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BRINGING SUSTAINABLE MANUFACTURING INTO PRACTICE: THE MACHINE TOOL CASE

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ABSTRACT

Bringing sustainable manufacturing into practical application demands knowledge of economic, ecologic and social impacts of industrial manufacturing processes. Against the background of rising costs of metals and energy as well as production induced environmental burden in combination with extending environmental regulations, it is increasingly desired to implement a sustainable manufacturing in order to minimize not only the economic load but also the potential environmental effects. Using an integrated process concept, which internalizes economic, ecological and social aspects, the relevant variables for improving the efficiency, consistency and sufficiency of manufacturing processes can be identified and options for improvement derived. In this paper in particular the possible strategies and practical applications to foster sustainability in manufacturing focusing on the machine and process level are described considering the strategies of a sustainable development.

KEY WORDS:

Sustainable manufacturing, machining processes, energy and material efficiency

INTRODUCTION

Metal working machine tools are used to create and finish products through removal of material using cutting tools. In various machining concepts, material removal processes (e.g. grinding, turning or milling) enable to produce variable quantities of products with high dimensional accuracy, flexibility, and cost-effectiveness (Klocke, F., König, W., 1997). Among the established machining operations, predominantly grinding is still a sophisticated procedure (especially as finishing operation), which is very cost-intensive due to the required machining equipment as well as operation and auxiliary materials (e.g. coolants). Applications of modern grinding processes cover today more and more the production of precision small-sized articles in mass production, e.g. components in the injection technology or the hydraulic industry. Therefore the demand for improved technical functionality increases further. The technical possibilities of processes are continuously improved by new technological devices, so that for instance same treatment results can be obtained with different procedures (e.g. achieving same work piece roughness by grinding or turning). Moreover, the application of manufacturing processes widens out on further ranges as high speed cutting and machining on micro-technological scale. Both are developed and applied in industry (Klocke, F., König, W., 2005 and Hesselbach, J., Hoffmeister, H.-W., Hlavac, M., 2005).

Machine tools require generally the usage of energy, compressed air and in particular coolants for operation. Among the several tasks of coolants, the reduction and absorption of the resulting process heat in the contact zone by cooling and lubrication has highest priority. Thus, the wear of the tool is reduced to an economic measure and the desired surface roughness of the work pieces is enabled (Klocke, F., König, W., 2005).

Since machining is predominantly a material removing process, the operation leads inherently to waste of material and energy through losses, heat and emissions (Dahmus, J. B., 2007). Against the background of increasing costs for materials and energy, the total costs of production will increase further and exert more pressure on manufacturing companies. Due to this development companies especially in the metal processing industry are looking for improvements in production processes in order to increase profitability, also with respect to the requirements of sustainable development.

In advance to the analysis and definition of potential variables for improving sustainability in manufacturing, a brief overview is given describing the consumption of material and energy (especially electrical energy and coolants) as well as estimations about the resulting potential environmental effects. On basis of these data, fields of actions can be identified and innovative strategies in alignment with a sustainable development proposed.

MATERIAL AND ENERGY CONSUMPTION IN THE METAL PROCESSING INDUSTRY

In the US, the electrical energy consumption of the metals processing industry (fabricated metal products) is published by the Energy Information Administration. From the statistics it can be concluded, that 47 billion kWh of the industry used electricity is consumed by the metal processing industry (see figure 1). This energy quantity corresponds to a portion of 5 % of the total industrial electricity consumption in the US (Adler, R., 2002 and Devoldere, T. et al., 2007). This equals approximately 35 Mio. t of electrical energy related carbon dioxide emissions (CO_2-equivalents).

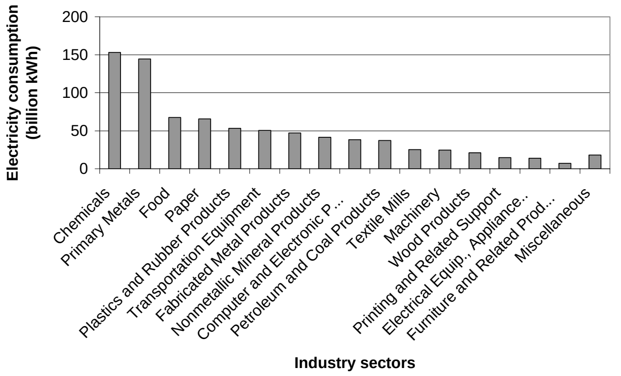

Figure 1: Electricity consumption per industry in the US (Adler, R., 2002)

In addition to the emissions related with the use of electrical energy (energy production and supply), further environmental issues of machining are directly caused by the use of cutting fluids. Coolants are indispensable system components that enable machining operations. They are used in more than 1 million machine tools in Germany and more than 1.8 million machines in the US (Murrenhoff, H., 2002 and Dahmus, J. B., 2007). The German market for coolants has a volume of more than 100.000 t/a. Mineral oil is the basis (with over 72.000 t/a in Germany) in cutting fluids for machining processes. All in all, the German metal processing industry consumes 1.15 million tons of mineral oil based products (e.g. coolants, hydraulic oils) per year. Their procurement and removal induce costs of approx. 3.3 billion € (BAFA, 2007).

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 %. The energy consuming machines of a production line in the automobile industry are displayed in figure 2. The results of the energy analysis show that metal cutting operations in machine tools 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 (Bode, H.-O., 2007). Obviously, the usage of coolants is connected with substantial energy expenditures for operation and treatment. Thus, the energy costs in the use phase can even exceed the acquisition costs.

With each operation of machine tools, material is transformed into valuable products using energy, compressed air, coolants and additionally generating used coolants, oil contaminated swarf and splinters as well as waste heat. Especially the use of mineral oil – in particular as base fluid in non-water miscible coolants – is connected to several critical aspects. Apart from the economic and ecological effects of using a non-renewable resource, multiple aspects as technically demanding cleaning procedures for processed products or health issues of people working with coolants at machines have to be considered and dealt with (e.g. established through administrative regulations as the Registration, Evaluation and Authorization of Chemicals (REACH)) (Herrmann, C., 2007a).

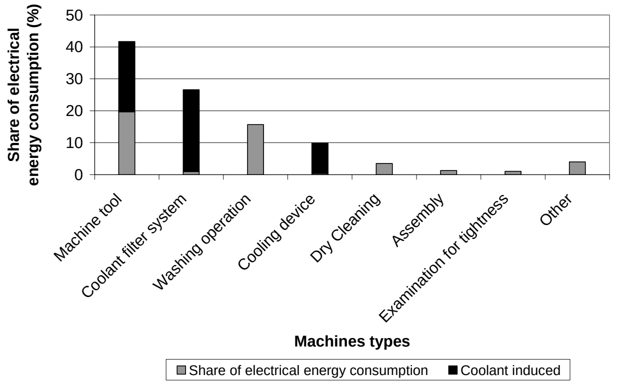

Figure 2: Energy consumers in production lines of a cylinder head manufacturing - aggregated from (Bode, H.-O., 2007)

Against the background of increasing processing costs (esp. induced by material and energy) and an increasing demand for protection of the environment and humans from negative impacts, starting points are to be identified that obtain an improvement of economic and ecological potentials. In order to reach these potentials, in particular sustainable solutions have to be derived and applied.

In the next section, the three strategies to improve the operation of machine tools with respect to the requirements of a sustainable development are presented.

STRATEGIES FOR SUSTAINABLE MANUFACTURING

Due to described changes, environmental and social aspects move closer into the focus of production companies. Thus, it is very obvious that an isolated consideration of traditional economic variables is not sufficient anymore. In fact, sustainability in manufacturing is the new necessary paradigm for manufacturing which involves the integration of the economic, environmental and social perspective (known as the triple bottom line) for all technological and organizational measures within the production management (figure 3) (Herrmann, C. et al., 2007b).

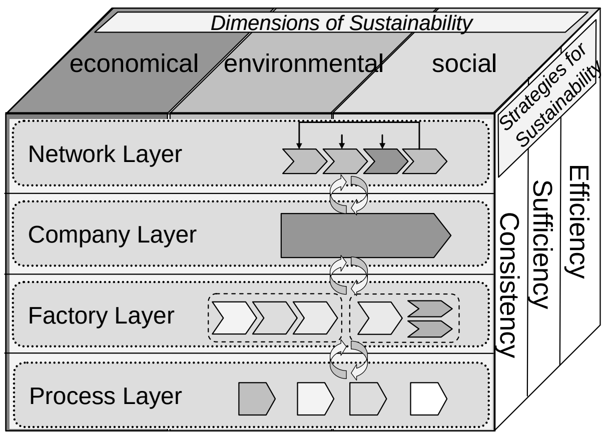

Figure 3: Framework for Sustainable Manufacturing (Herrmann, C. et al., 2008a)

As a holistic approach which strives to avoid problem shifting within producing companies, their supply chain and life cycle phases, this involves the consideration of all three basic strategies of sustainability (efficiency, sufficiency, consistency) on different layers beginning from the single (production) process, process chains on a factory layer, strategic decisions on a company layer or activities in closed looped supply chains like utilizing Re-X-options, such as remanufacturing or refurbishment (network layer) (Herrmann, C. et al., 2008a and Herrmann, C., 2007c).

In figure 4 the strategies of a sustainable development are visualized. While efficiency strives to minimize the material and energy usage in all life cycle phases by increasing resource productivity, sufficiency demands a change in the behavior of usage and consumption. The third strategy of sustainability is consistency, which can be defined as the adaptation of material and energy flows to fit adequately to biological process capacities.

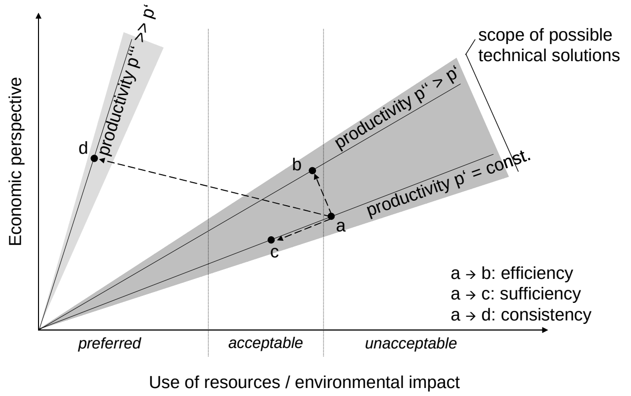

Figure 4: Strategies of a sustainable development (Schmidt, M., 2008)

Highest improvements in sustainability can be achieved by the preferential application of the strategy consistency, since this forces the substitution of processes, with which the potential environmental impacts are minimized and harmful materials are avoided. In contrast, the application of the strategy efficiency can result in *rebound effects*, if for instance the energy conservation from an efficiency improvement is used up by the integration and use of further energy receivers (Dahmus, J. B., Gutowski, T. G., 2004).

The interactions with pre-placed processes or system-oriented effects upon higher levels (e.g. in process chains or on factory level) can have significant impacts. They have to be considered in advance to the implementation of strategies. In the context of this work the focus is put on a single machine with its surrounding equipment that ensures a functional mode of operation.

BRINGING SUSTAINABLE MANUFACTURING INTO PRACTICE – THE MACHINE TOOL

Material and energy flows in machining operations

An integrative view of sustainability in production demands naturally the knowledge, measurement and evaluation of economic, ecological and social effects of production processes. Therefore an integrated process concept is necessary, 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) and includes beyond that ecological aspects (Herrmann, C. et al., 2007b).

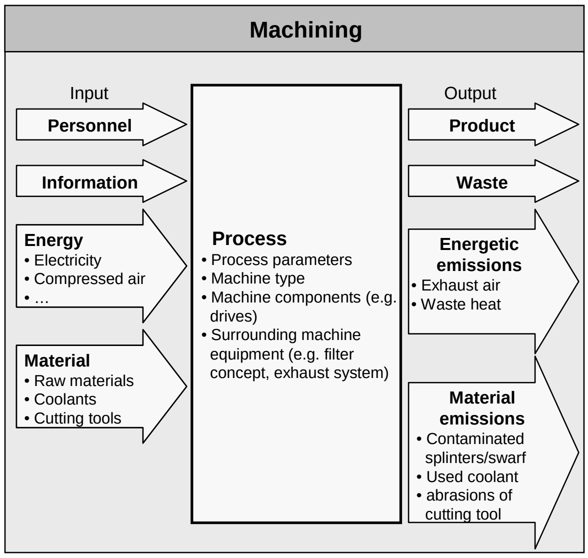

Figure 5: Integrated process concept for machining operations (adapted from Schultz, A., 2002)

Analyzing the inputs and outputs of machining, however, is complex as especially outputs are diverse (e.g. vaporization of coolants in air and heat loss) and not always quantifiable. In figure 5 the material and energy flows of a typical metalworking operation (e.g. grinding) are listed. Electrical energy, compressed air, cutting fluids, and raw material have to be considered as main inputs. 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 (Herrmann, C. et al., 2007).

Furthermore, the quantities of the respective energy and material flows are also determined in particular by the machine type (e.g. highly automated machining center), pumps and hydraulic systems as well as operating system (programming), the adjusted process parameters and the available peripherical subsystems (e.g. filter system) (Dahmus, J. B., Gutowski, T. G., 2004). 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/or the production setting (Eckebrecht, J., 2000 and Herrmann et al., 2007b).

As an example, the energy demand of a grinding machine with its individual energy profile is presented in figure 6. 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 (Eckebrecht, J., 2000). 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.

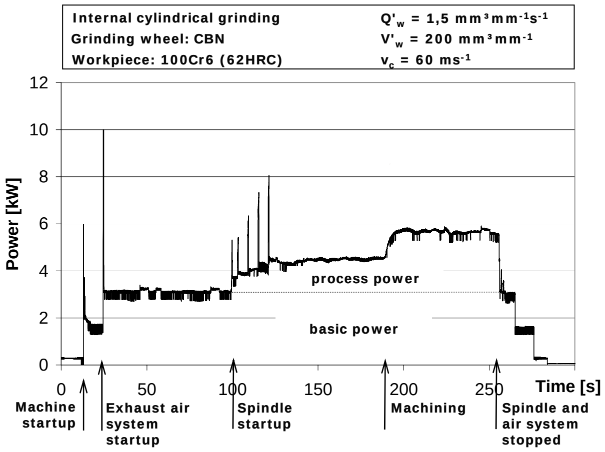

Figure 6: Electrical energy consumption of a grinding process (excluding filter system)

In the context of an integrated consideration of economic and ecological effects, in particular energy profiles are an important basis for deriving optimizations to improve sustainability in manufacturing.

Improving sustainable manufacturing in practice

In addition to using machines, which do not produce or at least have less environmental impacts due to their mode of operation, in particular the industrial employment of pollutant-free raw, auxiliary and operating materials is a promising approach. In the following section, possible measures are described which enable improvements in metal cutting processes with respect to the requirements of a sustainable development. The enumeration is not intended to lay a claim on completeness and focusing the following main subjects.

Energy

The consideration of energy profiles is an important basis for sustainable production optimization. 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 6) 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 (Hesselbach, J. et al., 2008).

In previous studies, Dahmus, J. B. and Gutowski, T. G., (2004) 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 (Dahmus, J. B., Gutowski, T. G., 2004).

The results from the mentioned studies were also determined by Devoldere, T. et al. (2007) for bending and milling operations.

Cutting fluids

Considering economic and environmental aspects of machining, fundamental concerns are linked to the use of coolants. Cutting fluids can have severe influences on the environment. Apart from the extraction of non-renewable resources as mineral oil, cutting fluid use, preparation, cleaning and recycling in production companies are directly connected to liquid and hazardous waste and health, environmental, economic and safety issues (Herrmann, C. et al., 2008b). Up to 30 % of coolant in machine tools can be lost through vaporization (which can be harmful to workers if substances are inhaled), adherences on work pieces and swarf or in the worst case through leakage (Byrne, G., Dornfeld, D., Denkena, B., 2003).

Against this background, possible solutions focus on the implementation of dry machining operations or minimum quantity lubrication (less than 50 ml/h) and the substitution of coolants through environmentally friendly coolants.

Dry machining (sufficiency) and minimum quantity lubrication (efficiency) are possible solutions to impede or at least reduce the issues of coolants. However, these strategies centre the problem but are often not realized or applicable on a comprehensive industrial scale. Especially grinding processes still depend on the use of coolants as over 90 % of the grinding power is converted into frictional heat and has to be absorbed. So far the removal of the induced heat in industrial grinding operations is yet not realized with dry machining technology or with reduced lubrication.

In addition to avoiding coolants, research activities have focused on the development of alternative coolants with minimum environmental impact (Herrmann, C. et al., 2007d and Dettmer, T., 2006). These have to be considered within a life cycle management framework (technological, ecological, economic and social aspects) in order to avoid the shift of risks and problems from one life cycle phase to another. While it is easy to simply exchange mineral oil for substances (e. g. plant seed oil), the economic and ecologic impacts of these coolants have to be observed for benefits or detriments of product use over all life cycle spans from raw material extraction, to use and disposal. This includes also local and global aspects as raw material availability.

As a current example, the use of rapeseed or palm oil as an alternative energy and coolant resource lead to a competitive situation with food provision and induced a drastic rise of prices. New substitutes for mineral oil coolants are water miscible bio polymers. The bio polymers are natural resources with a high industrial availability. They dissolve in water and can be used - enriched with additives - to set up clear water based lubricants (share of water > 90 %) with a higher specific heat capacity compared to mineral oil. Technical grinding experiments have proven even higher performance capability. Apart from reduced grinding forces in operation, the polymer fluid also enables to reduce the energy demand (e.g. no extra cooling necessary) and environmental impacts (Herrmann, C., Bock, R., Zein, A., 2007e). In table 1 the advantages of water based coolants are compared to mineral oil based coolants.

Table 1: Potentials of water based polymer coolant

	Polymer fluid
Raw material	➢ water is an infinite resource (thermodynamics) ➢ high availability of bio polymer ➢ cheap resources
Use phase	➢ high technological suitability compared to mineral oil ➢ no flashpoint ➢ renouncement of safety and fire protection mechanisms ➢ avoidance of oil residues on products and process residues in the machine and production area ➢ decrease of coolant induced specific electric power consumption (no cooling device required) ➢ avoidance of wash automats in process chains
Disposal	➢ simple disposal (e.g. vaporization)

The results of a life cycle assessment (LCA) for bio polymer fluids indicate less environmental impacts compared to mineral oil (see figure 7). The environmental impacts of a polymer fluid and mineral oil coolant have especially been analyzed for the raw material extraction and use phase. Figure 7 visualizes that the use of the polymer fluid reduces substantially the depletion of abiotic resources and has lower toxic impacts on humans and the environment.

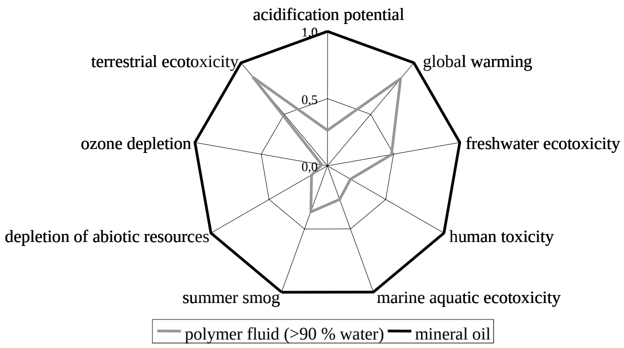

Figure 7: Reducing environmental load by substitution of mineral oil based coolants

All in all, the substitution of coolants enables significant reductions in energy consumption and environmental impacts. The usage of water-based coolant systems effects directly machine-related aspects but also reveals multiple improvement potentials along the process chain (compare figure 2). In this case, the substitution of coolants reduces instantly the environmental impact and moreover initiates further efficiency improvements at the same time.

Auxiliary components

Complementary to using energy efficient electrical drives and compressed-air devices, further potentials of auxiliary components to foster a sustainable manufacturing include resource-preserving filter technology and extractive oil removal procedures.

In machining operation, work piece particles necessitate an effective filtering in order to avoid negative influences of the particles in the chipping area and to allow a long-lasting use of the coolant. The filtering of these particles from the material flow is possible by using conventional filters with consumables or edge filters. A special characteristic of edge filters is that it lacks filtering consumables (e.g. cellulose). In contrast to filters with consumables, these filters extract only metal swarf from the coolant. Thus, the residue can directly be reused as secondary raw material and must not be disposed as waste material.

A second auxiliary device which can improve the economic and ecological performance of production companies is the extractive oil removal. In Germany, about 180.000 t to 200.000 t of oil contaminated metals cutting residues accumulate annually from the surface finishing of grinding processes (Schön, J. et al., 2003). This oily metal swarf has to be handled as hazardous waste. If one separates the metal from the coolant, however, the coolant can be reused in the subsequent machining processes. The oil-free swarf can be recycled after having been pressed to pellets and reused in steel mills.

Substitution of processes by sustainable process alternatives

In a previous study, Gutowski, T. G., Dahmus, J. B., Thiriez, A., (2006), analyzed the energy demand of 36 processes out of 10 manufacturing technologies (see figure 8). The processes in the lower right hand represent more conventional processes, while those in the upper left hand are newer technologies or advanced machining processes. In conclusion, modern processes enable to produce smaller dimensions and scales with larger specific electrical energy requirements. Apart from the optimization of individual machine components, a high potential to improve sustainability in manufacturing can be obtained by substitution of manufacturing processes with processes that are less energy-intensive (Gutowski, T. G., Dahmus, J. B., Thiriez, A., 2006).

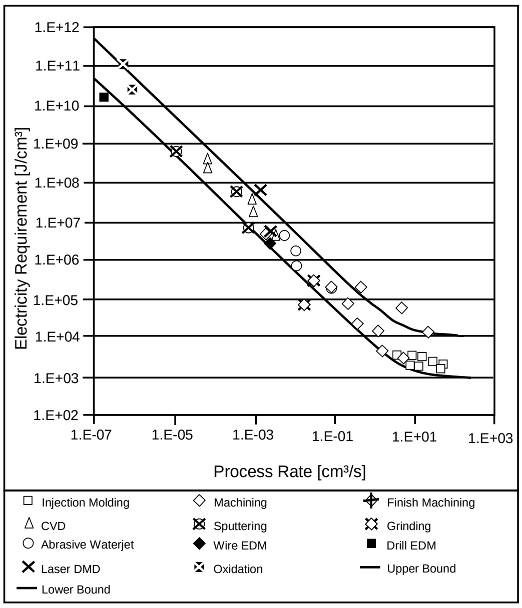

Figure 8: Specific electricity requirements for various manufacturing processes (Gutowski, T. G., Dahmus, J. B., Thiriez, A., 2006)

CONCLUSION

The analysis presented in this paper has pointed out that especially the material and energy consumption of machine tools increasingly exerts economic and ecological pressure on production companies. With respect to the requirements of a sustainable development, practical measures for companies need to be derived to improve their economic and ecological performance. In this paper, measures especially to improve energy efficiency of machine tools and to reduce environmental, costs and health issues of coolants are discussed.

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