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Sustainability analysis of grinding with power tools

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Grinding with power tools includes precision applications, such as polishing and engraving, but also high-performance applications such as cut-off grinding and deburring in foundries or construction. There is a growing demand for power tools in both industrial and consumer markets, but there is little literature on the sustainability of grinding with power tool available. Therefore, this paper summarizes the input-output-streams of manual grinding and reviews sustainability aspects, in particular the energy source of abrasive power tools, layout of grinding tools, safety, and health. A survey on angle grinders showed how companies advertise in particular social and economic features, but not environmental features. The discussion demonstrates that much work needs to be done on the sustainability of grinding with power tools.

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Keywords: sustainable manufacturing processes; manual grinding; power tools; cut-off grinding; deburring; performance indicators**1. Motivation**

Grinding with power tools includes precision applications, such as polishing and engraving, but also high-performance applications such as cut-off grinding and deburring in foundries or construction. Challenging applications include nuclear decommissioning and underwater cutting. There is a growing demand for power tools in both industrial and consumer market [1], but there is little literature on the sustainability of grinding with power tool available [2]. Therefore, this paper will review different aspects of the sustainability of grinding with power tools.

This paper discusses issues relating to the power supply, occupational health hazards and advertised sustainable features of abrasive power tools and the abrasive media options in the market today. This paper aims to give a first discussion of the sustainability of grinding with power tools.

2. Grinding with power tools**2.1. Applications**

Grinding with power tools occurs in several industrial and commercial applications. The value of shipments of power

tools reported in the 2002 US census by power tool manufacturers was \$3.28 billion USD, with shipments of abrasive tools (die grinders, angle grinders, polishers and sanders) accounting for \$196.8 million USD [3].

In the industrial market abrasive power tools are used in a factory or workshop setting for surface finishing operations such as weld grinding, deburring, polishing and the like. As opposed to machine tools, power tools can be used on large parts that would not fit on a grinding machine stage.

In addition to manufacturing in a factory setting, abrasive power tools are extensively used in the construction industry. Their portability and versatility make power tools indispensable in construction site and other field operations. The variety of power sources that can be used to supply the power to the power tools such as batteries, pneumatics, grid electricity, and liquid fuels further enhance the versatility of power tools. Abrasive power tools are used in the construction industry not only in the surface finishing operations previously mentioned, but also in more demanding operations such as cut-off operations in metal and reinforced concrete work. Also, wood finishing is nearly exclusively done with sanding power tools.

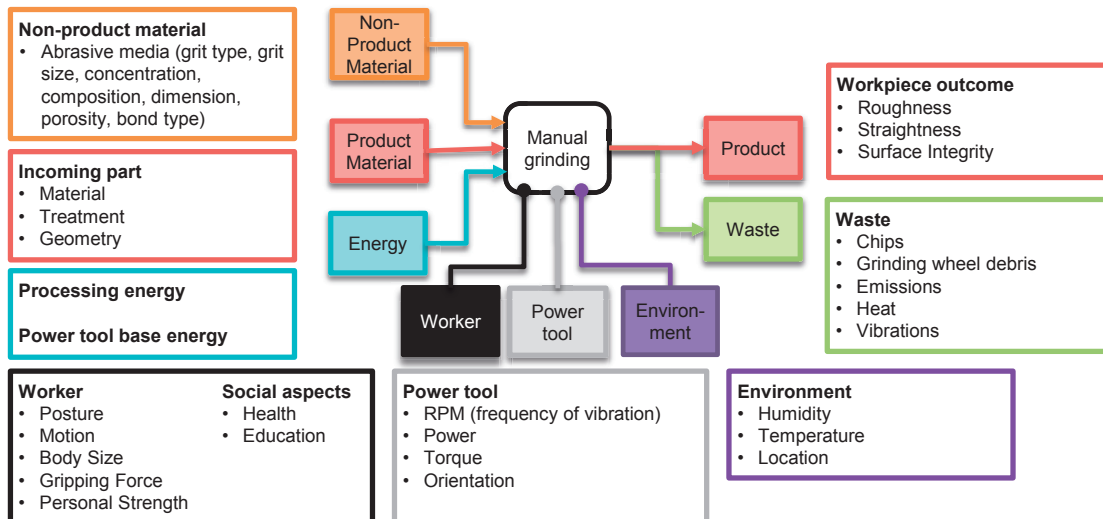


Fig. 1. Input-output diagram of grinding with power tools

Due to the relative low price and ease of operation of power tools as compared to machine tools, many power tools can also be found in home workshops of hobbyist and DIY (Do It Yourself) enthusiasts. Uses in the residential and hobbyist market are the same as have been listed above.

2.2. Input-output analysis of grinding with power tools

The first step to discuss a process is to define the boundaries and input-output streams. The main components of a manual grinding operation with a power tool are shown in Fig. 1. This diagram provides the scope for a Life Cycle Inventory (LCI) as used in Life Cycle Assessments (LCA). The LCI describes not only the energy and material streams, but clarifies potential levers for improving process sustainability.

Compared to automated grinding operations (e.g. input-output diagram in [2]), grinding with power tools is highly affected by the worker. Also the environment of flexible grinding operations is harder to control and needs to be addressed specifically. Commonly, there is no metalworking fluid present as non-product material, simplifying the process and avoiding waste fluid or filter media.

2.3. Energy in grinding with power tools

The energy source of power tools impacts transportability, flexibility, costs, and performance profile (power to torque and maximum rpm) of the power tool. The most common power sources are electricity (both grid and battery supplied) and pressurized air. Some abrasive power tools run on liquid fuel, though they account for a rather small portion of the commonly used abrasive power tools and are not discussed in this article.

2.3.1 Electrically powered abrasive power tools

According to the 2002 US Census the plug in electric power tools make up the largest share of the domestic power tool market [3]. Due to cost and size constraints most electric motors in power tools are small commutated, series-wound motors also known as universal motors. Though universal motors are lightweight, easy to control, and have desirable operating characteristics (high starting torque and high operating speeds) by the nature of their construction universal motors typically operate at less than 50 % efficiency [4]. Further, friction between the commutator and brushes in a universal motor causes wear and limits the lifespan of a universal motor.

Induction motors are a more efficient alternative to universal motors. Brushless Permanent Magnet (BLPM) motors are a very efficient type of induction motor that operate at efficiencies of 80 – 90 % [4]. Not only do BLPM motors run much more efficiently, putting the electro magnets on the stator and permanent magnets on the rotor obviates the need for a physical connection between the spinning rotor and stator prolonging the life of the motor. Eliminating the brush/commutator contact also eliminates sparking caused by the brushes and lowers the heat generated in the tool. Eliminating the sparks (which can act as an ignition source for flammable vapors) and lowering the heat generated by the tool will enhance worker safety in environments where flammable, volatile materials are used such as auto body repair shops. Transitioning from an initially cheaper universal motor to a longer lasting BLPM motor would improve the operational efficiency and average life of electrically driven power tools. However, to fully assess any potential improvement in sustainability gained by switching to BLPM motors a study that takes into account both the life cycle of the motor and costs contained in the supply chain of the materials used in construction in the motor would have to be conducted. Such a study is outside the scope of this paper.

2.3.2 Battery powered abrasive power tools

As mentioned earlier, one of the desirable attributes of power tools is their portability. Recent advancements in secondary battery technology, namely the development of rechargeable lithium ion batteries (LIB), have greatly improved the portability of power tools. Primary (non-rechargeable) lithium batteries contain a lithium metal cathode, though due to the propensity of lithium metal to catch fire when exposed to moisture. Secondary (rechargeable) LIBs use a lithium metal oxide in the form LiXMA_2 (most commonly LiCoO_2 , LiNiO_2 , and LiMn_2O_4) to lower the fire risk due to cell corrosion [5]. The inclusion of other heavy metals into the battery cathode creates a need to insure proper disposal of spent battery cells. A 2009 exergy analysis of waste LIB smelting for Mn, Ni and Co recovery in Europe has indicated the efficiency of metal production from waste LIBs is comparable to that of mining [6]. The heavy metals used in LIBs are both valuable and hazardous, making the efficient recovery of them both economically and environmentally sustainable.

2.3.3 Pneumatic abrasive power tools

Aside from electric power tools, pneumatic power tools that run on compressed air are the most common in the U.S. [3]. Some advantages of pneumatics are: the lack of electric shock hazards, absence of sparks or ignition sources during operation, and light weight due to the absence of a motor. For these reasons pneumatic tools are often used in environments where volatile, flammable substances are used (i.e. auto body shops or factories where paint and solvents are used) and in precision applications where the lower weight is needed for enhanced control of the tool by the user. One major drawback of compressed air as a power source from a sustainability point of view is the inherent power loss during air compression. Typical power tools operate at 0.689 MPa (100 psi).

Due to thermodynamic principles heat is generated during the compression of a gas. The inherent inefficiencies of compressing air lead to only 10 – 20 % of energy input into an air compressor being available to perform useful work [7]. Two strategies can be deployed to avert such massive losses of energy: replacing pneumatic tools with BLPM tools where possible and installing heat recovery systems on air compressors to use the low grade waste heat for temperature control or other useful processes.

2.4. Abrasive media

Depending on the applications discussed in section 2.1 different types of abrasive tools are applied with power tools. Precision grinding, smoothing of welds, or cutting-off operations are done with bonded grinding tools, also known as grinding wheels or discs. These wheels consist of abrasive grits, mostly alumina, silicon carbide, or diamond held in a resin, vitrified or metal bond. Sanding or finishing operations are conducted with coated grinding tools, also called grinding belts or sandpaper. These tools consist of abrasive grits held

on a paper, plastic, or metallic backing. Polishing pads consist of abrasive grits in woven material.

Cut-off wheels are a special type of bonded grinding tools. They need to be thin to reduce the amount of wasted material in the cut-off operation and to reduce power consumption. They are commonly made with resin bonds, which need to be reinforced to withstand side forces. Cut-off wheels are reinforced with glass fibers, nylon discs, carbon, cotton cloth, linen, wood, silk, materials on aramide basis, or other materials [8, 9]. The introduction of glass fiber reinforcements in 1952 boosted manual and automated cut-off grinding [10].

During grinding, however, glass fiber particles can be released and inhaled by the worker. Fiber glass can induce alterations of the cellular and enzymatic components of the deep lung [11]. Natural fiber cloth such as hemp is an alternative and does not release mineral particles during wheel use [12]. Challenges, however, are the lower strength of the natural material, inhomogeneous composition, susceptibility to micro organisms and strong water assimilation. With cleaned and preprocessed hemp fibers, Eschner et al. successfully produced cut-off wheels [12].

Joshi et al. state that the production of natural fiber reinforced resins (NFR) is more environmentally friendly than the production of glass fiber reinforced resins (GFR) [13]. Furthermore, natural fibers can be incinerated and might even give energy credit (e.g. the incineration of china reed gives an energy credit of 14 MJ/kg) [13].

Abrasive tools need to be designed for high productivity, safety, and wear resistance. They are consumed during the abrasive machining process and are therefore critical in terms of wear and debris release. This is of particular importance outside of a factory or containment or in a sensitive or flammable environment.

Grinding tools should operate in a self-sharpening state for highest process stability. They also need to be re-profiled and re-sharpened in nearly all grinding operations on grinding machine tools. Tool conditioning, however, is uncommon in grinding with power tools and therefore offers potential for process improvement.

2.5. Social sustainability and Occupational Health

The evolution of occupational health impact during grinding and handling power tools with its irreversible medical effects have been studied over many decades. Medically, the Hand Arm Vibration Syndrome was first diagnosed in France in 1862 when Dr. Maurice Raynaud, a Paris Physician first described an enfeebling condition of his patients in finger and hands [14]. From then on, different countries around the world have observed and researched the health impact of manual grinding and hand held power tools [14].

In Table 1, we have summarized the most common symptoms, their medical names, and the underlying hazards. The knowledge of these hazards has permeated into industry. For future studies, we will focus on finding international or regional regulations for employers and power tool producers to reduce the magnitude of the hazard.

Table 1. Hazards, syndromes, effects, and symptoms of power tools.

Hazard	Syndrome/Effects	Symptom
High frequency tool vibrations	Hand Arm Vibration Syndrome (HAVS) [15]	Reduced peripheral microcirculation Neuropathy leading to reduced tactile perception, numbness. Can result in permanent disability and handicap.
	Carpal Tunnel Syndrome [16]	Arthritis, joint and tendon degeneration, dupuytrans contracture.
	Temporary vascular effects [16]	Disturbance in sensibility, motor control and blood circulation Significant reduction of finger blood flow and increased vascular resistance
	Vibration White Finger (VWF) Syndrome or Cold Induced Raynaud's phenomenon [17]	Concomitant numbness. Reduction in peripheral blood flow. Spotted patches of blanching occur and followed by redness. Blanching results in reduced sensibility. Redness enhances sensation of pain. Cold Intolerance results from neurosensory or vascular dysfunction.
Low frequency tool vibrations	Neuro-Musculoskeletal Disorders [16]	Shoulder, hand and wrist tendonitis
Tool noise	Tinnitus [16]	Noise induced hearing loss
Tool and workpiece emissions	Thoracic Outlet Syndrome [16]	Decreased lung function due to dust and coating particle inhalation. Allergic reactions to lubrication and cooling liquids, which can irritate mucous membranes in the eyes, nose, throat.

3. Survey on current sustainable features in abrasive power tools

Marketing of sustainability efforts has become beneficial to the competitive advantage and superior financial performance of companies [18]. Therefore, we examined advertisements of power tools to understand the state-of-the-art of sustainable features.

Table 2 shows a survey where the 'features' sections for 76 angle grinders made by 10 major power tool manufacturers were examined. The sustainable features offered were categorized under the three pillars of sustainability: economic, social and environmental. Key words like comfort, protection, fatigue, weight, durability, and longer tool life guided the search for sustainable features. Below is an example of how a sustainable feature was selected from an advertisement:

The tool was described to have "Protective zig-zag varnish seal(ing) the armature from dust and debris for longer tool life". We deduced "Tool Protection and Durability: Armature sealed for protection" as sustainability feature.

Table 2 shows that clearly the environmental aspect is never specifically addressed in the tool advertisement. It is only indirectly addressed due to the overlap of the three pillars. Furthermore, out of the 10 companies surveyed, only two specifically mentioned the word "ergonomic" in their tool features. Even though all companies had designs geared to user comfort and grip comfort, these two companies labeled their modifications as ergonomic in the following ways:

- Rotating rear handle improves ergonomics
- 5 position side handle provides improved ergonomics
- Ergonomic soft grip provides increased comfort on the job
- Slim, ergonomic body design increases comfort during extended use

The word "ergonomic" can be used to describe many different modifications and is currently not quantifiable. This could be in the focus of future research and/or marketing efforts.

4. Conclusion and outlook

The preceding discussion demonstrates that much work needs to be done on the sustainability of grinding with power tools as evidenced by the widespread use of relatively inexpensive abrasive power tools, the necessary proximity of the operator to the tool and lack of standardized, clear vocabulary to describe the different features of the tools. A quantitative study of tools with different types of motors should be undertaken to quantify any potential energy savings (process, embodied and disposal) that could be realized by using BLPM motors while simultaneously analyzing any added environmental impact that would result from the use of more exotic materials in the motor construction. Also, the difference in embodied energy, tool life, and end of life costs between pneumatic and electric tools could be investigated. Tool conditioning in power tool grinding might be another research topic leading to higher sustainability. Further, the definition of 'ergonomic' should be standardized and a quantitative rubric should be developed to assess a tool's ergonomic qualities.

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Table 2. Survey on advertised sustainability of angle grinders.

Social sustainability	Economic sustainability	Environmental sustainability
Vibration Reduction <ul style="list-style-type: none"> Vibration reducing handle 	Servicing <ul style="list-style-type: none"> external brush cap for easy servicing 	
Grip Comfort <ul style="list-style-type: none"> smaller grip diameter cushioned grip 2, 3, or 5 position side handle contoured grip smooth start-ups enhanced micro-texture for secure grip right/left handed handle modification handle angle modification 	Motor Protection <ul style="list-style-type: none"> from dust and debris during stall and power disruption overload protection shuts off tool before overload or burn up motor cooling mechanisms motor shuts off in the event of bound wheel 	
Weight <ul style="list-style-type: none"> lighter tool high power-to-weight ratio without excessive weight 	Tool Protection <ul style="list-style-type: none"> armature sealed for protection durable armature material tool shuts off when brushes need replacing 	
Switches <ul style="list-style-type: none"> paddle switch trigger handle comfortable switch position safer one-touch quick off mechanisms 	Durability <ul style="list-style-type: none"> Tough durable cord steel gear heads machined bevel gears all-ball and needle bearings sealed ball and roller bearing design 	
Quieter tool		
Increased Productivity <ul style="list-style-type: none"> tool-free guard adjustments tool-free wheel removal quick brush replacement spindle lock oversized spindle lock button electric break wrench in side-handle grip closer to gear head for better control 		
Guard <ul style="list-style-type: none"> redirects sparks debris protection movable guard for improved visibility 		

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