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PRODUCTION PROCESS

Reusable unit process life cycle inventory for manufacturing: grinding

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Abstract This paper is a part of a series in which the goal is to provide users with calculation tools to estimate the energy use and mass loss of one unit process in a full manufacturing line. It is known as a unit process life cycle inventory (UPLCI). As such, this information is reusable in a wide range of products made of different materials. Grinding is the first UPLCI in this series, which is in the mass reduction category of the taxonomy of manufacturing processes. The energy calculations are not limited to the active or tip grinding energy, but include idle and basic energy values. In addition, an example calculation is provided to assist the UPLCI reader. The UPLCI can then be connected to others to estimate whole product manufacturing sequences.

Keywords Grinding · Process energy · Unit process · Unit process life cycle inventory · UPLCI

Abbreviations

Al_2O_3	Alumina
CBN	Cubic boron nitride
LCI	Life cycle inventory
SiC	Silicon carbide
UPLCI	Unit process life cycle inventory

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List of symbols

a_e	Depth of cut
a_p	Width of cut
d_w	Workpiece end diameter
d_{w0}	Workpiece start diameter
E_{basic}	Basic energy
E_{total}	Total energy
G	G-ratio or grinding ratio
l_c	Length of the cut or workpiece length
m_g	Grinding tool mass
m_s	Chip mass
N_p	Number of grinding passes
N_{parts}	Number of parts between dressing operations
N_t	Number of grinding transects to cover the whole area
P_{axis}	Axis power
P_{basic}	Basic power
$P_{controls}$	Controls power
$P_{dressing}$	Dressing power
$P_{grinding}$	Grinding power
$P_{coolant}$	Coolant power
P_{idle}	Idle power
$P_{spindle}$	Spindle power
t_{air}	Air travel time
t_{basic}	Basic time
$t_{dressing}$	Dressing time
$t_{grinding}$	Grinding time or active time
t_{idle}	Idle time
$t_{load/unload}$	Loading time
$t_{sparkout}$	Sparkout time
v_{fr}	Radial feed rate
$V_{removal}$	Material volume removed
V_{tool_wear}	Tool wear volume
v_w	Workpiece speed
ρ	Density of the material

1 Background

This paper is a part of a series in which the goal is to provide users with calculation tools to estimate the energy use and mass loss of one unit process in a full manufacturing line. It is known as a unit process life cycle inventory (UPLCI) [1–4]. As such, this information is reusable in a wide range of products made of different materials.

Grinding is the first UPLCI in this series, which is in the mass reduction category of the taxonomy of manufacturing processes [5–9]. Grinding is an important subtractive machining process for large scale production. Typically, grinding is performed as a finishing unit process at the end of process chains to improve surface quality and dimensional accuracy. For hard-to-machine materials, it can also be the major shaping process.

In grinding, abrasive grit particles are held in a bonding matrix as a monolithic body (grinding wheels or pins) or as coated tools (grinding belts, bands, pads). Conventional abrasives are alumina (Al_2O_3) and silicon carbide (SiC). Superabrasives with higher wear resistance are cubic boron nitride (CBN) and diamond. A cooling lubricant (grinding oil, emulsion, or solution) is used to lower the process heat, reduce friction and energy demand, clean the workzone, protect workpiece and machine, among other functions. The main cutting action comes from chip formation, but brittle materials can form cracks leading to particle break-out. Tool wear happens continuously during the grinding process and can be overcome by tool conditioning (dressing). This UPLCI profile is for a high production manufacturing operation, defined as the use of processes that generally have high automation and are at the medium to high throughput production compared to all other machines that perform a similar operation. This is consistent with the life cycle goal of estimating energy use and mass losses representative of efficient product manufacturing facilities.

The grinding mechanism is illustrated in Fig. 1. Main process variants used herein include cylindrical grinding (external and internal), surface and rotary grinding. Figure 2 gives the main parameters in surface slot grinding and external cylindrical grinding with transverse feed.

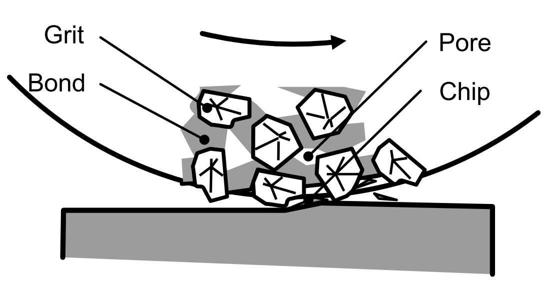

Fig. 1 Process schematics

2 Methodology for unit process life cycle inventory model

In order to assess a manufacturing process efficiently with reusable techniques in terms of environmental impact, the concept of a unit operation is applied. The unit process consists of the inputs, process, and outputs of an operation. The unit process diagram of a grinding process is shown Fig. 3. The diagram includes an overview of the environmental-based factors that are reusable when these analysis tools are applied to a wide range of applications for grinding operations. For a given workpiece the life cycle analysis yields energy use and mass losses as byproducts or wastes. Input energy is in the form of electricity, thermal energy, and compressed air [10].

2.1 Grinding process energy characteristics

This study focuses on electric energy. The UPLCI is based on a representative operational sequence, as follows.

1. Process set-up generally occurs once at the start of a batch of workpieces in production. Due to the fact that modern manufacturing is streamlined for productivity, the set-up time is divided by all the parts processed in that batch and is assumed to be negligible in most cases.
2. Since the grinding tool is commonly installed during machine set-up, we neglect the tool change time here.
3. Tool dressing is performed before a batch of workpieces is ground. Depending on the machine set-up, *dressing time* occurs separately or occurs during part loading.
4. *Basic time and power*: the overall cycle time (part in to part out) is used for basic energy calculations. It includes loading and unloading and each of these are in the range of 10–60 s depending on the size of the part. As seen from Fig. 4, the basic power is continuous over the cycle time and typically includes the items in Fig. 5.
5. *Idle time* is required for any tasks during the process cycle that do not engage tool and workpiece, Fig. 4. This idle time includes the tool approaching and retracting from the workpiece, tool movements between grinding features, adjusting machine settings, and changing between pre-mounted tools. The idle power P_{idle} is the W above basic power, Fig. 4.
6. *Grinding time* is the actual time when chip removal or spark-out (contact between tool and workpiece without depth of cut) happens. Grinding power $P_{grinding}$ is the W above that measured during idle, Fig. 4. Here the grinding energy is labeled Tip Energy.

For basic, idle, and grinding energy, the product of time and power can be used to calculate energy. For example, for profile grinding machines the tool spindle power can range from 15 to 75 kW [11, 12]. For external cylindrical

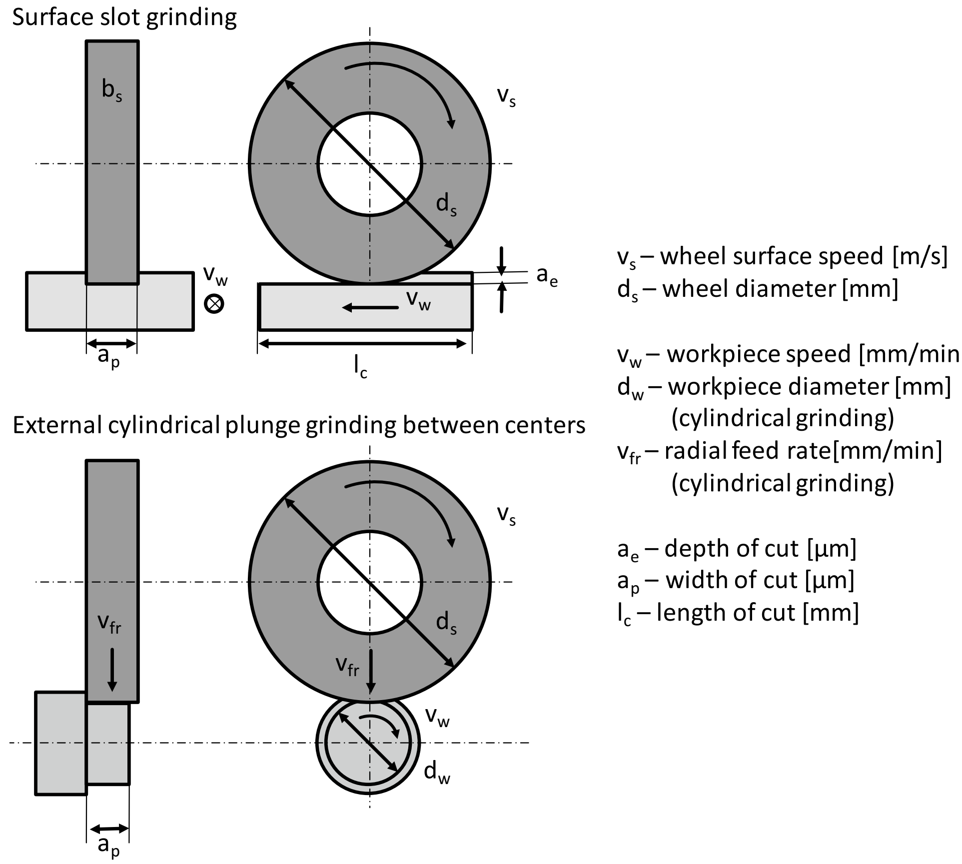

Fig. 2 Process variants used in this UPLCI

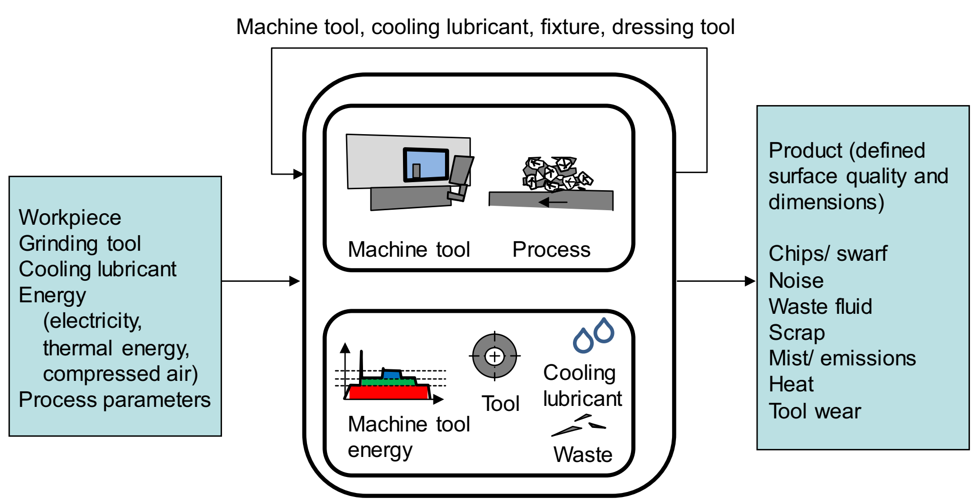

Fig. 3 Input–output diagram of a grinding process generating the LCI data

grinding machines, the tool spindle power can range from 3 to 30 kW, workpiece spindle power from 0.5 to 10 kW, and total connected load from 8 to 40 kVA [13]. A Round Robin test showed that grinding energy makes up only about 10–20% of the grinding machine energy [14]. Compressed air is mainly used for sealing and clamping applications. The power demand for compressed air can be calculated by multiplying compressed air demand with the specific compressor power demand [10].

The UPLCI system boundaries are set to include only the use phase of the machine tool, disregarding production, maintenance, and disposal of the machine. Moreover, the operation of the machine tool is isolated, without the influence of other elements of the manufacturing system, such as material handling systems and feeding robots, which is covered in other UPLCI reports.

The energy consumption of grinding per part is calculated as follows (Eq. 1):

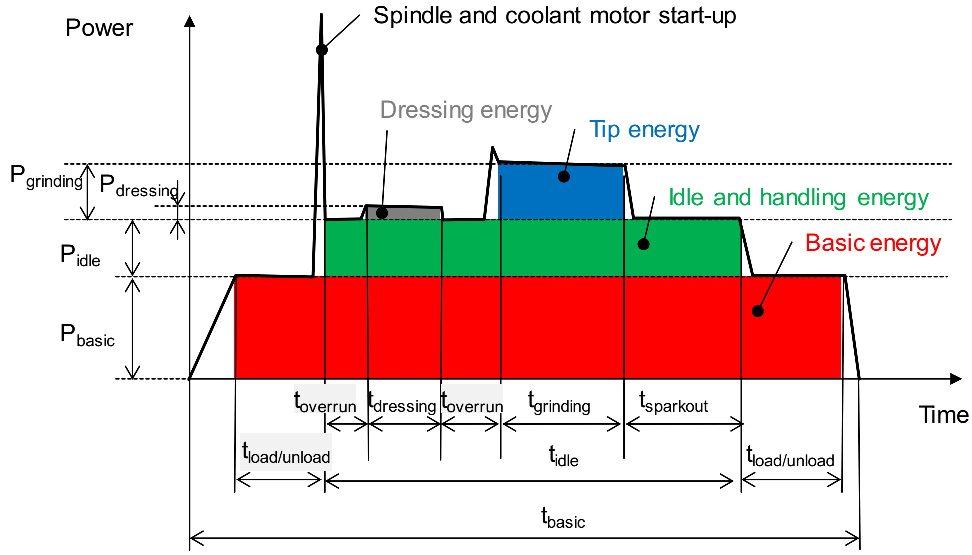

Fig. 4 Generic electric power and time profile in grinding with energy as the area under the power–time graphs as shown

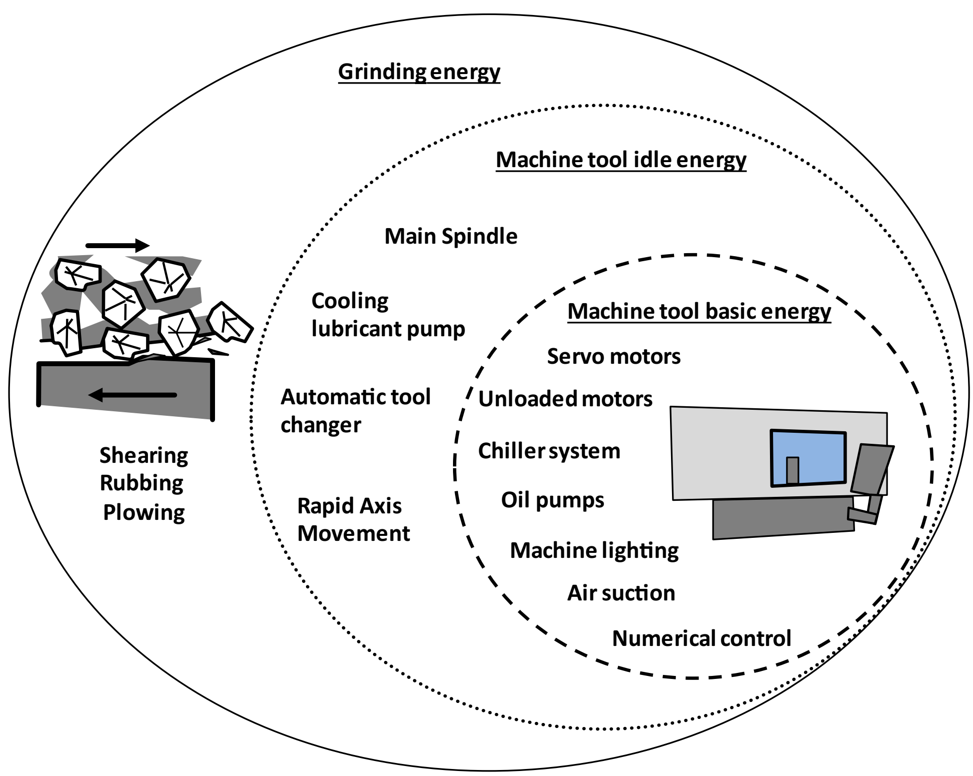

Fig. 5 System boundary of the grinding process

$$
\begin{aligned}
E_{total} &= P_{basic} \times (t_{basic}) + P_{idle} \times (t_{idle}) + P_{grinding} \\
&\quad \times (t_{grinding}) + P_{dressing} \times (t_{dressing})/N_{parts} \\
&= \text{Basic energy} + \text{Idle energy} + \text{Grinding energy} \\
&\quad + \text{Dressing energy},
\end{aligned} \tag{1}
$$

where power and time are illustrated in Fig. 4 and N_{parts} is the number of parts between dressing operations.

2.2 Parameters affecting the energy required for grinding

Grinding is characterized by many variables all of which play some role in achieving the desired part grinding. The most important in determining energy are ranked as follows from most important to lesser importance:

Table 1 Ranges of specific grinding energies [15]

Application	Material	Specific energy, e_c in [J/mm^3]	References
Grinding (variant not specified)	Brittle materials like glass or ceramics	1–7	[16]
Grinding with alumina wheel	Metal matrix composite Al-2009/sic-15W	10–25	[17]
Surface grinding	Aluminum	7–27	[7]
Grinding with alumina wheel	Steel	30–50	[18]
Surface grinding	Cast iron (class 40)	12–60	[7]
Surface grinding	Low-carbon steel (1020)	14–68	[7]
Surface grinding	Titanium alloy	16–55	[7]
Surface grinding	Tool steel (T15)	18–82	[7]
Grinding (variant not specified	Cemented carbide	80–200	[16]

1. Workpiece material properties,
2. Volume to be ground,
3. Feed rate,
4. Cutting speed,
5. Grinding wheel specification (grit type, size, bonding, hardness),
6. Tool sharpness, wear and dressing conditions,
7. Grinding wheel diameter,
8. Cooling lubrication supply,
9. Geometry and set-up.

From this parameter list, only the top 5 were selected for use in this UPLCI as these have the most influence on energy calculations and mass loss. The grinding, idle and basic energies are discussed below.

2.2.1 Grinding energy

2.2.1.1 Energy There are two basic UPLCI approaches to grinding energy. One is the power and time relationship is shown in Fig. 4 and Eq. (1). However, with the advent of specific energy information, Table 1, a second approach is available. In this approach, the specific energy (J/mm^3), Table 1 and Figs. 6, and 7, is grouped by material type and then representative values are given in Table 2. Next, the actual configuration of the part undergoing grinding is used to determine the area and depth of removal (mm^3).

There appear to be four general groupings of the workpiece material for which the specific energy is available, Table 2. In addition, for most metals (Fig. 6) and aluminum (Fig. 7) roughing thickness (0.4–0.8 mm/pass) and finishing thickness (0.05–0.3 mm/pass) provide a breakdown of these different specific energies. Thus we can use,

1. Brittle materials like glass or ceramics–about 4 J/mm^3.
2. Aluminum and composites–about 20 J/mm^3 for finishing and 10 J/mm^3 for roughing.

Table 2 Summary of specific energy of grinding (Table 1; Figs. 6, 7)

Material being ground	Roughing, specific energy, J/mm^3	Finishing, specific energy, J/mm^3
Brittle materials like glass or ceramics	4	
Aluminum and composites	10	15
Most metals	20	40
Sintered hard cutting tool materials	150	

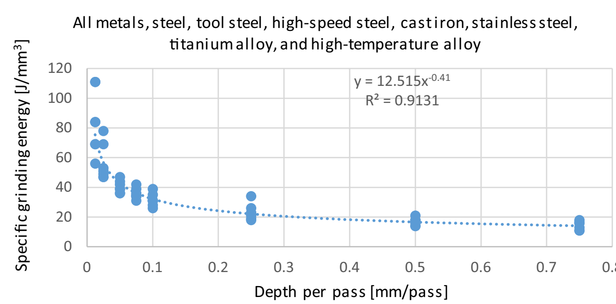

Fig. 6 Specific grinding energy for a variety of metals as a function of material removal rate (mm/pass) with roughing in the range of 0.4–0.8 mm/pass and finishing in the range of 0.05–0.3 mm/pass [19]

3. Most metals–about 30 J/mm^3 for finishing and 15 J/mm^3 for roughing.
4. Sintered hard cutting tool materials– about 150 J/mm^3.

The active or tip energy for grinding is thus based on the workpiece material being processed and the volume removed.

2.2.1.2 Volume removed For flat surfaces of length l_c, the volume removed (mm^3) in a single transect of the grinding wheel is

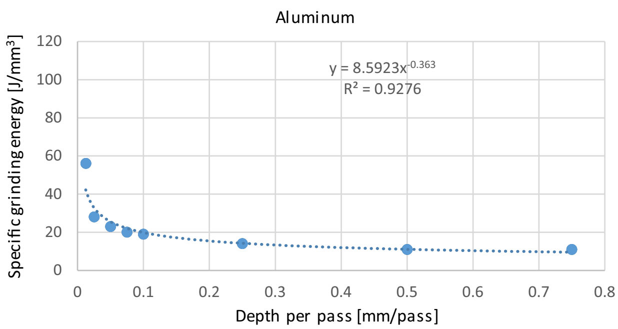

Fig. 7 Specific energy for aluminum grinding as a function of material removal rate (mm/pass) with roughing in the range of 0.4–0.8 mm/pass and finishing in the range of 0.05–0.3 mm/pass [19]

$$V_{removal} = a_p \times a_e \times l_c \times N_t \text{ (surface grinding)}, \quad (2)$$

where a_p is the width of cut (Fig. 2), a_e is the depth of cut, l_c is the length of the cut, and N_t is the number of transects to cover the whole area being ground.

For cylindrical surfaces to be ground, the workpiece start diameter, d_{w0} (mm), and end diameter, d_w (mm), are use to calculate the volume removed (Eq. 3).

$$V_{removal} = \left(\left(d_{w0}^2 - d_w^2\right)/4\right) \times \pi \times l_c, \quad (3)$$

2.2.1.3 Time The active time or grinding time ($t_{grinding}$) is needed to help calculate the idle and basic times (Fig. 4). *For surface grinding*, the grinding time is calculated from the workpiece speed, v_w, (see Table 3), workpiece length, l_c, and numbers of grinding transects N_t and passes N_p (Eq. 4).

$$t_{grinding} = l_c \times N_t \times N_p / v_w \text{(surface grinding)}, \quad (4)$$

For cylindrical plunge grinding, the grinding time is calculated with the radial feed rate, v_{fr} (Fig. 3) (Eq. 5)

$$t_{grinding} = \left(\left(d_{w0} - d_w\right)/2\right)/v_{fr} \text{ (external cylindrical plunge grinding)}. \quad (5)$$

The specific cutting energy for grinding is about 30–40 times higher in grinding than in turning, milling and drilling, which can be explained by the smaller chip thicknesses and the negative rake angle of the abrasive grits [22].

Thus with only the material to be ground, the tool material, the dimensions of the ground feature, and the representative processing parameters, one can calculate the UPLCI grinding energy for a variety of parts and materials. This then must be added to the idle and basic energies, see below.

2.2.2 Idle energy

Idling characterizes the machine state when there is relative movement of the tool and the workpiece without changing the shape of the body (e.g. rapid axis movement, spindle motor start, start of cooling lubricant, tool change), Fig. 5. The idle power (P_{idle}) of automated grinding machine tools can be between 1 and 10 kW depending on machine size and tool spindle power.

To calculate the idle energy, the idle time, tidle(s), is the sum of the grinding time, $t_{grinding}$, from equations 4 or 5; sparkout time, $t_{sparkout}$; air travel time, t_{air} (s); and dressing time for 1 part, $t_{dressing}/N_{parts}$ (Fig. 4).

Here, we define the air travel time as the air time of the tool moving from home or zero position to approach point, approach, overtravel, retraction after grinding, and traverse motion, if needed to other features on the same workpiece. For reciprocating grinding, the air travel time includes also all overtravel between grinding passes. Time for air travel is calculated with Eq. 7.

$$t_{idle} = t_{grinding} + t_{sparkout} + t_{air} + \left(t_{dressing}/N_{parts}\right), \quad (6)$$

$$t_{air} = \text{Home position to operating point} + \text{Approach/overtravel times} + \text{retraction times}. \quad (7)$$

The dressing time $t_{dressing}$ can be calculated from the dresser speed, travel distance, and number of dressing passes. Since the number of parts N_{parts} between dressing operations impacts the idle time, we can conservatively double the grinding time $t_{grinding}$ and eliminate the separate calculation of $t_{dressing}/N_{parts}$. In addition, improvements in spark-out have shortened this time and the power during spark-out is very low since little material is removed by the grinding wheel [23, 24]. Thus the spark-out energy is very small. So the idle time is approximated by Eq. (8).

$$t_{idle} = 2 \times t_{grinding}, \quad (8)$$

From these calculations the idle energy for a single feature is given by Eq. (9).

$$E\,(\text{J/feature})_{idle} = t_{idle} \times P_{idle}. \quad (9)$$

Thus with just the dimensions, the information used in calculating t_{idle}, and the idle power (1–10 kW), one can calculate the idle energy for a grinding unit process. The example illustrates a reasonable estimate for idle power.

2.2.3 Basic energy

The average basic power P_{basic} of automated grinding machines is between 1 and 20 kW. The largest consumers are the hydraulic power unit and the mist collector [25].

From Figure Fig. 4, the basic time is given by Eq. (10).

$$t_{basic} = t_{load/unload} + t_{idle}. \quad (10)$$

Loading time is the time to bring in a new part into the machine tool and remove the machined part at the end. For a universal chuck and workpiece weights between 0.5 and

Table 3 Recommended processing parameters

Application	Variant	Workpiece material	Grinding tool	v_s (m/s)	v_w (m/min)	Depth of cut, a_e	References
Surface grinding	Recipro-cating, slot	Tool steel	Alumina, A220, vitrified bond	26	25	5 µm (per pass)	[12]
	Recipro-cating	Tool steel	CBN, B126, vitri-fied bond	28–45		10–20 (per pass)	[12]
		Carbon steels, wrought, over 50 HRC	Alumina, A46JV	28–33	15–30	0.013 mm (finish) 0.05 mm (rough), crossfeed max. 1/10 of wheel width	[20]
		Tool steels, cast, over 58 HRC	Alumina, A60IV	15–20	15–30	0.013 mm (finish) 0.25 mm (rough), crossfeed max. 1/10 of wheel width	[20]
	Creep-feed			25–50	0.1–1		[7]
Application	**Variant**	**Workpiece material**	**Grinding tool**	**v_s (m/s)**	**v_w (m/min)**	**Allowance on diam-eter (mm)**	**References**
Cylindrical grinding	Roughing	Soft steel	Conventional	35–50	30–40	0.3–0.6	[21]
	Finishing	Soft steel		35–50	20–30	0.2–0.3	[21]
	Roughing	Hardened steel		35–45	20–25	0.3–0.6	[21]
	Finishing	Hardened steel		35–45	15–23	0.2–0.3	[21]
	Precision finishing	Hardened steel		35–45	8–12	0.01–0.02	[21]
	Roughing	Tool and high speed steel		35–45	15–20	0.3–0.6	[21]
	Finishing	Tool and high speed steel		35–45	12–16	0.2–0.3	[21]
Application	**Variant**	**Workpiece material**	**Grinding tool**	**v_s (m/s)**	**v_w (m/min)**	**Infeed on dia. and traverse feed**	**References**
Cylindrical grind-ing, transverse		Carbon steels, wrought, over 50 HRC	Alumina, A60KV	28–33	21–30	0.013 mm, 1/8 wheel width per rev. of work (fin-ish), 0.05 mm, 1/4 wheel width per rev. of work (rough)	[20]
		Tool steels, cast, over 58 HRC	Alumina, A60JV	20–28	18–30	0.01 mm, 1/8 wheel width per rev. of work (fin-ish), 0.05 mm, 1/4 wheel width per rev. of work (rough)	[20]
Polishing				25–40			[7]

30 kg, the load or unload time is about 10 s. Other holding systems are given in [26].

Thus the basic energy, E_{basic} (J), is given by Eq. (11).

$$E_{basic} = t_{basic} \times P_{basic}, \quad (11)$$

where t_{basic} is $10\,s + t_{idle}$.

Basic energy is significant because the time is the full cycle time in which all the basic components (Fig. 5) remain at normal power.

2.2.4 *Summary on unit process life cycle energy*

With only the following information the unit process life cycle energy for grinding can be estimated:

1. Material of part being manufactured,
2. Feature dimensions,
3. Table 3,
4. Machine power.

2.3 Method of quantification for workpiece material loss

The workpiece material loss after grinding can be specified as chip mass (m_s). The chip mass (m_s) can be calculated by multiplying the volume of material removed ($V_{removal}$, Eqs. 2, 3) by the density of the workpiece material, ρ (kg/m^3) (Eq. 12). Density of the material can be obtained from Table 4.

$$m_s = V_{removal} \times \rho. \quad (12)$$

2.3.1 LCI for cooling lubricant waste calculations

For grinding operations, cooling lubricants are important to reduce friction and cool the workpiece. Common fluids are grinding oil or water-based emulsions. The coolant supply system consists of nozzles, pumps, and a filtering system. The cooling lubricant usage per workpiece is commonly very small, because the fluids are filtered and reused. Cooling lubricant losses are not considered here, but can be included if removal of cooling lubricants through workpieces with undercuts or porous surfaces occurs.

Table 4 Density of workpiece material to be ground

Material	Density (g/cm^3)
Glass	2.5
Aluminum	2.66
Titanium	4.55
Aluminum bronze	7.46
Copper	8.82
Copper–nickel	8.33
Hastelloy X	8.22
Haynes 188	8.98
Inconel 625	8.44
Magnesium	1.71
Nickel	8.72
Rene 80	8.16
Silicon bronze	8.36
Stainless steel 300	7.87
Mild steel	7.85
Stainless steel 400	7.60
Cemented carbide (10% Co)	14.5

2.3.2 LCI for grinding tool mass loss calculations

The grinding tool wears during grinding on a microscopic level (sharpness loss) and a macroscopic level (profile wear). Both wear effects make tool reconditioning necessary. The grinding ratio or G-ratio, G, is an accepted parameter to relate the volume of workpiece material removed, $V_{removal}$ (mm^3), to the tool wear volume, V_{tool_wear} (mm^3) (Eq. 13). Table 5 gives example values.

$$G = V_{removal}/V_{tool\_wear}. \quad (13)$$

A conservative value for G is 10. The grinding abrasive waste is then estimated by the material of the grinding media used to remove product material. To calculate the grinding tool mass m_g, the tool density has to be measured or calculated from the weight and volumetric composition of bond and grits (Eq. 14). Example values from [27] for vitrified grinding wheels with representative volumetric structures and bond compositions are ρ = 2.6 g/cm^3 for an alumina wheel and ρ = 2.4 g/cm^3 for a CBN wheel.

$$m_g = V_{tool\_wear} \times \rho. \quad (14)$$

3 Case study on grinding

The machining process is performed on a representative cylindrical grinding machine tool in a high production mode. The relevant machine specifications are listed in Table 6.

3.1 Product and process details

A case hardened bearing steel is the workpiece material for a cylinder with 80 mm diameter and length of 200 mm, where the circumferential area is ground with a width of cut a_p = 50 mm (*cylindrical plunge grinding*). The product dimensions are shown in Fig. 8. The workpiece material has a density of 7.85 g/cm^3, Table 4. The process conditions and parameters are listed in Table 7. The right edge of the workpiece is considered as the origin (reference point). All dimensions are considered with reference to the origin.

Table 5 Example values of the grinding ratio

Application	Material	Grinding tool	G-ratio (mm^3/mm^3)	References
Precision grinding	Steel	Alumina	Max. 50	[16]
Precision grinding	Steel	CBN	10,000	[16]
Precision grinding	Polycrystalline diamond	Diamond	Max. 0.02	[16]
Surface grinding		Conventional	5–10	[12]
Creep-feed grinding		Conventional	10–50	[12]

Table 6 Specifications of example cylindrical grinding machine

Machine type	Cylindrical grinding
Tool spindle speed	Max. 3200 rpm
Tool spindle power	10.5 kW (motor spindle)
Tool dimensions (D × T × H)	500 × 50 × 203 mm
Workpiece spindle power	2 kW
Workpiece spindle speed	1–1500 rpm
Motor power (Z)	2 kW
Motor power (X)	2 kW
Speed (Z)	0.001–20,000 mm/min
Speed (X)	0.001–10,000 mm/min
Air pressure needed	5.5 bar
Coolant pump power	4 kW
Additional power needs (including controls, drives, etc.)	5.5 kW
Total max. power	24 kW

Table 7 Parameters for example case

Grinding conditions	
Workpiece material	Stainless steel 300
End diameter	79.8 mm
Removal on the diameter	0.2 mm
Feed rate v_{fr}	1 mm/min
Grinding wheel speed v_s	63 m/s
Grinding wheel rotational speed n_s	2407 rpm
Workpiece speed v_w	0.53 m/s = 31.5 m/min
Workpiece rotational speed n_w	125.4 rpm
Speed ratio	$q = v_s/v_w = 120$
Specific material removal rate Q'_w	4.2 mm^3/mm s
Material removal rate Q_w	210 mm^3/s
Spark-out	10 rev
Dressing process	
Dressing tool	Stationary single-grit diamond, effective dressing width b_d = 0.12 mm
Dressing frequency	N_{parts} = 15 workpieces
Overlap ratio, U_d	4
Wheel speed during dressing, n_d	2407 rpm
Overrun length during dressing	0.5 mm
Number of dressing strokes, N_d	3
Dressing depth of cut, a_{ed}	0.01 mm
Loading and unloading time	10 s each

3.2 Time and energy calculations

3.2.1 Grinding energy

The time for grinding the feature is calculated from Eq. (5) in Eq. (15).

$$t_{grinding} = \left(\left(d_{w0} - d_w\right)/2\right)/v_{fr} = ((80\ \text{mm} - 79.8\ \text{mm})/2)/1\ \text{mm/min} = 0.1\ \text{min} = 6\ \text{s}. \quad (15)$$

The volume of the material removed is calculated in Eq. (16) from Eq. (3):

$$\begin{aligned} V_{removal} &= \left({d_{w0}}^2 - d_w\right)^2/4) \times \pi \times a_p \\ &= \left((80\ \text{mm}/2)^2 - (79.8\ \text{mm}/2)^2\right) \times \pi \times 50\ \text{mm} \\ &= \left(1600\text{mm}^2 - 1592.01\text{mm}^2\right) \times \pi \times 50\ \text{mm} \\ &= 1255.1\ \text{mm}^3. \end{aligned} \quad (16)$$

Grinding tip energy (Table 2) is = 20 J/mm^3. Therefore, grinding energy is stated in Eq. (17).

$$E_{grinding} = V_{removal} \times e_c = 1255\ \text{mm}^3 \times 20\ \text{J/mm}^3 = 25\ \text{kJ}. \quad (17)$$

3.2.2 Idle energy

Idle time can be estimated to be twice the grinding time (Eq. 8) since it includes air travel and dressing time per part. For this case study this leads to Eq. (18).

$$t_{idle} = 2 \times t_{grinding} = 12\ \text{s}. \quad (18)$$

Idle power of the machine can be calculated based on the individual power specifications of the machine (Eq. 19).

$$P_{idle} = P_{spindle} + P_{coolant}. \quad (19)$$

The assumed values are as follows from Table 6 (80% of maximum value as a conservative estimate):

$$P_{spindle,\ max} = 10.5\ \text{kW},$$
$$P_{coolant,\ max} = 4\ \text{kW},$$
$$P_{idle} = P_{spindle} + P_{coolant} = (8.4 + 3.2)\ \text{kW} = 11.6\ \text{kW}.$$

Total energy during the idle process is therefore given by Eq. (20).

$$E_{idle} = P_{idle} \times t_{idle} = 11.6\ \text{kW} \times 12\ \text{s} = 140\ \text{kJ}. \quad (20)$$

3.2.3 Basic energy

We assume the basic power includes axes and controls. Therefore, the power consumed during the basic process is given by Eq. (21).

$$P_{basic} = P_{axis} + P_{controls} = 5.5\ \text{kW}. \quad (21)$$

Basic time is given in Eq. (22) and total basic energy in Eq. (23).

$$t_{basic} = t_{load/unload} + t_{idle} = 20\text{s} + 12\ \text{s} = 32\ \text{s}, \quad (22)$$

$$E_{basic} = P_{basic} \times t_{basic} = 5.5\ \text{kW} \times 32\ \text{s} = 180\ \text{kJ}. \quad (23)$$

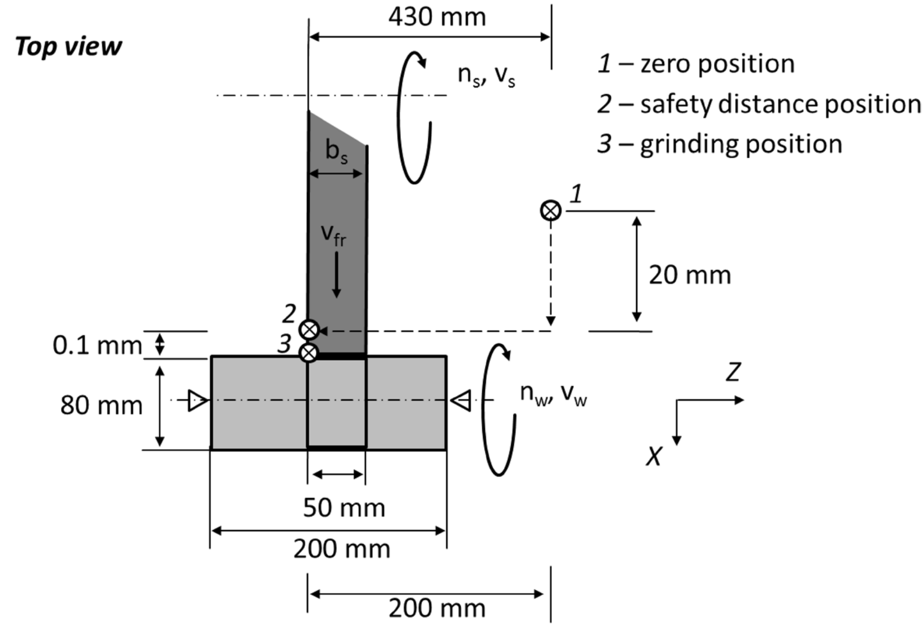

Fig. 8 Dimensions of the workpiece and tool positions (not to scale)

Total energy per unit is then given in Eq. (24).

$$E_{total} = E_{basic} + E_{idle} + E_{grinding} + E_{dressing}/N_{part} = 25\ \text{kJ} + 140\ \text{kJ} + 180\ \text{kJ} + 0 = 345\ \text{kJ}. \quad (24)$$

3.3 LCI material mass loss calculations

The volume of the material removed is calculated in Eq. (25). The resulting chip mass is then 9.88 g (Eq. 25).

$$\text{Chip mass}\ (m_s) = V_{removal} \times \rho = 1255\ \text{mm}^3 \times 7.87\ \text{g/cm}^3 = 9.88\ \text{g}, \quad (25)$$

$$V_{tool\_wear} = V_{removal}/G = 125.5\ \text{mm}^3, \quad (26)$$

$$m_g = V_{tool\_wear} \times \rho = 125.5\ \text{mm}^3 \times 2.6\ \text{g/cm}^3 = 0.33\ \text{g}. \quad (27)$$

The abrasive waste is given in Eqs. (26) and (27) for the assumption of a G-ratio of 10 and $\rho = 2.6\ \text{g/cm}^3$ for a standard vitrified alumina wheel. Here we neglect the material loss through cooling lubricants and greasing oils, but this could be a substantial amount of coolant for a smaller job shop application.

4 Conclusions

This paper presents the reusable calculation models, approaches, and measures used to analyze the environmental life cycle of common grinding unit operations in a simplified way. The three major environmental-based results are energy consumption, metal chips removed, and tool debris. In some cases, cooling lubricant drag-out should be considered as well as it impacts cooling lubricant waste and additional cleaning operations.

With only the following information the unit process life cycle energy for grinding can be estimated:

1. Material of part being manufactured,
2. Workpiece dimensions,
3. Dimensions of feature to be ground,
4. Tables above.

The life cycle of grinding is based on a typical high production scenario (on a CNC grinding machine with large series production) to reflect industrial manufacturing practices. These results can be linked to other UPLCI to evaluate larger processes for making products.

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References

1. Overcash M (1995) Evolving concepts in life cycle analyses. In: Cleaner technologies and cleaner products for sustainable development. NATO ASI Series. Springer, New York, pp 455–470
2. Overcash M, Twomey J, Kalla D (2009) Unit process life cycle inventory for product manufacturing operations. ASME 2009 International Manufacturing Science and Engineering Conference, vol 1, West Lafayette, Indiana, USA, October 4–7, 2009, doi:10.1115/MSEC2009-84065

3. Kellens K, Dewulf W, Overcash M, Hauschild M, Duflou JR (2011) Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: methodology description. Int J Life Cycle Assess. doi:10.1007/s11367-011-0340-4
4. Overcash M, Twomey J (2012) Unit Process Life Cycle Inventory (UPLCI)—a structured framework to complete product life cycle studies. In: Proceedings of the 19th CIRP conference on life cycle engineering, Berkeley, CA, USA, May 23–25, 2012, ISBN 978-3-642-29068-8, p 1–4
5. Ashby MF (2005) Materials selection in mechanical design, Butterworth-Heinemann, Oxford, ISBN 978-0750661683
6. DIN 8580 Manufacturing Processes-Terms and Definitions (2003) NA 152 Fundamental Technical Standards Committee, Deutsches Institut fuer Normung
7. Kalpakjian S, Schmid S (2010) Manufacturing engineering and technology, 6th edn, Addison-Wesley, Boston, ISBN 978-0136081685
8. Todd R, Allen K, Alting L (1993) Manufacturing processes reference guide, Industrial Press Inc., New York, ISBN 978-0831130497
9. National Research Council NRC (1995) Unit manufacturing processes: issues and opportunities in research. The National Academic Press, Washington DC
10. Winter M (2016) Eco-efficiency of grinding processes and systems. Springer, Berlin, ISBN 978-3-319-25203-2
11. Blohm (2017) Blohm products. https://www.blohmgmbh.com/en/products/. Accessed 10 Apr l 2017
12. Graf W, Gibree P (2001) Creep-feed and surface grinding. WST Winterthur Schleiftechnik AG, Switzerland
13. Studer (2017) Studer products. https://www.studer.com/en/products/overview.html. Accessed 10 Apr 2017
14. Aurich J, Carella M, Steffes M (2012) Evaluation of abrasive processes and machines with respect to energy efficiency. In: Proceedings of the 19th CIRP Conference on Life Cycle Engineering, Berkeley, CA, USA, May 23–25, 2012, Springer, ISBN 978-3-642-29068-8
15. Linke B, Overcash M (2012) Life cycle analysis of grinding. In: Proceedings of the 19th CIRP conference on life cycle engineering, Berkeley, CA, USA, May 23–25, 2012, Springer, ISBN 978-3-642-29068-8, pp 293–298
16. Helletsberger H (2005) Grindology papers G3 Schleifverhaeltnis/G-Faktor, published by Grindology College of Tyrolit Schleifmittelwerke Swarovski K.G., Schwaz, Austria
17. Ilio A, Di, Paoletti A, D'Addona D (2009) Characterization and modelling of the grinding process of metal matrix. In: Annals of the CIRP, vol 58/1/2009, pp 291–294
18. Oliveira JFG, Silva EJ, Guo C, Hashimoto F (2009) Industrial challenges in grinding. In: Annals of the CIRP, vol 58/1/2009, pp 663–680
19. Hindustan Machine Tools (2001) Production Technology, McGraw-Hill Education, Bangalore, India, May (cited in Murray. V, Zhao F, Sutherland J (2012), Life cycle analysis of grinding: case study of non-cylindrical computer numerical control grinding via a unit process life cycle inventory approach. Proc I Mech Eng Part B J Eng Manuf 226:1604
20. Machinability Data Center Cincinnati OH (1980) Machining data handbook, Sect. 8, vol 2, 3rd edn. Defense Technical Information Center, Virginia
21. 3M (2014) Handbook cylindrical grinding, 11/2014, published by 3M, Art. No.: W004 E
22. Oberg E, Jones F, Horton H, Ryffel H (2012) Machinery's handbook, 29th edn, Industrial Press, Norwalk, ISBN 978-0831129033
23. Hecker R (2003) Plunge grinding process surface roughness model and process control. PhD thesis, Mechanical Engineering, Georgia Institute of Technology 2003
24. Malkin S (1981) Grinding cycle optimization. In: Annals of the CIRP 30/1/1981, pp 223–226
25. Zein A (2012) Transition towards energy efficient machine tools. Springer, Berlin, ISBN 978-3-642-32246-4
26. Fridriksson L (1979) Non-productive time in conventional metal cutting, Report No. 3, design for manufacturability program. University of Massachusetts, Amherst 1979
27. Linke B (2016) Life cycle and sustainability of abrasive tools, Springer, Berlin, ISBN 978-3319283456