Thermo Energetic Design of Machine Tools and Requirements for Smart Fluid Power Systems

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Abstract

Modern production systems have to allow high performance cutting processes in a flexible production system environment at a high level of accuracy. The final workpiece accuracy is mainly influenced by the thermo-elastic behavior of the machine tool and can be improved by additional measures, compensation strategies and an optimized machine design. These measures are often implemented as stand-alone solutions. According to the Industry 4.0 all information should be connected in a single model of the actual machine state to increase machining accuracy. It is therefore necessary to integrate upcoming smart fluid power systems into the machine network.

KEYWORDS: Thermo Energetic Design, Machine Tools, Smart Fluid Power Systems

1. Introduction

In today's markets, the need for machine tools with an increasing productivity and accuracy is apparent /1/. High productivity (high quantity output) results in a high energy consumption of the drive systems, spindle and auxiliary units of the machine tool. Especially heat losses of the main drives are dissipated into the machine structure, which decreases machining accuracy. Therefore, the increase in productivity is limited by thermo-elastic deviations under a certain tolerance limit (**Figure 1**).

Accuracy requirements are continuously increasing /1/. In consequence, the influence of thermo-elastic deviations will most likely increase in the future /2,1/. Current investigations state an amount of thermo-elastic deviations on the overall workpiece error of up to 75 % /3,4/. Thus the thermo-energetic design of machine tools is a key competence for upcoming production systems.

This conflict between power efficiency, accuracy and productivity is the main focus within the CRC/TR 96 financed by the German Research Foundation DFG. Different solutions to enable a high accuracy manufacturing without an additional demand for energy under unstable thermal conditions are investigated. In addition to these measures, smart fluid power systems can contribute to enable both a resource and a cost efficient high accuracy manufacturing technology.
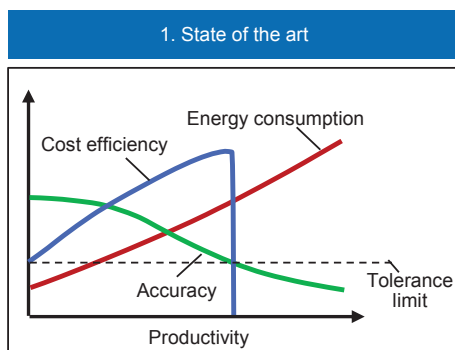

Figure 1: Conflict between power efficiency, accuracy and productivity. In style of /5/

2. Thermo Energetic Design of Machine Tools

The thermal machine characteristics, e.g. the temperature distribution and as a result the deformations of the machine structure (**Figure 2**), are influenced by different design and thermal factors. They can be divided into the categories environmental (external) and machine (internal) influences.
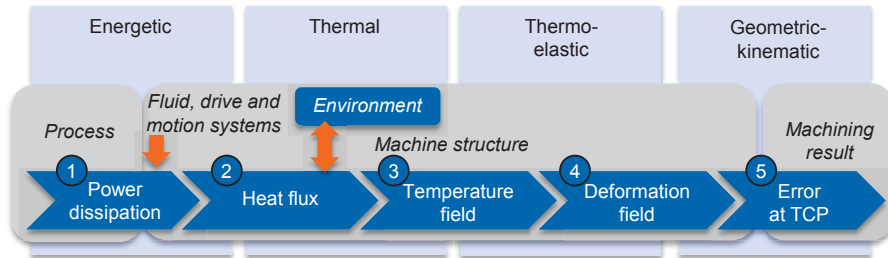

Figure 2: Causes for thermo-elastic deviations. In style of /5/

The ambient temperature of the shop floor is affected by meteorological (e.g. daily fluctuation of the ambient temperature) as well as machine shop specific (e.g. machine waste heat, air conditioning and heating) influences. The main machine internal heat sources and sinks are the drives of the motion systems, especially the main spindle, as well as the process heat and coolant.

These heat sources and sinks (1) lead to a heat transfer in the machine structure (2) which results in an unbalanced and unsteady temperature distribution within the machine structure (3). This distribution is dependent on thermal material properties like heat capacity, heat conductivity and mass distribution as well as on the distance or position to the heat sources and sinks. The temperature field leads to a thermal deformation of the machine structure (4) and finally to deviations and inclinations of the tool center point (TCP) (5). The deformation field is influenced by the effective strain lengths, the expansion coefficients, the components structure (ribbing, thickness), the position of the components to each other and the kind and setup of the position measuring systems.

A reduction of these thermo-elastic deviations of the TCP is done by

- additional measures,
- avoidance of emerge or reduction due to an optimized design,
- control-internal compensation methods or
- a reduced base load.

Additional measures (e.g. cooling, wait for thermal steady state and air conditioning) can reduce the resulting error of the TCP to meet the tolerances under a high productivity and thus a high thermal load of the machine tool (**Figure 3, 2**). These measures results in an increased energy consumption, which affects the cost efficiency negatively. Compensation algorithms can reduce this energy consumption as additional measures can be neglected (**Figure 3, 3**). In this regard, thermo-elastic deviations can be reduced by control-internal compensation models (indirect compensation) or by directly measuring the TCP offset (direct compensation). In case 4 the deviations will not occur due to a change of the machine design and reduction measures without additional energy input (e.g. optimized design, base load reduction, active thermal management).
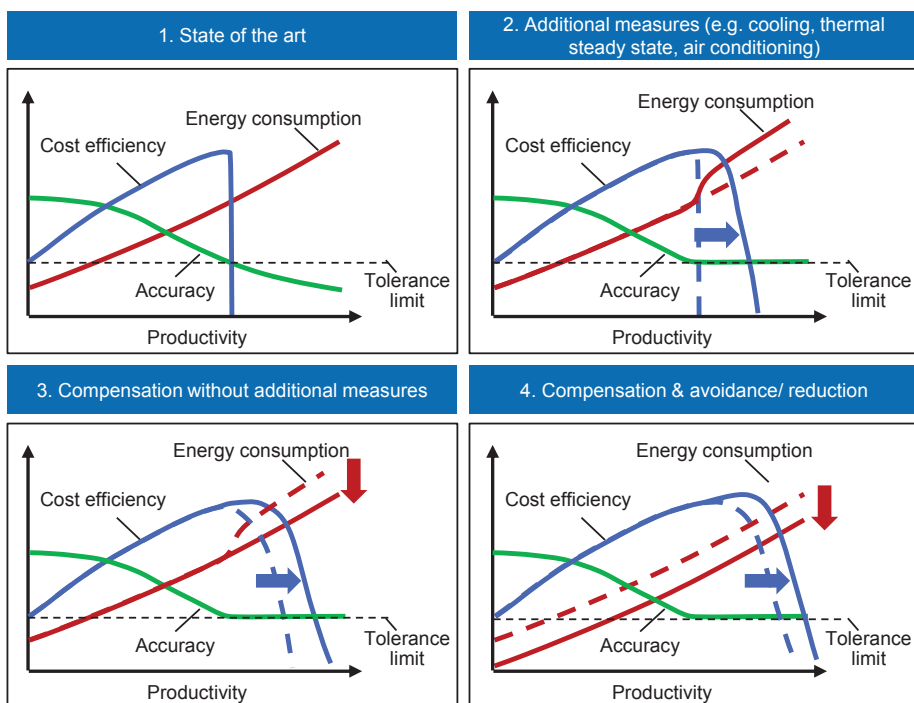

Figure 3: Conflict between power efficiency, accuracy and productivity. In style of /5/

An optimized thermo-elastic design of machine tools requires a deep understanding of the thermo-elastic behavior of the different machine components (**Figure 4**). Therefore, a detailed analysis and simulation of the machine components under typical thermal stresses is part of current research activities (CRC TR/ 96, DFG SPP 1480, EXC 128). An example of a modelling approach to optimize the design of the cooling circuit of a main spindle is given in /6/.
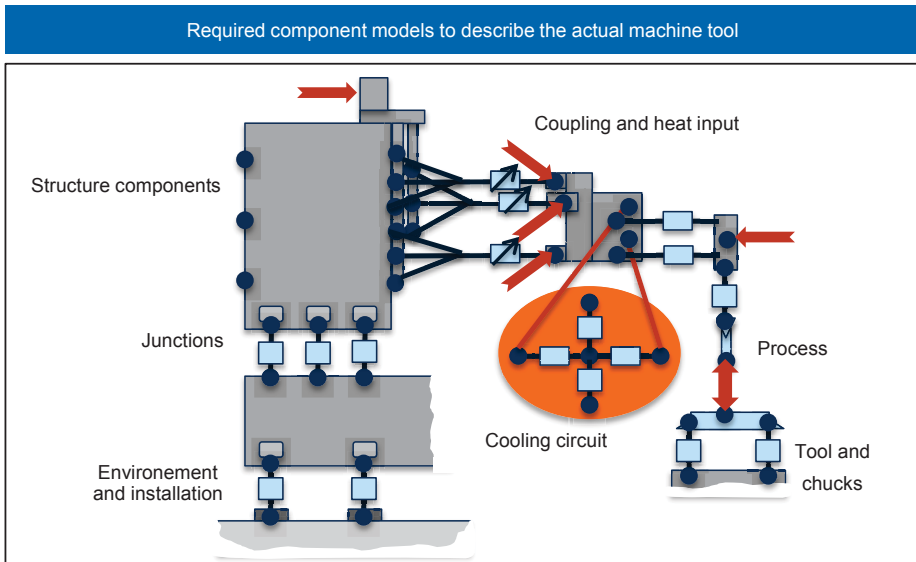
Figure 4: Required components models to describe the actual thermo-elastic behavior of a machine tool

As the machine design is optimized, further improvements of the remaining thermo-elastic deviations can be achieved by compensation. Research activities mainly focus compensation models based on

- control-internal data like power and speed of the drives (Figure 2, 1),
- the temperature field within the machine structure (Figure 2, 3),
- the deformation field (Figure 2, 4) and
- the direct measurement of TCP deviations (Figure 2, 5).

Common industrial thermo-elastic compensation methods are based on temperature measurements. The machine structure components are monitored by approximately 10 - 20 temperature sensors. The ideal position of these sensors can be calculated /7/. The final deviation of the TCP is often calculated by a linear assumption between temperature and resulting cartesian deviation of the TCP. These models are parameterized by deviation measurements under representative thermal loads of the machine structure. The method achieves good compensation results of position-independent deviations typical for a thermal load of the main spindle.

As thermo-elastic deviations often include position dependent deviations (especially due to thermal loads of the linear axes as well as the environment) a volumetric measurement and compensation method is necessary /9,8/. This is subject to current

research topics. A volumetric measuring method based on laser distance measurements is employed to measure the whole machine volume in a short time period /8/. The system consists of an interferometer mounted on two rotational axes able to follow the position of an optical target reflector (**Figure 5, left**). The target reflector is mounted at the TCP, while the interferometer is mounted on the machine table. The TCP with the mounted reflector moves to previously defined positions during measurement, while the interferometer records the relative distance changes between interferometer and reflector position. The position of the interferometer has to be alternated during measurement to at least four different positions. A multilateration technique combined with a rigid body model is used to calculate the deviations of each degree of freedom for each machine tool axis. **Figure 5 (right)** presents a partial result of these calculations. The position dependent yawing motion error of the x-axis of a machine tool over time is shown. An air-cut of the x-axis of 30 m/min over 6 h is applied as a thermal load followed by a cool-down phase of approximately 18 h.
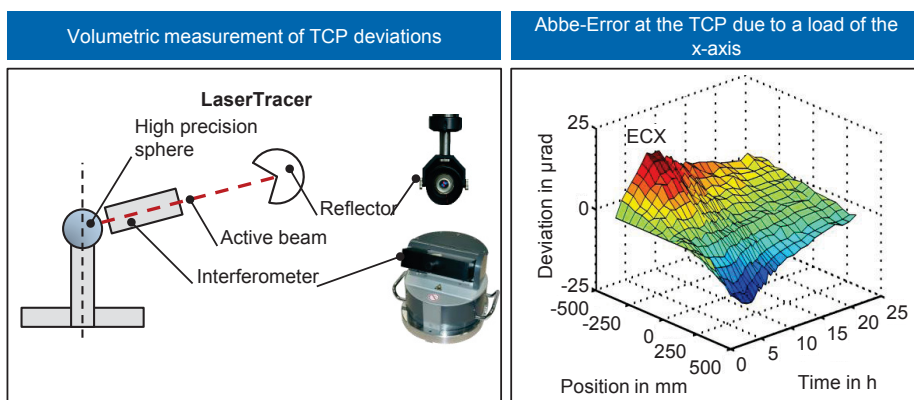

Figure 5: Volumetric TCP deviations of a milling machine due to load of a linear axis. In style of /8/

The measurement results will be used to develop a volumetric compensation approach based on control-internal data /9/ (**Figure 6**): Control-internal data of the different motion systems like power of the axes are already captured by the Numeric Control (NC). These data streams are averaged (1) to calculate model parameters from a predefined characteristic diagram (2). The characteristic diagram is captured beforehand by volumetric thermo-elastic deviation experiments for representative thermal loads. As a result, the deviation of all three degrees of freedom of single axes under different thermal loads is known. Each of these measured errors is approximated by first-order time delay elements to span the characteristic diagram. The interpolated

model parameters (3) are used to calculate the deviation of each degree of freedom of the single axes in time and in space domain (4). Finally, the computed volumetric deviations over time are stored in the NC for further processing (5). These are used by the NC to calculate the current cartesian offset vector of the TCP to apply its inverse value to the feed drive control.

The presented compensation algorithm based on control-internal data can significantly reduce the resulting error of the TCP due to machine internal influences to values under 5 µm /9,8/. Changes of the environmental temperature and variations of the actual process (coolant) would require a combination of additional compensation approaches, using other sensors.
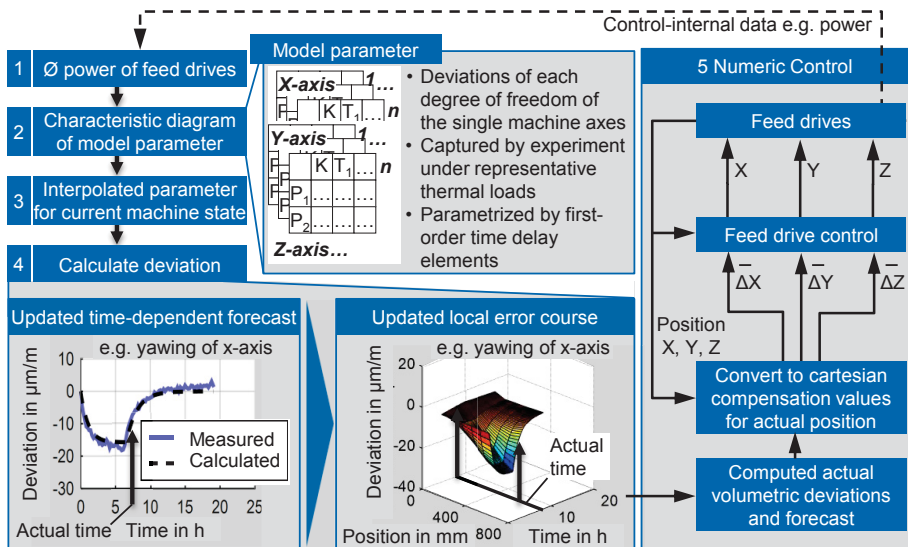

Figure 6: Control-internal volumetric compensation

An additional compensation approach is illustrated in **Figure 7**. Here, the local thermo-elastic relative deformations of relevant structure components are measured by linear strain sensors. The sensors are based on integrated carbon fiber rods in the machine structure, which act as a dimensional reference. With a displacement sensor, the relative mean strain of the respective structure can be measured with high accuracy. When the system is integrated into a machine tool, multiple sensors (usually three) are integrated in a structural component. By this approach, elongation and bending can be distinguished and quantified.

A test machine has been equipped with a system of 24 sensors (three located in the headstock). The headstock is an important component in the kinematic chain and prone to thermal deformation since it is directly exposed to the main spindle and the linear motors. Validation experiments, in which the headstock has been heated by motion of the Z-axis, result in a bending of the component and therefore a deviation of the TCP in Y-direction of up to 80 μm.

With the direct measurement of the deformation and a geometric-kinematic transmission model, the resulting deviation of the TCP can be calculated with good accordance. The experiments show a potential reduction of the resulting deviation of 86 %. The inverse of the calculated deviation is added to the nominal position value in order to correct the deviation via a feed motion of the machine axes /10/.
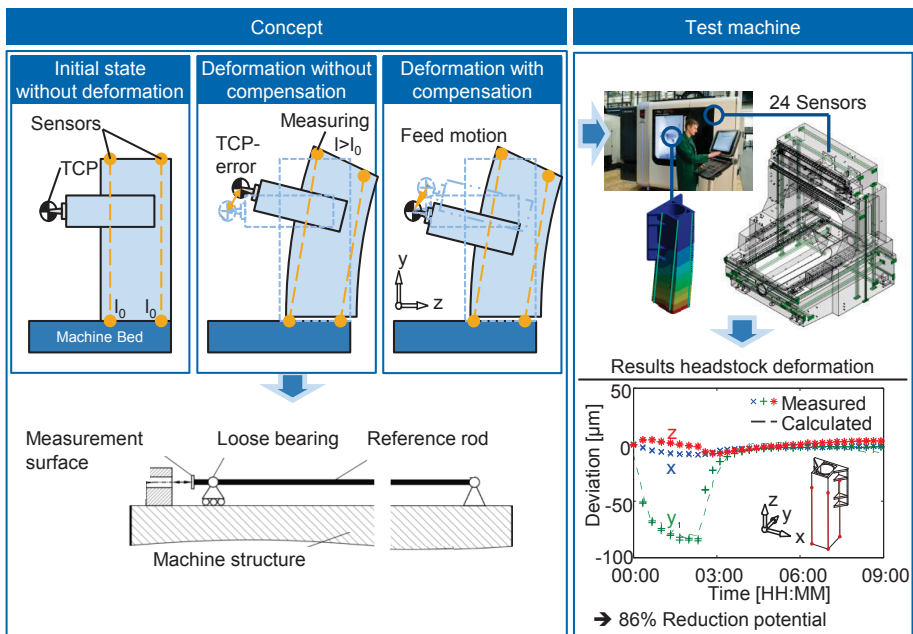

Figure 7: Indirect correction of thermo-elastic deviations by measuring the structural deformations of the machine components. In style of /10/

A direct measurement of the TCP deviation can be used to compensate thermo-elastic deviations. Here, as a rule, the TCP deviation is measured as the cartesian offset vector at one or several specific machine positions. A measurement of the full volumetric geometric state of the machine tool is an exceptional case as the cost and time effort is too great.

Each of the presented possibilities to improve the thermo-elastic machine tool behavior enhances the system understanding of single machine components to build up an understanding of the complete machine. Today, these methods are often used as stand-alone solutions. In the context of Industry 4.0 all available information, e.g. sensor data, control-internal data of the drive and motion systems as well as the auxiliary units and the machining code should be combined in a single model and lead to a profound system understanding. Any information can improve the predictive accuracy of the current thermo-elastic machine state for compensation, base-load reduction and an active thermo-management. In this context, the actual state of the auxiliary systems e.g. spindle cooling and fluid power systems have to be known and controllable by an integrated machine network to enable an active thermo-management.

3. Requirements for Smart Fluid Power Systems

As shown in Figure 3, No. 4, the cost efficiency can be further increased by reducing the energy consumption. Having a closer look at the energy consumption of machine tools during operation, **Figure 8** shows for an exemplary machine tool (Heller H2000) and a test workpiece, that fluid systems (auxiliary components) are the main consumers. The fluid systems "Cutting fluid supply", "Cooling System" and "Hydraulic" have a share of 66 % of the energy consumption for the exemplary break down of the test workpiece machined on the machine tool. /11/
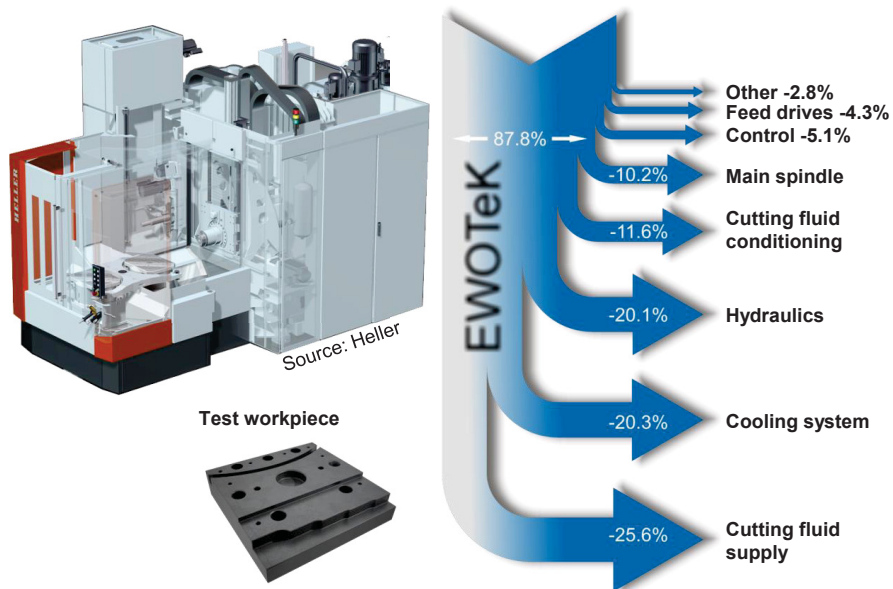

Figure 8: Exemplary break down of the energy consumption of a machine tool /11/

3.1. Approaches to improve the energy efficiency

The following section describes technical approaches to improve the energy efficiency of the fluid systems (auxiliary components). In addition to the state of the art the optimization with the achieved energy savings is shown. The approaches mainly aim a demand-based operation of the fluid systems.

3.1.1. Coolant fluid systems

For cooling and lubrication of the tools from inside, a high pressure pump is used. The high pressure coolant pump represents the highest active power consumer of the coolant system. The coolant is fed to the machining point through channels in the tool. Depending on the tool size, various pressure levels and flow rates for optimal machining are required. Thus, the high pressure coolant pump has a large variety of operating points. But today most of the high pressure coolant pump units are designed to the maximum required coolant volume flow. If a lower coolant volume flow is needed, the excess flows unused over the pressure reducing valve back to the tank (see **Figure 9, top left**). The energy consumption of the coolant fluid system is independent of the operating condition of the machine tool and the pumps are oversized for most applications. Thus, the efficiency under partial conditions is low and head is added unnecessarily to the coolant. /12/
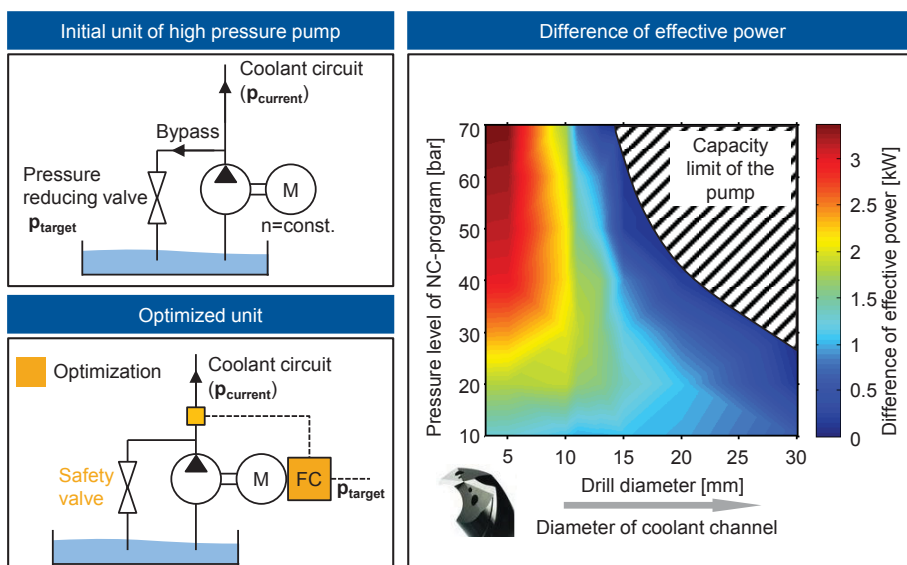

Figure 9: high pressure coolant pump units and difference of effective power /11/

The optimized high pressure coolant pump unit is equipped with a frequency converter and a pressure sensor. The exact flow rate and pressure level for each tool size is provided by the unit (see **Figure 9, bottom left**). The maximum possible power saving is 3.5 kW or 55 % at a pressure level of 70 bar and a tool size of 4 mm diameter (see Figure 9, right). The flow rate is reduced by 22 l/min. This corresponds to a hydraulic power loss in the bypass of 2.6 kW.

3.1.2. Cooling system

Cooling units in machine tools can be operated with water or oil. They serve to cool e.g. the spindle, drives, ball screws, the hydraulic unit, the coolant, the machine bed or the control cabinet. Cooling units are necessary to prevent certain components from overheating and to assure a certain accuracy of the machine tool. For the exemplary machine tool in the initial state, a hot gas bypass cooling unit is used. In general different approaches to energy efficient cooling systems exist.

- Clocked compressor
- Frequency-controlled compressor
- Digital-Scroll compressor

The **clocked compressor** is switched off when it is not used. It is a simple and effective solution to save energy, yet it can only be used for longer on/off intervals otherwise the durability is affected negatively /13/. For that reason the **hot gas bypass** method is the state of the art unit for high-precision machining. The cooling power of a hot gas bypass system can be controlled within the range of 10 – 100 % /14,13/ but as energy is burned off in the bypass, the active power consumption is fairly constant and mostly independent from the actual machine condition. The energy efficiency in the part-load case is low. A **digital-scroll compressor** does not reflect state of the art technology of cooling units of machine tools. First results on the power consumption of a prototypic cooling unit with digital-scroll compressor together with a description of the functionality can be found in /15/. The cooling power of a digital-scroll compressor can be varied between 10 – 100 % with constant speed. Due to the digital control of the compressor power, the active power of the cooling unit can be adapted to the demand.

For the exemplary machine tool the power consumption of the cooling unit with a hot gas bypass ranges from 2.4 kW to 3.3 kW for the three different operating conditions (see Figure 10) /16/. For the exemplary break down of the test workpiece machined on a machine tool (see Figure 8) the cooling system have a share of 20 % of the energy consumption /11/. To optimize the cooling unit, the hot gas bypass was removed and a

digital scroll compressor is used. In addition, the pump and fan motor was equipped with a frequency converter (see **Figure 10**). The power consumption of the cooling unit with digital scroll compressor now ranges from 0,89 kW to 2,7 kW for the three different machine conditions (see Figure 10). Due to the demand-based compressor power, the active power at operating condition "main switch on" (no production) can be reduced over 62 %. /16/
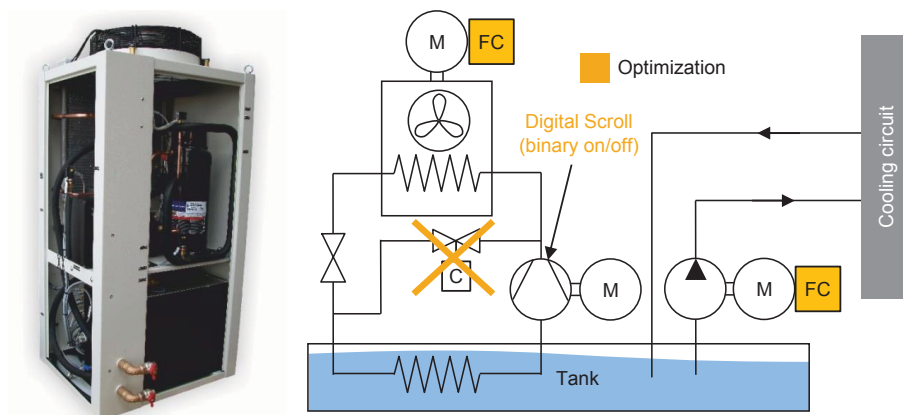
Operating condition	Ø active power **hot gas bypass**	Ø active power **digital scroll compressor**	Savings
Main switch on	2.36 kW	0.89 kW	62%
Machine ready to produce	2.74 kW	1.69 kW	38%
Production (spindle operation at the S1-boundary at room temperature)	3.33 kW	2.70 kW	19%

Figure 10: machine cooling Circuit

3.1.3. Hydraulic unit

Hydraulic units of machine tools are one of the main consumers of energy. Hydraulic functionalities of machine tools are for example the tool change, the work piece clamping, the palette change, the weight compensation of vertical axes or the supply of hydrostatic guidings. For the test workpiece machined on the machine tool Heller H2000 (see Figure 8) the hydraulic system has a share of 20 % of the energy consumption /11/. This machine tool has two hydraulic cycles with different hydraulic functions; a high pressure cycle (200 bar) and a low pressure cycle (60 bar). The state-of-the-art hydraulic unit therefore has a low and a high pressure pump on the same shaft and a constant drive. /17/ analyzes the energy efficiency of the state-of-the-art

and two optimized hydraulic units (see **Figure 11**). The description of the functionality of each hydraulic unit and a detailed analysis of the energy consumption for different machining conditions can also be found in /17/. Since there is no hydraulic function during most of the processing time, the behavior of the hydraulic units during base load condition is discussed in the following. For the hydraulic unit of optimization "one" (see Figure 11) the high pressure pump is replaced with a booster. Thus, the power consumption of the hydraulic unit can be reduced by 61 % (from 2,3 kW to 0,9 kW) during base load condition. Furthermore the oil warming could be reduced so that a cooling of the hydraulic unit is no longer needed.
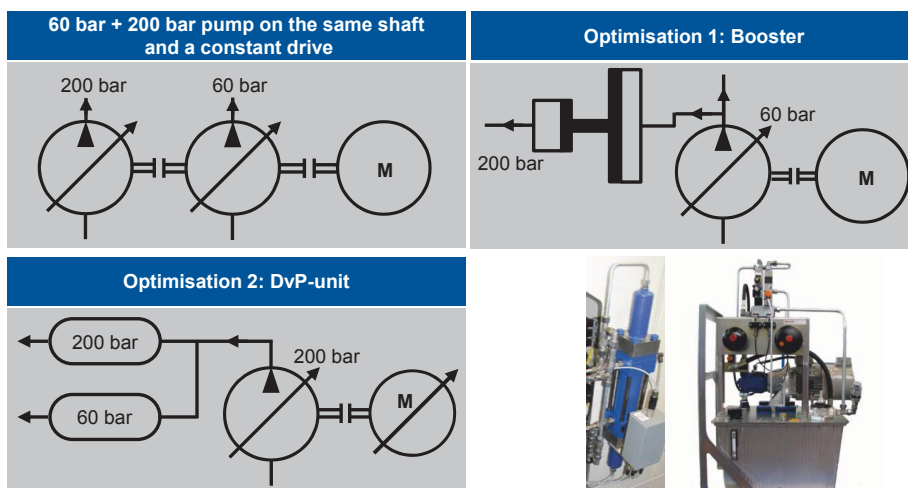
Figure 11: Scheme of the different hydraulic units /17/

The hydraulic unit of optimization "two" (see Figure 11) only has one variable-displacement axial piston pump. The motor is equipped with a pressure controlled frequency converter. The high-pressure pump loads two accumulators one low-pressure accumulator with 60 bar and one high-pressure accumulator with 200 bar. During times where no hydraulic function is fulfilled, the hydraulic drive is reduced to 4 Hz. Thus, the power consumption of the hydraulic unit can be reduced to 0,2 kW which represents a saving to the state-of-the-art unit of 91 %. Further advantages are the noise reduction of the DvP-unit through a very low turning speed and the reduction of thermal losses. /17/

3.2. First Steps to Smart Fluid Power Systems

The results of the described studies show that the base load of the fluid systems can be significantly reduced through demand based supply. Therefore the energy efficiency

can be increased and the heat energy introduced unnecessarily into the machine tool can be reduced. With the DvP-unit (see Figure 11) the hydraulic oil temperature could be reduced from 45°C to near ambient temperature. By the optimizing measures the cooling of the hydraulic oil can be completely avoided. For further optimizations new approaches are needed. A possible one is the use of smart fluid power systems. Following an approach is described which is being investigated in the research project "MinEnerWe – The mineral oil-free, energy-efficient machine tool". A first step towards a "smart fluid power system" has been made by using a combined hydraulic and cooling unit (see **Figure 12**). The combining of the hydraulic and cooling unit is possible due to the optimized DvP-unit described above.
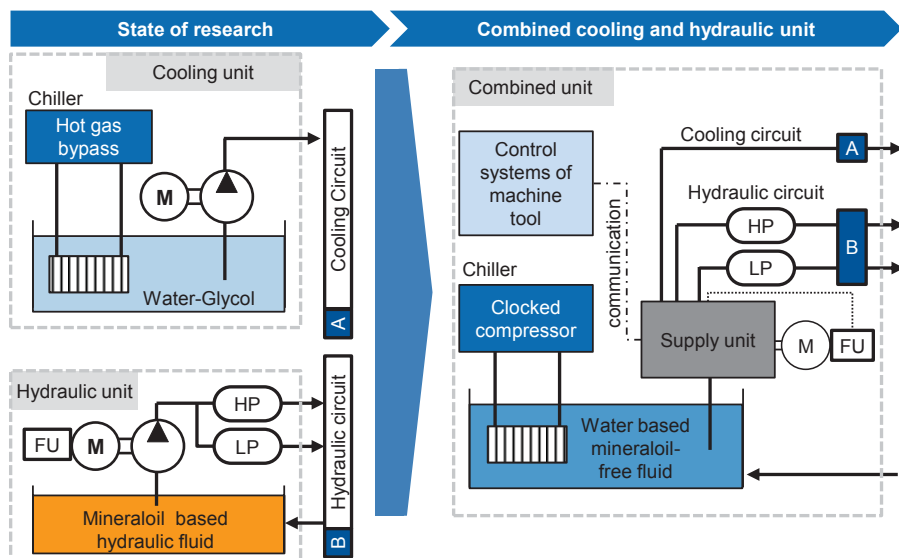

Figure 12: Combined Cooling and hydraulic unit

By combining the cooling and the hydraulic unit, both circuits can be powered from one power supply unit. By merging subfunctions of both units, synergy effects can be utilized. In addition, only one tank is needed and the required space can be reduced. The pressure accumulators in the high- (HP) and low-pressure circuits (LP) allow a shutdown of the hydraulic pump during times where there is no hydraulic function required. Due to the combination of the units the tank volume of the cooling unit is increased. As a result a clocked compressor can be used by holding the accuracy requirements, which previously could not be used (see. chapter 3.1.2). This compressor is both more energy-efficient and more cost-effective, than hot gas bypass units. In order to increase resource efficiency a water-based, mineral oil-free fluid is used that fulfills both the requirement of the hydraulic and the cooling circuit. The age-

related change of the new mineral oil-free fluid /18/ as well as the impact of the new fluid to the sealing materials /19/ are tested according to known procedures.

The common supply unit will be linked to the numeric control (NC) of the machine tool and will predictively analyze the current NC code. Thus, the hydraulic pump can be switched on shortly before a hydraulic function is needed. The cooling unit may in advance increase the flow rate to the spindle for high spindle loads (e. g. roughing).

4. Smart Fluid Power Systems in the context of Industry 4.0

With the measures described above, a first step towards Industry 4.0 in the field of the hydraulic and cooling fluid systems has been done. The future fluid systems will be intelligent and deeper linked with the machine tool (see **Figure 13**). The machine tool could be able to identify the workpiece automatically and load the appropriate NC code with associated thermo-elastic compensation models. The operating state of the machine tool including auxiliary units could be monitored by means of different sensors. Thus, the state of the hydraulic oil and the number of switching cycles of the valves could be analyzed. The coolant unit will show the upcoming maintenance work, for example when the fluid needs to be refilled or replaced. By integrating the sensor data and operating conditions into the machine tool control, the temperature distribution of the machine components, the power losses, the volume flows and active power input are known. These data allow the use of an intelligent thermal management and compensation system to reduce the thermo-elastic deviations of the TCP, which enables a high accuracy and energy efficiency by low demands on the ambient conditions.
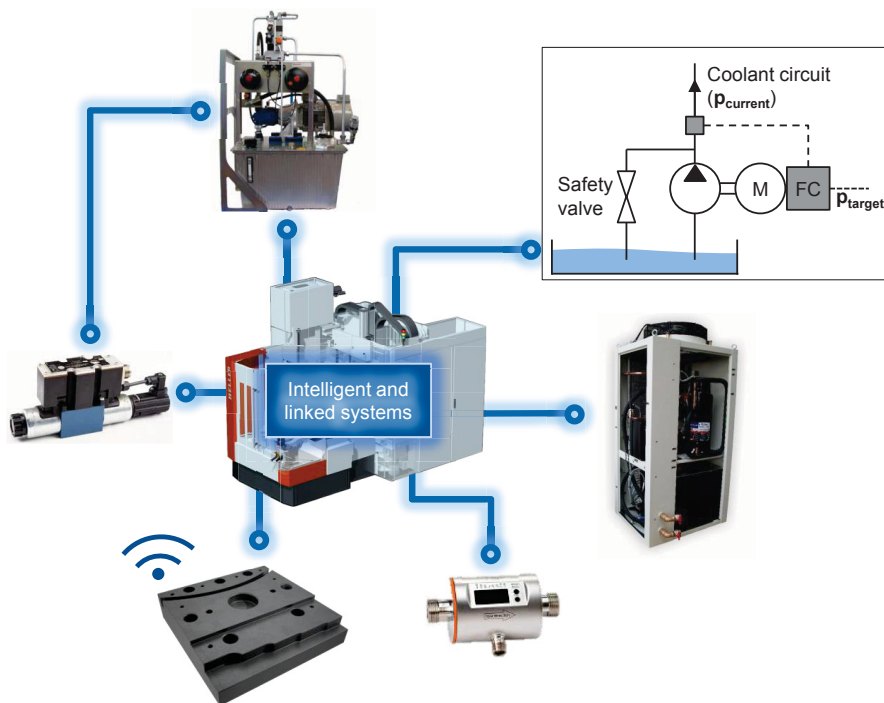
Figure 13: linked systems for an intelligent thermal management

5. Acknowledgments

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