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Technical paper

Application of axiomatic design principles to identify more sustainable strategies for grinding

Barbara S. Linke*, David A. Dornfeld

Laboratory for Manufacturing and Sustainability (LMAS), University of California at Berkeley, Berkeley, CA, USA

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ABSTRACT

It has become increasingly important for manufacturers to implement sustainability into tool and process design. Existing models that evaluate the sustainability of abrasive processes focus mostly on case studies of selected energy and resource streams and rarely contain holistic process models. This study uses basic principles of axiomatic design to fundamentally describe grinding technology in a way that can be used for life cycle assessment. The functional requirements of the machining process are linked to process, tool, and coolant design parameters based upon common process understanding. However, these connections leave space for future quantitative and qualitative formulae. Sustainability metrics are then connected to the axiomatic process model. This work represents a first effort in developing this type of model. Finally, the model is used to qualitatively evaluate the impact of grit size on process sustainability showing that the method is feasible to identify strategies to increase sustainability in grinding.

1. Introduction

Abrasive processes are key technologies to stably achieve high surface quality and dimensional tolerances [1,2]. Furthermore, they are often the only economical way to cut difficult-to-machine materials such as cemented carbides or nickel-based alloys.

Abrasive tools have a huge variety of compositions and specifications and are produced by many different manufacturing chains. The tool design affects the abrasive machining process (i.e., the tool use phase) in terms of productivity, workpiece quality, and wear behavior. There has been a lot of research done to understand the role of the grinding tool in the grinding process. Some expert systems exist that can choose grinding process parameters [3–5] or select the grinding tool [6,7] for certain applications. These tools are often based on fuzzy logic or artificial neural networks and implement data only for a certain range of applications. The reliable prediction of grinding process behavior and results remains impossible [8]. Furthermore, environmental aspects are rarely implemented in environmentally conscious product design methodologies [9]. Based on these aspects, current expert systems have limited transparency so that users and tool suppliers mostly choose the grinding tool based on personal experience.

Sustainability includes environmental and social aspects in addition to the economical view. Sustainability in abrasive machining is a growing concern that has been recognized by both academia and industry [10–14]. However, the essential aspect of abrasive tool design and its impact on process eco-efficiency have not yet been examined from a holistic perspective.

The grinding tool design process is often not transparent to the customer and relies on the expertise of the tool manufacturer. Therefore, it is hard to incorporate resource and energy efficiency considerations for tool manufacturers and users. The product design process needs to be supported by methodologies that enable an assessment of the environmental effects of every life cycle phase [15]. This paper intends to reduce the gap between tool design and sustainability considerations by building an axiomatic grinding process model that can be used for life cycle considerations. Appropriate sustainability metrics will be defined. The model is then applied to qualitative decisions on the grit size in tool design which proves the feasibility of the axiomatic model.

2. Methods

2.1. Life cycle inventory of grinding

Many different standards and methodologies exist to evaluate the environmental impacts of the life cycle of products, processes, and manufacturing systems. The most commonly used method is life cycle assessment (LCA), which includes its variants process LCA, Economic Input–Output LCA, and hybrid LCA [16]. However, evaluating discrete manufacturing processes is challenging because of multiple and interrelated system variables. Today, most life cycle

* Corresponding author at: University of California at Berkeley, 1115 Etcheverry, Berkeley, CA 94720, USA. Tel.: +1 510 717 9585.
E-mail address: barbaralinke@me.berkeley.edu (B.S. Linke).

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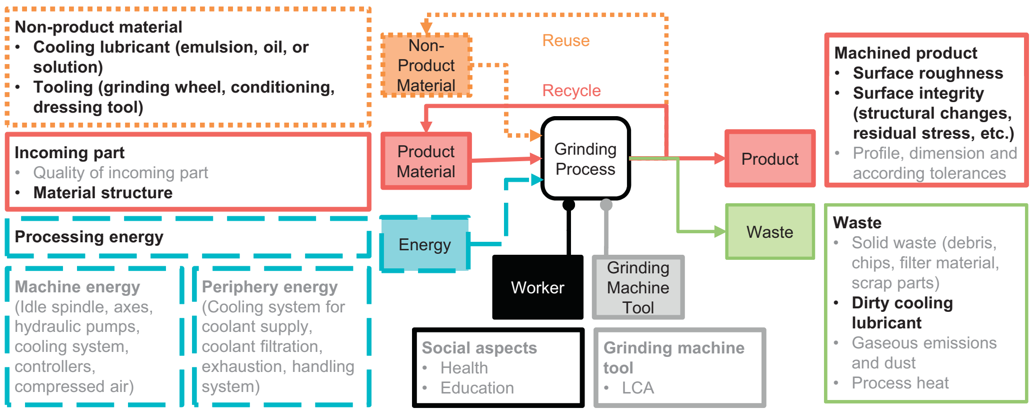

Fig. 1. Scope of the grinding process inventory analysis after [21]. This paper focuses on those items written in bold black.

considerations are based on measurements and evaluate only a few material streams or energy flows [17–19].

ISO 14040 gives a framework to conduct an LCA through four phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and life cycle interpretation [20]. This paper will focus on only the first two phases and will consider product quality and productivity in addition to environmental aspects.

The goal of this study is to find strategies for tool design to enable sustainable grinding. The model is focused on the finishing process of a ductile material component, for example a bearing surface on a transmission shaft made from case-hardened steel.

Fig. 1 shows the scope of a generic grinding process LCI. Our overview currently includes only the items in black, but future iterations should extend the analysis to the gray items as well. The system boundaries are around the single grinding process on one machine.

2.2. Axiomatic design methodology

Developed by Suh [22], axiomatic design is a way to describe systems and products systematically by generalizing the principles of the investigated system using self-evident truths [23]. This design method has been used for environmental considerations of manufacturing systems and product services [24], but axiomatic design has rarely been used for discrete manufacturing processes [25,26]. However, grinding processes have too many interdependencies between process components that prevent the complete implementation of all axiomatic design rules. So, we will only use some aspects to describe grinding technology.

The axiomatic design process works within four domains, which are shown in Fig. 2 for the abrasive process: customer domain, functional domain, physical domain, and process domain. The customer domain is characterized by customer attributes (CAs) of the grinding application for a defined workpiece. For example, we set demanded surface integrity, roughness, or tolerance. In the functional domain, the functional requirements (FRs, e.g., take away heat or control chemical reactions) and constraints (Cs, e.g., maximum dimensions of the components or maximum spindle power) are defined.

The design parameters (DPs) in the physical domain satisfy the FRs. DPs for grinding are coolant properties (e.g., coolant viscosity or supply system), process setup (e.g., clamping, parameters, or kinematics), and tool characteristics (e.g., grit type or wheel hardness).

Finally, the procedure to generate the specific DP in the process domain is characterized by process variables (PVs) [22]. PVs for grinding describe machine tool components or the production procedures for grinding tools and coolant. The last three design phases interact constantly with each other in concurrent engineering.

The relation between FR and DP can be expressed by vectors as shown in Eq. (1). This way of describing an abrasive tool system enables the implementation of qualitative connections or quantitative equations that can then be used for energy and resource calculations. Additionally, we can separate objectives (FR) from means (DP) to evaluate the necessity of all design items and get a holistic overview [27].

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (1)$$

This grinding process model does not strictly follow the rules for axiomatic design, which demands that the functional requirements should be independent from each other (independence axiom) [22]. This occurs because many components, such as coolant or grits, serve multiple functions. Additionally, information content should be minimal in axiomatic design (i.e., the design with highest probability for success should be chosen, which is the information axiom) [22]. This axiom is also not met in common discrete processes because high process complexity does not allow all variables to be simultaneously optimized. For example, if we were to choose an oil over a water-based emulsion for the cooling lubricant, then the friction heat may be reduced, but chip formation will be hindered and less heat will be removed from the process. So, representing grinding by axioms is one way to visualize the process mechanisms and understand process technology.

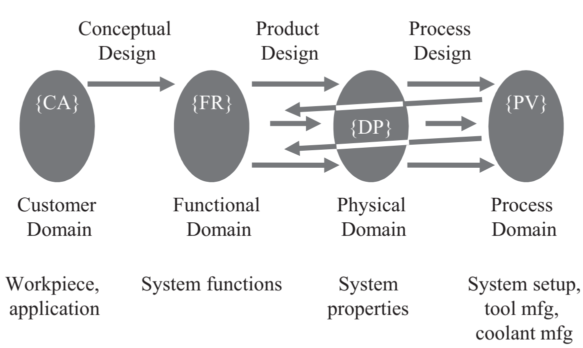

Fig. 2. Axiomatic description of a grinding process. After [22].

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3. Axiomatic model of grinding process

3.1. Basic structure

A production process has to accomplish certain tasks depending on workpiece material, stock removal (finishing or roughing operation), availability of machines, batch size, form and dimension tolerances, and desired surface roughness and integrity. Our grinding model focuses on ductile material processed in finishing operations, but it can be easily adapted to other applications. This model also includes the most established physical models in the literature.

The first requirement for the axiomatic grinding process model is that material has to be removed (FR0) (Fig. 3). Material can be removed by separation, vaporization, dissolvation, or another physical or chemical principle. These principles in fact underlie all manufacturing processes as described by Todd et al. [28] or the DIN 8580 standard [29].

Choosing material separation (DP0) requires that we determine how to generate the main separation effect (FR1) and control any side effects (FR2). For example, we can select hard particles to establish the main effect of material removal (DP1). The resulting side effects include heat and process forces that can be addressed by a bonded tool (DP2a). Cooling lubricant is also generally needed to reduce friction and remove heat and chips (DP2b). However, the presence of two design parameters for one functional requirement does not follow axiomatic design rules for good design [22]. Furthermore, DP2b affects material separation (FR1) by impacting friction. Nevertheless, we can use these conflicts with good axiomatic designs to enhance future grinding process designs. For example, we can try to separate certain functional requirements through different tool design parameters.

Side effects of material separation by hard particles include heat generation (FR21), heat removal (FR22), chemical reactions (FR23), mechanical load (FR24), removal of cut material (FR25), and disturbances (FR26). We will tackle each side effect separately, although grinding is a complex superposition of all these physical effects. Yet, very few models consider this coupled interaction [8]. For example, Mahdi and Zhang [30] examined how the temperature gradients, mechanical stresses, and phase transformations affect residual stresses in grinding. Duscha et al. [31] used a FEM approach to simulate phase transformation during grinding and add residual stresses that result from these phase transformations. Brinksmeier et al. [32] investigated the phase transformation of steel during grind-hardening, which involves multiple effects on surface integrity.

3.2. Main mechanism to generate a workpiece surface

The main mechanism of material separation depends on the workpiece material and is dominated by fracture and crack propagation for brittle materials or material shearing and chip formation for ductile materials. Either way, shear stresses have to be induced by generating force (FR31) and providing cutting edges (FR32).

We choose track-bound particles to generate the force (DP31a) (Fig. 3). Mechanical clamping (DP31b) fixes the component during machining to withstand the force on the workpiece. In addition, deflections or bending of cylindrical workpieces have to be considered as sources of errors [33].

The use of track-bound particles (DP31) in combination with abrasive grits (DP32) generates the three dimensional surface pattern. This creates a further functional requirement for the grinding system that the workpiece surface pattern must be controlled (FR311). Several researchers have been working on the description of cutting edge shape because this knowledge is crucial for modeling of wheel and workpiece topography [34]. The pattern can be important for component function such as in sealing systems where the directionality of grinding grooves has to be avoided or in engine cylinders where oil reservoirs are built. To avoid a regular pattern, the grits should be distributed statistically on the tool. For example, engineered grit patterns [35] or slotted wheels [11] are alternatives, but these strategies need higher care in process control. In addition, the process kinematics define how the abrasive grits engage the workpiece. Whole numbered RPM ratios lead to repeated surface pattern and should be avoided in common applications. Ultimately, the 3D appearance of the surface pattern and its influence on components' function still offer a lot of potential for future study.

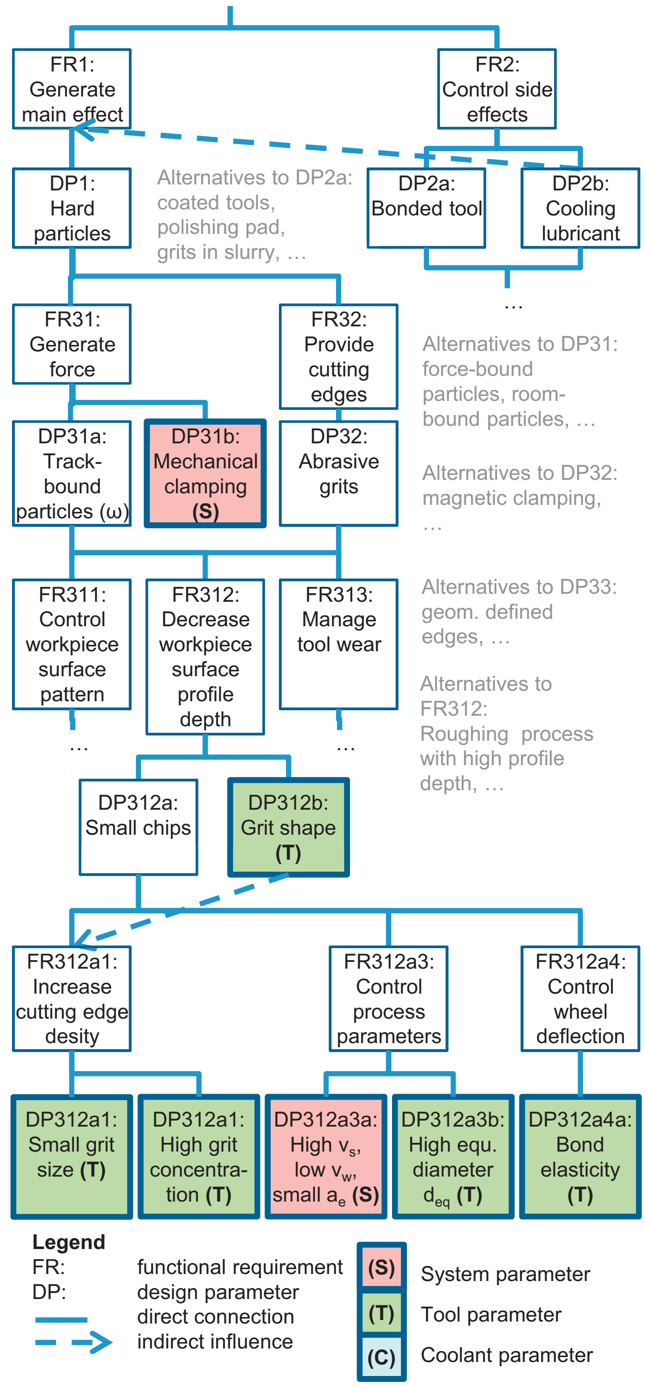

Fig. 3. Tree for the functional requirement of decreasing workpiece surface profile depth.

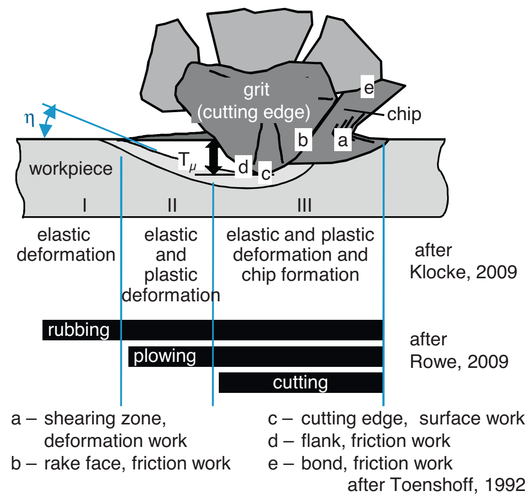

Fig. 4. The three phases of ductile chip formation [1] including the different contact types rubbing, plowing, and cutting (after [33]) and the sources of heat generation (after [36]).

The main functional requirement FR312 is to decrease workpiece surface profile depth (Fig. 3). On the one hand, the grit shape (DP312b) is responsible for the profile of a grinding groove and has to be considered. On the other hand, the depth per groove, i.e., the maximum undefined chip thickness, $h_{cu,max}$, should be small (DP312a). It is a powerful theoretical variable to describe grinding process mechanisms [2]. The chip thickness is related to the statistical cutting edge density, C_{stat}, the workpiece speed, v_w, the grinding wheel speed, v_s, the depth of cut, a_e, and the equivalent grinding wheel diameter, d_{eq} as shown in Eq. (2) [1,36,37].

$$h_{cu,\max} \approx k\left(\frac{1}{C_{stat}}\right)^{\alpha}\left(\frac{v_w}{v_s}\right)^{\beta}\left(\frac{a_e}{d_{eq}}\right)^{\gamma} \quad (2)$$

However, the factors, k, α, β, γ, have to be found empirically and Eq. (2) does not account for elastic and plastic material deformation. In addition, wheel deflection changes the chip distribution and needs to be controlled (FR312a4a). Rowe et al. [38] performed detailed calculations on wheel deformation.

The main mechanism of material separation also results in tool wear (FR313), which changes cutting edge shape and number. Measurement of the wear flat area informs about the state of the tool wear [39]. Grit friability, wheel hardness, and type of dressing process are the design parameters that must be selected to minimize the effects of wear. Because of its complexity, dressing will be addressed separately in an extended process model.

This demonstration shows how the axiomatic model quickly gets highly complex. Similar tree diagrams were created for all functional requirements.

3.3. Side effects involving heat generation

Process heat is a significant challenge in grinding technology that needs to be particularly well understood. Heat generation evolves from the special chip formation mechanisms in grinding. Fig. 4 shows the three phases of elastic and plastic deformation and chip formation within a single grit engagement in ductile material. Brittle material experiences similar phases, but cracks are induced and expanded in phases II and III and particles will break out rather than chips formed.

Control of heat generation (FR21) includes low heat per single grit interaction, few grit interactions per time, and short interaction time of the workpiece with the grinding tool. Heat generation per grit is very complex and includes the heat by rubbing, plowing, and cutting along the three phases of grit engagement (Fig. 4).

The sliding heat can be reduced by lubricants with high viscosity and a small tip wear flat area. Malkin and Guo [2] propose to obtain the sliding energy by measurements of the grit wear flat area (example in [39]) and the grinding forces.

There are only a few examinations of and models for the heat from plowing [33]. These studies suggest that the most important variables for heat generation from plowing include the contact conditions and shape of grit contact area.

Heat from cutting is produced at different shear zones in the single grit engagement (Fig. 4). Shear zones are beneath the grit (c and d), at the grit rake face (b), as well as in the chip formation zone (a). The friction work between chip and tool bond (e) can be reduced by lubrication and higher grit protrusion. The shear zone friction is harder to model and has complex influence factors.

Heat generation during grinding is also reduced by few grit interactions per time. Therefore, the geometric contact area between workpiece and tool has to be decreased as well as the active cutting edge density. These considerations lead to favored contact length, process parameters, and wheel design.

3.4. Side effects involving heat removal

Heat removal includes all aspects of cooling and lubrication and has been the focus of much research [8]. The two basic principles of heat removal (FR22) for grinding processes are heat convection and heat conduction. Convection transfers heat into fluids or air, but convection into air is neglected in most studies. Conduction transfers heat into the workpiece and the grinding wheel.

It is commonly assumed that all process energy is converted into heat flux, q_t, during grinding [2,33]. The heat flux is derived from Eq. (3) using the specific tangential force, F'_t, the cutting speed, v_c, and the contact length, l_c [33]. The total heat flux, q_t, is composed of heat to the chip, q_{ch}, to coolant, q_{fl}, to grinding wheel, q_{gw}, and to workpiece, q_{wp} [33].

$$q_t = \frac{F'_t . v_c}{l_c} = q_{ch} + q_{fl} + q_{wp} + q_{gw} \quad (3)$$

Malkin and Guo [2] defined the limit to the shear zone energy that can be carried away by the chips, q_{ch}, which is the melting energy. Heat to the grinding wheel, q_{gw}, depends on grinding wheel properties including grit, bond and structure characteristics. Wheel and grain contact analyses are two known approaches to estimate the partition ratio for the heat going into the grinding wheel [33].

Heat flux into the workpiece material, q_{wp}, is a main challenge for surface integrity and forms an important transfer process especially for materials with high heat conductivity. Heat flux into the cooling lubricant depends on coolant properties and contact arc length [33]. The useful flow rate and coolant volume per time affect the presence of cooling lubricant in the grinding contact area.

3.5. Side effects involving chemical reactions

Chemical reactions arise from reactivity between the system components. Therefore, low heat and mechanical pressure should be present, as well as low chemical reactivity between all system components including grits, tool bonding, workpiece material, and cooling lubricants and its additives.

Brinksmeier et al. [40] discuss case studies about chemical reactions within grinding technology, but there is potential for research. For example, the effect of contact time between grits and workpiece should be discussed in further grinding models.

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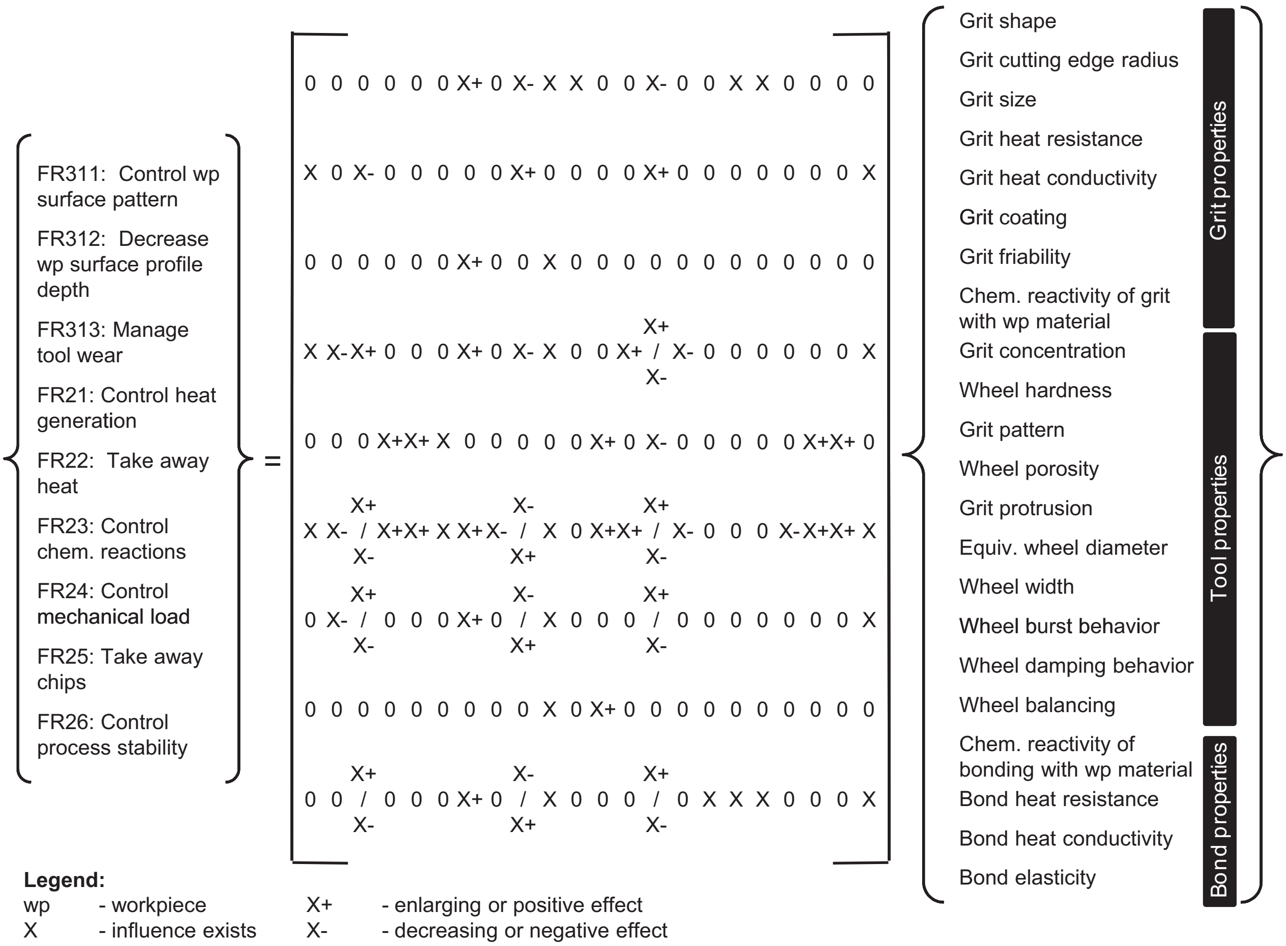

Fig. 5. Matrix for grinding tool properties.

3.6. *Side effects involving mechanical load*

The grinding force is divided into tangential, normal and axial forces. Tangential forces are associated with chip formation and normal and axial forces with sliding and plowing effects. The force ratio, μ, between tangential and normal force is an indicator for the effectiveness of chip formation, but it is rarely expressed by physical models.

Grinding forces result from the actual chip cross-sectional area, number of kinematic cutting edges, and contact arc length [36,37]. Additionally, managing tool wear (FR313) and forming chips effectively are also necessary to have low normal and axial forces.

3.7. *Side effects involving material transport*

In grinding, workpiece material is removed as chips, which have to be carried out of the contact zone (FR25). This is mainly achieved using grinding wheel porosity enhanced by cleaning nozzles, dressing, and wheel wear to clean the pore space from chips.

3.8. *Process disturbances*

Disturbances to the grinding process can be multiplex and involve process vibrations as well as the machining environment. Process vibrations can be managed by changing system stiffness and managing tool wear (FR313), especially through appropriate tool dressing. Outside influences can heat up the process and include HVAC, sunlight, friction in machine tool elements, hydraulics, and pump systems.

3.9. *Correlation matrix for tool properties*

All of the effects that we have discussed produce a complex grinding process model. We have chosen system, tool, and cooling lubricant as the main categories for design parameters. The complete grinding model represents a framework and has potential for enhancement.

Relations between the functional requirements and design parameters can now be expressed through matrices according to Eq. (1). Fig. 5 shows the matrix for tool properties. The interrelations between FR and DP are marked. We noted the trend of enlarging or decreasing the function FR where possible. Some cases show contradictory dependencies, but sensibility analyses per case study will indicate the dominant trend.

We like to note that this model is simplified and was generated with common existing models. While its main application was fine grinding of ductile material, this model can be applied to special process variants and other applications. Experimental data, sensitivity analyses, and empirical data could further enhance the axiomatic grinding process model.

4. Metrics for grinding sustainability

Prominent metrics for environmental impact assessment of manufacturing processes are energy use, global climate change, non-renewable resource consumption, and water consumption. In this study, some additional metrics on workpiece quality and productivity were chosen to incorporate more aspects on sustainability. The following metrics stand out due to their simplicity and historic relevance for economic evaluations. In the future, this list should be extended to include metrics in upcoming frameworks for sustainable manufacturing such as the OECD Sustainable Manufacturing Toolkit [41].

- **Productivity**: material removal rate (MRR), Q'_w (Eq. (4)).

$$Q'_w = a_e \cdot v_w \tag{4}$$

- **Energy**: specific grinding energy, u_c

  The specific grinding energy, u_c, is defined as energy to remove one volumetric unit of material. It is the energy required to form grinding chips, deform workpiece material, and overcome friction between grinding grits, tool bond, and workpiece. It can be expressed by Eq. (5) as the sum of the energies for sliding, u_{sl}, plowing material, u_{pl}, and chip formation, u_{ch} [2]. The kinetic chip energy is negligible.

$$u_c = u_{sl} + u_{fr} + u_{def} \tag{5}$$

  For highly effective grinding processes, the friction and deformation energies, u_{sl} and u_{pl}, decrease and the specific energy, u_c, tends to approach the chip formation energy, u_{ch}, which is assumed to be constant. Malkin and Guo [2] found for various materials that the minimum specific energy, u_{ch}, correlates to the melting energy of the material.

  It is commonly assumed that most process energy is converted into heat [33]. A smaller part of the energy input is required for surface generation and stored as potential energy in chips and in the workpiece as residual stresses [36]. However, the energies for sliding, plowing, and chip formation are implicitly found in the axiomatic model as heat from sliding, plowing, and cutting.

  Eq. (6) can be applied to any conducted experiment. It derives the specific grinding energy, u_c, from the specific tangential grinding force, F'_t, the grinding wheel speed, v_s, and the material removal rate, Q'_w, or the specific grinding spindle power, P'_c [1]. However, this correlation requires empirical data and cannot easily be used beforehand.

  The additional energy for the grinding machine and peripheral equipment, such as hydraulics, pumps, and cooling systems, can account for an enormous part of the total energy consumption [11]. Yet, more knowledge about the special setup is necessary to evaluate the total energy. However, it is well known that shortening the grinding process by increasing MRR reduces energy consumption even though the power demand increases with MRR [21].

$$u_c = \frac{F'_t \cdot v_s}{Q'_w} = \frac{P'_c}{Q'_w} \tag{6}$$

- **Process capability**, c_{pk}

  As end finishing process, grinding often is applied on components with high added value. Therefore, a high process capability reduces economical loss. Process capability is highly influenced by the machine tool and production environment and no common equations exist to describe it. Nevertheless, this study addresses process stability (FR26) for process capability.

- **Surface quality**, e.g., peak-to-valley height, *Rz*

  Most models relate the generated surface profile to the maximum undeformed chip thickness, neglecting elastic and plastic deformation effects. Moreover, the relationship still remains empirical and has to be defined via experiments for quantitative roughness values. Nevertheless, we use the established model of maximum undefined chip thickness, $h_{cu,max}$, for qualitatively assessing grinding sustainability (see Eq. (2)).

- **Surface integrity**, e.g., thickness of affected workpiece rim layer

  Due to the fact that grinding is a process at the end of the process chain, the produced surface quality is crucial. Residual stresses in particular indicate the thermal and mechanical influences during the manufacturing process [36]. Several models for surface integrity exist that mostly take the grinding temperature into account [36,42]. Therefore, we propose using heat generation (FR21) and heat removal (FR22) as characteristics in this assessment.

- **Water usage**

  The scarcity of water might be a present problem for a factory or come about in future through climate change or overuse of resources [43]. It is therefore a critical, regional factor for producers. The intrinsic friction processes in grinding generate high grinding process heat. Therefore, they make cooling and lubrication necessary in nearly all industrial cases (FR21 and FR22). Water-based lubricants serve the functional requirement of removing heat better than oil-based lubricants.

  The useful coolant flow is defined as flow volume through the contact zone of the grinding tool and workpiece [2]. Morgan et al. [44] defined the achievable useful flow rate, Q_u, based on mean pore depth, h_{pores}, wheel speed, v_s, wheel width, b_d, and empirical factors, f and Φ (Eq. (7)). The porosity factor, Φ, is typically 0.5 for a medium porosity wheel, and the factor, f, is based on measurement and can be approximated as 0.5.

$$Q_u = f \cdot h_{pores} \cdot b \cdot v_s \cdot \Phi \tag{7}$$

  To simplify our approach, we use this achievable useful flow rate as a first estimation for water use and apply the necessary jet flow rate as 4 times that of the useful flow rate as recommended by Morgan et al. [44]. However, industrial practice often overestimates the necessary coolant flow rate, resulting in very high water wastage [45]. Badger [45] showed that lower flow rates still enable sufficient product quality if the coolant jet speed is large enough.

- **Waste and emissions**

  The removed material accounts for the solid waste stream and can be estimated by the volumetric material removal. Most material is carried away from the processing zone as chips in the coolant and caught through coolant filtration. The resulting grinding debris is composed of chips, grinding tool swarf, filter aid, and coolant, and it can be hard to recycle because of this complex composition [10]. Gaseous emissions are commonly removed by industrially available exhaust systems.

4.1. Case study: grit-size choice

In the following we describe how the tool properties of grit size and grit size distribution affect the grinding process sustainability. This analysis focuses on the tool property of grit size and should show how the influence of other properties can be analyzed.

Besides grit type, bonding type, and wheel hardness, grit size is a main parameter in grinding tool choice. It can be controlled by grinding tool producers and grit suppliers for all in- and outgoing material. Grit producers also are able to actively influence grit size and its distribution during grit synthesis, post-processing, or sorting.

National and international standards exist to define particle size distributions of abrasive grits. They are based on sieving for coarser grits and sedimentation for finer grits [1]. Standards describe the sieving procedures and sieve properties. The choice of grit size, however, is subject to common rules and the expertise of the tool manufacturer.

Furthermore, how the distribution of grit sizes affects tool performance is rarely addressed. A narrow distribution band of grit characteristics potentially defines the tool performance more precisely. Controlling the grit size bandwidth could lead to highly efficient and well balanced abrasive processes.

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However, the sorting method to obtain the narrow band size might be more expensive. Additionally, a broad band size can facilitate tool manufacturing by lower mold pressure and higher packing density. Both the selection method and tool manufacture affect the price of the tool.

Regarding tool performance, grit size is also related indirectly to grit toughness. Smaller single-crystal grits, especially superabrasives, are commonly tougher because of fewer defects [46]. Hou and Komanduri [47] studied how the grit size distribution affects static and kinematic cutting edges and the interaction of grits with the workpiece. Their complex equations could to be linked into an enhanced axiomatic grinding process model.

Fig. 5 gives an axiomatic grinding model for the tool properties with the main application of fine grinding of ductile material. In this model, the grit size affects surface generation, heat generation, chemical reactions, mechanical load and process stability. The metrics for sustainability in the life cycle inventory are affected as follows:

- Grit size does not have a direct influence on *productivity* in path-controlled machining processes. However, a larger grit size enables higher MRR without thermal workpiece damage.
- Bigger grits at constant grit concentration reduce heat generation and, therefore, consume less *process energy*. So, bigger grit size also has a positive influence on *surface integrity*.
- The undeformed chip thickness increases with the grit size leading to higher forces. Especially for a small depth of cut the chip formation will become more effective with an earlier cutting phase and shorter phases of rubbing and plowing. These oppositional mechanisms enable no general statement for *process capability*.
- Equally to the undeformed chip thickness, the surface profile depth increases with bigger grit size, lowering *surface quality*. A higher grit size distribution might result in a surface profile with bigger variation of depth and worse predictability due to outlier grits. For example, when machining brittle materials, a maximum chip thickness marks the transition from ductile to brittle mode machining [1]. If this maximum chip thickness is exceeded, cracks can be induced to the brittle workpiece material.
- *Water usage, waste, and emissions* are also not directly affected. Reduced process heat, however, offers the option for reduced cooling lubricant use.

The tool user can implement this qualitative knowledge when comparing two different tool designs beyond the economical view. However, the grinding process matrix in Fig. 5 has to be filled with quantitative data by tool users and manufacturers so that it can provide a holistic basis for sustainability decisions.

5. Conclusions

Tool manufacturers have broad experience and good data on their products. This research aims at unlocking knowledge by a description method that allows implementing factory data and assessing strategies for higher sustainability of grinding technology. It is important to support the product design with methodologies to assess the environmental effect of every life cycle phase [15].

Axiomatic design represents an approach to invent product or system designs [23]. However, it has rarely been used for discrete manufacturing processes because of their highly coupled design [25,26]. This study took basic principles from axiomatic design and applied them successfully to grinding technology. Special emphasis was put on grinding tool design. The systematic way of axiomatically describing the grinding process identified how process, tool and coolant characteristics interact with functional requirements. The relationships were based on a common process understanding from an intense literature review, but leave space for new quantitative and qualitative formulae.

Metrics for sustainability were discussed and connected to the axiomatic grinding process description. A qualitative case study on grit size and grit size distribution proved the basic feasibility of the life cycle impact assessment via axiomatic process model.

We obtained some challenges in the axiomatic description because the potential axioms do not always match with reality or have complex and ambiguous effects. At the moment, interdependencies between different design parameters are difficult to express quantitatively in the grinding process matrix.

Overall, the axiomatic process model has proven to clarify complex process mechanisms and their interdependencies. It offers options for implementing sustainability metrics. The model is capable of development, especially regarding dressing technology and quantitative relations. Sensitivity analyses show promise to evaluate how conflicting trends affect sustainability.

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