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Energy, power and heat flow of the cooling and fluid systems in a cutting machine tool

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Abstract

Cooling is one of the main tasks of fluid systems in cutting machine tools. Cooling systems are essential for controlling the thermo-elastic properties of the whole machine structure. The paper describes an experimental investigation of a modern machining center's cooling system. Additionally, a network-based simulation strategy is presented, which has been utilized for the theoretical analysis regarding the energetic properties and thermal impact as well as the evaluation of improved design concepts. These for instance focus on the optimum placement of pipes and individually controllable supply units.

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Keywords: Machine tool; Cooling system; Compensation; Experimental investigation; Network-based modelling; Energy; Temperature

1. Introduction

Machining is a key aspect in the production of various components and assemblies for mechanical engineering, plant and car manufacturing [1]. Besides productivity, the demands regarding the components' accuracy as well as energy efficiency are increasing. To reduce inaccuracies, previous approaches for example suggest installing air-conditioning for the entire production areas or continuous operation to ensure steady state thermal behavior. However, these measures consistently increase energy consumption. In order to resolve this conflict of objectives between energy use, accuracy and productivity the Collaborative Research Center SFB/TR 96 develops methods for minimizing the thermo-elastic deformations by compensation and correction methods. The deformations are reduced by measures affecting the machine design, e. g. controlling the temperature distribution in the structural components by means of cooling fluids.

Although the usage of hydraulic systems in machine tools for motion control and tool clamping decreased in recent years [2], fluid systems in general are of increasing importance, particularly in view of the facts outlined above. The various fluid systems facilitate preheating or cooling of single components and entire assemblies. Due to the increasing complexity and performance of fluid systems, higher amounts of auxiliary power are required. This has to be critically examined from an economic and environmental viewpoint. For this purpose, the research activities at the Institute of Fluid Power are aimed at the development of principles and simulation models with a holistic approach (see [3,4]).

Nomenclature

c_p	Specific heat capacity (J kg^{-1} K^{-1})
F_c	Cutting force (kN)
$E_{el\,/\,hy\,/\,th}$	Electrical / hydraulic / thermal energy (kJ)
i_μ	phase current (A)
n	number of phases (-)
$P_{el\,/\,hy\,/\,Z}$	Electrical / hydraulic / mechanical power (kW)
p	Pressure (bar)
$Q_{T\,/\,L}$	Thermal energy / heat loss (kJ)
$\dot{Q}_{th}$ / P_{th}	Heat flow, heat in- / output (kW)
T	Temperature (K, °C)
t	Time (s)
$u_{\mu 0}$	Virtual star voltage (V)

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v_c	Cutting speed (m s^{-1})
V	Volume (m^3)
$\dot{V}$	Flow rate (L min^{-1})
W_z	Mechanical work, chipping work (kN m)
ΔT	Temperature difference (K)
ΔE	Energy difference (kJ)
ε	Energy efficiency (-)
η	Efficiency (-)
ρ	Density (kg m^{-3})

2. The investigated machine tool

2.1. General characteristics and fluid systems

The analyzed demonstrator machine is a 5-axis machining center and is used in research for performance tests of tools and the examination of process stability. Machines of this type are mainly used for heavy-duty cutting, turning, drilling and milling operations.

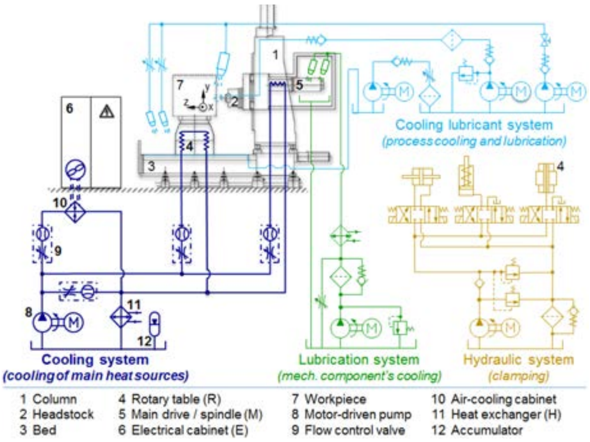

Fig. 1. Demonstrator machine with its main fluid systems, adapted from [5].

In fig. 1 the simplified structures of the investigated main fluid systems are displayed. Overall, four systems were analyzed in detail according to their specific function. The cooling system consists of a cooling unit with a fixed displacement pump (8) and a heat exchanger (11) that cools the heated fluid to a set temperature. The cooling fluid is a mixture of water and up to 20 % Antifrogen® N. This fluid is resistant to freezing and protects contacting metal surfaces from corrosion and scale. The components with major cooling needs are rotary table (4), main drive (5) and electrical cabinet (6). The cooling of the electrical cabinet is realized by an air-to-water heat exchanger (10). Rotary table (4) and main drive (7) are directly cooled by the water / Antifrogen® N mixture, which flows through implemented cooling channels. For detailed information on the other fluid systems refer to [5,6].

2.2. Investigation of power, energy and heat flow

For a systematic analysis of the fluid system's energy demand and thermal behavior, a definition of appropriate system boundaries is essential. Fig. 2 shows an energetic analysis of the demonstrator machine considering the occurring energy conversions. In the generator section, shown on the left, the pump motor units convert electrical into hydraulic energy. Furthermore, the drive motors directly convert electrical into mechanical energy, which is delivered to the main drive (M) and motion axes. Additional consumers such as illumination, CNC control or pneumatic subsystems are summarized within the auxiliary equipment.

In fluid systems the hydraulic energy is distributed through tubes and valves. Here, a small amount of energy is dissipated into heat due to viscous friction. According to their function, fluid systems can be classified in four subsystems, shown in the center of fig. 2. Within the hydraulic system the cylinders are responsible for the conversion of hydraulic energy into mechanical work used for tool clamping, the rotary table and the holding brake. The cooling lubricant system realizes the internal and external coolant supply to the machining zone. Thus, friction between tool and workpiece is reduced during machining and less heat is generated. Additionally, the heat is directly carried away by the coolant or indirectly by removal of the chips from the machining zone. Since the machining process is not directly observed, also a fraction of thermal (cooling) energy is exported across the system boundaries. To reduce friction and thus heat losses between moving mechanical parts, the lubrication system is indispensable. As stated in section 2.1., main drive, rotary table and electrical cabinet are cooled within the cooling system. In the cooling and lubrication system additional electrical energy is used to cool down the fluid by heat exchangers. This implies that electrical energy is converted into thermal energy. Summing up, the total electrical energy E_{el} supplied to the machine is converted into cutting work W_Z, thermal energy Q_T and heat losses Q_L.

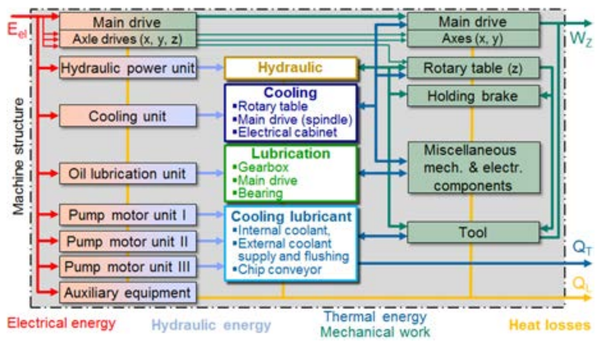

Fig. 2. Energetic system boundaries of the demonstrator machine [6].

Neither electrical and mechanical nor hydraulic performance can be measured directly, because power is calculated from the mathematical product of potential and flow variables. Especially for multi-conductor circuits, DIN 40110-2 [7] can be used to determine the electrical power P_{el} according to eq. 1. The active power P_Σ at time t results from the product of phase current i_μ and virtual star voltage $u_{\mu 0}$ cumulated over all phases n. The electrical power P_{el} is equivalent to the arithmetic average of the active power P_Σ. The hydraulic power P_{hy} is derived from the measured pressure p and volume flow $\dot{V}$ with eq. 2. By analogy, the mechanical power P_Z can be calculated by the product of the cutting force F_c and the cutting speed v_c