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Energy Efficiency of Machine Tools: Extending the Perspective

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Abstract

Due to increasing energy costs and the environmental impact of energy generation, energy consumption has become a major topic in manufacturing in the last years. Thereby, the energy consumption of production machines as interaction of different components is not static but rather highly dynamic depending on the operation mode. Hence, as a prerequisite for optimizing energy efficiency on the machine level it is crucial to understand the energy consumption behavior. Analyzing certain energy profiles of production machines is a common way in research nowadays to identify main drivers of consumption and derive optimizing measures. However, whereas only focusing on electricity as input variable these analyses do not provide the full picture of energy flows within the machines and neglect existing coherences and significant energy losses. Therefore a holistic perspective on the system machine tool considering all relevant input and output flows (e.g. heat, compressed air, coolant) and supporting equipment (e.g. filter systems) with all interdependencies is necessary to avoid problem shifting and enable the identification of further optimization potentials. Against this background, based on an overview of recent research and own findings / measurements the paper shows the necessity and potentials of an extended perspective on machine tool energy consumption.

Keywords:

Machine Tools; Energy Efficiency

1 INTRODUCTION

Machine tools are non-portable, powered machines to cut, shape or finish products from different materials (e.g. [1]). As one major group metal working machine tools are used to create and finish metal products through selective removal of material using cutting tools. Besides diverse input materials (e.g. raw material, coolants), machine tools require the usage of energy (e.g. electricity, compressed air) for operation [1]. The usage of energy incorporates both an economic as well as ecological significance for companies nowadays.

Considered from an economic perspective, total energy costs of a metal fabricating company can sum up to a share of 0.5-6 % of revenue nowadays [2]. Due to the high amount of involved electric drives (e.g. spindles, pumps) in typical metal processing companies these energy costs are dominated by cost for electricity which can make up to 70% [3]. A cost analysis of metal cutting processes in the automobile industry stated that the costs of electrical energy consumption can exceed tooling expenses over 76 % [4]. This aspect is likely to get more relevant and exerts even more pressure on manufacturing companies in the future while prices for all primary energy sources and specifically electricity prices have been steadily increasing for the last couple of years. This is not just an issue for high-cost countries like Germany. While certainly still quite different regarding absolute prices the clear tendency of energy rising prices can be noted throughout Europe as depicted in Figure 1 as graphical representation of the average (as well as minimum and maximum) energy prices in the European Union over the years [5].

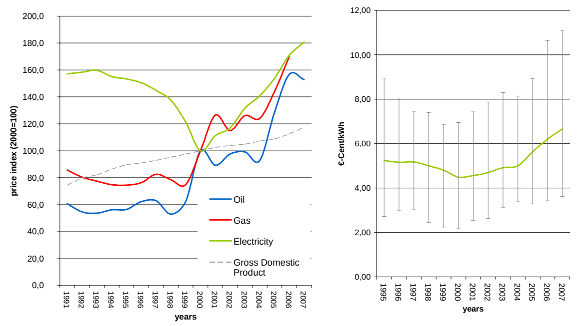

Figure 1: Energy price development in Germany (left) and comparison of energy prices in Europe (right) [5] [6].

From an ecological perspective the whole industry sector is directly responsible for 20 % of CO_2-emissions. Additionally, the industry sector consumes 47 % of total electricity consumption. Whereas power and heat consumption counts up for 38 % of CO_2-emissions industry is also indirectly responsible for further 18-19 % of CO_2-emissions [5] [7].

From the statistics of the US Energy Information Administration it can be concluded, that 47 billion kWh of the industry used electricity is consumed by the metal processing industry (fabricated metal products, see). This energy quantity corresponds to a portion of 5 % of the total industrial electricity consumption in the US [8] [9]. This equals approximately 35 Mio. t of electrical energy related carbon dioxide emissions (CO_2-equivalents).

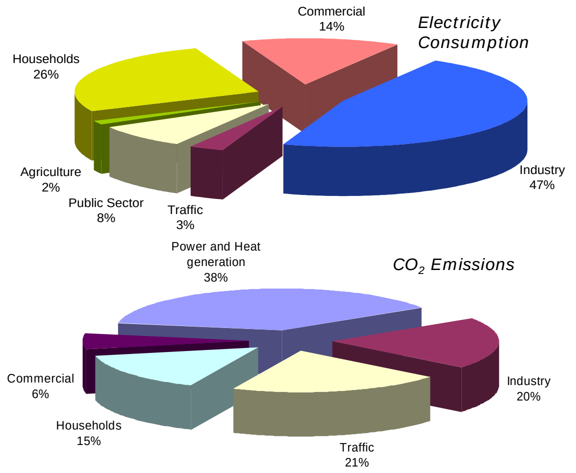

Figure 2: Energy consumption and CO_2-emissions of industry [5].

As shown above machine tools induce a high economic relevance for companies as well as a significant ecological leverage on a national respectively global scale with more than 1 million machine tools in Germany and more than 1.8 million machines in the US [10] [11] for example. Striving towards sustainability as new paradigm in manufacturing simultaneously considering economic, ecological and also social aspects leads to the requirement of more energy efficient machine tools. Energy efficiency is defined as the ratio of valuable / usable output of the machine and the necessary energy input. Hence, increasing energy efficiency means more or the same output with less energy input. Machine tools necessarily always need energy to produce goods - however, from that perspective increasing energy efficiency is a promising way to decouple economic growth (and requirements) and the amount of energy input.

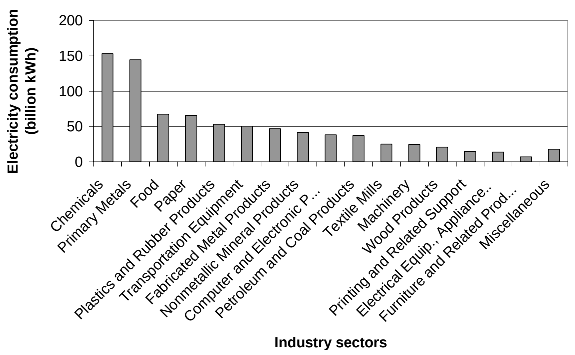

Figure 3: Electricity consumption per industry in the US [8].

Due to this development companies especially in the metal processing industry are looking for improvements in production processes in order to increase energy efficiency. To avoid problem shifting through just local optimization it is important to consider a realistic background regarding energy consumption behaviour of machine tools. This basically requires the analysis of all involved material and energy flows (e.g. including losses) for the machining process (dynamically depending on the actual state of the machine) as well as their coherences with other involved technical systems (e.g. peripheral equipment).

2 ENERGY CONSUMPTION OF MACHINE TOOLS

As one important prerequisite for energy related analysis of machine tools on a realistic base it is important to understand energy consumption is not static, but directly depend on the specific actual state of the machine [12] [13]. As an example, the energy demand of a grinding machine with its individual energy profile is presented in figure 4. The energy demand can be separated into a basic power and specific process power. The basic power covers the power demand, which is necessary to ensure a functional mode of operation (ready for operation). The process power considers the power demand for proceeding the machining operation without touching the work piece (so called air-cut) and the material removing capacity [12]. The energy profile shows that more than 3.5 kW are used as basic power and that short-term energy peaks up to 10 kW arise with the use of the machine. In previous studies, Dahmus and Gutowski [14] [15] have shown that machine tools with increasing levels of automation reveal higher basic energy consumptions which result from the amount of additional integrated machine components. The energy consumption is therefore not mainly determined by the cutting operation, but dominated by the basic power consuming components. As a consequence, the energy consumption during non production time is substantial and should be reduced through organizational and technical (standby-mode) measures [14] [15]. The results from the mentioned studies were also determined by Devoldere, T. et al. [9] for bending and milling operations.

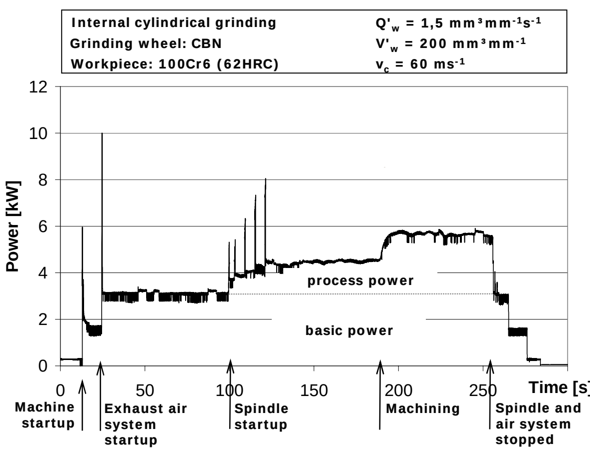

Figure 4: Electrical energy consumption of a grinding process (excluding filter system).

The consideration of energy profiles is an important basis for production optimization regarding energy efficiency. On machine and process level, these profiles permit the identification of substantial energy drivers in machines. Analyzing the energy profile of the grinding machine (displayed in figure 4) enables to identify the high energy demand of the air exhaust system. As a consequence, further measures as reducing the operation mode or replacing air system components through more efficient technology can be applied to reduce the total basic power consumption. Furthermore, the energy profile shows that the exhaust air system substantially increases the power consumption to a short-time maximum of 10 kW when started. The same effect is visible with employing the cutting tool spindle. Energy peaks induce extra energy costs and should therefore be minimized or at least harmonized considering process chains of several machine tools [16].

Looking at the research regarding energy consumption of machine tools so far it gets clear that general recommendations are hard to derive. There are various influencing variables regarding the actual energy consumption like the type of manufacturing process, process parameters and the structure/components and control of the specific machine. Hence, increasing energy efficiency of machine tools on a broad base requires many measurements for diverse processes (and parameters) and machine types and (based on that) valid description models to predict the energy consumption of a specific machining process. Additionally electricity is just one input factor for machine tools – however, these machines also need other forms of energy (e.g. compressed air) and auxiliary material (e.g. lubricants). To avoid just local optimisation and possible shifting of problems an extension of the perspective is necessary dynamically including all these input factors with connected peripheral processes (e.g. supply, filtering) as well as all energy flows which are related to the specific machining process (e.g. losses through heat).

3 EXTENDING THE PERSPECTIVE

Up-to-date in research diverse time-based profiles are compiled using power measurement for depiction of machine tools energy consumption. Thereby, the capturing and visualization of the electric energy consumption of machine tools is the center of attention used for instance to differentiate process and basic power consumption and moreover to identify components with precipitous energy consumption (e.g. leading to energy peaks). Gutowski et al. and Dahmus have shown the relevance of increased basic power consumptions for a specific production task among various machining concepts and indicate improvement potentials in order to foster resource efficient machining [15] [17].

In contrast to observing the electrical energy consumption of machine tools, an integrative view of sustainability in production demands additionally the measurement, analysis and evaluation of economic, ecological and social effects of production processes. Therefore an integrated process concept is presented, which supplements the conventional – so far often purely economically shaped – aspects (see figure 5). The integrated process concept covers the economic input and output flows (e.g. energy and material or waste) on a process and machine level and includes beyond that ecological aspects [13].

Analysing the inputs and outputs of machining, however, is complex as especially outputs are diverse, depend on interrelated factors and are not always quantifiable (e.g. vaporization of coolant in air and energy dissipation). In figure 5 the material and energy flows of a typical metalworking machine (e.g. grinding) are listed. Electrical energy, compressed air, cutting fluids, and raw material have to be considered as main inputs on a machine level. In addition to the processed product, basic outputs of a cutting tool operation are coolant covered splinters or swarf (in most cases oil covered), waste heat and in particular used coolants [13].

Furthermore, the quantities of the respective energy and material flows are also determined in particular by the machine type (e.g. highly automated machining centre) and the processing parameters. The specific machine type equipment encompasses pumps, hydraulic systems, spindles, sensors and filter systems which all use electric energy for operation. Apart from that, the machining process parameters directly impact the electric energy consumption through employing and controlling of operation modes of components. Thus, it is important to understand that process conditions and energy consumption are normally not static, but depend directly on the specific conditions of the process and the machine setting/equipment [12] [13].

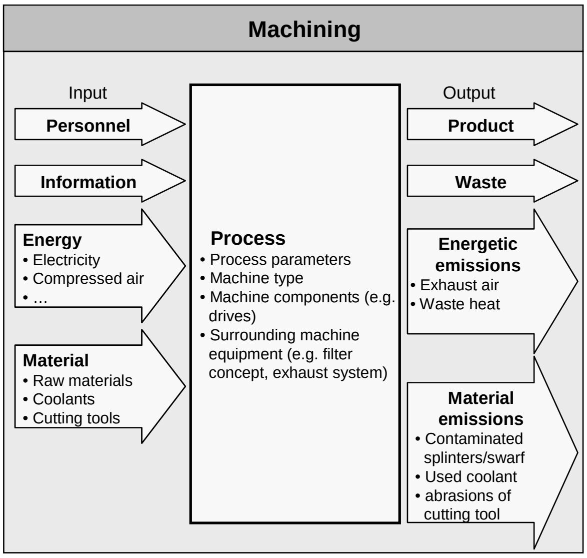

Figure 5: Integrated machining model for machine tool analysis - adapted from [18].

4 INTERDEPENDENCIES OF MATERIAL AND ENERGY FLOWS IN MACHINING OPERATIONS

Only by the combination and coordination of components it is possible that a machine tool fulfils the demanded tasks of processing. The analysis of energy-relevant couplings within the machine tool, for example of interrelations between the energy consumption of the individual operating components and thereby the heating up of the machine, are to be included into extended energetic examination and optimization.

Such influences considerably determine the attainable production accuracy and are thus decisive for an economic manufacturing. If the underlying mechanisms and coupling effects would be well-known, need-oriented energy-efficiency-increasing strategies (e.g. optimization of operation or cooling strategy) could be determined and optimized for existing and new machines. Furthermore, energy and concomitantly cost-relevant couplings, e.g. energetic expenditures for supply and processing of cooling and lubricants, can be identified and examined.

As an example, an extended analysis of the electric energy consumption is accomplished for a machine tool with an internal cylindrical grinding process to demonstrate energy dynamics and couplings. The overall energy profile is already displayed in figure 4. The energy profile is extended to clarify the energy-related effects of process parameters, the integrated machine components and the induced meta-scale effects of machining on process chains.

4.1 Process Parameters

The specific consumed energy consumption represents the energy that is solely induced for material processing. Energy profiles capture the specific energy for one single process with subjectively chosen process parameters. A deep understanding of the dynamics between process parameters and resulting processing power is yet not present.

One of the first approaches has been published by Draganescu [19]. The statistical model for milling operations seizes the efficiency of a machine tool with special consideration of variations in process parameters. The illustration in figure 6 shows the effect of attitude of torque and speed of the cutting tool spindle, which enables to determine optimal processing efficiency. This model is integrated into the computation of the total energy consumption.

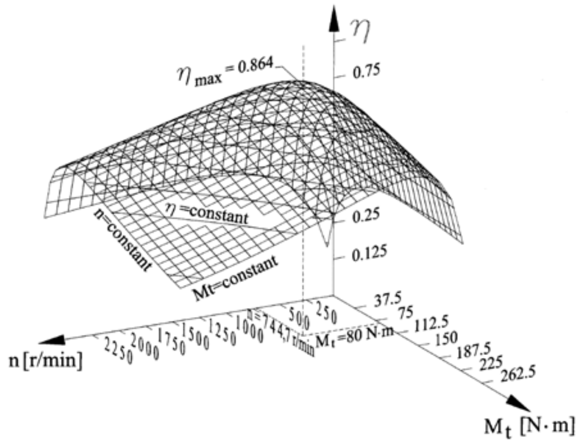

Figure 6: Impact of process parameters on the specific process energy [19].

In accordance to the presented efficiency model, an energetic process model for grinding processes is actually developed using statistical analysis. As input data the three key indicators for grinding processes (specific material removal rate, specific volume of metal removed by cutting and cutting velocity) are used. They can be used to entirely determine the mode of operation. It is intended to statistically characterise the energetic correlations of process conditions and thus conclude the demand of specific process energy.

The experimental data are obtained by measuring specific process energy for diverse test series. First results (obtained in cooperation with the Institute of Machine Tools and Manufacturing (ETH Zurich)) are exemplarily visualized in figure 7.

The statistical model enables to establish a relationship between process parameters and the resulting energy demand for grinding processes. Further research will focus on the further development and validation of the model as well as derivation of energy efficient process parameters.

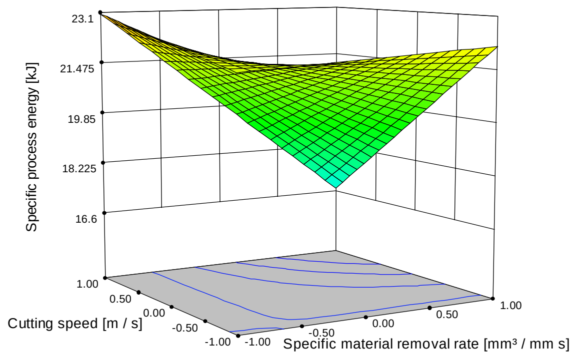

Figure 7: Leverage of process parameters on specific process energy.

4.2 Energy Flows in Production Machines

In contrast to the specific energy consumption, the basic power includes the energy demand of the functional mode considering peripheral systems as coolant filter or air filter systems. Figure 8 visualizes the averaged electric energy consumption of all components and clarifies that in particular the hydraulic, air filter system and coolant filter pumps represent the main energy consumers. These components account up to 73 % of the total power demand.

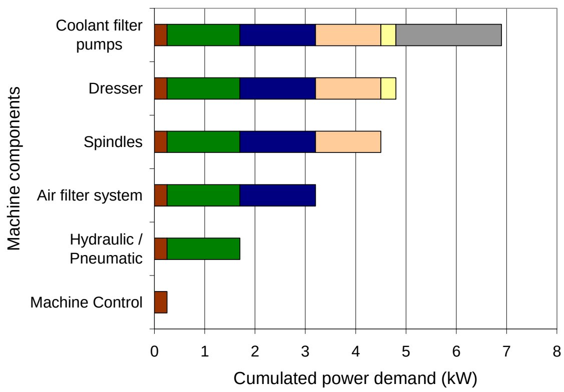

Figure 8: Energy demands of machine tool components.

Thus, improving the energy efficiency of machine tools is directly possible through substitution with energy efficient devices of these major energy consumers.

But within an extended energy optimization of machine tools, means to improve the efficiency should not only focus on the integration of energy efficient devices but moreover consider the couplings of short-term energy demands and resulting energy peaks. While energy profiles predominantly capture the overall time-based electric energy demand, it is absolutely evident to additionally analyze time-based energy demands of starting components. As an example, figure 9 displays the electric energy demand for two different starting procedures. While the instant start of the hydraulic and air filter system (which is the usual mode of operation) leads to an energy peak of 21.56 kW, the sequential (manual) start of both components enables to reduce the total height of energy peaks to 14.5 kW.

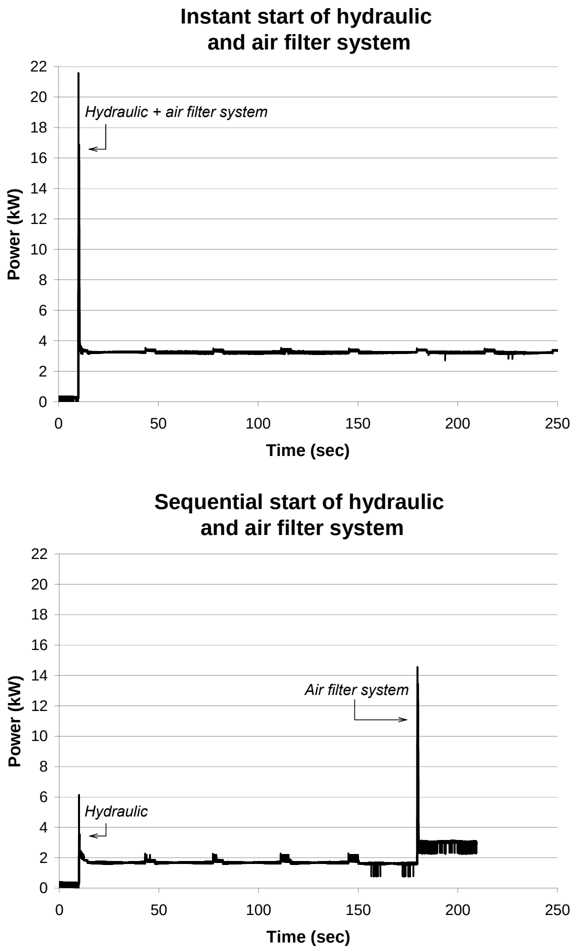

Figure 9: Energy dynamics in machine tools.

Apart from the consideration of energy consumption, another important aspect within an extended analysis is the conversion of electric energy within the machine tool and the resulting energy liberation in components.

As displayed in figure 8, the coolant filter pumps contribute substantially to the overall power demand. The considered filter system covers a tank volume of 120 litres and conveys a water based coolant with two pumps. In order to clarify the transformation of electricity into other forms of energy (e.g. kinetic and thermal energy), the heat transfer into the coolant through operation of pumps is examined. The results for a test period of 180 minutes are visualized in figure 10. The pumping of coolant leads to an increase of coolant temperature by 10.4 K during trial period. The energy balance of the filter system shows that 24 per cent of consumed electricity is liberated as heat into the coolant. In addition, an unknown quantity of electricity is emitted as heat directly over the pump housing which is not considered. Thus, less than 74 % of the electric energy is used to convey the coolant.

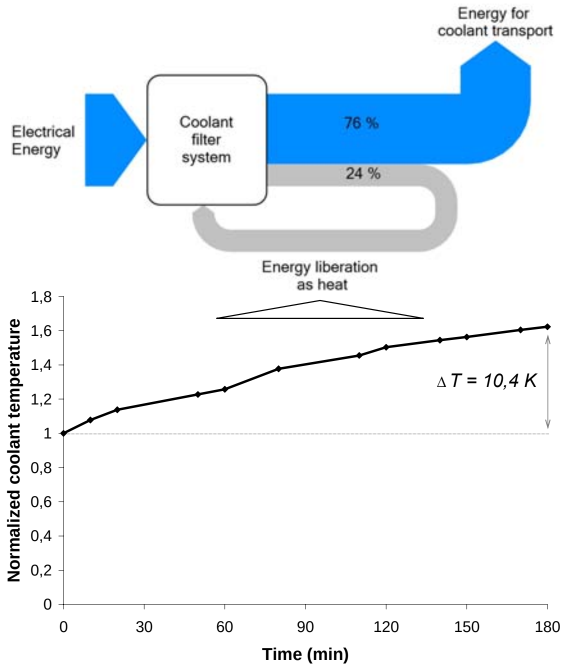

Figure 10: Energy liberation in machining (coolant filter)

On the basis these two examples, it is pointed out that increasing energy efficiency in machining demands not only capturing energy consumption but moreover requires an integrated energy analysis of the dynamic dependences of components and of energy liberation.

4.3 Machine Tool and Supporting Processes in the Process Chain

Machine tools are important elements in industrial process chains. They are encircled by supporting processes as cleaning, drying and assembly which are compiled up- and downstream. Thus, the operation of machine tools induces energy and material expenditures in further processes which have to be considered within an extended analysis and optimization of energy efficiency for manufacturing.

As an example, the machining induced energy consumption of a production line in the automobile industry is displayed in figure 11. The results of the energy analysis show that metal cutting operations in machine tools still constitute the largest share of total energy consumption directly followed by the filter systems. It must be pointed out that a substantial portion of the energy during processing is required to handle and apply coolants [4]. Apart from the direct electric energy consumption, the usage of coolants is obviously connected with substantial energy expenditures for operation and treatment. Thus, further research in the scope of energy efficiency will focus not only focus on the energy demands of machine tools but also on the energy couplings for provision and handling of auxiliary substance like coolants.

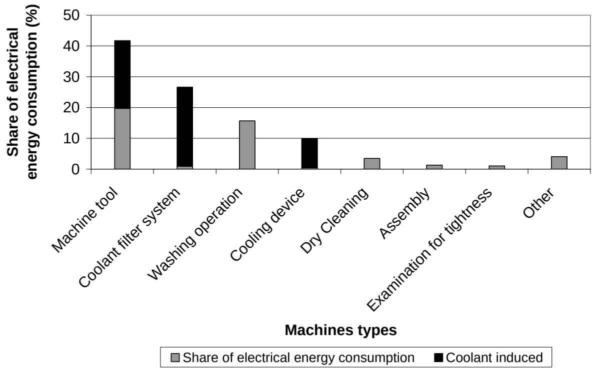

Figure 11: Induced energy consumption of machining in process chains [4].

5 CONCLUSION

The extended analysis of energy consumption of machine tools presented in this paper has pointed out the need for a comprehensive consideration of energy dynamics of process parameters and components as well as energy transformation in order to substantially improve the overall energy efficiency of machining processes. The presented influences and couplings considerably determine the attainable production accuracy and are thus decisive for implementing an economic and ecologically sound manufacturing.

6 REFERENCES

[1] Tönshoff, H.K., 1995, Werkzeugmaschinen – Grundlagen, Springer.

[2] EnergyAgency NRW (official website), 2007, Energy in companies, http://www.ea-nrw.de/unternehmen/

[3] VDW, 2008, press release in context of METAV 2008: Energieeffizienz in der Fertigung wird zum Wettbewerbsfaktor.

[4] Bode, H.-O., 2007, "Einfluss einer energieeffizienten Produktion auf Planungs- und Produktprämissen am Beispiel der Motorenfertigung"; in XII. Internationales Produktionstechnisches Kolloquium, Berlin, pp. 299-305.

[5] German Federal Ministry of Economics and Technology, 2007, Energy Statistics, http://www.bmwi.de/BMWi/Navigation/Energie/energiestatistiken.html.

[6] Federal Statistic Office Germany, 2007, http://www.destatis.de.

[7] Rebhan, E., 2002, Energiehandbuch - Gewinnung, Wandlung und Nutzung von Energie, Springer, Berlin.

[8] Adler, R., 2002, First Use of Energy for All Purposes, Energy Information Administration, http://www.eia.doe.gov/emeu/mecs/mecs2002/data02/pdf/table1.1_02.pdf, last revised: 28.07.2008.

[9] Devoldere, T., Dewulf, W., Deprez, W., Willems, B., Duflou, J.R., 2007, "Improvement Potential for Energy Consumption in Discrete Part Production Machines"; in Proceedings of the 14th CIRP Conference on Life Cycle Engineering, ed. by Takata, S., Umeda, Y., Tokyo, Japan, Springer, London, pp. 311-316.

[10] Murrenhoff, H., 2002,. Bericht über biologisch schnell abbaubare Schmierstoffe und Hydraulikflüssigkeiten, ed. by Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft, http://www.fnr-server.de/ftp/pdf/literatur/ pdf_35schmstbe.pdf, last revised: 28.07.2008.

[11] Dahmus, J. B., 2007, Applications of Industrial Ecology: Manufacturing, Recycling and Efficiency, pages 15-42, Massachusetts Institute of Technology, http://dspace.mit.edu/bitstream/1721.1/39901/1/182546884.pdf, last revised: 28.07.2008.

[12] Eckebrecht, J., 2000: Umweltverträgliche Gestaltung von spanenden Fertigungsprozessen, Shaker Verlag, Aachen.

[13] Herrmann, C., Bergmann, L., Thiede, S., Zein, A., 2007, Framework for Integrated Analysis of Production Systems; in Proceedings of the 14th CIRP Conference on Life Cycle Engineering, ed. by Takata, S., Umeda, Y., Tokyo, Japan, Springer, London, pp. 195-200.

[14] Dahmus, J. B., Gutowski, T. G., 2004, "An Environmental Analysis of Machining"; in Proceedings of IMECE 2004, ASME International Mechanical Engineering Congress and RD&D Expo, November 13-19, Anaheim, USA.

[15] Gutowski, T. G., Dahmus, J. B., Thiriez, A., 2006, "Electrical Energy Requirements for Manufacturing Processes"; in Proceedings of the 13th CIRP Conference on Life Cycle Engineering, ed. By Duflou, J. et al., Leuven, Belgium, pp. 623-627.

[16] Hesselbach, J., Herrmann, C., Detzer, R., Martin, L., Thiede, S., Lüdemann, B., 2008, "Energy Efficiency through optimized coordination of production and technical building services"; in Proceedings of the 15th CIRP International Conference on Life Cycle Engineering, Sydney, Australia, pp. 624-629.

[17] Dahmus, J. B., (2007), Applications of Industrial Ecology: Manufacturing, Recycling and Efficiency, pages 15-42, Massachusetts Institute of Technology, http://dspace.mit.edu/bitstream/1721.1/39901/1/182546884.pdf, last revised: 2.02.2009.

[18] Schultz, A., (2002), Methode zur integrierten ökologischen und ökonomischen Bewertung von Produktionsprozessen und -technologien, dissertation, Magdeburg.

[19] Dranganescu, F., Gheorghe, M., Doicin, C.V.: Models of machine tool efficiency and specific consumed energy, Journal of Materials Processing Technology, Vol. 141, S. 9-15, 2002.