occurs frequently as a result of the incorrectly set clearance in the master-slave system. In such case it is necessary to reduce deformations in this direction as well.

The deformations of the bed were evaluated in the axis of the clamping plate. All vertical turning machines have the general problem, that the axis of the clamping plate moves in the direction of the Y-axis due to thermal errors. The machine has no movable axis in this direction, so this error cannot be compensated. The power input of these machines is very high. It causes high temperature changes from the local sources and large temperature gradients, which leads to large deviations - the order of tenths of a millimeter. For this reason, the thermal stability caused by the concrete filling appears to be an advantageous solution for reducing the impacts of the temperature gradients.

5 CONCLUSION

Development of steel-concrete components for the bigger machines in terms of size and power is a relatively difficult process that requires a lot of experimenting and testing. The authors of this article have been focusing on this issue since 2014. Several machines of various configurations have been implemented and then introduced to the real production process. Practical knowledge, the authors' experience and findings presented in this article indicate that the steel-concrete components can be applied in the construction of larger and more robust machining centers. The great impact of steel-concrete parts on the static and dynamic stiffness have been already discovered by the authors in the past. Therefore, the use of such parts is particularly suitable in the field of hi-tech machines, which are subsequently used in areas where it is necessary to machine difficult-to-machine materials. The typical representative of such areas is the aviation industry.

For this type of machines, however, it is also necessary to pay particular attention to the high production accuracy. As mentioned earlier, thermal expansions have the largest share in the machine error, which leads to an inaccuracy of the production. This article showed that the steel-concrete bed has indubitably better thermal-deformation properties than similar components made of conventional materials. The higher heat capacity causes higher resistance to the temperature changes. The possibility to apply the active concrete tempering system is the advantage of this material variant.

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