21st CIRP Conference on Life Cycle Engineering

Eco-Efficiency of alternative and conventional cutting fluids in external cylindrical grinding

Marius Winter[a]*, Christoph Herrmann[a]

[a] *Institute of Machine Tools and Production Technology (IWF), Sustainable Manufacturing & Life Cycle Engineering Research Group, Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany*

* Corresponding author. Tel.: +0049-531-391-7154; fax: +0049-531-391-5842. *E-mail address:* m.winter@iwf.tu-braunschweig.de

Abstract

Grinding is a common finishing process to meet specific technological requirements such as a specific surface roughness or a high geometrical accuracy. The achievements of these requirements are influenced by the workpiece properties, the process parameters and different enabling factors. One of these enablers is the cutting fluid. The fluid type and composition has a major impact on the grinding process and therefore on the overall technological, environmental and economic impact of the product. This paper presents an approach to evaluate the environmental and cost influence of alternative and conventional cutting fluids in grinding by calculating their impact and eco-efficiency.

1. Introduction

Grinding, a machining process with geometrically undefined cutting edge, is commonly used as a finishing process. Purpose of the grinding process is the achievement of specific requirements such as a high surface roughness or a high geometrical accuracy. However, the achievement of this technological objective occurs under the consideration of economic and environmental objectives. These objectives partially constrain and partially support each other [1].

Nomenclature

$CO_{2,cf}$	kg CO_2-eq. per kg cutting fluid used
$CO_{2,gw}$	kg CO_2-eq. per kg lost grinding wheel
$CO_{2,e}$	kg CO_2-eq. per energy used in kJ
$CO_{2,m}$	kg CO_2-eq. per machine tool embodied CO_2 kg
$C_{d,gw}$	Grinding wheel consumption in kg
$C_{i,cf}$	Cutting fluid consumption, with i for grinding and dressing process (kg)
$C_{i,e}$	Electrical energy consumption; with i for machining system, grinding and dressing process in kJ
$C_{i,m}$	Wear related machine tool consumption; with i for machining system and components in kg
p_{cf}	Price cutting fluid in €/kg
p_e	Price energy in €/kJ
p_{gw}	Price grinding wheel in €
p_l	Price labour hour in €/h
p_m	Price machine hour in €/h
t_l	Working time of the labour in s

These objectives and therefore also the grinding process can be influenced by a number of different input process variables. As presented in fig. 1 on the left side, these input process variables are the workpiece properties, the process parameters and different enabling factors, such as tool, cutting fluid and machining system (machine tool, cutting fluid filter, and exhaust air filter). Each variable influences one or more aspects of the grinding process presented in the centre of fig. 1. During the grinding process the workpiece properties have influence on the transformation of product attributes, due the workpiece machinability. The process parameters influence
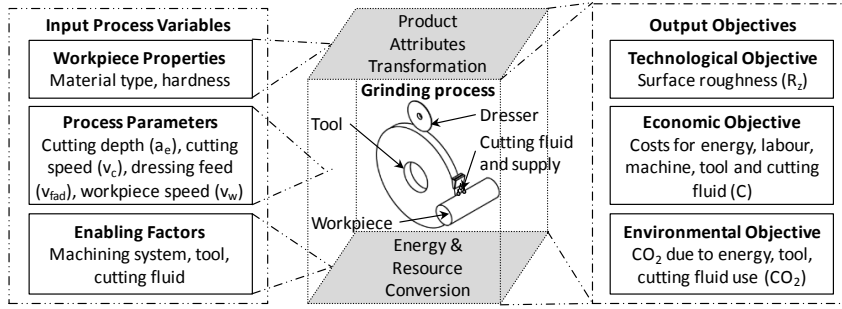
Fig.1   Composition of a grinding process (adapted from [2] and [3])

the performance of the grinding process on the middle layer, due to the selected cutting depth (a_e), cutting speed (v_c), workpiece speed (v_w) and dressing feed (v_{fad}). The enabling factors have influence on the resource and energy conversion during the grinding process. The right side of fig. 1 shows the aforementioned technological, economic and environmental output objectives of the grinding process. Since one of the main purposes of the grinding process is to achieve a desired surface roughness, the surface roughness (R_z) can be selected as the measurand to represent technological objective [2]. The cost and carbon footprint can be used to quantify the economic and environmental objectives.

Against this background, this paper presents an approach to evaluate the environmental and cost influence of alternative and conventional cutting fluids in grinding by calculating their impacts and eco-efficiency. The focus of the approach is not only limited to the grinding process but also considers the whole machining system. The term conventional cutting fluid describes fluids based on the non-renewable resource mineral oil, while the term alternative cutting fluid describes fluids based on renewable cutting fluids, such as vegetable oil, animal fat or natural by-products (e.g. glycerol).

2. Method

2.1. Methodology description

In accordance with fig. 1 three types of input process variables can be distinguished: workpiece properties, process parameters and enabling factors. Each factor has, via the grinding process, influence on the technological, environmental and economic objective. Based on the in Winter et al. proposed approach [4], the relationship between input variables and output objectives can be systematically analyzed, to calculate environmental and economic impact, when changing selected input process variables.

2.2. Calculation of the costs and environmental impact

In the following section (adapted from [4]), equations for the calculation of the environmental and economic impact are presented. The equation symbols and abbreviations are presented in the nomenclature. Equation (1) calculates the carbon footprint of a grinding process. It consists of the environmental impact due to the proportionate consumption of the accumulated electrical energy ($C_{i,e}$), the grinding wheel

($C_{d,gw}$), the accumulated cutting fluid ($C_{i,cf}$) and the accumulated impact of the machine tool ($C_{i,m}$). Equation (2) calculates the direct costs related with a grinding process. The total costs include the costs for the accumulated consumed electrical energy, the grinding wheel and the accumulated cutting fluid, as well as the labour and the machine costs.

$$Environm.\,impact = \sum C_{i,e} \cdot CO_{2,e} + C_{d,gw} \cdot CO_{2,gw} \qquad (1)$$
$$+ \sum C_{i,cf} \cdot CO_{2,cf} + \sum C_{i,m} \cdot CO_{2,m}$$

$$Cost\,impact\ = \sum C_{i,e} \cdot p_e + C_{d,gw} \cdot p_{gw} \qquad (2)$$
$$+ \sum C_{i,cf} \cdot p_{cf} + t_l(p_m + p_l)$$

2.3. Calculation of the eco-efficiency

The term eco-efficiency (E/E) describes an empirical relation of economic activities between environmental costs or value and environmental impact [5]. No standard definition has been concluded for the E/E term, it is moreover defined as a general goal of creating value while decreasing environmental impact [5]. When calculating the E/E two equivalent variants are available regarding the question which variable is in the denominator or in the numerator. Either the ratio of product or service value related to the environmental impact (according to the World Business Council for Sustainable Development (WBCSD) [6], equation (3)) or the ratio of environmental impact to product or service value (according to the United Nations (UN) [7], equation (4)).

$$E/E_{WBSCD} = \frac{product\ or\ service\ value}{environmental\ impact} \qquad (3)$$

$$E/E_{UN} = \frac{environmental\ impact}{product\ or\ service\ value} \qquad (4)$$

The product or service value can be represented by the calculated cost, the value of the product or service by using life-cycle costing or cost-benefit analysis. The environmental impact can be determined in a screening life cycle assessment according to ISO 14042 and be represented by environmental impact categories like global warming potential (GWP) or ozone depletion potential [5].

The calculation of E/E can be used on a macro level to determine the efficiency of society or on a micro level to calculate the efficiency of technologies, products, regions and

countries [5]. Accordingly, the E/E calculation of a manufacturing process represents the micro level. Examples for the application of the E/E concept on the manufacturing level are presented by Gutowski [8], Li et al. [2], Cagno et al. [9].

In the following a modified approach for the E/E calculation will be presented. Basis for the calculation is the description of the E/E according to the WBSCD. To represent the value of the grinding process the average achieved surface roughness per part, the costs per part and a product of both were selected. The surface roughness (R_z) represents the technological value and the costs (C) represent the economic value. In order to represent the aforementioned affinity of the objectives to partially constrain or support each other, the equally weighted product of roughness and cost is also calculated. All three values were used as enumerator while the environmental impact (CO_2) is the denominator. Due to the different units of enumerator and denominator the E/E calculation bases on ratios. The ratio is calculated by relating a reference scenario (marked with the index Ref) on an alternative scenario (marked with the index Alt). The following equations arise: Equation (5) for the technological value (E/E$_{tech}$), equation (6) for the economic value (E/E$_{econ}$) and equation (7) for the combined value (E/E$_{t\cdot e}$).

$$E/E_{tech} = \frac{Roughness}{Environm.\,impact} = \frac{R_{z,Ref}}{R_{z,Alt}} \bigg/ \frac{CO_{2,Ref}}{CO_{2,Alt}} \qquad (5)$$

$$E/E_{econ} = \frac{Cost}{Environm.\,impact} = \frac{C_{Ref}}{C_{Alt}} \bigg/ \frac{CO_{2,Ref}}{CO_{2,Alt}} \qquad (6)$$

$$E/E_{t\cdot e} = \frac{Roughness \cdot Cost}{Environm.\,impact} = \left(\frac{R_{z,Ref}}{R_{z,Alt}} \cdot \frac{C_{Ref}}{C_{Alt}}\right) \bigg/ \frac{CO_{2,Ref}}{CO_{2,Alt}} \qquad (7)$$

3. Materials, experimental details and case study details

The application focus of the presented methodology is the impact evaluation of different cutting fluids. Therefore, it is assumed that the workpiece properties, the machining system and the tool are fixed. Accordingly, the following section presents the used materials and the the experimental and case study details when comparing the application of different cutting fluids in an external cylindrical grinding process.

3.1. Devices and materials

The grinding process was performed on a Studer S40 CNC universal cylindrical grinding machine. Connected to the grinding machine were a cutting fluid filter and an exhaust air filter. In the grinding process solid shafts of hardened carbon alloy steel (62 HRC) with the designation 1.3505 were used as workpieces. Three different cutting fluids were applied and examined. The first fluid was a non-water miscible conventional grinding oil on a mineral oil basis (kinematic viscosity of $v_{40°C} = 10.9$ mm^2/s), the second fluid was a water miscible polymer based dilution ($v_{40°C} = 4.8$ mm^2/s) and the third fluid was a water miscible mineral oil based emulsion ($v_{40°C} = 1.2$ mm^2/s). A vitrified bonded aluminium oxide (Al_2O_3) grinding wheel with the specification A 120 K10 V3 50 was used. The tool had a diameter of 400 mm and was

dressed with a CNC controlled diamond form roll with a radius of $R_{sp} = 1.2$ mm. It was assumed that the utilization potential, respectively the quantity of possible dressing times of the grinding wheel was 500.

The power consumption of machine and process was measured with a three phase power meter type PPC-3 from Load Controls. The surface roughness R_z was measured at four different points at the workpiece with a T1000 basic surface measurement device from HOMMEL-ETAMIC. Furthermore, the radial grinding wheel wear Δr_s was measured with the flat blank method.

3.2. Experimental details and case study details

The cutting speed of the grinding wheel was 45 m/s and the workpiece speed was 0.45 m/s. For each cutting fluid four experimental series were performed, which differed regarding the used specific material removal rates ($Q'_w = 2.5$–5.0–7.5–10.0 mm^3/(mm·s)). In each series a total specific volume of material removed by cutting of $V'_w = 1200$ mm^3/mm was removed in six steps of $V'_w = 200$ mm^3/mm. The test series was stopped if the measured surface roughness R_z was higher than 10 µm. After exceeding the abort criterion or after ending the series of experiments the wheel was dressed. A diamond dressing roll was used with an infeed of $a_{ed} = 10$ µm and dressing overlap of $U_d = 5$.

Within the case study it is assumed that in serial manufacturing a workpiece is machined by an external grinding process. Therefore at each workpiece a volume of material removed by cutting of $V_w = 1000$ mm^3 (grinding width a_p of 5 mm) is removed. For this case three cutting fluids were examined. The cutting depth a_e, therewith connected Q'_w, were changed. The increase of the Q'_w leads to a reduction of the process time because more material is removed per second. However, this increase also leads to higher process temperatures and specific grinding energy. The variation of Q'_w allows the identification of the maximum amount of workpieces that can be produced per day under the consideration of a boundary value for acceptable parts. The boundary value is a technological workpiece restriction; in accordance with this restriction the measured surface roughness has to be $R_{z,max} \leq 3.5$ µm. The working day has a theoretical duration of 16 hours per day with the assumed real production duration of 12.8 hours.

The polymer dilution and the mineral oil based emulsion are water miscible and contain additives. Owing to this feature, lost fluid can be replaced with a large share of water and a small share of the original cutting fluid or concentrate. The assumed water price was 1.76 € per m³. Loss of grinding oil has to be replaced with the original fluid. The price of the original fluid or concentrate can differ between 2 to 6 € per kg, due to its composition. The environmental impact was calculated on the basis of Li et al. [2], Zein et al. [10] and the Ecoinvent 2.2 database [11]. The environmental impact of the Al_2O_3 grinding wheels are calculated on the basis of Aurich et al. [12]. Notably, the data presented in [12] only includes the necessary energy for the sintering process, the embodied energy of bonding and abrasive material. The needed energy for mixing, molding and pressing of the grinding wheel green

body and the disposal phase were excluded due to absent data. The economic impact of the Al_2O_3 grinding wheel depends on the tool specification and the size. Correspondingly, the price of the Al_2O_3 grinding wheel for external cylindrical grinding can differ between 300-700 €. The total costs depend on the machine costs, the labour costs and the costs for the consumed electrical energy. The machine costs consist of the calculative depreciation, imputed interest, occupancy and maintenance costs. These costs depend on the machine setup and the financial options, etc. The labour costs were calculated with 17.50 €/h, with the assumption that one worker can operate two machines [13]. The electrical energy includes the consumption of the machining system (grinding machine and filtration systems), the grinding process and the dressing process. The assumed price for the electrical energy was 0.1 €/kWh, and the environmental impact was calculated with 0.000128 kg CO_2-eq per kJ [11]. The accumulated environmental impact of the machine tool was not calculated, due to lack of data.

4. Results

4.1. Technological impact

The technological impact of grinding experiments is presented in fig. 2. The experimental parameters are presented in the upper part. In the centre part the measured surface roughness R_z at different spec. material removal rates are shown above the spec. material removed by cutting. In the lower part are the produced parts per day, the needed dressing operations per day and the amount of produced parts between dressing operations in dependence of the specific material removal presented.

The experimental result shows that the cutting fluid composition has a major influence on the achieved and measured surface roughness. As explained in Winter et al. [1] the grinding oil has a higher lubrication capacity than the polymer dilution and the mineral oil based emulsion. This results in a better surface roughness even at a higher spec. material removal rate. The polymer dilution has a medium lubrication capacity and the mineral oil based emulsion a low lubrication capacity. This leads, among other reasons [1], to a higher wear of the grinding wheel and therefore a higher surface roughness. In the case of the application of the mineral oil based emulsion at Q'_w of 10 mm³/(mm·s) the experimental series was terminated due to a high surface roughness and grinding wheel wear.

For the further calculation only the measurement values were considered, which were below the boundary value for acceptable parts. These values were extrapolated to one day, to determine the maximum producible output and the number of dressing operations depending on the investigated cutting fluids. The results show, that in dependence of Q'_w and the applied cutting fluid, the possible production volumes and number of dressing operations vary (fig. 2 below). Particularly evident is the high influence of Q'_w on the quantity of produced parts and needed dressing operations. Therefore Q'_w can be used to identify the technological limits of the cutting fluid. In the case of the mineral oil based emulsion this point was reached at a Q'_w of 5.0 mm³/(mm·s) and for the polymer dilution at a Q'_w of 7.5 mm³/(mm·s) respectively. Accordingly, the number of machined work-pieces is reduced by the reduced number of workpieces that can be produced between two dressing operations. This means, that the machining time decreases and the dressing time increases. In the case of the grinding oil this limit is slightly at a Q'_w higher than 10.0 mm³/(mm·s).

4.2. Environmental and economic impact

Fig. 3 presents the environmental and economic comparison of the three cutting fluids based on fig. 2. The comparison is made for each part and maximal quantity per day. The presented intensity values were calculated and scaled based on the equations presented in section 2.2.
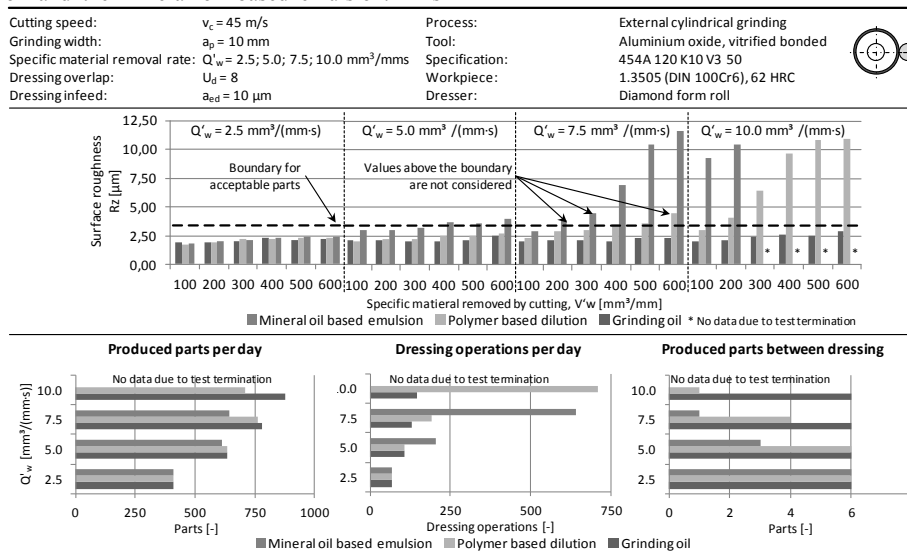

Fig.2   Influence of the cutting fluid on the produced parts and dressing operations per day

The calculation of the machining system's environmental impact is based on the energy consumption, while the economic impact is based on the energy costs, labour costs and machine costs. Clearly discernible is the influence of the process parameters on the energy consumption. With increasing Q'_w the cutting time decreases. Consequently, this reduces the time in which the machining system has to be operated per part. In the case of the energy consumption per day this reduction is compensated by the amount of additional manufactured workpieces. When comparing the cutting fluids, there is no remarkable influence of the cutting fluid on the energy consumption of the whole machining system. Compared to the costs for the cutting fluid and the tool, the costs for the machining system have a major impact.

Regarding the cutting fluid application, only the amount of cutting fluid to refill the cutting fluid loss is considered. When comparing the results, a clear influence of the cutting fluid composition can be determined. The environmental and economic impact of both water miscible fluids is, compared to the grinding oil, very low. Reason is the aforementioned composition of the fluids. With increasing Q'_w the amount of lost cutting fluid per part decreases slightly. Again the reason is the decreasing cutting time, therewith connected is the time when cutting fluid can be lost due to drag-out. In the case of the per day calculation the amount of cutting fluid that needs to be refilled is also connected with the produced workpieces. Compared to the machine tool and the tool, the fluid has the second highest economic impact. The fluid composition has influence on the level of the environmental impact as well.

The tool has, in dependence of the used cutting fluid and the selected spec. material removal rate, a major environmental impact and causes high costs. Throughout the experiments the application of grinding oil leads to a low impact due to tool related costs or CO_2 intensities. The application of the polymer dilution leads with increasing Q'_w to a growth of the tool impact on both intensities. Particularly the application of the mineral oil based emulsion leads with increasing Q'_w to an increasing tool impact for either environmental or economic perspective.

4.3. Eco-efficiency

For comparing different E/E, the application of the grinding oil has been selected as reference scenario. The application of the polymer dilution and the mineral oil based emulsion were selected as alternative scenarios. Three eco-efficiencies (E/Etech, E/Eecon and E/Ee·t) were calculated on the basis of the equation of section 2.3 as well as the results of section 4.1 and 4.2. The results are presented in fig. 4. On the left side of the figure the average measured surface roughness of acceptable parts, the absolute environmental and economic impact part is presented. On the right side the three eco-efficiencies are shown as a single-point indicator.

As aforementioned in section 1 the total achievement and compliance of each objective is limited, due to the characteristic of the three objectives to partially constrain and partially support each other. This is evident when considering the trend of the surface roughness compared with the trend of either the environmental impact or economic impact. While the measured surface roughness increases, the economic and environmental impacts decrease. However, the percental difference between the measured surface roughness values of the applied cutting fluid is not as high as the differences of the caused environmental impact between the three fluids.
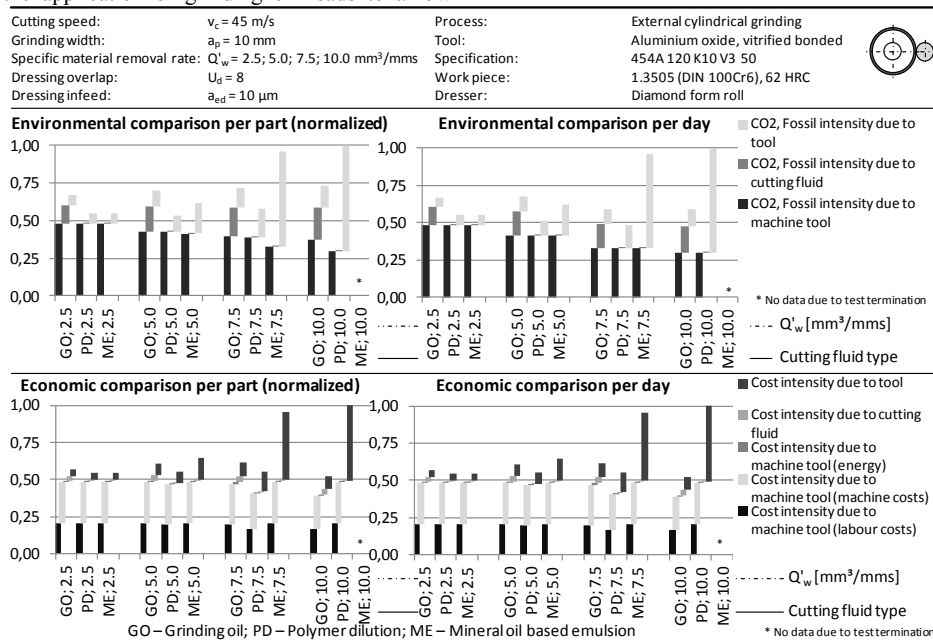

Fig.3   Environmental and economic comparison when applying different cutting fluids
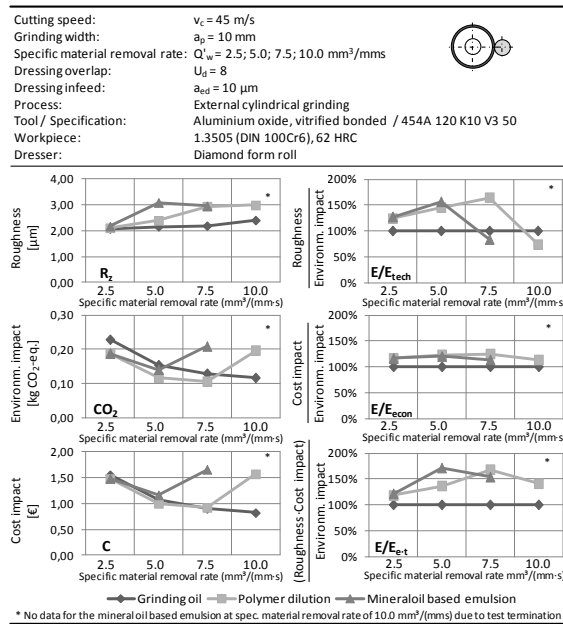
Cutting speed:	v_c = 45 m/s
Grinding width:	a_p = 10 mm
Specific material removal rate:	Q'_w = 2.5; 5.0; 7.5; 10.0 mm³/mms
Dressing overlap:	U_d = 8
Dressing infeed:	a_{ed} = 10 µm
Process:	External cylindrical grinding
Tool / Specification:	Aluminium oxide, vitrified bonded / 454A 120 K10 V3 50
Workpiece:	1.3505 (DIN 100Cr6), 62 HRC
Dresser:	Diamond form roll

Grinding oil — **Polymer dilution** — **Mineraloil based emulsion**
* No data for the mineral oil based emulsion at spec. material removal rate of 10.0 mm³/(mms) due to test termination

Fig.4 Eco-efficiency when applying different cutting fluids

Accordingly, when calculating the E/E_{tech} and E/E_{econ} the respective values are different. To consider this impact the $E/E_{e\cdot t}$ is also calculated. The comparison of the three fluids shows that the E/E trend is dependent on the fluid composition and the specific material removal rate. Both water based alternatives show a better E/E trend than the reference. This is caused by the low environmental and economic impact of both water miscible fluids. As before the E/E values are dependent on the technical achievement potential of the cutting fluid when changing the spec. material removal rate. The application of the mineral oil based emulsion is a better option until a Q'_w of 5 mm³/(mm·s) and the polymer dilution until a Q'_w of 7.5 mm³/(mm·s). Above this value the application of the oil is the better option.

5. Conclusion

This paper presents an approach to evaluate the environmental and cost impact of a grinding process when changing the applied cutting fluid by calculating the respective impacts and eco-efficiency. Based on a theoretical description the presented approach was applied in a case study. The case study covers the application of three different cutting fluids in an external cylindrical grinding process. Two conventional fluids, a mineral based emulsion and a grinding oil, where compared with an alternative cutting fluid, a polymer dilution. Beside the grinding process the influence of the whole machining system (machine tool, filtration systems, and tool) was considered. It could be shown that the cutting fluid composition has a major influence on the technological, environmental and cost impact and therefore on the eco-efficiency of the grinding process. In dependence of the grinding process parameter the values of the three impact

categories and the eco-efficiency for each cutting fluid differs, due to the different technological achievement potentials of the fluids. As a general recommendation, the analysis of grinding wheel impact requires improvements to consider its entire life cycle, since it is one of the main contributors regarding the cost and environmental impacts. A more accurate analysis can be achieved in the future.

Notably, the in fig. 4 shown use of single-point indicators to present the E/E, can lead to concealing of goal conflicts between the output objectives. Furthermore, it can give the impression that the output objectives are weighted equally, which is however case dependent. Both effects can lead to biased results and assumptions. To solve this problem in future studies alternative possibilities to present the eco-efficiency will be used, for example eco-efficiency portfolios [5].

Furthermore, in future studies the approach will be extended to include the impact of further input process variables on the energy and resource conversion of the machining process and therefore on the technological, environmental and cost impact as well as the eco-efficiency.

References

[1] Winter M, Bock R, Herrmann C. Investigation of a new polymer-water based cutting fluid to substitute mineral oil based fluids in grinding processes. CIRP Journal of Manufacturing Science and Technology 2013; 6/4:254–262.

[2] Li W, Winter M, Kara S, Herrmann C. Eco-efficiency of manufacturing processes: A grinding case. CIRP Annals - Manufacturing Technology 2012; 61/1:59-62.

[3] Winter M , Li W, Kara S, Herrmann C. Determining optimal process parameters to increase the eco-efficiency of grinding processes. Journal of Cleaner Production 2013; in press.

[4] Winter M , Li W, Kara S, Herrmann C. Stepwise approach to reduce the costs and the environmental impact of grinding processes. International Journal of Advanced Manufacturing Technology 2013; in press.

[5] Huppes G, Ishikawa M. Quantified Eco-Efficiency: An Introduction with Applications. Dordrecht: Springer; 2007.

[6] World Business Council for Sustainable Development (WBCSD). Eco-efficiency: Creating More Value with Less Input. Geneva; 2000.

[7] United Nations (UN). A manual for the preparers and users of eco-efficiency indicators. New York: United Nations Publication, UNCTAD/ITE/IPC/2003/7 (Sales No. E.04.II.D.13); 2003.

[8] Gutowski TG. The Efficiency and Eco-efficiency of Manufacturing. International Journal of Nanomanufacturing 2010; 6/1-2-3-4: 38-45.

[9] Cagno E, Micheli GJL, Trucco P. Eco-efficiency for sustainable manufacturing: an extended environmental costing method. Production Planning & Control: The Management of Operations 2011; 23/2-3:134-144.

[10] Zein A, Öhlschläger G, Herrmann, C. Polymer Water as Optimal Cutting Fluid: Analysis of Environmental Advantages. 44th CIRP Conference on Manufacturing Systems. Madison; 2011.

[11] Ecoinvent Centre. Database ecoinvent Data v2.2. Centre for Life Cycle Inventories. Dübendorf; 2010.

[12] Aurich JC, Linke B, Hauschild M, Carella M, Kirsch B. Sustainability of abrasive processes. CIRP Annals - Manufacturing Technology 2013; 62/2: 653–672.

[13] Schröder C. Industrielle Arbeitskosten im internationalen Vergleich. IW-Trends, 3/2012, Köln; 2012.