Chapter 8
Sustainability Case Studies

8.1 Case Study on Conventional Abrasives Versus Superabrasives for Vitrified Bonded Tools

The user can decide between conventional tools with corundum or silicon carbide or superabrasive tools with diamond or cubic boron nitride. Not only do the tools have different performance profiles, but also different embodied energies, which is important for accounting manufacturing energy to products. Embodied energy is usually understood as the energy that must be used to create 1 kg of usable material measured in MJ/kg [ASHB09]. It is more than the theoretical energy and includes inefficiencies and losses in the processing systems and transport.

Comparing sustainability of conventional and superabrasive grinding tools is of high interest to the research community. However, there is no comprehensive information available on tool manufacturing. To foster understanding of energy use in grinding tool manufacturing, the following case study evaluates the energy for the manufacturing of two different types of vitrified bonded grinding wheel, with CBN and with corundum grits.

8.1.1 Scope and Method

This study focuses on vitrified grinding wheels with corundum and cubic boron nitride as abrasive grit material. The raw material production is not analyzed itself, but the available data on embodied energy is reviewed and included in the analysis. The boundaries are from the cradle (i.e. raw material mining and processing) to the tool manufacturer's outer gate (i.e. the finished grinding tool ready to be shipped to the customer) (Fig. 8.1). Tool manufacturing includes the steps of measuring, mixing, molding, pressing, drying, sintering, and finishing. Transport of material and tools is neglected, even though it might add substantially to the energy used for tool manufacturing. Furthermore, the subsequent use and disposal of the grinding

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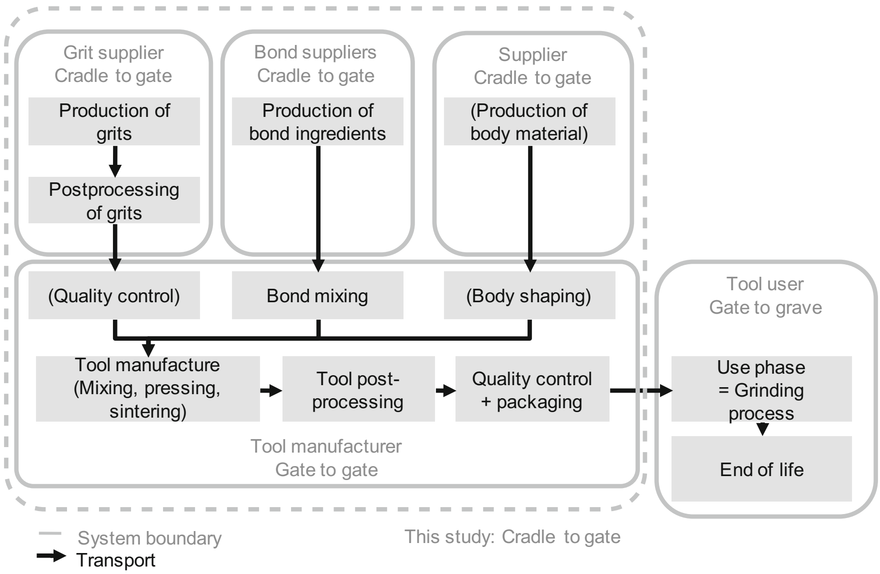


Fig. 8.1 Wheel life cycle and system boundaries for analysis

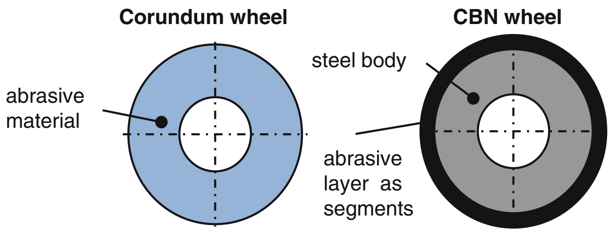
tools is not analyzed in detail, but the discussion highlights how the tools will be applied and disposed differently.

The functional unit of this study is a single grinding wheel. Figure 8.2 shows the respective grinding wheel designs. The conventional wheel is a monolithic cylinder; the superabrasive wheel consists of a steel body of low carbon tool steel and segments of the abrasive layer. The outer and inner diameters of both wheels are similar.

The results have to be evaluated carefully, because the grinding wheel specification includes various parameters such as abrasive grit type, mean grit size or mesh size, bond type, structure, and effective hardness. Abrasive tools are often adapted to a special application, e.g. high porosity for high material removal processes, CBN for precision grinding of hardened steel, soft bond for internal grinding, etc. Therefore, the comparison of different tools without regarding the application is difficult and not always reasonable. However, this study regards a use case where conventional or superabrasive wheels are interchangeable. For example, in a gear shaft grinding process, vitrified bonded corundum wheels or vitrified bonded CBN wheels can be used. The necessary change of process parameters such as wheel speed, machine periphery or coolant have to be considered.

8.1.2 Energy of Raw Materials

Manufacturing of the abrasives corundum and CBN is described in Chap. 2 “Abrasives”. The energy consumed in their primary production can be estimated



Grinding wheel width	20 mm	20 mm
Outer diameter	400 mm	400 mm
Inner diameter	200 mm	200 mm
Segment length	-	31.4 mm
Segment height	-	5 mm
Number of segments	-	40

Fig. 8.2 Examined grinding wheels

with a maximum value of 54.7 MJ/kg for alumina (99.95 % purity) and a maximum of 133 MJ/kg for HBN (Table 2.9) [GRAN12]. HBN is the basic raw material to produce CBN. Expert interviews indicate that the synthesis of CBN from HBN consumes presumably much less energy than the initial HBN production, so the energy values for HBN are taken as estimation for CBN in this study.

Table 8.1 shows the composition of a representative vitrified bond including the proportion of ingredients within the bond, densities, and embodied energies from raw material processing. Here the bond ingredients are not added as frits, which would lead to additional embodied energy, because frits have additional preprocessing steps (see Sect. 3.2.2 “Manufacturing of Vitrified Bonds”). In industry, the bond composition can be adjusted precisely to the abrasive type, desired wheel properties, expertise of the particular manufacturer, etc. Table 8.1 leads to an assumed embodied energy of 43.3–54 MJ/kg for the bonding mixture. Table 3.5 gives more information on environmental and health properties of critical bond ingredients.

8.1.3 Manufacturing Energy of a Vitrified Bond

Vitrified bonded tools are manufactured through mixing of the components, molding, pressing, sintering, pre-processing, and quality control (see Sect. 3.2 “Vitrified Bonds”). This study leaves out the embodied energy in the tooling equipment and assumes that a sufficiently large number of grinding wheels are

Table 8.1 Bond ingredients for a representative bond

Bond ingredient [BOTS05]	Formula	Proportion in bond (w%) [BOTS05]	Density (g/cm^3) [GRAN12, GEST12]	Embodied energy (MJ/kg) [GRAN12]
Silicon oxide	SiO_2	56.88	2.65	37.4–41.4
Boron oxide	B_2O_3	16.61	2.46	Estimated 50–75
Aluminum oxide	Al_2O_3	10.01	3.94	49.5–54.7
Calcium oxide	CaO	8.14	3.37	Estimated 50–75
Sodium oxide	Na_2O	4.62	2.27	Estimated 50–75
Potassium oxide	K_2O	3.52	2.32	Estimated 50–75
Magnesium oxide	MgO	0.22	3.58	120–133

Table 8.2 Volumetric structural composition of the grinding wheels

	Corundum wheel (V%)	CBN wheel (V%)
Bond volume	15	30
Grit volume	55	45
Pore volume	30	25

produced, so that the equipment accounts for a negligible amount of embodied energy per grinding wheel. The proportion of grit, bond and pore volume defines the structure and hardness of a grinding tool. Close to industrial practice, this study assumes the structural compositions as in Table 8.2.

The raw materials need to be mixed and pressed before the actual sintering process can take place. For the analysis of the mixing energy two representative mixing machines were chosen. The total amount of raw material for the production of a conventional grinding wheel greatly differs from the amount used for superabrasives. Table 8.3 provides basic information for each mixer and possible production rates. The larger mixer has a maximum capacity of material for 26 conventional grinding wheels whereas the small mixer can contain material for the abrasive layer of 15 superabrasive wheels.

Table 8.3 Mixer characteristics and energy consumption [WAB09]

	Corundum wheel	CBN wheel
Volume	50 l	2 l
Material capacity	5–26 wheels	2–15 wheels
Power	1.1 kW	0.18 kW
Mixing time	1 h	1 h
Total mixing energy (power over time)	3.96 MJ	0.648 MJ
Mixing energy per grinding wheel (at max. capacity)	**0.152 MJ**	**0.0432 MJ**

Table 8.4 Molding press characteristics and energy consumption, adapted from [SCHT11]

	Corundum wheel	CBN wheel
Table size	710 × 800 mm	400 × 400 mm
Plunger size	500 × 630 mm	320 × 320 mm
Max. press capacity	2500 kN	125 kN
Power	22 kW	4 kW
Molding time	5 min	5 min
Molding and pressing energy per grinding wheel	**6.60 MJ**	**1.20 MJ**

The total mixing time can be up to one hour in which the material is mixed by a three-dimensional movement in a sealed chamber. An advantage of this method is that no potentially hazardous dust can exhaust during the mixing process. Table 8.3 gives the consumed energy for the mixing time of 1 h in total and per grinding wheel. The overall energy consumption for the mixing of one grinding wheel is 0.152 MJ for the conventional type and 0.0432 MJ for the superabrasive. In the case that the wheels are produced in smaller batches, the mixing energy per wheel will be higher.

In the next step, the homogenous tool mixture needs to be molded into the appropriate form. To achieve a certain porosity, a preselected pressure is applied to the mixture in the mold until the mixture reaches a predefined volume. The pressure depends on the mixture itself, its volume, and the desired porosity of the final abrasive layer. The segments for a superabrasive grinding wheel require a comparably lower pressure and are sometimes even molded manually. In contrast, the compressive force for a complete vitrified bonded grinding wheel can range from 500 up to 45,000 kN. For this study, two hydraulic single column presses were selected according to Table 8.4. Selecting a molding time of 5 min for both grinding wheels results in total molding energy of 6.60 MJ for a conventional grinding wheel and 1.20 MJ for the segments on a superabrasive wheel.

For the sintering process, two example industrial furnaces are chosen with the same maximum temperature of 1600 °C, but different chamber sizes (Table 8.5).

Table 8.5 Furnace data and consumed energy during sintering, adapted from [NABE12]

	Corundum wheel	CBN wheel
Dimensions of working chamber	500 mm × 550 mm × 550 mm	150 mm × 150 mm × 150 mm
Segments produced per cycle	–	360
Max. number of wheels produced per cycle	22	9
Max. furnace power P_{max}	21.0 kJ/s	5.2 kJ/s
Max. temperature	1600 °C	1600 °C
Sintering temperature	1250 °C	1250 °C
Sintering time	100 h	100 h
Consumed energy for one sintering process	4162.62 MJ	1030.77 MJ
Consumed sintering energy for one wheel (at max. capacity)	**189.21 MJ**	**114.53 MJ**

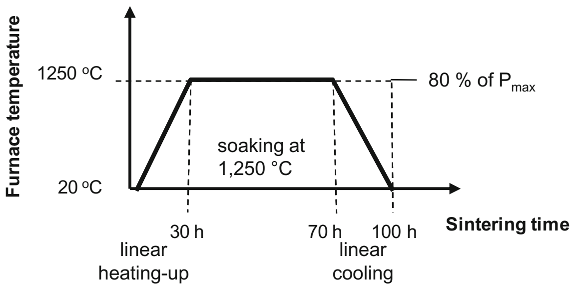


Fig. 8.3 Sintering temperature profile

The CBN segments are sintered in a smaller furnace. A total amount of 22 conventional wheels can be stacked including a 5 mm thick spacer between each layer in the larger furnace. The smaller furnace holds 15 layers of superabrasive material segments. Each layer consists of 24 individual segments. In total, an amount of 360 segments can be stacked in the small furnace. This is enough material for nine superabrasive grinding wheels.

Both furnaces feature a maximum temperature of 1600 °C at the maximum heating power, P_{max}. As the sintering process requires a lower sintering temperature of 1250 °C, the maximum sintering power is only 80 % of P_{max}. The sintering temperature profile in Fig. 8.3 left is representative and allows for calculating the sintering energy for both grinding tools. In the first 30 h of the heating cycle the furnaces, containing the abrasive material are heated-up linearly from room temperature to the sintering temperature of 1250 °C. The wheels are then soaked at this sintering temperature for 40 about hours. After the soaking period, the grinding wheels and segments are cooled down linearly to room temperature in about 30 h. The same heating cycle applies to both wheel type and segments, because sintering temperature and time does not depend on the volume of the sintered material, but on the material and chemical reactions.

For simplification, it is assumed that the power consumption runs linearly to the temperature. The total consumed energy during the sintering process is the power over time. For the large furnace with conventional grinding wheels, energy accounts to 4162.62 MJ, leading to an energy consumption of 189.21 MJ for one conventional grinding wheel. The smaller furnace uses 1030.77 MJ, which results in 114.53 MJ for the segments needed for one superabrasive grinding wheel.

8.1.4 Manufacturing Energy of the Steel Body for Superabrasive Wheels

This case study assumes that the body of the superabrasive wheel is made of tempered low alloy steel 42CrMo4 (oil quenched). This steel offers a high strength along with good durability and advantageous thermal characteristics.

First, the steel is cast into a round steel bar of a diameter of 394 mm. Then the bar is forged and rough rolled. A sawing process follows in which blanks of 25 mm

Table 8.6 Material and machining properties for tempered 42CrMo4 [GRAN12]

Density	7.8 g/cm^3
Embodied energy of cast material per mass	0.0288–0.0319 MJ/g
Rough rolling and forging energy per mass	0.0056–0.0061 MJ/g
Max. casting energy for blank with a width of 30 mm	**910.10 MJ**
Max. rolling energy	**174.89 MJ**

Table 8.7 Sawing process on a representative band saw [MASC12]

Power	110 kW
Sawing blade width	5 mm
Machining time for blank with a diameter of 394 mm	160 s
Sawing energy	**17.60 MJ**

thickness are produced. Because the sawing blade (5 mm width) produces waste, the casting energy and rolling energy has to be calculated for blanks with 30 mm thickness. Table 8.6 shows the respective energies for casting and rolling. The sawing process can be estimated with the values in Table 8.7 to account for a maximum energy of 17.6 MJ per steel body. This is an upper boundary for a not optimized sawing process.

The steel cylinders are then machined to the desired final shape through different turning processes. With coarse machining the outer diameter of 394 mm is reduced to 390.2 mm, the body width is reduced from 25 to 20.2 mm, and an inner hole is produced with a diameter of 199.8 mm. With the specific machining energies from Table 8.8 the coarse machining energy accounts to 6.10 MJ. The final fine machining operations reduce the outer diameter to 390 mm, the body width to 20 mm, and opens the inner diameter to 200 mm, resulting in fine machining energy of 1.54 MJ. The CBN segments are then glued to the steel body, but the gluing energy is neglected. Material data and energy data for rough rolling, coarse machining, and fine machining are taken from a database [GRAN12].

8.1.5 Embodied Energy in Grinding Tools

Mixing, pressing and finishing energy are negligible in comparison to the raw processing and sintering energies. All relevant energies for both grinding wheels are summed up in Fig. 8.4. The corundum wheel has only around 36 % of the embodied energy of a CBN grinding wheel of similar dimensions (Fig. 8.4). Then main energy proportion, however, lies in the steel body of CBN wheels.

Nevertheless, CBN grits have much higher wear resistance and the tool body can be re-used. The maximum useful abrasive volume in Table 8.9 depends on stability

Table 8.8 Machining properties for tempered 42CrMo4 [GRAN12]

Coarse machining energy per mass	0.0013–0.0014 MJ/g
Fine machining energy per mass	0.0084–0.0093 MJ/g
Coarse machining energy	**6.10 MJ**
Fine machining energy	**1.54 MJ**

aspects, clamping setup, and number of spindle revolutions. Here it is assumed that a diameter of 250 mm is the limit for the conventional grinding wheel. For the superabrasive wheel, it is assumed that the segments can be used down to 1 mm in thickness before they start to lose their stability and begin to crumble away. This leads to a minimum diameter of 392 mm.

With the G-ratios in Table 8.9, the CBN wheel in this case study can produce 13 times more workpieces than the conventional wheel, so that the energy per workpiece volume is only 1.3 J/mm^3 for the CBN tool compared to 5.9 J/mm^3 for the corundum wheel (Table 8.9). With a tool body re-use of five times, the embodied energy even decreases to only 0.4 J/mm^3 for the CBN tool, which is about 7 % of the embodied energy per workpiece volume of the corundum wheel.

Yet there is more to consider. Abrasive tools are often adapted to a special application, e.g. high porosity for high material removal processes, CBN for

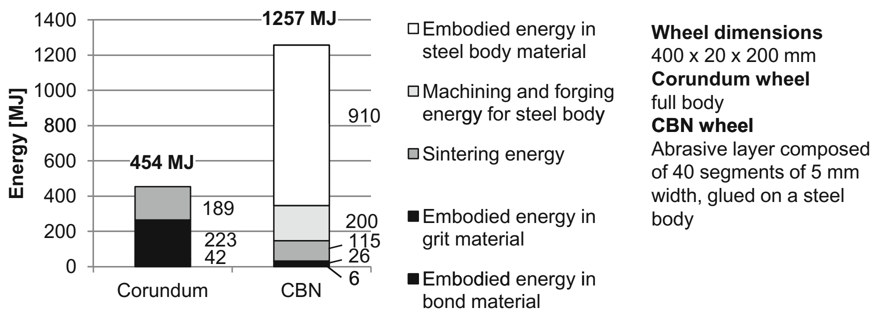


Fig. 8.4 Results for grinding tool manufacturing energy (upper boundary)

Table 8.9 Embodied tool energy per workpiece volume

	Corundum wheel	CBN wheel
Max. useful volume (mm^3)	1,531,526.40	99,525.70
Max. G-ratio when grinding steel [JACK11, HELL05a]	50	10,000
Max. workpiece volume per wheel (mm^3)	76,576,320	995,257,000
Embodied energy per wheel (MJ)	454	1257
Embodied energy per workpiece volume in (J/mm^3)	**ca. 5.9**	**ca. 1.3**
Embodied energy per workpiece volume in (J/mm^3) when steel body is re-used five times		**ca. 0.4**

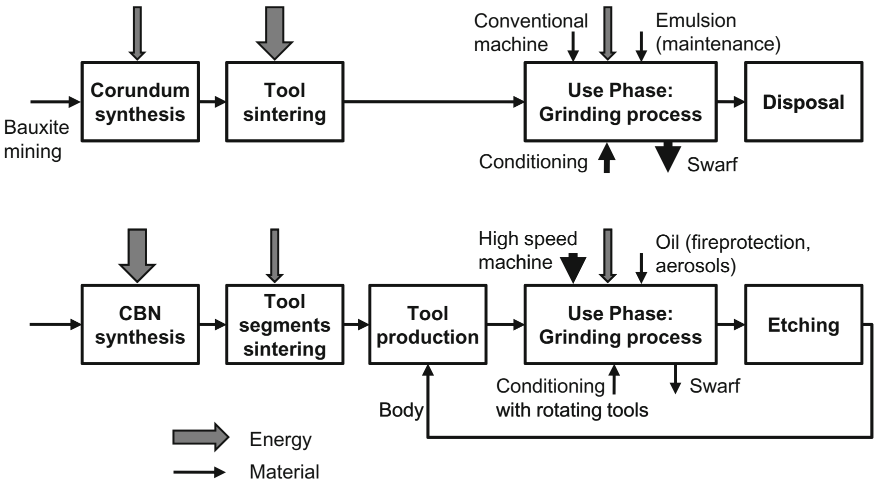


Fig. 8.5 Wheel life cycle with qualitative resource streams

precision grinding of hardened steel, soft bond for internal grinding, etc. Therefore, the comparison of different tools without regarding the application is difficult and not always reasonable. Moreover, the applications of superabrasive and conventional wheels differ in terms of machine tool, coolant supply, dressing, machine periphery, etc. (Fig. 8.5).

Superabrasives are in particular highly wear resistant in combination with high grinding wheel speeds. However, choosing superabrasives as grinding tool material should follow a thorough evaluation of the higher tool costs and the requirements on machine tool and cooling lubricant supply [LINK12b]. Further discussions touch the following aspects:

- Flexibility—In small or single batch production it is often required to use an abrasive tool with several effective surface roughnesses or even different profiles. For this, conventional tools are superior against superabrasives because of their better dressability and lower costs. New conventional tool systems with sol–gel corundum even allow to be used at high cutting speeds with the according advantages [KLOC03].
- Machine park—Often the high efficiency of superabrasives is only emerging from high cutting speeds. High-speed applications hold the advantage of small chip thicknesses resulting in tight workpiece form tolerances and high surface quality or high productivity. However, the complex machine setup needed (spindle power, encapsulation, more complex cooling lubricant system, etc.) might dissolve the technological advantages.
- Tool costs—Superabrasive tools are commonly more expensive than conventional tools, so that their economic efficiency is focussed on larger scale production [KLOC03].

The embodied energy of a product can vary along its life time depending on the intensity of usage and end of life stages [KARA10]. A manufacturer can manage the embodied energy from cradle-to-factory gate better than the users because the usage behavior and maintenance may vary [KARA10].

Kara and Manmek [KARA10] reviewed the embodied energy of composite materials in a cradle-to-gate analysis and found location of the suppliers was a significant factor for embodied energy. The embodied energy could be reduced considerably by carefully selecting local suppliers and by using rail or water transportation in the case of high quantities of raw materials and long distances.

8.2 Case Study on Comparing Hard Turning and Grinding

Araujo and Oliveira [ARAU12] compared the sustainability of hard turning and grinding based on 29 sustainability indicators in a case study. They chose five social indicators for the comparison:

- labor relations: hourly wages,
- health and safety: number of occupational accidents, noise level, operator risk level,
- training and education: average number of hours of training per operator.

From their data, Araujo and Oliveira [ARAU12] found that the grinder earns higher salary and gets more hours of training and education, but health and safety indicators were worse (higher noise level, more accidents and higher operator risk per accident). In particular, grinding has a potential for more severe accidents if the rotating grinding tools get damaged [ARAU12].

The overall sustainability assessment of hard turning versus grinding can be done considering different scenarios, weighting the criteria differently. When the environmental and social dimensions grow in relevance, hard turning has an advantage because of lower specific energy per unit of material processed. The economic performance of grinding appears to be superior to turning. [ARAU12]

8.3 Leveraging Abrasive Machining

Leveraging is a term known in financial discussions and describes employing resources in such a way as to insure a larger return on the effort than might otherwise be realized [DORN11]. One example is using higher efforts to improve the machining tolerances of an aircraft airframe and gaining high savings in fuel during the life time of the produced airplane [DORN11]. Dornfeld [DORN11] points out that manufacturing-driven improvements are indeed responsible for substantial environmental impact reductions. Leveraging is critical for abrasive machining since it is often decisive for product function [AURI13].

8.3.1 Case Study on Speed-Stroke Grinding with High Grinding Wheel Speeds

Speed-stroke grinding is surface pendulum grinding with increased table speeds up to v_w = 200 m/min. Advantages arise from the changing active chip formation mechanisms [INAS88, ZEPP05]. Chips gets shorter and thicker, which accounts for a more effective chip formation. The specific material removal rate, Q'_w, results from depth of cut, a_e, and workpiece speed, v_w (Eq. 8.1). Increasing the material removal rate by the workpiece speed v_w affects the the maximum undeformed chip thickness stronger than the depth of cut a_e [DUSC12].

$$Q'_w = a_e \cdot v_w \tag{8.1}$$

a_e depth of cut
v_w workspiece speed

The total power consumed by a machine tool sums up from idle power of spindles, axes, and periphery, and the processing power to accomplish the chip formation. As the specific grinding energy accounts for a minor part of the total energy consumed by the machine tool, the grinding time reduction by a higher table speed facilitates higher energy efficiency [DUSC12].

CBN grinding tools have higher wear resistance than conventional grinding tools resulting in reduced waste. However, due to the higher thermal conductivity, positive compressive stresses can be added to the workpiece surface. Because of the higher price and the needed high spindle power finding the proper process window is crucial for a sustainable usage of CBN tools [LINK11, DUSC12].

Speed stroke grinding of bearing steel with CBN grinding wheels can produce lower tensile stresses than other grinding variants [DUSC12]. These surface conditions are favorable for low crack propagation in rolling contacts. The product life for rolling contact or cyclic load applications can be prolonged through speed-stroke grinding, which would result in products with lower overall environmental impact [DUSC12].

8.3.2 Leveraging Example for Gear Grinding

The use phase rather than the manufacturing phase of most consumer products dominates the environmental impacts [ASHB09]. The case study of an automotive manual transmission drivetrain exemplifies how higher manufacturing efforts can reduce the overall environmental impact [HELU11].

The automotive powertrain consists of the engine, transmission, and drivetrain (drive shaft, differentials and drive wheels). Gears are functional elements in the transmission. Several abrasive processes exist for gear finishing [KARP08]. In this study, general grinding processes are applied [HELU11]. The empirical equation (8.2) relates the average surface roughness, Ra, to the specific material removal rate and wheel speed [MALK08, HELU11].

$$Ra = R_1 \cdot \left(\frac{Q'_w}{v_s}\right)^x \tag{8.2}$$

Ra average surface roughness
R_1 experimentally determined constant
Q'_w specific material removal rate
v_s wheel speed
x experimentally determined constant ($0.15 < x < 0.6$)

The specific energy requirement is assumed as 200,000 J/cm^3 for a process rate of about 10^{-3} cm^2/s [GUTO06]. With this specific energy, a constant wheel speed, and a Michigan energy mix, the specific energy to decrease the surface roughness of the gears in the final drive reduction is calculated [HELU11]. The roughness, *Ra*, can be decreased to 20–60 % for less than 0.5 MMBtu of primary energy [HELU11].

In the gear use phase, the powertrain delivers power to accelerate the vehicle, overcome losses in the drivetrain and engine and to power accessories [HELU11]. With the frictional losses and all accessories constant, fuel power changes with drivetrain efficiency. For a helical gear pair modeled after a final drive reduction the gear mesh efficiency depends on the root mean square surface roughness, *Rq*, of the gear [XU07]. During vehicle usage, the power to overcome tractive losses and accelerate the vehicle depends on the vehicle velocity, climbing resistance, rolling resistance, and aerodynamic drag [HELU11]. Assuming a standard driving cycle from the U.S. EPA Federal Test Procedure 75 and a regular gasoline, the primary energy demand of the transmission can be calculated in dependence of a range of the root mean square surface roughness, *Rq* [HELU11]. Decreasing Rq lowers primary energy demand relative to a standard finished final drive reduction in a range of 2–5 MMBtu depending on the lubricant temperature in the final drive reduction [HELU11].

Comparing the manufacturing energy for decreasing surface roughness and gained reduction of use phase energy demand shows that manufacturing precision has a big impact. Since there are several gears in a vehicle in addition to the final drive reduction there is an even much bigger opportunity for manufacturers to improve efficiency [HELU11].