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STUDY ON REDUCING ENERGY CONSUMPTION IN MANUFACTURING SYSTEMS

The paper presents the complexity and importance of energy saving in industry, manufacturing facilities, machine tools and machining processes. The increasing energy demand and the necessity of conscious energy use are highlighted. Problems relating to the reduction of energy consumption by machine tools and manufacturing facilities, the necessity of basing new energy-efficient designs on knowledge, the accurate modelling of power losses and the use of intelligent energy consumption control with special regard to the drives of controllable axes are discussed. Also the energy-intensiveness of machining processes and whole manufacturing systems is considered. The need for a rational strategy of reducing energy consumption by machine tools and manufacturing processes is indicated.

1. INTRODUCTION

The reduction of machine tool energy consumption has several aspects, such as natural environment resources protection and the enterprise's profits, product manufacturing competitiveness and high performance, which means increased machining capacity on one hand and on the other hand, energy savings dictated by the national, regional and global considerations. The importance of the aspects changes depending on the global needs and benefits.

Since the interdependencies between the technical, economic and environmental benefits are highly complex, in order to reduce energy consumption in general, and that of machine tools and machining processes in particular, in-depth analyses need to be carried out and the energy consumption components and their shares in the energy consumption by the machines and the processes must be precisely determined. The aim is to rationally shape the development of machine tools, product manufacturing processes and industry as a whole, taking into account the energy saving needs and directions, as regards both resources and products (including machine tools).

As a result of the intensive development of product manufacturing and the rise in broadly understood productivity the energy consumption keeps on increasing. It is predicted that the increased demand for energy (whose cost steadily rises contributing to higher

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manufacturing costs) will persist for the next 30 years. This is one of the major factors in the competition on the global product markets, especially in the current crisis. On the other hand, the available resources are limited whereby the individual countries and the EU have to take measures to save energy.

According to the data for the year 2010, industry consumes about 27% of the generated energy [12]. Moreover, it uses up resources in the form of:

- materials, i.e. raw materials, semi-finished products and so on, whose production is highly energy-intensive;

- water, as the component of coolants and the medium in many industrial installations, including in machine tools and manufacturing systems;

- processed materials, i.e. machines, technological facilities and tools;

- other.

Machine tools and machining processes use up:

- energy directly;

- energy-intensive compressed air;

- energy-intensive cooling media, including water, emulsion and oils;

- production space with energy-intensive temperature regulation;

- energy needed to manufacture components;

- other.

Consequently, the resources are consumed at a high rate, and with time the requirements concerning products and the use of resources are made more stringent. On one hand, the use of the resources needs to be reduced while on the other hand, productivity is required to be considerably increased. In order to increase productivity and product competitiveness more energy efficient machine tools, manufacturing processes and whole machining system are needed.

Machine tools must be geared to the manufacture of more resource-efficient products. This means that a new direction in the design of machine tools, material removal processes and whole machining systems, which still predominate in the manufacture of products, is needed. The designers of machine tools, machine processes and systems face the following major tasks:

- to increase productivity through higher motion speeds, process multitasking and hybridization;

- to increase precision,

- to make sure that the component parts, their manufacture and operation are energy-efficient,

- to consciously plan energy consumption,

- to consciously reduce material consumption,

- to reduce the need for production space.

The above measures are dictated by both competitiveness and the environmental and economic policy of the national governments, the EU and world organizations. The Directive of the European Parliament on Energy using Products (Directive 2005/32/EC) aims to establish a framework for this purpose.

In the EU Directive on Eco-design (2008), machine tools are one of the three priorities as regards energy consumption reduction. This is supported by the research results

presented by Detmair [5], indicating that during simple milling 75% of the energy is consumed by the machine tool and its devices and 25% by the cutting process itself.

The particular types of machine tools (such as lathes, milling machines, grinders, etc.) and processes differ in their energy consumption, which depends on their automation, complexity and intended use [14]. Since it is difficult to generalize about this, some examples are provided below. Abele et al. [1] present the results of their study on energy consumption by a turning system (Fig.1), according to which most energy (65%) was consumed by the machine tool itself, 15% by the air-conditioning, 6% by the lighting, 5% by the turning process, 5% by the transport facilities, 3% by the cooling/lubrication and 3% by the exhaust system. The most expensive were found to be the operation of the system, followed by the energy consumed and the cooling-lubricating medium.

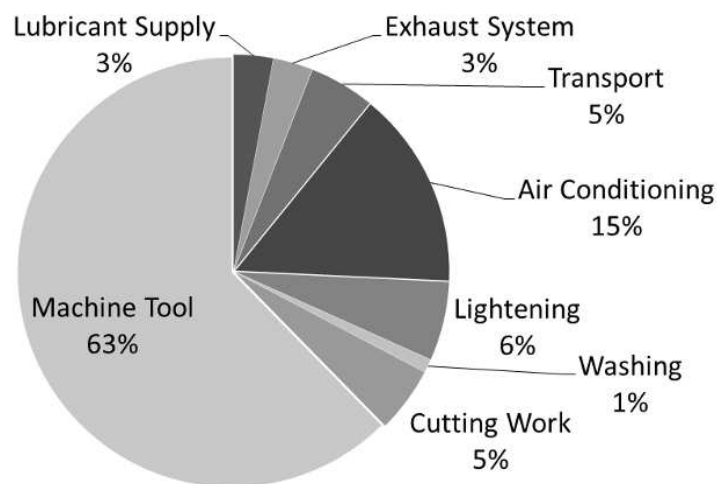


Fig. 1. Breakdown of energy consumption for work piece turning

The results of the research into the energy consumption by a machining centre (Pause [13]) and by a grinder (Kuhrke [9]) are presented in Figs. 2a and 2b, respectively. It is evident that in the case of the machining centre the motor spindle consumes the most electrical energy (18.9%), almost the same amount (19.5%) is consumed by respectively the cooling system and the cooling lubricant system, followed by the feed drives (in total 12.8%), the hydraulic pump (9.1%) and the other devices (each no more than 3%). In the case of the grinder with hydraulic drives, 79% of the power is consumed by the hydraulic parts and 21% by the spindle. Grinders of this type are highly energy-intensive.

The provided examples show the main directions for actions aimed at reducing energy consumption by the different varieties of machine tools. In modern machine tools for high-speed and high-efficiency manufacturing, the direct drives, characterized by high dynamics in the controllable axes and high torques, greatly contribute to energy consumption. In order to reduce this energy consumption, motor producers and research centres have undertaken intensive research on novel energy consumption reducing designs and materials. The research is supported with precise modelling, numerical simulation and optimization. The EU funds many such projects. Each reduction in energy consumption (even one

previously considered to be negligible) greatly contributes to the environmental friendliness and effectiveness of global manufacturing.

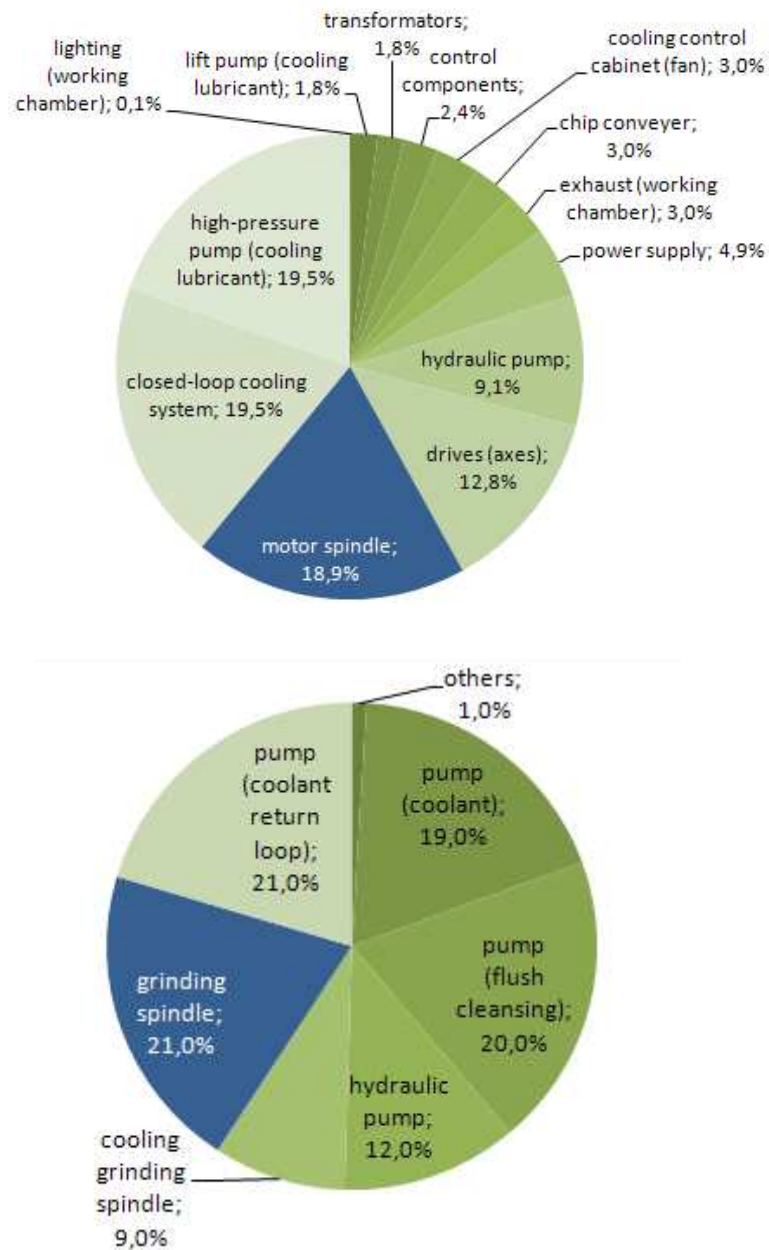


Fig. 2. Electrical power consumption by: a) machining centre and b) grinding machine

2. REDUCTION OF ENERGY CONSUMPTION BY MACHINE TOOLS

The modern high-efficiency machine tools are complex products competing on the local and global markets and they are based on the latest knowledge and material technologies, advanced manufacturing of their components as well as on the state-of-the art software and control systems and intelligent action and machining process execution. The

reason is that they must be as productive as possible, which entails low costs, short work and ancillary operation times, high efficiency, high flexibility (including multitasking), etc. Consequently their dynamics must be high whereas their deformations and thermal errors must be low (which requires the intensive cooling of the main heat sources) [7].

By nature of its structure a modern high-efficiency machine usually consumes a lot of energy. This is compounded by the growing demand for higher rotational and feed motions, greater accelerations, greater jerks and higher spindle torques, whereby each of the motors consumes even more energy and so it becomes necessary to install two integrated motors on the spindle. The cost of energy is very high – much higher than in the past and steadily increases. Therefore sustained efforts are made to reduce the energy consumption by machine tools, especially to reduce the intensity of all the heat sources causing deformations and displacements of machine tool assemblies in the controllable axes whereby the accuracy of machining deteriorates. Even though these efforts are made mainly because of the precision requirements, they contribute to a reduction in the energy consumption by machine tools. Direct drive motors in controllable spindle and feed axes are a major concern here. The motors, characterized by high or very high rotational speeds or very high linear accelerations and acceleration rates, consume a lot of energy and require energy-intensive cooling with a water jacket in order to ensure high and stable torque. The manufacturers of such motors, especially the leading ones (Siemens and Fanuc), make in-depth analyses of the causes of the high energy consumption by the motors and take measures to reduce it. This is done by adapting the motors to the task at hand, introducing design modifications and through highly complicated control which makes it possible to effectively recover the energy lost at deceleration (which often occurs in HSC machining). For this purpose the SINUMERIK Ctrl-Energy system (Fig. 3) [17] produced by Siemens is used. The system is capable of controlling energy recovery in the controllable axes and adjusting the speed and the energy use in all the ancillary assemblies equipped with high-efficiency asynchronous motors to the level required at the particular stages of machining. The system can also reduce the flow of current in asynchronous spindle motors running under less than full load.

Thanks to the recovery of energy during deceleration, which is then returned to the network by intelligent power modules, heat dissipation through resistors can be eliminated. This previously required energy-intensive air-conditioning of the space into which the energy from the resistors was dissipated. These energy-saving measures are supported by the SIZER software module whose task is to compute the energy consumption and losses connected with the load cycles (ramp-up, idle running, running under load, braking, cycle times etc.). In this way one can optimally configure the operation of the feed drives and the spindles and minimize the energy consumption.

A quite similar solution – GE Fanuc Intelligent Platform Inc [8] – is offered by Fanuc. For high-speed drives this platform can reduce energy consumption by 55% while tasks will be performed 68% faster (Fig. 4). This is possible thanks to the recovery of energy from the spindle motor and the feed motors in the cycle phases during which the drives reduce their speed. Without going into details, energy recovery (additionally resulting in a reduced energy peak) and the adjustment of the drives' characteristics to the machining tasks definitely contribute to energy savings.



Fig. 3. SINUMERIK Ctrl-Energy – Siemens proposal for increasing energy-efficiency of machine tools

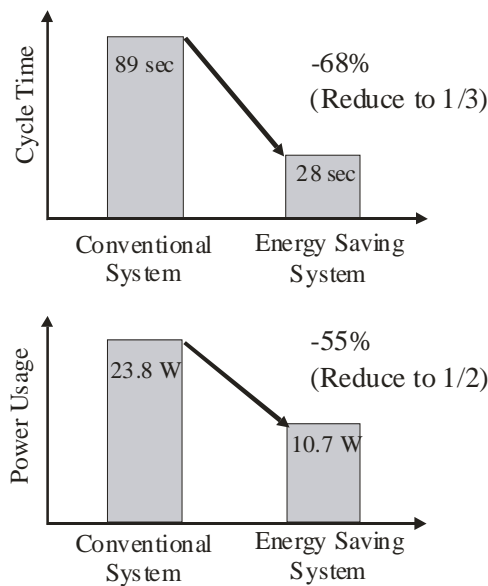


Fig. 4. Modern drive technology from GE Fanuc

Recent research on the reduction of energy consumption by induction motors conducted in the Machine Tools Laboratory in Aachen (WZL) indicates that when the magnetic flux is reduced from 100% to 30%, the power consumption decreases by 14% and the temperature goes down [2]. In the case of feed drive permanent-magnet motors, which do not need to be supplied with energy, the material plays a vital role. Magnets made of rare earth elements have more advantageous properties.

Energy consumption reduction applies to the whole machine tool. Considering this, the principle that drives, and so their motors, should run only when it is necessary to perform work operations, i.e. Just In Time (JIT), has started to be implemented. This especially applies to all ancillary devices, such as: machining chips transporters, cooling and coolant supply systems, tools, systems for cooling linear and rotary motors, and so on. The appropriate measures have been taken by several reputable machine tool and control system manufacturers, such as: MAKINO, Yamazaki MAZAK and OKUMA. For example, Yamazaki Mazak currently advertises that it can reduce machine tool energy consumption by 20% by:

- replacing the traditional light bulbs with energy-saving bulbs whose lifetime is ten times longer,
- automatically dimming or switching on and off the lights according to predetermined criteria,
- switching on the lights and the CNC monitor on signal from a sensor reacting to the approach of the operator,
- automatically switching on the chips transporter when a need arises,
- equipping the machine tool with an energy meter in order to monitor energy consumption.

Generally speaking, the aim is to adjust energy consumption by the ancillary systems to the level actually needed at the particular stages of machining, to recover deceleration energy during dynamic drive operation and its going to partial hibernation similarly as computers do [8].

In [13] and [12] the following ways of improving the energy-efficiency of machine tools and reducing lubricant and pressurized air consumption are suggested:

- the optimal tuning and dimensioning of the motors,
- reducing the mass of the slides,
- reducing the warm-up phases through efficient error compensation,
- a proper work chamber design (small size, sloped walls, etc.) ensuring optimal chip removal,
- shorter process times through coolant MQL,
- implementing standby modes and shut-off machine tool components in standby pumps, axes drives, chillers and so on,
- machine turn-off after a set idle time,
- automatic switching off the lights when the working chamber door closes,
- a closed-loop oil bath,
- using dry-cutting to increase productivity in some cases,
- implementing new-generation smart control technologies, e.g. Sinumeric 840DSL.

The amount of energy spent on cooling motors and friction nodes, such as bearings, ball screws and slides, can be somewhat reduced by reducing cooling if effective error compensation is employed. The main effort here, however, should concentrate on reducing the friction moment through the economical and effective lubrication and on reducing the friction moment produced by the load.

In the case of rolling bearings, especially in high-speed spindles, sparing lubrication with special grease or air-oil lubrication, consistent with the allowable value of high-speediness parameter $d_m n$ (revolutions times mean bearing diameter), ensures that the moment of elasto-hydro-dynamic friction remains minimum. When air-oil lubrication is used in very high speed (e.g. 40-60 thousand rpm) bearings, parameter $d_m n$ exceeds the permissible value of 4×10^6 . Therefore in such cases jet lubrication at a high lubricant flow rate is employed. This results in high energy consumption by the bearing, as shown in Fig. 5 [18]. Through the innovative improvement of the supply of oil to the friction zone for air-oil lubrication one can increase the high-speediness parameter value to 5×10^6 and ensure minimum energy consumption (similar to that for air-oil lubrication) by the bearing [6].

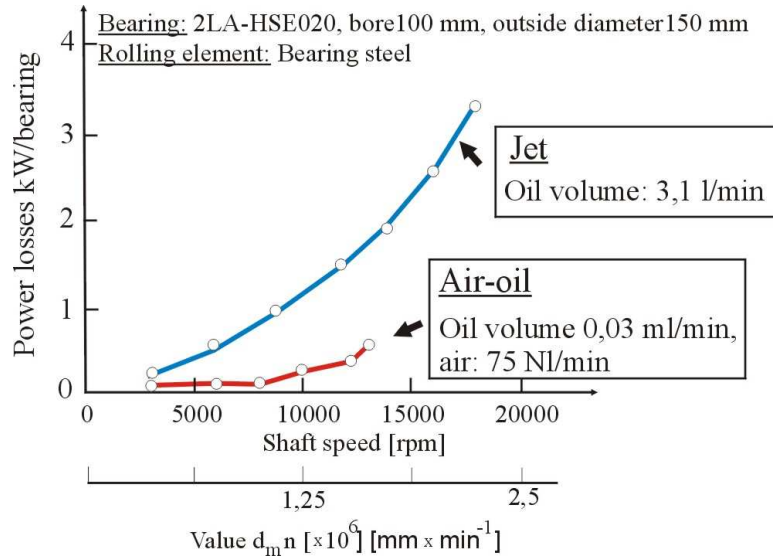


Fig. 5. Comparison of power loss for air-oil lubrication and jet lubrication.

As regards the energy consumption by bearings, because of the linear contact between the roller and the race, roller bearings consume more energy than ball bearings. Therefore properly preloaded angular contact thrust ball bearings are used in high-speed spindle units.

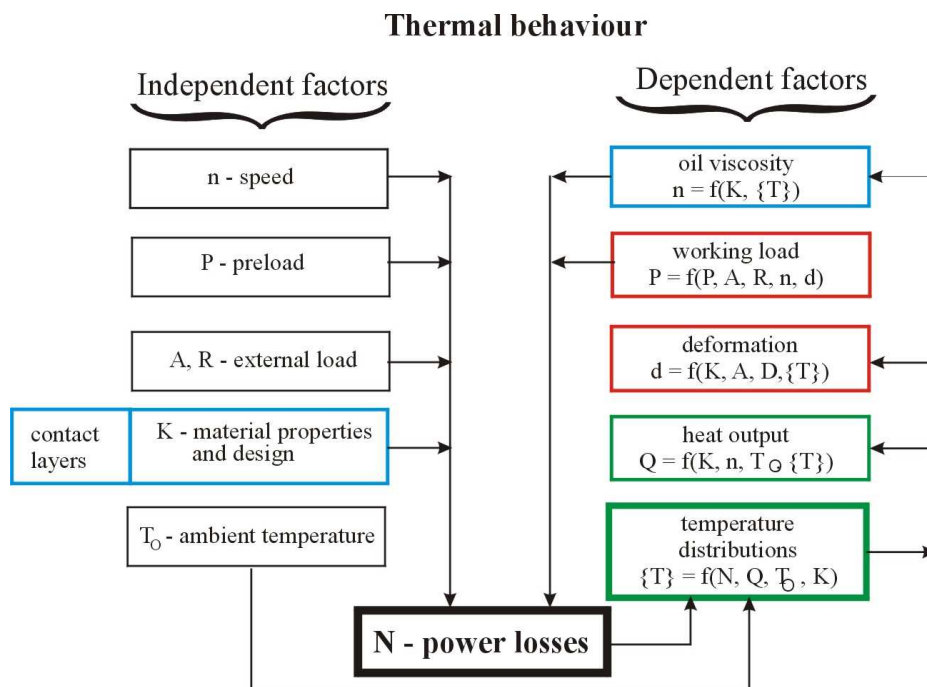


Fig. 6. Interdependencies between factors affecting power losses in bearing assembly

A power loss model is needed in order to determine and minimize the energy consumption by bearings. Such a model, very precisely representing the friction

phenomena, the external and internal loads, the thermal displacements and the interactions, is shown in Fig. 6 [7]. The model is integrable with the other power loss models used for the computer modelling and simulation of power losses for the whole machine tool.

The model, covering the heat sources located within the machine tool structure, is the basic tool for analyzing the thermal behaviour (including temperatures, deformations, assembly displacements and thermal errors) of the machine tool in operating conditions in order to minimize and compensate thermal errors.

The model is part of the SATO system (developed in-house) for machine tool thermal behaviour computations [16]. The system takes into account the whole complexity of the interdependencies between power (energy) losses and the thermal behaviour of the machine tool. In order to reduce the heating up of machine tools, and so the amount of energy consumed by them, comprehensive improvement of the machine tool design, in accordance with the UNE 150.301:2003 Directive (Product Design and Development Process Management System – Eco Design), has been undertaken. There are indications that significant energy savings can be made through the use of the smallest possible machine tools (requiring much less energy for their manufacture) or lightweight (skeleton) machine tools with a partially dematerialized structure (but at no deterioration to machining process precision).

Among energy-saving machine tools one should include multitasking machine tools (with a high concentration of operations) and hybrid machine tools (carrying out hybrid processes) since they replace several machine tools carrying out different processes. The European Machine Tool & Manufacturing Technology Association (CECIMO) has drawn up a list of potential improvements, which includes:

- avoidance of the machine tool heating up phase,
- reduction of friction in the bearings and the slides,
- proper control of the running time of the hydraulic pumps and the cooling systems,
- improvement of the converters/inverters (control couplings),
- intensive research on the measurement and balancing of energy consumption in machine tools,
- searching for new energy-saving machine tool concepts.

These are parts of a consistent strategy aimed at reducing the consumption of energy by machine tools. One should also note that big energy savings can be achieved by reducing and eliminating spoilage and increasing the lifetime of whole machine tools and their heavily loaded (in operating conditions) components/modules.

As already mentioned, CNC and PLC systems play a major role in energy saving. Through proper software the central control unit manages the energy consumption by the machine tool and the whole system. But each extension of the control capability increases the costs of the controller and the whole machine and what counts for the user are the total economic effects.

As regards the path measuring systems (rotational and linear encoders), very little energy is consumed for cooling them with dry air to prevent their thermal deformation under the action of external heat sources and it would be hard to make any energy savings here. The linear magnetic gauges (ensuring high measuring precision at direct linear drive high feed rates) being introduced now are less sensitive to temperature changes. The

increase in measuring precision results in higher machining precision, less spoilage and consequently in lower energy-intensiveness of the manufacturing process.

As described by Diaz et al. in [4], the power demand of a machine tool is comprised of cutting, variable, and constant power components (Fig. 7). The cutting power is additional power drawn for the removal of material. If one compares the energy-intensiveness of the cutting process with that of the machine tool it becomes apparent that the increased loading with cutting forces/cutting power does not result in high power consumption in some machine tool assemblies, but more power is consumed in the axis drives and power consumption significantly increases (linearly) with cutting load.

The power demand of the ancillary devices (the controller panel, the lamps, the cooling systems, etc., which consume energy independently of the cutting process parameters) may be considered to be constant. The power demand of the main drives and the feed drives, which together with the ancillary devices determine the “tare” power (the minimum power demand required for a given set of process parameters) is variable. The tare power share in the total power demand is an indicator of machine tool energy consumption, which means that it should be the lowest possible.

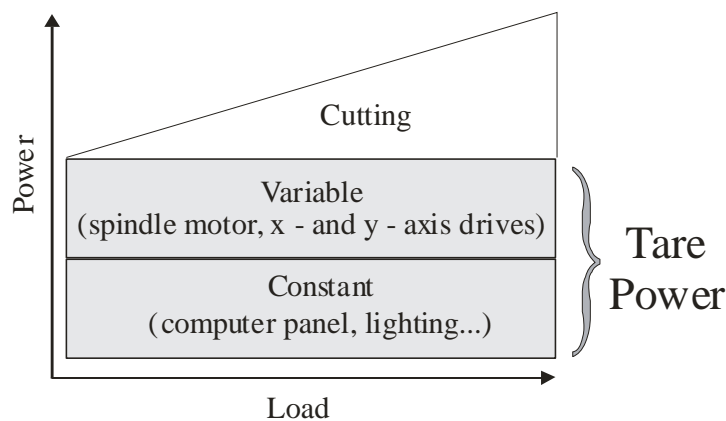


Fig. 7. Power breakdown depending on material removal load

The existing models of power consumption by machine tools are far from perfect. Therefore intensive research on their improvement is needed in order to make accurate analyses of energy consumption and its effective minimization possible [10].

3. REDUCTION OF ENERGY-INTENSIVENESS OF MACHINING PROCESSES

Similarly as machine tools, the machining processes carried out by them can be designed so that their energy-intensiveness is the lowest possible. This can be done through:

- increasing broadly understood productivity,
- optimization based on modelling,
- energy conscious planning,

- optimum control and supervision,
- preventing failures,
- developing energy balancing methods.

Machining processes have been the object of improvement for a long time. The research in this field has been conducted by both academic centres and the R&D units in factories which sell machine tools jointly with technology and so must be competitive in this regard.

The material removal rate (MRR) has a particularly strong effect on energy consumption during machining (Fig. 8) [3]. As this rate increases, the energy consumption sharply decreases, despite the increase in cutting power. This depends on many factors, such as the type of machined material and tool used, the cutting tip coating, the cutting speed, the lubricating-cooling medium, the process duration, the tool path and so on. Typically, the longer the tool path and the higher the cutting speed, the higher the power demand. Thus any energy savings will be the result of the energy conscious planning of the machining process and a compromise between the power demand and the process duration.

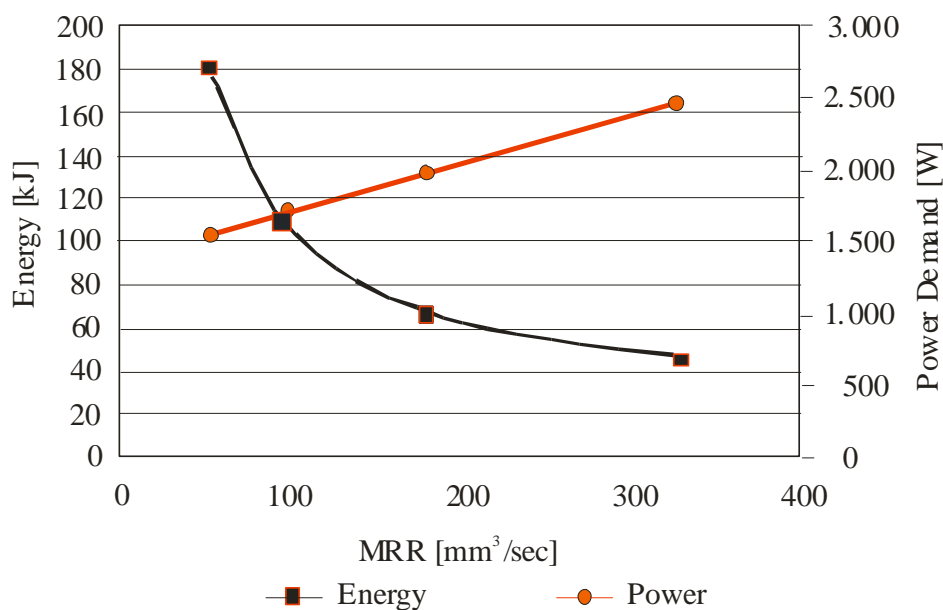


Fig. 8. Energy and power demand as a function of M.R.R. for depth of cut experiments with cutter

Recently more and more multitasking machine tools, e.g. twin-spindle and three-head turning centres capable of simultaneous machining with three tools, appear on the market. Even more advanced is the turning centre with two headstocks and four heads, recently presented by the TRAUB company at EMO 2011 in Hanover. In this way a high increase in productivity and at the same time energy savings are obtained. Similar results are achieved when 5-axis machining centres and centres carrying out hybrid processes (in most cases involving laser machining) are employed.

As regards the energy conscious planning of processes, many research projects are currently underway. They are based on process models and focus on the optimum choice

of cutting parameters and tools and optimum tool path design. Energy savings as high 6-40% can be obtained in this way [11].

4. ENERGY-SAVING MANUFACTURING SYSTEMS

Energy-saving machine tools and machining processes are of great importance for product manufacturers, but the latter benefit most when their whole manufacturing system and system components as well as their products are resource-saving.

The following recommendations are made [2]:

- balanced resource-efficiency of the products should be ensured,
- energy consumption should be continuously monitored and visualized,
- energy consumers in manufacturing systems should be effectively configured,
- energy consumption by machine tools and whole manufacturing systems should be continually reduced.

The holistic approach to energy consumption reduction in enterprises is dictated by the increasing material and labour costs and the competition with producers for whom the costs are locally significantly lower. Therefore energy saving should be based mainly on knowledge, experience and a well-thought-out strategy [15]. Figure 9 shows an energy saving strategy according to DENSO (Japan) – the world leader in the manufacture of components for the automotive industry. The Kaizen management system TCM is based on four areas of continuous elimination of imperfections and management of the changes. The areas are: TFM (Total Flow Management), TPM (Total Productive Maintenance), TQM (Total Quality Management) and TSM (Total Service Management). Each of the areas has its own specific tools and techniques for improving the activity.

DENSO, not only as a global designer, producer and distributor of car components, has defined actions to be taken within the eco-production and eco-plant framework, including actions concerning the energy-intensiveness of products (their materials and production). The EU takes similar measures as part of its research programmes.

The strategy illustrated in Fig. 9 is based on the in-house development of production engineering technology and on the innovative operation of the equipment, with the whole plant participating in the improvement effort.

Thanks to the holistic approach to manufacturing systems, energy savings and cost cuts can be sought in different spheres. In many varieties of electrically driven production machines used for, e.g., mould casting and forming, energy consumption has already been reduced by half, the cost of equipment by 1/5-1/2, the occupied space by 1/3-1/2.

Substantial energy savings can also be made in abrasive machining through minimal quantity lubrication (MQL). It is estimated that the pumps and thermoregulators in manufacturing systems consume as much as 30% of the energy [11].

The improvement of machine tools and manufacturing systems will benefit the user (generally, the user of products). Taking this into consideration, TOYOTA has formulated its own improvement strategy which says that “one should ensure what is needed there where it is needed, in the required amount at the lowest needed energy possible, in accordance with the development of the components technology, ensure a proper

manufacturing system, equipment in a continuous way and equipment capable of development depending on the circumstances and the needs". This strategy is worth recommending to all manufacturing system producers and users for the fulfilment of business tasks.

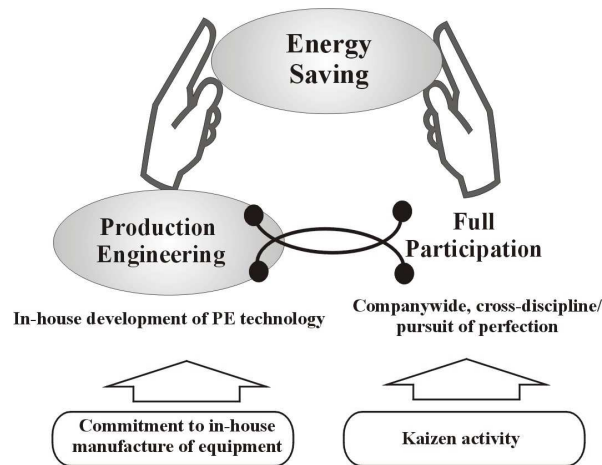


Fig. 9. DENSO style energy saving activities

5. CONCLUSION

The reduction of energy consumption by machine tools, machining processes and whole manufacturing systems is of great importance not only for the economical management of resources, but also for sustained development and increasing the competitiveness of products on the local and global market. The measures and strategies adopted so far have already resulted in significant energy savings. The consistent and effective reduction of the energy-intensiveness of product manufacturing requires energy conscious action using accurate modelling, numerical simulation and optimization based on the latest knowledge. It is also necessary to closely monitor energy consumption in order to be able to consciously and actively control machining processes to achieve the highest energy savings possible and the synergy effect.

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