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Technical Paper

New concepts for bio-inspired sustainable grinding

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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.

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 dentin 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 Section 4. 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

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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.

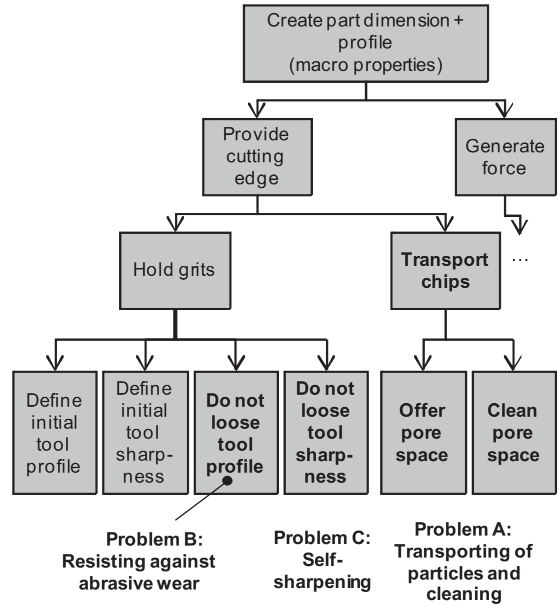

Fig. 1. Axiomatic grinding model part 1.

The first main function of grinding is creating the part dimension and profile (part macro properties) (Fig. 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”).

The second function of the grinding process, creating a surface, splits into surface topography and integrity (Fig. 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 (Fig. 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