GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

12.3 Ecological evaluation of PVD and CVD coating systems in metal cutting processes

F. Klocke [1], B. Döbbeler [1], M. Binder [1], N. Kramer [2], R. Grüter [2], D. Lung[1]

[1] Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Germany
[2] KOMET Group GmbH, Besigheim, Germany

Abstract

Due to the ongoing demand for sustainability assessments regarding manufacturing processes, this paper concentrates on the factor of coated cemented carbide tools. Previous publications have shown the potential ecological benefit of coated vs. uncoated tools. In this paper data which has been gathered from the KOMET group providing PVD- and CVD-coatings as well as sound assumptions for the assessment of coatings for cemented carbide tools, especially for indexable inserts, will be presented. Furthermore, the performed ecological assessment and its respective results will be shown. These results can be used for further and broader studies regarding the impact of cutting tools within manufacturing. Finally, the use of coatings for cemented carbide tools and their advantageousness will be discussed.

Keywords:
Ecological evaluation, Sustainability, Manufacturing

1 INTRODUCTION

The scarcity of resources, not only energy resources such as oil or natural gas, but also noble earths and metals like zinc and copper stands in sharp contrast to the tremendously rising demand for goods and services due to growing world population and the striving for a higher living standard in emerging economies. In order to meet the challenges which accrue from this fact, more transparency concerning energy and material consumption is required. Furthermore, the outlined development causes severe environmental concerns. Phenomena like the global warming are very complex and the impacts of processes are hard to quantify.

The Life Cycle Assessment methodology is a widespread procedure to both foster the understanding and transparency of material and energy streams and to generate resilient conclusions about the ecological performance. Whereas Life Cycle Assessments in the narrow sense cover the entire Life Cycle of a product embracing raw materials production, manufacturing, use and recycling or disposal, the assessments in the area of production often focus on the phase of manufacturing [1][2]. The perspective is also called the cradle-to-gate point of view which takes raw materials exploitation, processing and manufacturing into account. The results of cradle-to-gate investigations can be combined with results obtained for the use and disposal phases in order to achieve a holistic Life Cycle Assessment.

The manufacturing sector is the backbone of modern economies. As such it allows for employment, prosperity and innovation. A contribution of the manufacturing sector is indispensable for a sustainable development, since much energy and resources are spent for production directly and indirectly. Furthermore, the energy and material consumptions of many products, such as gas turbines or combustions engines, are extensively affected by the manufacturing phase. Therefore, manufacturing is a key sector to enable a sustainable development. [3]

Aware of their responsibility, many companies define and communicate targets for them selves regarding environmental issues. The reduction of equivalent carbon dioxide emissions for instance is a prevalent goal for companies. Therefore, it is necessary to assess industrial production to obtain the ability of comparing the goals with the achieved progress. Furthermore, environmental issues increasingly gain importance for marketing reasons. Customers ascribe a rising importance to the sustainability of products. Some automotive companies even commit their suppliers to provide information about environmental issues such as the carbon footprint [4][5].

The metal working industry is affected by this development. Since the EU 2009 explicitly identified the machine tool as a energy using product [6] with a high improvement potential concerning energy efficiency, many initiatives [7] and scientific projects [8] dealt with the machine tool hardware and software and aimed at a higher efficiency. Besides, the processes have been analysed and balanced [9][10]. It has been shown, that in metal cutting, the energy and resource consumption per manufactured part is highly dependent on the chosen set of machining parameters. If the use of cutting tools is neglected, the efficiency of the metal cutting process rises with higher cutting parameters. This is due to two reasons. Firstly, the metal cutting itself becomes more efficient [9][10]. Secondly, the base load of the machine tool which is caused by hydraulics, ventilation or coolant pumps for instance can be attributed to a higher output and thus the efficiency rises. Because the use of the cutting tools needs to be taken into account for a holistic analysis, the production of the cutting tools including an optional coating needs to be assessed. The increase in cutting parameters under consideration of the efforts for tool production leads to opposing trends. Whereas the process itself is more efficient, the expenditure of cutting tools is higher. An optimum in the process design can only be determined if the cutting tools are thoroughly balanced and assessed.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

2 COATINGS IN METAL CUTTING PROCESSES

In this chapter of this paper, the basic properties of CVD and PVD processes in general and the investigated processes in detail have to be elaborated in order to evaluate the results later on.

Coatings in metal cutting processes are supposed to increase the productivity due to higher cutting parameters as well as the wear resistance of the tools. Since most of the cutting tools nowadays are coated, the importance of the underlying process and the necessary environmental impact has grown significantly. Coatings are used to decrease the effects of the causes for wear development, namely abrasion, adhesion, oxidation and diffusion [11].

On the one hand, coatings prohibit the mechanisms of adhesion, oxidation and diffusion due to their surface properties and act as a barrier between the workpiece and the tool material. The coating itself has to be worn off in order for the tool substrate to be affected. On the other hand, the coating material itself usually features high hardness and thermal stability and thus is able to withstand the mechanical and thermal loads of cutting processes in an enhanced manner. By using coatings, the cutting parameters and therefore the productivity often can be increased [11]. Furthermore the coatings need to be selected carefully, since different work piece materials require different coating systems in order to increase productivity or process stability.

Additionally to these basic properties of coatings, it is necessary to emphasize that the coating process itself should not reduce the inner bonding strength, e.g. the toughness of the substrate, whilst applying the necessary tool wear development inhibition features. For coating cemented carbide tools several processes are available which can be divided into physical vapour (PVD) and chemical vapour deposition (CVD). A short overview about both process designs is necessary for the underlying investigations. CVD processes take advantage of chemical reactions in a gaseous phase under vacuum conditions (10^3-10^5 Pa). With help of thermal energy hard materials such as TiC and TiN can be formed and chemically applied to the substrate material. This chemical reactions highly rely on the partial pressure of the gaseous components and the temperature of the process [11]. In the investigated process gases such as hydrogen (H_2), nitrogen (N_2), methan (CH_4), carbon monoxide and carbon dioxide (CO, CO_2), titaniumtetrachlorid ($TiCl_4$) as well as acetonitrile (CH_3CN) were measured, see Figure 1.

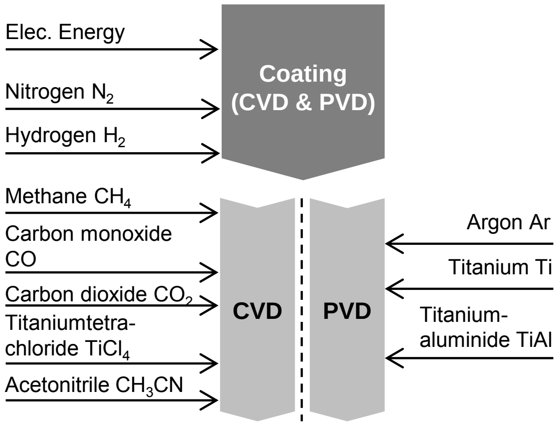

Figure 1: Measured data in the CVD and PVD process

Furthermore, the necessary electrical energy has been acquired during the process time. The investigated coating is TiCN-TiN-Al_2O_3. The small amount of Al_2O_3 could not be measured and therefore is neglected.

Both process designs can further be sectioned into different process principles. Within this paper a sputter PVD as well as a high temperature CVD process, which are common for applying coatings for metal cutting, are highlighted and investigated.

PVD sputter processes are fueled by an inert gas, often argon, which is ionized by applying high voltage in a low pressure plasma. This positive inert gas is accelerated on the target switched as a cathode and thereby knocks out atoms, molecules of the coating material via impulse exchange. This target material then applies on the substrate material on the one hand because of the high speed as well as due to a condensation process on the other hand. Beside the electrical energy, during the investigations argon (Ar), nitrogen (N_2) and hydrogen (H_2) gas have been measured in order to provide solid data for the whole process. The applied coating is TiAlN/TiN. Both results can be seen in the results part.

CVD and PVD coating principles lead to different properties of the cutting tool coatings. In a sputter PVD processes the bonding power of substrate and coating is not as high as in CVD processes. CVD processes on the other hand have the big advantage of being able to coat complex geometries due to the gaseous chemical reaction. PVD processes have a direction-based principle, which leads to the necessity to turn all tools during the process in order to assure a evenly distributed coating. One very important difference is the generation of residual stresses in the substrate and coating. Whereas by a PVD process usually residual compressive stress can be observed, CVD processes often induce residual tensile stresses. For the application in cutting processes, the compressive stresses prohibit crack initiation and further crack development and are therefore more valuable in many situations. Also the PVD principle, specially the sputter process, does not require very high temperatures, such as the high-temperature CVD process. This is beneficial when coating high speed steel (HSS) substrate materials, because by typical HT-CVD temperatures the material itself will be altered with respect to the material structure similar to a heat treatment process [11].

Furthermore the different principles for applying coating materials offer various possibilities with respect to coating thicknesses and coating materials. For the most common materials such as TiN, TiC, Al_2O_3 both principles are possible. Diamond-like-carbon coatings and diamond coatings itself are applied using CVD-techniques. [11]

In the following Figure 2, the typical process chain of cemented carbide cutting tools, including the coating processes, is shown. Usually the metal powder is prepared and sintered. Furthermore, additional processes such as grinding for complex geometries, i.e. for chip breakage, or the application of coating are possible finishing operations. In order to provide valuable data several variations have been investigated.

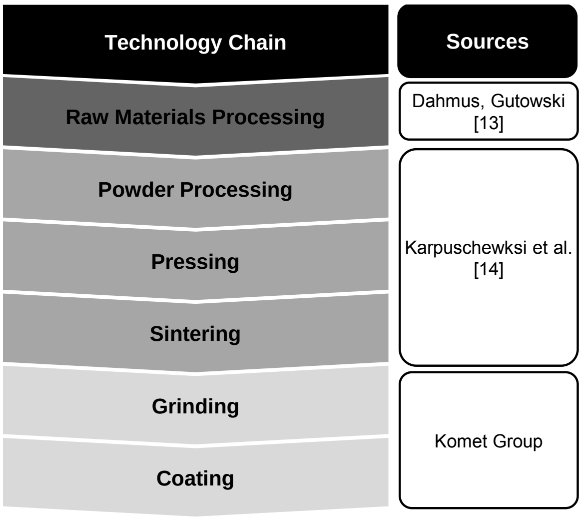

Figure 2: Underlying technology chain for the indexable inserts

The additional grinding processes as well as the coating process are not performed for every tool. In the investigations the whole process chain has been evaluated in order to estimate the relation of coating processes to the whole efforts for the finished cutting tool.

For the final application in industrial cutting processes, the information how high the impact of applying coatings and finishing grinding operations actually is, can change the ecological advantageousness. As already mentioned, the application of coatings may allow higher cutting parameters. These higher parameters usually lead to a reduced energy consumption per volume during the process due to the reduction of process times. Furthermore, this reduction leads to less consumption of the non-process related components of machine tools such as hydraulic systems, lubricoolant pumps and the control unit, which often are responsible for the major share of the total power consumption. Still, high performance cutting processes, in which the major share of the power consumption can be lead back to the process forces, may not show reduced energy consumptions due to the working point of the spindle motor or machine tool components. From a theoretical point of view higher cutting parameters such as increased cutting speed or feed, lead to lower process consumptions. The cutting forces increase degressively whereas the material removal rate increases linearly. Previous works already focused on the influence of the different cutting parameters and the effect of the component related consumptions [9][10]. It can be stated that the application of coatings often leads to energy consumption reductions per part due to shorter process times. On the contrary, additional efforts have to be invested into the application of the coatings, which are the main focus of this paper.

3 METHODOLOGY

The evaluation procedure is based on the LCA methodology in accordance with DIN EN ISO 14040/14044 [1][2]. This widely accepted systematic approach offers a framework to assess the ecological performance of a product. The approach is divided into four steps, as visualized in Figure 3. In a first step, the appropriate definition of the balance shell is set and a functional unit is specified. The results of a LCA are always related to a functional unit as it is a relative approach. The functional unit can be a product, i.e. a tool or a coating, or more abstract the transportation of a ton of goods over one kilometer. The functional unit is a quantitative measure of the functions that the good or the service provides [12]. In addition to the balance shell and the functional unit, the impact categories of interest have to be named. The impact category specifies the environmental category of concern such as climate change or the scarcity of resources. Finally, the goal of conducting the study is of crucial importance to the the entire investigation as it determines the specification for the study.

Subsequently, the energy and material flows within the specified balance shell are determined and quantified. The data acquisition within this second step of inventory analysis can be based on different strategies. The material and energy flows can be measured, calculated, estimated or provided by data available in accountancy. Both, effort and quality of the executed LCA dramatically depend on the data acquisition. Therefore, the data acquisition needs to be performed as detailed as necessary to meet the goals set in the first step. Nevertheless, as the data acquisition is a major effort in the entire approach, it should not be performed as detailed as possible.

The result of the inventory analysis is a input/output-balance of the investigated process, which is not yet assessed. It covers different material or energy streams that cannot be directly compared, as they are measured in different units. Thus, in a third step, the inventory data is assessed. During the assessment, the environmental significance of a certain flow against the background of an impact category or several categories is evaluated. Thus, the perspective changes from a exclusively quantitative to a qualitative perspective. Impact categories are a set of scientifically elaborated factors. They quantify the theoretical impact of every material and energy flow gathered within the inventory analysis. The most discussed impact category for example is the Global Warming Potential which, is measured in kg CO_2-Equivalents. For the assessment of the energy and material flows, the use of Life Cycle Inventory Databases is widespread. These databases contain sets of factors that can be used to assess common energy and material flows against the background of common impact categories.

In a fourth step, the generated results are critically questioned, checked for consistency and carefully interpreted due to the fact that the results of a LCA need to be considered as potential effects, not actual effects. Although the LCA follows the described four-step procedure, it’s progress should be understood as iterative. As the steps are interdependent, a critical reflection of the results may lead to an adaption of the chosen balance shell or assumptions made and thus may lead to another iteration through the four steps.

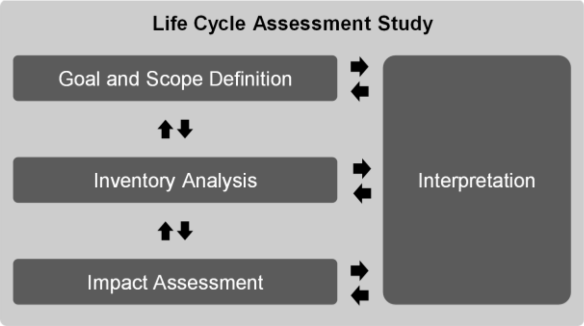

Figure 3: Framework of LCA according to DIN EN ISO

The case study of this paper bases on the described procedure. The goal of the study was to identify the energies and materials that are expended for the coating of tools for metal cutting. The motivation of KOMET was to investigate the environmental performance of their products and to proactively give customers information about performance indicators, such as the carbon footprint of their products. In order to meet that goal, a cradle-to-gate analysis was performed on a set of products, in a first step. These products cover coated and uncoated indexable inserts, solid carbide twist drills, drills for indexable inserts, replaceable drilling and drilling heads and a standard tool holder and thus, a representative set of products. In this paper the focus lays on insert cutting tools of two different sizes (small: 5 mm, big: 12 mm).

For the balance shell the cradle-to-gate approach was selected and thus the raw material production was accounted for by using data from the literature [13][14]. The energy and material flows for the process chain were quantified by both measurements and estimations combined with data obtained by the ERP system. The measured processes include the cutting tool grinding and coating, which is performed at the company. In order to provide holistic data, the infrastructural consumptions, such as lighting, heating and pressurized air, have been accounted to the single processes. Yearly calculations and the total machine hours have been used to determine key consumption indicators per machine hour. In this scenario only the consumptions of the production areas have been considered. With this approach the carbon footprint of cutting tools can be provided. Nevertheless, the infrastructural efforts have been neglected for this paper, in order to compare the processes on a technological level.

The environmental data for different materials has been gathered from the life cycle assessment software Gabi 5 [15]. In order to provide reliable results the assumptions during material attribution has to be elaborated. For H_2, N_2, CH_4, CO, CO_2, Ar and Ti values were taken from the software database. Since raw titanium usually can be gathered from $TiCl_4$ as an intermediate product, titanium values were used as a estimation to the safe side. This investigation lacks clear data for H_2S, therefore these small consumptions are neglected. CH_3CN is a joint product of the acrylonitrile production. Therefore this material with a factor of 50 % has been used.

4 RESULTS

As stated in the methodology approach of this paper, the results can be divided into different sections. Firstly, the comparison of the different coating procedures is obvious. In this case, the high temperature and middle temperature CVD vs. the sputter PVD. Secondly, the influence of the grinding and coating process after the sintering of the metal powder will be highlighted in order to estimate the relations of necessary consumptions during the manufacturing of the substrate, complex geometries and the coatings. This also leads to the cradle-to-gate balance shell, which includes all processes of the technology chain of the cutting tool manufacturing excluding the industrial application in cutting processes.

In Figure 4 both coating technologies for the two different cutting inserts are compared. The figure envisions the shares of primary energy demand for different processes, the material, grinding and coating (electrical and gases). The scale of the diagrams are different as the production of the bigger insert requires more than 10 times the primary energy demand of the small insert due to the higher volume and thus higher efforts for the substrate material itself. Also the CVD coated big insert is slightly bigger (13,2 instead of 12 mm) than the PVD-coated insert, which accounts for the higher material energy demand shown below.

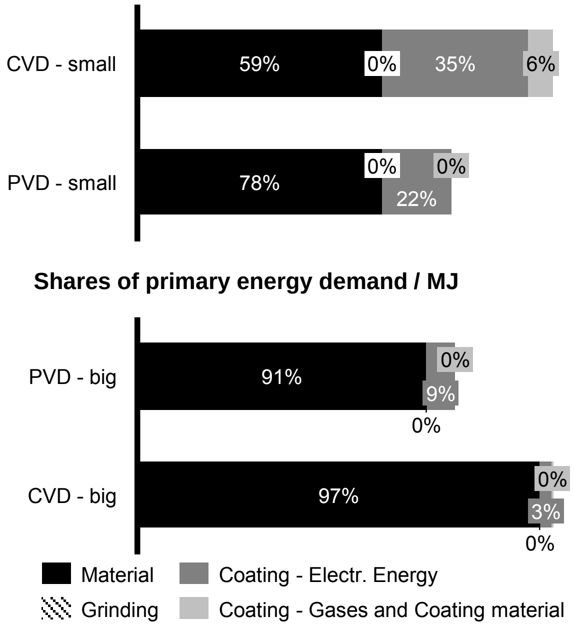

Figure 4: PVD vs. CVD coating process (small and big insert)

The figure above shows that the investigated PVD coating process usually demands less electrical energy as well as efforts for the gases during the process. Especially for the smaller tools this finding can be observed as the impact of the substrate material is not as dominant as in the manufacturing of the big insert. Furthermore, the results show that the influence of the process gases is mostly neglectable, especially for the PVD process. During the high temperature CVD process hydrogen and titanium tetrachloride have the most significant impact by far. Still it only contributes a small share to the total consumption of primary energy of the investigated coating processes.

The second result diagram can be found in Figure 5. It also envisions the shares of primary energy demand. In this case the PVD-coated 12 mm cutting insert from the previous figure is compared to inserts, which a grinded after sintering. This leads to much higher demands of primary energy. Grinding of tools it not always necessary. Data from KOMET Group states that around 30 % of the inserts have to be ground and therefore require the additional effort shown below.

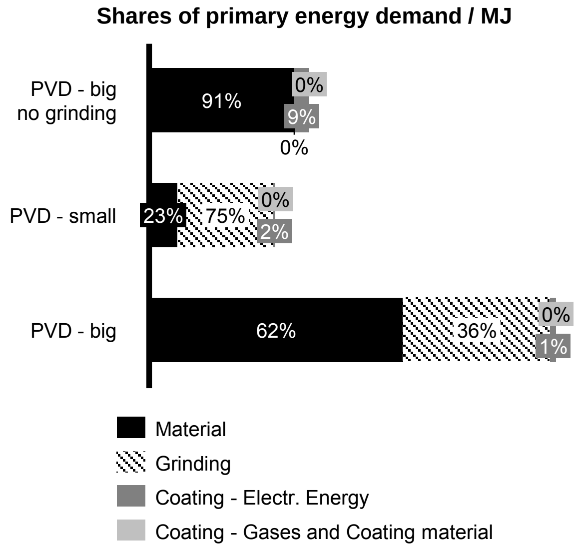

Figure 5: Geometry grinding vs. no finishing process

The small PVD-coated cutting insert, which needs to be ground after the sintering process due to required complex geometries such as chip breakers or cutting edge roundings, demands almost as much primary energy as the big PVD-coated insert without any grinding process. When highlighting the big tool with complex geometry requirements, thus necessary efforts due to grinding, the increased primary energy demand is even more significant. The demand of the big and ground PVD-coated insert is more than doubled in comparison to both inserts (small PVD-coated and ground, small PVD-coated) shown in the figure above.

Basically, the share of the coating process decreases with the increasing size of the cutting insert due to the material and grinding efforts. This is easily explained by the process principle, which allows to coat several thousand parts in one process. Nevertheless, the grinding process can only handle a few work pieces at a time on a machine tool.

5 CONCLUSION

As shown in the results part of this paper, the ecological impact of manufacturing cutting tools highly depends on the final geometry complexity, the size of the tools and the coating. Whereas manufacturing efforts of small CVD-coated tools may be influenced by the coating process in relation to the total manufacturing demands due to the small weight, manufacturing efforts for bigger tools (12 mm) are not significantly influenced by the coating process. This can change for very big and complex tools, since less numbers of tools can be coated simultaneously. Furthermore, the PVD process, which is less consuming in respect to gases and electrical energy compared to the CVD-process, cannot be used for any desired geometry due to the directional principle of applying the coating material and thus the necessity to turn the work pieces. Therefore higher consumptions have to be tolerated, if only CVD-coatings can achieve the necessary properties.

The shown results indicate that for a broad bandwidth of cutting inserts without complex geometries the accounting of the material is of utmost importance and leads to valuable results, which can be used for the carbon footprinting. With respect to complex geometries the machine tools necessary should be included into the investigations, because of their significant impact on the total manufacturing efforts of cutting inserts.

As shown in previous works, the advantageousness of coatings for cutting tools depends on the productivity and tool life time benefits provided by the coating [16]. As the results show, already small benefits may lead to the desired increased material and energy efficiency. Coating efforts do not account for more than 10 % of the total manufacturing efforts of the tools in this investigation, except for very small tools. Savings can mainly be achieved by using less tools, thus less primary energy demand.

It might be interesting to investigate very big and complex cutting tools in order to determine the impact of the material and the processes under more extreme conditions.

The investigations of this paper lead to further research areas, as the real connection between the necessary ecological impact during manufacturing cutting tools and the application including the tool life time and process parameters has not been finally established. Further investigations may lead to empirical decision supporting models and methodologies, which enable especially small and medium-sized enterprises to choose suitable cutting tools from an economic and ecological point of view.

6 ACKNOWLEDGMENTS

The authors of this paper would like to kindly acknowledge the support and data supply performed by the KOMET Group GmbH.

7 REFERENCES

[1] DIN EN ISO 14040 (November 2009). Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen.

[2] DIN EN ISO 14044 (Oktober 2006) Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen

[3] Brühl, J.; Döbbeler, B.; C. Essig C. Hein C. Herrmann P. Jahns M. Kleinjans F. Klocke D. Lung R. Schlosser A. Werner: Nachhaltige Produktion. In: Brecher, C.; Klocke, F.; Schuh, G.; Schmitt, R. (Hrsg.): Tagungsband Aachener Werkzeugmaschinenkolloquium 2011. Aachen. Aachen: Shaker, 2011, S. 196–227.

[4] BMW Group: BMW Group International terms and conditions of purchase for production material, 2010.

[5] DAIMLER AG: Daimler Nachhaltigkeitsbericht 2011, 2012.

[6] European Comission (2009). Guideline 2009/125/EG

[7] N.N. (2011): Zukunft im Blick – Nachhaltigkeit und Effizienz in der Produktion (Blue Competene, VDW)

[8] Brecher, C.; Triebs, J.; Heyers, C.; Jasper, D. (2012): Effizienzsteigerung von Werkzeugmaschinen durch Optimierung der Technologien zum Komponentenbetrieb –EWOTeK. Apprimus Verlag,, ISBN 978-3-86359-088-8

[9] Schlosser, Ralf; Klocke, Fritz; Lung, Dieter (2010): Energy and Resource Consumption of Cutting Processes. How Process Parameter Variations can Optimise the Total Process Efficiency. In: CIRP (Hg.): 17th CIRP International Conference on Life Cycle Engineering (LCE 2010). 19.05-21.05, Anhui, China, 19.05-21.05.

[10] Schlosser, Ralf; Klocke, Fritz; Lung, Dieter (2010): Sustainability in Manufacturing. Energy Consumption of Cutting Processes. In: Günther Seliger und N. Khraisheh M. K. Ibrahim (Hg.): Proceedings on the 8th GCSM conference. GCSM 2010, Abu Dhabi, 22.-24.11.2010.

[11] Klocke, Fritz (2011): Manufacturing Processes. Berlin, Heidelberg, New York: Springer (RWTH edition).

[12] Finnveden, G.; Hauschild, M.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S., 2009, Recent developments in Life Cycle Assessment, in Journal of Environmental Management, S. 1-21.

[13] Dahmus, J.; Gutowski, T. (2004): An Environmental Analysis of Machining. Proceedings of IMECE2004. S.1-10

[14] Karpuschewski, B.; Kalhöfer, E.; Joswig, D.; Rief, M. (2011): Energiebedarf bei der Herstellung von Hartmetallwendeschneidplatten. In ZWF 09, S. 602-605

[15] GaBi 4 / GaBi 5: Software und Datenbank zur Ganzheitlichen Bilanzierung. IKP, Universität Stuttgart und PE International AG, Leinfelden-Echterdingen, 1999-2011. www.gabi-software.com.

[16] Klocke, Fritz; Döbbeler, Benjamin; Binder, Marvin; Schlosser, Ralf; Lung, Dieter (2013): Ecological Assessment of Coated Cemented Carbide Tools and their Behavior during Machining. In: Re-engineering Manufacturing for Sustainability. Proceedings of the 20th Cirp International Conference on Life Cycle Engineering, Singapore 17-19 April, 2013: Springer Verlag.