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4.1 Improving energy efficiency of machine tools

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Abstract

Manufacturing is responsible for about one half of global consumption of primary energy, a great deal of which is consumed by machine tools producing discrete parts. The topic of energy efficiency is driven forward by machine tool users who demand low operational costs, as well as social and legislative forces requiring environmentally friendlier manufacturing. This paper aims to provide examples and good practices for improving machine tool energy efficiency with a focus on metal cutting machine tools. During the design stage, there are various opportunities to minimize inherent energy losses by selecting and dimensioning drives and peripherals. On the other hand, users have a large impact on productivity by using the machine effectively and knowledgeably. The paper also presents techniques for measurement and analysis of the energy profile of machines which help to better target energy saving measures on already existing machines.

Keywords:

Design Modification, Electrical Power, Energy Efficiency, Machine Tool

1 INTRODUCTION

Manufacturing efficiency is an important factor for life cycle balance of production machines and their products. Former studies have shown, that the most important negative environmental impact of machine tools is the energy consumption during the use phase [1]. The energy costs also contribute to double-digit percentage of total life cycle costs, [2].

Energy efficiency of machine tools is a topical issue with motivation coming from several sides: machine manufacturers and users aiming at lowering processing costs, legislation requiring reduced environmental impact, as well as social aspects considered by customers and shareholders, [3] and [4]. Also CECIMO, the European Machine Tool Builder's Association, prepares a self-regulatory initiative for supporting the energy and resource efficiency of the machine tools produced in the EU [2]. The ISO 14955 standard 'Environmental evaluation of machine tools' [5] aims at improving energy efficiency by application of unified methods for energy consumption measurement, evaluation and reduction.

This paper summarizes experience gained through practical measurements and application of energy saving measures on metal cutting machine tools. Section 2 brings an overview of recommended methods for determining the energy profile of a machine. In Section 3 well tried general design principles for improving energy efficiency are mentioned. Section 4 introduce three case studies on three machine tools.

2 ENERGY PROFILE MEASUREMENT

The first task when measuring energy consumption of a machine tool is the decision on the system boundary. This topic is addressed in detail in ISO 14955-1 [5] even for rarer cases e.g. machines with waste heat exchangers. In most cases the machine is connected to the mains and to the central compressed air system which are enough to monitor.

The second task is choosing a relevant operating scenario typical for the machine. It should include productive time (typical workpieces, batches) as well as nonproductive time (stand-by, spindle idle run, warm up). If there is no 'typical' process specified, Research Center for Manufacturing Technology (RCMT) uses a workpiece from the TS B 0024-1:2010 standard [6] (Figure 1) suitable for milling machines with 3 and more axes. Scaling its size and cutting conditions is necessary to match machine tools of various sizes and spindle power.

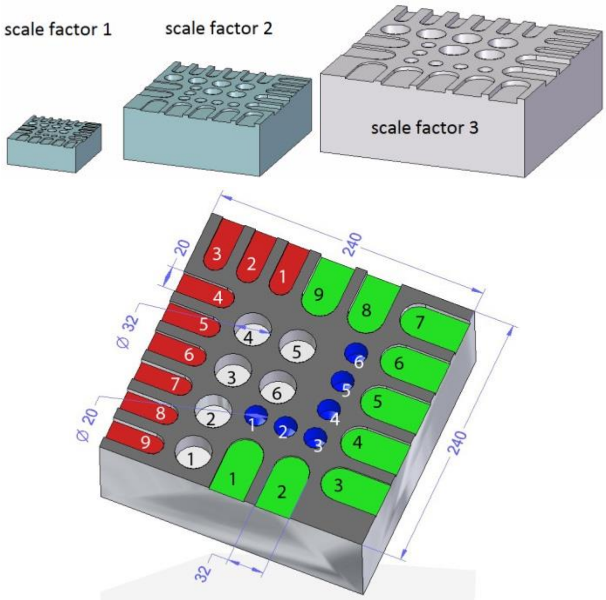

Figure 1: Test pieces including face milling, slotting and drilling with progressive cutting parameters, inspired by standard [6]; a) scale factors 1 (edge 120 mm), 2, 3; b) geometric details for scale factor 2.

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2.1 Equipment for power measurement

The third task is choosing the equipment for basic energy consumption measurement. Figure 2 schematically shows standard electric circuits layout of a machine tool.

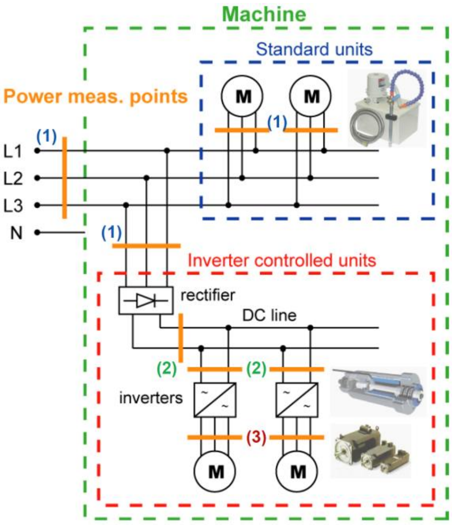


Figure 2: Schematic machine tool electric circuits with 3 types of electrical power measuring points: (1) 3-phase 50Hz AC, (2) DC line, (3) 3-phase AC with PWM voltage.

There are three types of energy flows which need to be monitored for obtaining the energy profile of a machine:

- 3-phase 50 Hz AC power measured at more locations by a multichannel equipment (type (1) in Figure 2);
- Power consumption of NC drives; RCMT uses current transducers based on the Hall - effect for monitoring currents from the DC line into inverters (type (2) in Figure 2); control system information is also an alternative.

Figure 3: Mounted Hall-effect current sensors for measurement on the DC link to drive inverters.

- Compressed air consumption measured by flow, temperature and pressure sensors; conversion rate for common 6 bar systems is approximatelly 18 W ~ 1l/min considering ideal compressor, 30 W ~ 1 l/min realistically.

In some cases it is advantageous to go for a more detailed analysis and also measure:

- thermal power (measured by thermometers and flow meters) for estimation of cooling power and efficiency of coolers / chillers or heat exchangers;

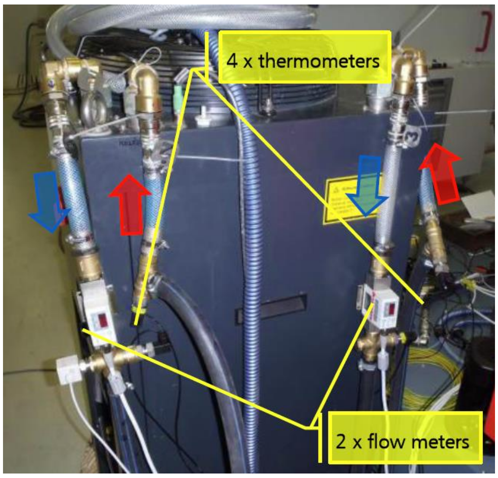


Figure 4: Cooling power and chiller's efficiency measurement setup on a two-circuit chiller.

- fluid power (measured by sensors of pressure and flow) for estimation of effectiveness of hydraulic circuits / components and efficiency of relevant pumps (e.g. cooling lubricant, Figure 7);

2.2 Basic energy consumption breakdown

Normally three basic energy flows into the machine tool and its components need to be monitored:

- spindle / axis NC drives;
- peripherals (electric);
- compressed air (converted to electrical power);

ISO 14955 suggests a functional approach, which is advantageous for comparing different ways for obtaining the same function within a machine tool. For example the function 'conditioning of the cutting process' can be performed by liquid coolants, compressed air, nitrogen cooling or minimum quantity lubr. (MQL). Their parameters including energy consumption will differ significantly.

There are various means of displaying the measurement results. These include pure time series, Sankey diagrams with component breakdown, pie graphs, or other graphs showing dependencies among parameters. Figure 5 shows the measured relation of machine total power consumption and the metal removal rate. Results show a pattern similar to the 'efficiency envelope' published in [7] and [8].

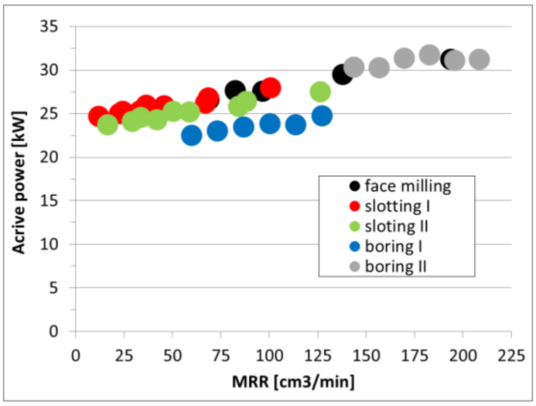


Figure 5: Power consumption in relation to machining intensity (machine TM1250, Case study 2).

2.3 Estimation based on a model

Using a computational model for estimation of energy consumption can be suitable during the design phase when no real machine is available for measurement.

RCMT has developed a model of machine tool energy consumption which consists of a list of energy consumers (main drives, peripherals), main machine parameters (moving masses, max. acceleration / velocity) and control information (mainly the PLC setup). The model can process a standard NC program in the ISO code (including M-function) and provide time-dependent series of parameters such as machine tool kinematics and power consumption of main drives and peripherals. The model uses the state-based approach from [2] and [9].

Simplified version of the model, the state / function breakdown of machine tool energy consumption, can help to estimate energy consumption during various operational scenarios. The functions are defined according to ISO 14955-1 [5]. Such model is based on the operational scenario and time shares of the machine states, example in Fig. 6. It cannot process the NC code, unlike the above mentioned full approach.

Both approaches need to be based either on measurement, analysis or on a qualified guess of power demands of respective components during different scenarios.

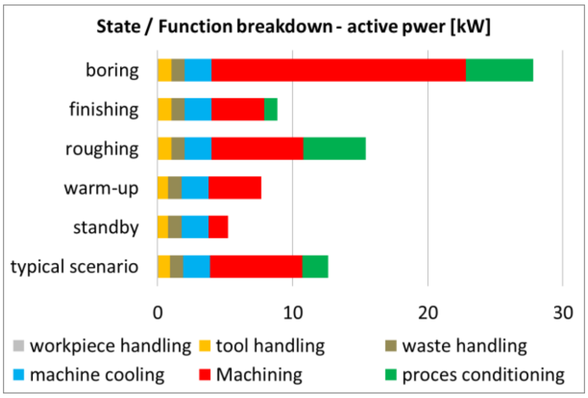


Figure 6: Example of ‘state / function’ profile of WHN13 CNC milling / boring machine (Case study 3).

3 ENERGY SAVING MEASURES

This chapter provides a list of well-tried principles for improving machine tool energy efficiency. These are based on RCMT’s own experiments which were inspired by ISO 14955-1 [3] Annex A, CECIMO LIP [10], or Fraunhofer IZM study [11] in the initial stage. The measures are divided into two main groups with respect to the phase of application: the design and the use phase. This general part of the paper is followed by selected practical examples.

3.1 Machine tool manufacturer - ecodesign

Saving measures are divided into groups according to their type:

Main drives

- The main drives (together with the machine tool frame) should mainly ensure effective manufacturing. Due to usually large share of constant ‘gray’ power in the total machine consumption: time = money; time = energy.
- The energy regenerative feedback from inverters and the rectifier (ER module) is usually not significant, unless the typical machine use scenario includes frequent tool change (spindle start / stop).
- The consumption of the linear axes is usually not significant.
- The energy efficiency of a milling spindle / turning spindle and its drive is of a greater importance and care needs to be taken to use an efficient (preferably synchronous) motor, transmission and bearings.

Peripherals

- It is crucial to know, what do we need from peripherals during various types of machining processes and ambient conditions (e.g. cooling lubricant quantity, cooling power of chillers). Oversizing of peripherals usually causes losses during the run with lower intensity.
- There are usually more design possibilities for providing a specific peripheral function; we need to be aware of the best available technology for a given purpose (e.g. the use of fluid-air fan cooling units with frequency control is sufficient for many machine tool applications, cheap and much more energy efficient compared to standard chillers) and seek for the best ratio of added value and energy demands.
- If the demands on peripherals depend on cutting process intensity, peripherals control targeting constant energy efficiency (e.g. frequency controlled pumps, example in Fig. 7, and compressors) is advantageous.

Fluid circuits

- These are: compressed air, cooling lubricant and hydraulic oil. The energy transformation from mechanic to fluid and back to mechanic always costs losses.
- Sometimes it is possible to avoid compressed air (e.g. replacing spindle air purge with advanced seals) or hydraulic systems (e.g. replacing hydraulic cylinders by electro-mechanical components) altogether. Such change usually saves a lot of energy normally lost in leakages and during energy transformation to the target functions.
- Being aware of the before mentioned conversion rate between compressed air flow and its electrical power equivalent.

Machine control

- Adaptive feedrate (automatic adjustments of the feedrate according to the tool, workpiece material, spindle speed, axial and radial depth of cut) helps to reduce machining time and ‘gray’ energy.
- Hibernation during nonproductive time with no user input (available in control systems from most manufacturers, needs PLC setup) after a specified time period. Automatic switching the compressed air supply off after the machine is stopped and the spindle cools down.
- Advanced compensation of thermal errors reducing warm-up time before precision machining.
- PLC setup enabling variable adjustment of machine peripherals according to variable minimal process needs.

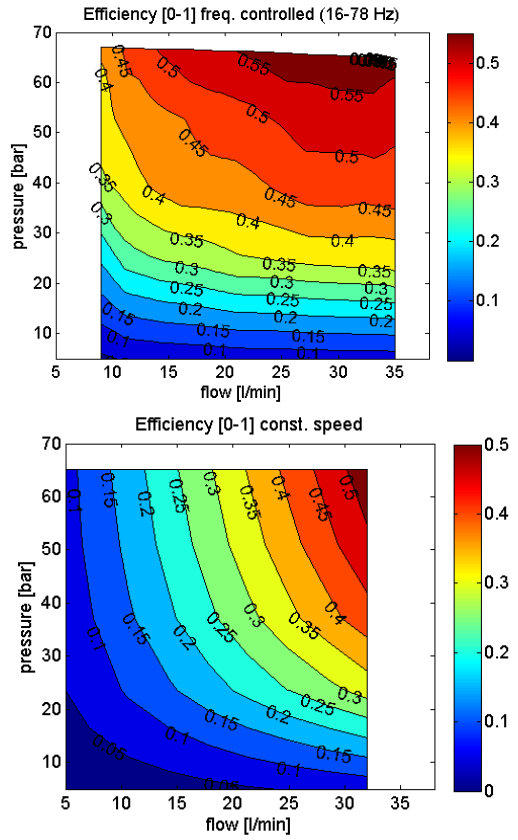


Figure 7: Example: efficiency of the high pressure cooling lubricant pump (ratio of hydraulic to electric power) a) frequency controlled, b) constant speed with relieve valve.

3.2 Machine tool user

- Machine tool selection according to particular needs; no oversizing.
- Selecting specialized machines for large series production when applicable (e.g. transfer machines, multi-spindle machines).
- Cutting conditions (tool, parameters, cooling lubricant) selection for productive machining. Devoting time and care to adjustment of the peripherals according to variable minimal process needs.
- NC tool path programming has usually a great potential for improvement during 5-axis machining.
- Reducing machine ON state to minimum. Process optimization OFF machine; using touch probes; automated tool / workpiece handling.

4 CASE STUDIES

The chapter presents the examples of three machines which have been subjected to:

- energy consumption measurement;
- analysis and suggestion of design improvements for improving the energy efficiency;
- application of design changes and measurement of their effect;

The three milling metal cutting machine tools are of different types. The testing scenario is based on manufacturing of the test workpieces (Figure 1) with scale factors 1-3.

The measurement results revealed that each of them had an obvious energy leakage. This could be fixed with low / medium effort and resulted in a double digit percentage of improvement. The case studies are presented in Table 1 - 3.

Table 1: Case study 1 - description and results

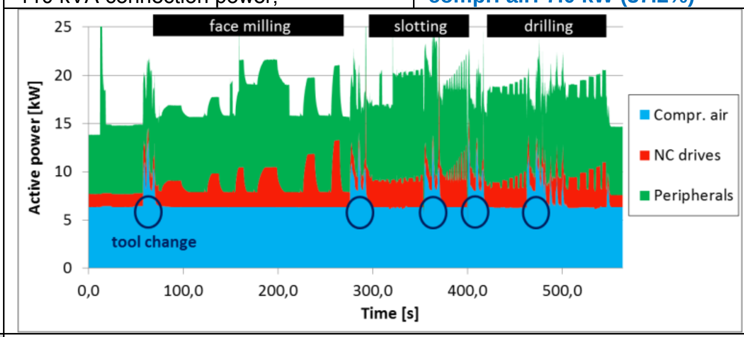
Case 1: Kovosvit MAS; MCU630V-5X; (workpiece scale factor 1)		**energy measurement results**
	5 axis milling center; 462 l workspace; 35 kW, 18000 rpm spindle; 110 kVA connection power;	**mean total: 18.8 kW** **NC drives: 2.7 kW (14.4%)** **peripherals: 9.1 kW (48.4%)** **compr. air: 7.0 kW (37.2%)**
		
analysis / main issue	NC drives' (5 axis + spindle) consumption is low, peripherals are also sized adequately. There is an obviously high energy demand related to compressed air. The pressure in the system is higher than necessarily needed for spindle air purge and linear axes measurement purge.	
solution	**Compressed air system redesign:** reduction valves mounted.	
power saved	The compressed air demand was lowered by 47%, which means: **18% of the overall machine active power consumption**	

Table 2: Case study 2 - description and results

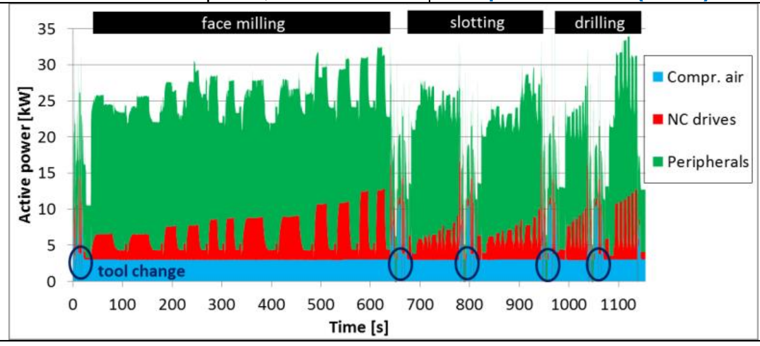
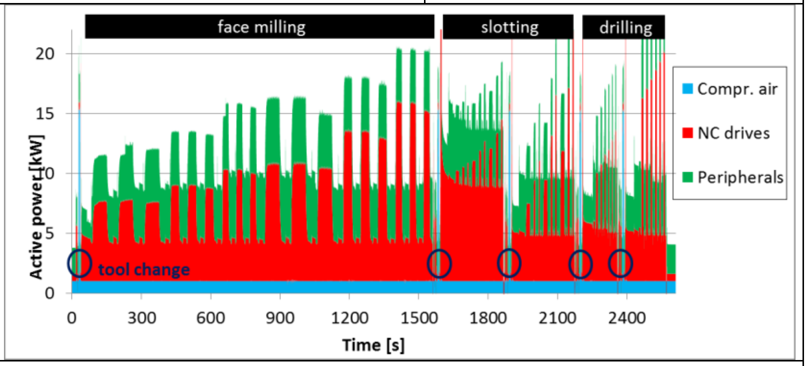
Case 2: Tajmac-ZPS; TM 1250; (workpiece scale factor 2)		**energy measurement results**
	4 axis milling / turning center; 2.62 m³ workspace; 48 kW, 6500 rpm mill. spindle; 100 kVA connection power;	**mean total: 23.8 kW** **NC drives: 4.0 kW (16.8%)** **peripherals: 16.5 kW (69.3%)** **compr. air: 3.3 kW (13.9%)**
		
analysis / main issue	NC drives' and compressed air consumption is adequate. There is a significant consumption of peripherals: mainly the high pressure central cooling lubricant pump (5 kW), the chillers for cooling the milling and turning spindles (4 kW) and the hydraulic pump with constant input of 3.2 kW	
solution	**Peripherals optimization:** the cooling lubricant pump was equipped with frequency inverter and user interface for active setup; the cooling circuits merged to a single system with reduced installed power and real consumption as well; the hydraulic circuit was optimized using a bigger accumulator and saddle valves; automatic hibernation of the machine during nonproductive time.	
power saved	Mean peripheral consumption was reduced by 28%, which means: **19.4% of the overall machine active power consumption**	

Table 3: Case study 3 - description and results

Case 3: TOS Varnsdorf; WHN13 CNC; (workpiece scale factor 3)		**energy measurement results**
	horizontal boring / milling machine; 11 m³ workspace; 46 kW, 3200 rpm spindle; 85 kVA connection power;	**mean total: 12.0 kW** **NC drives: 6.3 kW (52.5%)** **peripherals: 4.3 kW (35.8%)** **compr. air: 1.4 kW (11.7%)**
		
analysis / main issue	NC linear axes, peripherals and compressed air system consume relatively low power. However, significant consumption of the spindle can be observed during the spindle idle run (up to 8 kW during 3200 rpm).	
solution	**Spindle drive optimization:** the asynchronous motor of the spindle was replaced with a more efficient alternative; the transmission oil viscosity reduced; the lubrication of bearings was changed from grease to oil-air.	
power saved	The spindle losses have been decreased by 37%, which means: **15.4% of the overall machine active power consumption**	

Results show that relatively simple and straightforward saving measures can have a great impact in real. It of course depends on the initial level of machine energy optimization; nevertheless the nature of the problem is the same: finding the weakest point and fixing it.

5 SUMMARY

In this paper examples and good practices for improving machine tool energy efficiency with a focus on metal cutting machine tools have been presented.

There are no generic saving measures effective on all types of machines. Machines are different, and their energy efficiency weaknesses are even more so. This conclusion is absolutely in line with CECIMO SRI [10] argumentation to the European Commission when discussing the ecodesign legislation.

Very commonly, finding the weakest point in machine energy efficiency and modifying it with keeping the best available technologies in mind, makes a big difference in the overall improvement (similar to the “80% of problems - 20% of causes” rule).

When making ecodesign modification on a machine, it is always necessary to: a) measure with multichannel equipment / estimate the energy supplied to components; b) be aware of the best available technologies for specific machine tool functions.

Saving machining time per piece normally also saves energy. It means that machine designers and users can still keep productivity as the traditional main target. Also, even though machine designers do their best, energy-conscious user behavior is vital for energy efficient manufacturing in practice.

6 ACKNOWLEDGEMENTS

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