Chapter 7
Sustainability of Grinding Tools

In 1822, grinders did not become old:.
About thirty years ago, the steam engine was first adapted to the purposes of grinding; and then a very important era arrived in the annals of the grinder. He now worked in a small low room, where there were ten or twelve stones; the doors and windows were kept almost constantly shut; a great quantity of dust was necessarily evolved from so many stones, and there was scarcely any circulation of air to carry it away. [...] If, then, the grinders' asthma were a disease of not unfrequent occurrence before, it is probable that its frequency would have been much increased now. Such, indeed, was the fact; and it is at the present time become so general, that out of twenty-five hundred grinders, there are not thirty-five who have arrived at the age of fifty years. [KNIG22].

Sustainability of grinding tools can only be discussed with a deep understanding of all relevant system components. This chapter summarizes the analyses and conclusions from the preceding chapters into a holistic description model. The study on abrasive tooling systems began with explaining the abrasive grits, followed by the bonding systems (Chaps. 2 and 3). Then it eluded on the different tooling types and grinding wheel body shapes and materials (Chaps. 4 and 5). The composition and structure of the abrasive layer has complex implications on tool manufacturing and use (Chap. 6). Understanding of wear and tool conditioning is crucial to the grinding process. Based on this technological base a comprehensive evaluation of sustainability of tooling systems becomes possible. Therefore, existing methods of life cycle engineering, namely Life Cycle Assessment, Life Cycle Costing, Social Life Cycle Assessment, and Sustainability Indicators are introduced in the following chapter. The Input-Output streams of grinding will be derived to provide the life cycle inventory. As a new method axiomatic design principles will be applied to analyze all functions and design parameters of grinding. The generated matrix will allow a new, detailed evaluation of grinding process sustainability.

B. Linke, *Life Cycle and Sustainability of Abrasive Tools*,
RWTHedition, DOI 10.1007/978-3-319-28346-3_7

7.1 Life Cycle Engineering

Companies have to find ways to capture and measure their sustainability performance. The overall goal of sustainability encompasses the three dimensions of economic, environmental and social sustainability [HAUS05]. Life Cycle Costing (LCC), Life Cycle Assessment (LCA), and Social Life Cycle Assessment (SLCA) are methods to assess each dimension. Sustainability indicators evaluate the overall performance in all dimensions. In this study, technology is added as forth dimension to sustainability.

Life cycle engineering (LCE) incorporates concepts, approaches, and methodologies to address environmental challenges, such as generation of waste, releasing hazardous substances, resource depletion, and green house gas emissions [UMED12]. Considering life cycles enlarges the narrow view on product, production, and use onto viewing the whole product life from raw material extraction to disposal [HERR10, p. 83]. Umeda et al. [UMED12] propose that product design and life cycle flow design should be integrated to reduce the resource consumption and environmental loads of the entire product life cycle.

7.1.1 Environmental Aspects—Life Cycle Assessment (LCA)

Many different standards and methodologies exist to evaluate the environmental impacts of products, processes and manufacturing systems. The most commonly used method is Life Cycle Assessment (LCA), including its variants process LCA, Economic Input-Output LCA and hybrid LCA [REIC10]. Reich-Weiser et al. [REIC10] discussed the differences between frameworks and sorted them into different spatial and temporal levels of complexity. Hybrid LCA methodologies were found to be effective at capturing full supply chain and enterprise level emissions; however, trade-offs at the factory or machine tool level are best analyzed by process LCA approaches [REIC10]. LCA focuses on environmental aspects.

ISO14040 gives a framework to conduct a process LCA. Figure 7.1 transfers the framework to grinding tool production. First, goal and scope of the study are defined as well as functional unit, i.e. the basis for the quantification of resource and energy streams. In the next step, life cycle inventory (LCI) analysis, all resource and energy streams are collected. Table 7.1 summarizes common environmental attributes, but are not grinding process specific. For grinding analysis, water, air, sound, resources, and human aspects are most important.

The third step consists of the life cycle impact assessment (LCIA). The inventory data is converted into impact indicators, which will form the environmental fingerprint of the process. Impact is defined as the consequences caused by the input and output streams on the Areas of Protection (AoP). Four AoP are defined: human health, man-made environment, natural environment, and natural resources [DEHA99]. Typical impact categories enclose global warming, stratospheric ozone

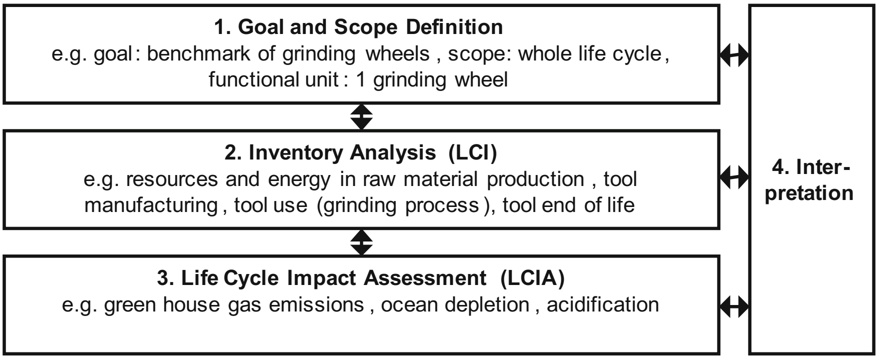

Fig. 7.1 Life cycle assessment of abrasive tooling systems (after ISO14044)

Table 7.1 Environmental attributes [JAIN12, p. 459 ff]

Water—physical • Aquifer safe yield • Flow variations • Oil • Radioactivity • Suspended solids • Thermal discharge	**Water—chemical** • Acid and alkali • Biochemical oxygen demand • Dissolved oxygen • Dissolved solids • Nutrients • Toxic compounds	**Water—biological** • Aquatic life • Fecal coliforms
Air • Diffusion factor • Particulate matter • Sulfur oxides • Hydrocarbons • Nitrogen oxides • Carbon monoxide • Photochemical oxidants • Hazardous toxicants • Odors	**Sound** • Physiological effects • Psychological effects • Communication effects • Performance effects • Social behavior effects	**Ecology** • Large animals (wild and domestic) • Predatory birds • Small game • Fish, shellfish, and waterfowl • Field crops • Listed species • Natural land vegetation • Aquatic plants
Land • Erosion • Natural hazards • Land-use patterns	**Human aspects** • Lifestyles • Psychological needs • Physiological systems • Community needs	**Resources** • Fuel resources • Nonfuel resources • Aesthetics

depletion, acidification, eutrophication, photochemical smog, terrestrial toxicity, aquatic toxicity, human health, resource depletion, land use, and water use [CURR06, p. 49].

LCIA methods are either midpoint or endpoint oriented. The midpoint methods model impacts at some midpoint in the environmental mechanism [HAUS05]. The endpoint methods are also called damage oriented methods and calculate an overall impact score for the AoP at the end [HAUS05]. Normalization and weighting is conducted on the impact indicators. The environmental attributes in Table 7.1 have been of interest to life cycle assessment over time [JAIN12, p. 459 ff].

7.1.2 *Social Life Cycle Assessment (SLCA)*

Companies start to include Corporate Social Responsibility into their corporate culture [MCCL10]. Traditionally, lower need levels of people were regarded, such as food, health and safety, but in the future the social aspects will likely be extended to higher levels such as worker satisfaction, self-esteem, etc. [HUTC10]. Societal aspects of product or process assessment include furthermore customer requirements, legislation, cooperative strategies, market trends, technological development, and consumers' behavior [UMED12].

Social Life Cycle Assessments are still in development [HAUS08]. Hauschild et al. suggests to add "human dignity and well-being" as fifth Area of Protection (AoP), including having a good and decent life enjoying respect and social membership and with fulfilment of the basic needs for food, water, medical care [HAUS08, WEID06, DREY06]. The Committee on Sustainable Development of the United Nations has a large set of indicators with a strong focus on social sustainability and countries [UN07]. Social indicators include poverty, governance, health, education [UN07]. Hutchins et al. [HUTC10] propose a social sustainability indicator framework, which maps the needs to the different entities involved into the manufacturing system (Fig. 7.2).

		Need				
		Basic needs - requirements to maintain the primary functions of the entity	**Safety/ Security needs** - freedom from real or perceived external threats to the entity	**Affiliation needs** - an understood role within a group and meaningful relationships with other entities	**Esteem needs** - having both self-respect and the respect of other entities	**Actualization needs** - realizing the full potential of the entity
Entity	**Employees**					
	Customers					
	Stockholders/ Owners					
	Suppliers					
	Community					
	Public					

Fig. 7.2 Social sustainability indicator framework after [HUTC10]

7.1.3 Life Cycle Costing (LCC)

The method of Life Cycle Costing has been developed in the USA for calculation of the economic feasibility and design for projects in industrial plant construction [VDI05]. Life Cycle costs include not only the product's manufacturing costs, but also usage and disposal costs.

The grinding costs per part enclose the machine costs, labor costs, tool costs, coolant costs, and nonconformity costs as shown in Fig. 7.3 [HENN84]. The time per part needs to incorporate nonproductive time per part besides the primary processing time, which is defined by the material removal rate and the process set-up (Fig. 7.4).

Increasing material removal rate reduces processing time and time dependent costs (Fig. 7.5). Higher material removal rate also leads to higher load on the grinding system components, higher tool wear, potentially higher scrap rate, etc. Therefore, the load dependent costs rise. The total costs as the sum of the load and time dependent costs has a minimum.

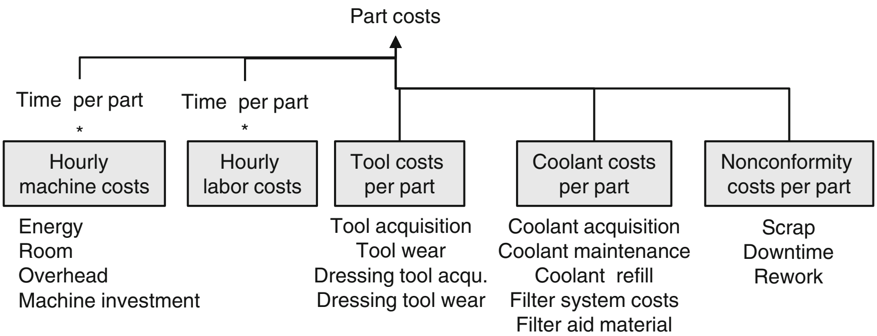

Fig. 7.3 Grinding costs per part

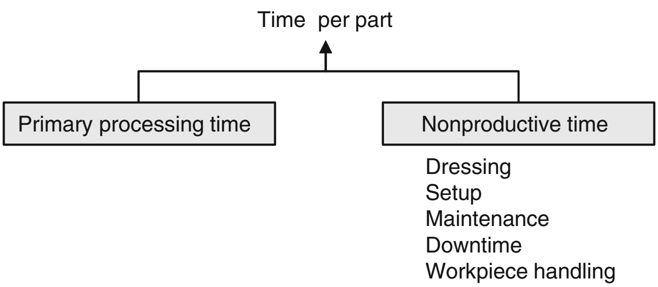

Fig. 7.4 Grinding time per part

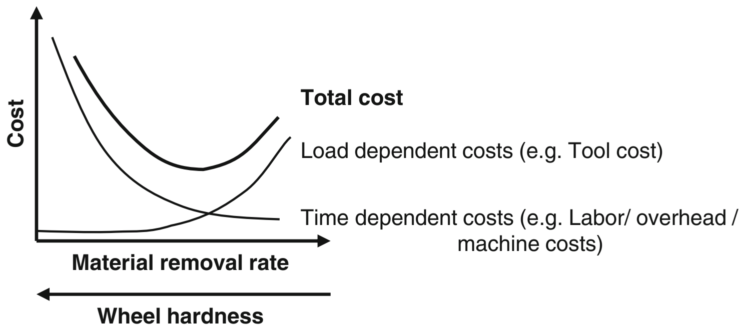

Fig. 7.5 Part costs after [METZ86, p. 11, COES71, p. 13]

A comparison of superabrasive and conventional tools highlights how important it is to account for all costs. The superabrasive tool costs more and, despite the higher tool life, the tool costs per part might be higher (Fig. 7.6). However, the time dependent costs such as labor and machine costs are likely much smaller per part, because the superabrasive tool needs fewer tool changes, cycle times are likely higher, process stability is better and less rejects happen, less down-time occurs by dressing, etc. [KING86, p. 105]. The total costs per machined part are then lower for the superabrasive tool than for the conventional wheel (Fig. 7.6).

Costs for cooling lubricant need to be split between costs per batch or part and costs per disposal interval. Coolant treatment costs appear per liter of coolant, disposal costs for old coolant, and purchase costs for new coolant. Coolant treatment includes maintenance and control, adding of additives such as biozides, emulgators, foam inhibitors, and filtering. In emulsions, water needs to be refilled due to evaporation. Filtering systems can be belt filters with filter material, separators, magnetic filters, hydrocyclones, or others [KLOC09, p. 131].

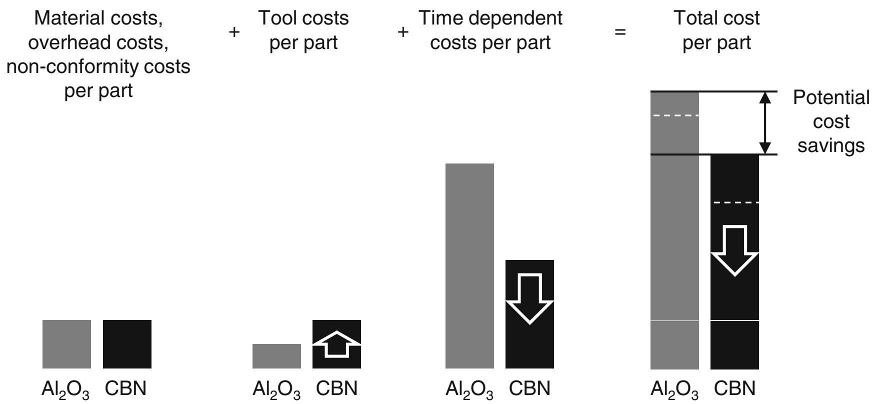

Fig. 7.6 Part costs for conventional and superabrasive grinding tools after [KING86, p. 105]

7.1.4 Sustainability Indicators

Sustainability indicators are less formalized assessment indicators than the ones in LCA, SLCA or LCC and can capture more than one dimension of sustainability. An indicator is “a measure or an aggregation of measures from which conclusions on the phenomenon of interest can be inferred” [JOUN12]. Sustainability indicators are good for users with limited databases and resources. Companies can assess their actual situation with the indicators, raise their awareness and set their goals [KRAJ03].

In the last years, different approaches to measure sustainability performance have arisen [JOUN12, SING12, JAYA10]. For example, the Process Sustainability Index (ProcSI) regards the six clusters: manufacturing costs, energy consumption, waste management, environmental impact, operator safety, and personnel health [LU127]. The methods should be simple and affordable to apply, have low assessment time, and should not rely on user experience. The indicators have to be specified in the period of tracking and calculating (e.g. fiscal year, calendar year, month, etc.), boundaries (e.g. process level, factory level, etc.), and units of measurement [KRAJ03].

It is advisable not to choose too many indicators to keep the analysis manageable [LINK13]. In addition, sustainability indicators should be independent. Indicators should be normalized, which means they do not present their value as absolute amount but show relative terms as a ratio of performance per specific unit of output [OECD12]. A wide variety of factors can be used to normalize performance, such as number, weight or units of products produced in the facility, value added, person-hours worked in the facility, or lifetime of the products produced [SING12, OECD12]. Example sustainability indicators are energy intensity, residuals intensity, non-renewable materials intensity, safety, blood lead level, product costs, etc. For grinding, a smaller set of indicators seems to be useful (Fig. 7.39) [LINK13].

7.2 Life Cycle Inventory of Grinding Processes

7.2.1 Evaluating Sustainability of Unit Processes

In addition to economic, environmental and social sustainability, the technological dimension needs to be considered as a fourth dimension. Yuan et al. [YUAN12] suggest three strategies to increase sustainability in manufacturing processes: (1) Optimizing of the manufacturing technology by detecting and changing the parameters that affect material and energy streams, (2) Using clean energy, (3) Using lower impact materials.

The production of a part can be broken down from all involved production chains into discrete manufacturing processes. The unit process consists of inputs, process, and outputs of an operation. Each unit process is converting material or chemical inputs into a transformed material or chemical output. Cradle to grave views a product from raw material extraction to end of life, cradle to cradle considers re-use and recycling, cradle to gate or gate to gate evaluates only parts of the life cycle.

The CO_2PE! UPLCI-Initiative provides a framework to aquire data for unit manufacturing processes [KELL11]. The in-depth approach in the CO_2PE! UPLCI-Initiative studies energy through power consumption measurements and time studies, as well as consumables and manufacturing emissions [KELL12a, KELL12b, KELL11]. The basic screening approach in the CO_2PE! UPLCI-Initiative quantifies energy consumption as well as other environmental impact information of manufacturing processes, and is largely based on data from publications, catalogs, and handbooks [KELL11]. It focuses on manufacturing energy and chemicals/ materials required at the machine level and can be refined by measured data.

Energy and resource efficiency of manufacturing processes can be enhanced by reducing the machine basic and idle energy through machine setup or shorter production times or by minimizing the processing energy [DORN10].

7.2.2 Input-Output Streams of Grinding

The complex tool design with multiple cutting edges and the complex chip formation mechanisms complicate the analysis of the grinding process [KLOM86]. Figure 7.7 shows all input and output streams that can be considered in grinding and provides a basis for a life cycle inventory. The items have different relevance for different applications.

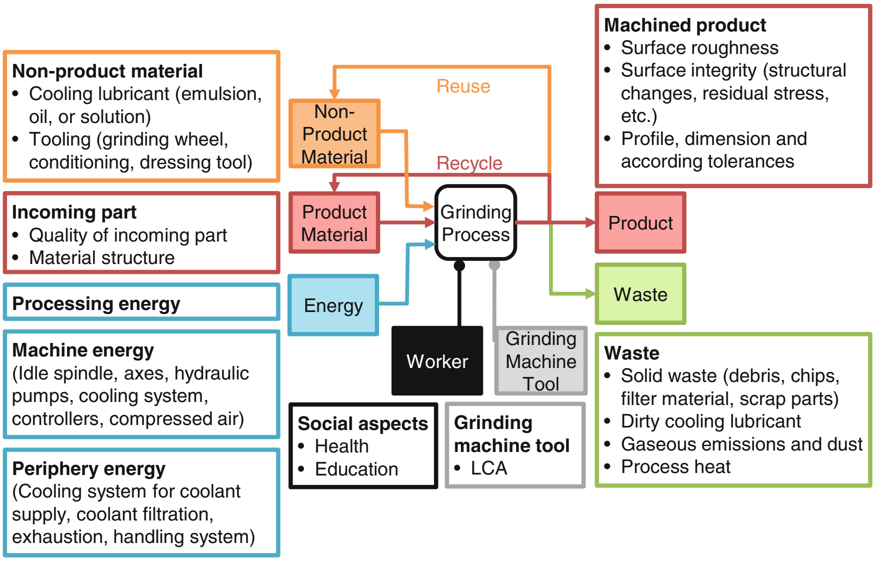

Fig. 7.7 Comprehensive input-output diagram of a grinding process [LINK12], with kind permission from Springer Science and Business Media

The tooling is part of non-product material. Grinding wheel design, tool conditioning, and dressing tools are described in Sects. 6.3.3 "G-Ratio" and 6.5 "Tool Conditioning". Cooling lubricant is important to cool and lubricate the grinding process, clean, transport chips, cool the machine tool, and protect against corrosion [BRIN99, KLOC09, MARI07].

Grinding oil, water-based emulsions or watery solutions are common cooling lubricants. These coolants have a different amount of non-renewable material content and affect the environmental attributes of water differently, such as contents of oil, acids, alkalis, toxic compounds, etc. [JAIN12, p. 497 ff]. Furthermore, the grinding fluid can attract bacteria and fungi or be irritating to the worker's skin.

Water scarcity is a local measure, which predicts the long-term sustainability of a manufacturing location [REIC09]. The importance of water use is perceived differently in different geographical regions. The German industry, for example, does not perceive water scarcity in the same way as the Californian industry does. Research on new coolant media is ongoing to address the growing concerns on recyclability, toxicity and water consumption [KALI11, ZEIN11b].

Cooling lubricant type, flow volume, flow rate and supply systems affect the grinding process performance [BADG09a, BRIN99, KLOC09, WITT07, MORG08]. However, there is no easy estimation for the necessary flow volume and the flow rate of cooling lubricant, and it is often adjusted by the rule of thumb of 1 l/(min mm) [liter per minute and millimeter of grinding wheel width] [LINK12]. The high process heat limits dry grinding or Minimum Quantum Lubrication (MQL) to few applications [BECK02, MARI07].

The total energy consumed to generate part shape and surface by grinding consists of the processing energy and the energy consumed by machine tool and periphery (Fig. 7.7) [CRAT10, LINK12]. The processing energy or specific grinding energy, e_c, is defined as energy to remove one volumetric unit of material and is used for forming grinding chips, plowing material, and mastering friction between grinding grits, tool bond and the workpiece [MALK08, OLIV09].

Commonly, the specific grinding energy, e_c, is calculated from the grinding power, P_c, and the material removal rate, Q_w, after Eq. 7.1 [KLOC09]. Grinding power consists of the forces and speeds in tangential, normal and axial direction (Eq. 7.2) [ROWE09, p. 25]. However, normal and axial feed rates are much smaller than cutting speed in tangential direction and workpiece speed is smaller than the wheel speed, so that the simplified Eq. 7.3 is commonly used.

$$\text{Specific grinding energy } \mathrm{e_c} = \frac{\mathrm{P_c}}{\mathrm{Q_w}} \tag{7.1}$$

$$\text{Grinding power } \mathrm{P_c} = \mathrm{F_t} \cdot (\mathrm{v_s} \pm \mathrm{v_w}) + \mathrm{F_n} \cdot \mathrm{v_{fr}} + \mathrm{F_a} \cdot \mathrm{v_{fa}} \tag{7.2}$$

$$\text{Simplified grinding power } \mathrm{P_c} = \mathrm{F_t} \cdot \mathrm{v_s} \tag{7.3}$$

Q_w material removal rate
F_t tangential grinding force
v_s grinding wheel speed
v_w workpiece speed
F_n normal grinding force
v_{fr} radial feed rate
F_a axial grinding force
v_{fa} axial feed rate

Researchers have developed several grinding force models in close correlationship to the undeformed chip thickness, but these grinding force models are empirical and hardly applicable for generic applications [TÖNS92]. Grinding energy cannot be predicted accurately and variations in wheel sharpness lead to large variations in grinding energy [ROWE09]. Table 7.2 gives example processing energies.

Machine tool energy and peripheral energy can add much to the total energy [DAHM04]. This includes energy to run machine control, hydraulics, lighting, coolant system, compressed air, etc. Some machine power profiles have been published and databases provide basic information on machine power demands [ZEIN11, DENK05, KLOC10, BANI05]. Coolant pumps can account for a big portion of grinding energy as well as heating, ventilation and air conditioning (HVAC) and lighting [LINK12, DIAZ10].

The total grinding energy per part, E_{total}, can be calculated from processing, handling, setup and dressing time per single part (Eq. 7.4, Fig. 7.8) [LINK12]. Here, the power consumed by the dressing spindle and axes is neglected.

Table 7.2 Examples for specific grinding energies [LINK12]

Application	Specific energy in [J/mm^3]	Reference
Grinding of brittle materials like glass or ceramics	1–7	[HELL05a]
Surface grinding of aluminum	2.5–10	[KALP97]
Grinding of the metal matrix composite Al-2009/SiC-15 W with alumina wheel	10–25	[ILIO09]
Speed stroke grinding of γ-titanium aluminum alloy with vitrified diamond wheel	10–30	[ZEPP05]
Surface grinding of cast iron	12–60	[KALP97]
Surface grinding of tool steels	18–82	[KALP97]
Grinding of steels with conventional aluminum-oxide wheels	30–50	[OLIV09]
Grinding of cemented carbide	80–200	[HELL05a]

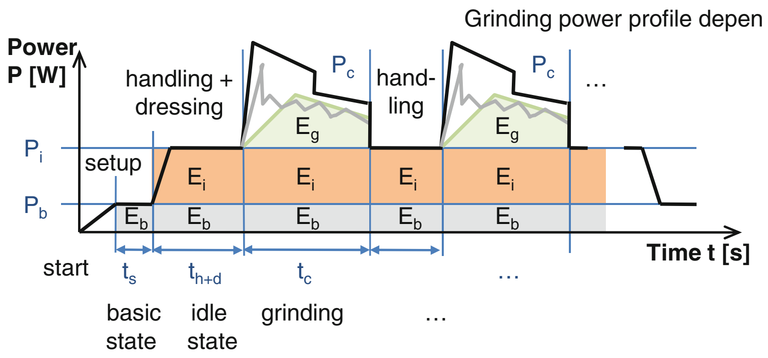

Fig. 7.8 Simplified power profile for grinding processes [LINK12], with kind permission from Springer Science and Business Media

$$E_{total} = \underbrace{t_s \cdot (P_b)}_{\text{setup energy}} + \underbrace{t_{h+d} \cdot (P_b + P_i)}_{\substack{\text{handling and}\\ \text{dressing energy}}} + \underbrace{t_c \cdot (P_b + P_i) + e_c \cdot V_w}_{\text{grinding energy}} \tag{7.4}$$

t_s setup time
t_{h+d} handling and dressing time
t_c grinding time
P_b base power
P_i idle power
e_c specific grinding energy
V_w machined material volume

The specific grinding energy, e_c, can be calculated through Eq. 7.1 if forces are measured or through Eq. 7.5 if the spindle power profile is measured [LINK12].

$$e_c = \frac{\int (P_c(t) - P_b(t) - P_i(t))dt}{V_w} \tag{7.5}$$

P_c spindle power
P_b base power
P_i idle power
t time
V_w machined material volume

Higher material removal rate decreases process energy for the same volume of material removed [MARI07, LINK11, ZEIN11, KLOC10]. This results from the decreasing processing time, which dominates over the increasing processing power demand. Nevertheless, higher material removal rates lead to higher process forces, larger tool wear, and higher surface roughness.

Waste streams from the grinding process include heat waste. The common assumption is that nearly the total energy in the contact zone is converted to the total heat flux, q_t (Eq. 7.6) [MARI07]. Abrasive grits with higher thermal conductivity can reduce temperatures drastically, e.g. CBN instead of Al_2O_3, [ROWE09].

Grinding debris and filter material are another waste stream from the grinding process [ECKE00]. Grinding debris can be composed of 10–80 % of chips, 2–75 % of grinding tool swarf and up to 50 % of filter aid [SCHÖ03]. The oil or emulsion content defines the recyclability of the grinding debris. Recycling options for abrasive tools are addressed in Sect. 4.8 “Tool End of Life”.

Machine tools have a life cycle of their own [DIAZ10]. Enparantza et al. [ENPA06] calculated life cycle costs for a centerless grinding machine tool. In this case study, 80 % of the life cycle costs happen during the use phase due to the grinding operation itself and maintenance. Direct labor accounted for 51 % of the total costs, the grinding wheel for 13 %, the machine tool purchase for 8 % and energy consumption for 6 % [ENPA06].

$$q_t = \frac{F'_t \cdot v_c}{l_c} = q_{ch} + q_{cool} + q_w + q_s \tag{7.6}$$

q_t total heat flux
F'_t specific tangential force
v_c cutting speed
l_c contact length (Eq. 6.7)
q_{ch} heat flux to the chip
q_{cool} heat flux to the cooling lubricant
q_s heat flux to the wheel
q_w heat flux to the workpiece

7.3 Axiomatic Grinding Process Model

Section 7.1 described different methods for evaluating sustainability and Sect. 7.2 derived the life cycle inventory for grinding to implement these methods. Data for the analysis is either measured empirically, estimated or obtained from databases. Ideally, fundamental process knowledge would allow calculating all input and output streams from physical and analytical models. The following study uses axiomatic design principles to display how sustainability characteristics are connected with physical process principles. This new approach is still in development but creates a holistic model and points out where further research and quantitative equations are needed.

7.3.1 Methodology

Axiomatic design is a way to describe systems and products systematically and was laid out by Suh [SUH01, COCH01]. The idea of axiomatic design is to generalize the principles of the investigated system by axioms. This design method has been used for environmental considerations of manufacturing systems and product services [STIA07]. However, grinding processes have too many interdependencies between their process components and, therefore, some axiomatic design rules cannot be fulfilled completely, such as the interdependence axiom [LINK12c].

The axiomatic design process works within four domains, which are shown in Fig. 7.9 for the abrasive process including process setup, tool, and cooling lubricant. The customer domain is characterized by the customer attributes {CAs} of the grinding application at a defined workpiece. For example, we are aim at a certain surface integrity, roughness or dimensional tolerance. In the functional domain, the functional requirements {FRs}, such as "take away heat from the workpiece", "control chemical reactions on the work surface", etc., and constraints {Cs}, such as maximum dimensions of the components, are defined.

The design parameters {DPs} in the physical domain satisfy the FRs. Here, DPs are cooling lubricant properties (heat capacity, supply system, etc.), process setup (thermal conductivity, kinematics, etc.) and tool characteristics (grit type, wheel hardness, etc.).

Finally, in the process domain the procedure to generate the specific DP is characterized by process variables {PVs} [SUH01]. Here, PVs describe machine tool components or the production procedures of grinding tool and cooling lubricant. In concurrent engineering the last three design phases interact constantly with each other.

The relation between FR and DP can be expressed by vectors, see example in Eq. 7.7. This way of describing an abrasive tool system offers the possibility to implement qualitative connections or quantitative equations, which then can be used for energy and resource calculations. Additionally, we are able to separate the objectives (here FR) from the means (DP), evaluate necessity of all items and get a holistic overview [COCH01].

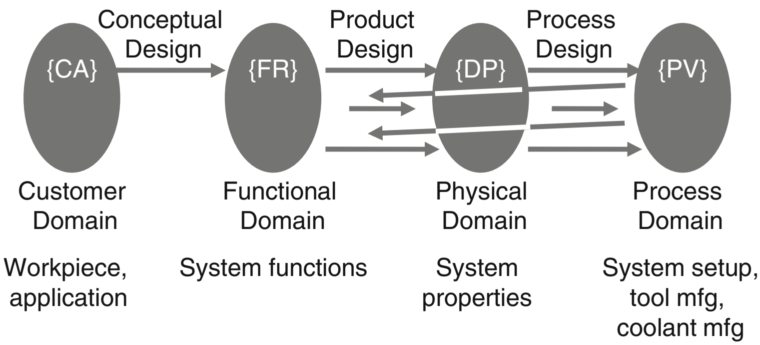

Fig. 7.9 Axiomatic description of a grinding process after [SUH01], reprinted from [LINK12c] with permission from Elsevier

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{7.7}$$

Axiomatic design demands that the functional requirements should be independent from each other (Independence Axiom) [SUH01]. This is not fulfilled in grinding processes because many components serve multiple functions, e.g. cooling lubricant or grits [LINK12c]. Additionally, in axiomatic design the information content should be minimal, i.e. the design with highest probability for success should be chosen (Information Axiom) [SUH01]. This axiom is not satisfied within most common discrete processes because the high process complexity does not allow for optimizing all variables simultaneously. For example, if oil is chosen as cooling lubricant instead of water-based emulsion, the heat from friction will be reduced, but chip formation will be less effective and less heat will be removed from the grinding zone [LINK12c].

In conclusion, representing grinding by axioms is one way to visualize the process mechanisms and aims at understanding the technology. Figure 7.10 explains how the axiomatic grinding process model is visualized in the following. Every functional requirement is met by a design parameter and the according boxes are connected by a line (Fig. 7.10). In axiomatic design, the model has to be decomposed until only one DP appears for one FR [BROW11]. DPs can be prioritized and additional DP create an alternative tree. In this study, this decomposition was not completely possible because the real grinding process has overlaying DPs. In addition, each DP should have more than one FRs [BROW11]. Final design

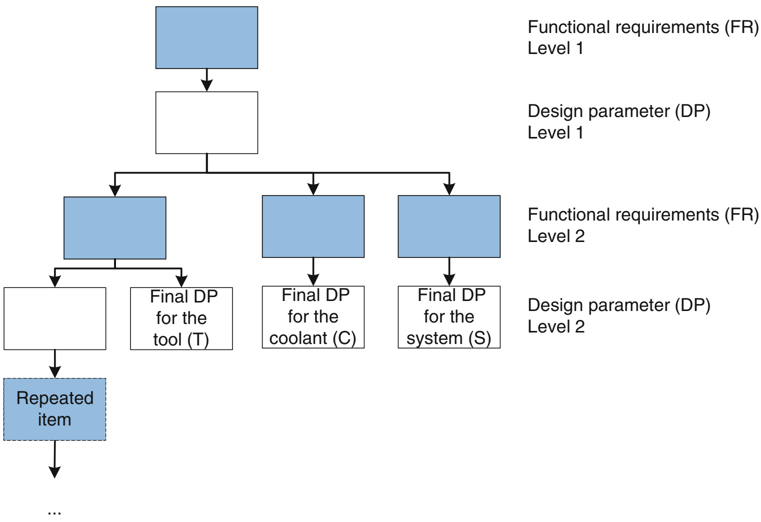

Fig. 7.10 Legend for visualizing the axiomatic grinding model

parameters, which cannot be broken down to smaller variables, are indicated by the letters (S), (T), or (C) (Fig. 7.10). A dashed line indicates a functional requirement or design parameter that is repeated elsewhere in the axiomatic model on the same or earlier level.

7.3.2 Grinding Process Model

7.3.2.1 Traditional Fundamental Requirements in Grinding

Manufacturing processes have to accomplish certain tasks depending on workpiece material, stock removal (finishing or roughing operation), availability of machines, batch size, form and dimension tolerances, achieved surface roughness and integrity, and more [LINK12c]. The following discussions focus on ductile material in finishing operations and the choice of the grinding tool, but the model can be easily adapted to other applications.

Dominant traditional functional requirements are creating part dimension and profile, i.e. the part's macro properties, creating the part surface, i.e. the part's micro properties, and being cost-effective (Fig. 7.11 top row). The first requirement for a given raw part can be achieved by several physical or chemical principles, such as material separation, evaporation, dissolvation, additive processes, etc. These principles underlie in fact all manufacturing processes as described by Todd, Allen and Alting [TODD94] or in the DIN8580 standard. In here, material separation is chosen (Fig. 7.11 left).

For the second requirement to create the part surface, the design parameters of part surface area and the surface integrity have to be considered (Fig. 7.11 middle). The third requirement for cost-effectiveness calls for high productivity, low scrap rate, and low tool costs (Fig. 7.11 right). Having more than one design parameter

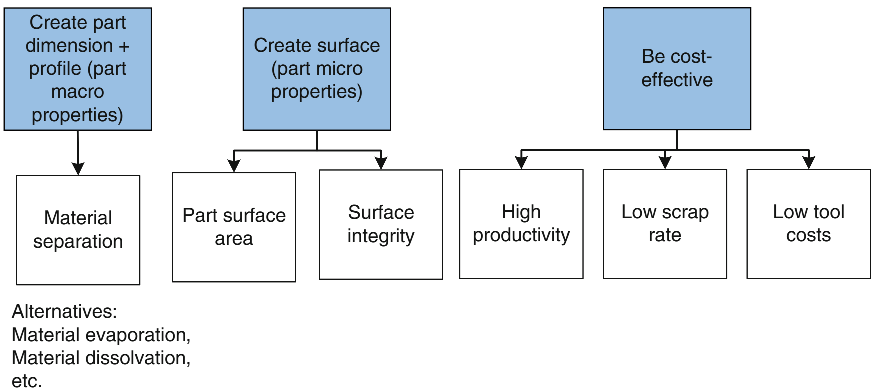

Fig. 7.11 Main fundamental requirements

for one functional requirement does not follow the axiomatic design rules for a good design [SUH01, BROW11]. The system is overdetermined, but these conflicts highlight problems and could give hint at improvements for future grinding process designs.

The main mechanism of material separation depends on the workpiece material and is dominated by material shearing and chip formation for ductile material or fracture and crack propagation for brittle material. Either way, shear stresses have to be induced by forces applied to the material through cutting edges (Fig. 7.12 top). In grinding, abrasive particles and a track-bound principle are selected over of the alternatives shown in Fig. 7.12.

The abrasive grits have to be held together, which is done by a bonded tool in the shown axiomatic model. Alternatives are coated tools or polishing pads. The abrasive material separation generates chips, which have to be carried out of the contact zone. The grinding tool is chosen as transport mechanism to achieve this.

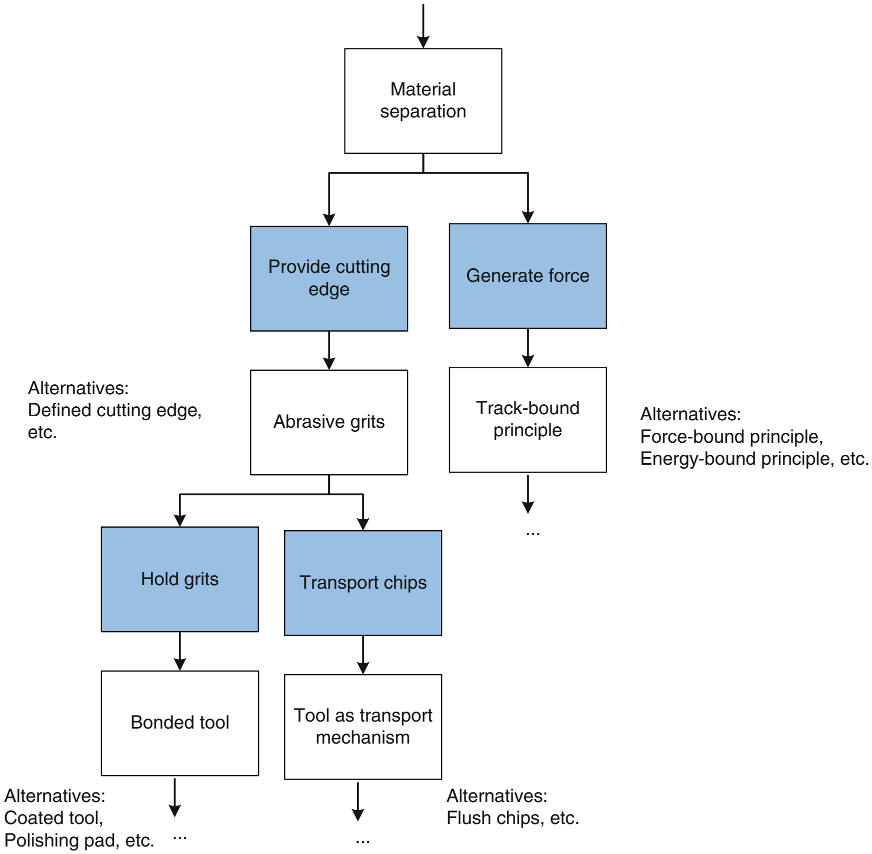

Fig. 7.12 Material separation (diagram follows Fig. 7.11)

7.3.2.2 Implications of a Bonded Tool

The design parameter of a bonded tool implies that an initial tool profile needs to be defined and then maintained as well as an initial tool sharpness needs to be defined and maintained (Fig. 7.13). Design parameters to define profile and sharpness are profiling and sharpening respectively. Profiling and sharpening can be combined to one dressing process, but then the design parameters are coupled (Fig. 7.15).

Loosing the tool profile can be overcome by a sufficient bond strength, low grit friability, and high grit hardness (Fig. 7.13). Loosing the tool sharpness is partially conquered by low grit wear and partially by tool self-sharpening (Fig. 7.14). In the case of a single-layered grinding tool, only low grit wear counts, whereas the multi-layered tools need self-sharpening largely.

Low grit wear is achieved by avoiding abrasive, thermal, and chemical grit wear. The according design parameters are high grit hardness, grit heat resistance, and chemical resistance of the grit material respectively (Fig. 7.14). Tool self-sharpening leads to the functional requirements of having grit splintering and providing new grits. The design parameters high grit friability and adjusted bond strength or a continuous dressing process respectively serve these requirements.

If only one dressing process is conducted instead of separate profiling and sharpening, the initial tool profile and initial sharpness are coupled (Fig. 7.15). The functional requirements of a dressing process are defining the dressing tool, the engagement of the dressing grits into the tool and the dressing intervals. Here, a diamond form roller is chosen as dressing tool, so the axial dressing feed rate v_{fad}, dressing speed ratio q_d, and depth of dressing cut a_{ed} are the parameters defining the

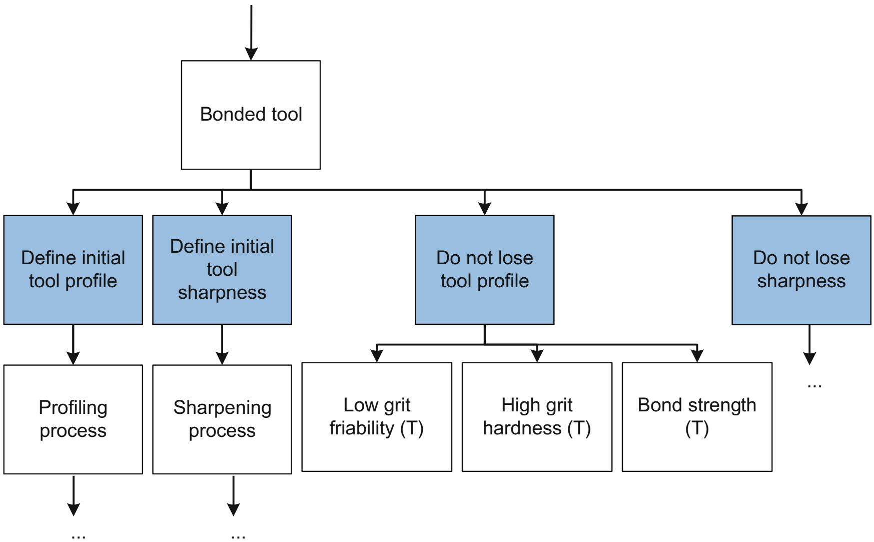

Fig. 7.13 Bonded tool (diagram follows Fig. 7.12)

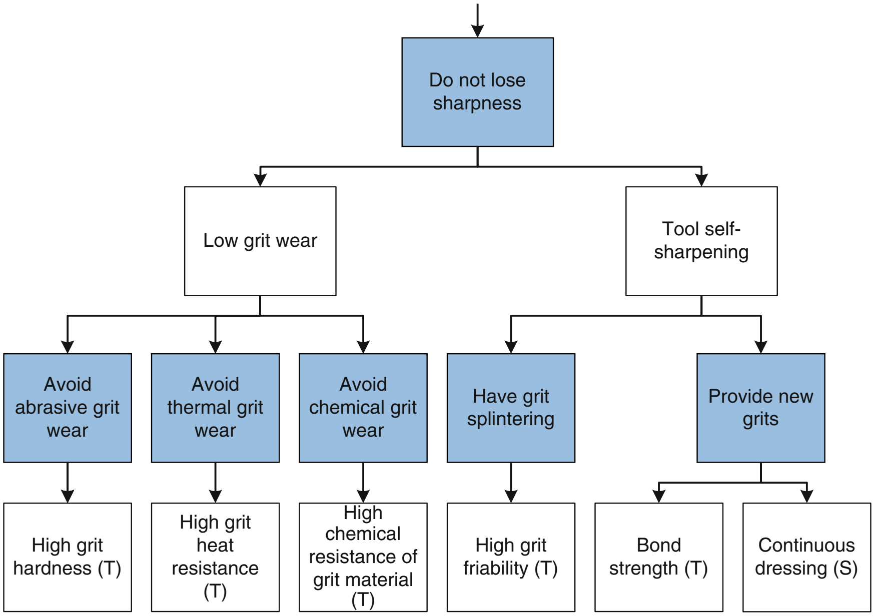

Fig. 7.14 Sharpness (diagram follows Fig. 7.13)

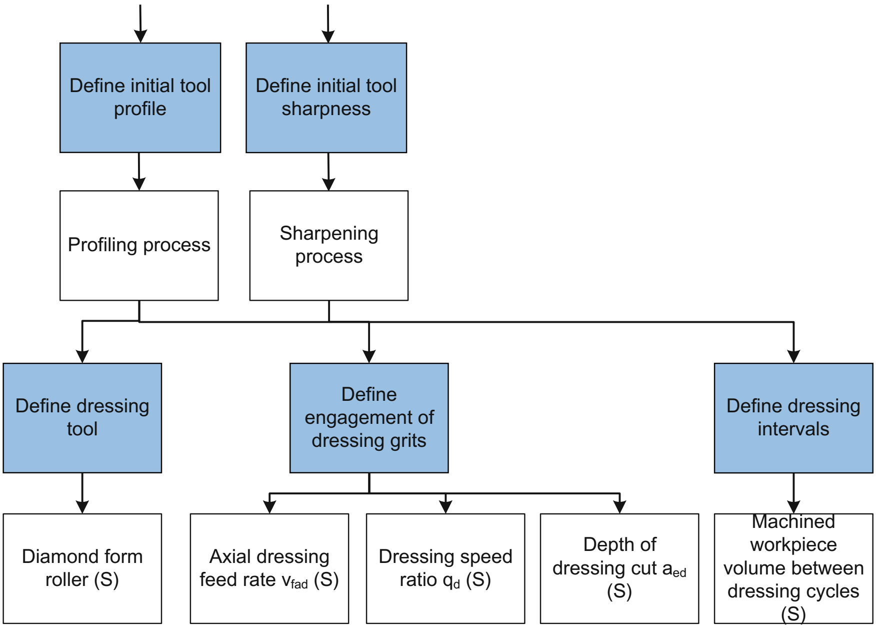

Fig. 7.15 Profiling and sharpening (diagram follows Fig. 7.13)

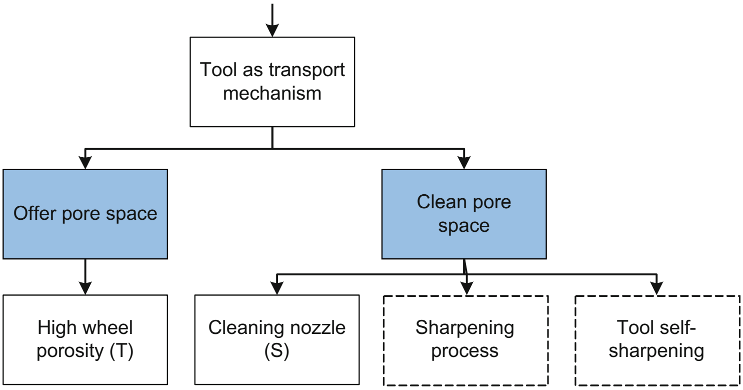

Fig. 7.16 Chip removal (diagram follows Fig. 7.12)

interaction between dressing tool and grinding tool. The machined workpiece volume between the dressing cycles defines the dressing intervals.

The grinding tool transports the generated chips (Fig. 7.16). On the one hand, pore space needs to be available, i.e. the design parameter is high wheel porosity. On the other hand, the pore space needs to be cleaned, which is done by a cleaning nozzle, the sharpening process, and/or self-sharpening of the tool.

7.3.2.3 Implications of the Track-Bound Principle

Having chosen the track-bound principle for force generation, the functional requirements arise to hold the workpiece, provide the cutting speed and feed of the grits, and reduce the mechanical impact that is not crucial for the cutting action (Fig. 7.17). The workpiece can be held by mechanical or magnetic clamping, or the centerless principle can be applied for cylindrical parts that are machined on their external circumference or the inner diameter (Fig. 7.17 left). In addition, deflections, bending of cylindrical workpieces, etc. have to be considered as sources of errors, so that additional counter-measures have to be taken [ROWE09].

The cutting speed results from the wheel spindle rotation and the grinding wheel diameter (Fig. 7.17 middle). The grit feed is generated by the tool axis movement and the process kinematics, such as face or circumference grinding, transverse or plunge cut grinding, external diameter, internal diameter, etc. (Fig. 7.17 right). Mechanical impact on the workpiece is a side effect of the chip formation and has to be minimized (Fig. 7.18). A low normal force per single grit and a small number of grit contacts both reduce the mechanical impact on the workpiece (Fig. 7.18). The normal single grit force is decreased by having a small load per grit and by changing the chip formation process to be more effective.

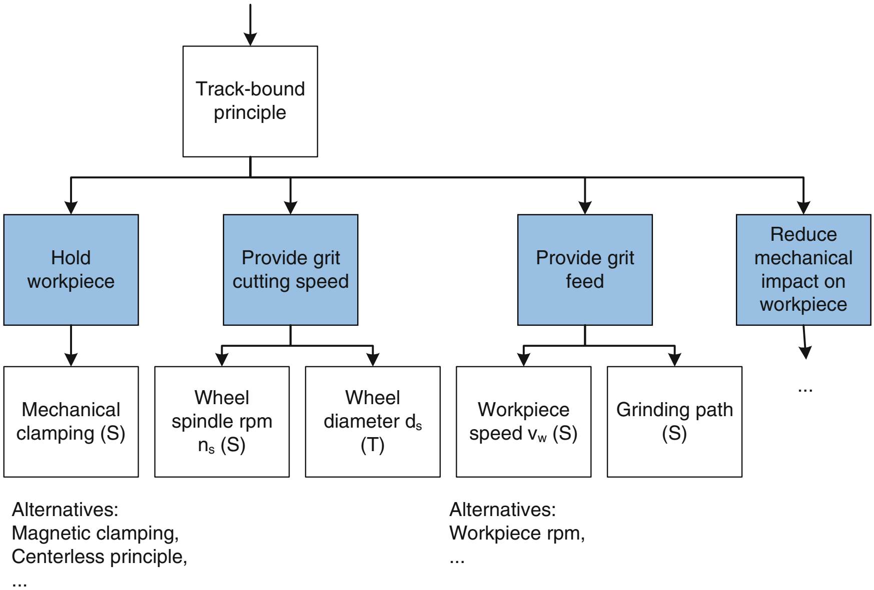

Fig. 7.17 Track-bound principle (diagram follows Fig. 7.12)

The maximum undeformed chip thickness, $h_{cu,max}$, is directly tied to the single grit load (Fig. 7.19). Chip thickness is related to statistical cutting edge density, C_{stat}, workpiece speed, v_w, grinding wheel speed, v_s, depth of cut, a_e, and equivalent grinding wheel diameter, d_{eq} (Eq. 7.8) [WERN71, TÖNS92]. Factors, k, α, β, γ, have to be found empirically, and Eq. 7.8 does not account for elastic and plastic material deformation. A common assumption is $\alpha = \beta = 1/3$, $\gamma = 1/6$, showing that the factor (a_e/d_{eq}) is of smaller significance than the other factors [WERN71]. A simplified approximation for the chip thickness is the equivalent chip thickness, h_{eq} (Eq. 7.9).

In reality, the real chip thickness is smaller than the maximum undeformed chip thickness [KLOC09, ROWE09]. This results from the elastic and plastic deformation effects overlaying the chip formation process (Fig. 7.20). The grit cutting depth, T_μ, is the grit engagement depth, at which chip formation starts. A high chip thickness increases the effectivity of the chip formation process, because the grit cutting depth T_μ is reached sooner. The same applies for the down-grinding mode in comparison to up-grinding and the use of a cooling lubricant with low lubrication properties to increase friction.

$$\text{Maximum undeformed chip thickness } h_{cu,max} \approx k\left(\frac{1}{C_{stat}}\right)^{\alpha}\left(\frac{v_w}{v_s}\right)^{\beta}\left(\frac{a_e}{d_{eq}}\right)^{\gamma} \quad (7.8)$$

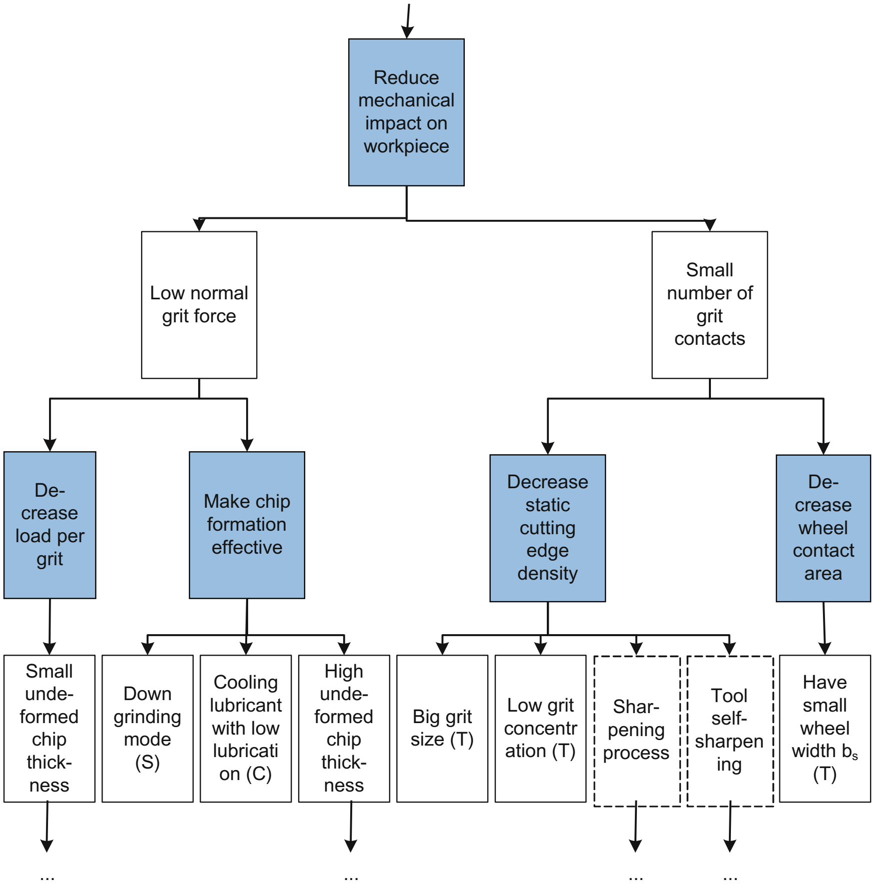

Fig. 7.18 Mechanical impact (diagram follows Fig. 7.17)

$$\text{Equivalent chip thickness } h_{eq} = \frac{Q'_w}{v_s} \tag{7.9}$$

k	constant depending on grinding wheel; e.g. k = 0.695 [WERN71]
C_{Stat}	static cutting edge density; e.g. $C_{stat} = 4420\ mm^{-3}$ for A46 [WERN71]
κ	half of the cutting edge angle; e.g. $\kappa = 82.4°$ [WERN71]
v_w	workpiece speed
v_s	wheel speed
a_e	depth of cut
d_{eq}	equivalent grinding wheel diameter (Eqs. 6.15, 6.16 and 6.17)
α, β, γ	empirical coefficients

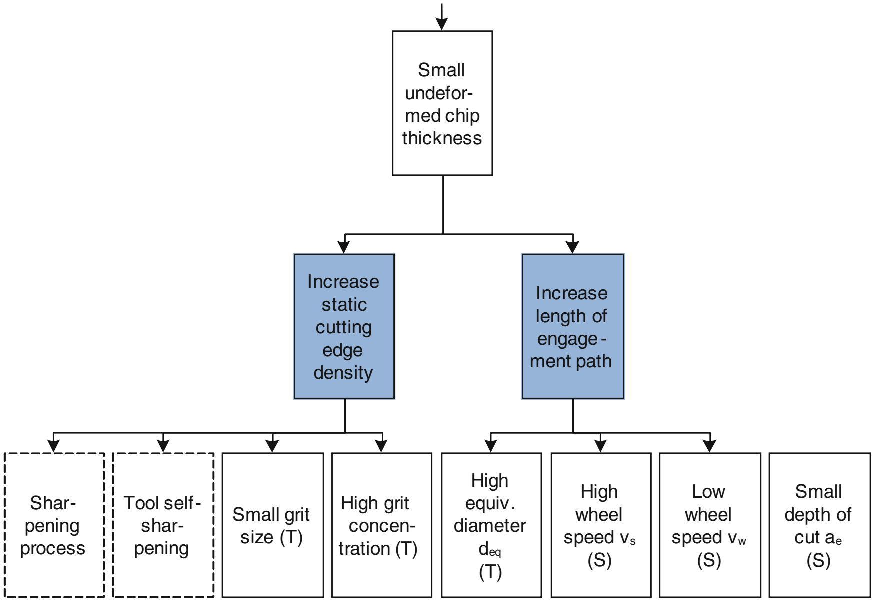

Fig. 7.19 Undeformed chip thickness

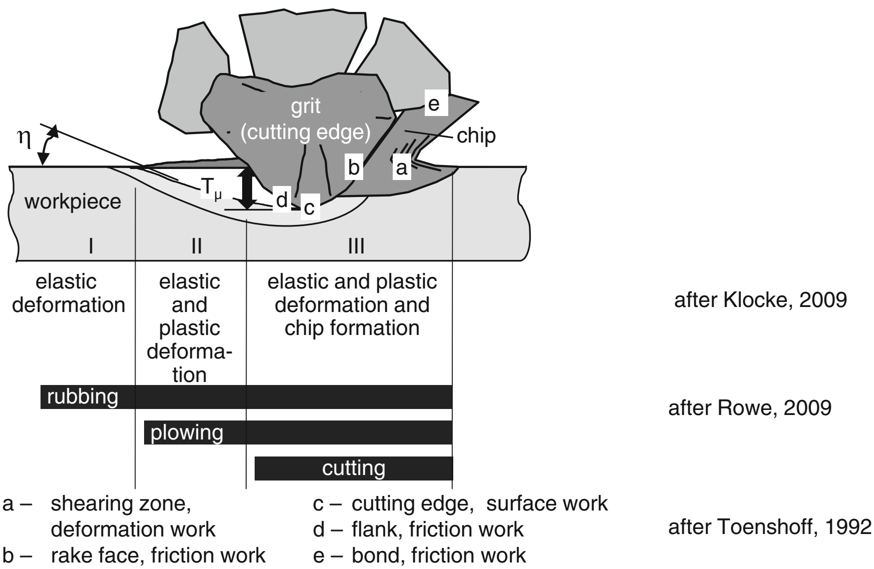

Fig. 7.20 Three phases of ductile chip formation [KLOC09] including the different contact types rubbing, plowing and cutting [ROWE09, TÖNS92], reprinted from [LINK12c] with permission from Elsevier

7.3.2.4 Functional Requirements of Controlling Workpiece Surface Pattern

The track-bound principle and use of abrasive grits in combination generate grooves and a pattern on the workpiece surface (Fig. 7.21). The pattern can be important for component function, e.g. in sealing systems where directionality of grinding grooves have to be avoided, or in engine cylinders where oil reservoirs are built. To get a random surface pattern, neither the grit engagement paths nor the grit pattern on the grinding tool should be regular. A statistic grit pattern on the tool serves the latter requirement. Engineered grit patterns [AURI03] or slotted wheels [UHLM10] have regular grit patterns, yet need higher care in process control to generate a random surface pattern (see Sect. 9.2 “Innovative and More Sustainable Tools”).

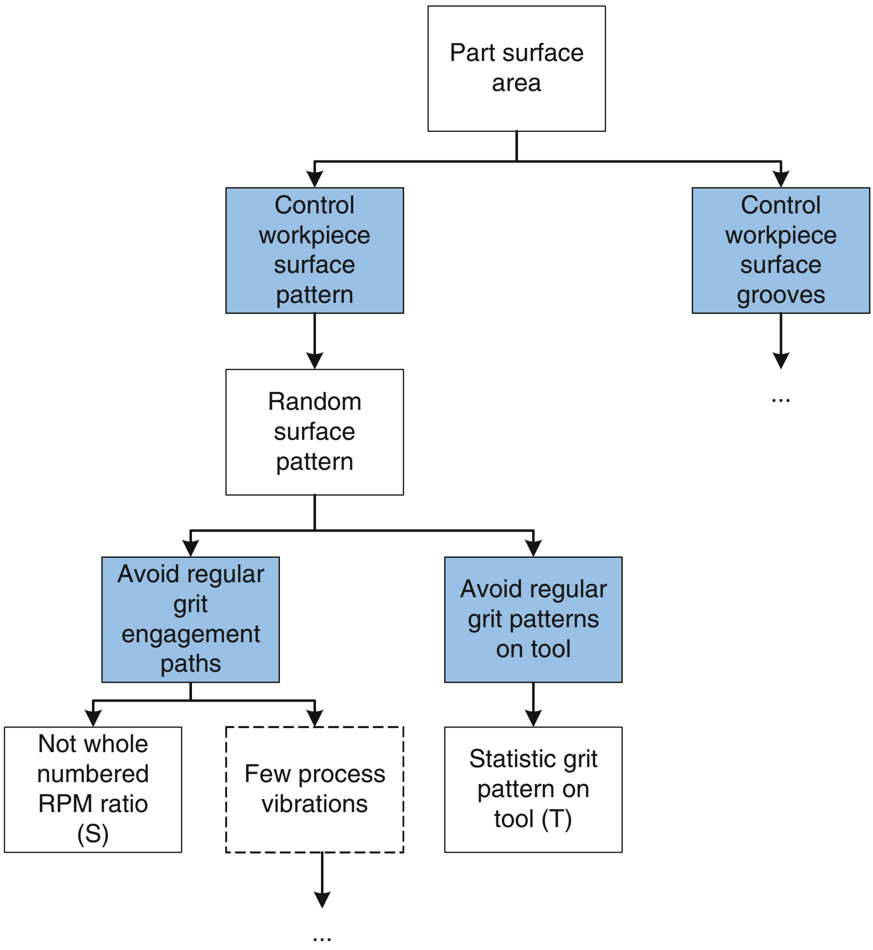

Fig. 7.21 Workpiece surface pattern (diagram follows Fig. 7.11)

The process kinematics defines how the abrasive grits engage the workpiece. Whole numbered RPM ratios and process vibrations lead to repeated surface pattern and should be avoided (Fig. 7.21). The 3D appearance of the surface pattern and its influence on components function offers a lot of potential for studies.

7.3.2.5 Functional Requirement of Controlling Workpiece Surface Grooves

The workpiece surface profile is defined by the generated surface grooves. A small roughness band needs shallow grooves and small chip thicknesses (Figs. 7.22 and 7.19). Shallow grooves can only be generated when both groove bottom shape and wheel deflection are controlled. The groove bottom is shallow for grits with large cutting edge radius and small depth of cut. Bond elasticity defines wheel deflection and groove generation [BORK92].

7.3.2.6 Functional Requirement of Reducing Heat Generation

Process heat is a dominant challenge in grinding technology and affects the part's surface integrity. It is favorable that little heat is generated, existing heat is removed, and chemical reactions are suppressed to reduce the impact on surface integrity (Fig. 7.23).

Control of heat generation includes low heat per single grit interaction, few grit interactions per time, and short interaction time between workpiece and grinding tool. Heat generation per grit is very complex and includes heat generated by rubbing, plowing and cutting during all three phases of grit engagement (Fig. 7.20).

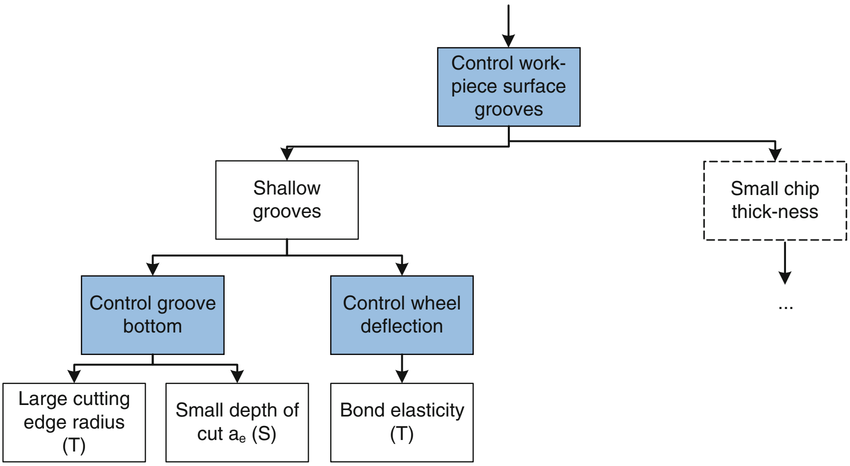

Fig. 7.22 Workpiece surface grooves (diagram follows Fig. 7.21)

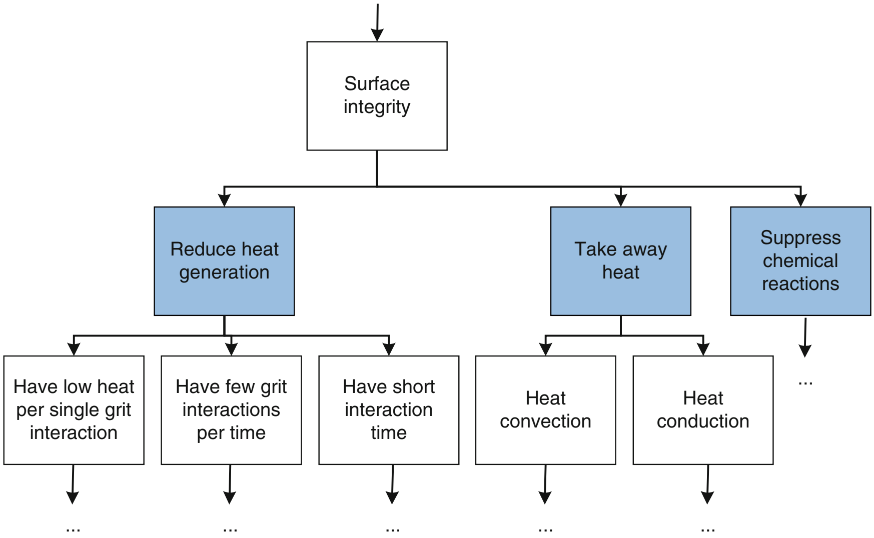

Fig. 7.23 Surface integrity (diagram follows Fig. 7.11)

Although Fig. 7.20 applies for ductile material, brittle material experiences similar chip formation phases, but cracks are induced and expanded in phases II and III and particles will break out rather than chips formed.

Sliding heat can be reduced by lubricants with high lubrication ability, a small contact area in normal direction, and short kinematic contact length, l_k (Fig. 7.24). The kinematic contact length, l_k, evolves from the contact arc and the grit engagement angle (Eq. 7.10). Malkin and Guo propose to obtain the sliding energy by measurements of the grit wear flat area [MALK08].

$$l_k = l_g \cdot \left|1 - \frac{1}{q}\right| \tag{7.10}$$

l_k kinematical contact length
l_g geometrical contact length (Eq. 6.7)
q speed ratio between v_s and v_w, positive for down-grinding, negative for up-grinding

There are only few examinations and models for the heat from plowing [ROWE09]. Contact conditions and shape of grit contact area seem to be most important.

Heat from cutting is produced at different shear zones within the single grit engagement (Fig. 7.20) [TÖNS92]. Shear zones are beneath the grit (c, d), at the grit rake face (b) as well as in the chip formation zone (a). The friction work between chip and tool bond (e) can be reduced by a higher grit protrusion (Fig. 7.25).

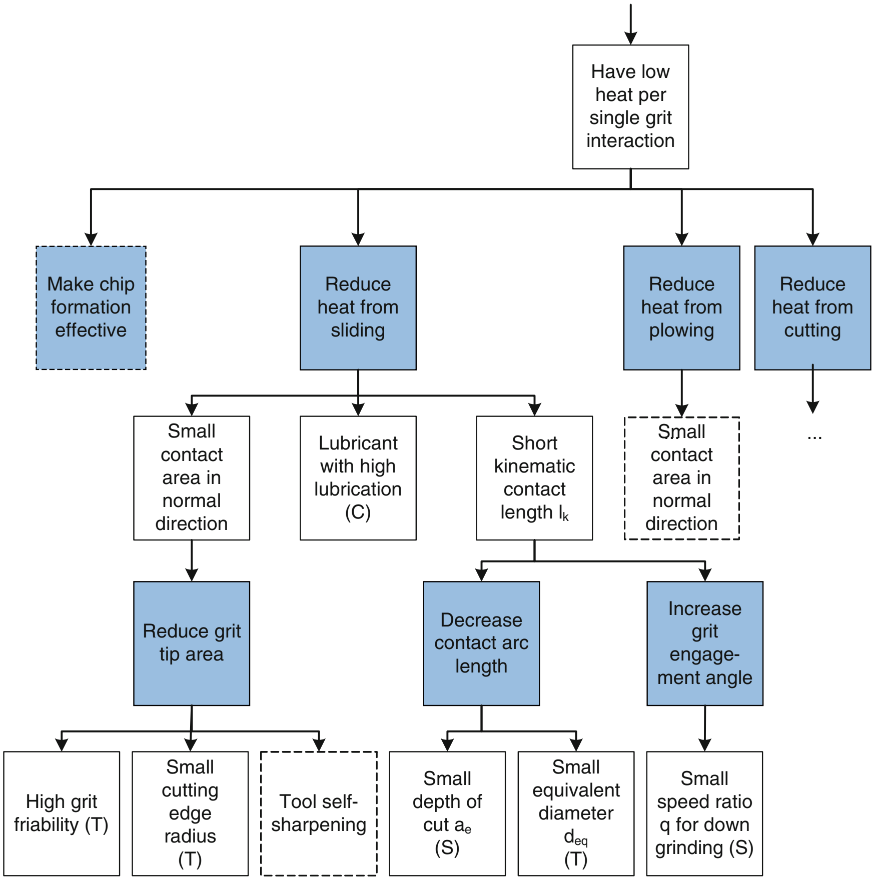

Fig. 7.24 Low heat per single grit interaction—sliding heat (diagram follows Fig. 7.23)

Rowe argues that shear energy at the shear plane (zone a) and at the rake face (zone b) add up to the total energy depending on the shear plane angle [ROWE09, p. 343 f., ROWE79]. A favorable shear plane angle near 45° exists with minimum shear energy. The mechanisms are not modeled. Qualitatively, the favorable shear plane angle has to regard grit shape and friction conditions. Furthermore, shear energy is reduced by a small shear strain rate, i.e. small grinding wheel speed, v_s, and by a small chip cross-sectional area, which can be achieved by a small undeformed chip thickness (Fig. 7.19).

The heat sources at zones b and d can be minimized by changing rake angle respectively clearance angle (Fig. 7.25). These strategies are derived from machining with defined cutting edges and can therefore only be applied if grit shape and orientation on the grinding tool are taken into account [KLOC11]. The heat at zones b, c, and d seem to have minor influence and a sensitivity analysis can indicate their relevance for process heat.

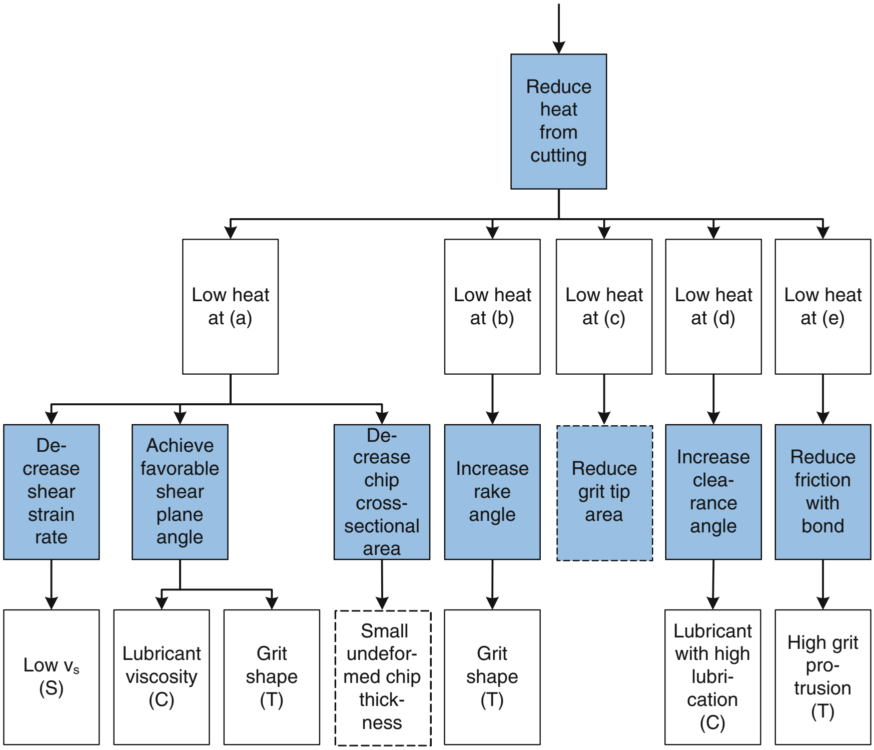

Fig. 7.25 Low heat per single grit interaction—cutting heat (diagram follows Fig. 7.24)

Few grit interactions per time express the second design parameter to serve the requirement of reduced heat generation during grinding (Figs. 7.23 and 7.26). On the one hand, the contact area between workpiece and tool has to be decreased, for example by a small wheel width, b_s (Fig. 7.26) [METZ86, 78]. One example for a small wheel width is the traverse grinding variant "Quick Point Grinding".

On the other hand, the active cutting edge density should be minimal, for example by a low number of kinematic cutting edges. The kinematic cutting edges, N_{kin}, are the only ones from the overall static number of cutting edges, N_{stat}, that are exposed to the workpiece (see Sect. 6.2). Therefore, N_{kin} is influenced by N_{stat}, by process parameters, tool wear and grinding tool deflection (Fig. 7.26).

A short interaction time of workpiece and grinding wheel comes from increased heat source speed, which is the workpiece speed, v_w (Fig. 7.26).

7.3.2.7 Reducing Heat by Convection and Conduction

Heat removal includes all aspects of cooling and lubrication and has been researched a lot [HEIN09b]. The basic principles for heat removal are heat convection

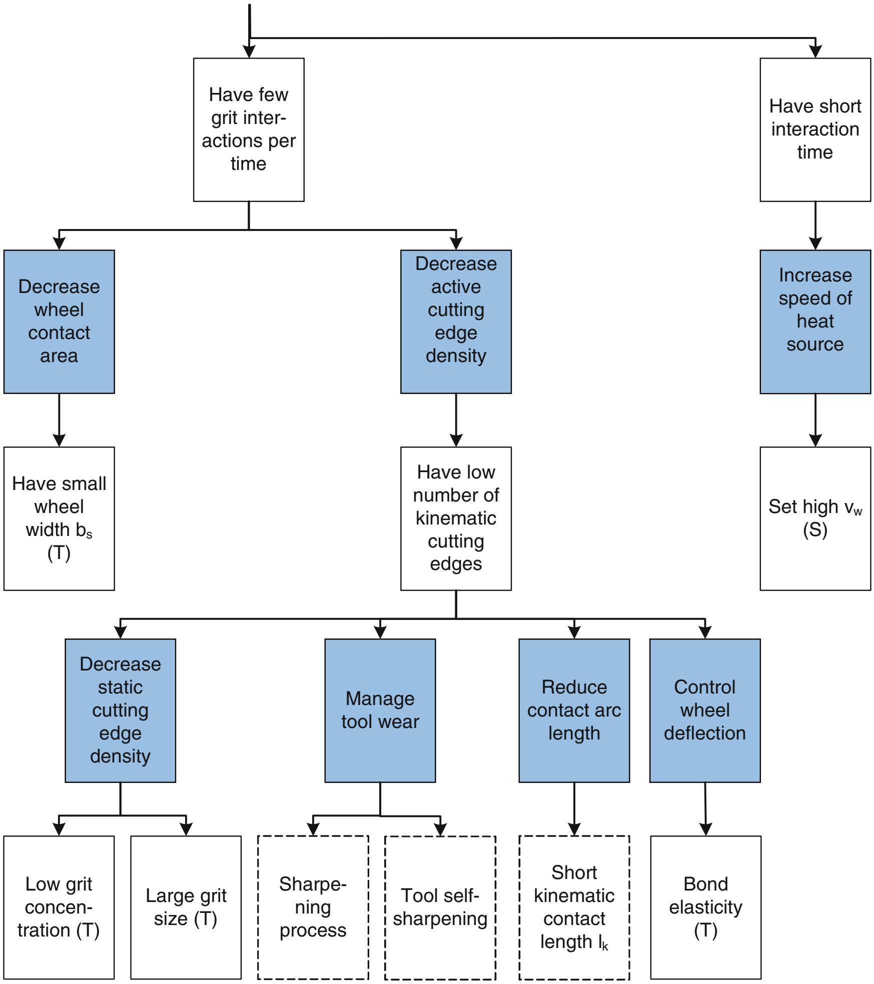

Fig. 7.26 Few interactions per time and short interaction time (diagram follows Fig. 7.23)

and heat conduction (Figs. 7.23, 7.27 and 7.28). It is commonly assumed, that all process energy is converted into the heat flux, q_t, during grinding (Eq. 7.6) [ROWE09, MALK08]. Heat convection takes place into fluids or air, even though convection into air is neglected in many considerations and cooling lubricant is most important for heat convection in grinding. The cooling lubricant must be present in the grinding zone and have a high heat transfer coefficient and high heat capacity (Fig. 7.27).

Equation 7.11 offers one approach to calculate the heat flux into the cooling lubricant, q_{cool} [ROWE09, p. 376]. The temperature before boiling, T_{max}, estimates the maximum energy flow into the fluid. The heat transfer coefficient, h_f, depends

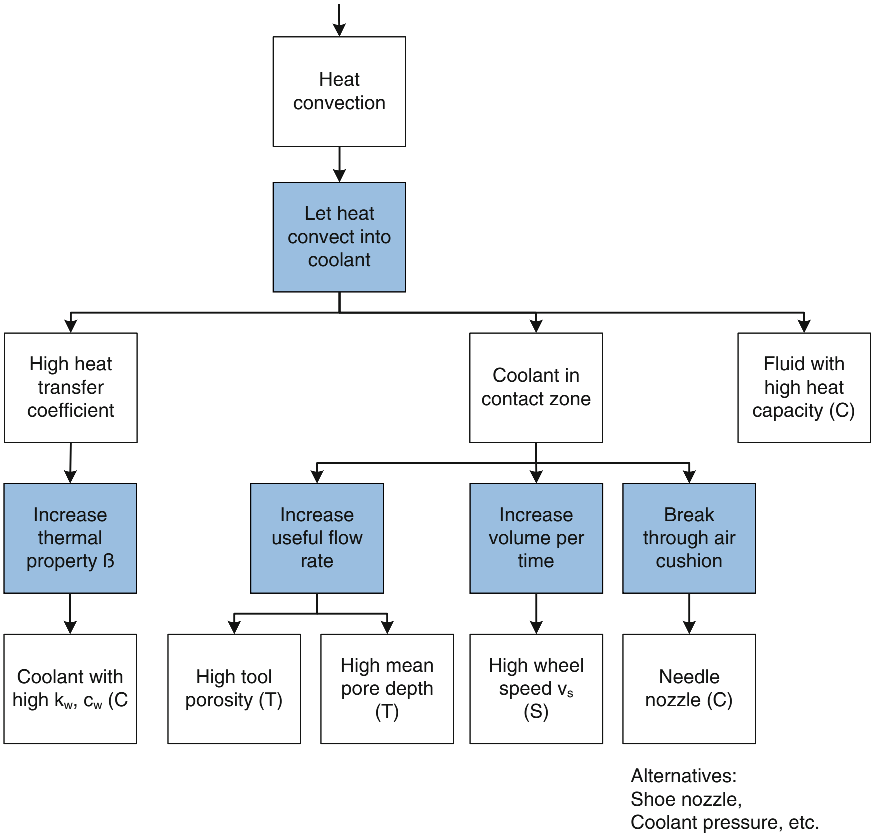

Fig. 7.27 Heat convection (diagram follows Fig. 7.23)

on the thermal properties of the fluid as well as on the contact arc length, l_c (Eqs. 7.12 and 7.13).

$$q_{cool} = \frac{2}{3} \cdot h_f \cdot T_{max} \tag{7.11}$$

$$h_f = \frac{3}{2} \cdot \beta_f \cdot \sqrt{\frac{v_s}{l_c}} \tag{7.12}$$

$$\beta_f = \sqrt{k_f \cdot \rho_f \cdot c_f} \tag{7.13}$$

q_{cool} heat flux into the cooling lubricant
h_f fluid convection coefficient
T_{max} temperature before boiling

β_f fluid thermal property
k_f thermal conductivity
c_f specific heat

Cooling lubricant can be brought into the contact zone by a high useful flow rate and high volume per time (Fig. 7.27). The air cushion around the rotating grinding wheel is particularly important for high grinding wheel speeds and can be broken by several supply systems, such as needle nozzles (Fig. 7.27).

The useful cooling lubricant flow, Q_u, is defined as flow volume through the contact zone of grinding tool and workpiece [MALK08]. Morgan et al. [MORG08] estimated the achievable useful flow rate based on wheel porosity, wheel speed and empirical factors.

$$Q_u = f \cdot h_{pores} \cdot b \cdot v_s \cdot \Phi \quad (7.14)$$

Q_u useful cooling lubricant flow
f factor based on measurement (approximately equal to 0.5)
h_{pores} mean pore depth (roughly equal to mean grit size)
b wheel width
v_s wheel speed
Φ porosity (typically 0.5 for a medium porous wheel)

Heat conduction happens into the grits, grinding wheel, and workpiece material (Eq. 7.6) (Fig. 7.28). Malkin and Guo [MALK08] defined the limit to the shear zone energy which can be carried away by the chips, q_{ch}, as the melting energy. Heat to the grinding wheel, q_{gw}, depends on the grinding wheel properties including grit, bond and structure characteristics. Wheel contact analysis and grain contact analysis are two approaches to estimate the partition ratio for q_{gw} [ROWE09]. Grit and bond conductivity should be high as well as grit coating conductivity (Fig. 7.28). In addition, grit and bond need high heat resistance to avoid damage.

Heat flux into the workpiece material, q_{wp}, is a main challenge for surface integrity, but forms an important transfer process especially for materials with high heat conductivity.

7.3.2.8 Functional Requirement to Suppress Chemical Reactions

Chemical reactions arise from the reactivity between the system components. Therefore, low chemical reactivity between all system components including grits, tool bonding, workpiece material, cooling lubricants and their additives is favored (Fig. 7.29). In addition, low mechanical pressure slows down chemical reactions as does low heat, which has been tackled earlier.

Brinksmeier and Wilke [BRIN04] gave case studies about chemical reactions within grinding technology. There is still big demand for research. The effect of

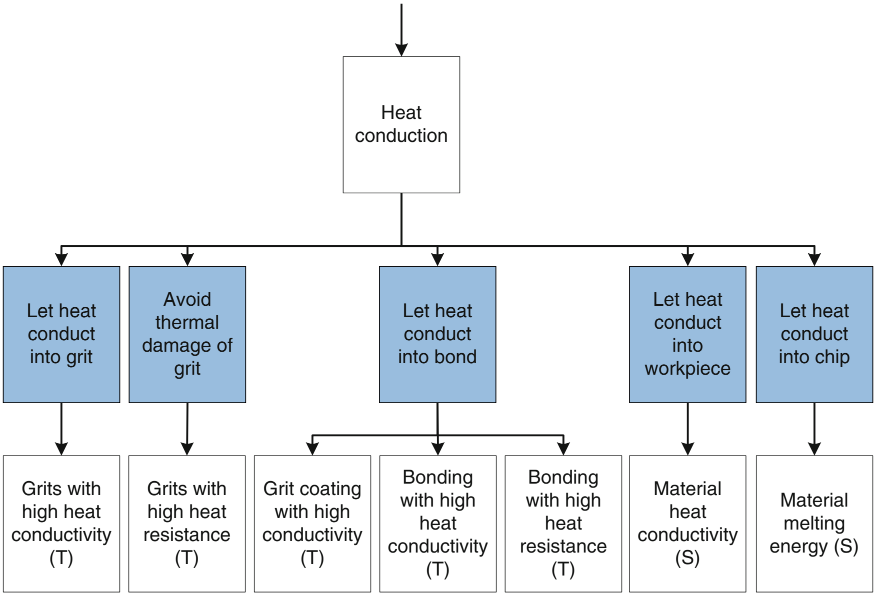

Fig. 7.28 Heat conduction (diagram follows Fig. 7.23)

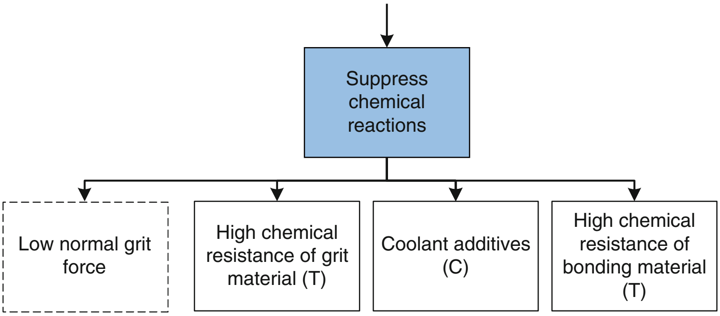

Fig. 7.29 Chemical reactions (diagram follows Fig. 7.23)

contact time between grits and workpiece needs to be discussed in further grinding models.

Depending on the process temperature, the mechanisms of cooling lubricant/part surface interaction change. At low temperatures, physisorption and chemisorption occur resulting in weakly linked sorption layers [BRIN00]. At higher processing temperatures, reactions between additives in the cooling lubricant and the part surface can take place and result in reaction layers on the workpiece [BRIN00].

In chip formation, many side effects overlay, such as heat generation, heat reduction, chemical reactions, mechanical load, and disturbances. Often these side effects are tackled separately, although grinding is a complex superposition of all these physical effects. Mahdi and Zhang [MAHD00] examined, for example, how the temperature gradients, mechanical stresses and phase transformations affect residual stresses in grinding. Duscha et al. [DUSC11] used an FEM-approach to simulate phase transformation during grinding, adding residual stresses resulting from phase transformations. Brinksmeier et al. [BRIN03] investigated the phase transformation of steel during grind-hardening which involves multiple effects on surface integrity. Yet, very few models take the coupled interaction of the effects during chip formation into account [HEIN09b].

7.3.2.9 Functional Requirement of Being Cost-Effective

An important requirement is being cost-effective. For this, the time-dependent costs, scrap rate, tool costs and auxiliary costs need to be low (Fig. 7.30). Time-dependent costs come from the processing time and dressing time (Figs. 7.3, 7.4 and 7.31). Processing time can be reduced by a high material removal rate either by more effective chip formation at given process parameters or increased material removal rate.

Low scrap rate is achieved by monitored and increased process stability and regarding outer disturbances from the environment, in particular heating (Fig. 7.32). HVAC, sunlight, friction in machine tool elements, hydraulics, pumps systems, etc. heat the process from outside. Process vibrations can be reduced by smaller tool vibrations, lower system stiffness, less mechanical impact on the workpiece, and a sharp tool (Fig. 7.32).

Tool costs summarize grinding tool costs and dressing tool costs (Fig. 7.33). Tool wear during the grinding process needs to be minimized as well as the dressing frequency.

Dressing tool wear is induced by thermal and mechanical load (Fig. 7.34). Thermal load can be explained by friction processes and the dressing grit collision

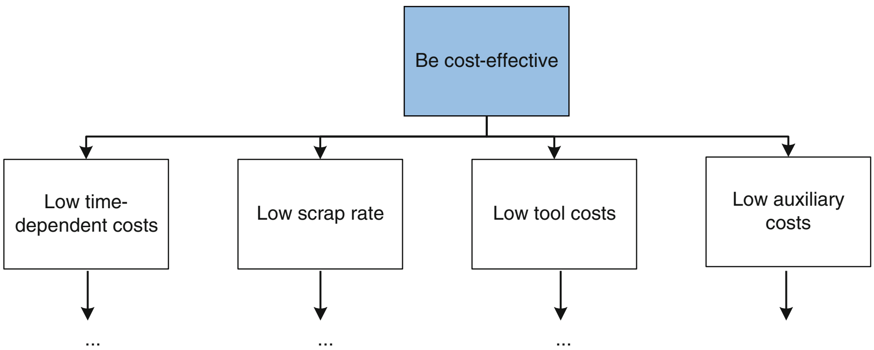

Fig. 7.30 Being cost-effective (diagram follows Fig. 7.11)

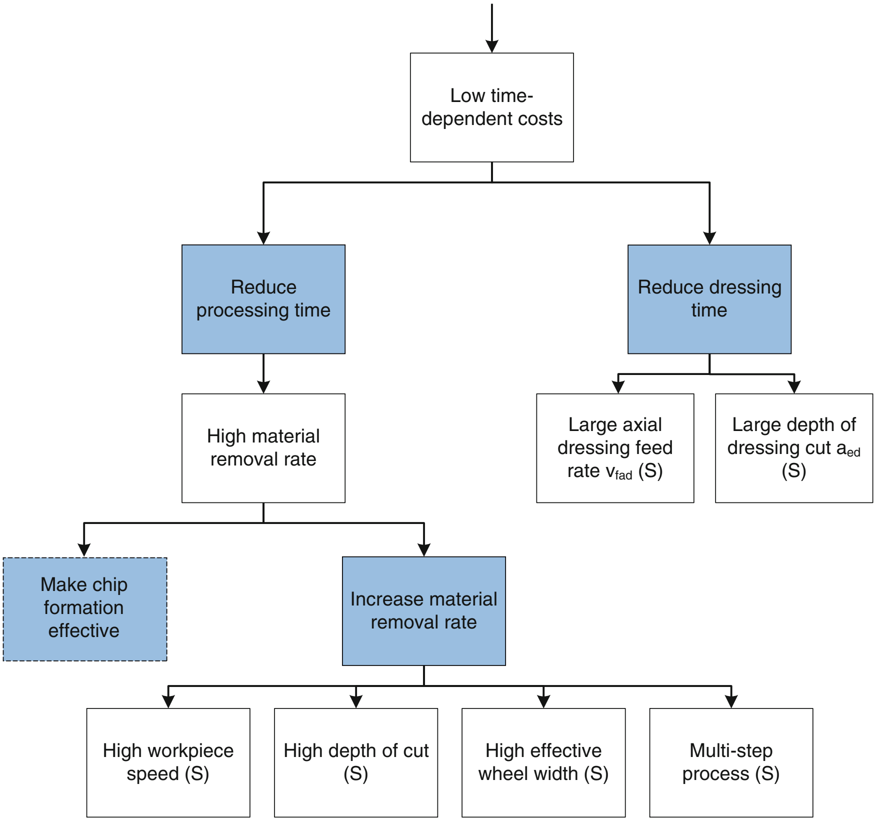

Fig. 7.31 Low time-dependent costs (diagram follows Fig. 7.30)

model [CINA95, LINK07]. Mechanical load arises from the single dressing grit forces, which is modeled through the dressing chip cross section [LINK07]. A dressing tool with higher wear resistance, e.g. by high quality diamond grits or a large diamond volume, withstands wear better (Fig. 7.34).

The most relevant auxiliary costs are the cooling lubricant costs (Fig. 7.35). They are impacted by the filtering system, exchange intervals, additives, maintenance, and cooling lubricant loss when fluid stays on the workpieces and chips.

7.3.3 Matrixes from Axiomatic Model

All discussed effects produce a complex grinding process model. This axiomatic model, however, is simplified and based on existing models. The main application is fine grinding of ductile material, leaving exemptions, special process variants and

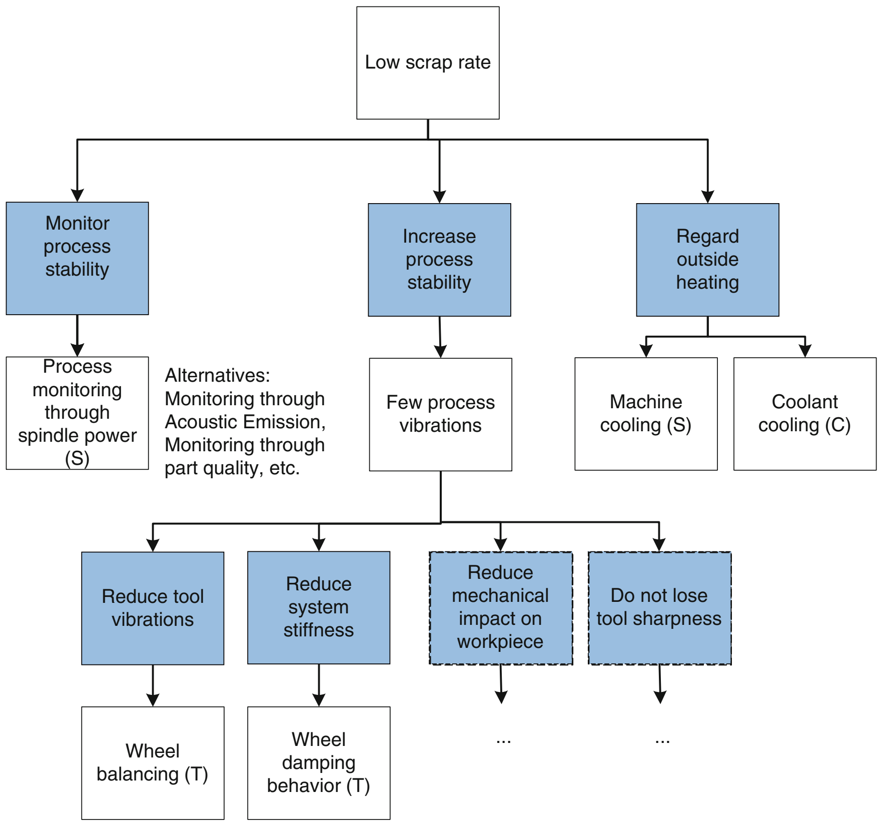

Fig. 7.32 Low scrap rate (diagram follows Fig. 7.30)

other applications open. Experimental data, sensitivity analyses and empirical data could enhance the axiomatic grinding process model a lot.

Relations between the functional requirements and design parameters can now be expressed through matrixes according to Eq. 7.7. Figure 7.36 shows the matrix for tool properties, Fig. 7.37 for the grinding system, and Fig. 7.38 for the cooling lubricant properties. A known interdependence is marked with “x”, an enlarging or positive effect of the parameter on the functional requirement on the left by “+”, a minimizing or negative effect by “−”, and a known bilateral effect by “±”. Equations are given where known and important. The contradictory dependencies would need sensibility analyses to determine the dominant trend.

The matrixes Figs. 7.36, 7.37 and 7.38 are not exhaustive. They do not display linear relationships, but rather general dependencies that have to be put into equations. For example, the functional requirement “Reduce mechanical impact on workpiece” is a function, but not a sum, of grit size, grit concentration, equivalent wheel diameter, wheel speed, workpiece speed, depth of cut (Eq. 7.15), and also grit friability, wheel width, grinding mode, and lubrication ability of the cooling

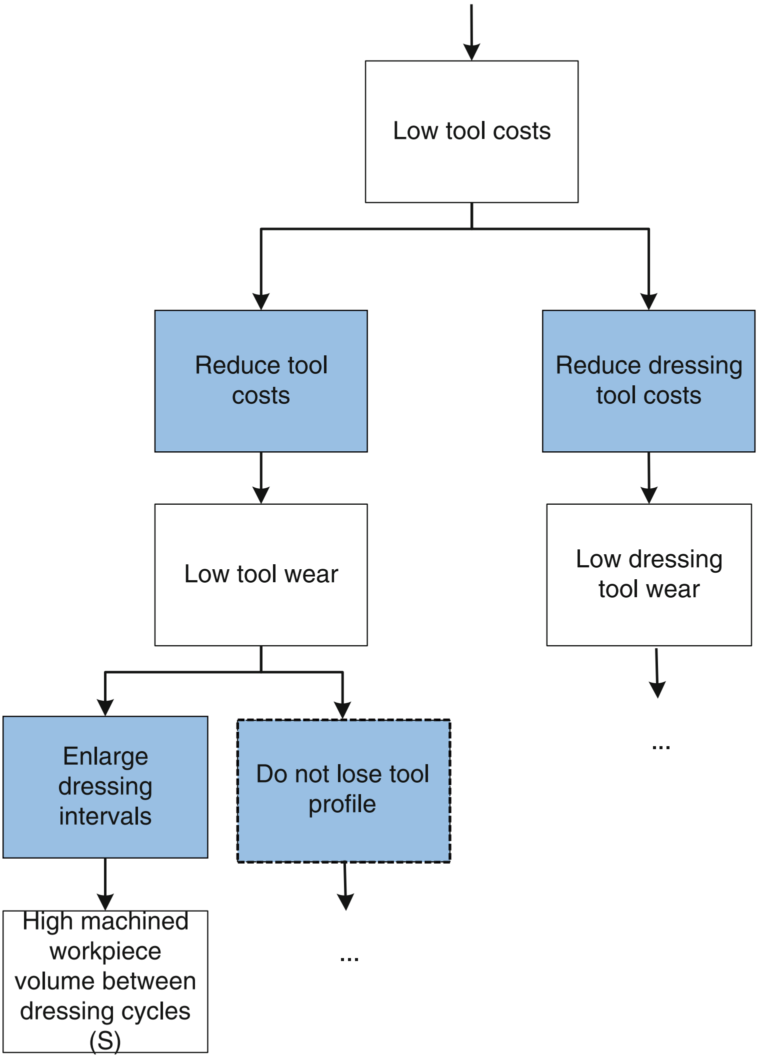

Fig. 7.33 Low tool costs (diagram follows Fig. 7.30)

lubricant. The impact of each of the parameters can be found by sensitivity analyses.

$$\begin{aligned}&\text{Reduce mechanical impact on workpiece}\\&\quad = \mathrm{f}(\text{max. undeformed chip thickness } (7.10),\ \text{grit friability, wheel width,}\\&\qquad \text{grinding mode, lubrication ability of the coolant})\end{aligned} \tag{7.15}$$

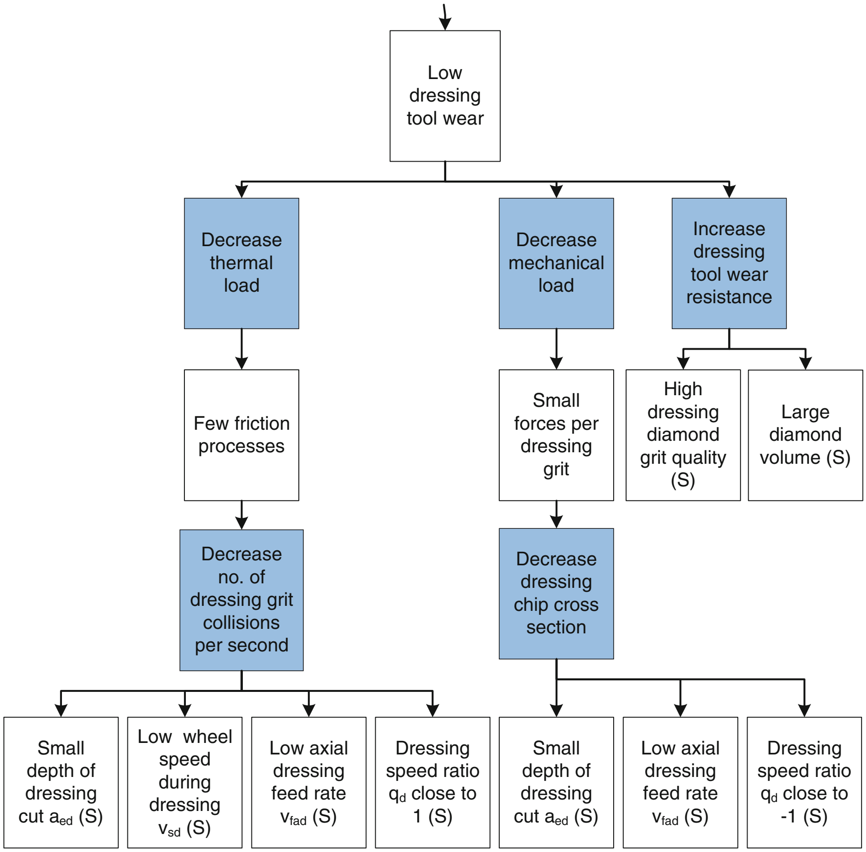

Fig. 7.34 Low dressing tool wear (diagram follows Fig. 7.33)

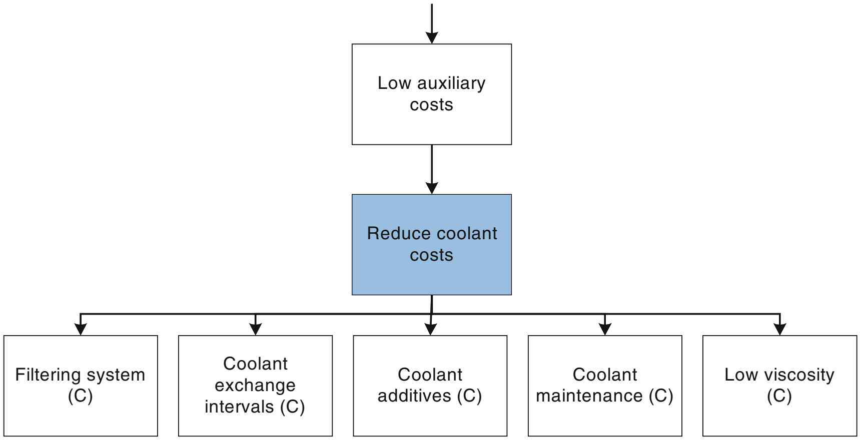

Fig. 7.35 Low auxiliary costs (diagram follows Fig. 7.30)

	Grit properties								Tool properties												Bond properties			
	Grit shape (T)	Grit cutting edge radius (T)	Grit size (T)	Grit heat conductivity (T)	Grit heat resistance (T)	Grit coating heat conductivity (T)	Grit hardness (T)	Grit friability (T)	Chemical resistance of grit materials (T)	Grit concentration (T)	Bond strength (T)	Grit pattern on tool (T)	Wheel porosity (T)	Mean pore depth (T)	Grit protrusion (T)	Eq. wheel diameter (T)	Wheel diameter (T)	Wheel width b_s (T)	Wheel damping behavior (T)	Wheel balancing (T)	Chemical resistance of bonding material (T)	Bond heat resistance (T)	Bond heat conductivity (T)	Bond elasticity (T)
Make chip formation effective			+					+		-	x					-								
Do not lose tool sharpness					+		+	+	+		x													
Transport chips								+			x		+											
Reduce mechanical impact on workpiece			±					x		±	x					± (7-8)		-						
Control workpiece surface grooves		+	-				x			+	x					+ (7-8)								x
Control workpiece surface pattern			±		+		+	x	+	±	x	x				± (7-8)		-	x	x				
Take away heat				+	+	+							+	+								+	+	
Reduce heat generation	x		±					x		±	x				+	± (7-8), + (6-7)		-						x
Suppress chemical reactions			±					x	x	±	x					± (7-8)					x			
Be cost-effective			±		+		+	x	+	±	x					±		±	x	x				

Fig. 7.36 Axiomatic matrix for the grinding tool ("+": enlarging or positive effect, "–": minimizing or negative effect, "±": enlarging and minimizing effects are known, "x": effect with unclear tendency)

	Grinding parameters									Dressing process									others				
	Wheel speed v_s (S)	Multi-step process (S)	Wheel spindle RPM (S)	Workpiece speed v_w (S)	Grinding path (S)	Depth of cut a_e (S)	Speed ratio q (S)	Down grinding mode (S)	RPM ratio (S)	Diamond form roller (S)	Dressing diamond grit quality (S)	Diamond volume (S)	Wheel speed during dressing v_{sd} (S)	Axial dressing feed rate vf_{ad} (S)	Dressing speed ratio q_d (S)	Depth of dressing cut a_{ed} (S)	Mach. wpvolume btw dressing cycles (S)	Continuous dressing	Mechanical clamping (S)	Material heat conductivity (S)	Material melting energy (S)	Machine cooling (S)	Process monitoring through spindle power (S)
Make chip formation effective	-			+		+		+		x				x	x	x	x	x					
Do not lose tool sharpness																		x					
Transport chips										x				x	x	x	x						
Reduce mechanical impact on workpiece	± (7-8)			± (7-8)		± (7-8)		+		x				x	x	x	x						
Control workpiece surface grooves	+ (7-8)			- (7-8)		- (7-8)				x				x	x	x	x						
Control workpiece surface pattern	± (7-8)			± (7-8)		± (7-8)		+	x														
Take away heat	+																			+	+		
Reduce heat generation	± (i.a. 7-8)			± (i.a.7-8)		± (7-8), - (6-7)	x	+		x				x	x		x						
Suppress chemical reactions	± (7-8)			± (7-8)		± (7-8)		+															
Be cost-effective	±	x		±		±		+		x	±	+	-	x	x	x	x	x				x	x

Fig. 7.37 Axiomatic matrix for the grinding system ("+": enlarging or positive effect, "–": minimizing or negative effect, "±": enlarging and minimizing effects are known, "x": effect with unclear tendency)

	Cooling lubricant properties							Cooling lubricant supply				
	Lubrication ability (C)	Lubricant viscosity (C)	Degeneration stability (C)	Coolant properties k_w, c_w (C)	Haet capacity (C)	Cooling lubricant and additives (C)	Maintenance (C)	Needle nozzle (C)	Cleaning nozzle (C)	Coolant cooling (C)	Filtering system (C)	Coolant exchange intervals (C)
Make chip formation effective	-											
Do not lose tool sharpness												
Transport chips									+			
Reduce mechanical impact on workpiece	-											
Control workpiece surface grooves												
Control workpiece surface pattern	-											
Take away heat				+				x				
Reduce heat generation	±											
Suppress chemical reactions	-					x						
Be cost-effective	-	-				x	x			x	x	-

Fig. 7.38 Axiomatic matrix for the cooling lubricant ("+": enlarging or positive effect, "–": minimizing or negative effect, "±": enlarging and minimizing effects are known, "x": effect with unclear tendency)

The matrix can be helpful in clarifying how the system components and parameters in grinding are intertwined [LINK12c]. The functional requirements that are related most to process sustainability can be discussed with the matrix.

Sustainability needs to consider the four dimensions of technology, economics, environment, and society. Specific sustainability indicators cover these dimensions, depending on the framework and user. Figure 7.39 lists the most useful indicators for common grinding processes [LINK13]. These indicators are connected to functional requirements of the axiomatic grinding process model from Figs. 7.36, 7.37 and 7.38.

The matrixes Figs. 7.36, 7.37 and 7.38 highlight where research is needed on better process understanding and quantitive equations for grinding.

7.3.4 Case Study on Grit Size Choice

Grit size and grit size distribution affects tool manufacturing and tool use (see Sect. 2.8.1 "Grit Size"). Therefore, these grit characteristics provide a good case study on sustainability [LINK12c]. Grit size can be controlled by different standardized methods, such as sieving and sedimentation (Sect. 2.9.1 "Grit Size Selection"). The user might want to consider the three conventional pillars of sustainability plus the technological pillar. The costs of tool making is not included.

Figure 7.39 suggests looking into productivity and process stability for economic sustainability, which is affected by the functional requirements "Make chip formation effective" and "Be cost-effective". Figure 7.36 shows that grit size has a positive effect on the effective chip removal and on high material removal rate, but grit size has a bipolar effect on cost-efficiency. The undeformed chip thickness increases with grit size (Eq. 7.8), leading to a more effective chip formation with an earlier cutting phase and shorter phases of rubbing and plowing (Fig. 7.20). The grit forces however increase with chip thickness leading to higher mechanical load, a less stable process, and higher scrap rate and costs (Fig. 7.32). These mechanisms are contrasting, but the more effective chip formation is mostly dominating so that economic sustainability is basically improved with bigger grits.

Environmental sustainability can be evaluated through energy intensity for example (Fig. 7.39). Bigger grits at constant grit concentration make chip formation more effective, i.e. less plowing and rubbing happens and chip formation consumes less processing energy per material volume removed.

Social sustainability is connected to labor intensity and therefore processing time (Fig. 7.39). A high material removal and effective chip formation coming from bigger grits as discussed both reduce processing time, hence improving social sustainability.

Technological sustainability includes surface integrity and roughness, which are affected by heat, chemical reactions, and grinding grooves. Bigger grit sizes have a mainly reducing effect on heat generated, although the inner material shearing at large chip thicknesses increases heat generated. Low process heat has a positive

	Indicators	Acquainted functional requirements
Technological sustainability	• Product quality, e.g. surface structure, surface integrity, and • Product performance and lifetime	Suppress chemical reactions Reduce mechanical impact on workpiece Control workpiece surface grooves Control workpiece surface pattern Take away heat Reduce heat generation Do not loose tool sharpness …
Economic sustainability	• Grinding costs, • Productivity, • Process stability and capability.	Make chip formation effective Be cost-effective …
Environmental sustainability	• Energy intensity, • Residuals intensity, • Intensity of pollutant releases to air.	Suppress chemical reactions Do not lose tool profile Reduce heat generation Make chip formation effective …
Social sustainability	• Labor intensity, • Worker noise level, • Hours of training and education per operator.	Reduce processing time …

Fig. 7.39 Useful sustainability indicators for grinding technology and acquainted functional requirements [after LINK13]

influence on surface integrity. However, big grits lower the surface quality due to the larger undeformed chip thickness. A high distribution of grit sizes might result in a surface profile with large variation of depth and low predictability due to outlier grits [LINK12c]. The technological sustainability is therefore affected controversially by grit size. The negative effect on surface roughness is often dominating over the positive impacts on the other three pillars of sustainability, leading the user to choose small grit sizes after all.

This case study showed how the axiomatic matrixes on grinding tool user highlight qualitative knowledge on grinding process functions and help to compare sustainability of different scenarios [LINK12c]. Quantitative equations would allow to calculate the benefits and impacts of the grinding system components.