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Authors
Linke, Barbara S
Moreno, Jorge

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Title: New Concepts for Bio-inspired Sustainable Grinding

Authors: Barbara S. Linke[1], Jorge Moreno

Affiliation:
Department of Mechanical and Aerospace Engineering
University of California Davis
Davis, CA, USA

[1]**Corresponding author:**
Barbara S. Linke
Email: bslinke@ucdavis.edu
Phone: (+1) 530 – 752-6451
Address: University of California Davis
Department of Mechanical and Aerospace Engineering
One Shields Ave
Davis CA 95616, USA

ABSTRACT

Sustainability in manufacturing processes needs to be increased. Bio-inspired design is one promising and innovative approach to design better products and processes. Therefore, this study uses bio-inspired design to find new process setups for novel grinding system components to address problems defined through an axiomatic grinding model. This paper discusses bio-inspired ideas for chip transport and tool cleaning, abrasive wear resistance, self-sharpening, breaking air barriers, cooling, and new process environments. Case studies and new concepts highlight potential improvements, but future research needs to validate these ideas. This study shows how nature can inspire improvements in grinding processes.

KEYWORDS

Grinding, sustainable manufacturing, bio-inspired design

1. INTRODUCTION

Pressing environmental and social troubles challenge manufacturing engineers to find machining processes that are both more cost efficient, as well as, more environmentally and socially friendly [1]; abrasive machining is no exception to this demand. Renewable and vegetable based cooling lubricants are one example [2, 3], but there are more ways to make grinding more sustainable.

Considering nature as inspiration is alluring as nature produces outcomes that stand the test of time [4]. This study will explore how nature can inspire and better grinding and its sustainability.

Sustainability needs to be integrated early into design and manufacturing practices [5]. Although bio-inspired design is not specifically recognized as a design concept for sustainability, it leads to promising new materials, products, and technologies. For example, the understanding of the micro-deformation mechanisms in bones, antlers, teeth, horns, and hooves was used to design high-energy absorbing composite materials [6]. Surfaces with special wettability, e.g. hydrophobic surfaces, can be used as transparent and antireflective coatings for liquid transportation, anti-bioadhesion, etc. [7].

Self-sharpening cutting tools have been inspired by the way rodent teeth wear. When a rodent eats, the softer dentine backing continually wears away, exposing new sections of harder enamel material which comprises the sharp cutting edge. [4]

In addition, some bio-inspired manufacturing processes exist. Wells and Camelio propose a dimensional error-compensation approach for compliant sheet metal assembly processes based on immunological principles [8].

This study seeks to apply bio-inspired design methods to grinding processes. First, methods of designing products inspired from biology are explained. Following the problem-driven design approach, the problems are defined and reframed through an axiomatic grinding model. This model is based on the axiomatic design method and breaks the grinding process down into its low-level functions such as “remove heat through conduction”, “have self-sharpening”, or “have high abrasive wear resistance”.

These functions are then translated into biologized problems in the fourth section. Several important functions of the grinding system are discussed and biological solutions are found and applied to grinding. The study concludes with a discussion and outlook.

2. BIO-INSPIRED DESIGN METHODS

The definition of Bio-Inspired Design, as Shu et al. states, is “emulating natural models, systems, and processes to solve human problems”[4]. This design process is used in order to look at already evident signs of natural designs that withstand the test of time. In order to come up with a bio-inspired design, one must follow certain procedures to make the best of the biological inspiration.

Helm et al. illustrate two main approaches when having a bio-inspired idea: a ‘problem-driven’ approach and a solution-driven approach [9]. A problem-driven approach is where a given problem motivates the search for biological analogies that could help solve the problem [4, 9]. A solution-driven approach is where one isolates a biologically occurring mechanism and uses it as an inspiration to solve a problem. [9]. This study focuses on the problem-driven approach in analyzing grinding functions need to be improved. In the case of a ‘problem-driven’ potential bio-inspired design, Helm et al. suggest performing the following steps [9]:

1. Problem definition
2. Reframe the problem
3. Biological solution search
4. Define the biological solution
5. Principle extraction
6. Principle application

In step 2, we used the approach of reframing or ‘biologizing’ the problem [9]. This is done by redefining problems in biological terms, often in the form of a question, e.g., ‘How do biological solutions accomplish the desired function?’ [9].

Biological solutions can be found through discussions with biologists, database searches, natural-language based search, etc. in step 3 [4]. However, choosing the right keyword for the search increases the number of solutions [10]. In this study, internet research with the reframed problems was conducted. In addition, we used brainstorming methods based on buzz words with students to find biological solutions. Helm et al. also warned of errors in biomimetic design [9]:

- Misapplied analogy
- Improper analogical transfer
- “Off-the-shelf” biological solutions
- Vaguely defined problems
- Poor problem-solution pairing
- Oversimplification of complex functions
- Simplification of optimization problems
- Solution fixation

The next paper section discusses steps 1 “Problem definition” and 2 “Reframe the problem” with the help of an axiomatic model of grinding.

3. AXIOMATIC GRINDING MODEL TO DEFINE AND REFRAME THE PROBLEMS

Grinding is a complex process with interdependent input and output parameters. Nevertheless, grinding can be broken down piece by piece in an orderly fashion using an axiomatic design approach [11]. The resulting axiomatic model of grinding highlights functions of a grinding process which can be then analyzed with further design methods. Reducing the inherent redundancies and contradictions in the grinding processes offers a potential for improvement in design.

The axiomatic grinding model has been used for this study in order to pinpoint the processes and problems which occur in grinding. The processes are tackled separately, but the detailed description provided by the axiomatic model allows the visualization of where interconnections between other problems develop. Furthermore, axiomatic design allows implementing environmental considerations early so an environmental-friendly product or service can be developed [12].

Today, the majority of grinding systems consists of the following components: grinding tool with abrasive layer made of grits, bond, and pores, grinding machine, workpiece, cooling lubricant, coolant supply, and filtration system.

The axiomatic grinding model from [11] has been improved and starts in its recent state with separating the grinding process into three main functions: create part dimension + profile (= part macro properties), create surface (= part micro properties), and cost-effectiveness. These three main functions of the axiomatic model split into subcategories that become more specific when dealing with certain aspects of the process.

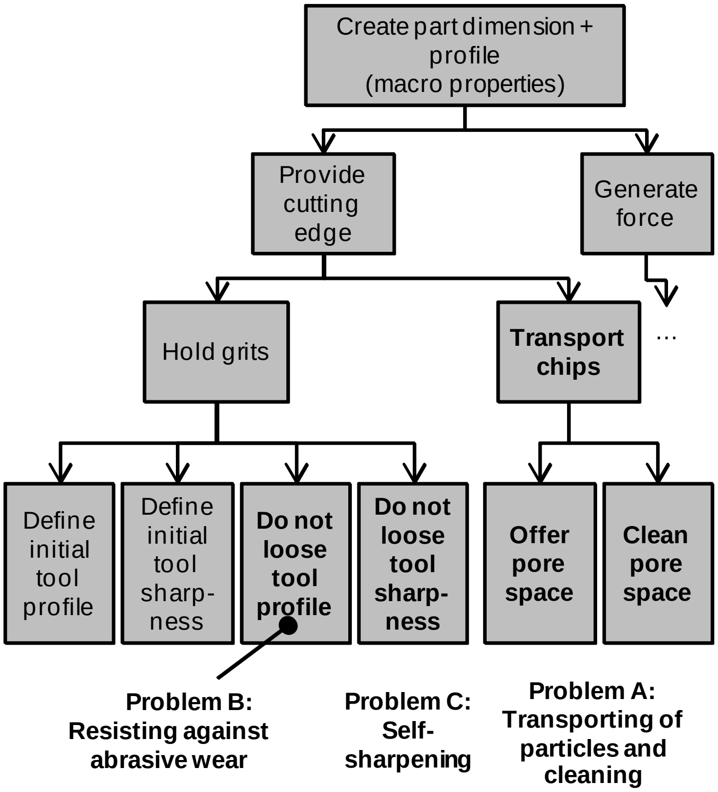

Figure 1. Axiomatic grinding model part 1.

The first main function of grinding is creating the part dimension and profile (part macro properties) (Figure 1). In order to cut an object, a tool must be present that will provide the proper cutting edge and force in order to produce a quality abrasive process [11]. In grinding, abrasive grits prompt the removal of the workpiece material. The abrasive grits need to be held, which is achieved by different kinds of bonding (resin, vitrified, or metal). When considering the possible conditions that affect abrasive grits, the axiomatic model branches into how the chips created from the removed material will be transported and how the grits are held [11]. This formulates “Problem A: Transporting of particles and cleaning”.

The composite of abrasive grits and bond needs a specific profile and sharpness, which need to be initially defined and should not be lost during the process. So the requirement to have a stable tool profile includes “Problem B: Resisting against abrasive wear”. On the other hand, wear of the grinding tool is inevitable and self-sharpening can overcome the sharpness loss (“Problem C: Self-sharpening”).

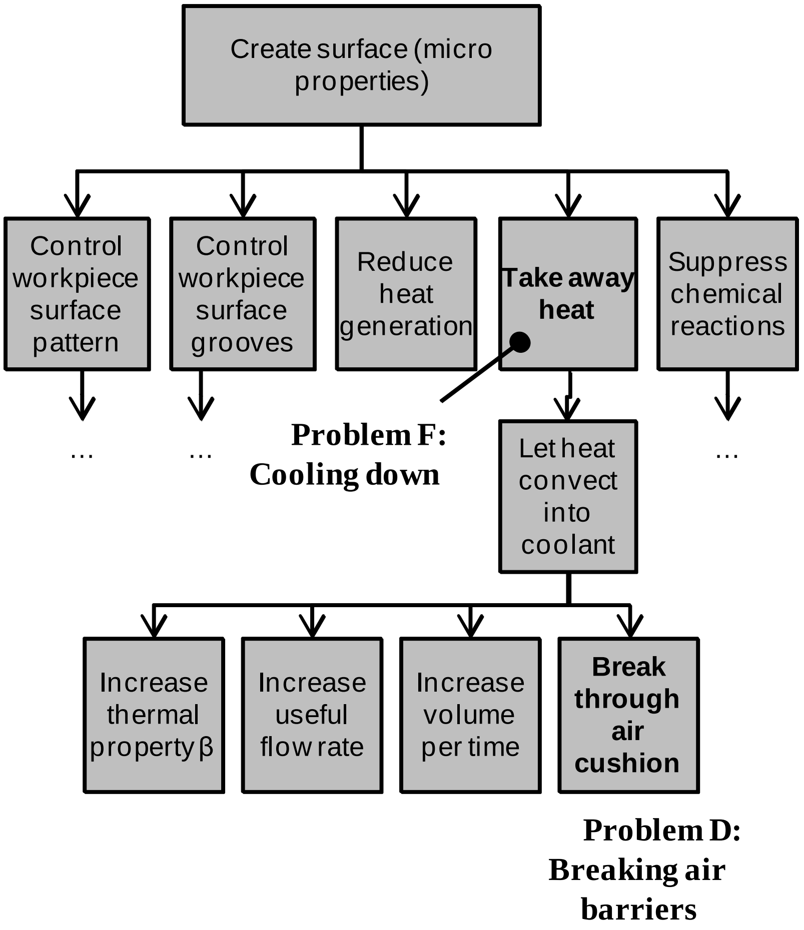

Figure 2. Axiomatic grinding model part 2.

The second function of the grinding process, creating a surface, splits into surface topography and integrity (Figure 2). This makes necessary that: the workpiece surface pattern and grooves need to be controlled, generated heat needs to be reduced and apparent heat to be taken away, and chemical reactions be suppressed (Figure 2). Removing heat is translated into “Problem F: Cooling down”. In actual grinding processes, the heat is removed through heat convection into coolant. Different parameters make heat convection through a coolant most effective: a high thermal property [13], high useful flow rate [14], and high volume per time. Furthermore the coolant needs to penetrate the air

cushion around the rotating grinding wheel in order to reach the workzone. This is defined as “Problem D: Breaking air barriers”.
The third main function of the axiomatic model is being cost-effective, which we expand to “Problem E: Being sustainable”.

4. BIO-INSPIRED CONCEPTS IN GRINDING

The preceding chapter has defined and reframed the problems in grinding, which are the first and second steps of the problem-driven bio-inspired design method. In the following section, steps 3 – 6 are conducted: Biological solutions are defined and sought out; the principle is extracted and applied for the grinding problem.

4.1 Problem A: Transporting of particles and cleaning

The chips produced in grinding need to be transported out of the workzone so they do not rub against part or tool thereby producing heat or damaging the part surface.

Today`s solution. In most grinding applications pores in the grinding tools and metalworking fluids transport the chips. The metalworking fluids also cool, lubricate, and prevent corrosion of the parts and machine [15]. The pores allow space for both chips and fluids and can be varied widely in number, size and total volume. Foremost, porosity is influenced by the volumetric composition of grit and bond material. In addition, there are two ways to actively create porosity [16]: either by the burning up substances during tool manufacturing or by hollow substances breaking up during the abrasive machining process. For high material removal rates, cleaning nozzles with high flow rate and high pressure are needed to unclog the pore space [17].

Biological solution 1. One inspiration for removing the chips created in the machining process comes from the natural flowing rivers, oceans, waterfalls, and other bodies of water on earth. Rivers are used to transport logs in the logging industry, oceans transport many debris onto the coastline with their waves, and waterfalls with their vast drop in altitude create huge forces that can move anything their path. These bodies of water have *underwater streams* that allow debris to move from one point to another.

Principle application 1. The abrasive process can be exposed to any of these watery environments on a smaller scale. We suggest mimicking an *underwater process with streams* that simulates the ocean (Figure 3). Continuous pumping and filtrating will keep the water moving and clean. Additives will be needed in the water to prevent degradation and foaming as common in regular grinding emulsions or solutions.

Molfino et al. studied an underwater diamond wire cutting process and concluded that the temperature of the cutting surfaces is lower than conventional cutting temperatures in air because of the water immersion [18]. Furthermore, the chips were removed from the cutting zone regularly and efficiently. However, it must be noted that due to the higher density and viscosity of a water environment compared to air, the grinding process will behave differently. Thuot et al. conducted experiments on an underwater grinding system and discovered that the water drag forces significantly affect the power needed [19]. In order to fix this predicament, Thuot et al. added a pressurized air nozzle that introduced air bubbles on the grinding wheel surface resulting in an 80 % increase in the power available for the grinding process [19]. This concept is added to the idea in Figure 3.

Underwater abrasive processes could also be beneficial when one is concerned about heat transfer (Problem F). Another improvement of the conceptual idea in Figure 3 is changing the liquid media such that it reduces the drag on the abrasive wheel while not compromising the cooling and transportation of chips.

This principle can only be applied to materials which do not react or become damaged due to the interaction between the fluid and the material. In addition, the grinding wheel and spindle need to be designed for fluid immersion in order to reduce the drag force created by the fluid itself. Maintaining the fluid in the tank and grinding machine is a challenge, but design solutions from EDM machines or other machine tools could be applied, preferably if they have shown to effectively filter out particles from the fluid and provide a clean cutting environment.

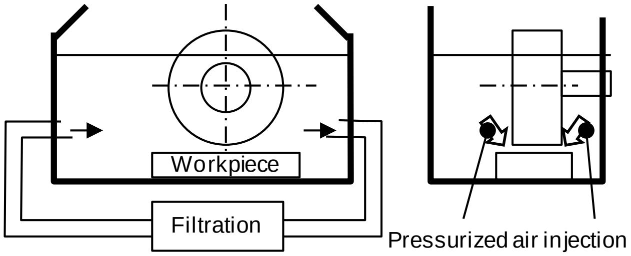

Figure 3. Suggested ocean-like underwater grinding process with pressurized air injection

Biological solution 2. The *self-cleaning property* of lotus leaves inspired many applications with super hydrophobic surfaces [7]. The super hydrophobic characteristic of the lotus leaf is attributed to a self-produced organic wax which has low surface energy [20]. The structure on the front surface of the lotus leaf is another contributing factor to its hydrophobicity [21]. The average periodic distance between its micro-pillars is 20 μm while the average distance between its nano-pillars is 240 nm [21]. The small spacing between each pillar prohibits the water from entering the grooves while still allowing gases to exist in the grooves, which in turn further prohibits the water from entering the grooves increasing hydrophobicity [21]. The hydrophobicicity also causes the lotus leaf to impart a self-cleaning mechanism as the water molecules, which are repelled, wash away any particulates on the leaf [20].

Principle application 2. As mentioned in the paragraph on today`s solution for transporting of particles, pores can be embedded in a grinding tool through hollow substances breaking up during the abrasive machining process [16]. Hollow corundum is a sintered abrasive in the form of a hollow sphere and has been successfully used as pore builder for grinding belts [22]. One idea is to have *self-cleaning hollow pore builders* (Figure 4). The insides of hollow particles that form the pores need to be engineered with non-sticking, super hydrophobic surfaces. The inside of the particles could have a structure similar to the micro- and nano-pillar structure found on the surface of a lotus leaf or some other hydrophobic coating.

Matsumura et al. produced microstructures that changed wettability by micro-stamping [23]. Schmid et al. created a highly porous complex structure using titanium in order to simulate trabecular bone [24]. The method in creating this structure could also be used to create the non-sticking, super hydrophobic surfaces in the pores.

The main challenges for this principle are finding appropriate materials and production processes that keep the tooling costs low enough to be attractive to customers. Once the design is implemented, it could also possibly reduce operating costs by reducing the amount of fluid needed for the abrasive process. Since the surface is hydrophobic, debris could possibly be less likely to cling to the surface with the help of the fluid and thus, less fluid would be needed. The new grinding tools should not create hazards to the worker and environment.

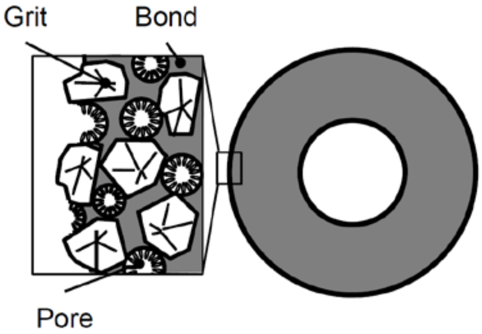

Figure 4. Concept of pores with non-sticking inner surface in a grinding wheel

4.2 Problem B: Resisting against abrasive wear

Grinding tool wear causes defects such as workpiece shape defects, undercuts, and chatter marks [15]. Wear is caused by mechanical effects (vibrations and grinding forces), chemical effects (reactions with cooling lubricant and workpiece material), and thermal effects (grinding pressure and friction) [25]. Resisting against abrasive wear enables the grinding tool to perform a stable grinding process.

Today`s solution. The grits are preferably harder than the workpiece material to conduct chip formation [25]. In addition, a high strength bonding prevents material loss from the wheel and maintains the tool profile. Frequent tool conditioning restores tool sharpness and profile.

Biological solution 1. The *ridged surfaces* of a Farrer’s Scallop resist abrasive wear in such an effective way that “the percentage of the reduction of mass loss […] is on average about 63 %” less when compared to flat surfaces [26].

Principle application 1. The bonded grinding tool can take inspiration from the scallop structure, a *structure with unidirectional wear-resistance*, which would cause the grinding tool to have less wear and last longer. It is already common practice to emulate milling tools in the design of grinding tools by attempting to define distances between the grits, so called “engineered grinding wheels” [27]. One advantage is the defined grit distribution and orientation simplifying modeling [28]. In addition, grinding wheels with discontinuous cutting faces can remove chips similarly well as highly porous wheels [22].

Combining the positive effects on wear resistance and chip removal, a grinding wheel with scallop structure is suggested (Figure 5). Challenges lie in the production and conditioning of such a tool. Dressing with synchronized revolutions between wheel and a noncircular dressing roller provides an unconventional way of producing wheels with lobes [EICHH]. The higher surface roughness of the wheel would probably make this design only applicable to roughing operations.

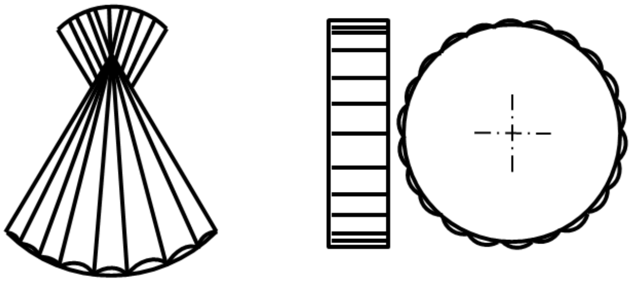

Figure 5. Left**:** Scallop structure, right: suggestion for peripheral grinding wheel with ridges

Biological solution 2. Bamboo, a grass plant, shows the highest abrasive wear resistance when its fibers are orientated normal to the sliding abrasive surface [26]. Therefore, *oriented fibers* is another bio-inspired solution.

Principle application 2. If the bonding material that holds the abrasive grits together has its "fibers" or *reinforcements normal to the cutting forces*, it will result in longer life because it is more resistant to wear. For example, Madhavan et al. machined unidirectional carbon fiber reinforced plastic discs and observed significant variations of the cutting forces depending on the fiber orientation [29].

Figure 6 shows a design idea of a reinforced wheel for peripheral grinding with the respective cutting forces, Figure 7 shows the same for face grinding. In both cases, the normal and tangential forces are the highest cutting forces and the fibers are perpendicular to them. These nature inspired designs of reinforced grinding tools can help reduce the profile wear making the tool last longer and reducing waste.

We suggest adding high hardness bond elements or elongated grits instead of fibers. Interpenetrating bonding systems are already applied in grinding wheels, such as resin fibers in a metal matrix [30]. Resin bonds have a high elasticity, whereas metal bonds build up higher bonding forces. Both advantages can be combined in an interpenetrating bonding system.

An example for elongated grits are long needle diamond grits with a length to thickness proportion of between 2:1 and 5:1 [31]. They are synthesized with the growth direction in the diamond main axis direction, the crystallographic [100]-direction [31]. Another example are needle-shaped, extruded sol-gel alumina grits. This grit type can have aspect ratios as high as 8:1 and are manufactured from the sol-gel process with additional extrusion processes [15].

Again, wheel manufacturing might be problematic and result in high tool prices. High dressing tool wear can also be expected if the grinding tool itself is reinforced. The additional tool ingredients need to be harmless to workers and the environment to improve overall sustainability in grinding. The success of this design could possibly reduce the amount of waste created by the manufacturing of abrasives wheels since each wheel would have a longer life cycle.

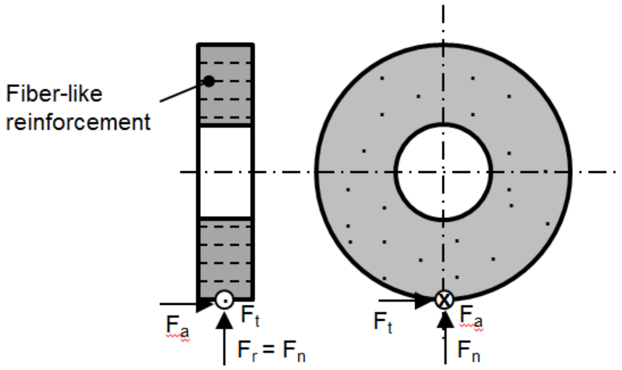

Figure 6. Concept of a fiber-reinforced grinding wheel for peripheral grinding (F_a = axial force, F_n = normal force, F_r = radial force, F_t = tangential force)

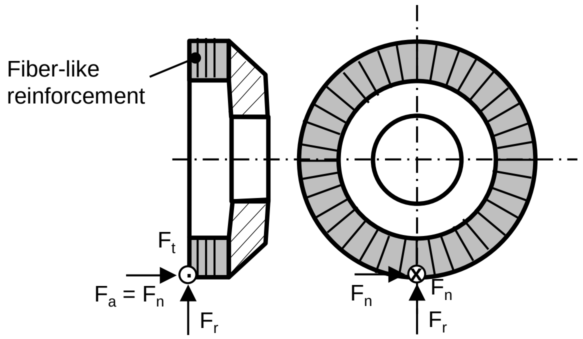

Figure 7. Concept of a fiber-reinforced grinding wheel for face grinding (F_a = axial force, F_n = normal force, F_r = radial force, F_t = tangential force)

4.3 Problem C: Self-sharpening

Preferably, a grinding wheel stays sharp throughout the grinding process. The grits can splinter, which leaves new cutting edges, or flatten, which decreases chip formation efficiency. Bond and grit strength and wear behavior have to be balanced. If the bond wears too slowly compared to the grit wear, the tool might become blunt and induce thermal changes in the workpiece rim zone; if the bond wears too fast compared to the grits, the grit protrusion increases along with dimensional change of the tool [15]. Thus, the ideal bond is one that adjusts to the grit wear [15].

Today`s solution. Self-sharpening of the abrasive tool is achieved by carefully choosing the tool composition and finding the best tool conditioning strategy and grinding parameters for the actual application. Process expertise is needed, but often accompanied by trial-and-error testing.

Biological solution 1. *Shedding* is a biological solution that can continuously provide a sharpened surface by replacing the old surfaces. For example, the cling fish has specialized attachment organs on its mouth area and thorax which provide spines to prevent the fish from slipping in streams [32]. These spines are continuously exposed to drag from the streams and are replaced by an underlying layer of new spines once they are worn away [32]. In addition, these layers of spines have to find a way of not interfering with one another when they are on top of each other.

This problem resembles another adaptation of having multiple layers on top of each other by some lianas like the liana Parthenocissus tricuspidata [32]. This plant's growing tissues "can exactly replicate a surface profile by growing into the surface depressions" [32]. These tissues then harden by thickening their cell wall and the surface-plant interface becomes a firmly attached mechanical grip [32].

Principle application. If an abrasive wheel had multiple layers of sharpened surfaces like the cling fish, the wheel could continuously stay sharp by *shedding off its older worn outer layers*. Shedding could be induced by exceeding certain binding forces or softening temperatures if the layers were glued together.

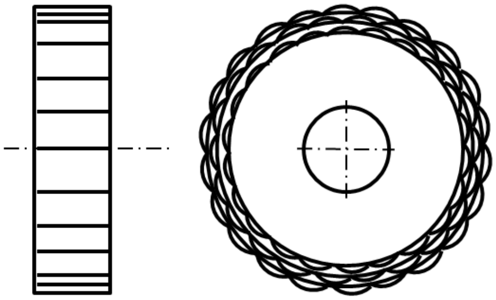

Figure 8. Shedding layers with ridges inspired by the scallop structure (Figure 5)

The multiple layers of the abrasive wheel could be interlocked by a mechanism similar to the liana layer interface. This would allow the sharpened layers to coincide on top of one another without interfering with one another. This structure resembles existing concepts for deburring tools with non-woven synthetic fiber webs and molded wheels impregnated with abrasive minerals [33].

Figure 8 combines the scallop structure with the shedding principle. This seems beneficial for both self-sharpening and wear resistance. In any case, the tooling costs need to be competitive thus putting an emphasis on raw material costs and wheel manufacturing. The wheel must endure a high number of revolutions and grinding forces, which, in turn, stresses the layer integrity. During the grinding process, the shed layers must not interfere with the grinding process or clog the machine's coolant supply system. In addition, the metalworking fluids themselves should not harm or alter the grinding wheel. The shed layers could possibly be recycled and reused for new grinding wheels making it a more sustainable process.

4.4 Problem D: Breaking air barriers

The rotating grinding tool builds an air barrier ("air cushion") around itself. The air barrier pushes metalworking fluid away and is more pronounced at higher wheel speeds. Metalworking fluids need to break this air barrier to lubricate and cool the workzone [17].

Today`s solution. High pressure lubricant nozzles are used today, but the energy demand of high pressure pumps can add significantly to the process energy [34]. Other nozzle designs include shoe nozzles, which break the air barrier with a plate, and needle nozzles, which can bring the coolant close to the workzone. Both nozzle types depend on the wheel profile and need to be readjusted if the wheel size changes.

Biological solution. *Geysers* are a great source of inspiration when thinking about ways of breaking this air barrier. Geysers build immense pressure and finally erupt blasting water high up in the air. The general concept for a geyser is that water trickles down to underground plumbing which is then heated up by magma far below the surface [35]. This in turn causes pressure to build up underneath the geyser's reservoir until eruption occurs [35].

Principle application. A *geyser nozzle* could have pulsed, discontinuous ejections of metalworking fluid or a fluid/air mixture. The geyser nozzle could be kept highly pressurized until the workpiece reaches a critical temperature; then the nozzle releases the metalworking fluid much like a geyser. Once the geyser nozzle will reach ambient pressure, the nozzle needs to be closed off in order for the pressure to be built up again. This nozzle type could also benefit resource efficiency and lead to a Minimum Quantity Lubrication (MQL) setup.

The pulse control of the nozzle is a challenge due to the involvement of temperature sensors and feed-back control loops. The nozzle material and shutter in particular must have high resistance against considerable fluid pressures and abrasive wear brought on by unfiltered particles from the tool or workpiece. A shield around the nozzle and the shutter should be considered to protect against the barrage of particles from the grinding process. The nozzle should be installed closely to the wheel to maximize the benefits, which might constraint the nozzle design. The necessary high pressure pumps add to the power demand of the grinding process, which needs to be offset by a higher process performance.

4.5 Problem E: Being sustainable

Grinding technology is under constant pressure to satisfy customer demands while controlling costs. Some traditional applications have already been overtaken by hard-machining; in other production chains grinding is removed completely because of near-net-shape forming operations.

Today`s solution. Grinding stays an important manufacturing process through incremental improvements of existing systems and sporadic big leaps in new machinery and tool design.

Biological solution. Nature has always actively conquered new environments through the *evolution of existing concepts*. The aforementioned inspiration for a new nozzle type, the geyser for example, has a very interesting ecosystem. Even though geysers operate at very high temperatures where most living cells will not survive, thermophiles and hyperthermophiles thrive as they grow best at temperatures higher than 45 °C and 80 °C, respectively [36].

Principle application. The extreme condition in which extremophiles live under can be taken as inspiration when creating new methods for the abrasive process. Extremophiles are able to adapt to such extreme conditions by either having their cell membrane shield their intracellular environment from the extreme conditions or by making their intracellular environment functional at those extreme conditions

[37]. In the same way, the grinding process can either be shielded from the extreme conditions or made functional by adding components.

An *abrasive underwater process* was discussed earlier in which the cooling and removal of chips benefited but not the efficiency. A probable solution was provided in order to increase the efficiency by introducing pressurized air [19] or even a different type of fluid environment into the abrasive process. The pressurized air would shield the abrasive process from the extreme condition by allowing more of the power to be transferred to the abrasive process rather than consumed in overcoming the drag due to the oncoming fluid.

Another example of an extreme environment is the *space frontier* with almost a perfect vacuum with little or no oxygen. Buckley performed experiments on tribology by reducing the ambient pressures and creating a vacuum [38]. He discovered that the presence of adsorbed films, which are comprised of adsorbed species such as the atmospheric gas and water vapor, and metal oxides reduces the tendency for metal surfaces to adhere to one another [38]. When Buckley reduced the ambient pressure to vacuum it was revealed that materials will have a tendency to “desorb adsorbed species as well as to reduce the thermodynamic stability of the metal oxides” [38]. Thus, if one reduces the ambient pressure, the coefficient of friction will increase drastically due to the decrease of adsorbed films. For example, the friction coefficient of copper crystals increased 20 times on the [111] plane in vacuum compared to air [38].

Reducing the ambient pressure causes the friction coefficient to increase dramatically because of the desorption of the adsorbed films but one could go in the opposing direction and increase the ambient pressure to uncover what might happen. Barash et al. discovered that increasing the ambient pressure raises the material removal rate substantially when using ultrasonic machining on glass [39]. This increase in the material removal rate is perhaps related to a possible increase in the adsorbed species due to the increase in pressure. If more adsorbed species are present in the adsorbed film, this will perhaps reduce the tendency even further for the metal to weld to itself. Increasing the pressure in order to increase the adsorbed species could be applied to the grinding process in order to achieve a possible increase in the removal rate.

Additional experiments showed that oxygen is essential to machining processes. Shaw points out “in the absence of oxygen, chips will reweld to the finished surface, […] this mechanism accounts for the large increase in grinding energy when grinding in an inert atmosphere” [40]. After experimenting with inert gases like Nitrogen and Helium, Shaw realized that these inert gases produced much higher grinding forces compared to atmospheric air: The force F_Q was 12 N for air compared to 267 N and 278 N for nitrogen and helium respectively [40]. He also warns that “were it not for the oxygen present in the air, the rate at which metal is removed in finish grinding would have to be greatly reduced, due to the danger of damaging the finished surface by the development of excessively high temperatures” [40]. Therefore it is necessary for oxygen to be in the environment when machining.

One idea is that oxygen could be used to protect the abrasive process from extreme environments such as vacuum or space similar to how the extremophiles’ cell membrane shields its intracellular environment. However, oxygen fuels some of the following reactions with grit materials: SiC oxidizes at high temperatures to SiO_2 (equation 1) [41].

$$SiC + O_2 \rightarrow SiO_2 + C - 183.6\ \text{kcal} \qquad (1)$$

CBN is covered with boron oxide, B_2O_3, in dry air at temperatures of 1200 °C (equation 3). In grinding, this layer has supposedly a wear-inhibiting effect [25].

$4BN + 3O_2 \rightarrow 2B_2O_3 + 2N_2$ (3)

At temperatures above 800 °C, diamond burns to carbon dioxide with air oxygen (equation 4), but reactions can also happen at lower temperatures [42].

$C + O_2 \rightarrow CO_2$ (4)

If oxygen is scarce like on a spacewalk, or the process is conducted in a highly reactive environment, the ambient pressure could be increased in order to increase the adsorbed species and possibly enlarge the removal rate. This could limit the need to use large amounts of oxygen when machining outside of earth’s atmosphere where oxygen is very scarce. This section showed just a couple of different options inspired by the extreme environments in which extremophiles dwell in. These possibly unconventional environments might bring inevitable constraints to the grinding process or could be employed to target certain benefits. In the latter case, the additional equipment, housing, and safety devices should not outweigh the higher productivity or better surface quality of the abrasive process.

4.6 Problem F: Cooling down

Process heat is a dominant challenge in grinding technology and affects the part`s surface integrity. To reduce the impact on surface integrity it is favorable that minimal heat is generated, existing heat is removed, and chemical reactions are suppressed.

Today`s solution. The basic principles for heat removal are heat convection and heat conduction. Both air and metalworking fluid are involved in heat convection, though the influence of the metalworking fluid dominates and convection into air is often neglected in heat management considerations for grinding. A cooling lubricant with a high heat transfer coefficient and heat capacity must be present in the grinding zone. Conductive heat flow into the grinding tool also occurs, though at a slower rate than convection into the cooling lubricants. Heat flow into the grinding tool can be changed by modifying the heat conductivity and capacity of grit and bond materials [43].

Biological solution. We take inspiration from the convection that occurs off a dog’s tongue. The tongue acts as a *heat sink*. The machine that holds the workpiece can also have high heat conduction coefficient in order for the heat to dissipate into the machine which can be transferred using ground loop heat exchangers to nature itself: the earth.

Principle application. The coldest places on earth have temperatures in subzero ranges such that all the water is frozen into ice. Taking this as inspiration for *natural heat sinks*, water in its solid stage is cold but carbon dioxide in its solid state, also known as dry ice, is even colder. Jerold and Kumar used cryogenic carbon dioxide for turning of steel and measured lower cutting temperatures and improved surface finishes than for wet machining [44]. For grinding, Suzuki et al. stated that “by using dry ice grains jet together with minimal quantity lubrication, grinding force decreased by nearly 20 %” [45].

Another possible coolant that can be used due to its very low temperature is liquid oxygen. As the previous section states, it is necessary for oxygen to be present in the machining process or else the coefficient of friction and forces required to machine increase drastically. The exceptionally low temperature of liquid oxygen could also act as a heat sink. Used as a coolant, liquid oxygen could help with both heat convection and reducing of grinding energy. Creating an environment which is rich in oxygen and liquid oxygen can greatly benefit the heat dissipation and efficiency of the abrasive process but a balance must be found as the previous section also warns about the dangers of having excess oxygen in the abrasive process.

Cryogenic cooling with liquid nitrogen has already shown promising results in cutting [46, 47, 48]. Even less low cooling temperatures are beneficial. Lee et al. found that grinding with compressed chilly air at -20°C reduced the normal and tangential grinding forces by 69.6 % and 72.8 % respectively when compared to grinding with room temperature air at 25°C and tool wear also decreased [49].

As a drawback, using cryogenic carbon dioxide, liquid oxygen, or liquid nitrogen for cooling increases equipment costs, safety measures and necessary training. These process variants would need to be closely regulated in order to produce a safe and efficient working environment.

5. CONCLUSION AND OUTLOOK

Manufacturing processes need to be constantly improved and changed towards higher sustainability. The bio-inspired design process is highly creative and brings new ideas, which would not have been found without the inspiration through nature. Bio-inspired design methods were used for grinding, but a possible problem in our concepts could be the oversimplification of complex functions. This danger is intensified because of the complexity of the grinding process and has to be kept in mind when applying the bio-inspired solutions.

This study has found promising new concepts for self-sharpening tools, tools with better chip transport and higher abrasive wear resistance, a new nozzle concept for breaking air barriers, and new strategies for adapting grinding to new environments. Further research and actual implementation of the presented ideas is needed. Nevertheless, this first study has revealed many interesting approaches as to how bio-inspiration can bring more sustainability into grinding.

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