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Chapter

Optimization of Industrial Grinding Processes Using the Theory of Aggressiveness: Case Studies from Real-World Manufacturing

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Abstract

In the first 60 years of grinding research (1914–1974), various dimensionless parameters were introduced to account for the fundamental mechanics of an abrasive contact. Later, these parameters were superseded by various chip-thickness models, which required the difficult and often ambiguous quantification of grinding-wheel topography. The first-principles approach has recently re-emerged via the grand-unifying Theory of Aggressiveness and the practical aggressiveness number, a dimensionless parameter that has proved to be powerful in optimizing any arbitrary abrasive process, including grinding and truing/dressing. It has now gained wider popularity and use because of its ability to capture the fundamental process geometry and kinematics while circumventing the need to quantify the wheel topography. This paper reviews the use of the dimensionless aggressiveness number in several case studies from real production, demonstrating how the concept can be used to optimize industrial processes, including camshaft and crankshaft grinding, saw-tip grinding, flute grinding, double-disc grinding, and diamond-wheel truing.

Keywords: grinding, modeling, geometry, kinematics, optimization

1. Introduction

Of all metal-cutting processes, machining with abrasives seems to remain the least understood. This perception has been present since at least the 1950s, when investigations of the fundamental process mechanics began to be published. In words of L. P. Tarasov, "grinding is such a complex process to analyze mathematically" [1]. Seventy years later, new grinding models are continuously being published. These are often either (i) incremental in advancing the process understanding or (ii) overly complex, for example, by integrating macro-scale quantities (e.g., kinematics) with micro-scale properties (e.g., number of dynamic cutting points on the wheel) without careful consideration of the benefits of such an approach in real-world manufacturing. Early advances in grinding technology were primarily achieved by practical experiments alone, whereas nowadays, experiments are often combined with some sort of modeling. Consequently, advances in our understanding of first principles consist of a deeper knowledge of why a certain phenomenon arises, which can be applied to many applications. Research in which only new experimental data are produced – for example, the effect of truing-wheel direction on the efficiency of diamond-wheel truing – is indeed an advance in technology and is of value to industrial end-users, but it does not lead to a better process understanding with respect to first principles. However, if a new insight into the truing mechanics (such as in [2]) is revealed, the research of this type is more generic and can be applied to other wheel-conditioning applications. In other words, research that not only presents experimental results but can also explain these results from fundamental engineering principles is more useful than experimental results alone.

In this regard, classical grinding research is first discussed with respect to its use of fundamental grinding models. These are then put into the context of the recently developed Theory of Aggressiveness [3], which accounts for the fundamental process mechanics (e.g., specific energy, shear) and its dependence on all-inclusive parameters of process geometry and kinematics.

The early analytical models to describe process geometry and kinematics and the resulting undeformed chip thickness were reviewed by Reichenbach et al. [4]. Studies of wheel topography and its parameters to a large extent originate in Germany [5–7]. For these models, wheel topography needs to be measured and quantified, including static and dynamic cutting-edge spacing or density. The cutting-point density is a key parameter in the calculation of the maximum undeformed chip thickness. Even though it was introduced decades ago [8], it still has limited use in optimizing grinding operations in industry as practitioners in the field do not have readily available methods to quantify wheel topography. Nevertheless, the wheel topography is fundamentally interrelated with process geometry and kinematics in grinding [7, 9, 10], which happens to be a dimensionless quantity equivalent to the aggressiveness number promoted by the authors of this work. The aggressiveness number is proportional to chip thickness but avoids the problems associated with quantifying the wheel topography. Moreover, the aggressiveness number has been shown to better correlate to grinding data such as grinding forces, specific energy, and surface roughness in comparison to equivalent chip thickness introduced in 1974. It is therefore important to clarify how this fundamental relationship of quantifying the interaction of two surfaces in abrasive contact can be used to advance process understanding and, at the same time, optimize an abrasive process. The Theory of Aggressiveness is based on first-principles mechanics and is, as such, not process-specific. Therefore, it can be used to improve any abrasive operation, from complex grinding processes to truing/dressing of grinding wheels.

2. Evolution of grinding theories

Early grinding models were derived from metal-cutting theories, such as Merchant's force diagram [11]. For example, Merchant himself, with Backer, proposed a force system acting on an abrasive grit where the radial and tangential forces are in equilibrium with the normal and frictional forces [1]. In contrast to orthogonal cutting, however, the grit geometry in grinding is geometrically undefined. Hence, the effective rake angle on the tool is not known. Therefore, Backer and Merchant [1] attributed the fundamental process mechanics to the specific energy and the ratio of radial to tangential force. Another distinctive characteristic of a grinding process in comparison to metal cutting refers to the magnitude of shearing process and the increase in specific energy with decrease in undeformed chip thickness. The specific energy is a fundamental process parameter, defined as the energy required to remove a unit volume of material [12]. It was first reported in the same volume of Transactions of ASME in 1952 as "The Size Effect in Metal Cutting" [8]. The elaboration of the specific-energy law was purely experimental, based on surface-grinding trials. Here, a dynamometer was fitted to a surface grinder to measure the tangential-force F_t and normal-force F_n components for four different types of grinding wheels. The force components were measured while varying the wheel depth of cut a, the workpiece speed v_w, the wheel speed v_s, and the grinding width b. Based on the observed grinding-force data, the following expression for specific energy was established:

$$u = \frac{F_t \cdot v_s}{v_w \cdot a \cdot b} = \frac{P}{Q_w} \tag{1}$$

where the numerator is the grinding power P, and the denominator the volumetric material removal rate Q_w. The elegance of specific energy lies in its simplicity: not only can it be easily derived from the power (or force) measurements and grinding conditions, but it can also be associated with the three distinct abrasive mechanisms of rubbing, plowing, and cutting (shearing) – and hence the efficiency of material removal.

The 1952 work of Backer et al. [8] further defines the geometric relationship for the (wheel-workpiece) contact length:

$$l_c = \sqrt{a \cdot d_e} \tag{2}$$

where d_e is the equivalent wheel diameter calculated as $d_e = d_w \cdot d_s/(d_w \pm d_s) = d_s/(1 \pm d_s/d_w)$. Here the plus sign in the denominator is for outside diameter (OD) grinding, the minus sign for internal diameter (ID) grinding, and $d_e = d_s$ for straight (surface) grinding (as $d_w \to \infty$). Note that for practical use, there is no need to distinguish between the contact length l_c and the cutting-path length l_k as the difference is extremely small for typical workpiece v_w and wheel v_s speeds. The other fundamental parameter from [8] is the derivation of maximum undeformed chip thickness, or the "grit depth of cut". The difficulty here is the need to determine the two wheel-topography parameters: (i) the number of cutting points per unit area, C; and (ii) the ratio of width-to-thickness of undeformed chip (or chip-shape ratio), r. With these, the maximum undeformed chip thickness was defined as:

$$h_m = \sqrt{\frac{4}{C \cdot r}\left(\frac{v_w}{v_s}\right)\sqrt{\frac{a}{d_e}}} \tag{3}$$

The role of chip thickness in grinding was originally investigated in 1914 [13] by George I. Alden of Worcester Polytechnic Institute. Alden co-founded the Norton Company. This work can likely be considered the first grinding-modeling paper. Alden derived a mathematical relationship for the "grit depth of cut" or chip thickness as a function of the grinding conditions for the case of cylindrical OD grinding. His model translates to maximum undeformed chip thickness as $h_m = (2/n)(v_w/v_s)\sqrt{a/d_e}$ using established symbols (as per [10]), where n is the number of cutting points per unit length of circumference. Note that the inverse of n corresponds to the cutting-point spacing L, which is a more established wheel-topography parameter.

Such formulation of $h_m = 2L(v_w/v_s)\sqrt{a/d_e}$ was adopted in 1943 in Germany by Pahlitzsch [14]. One can observe that Alden's model includes a wheel-topography quantity $n = 1/L$, next to the dimensionless value of $(v_w/v_s)\sqrt{a/d_e}$. This perhaps planted the early seed of overlooking the role of dimensionless numbers in grinding research and adding to the complexity of process understanding as Alden did not propose any convenient method of determining n. Later in Germany, researchers such as Peklenik adopted the h_m model (Eq. (3) [8]) and identified the importance and the role of geometrical (l_c, a) and kinematical (v_w, v_s) parameters/ratios on process mechanics [5]. While the dimensionless parameter accounting for the process geometry and kinematics $(v_w/v_s)\sqrt{a/d_e}$ was called "Spandickenkoefficient", or chip-thickness coefficient by Werner [15], the early topography models used in the calculations of chip thickness usually included the spacing L, which was termed "Kornabstand" in German [16]. The focus, however, was on incrementally upgrading the wheel topography models with empirical constants – for example, to account for the non-uniform wheel topography. In this regard, Peklenik postulated that the cutting points are not equally spaced (i.e., $L \neq$ const.) and do not protrude uniformly. This leads to topography-dependent grit depth of cut (undeformed chip thickness). In addition to the wheel topography, the number of active cutting points also depends on grinding conditions. The effect of the radial distribution of active cutting points (grit protrusion) on undeformed chip thickness was studied in detail by Kassen [6]. In his doctoral dissertation, he integrated the analysis of the "static" cutting-point density as determined from direct measurements of the wheel topography and the "dynamic" cutting-point density, C_{dyn}, depending on process geometry and kinematics. To prove this further, Tigerström and Svahn [9] developed a measurement method to correlate the C_{dyn} against $(v_w/v_s)\sqrt{a/d_e}$ which proved that the number of active cutting points not only increases, but uniquely depends on this dimensionless number. In this respect, one would expect that researchers would subsequently analyze their grinding results against fundamental dimensionless values to capture the process geometry and kinematics and only extend analysis to undeformed chip thickness when necessary, such as for modeling and prediction of surface roughness. This was not the case, and the concerned dimensionless expression was only sporadically featured in grinding models, sometimes not given a specific name as in [17], when charting C versus $10^6(v_w/v_s)\sqrt{a/d_e}$ for coarsely and finely dressed grinding wheels. At about the same time, Tigerström and Svahn charted C_{dyn} (and the average cross-sectional area of chip A) over a nondimensional quantity termed $\tan\varepsilon$ [9]. The authors derived $\tan\varepsilon$ for geometry and kinematics of various grinding operations, such as OD and ID, and for both up-grinding and down-grinding operations. The angle ε was originally adopted from Werner's 1971 PhD thesis, where it was termed "Schneidenversatz-Grenzwinkels" [7]. Finally, Malkin adopted this quantity and called it the infeed angle ε (of material flow relative to a cutting point on the wheel periphery) [10]. The maximum value of the infeed angle is [7]:

$$\tan\ \varepsilon_{max} = 2\left(\frac{v_w}{v_s}\right)\sqrt{\frac{a}{d_e}} \tag{4}$$

but as ε is an extremely small angle, its average value $\overline{\varepsilon}$ halfway, the contact length equals $\tan\overline{\varepsilon} = (v_w/v_s)\sqrt{a/d_e}$ [10]. It was not until 2008 that this dimensionless quantity was given a new name – the aggressiveness number, $Aggr$, introduced as [18]:

$$Aggr = 10^6 \left(\frac{v_w}{v_s}\right) \sqrt{\frac{a}{d_e}} \tag{5}$$

Here, a scaling constant of 10^6 was used to obtain more graspable numbers, just like in [17]. *Aggr* is constructed as ratios of kinematical (v_w/v_s) and geometrical (a/d_e) quantities having the same dimension. When Badger coined the term *Aggr*, his goal was practical: to circumvent the necessity to measure or adopt topography parameters (i.e., C and r). It was not until 2020, however, that the *Aggr* was derived from the first-principles kinematics of an arbitrary abrasive interaction (see Section 3 for more details).

What is surprising, however, is that in 1974, the "dimensionless" quantity $(v_w/v_s)\sqrt{a/d_e}$ was superseded by a "dimensional" parameter, called the equivalent chip thickness, by Snoeys et al. [19]:

$$h_{eq} = v_w \cdot a/v_s = Q'_w/v_s \tag{6}$$

The motivation for introducing h_{eq} was to circumvent the need of quantifying the wheel topography and to reduce the experimental effort. Another reason perhaps refers to the empirical legacy of grinding research that "requires" a dimensional value, despite its limited value to solve fundamental aspects of the process. The h_{eq} can be interpreted as the "thickness of a continuous layer of material" (chip) being removed at a specific material removal rate Q'_w and wheel speed v_s [10]. Here, h_{eq}, has nothing to do with a real chip thickness (e.g., measuring 0.7 μm); hence, this quantity should not be confused with the maximum undeformed chip thickness hm. Nevertheless, the equivalent chip thickness was "institutionalized" by the International Academy for Production Research (CIRP) in 1974 [19]. Its origins, however, can be traced to Kurrein in 1927, who termed this parameter in German as "Momentan-Spanquerschnitt", $Q_{mom,ges} = (v_w/v_s) \cdot a \cdot b$ [20], which translates to instantaneous chip cross-section (measured in mm^2). Interestingly, Werner, who a year earlier charted grinding forces and surface roughness [15] over a dimensionless "chip-thickness coefficient" (i.e., *Aggr*), charts the same grinding results over "bezogenen momentanen Gesamtspannungsquerschnitt" in his 1971 PhD thesis, $Q'_{mom,ges} = (v_w/v_s) \cdot a$ (measured in mm^2/mm) [7], which equals h_{eq}. Nevertheless, Werner's charting of the grinding forces and surface roughness values over h_{eq} instead of *Aggr* did not improve the obtained correlation. This is further illustrated in **Figure 1**, based on the data by Opitz and Gühring [21].

Here we can compare the parameters of equivalent chip thickness (**Figure 1a**) and aggressiveness number (**Figure 1b**). The *Aggr*, with a correlation value of 0.99, is clearly the most accurate. This result is in fact quite remarkable considering the large spread typically associated with measuring surface roughness. This is because the equivalent chip thickness does not consider the contact length (or equivalent diameter) and hence incompletely accounts for the process geometry and does not enable unambiguous comparison of different grinding operations (e.g., OD and ID). This observation is in direct contradiction with the statement of Snoeys et al. [19] that "using the basic parameter of h_{eq}, grinding data may be represented in a much more concise form and the influence of some working conditions may be readily extrapolated from this kind of representation". Now, to put this into a more general perspective, consider Newton's second law from classical mechanics. Here, if one is to fundamentally describe the changes that a force does to the motion of a body, one

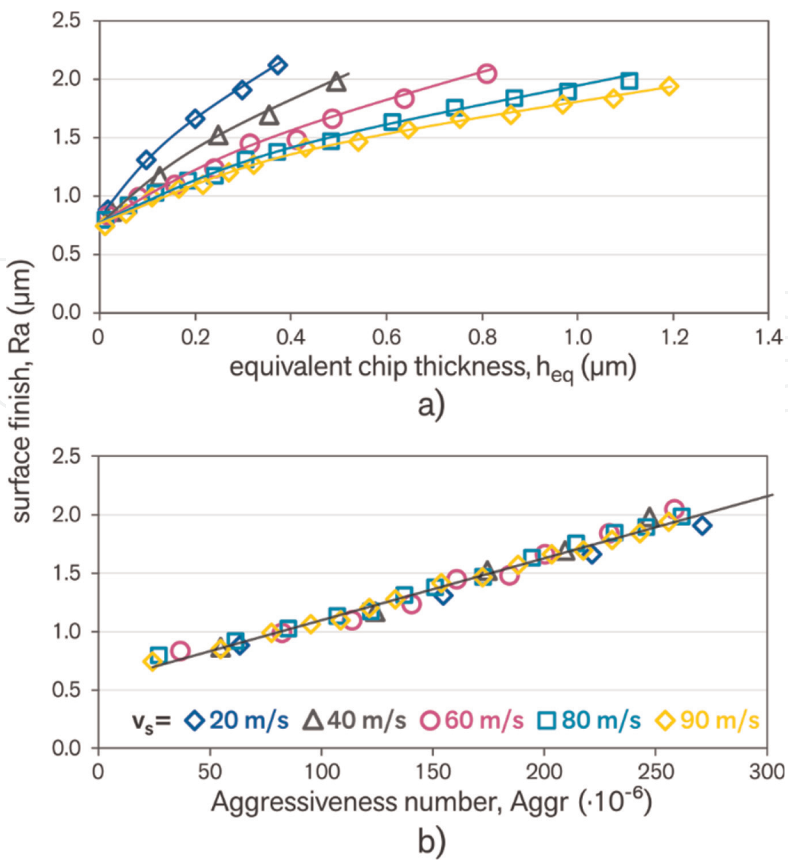

Figure 1.
Surface finish versus (a) equivalent chip thickness and (b) aggressiveness number (data from [21]).

needs to establish a relationship between the acceleration of an object a and its mass m. If a body has a force F acting on it, it is accelerated in accordance with the equation $F = m \cdot a$. Therefore, to chart Newton's laws of motion – it only makes more sense to chart F vs. a. In case of charting F vs. velocity v instead, one would get several lines instead of one (definite) fundamental line. This is an analogous case, if one is to chart Ra over h_{eq}, instead of $Aggr$.

The introduction of equivalent chip thickness in 1974 led to empirical "curve-fitting", such as $Ra = R_1 h_{eq}{}^r$ and $Q'_w = Q_1 h_{eq}{}^q$ [19]. Based on this paradigm, a large number of empirical models were reduced to "basic models" [22], such as for:

Maximum undeformed chip thickness:

$$h_m = C_s \left(\frac{v_w}{v_s}\right)^{e_1} (a)^{\frac{e_1}{2}} \left(\frac{1}{d_e}\right)^{\frac{e_1}{2}} \tag{7}$$

Surface roughness:

$$R_t = C_s C_w \left(\frac{v_w}{v_s}\right)^{e_1} (a)^{e_2} \left(\frac{1}{d_e}\right)^{-e_3} \tag{8}$$

where C_s is a constant for a given grinding wheel, C_w is a constant for a given workpiece, and e_1–e_3 are exponents which need to be determined experimentally for a given wheel-workpiece combination. The practical application of such empirical models is of course time-consuming. Moreover, the identification and quantifying of

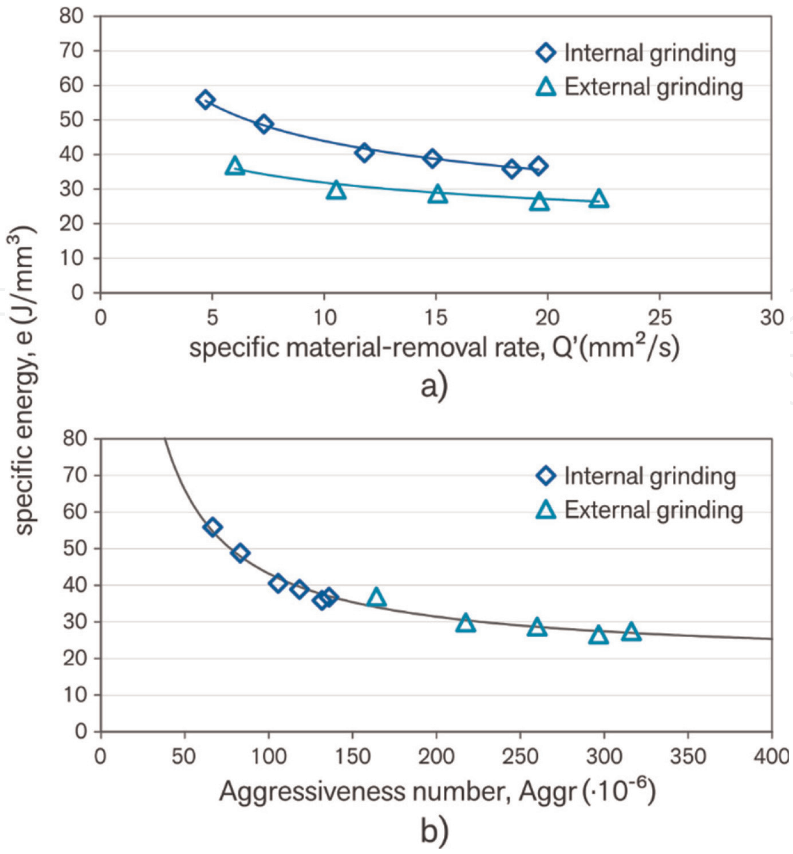

Figure 2.
Specific energy in inner-diameter and outer-diameter grinding versus (a) specific material-removal rate and (b) aggressiveness number [24].

empirical distributions by fitting an approximately straight-line on a grinding chart (often on a logarithmic scale) [19] is nowadays obsolete. While recognizing that such grinding charts were once necessary and practical, they are by no means suitable for exploring the underlying process mechanics. In analyses of grinding results, for example, the distribution of specific energy over Q'_w appears to follow a power-law. But upon a more careful analysis [23], it proves impossible to make a strong case for the fundamental correlation; here, the power-law distribution is not ruled out, but a competing distribution over *Aggr* offers a better fit to the data, as illustrated by comparison of **Figure 2a** and **b**.

3. The theory of aggressiveness

During the last 30 years, several fundamental analytical problems have emerged in grinding research, which require new modeling approaches. Based on the above, it seems reasonable to revisit the role of *Aggr* as this dimensionless quantity has been featured in almost all analytical models since 1914 [13] as well as in empirical "basic" models [22]. Grinding research once more reached a point where dimensional parameters such as h_{eq} are not the most appropriate, and dimensionless values can provide a better insight into fundamental process mechanics. The empirical legacy of grinding research, especially in Germany, may regard dimensionless approaches as too abstract or generalized, especially when the majority of grinding models were developed for a specific grinding operation (e.g., cylindrical OD grinding [13]).

The Theory of Aggressiveness [3] reduces to the assertion that any abrasive process (tool-workpiece contact) can be expressed in dimensionless form. We further claim that only if it is so expressed can the fundamental process mechanics be solved. The fundamental definition of aggressiveness is the ratio of the normal component v_n and the tangential component v_t of the relative-velocity vector [3]:

$$Aggr^* = \frac{v_n}{v_t} = \frac{\vec{v} \cdot \vec{n}}{\sqrt{\vec{v} \cdot \vec{v} - \left(\vec{v} \cdot \vec{n}\right)^2}} \tag{9}$$

This fundamental parameter of the abrasive interaction is termed point-aggressiveness $Aggr^*$. It captures the essential process geometry by describing the surface of the abrasive tool by the vector field of surface normal $\vec{n}$ at a point on contact surface (see **Figure 3**). Next, the fundamental process kinematics is embedded in the vector field of relative velocity $\vec{v}$ (incorporating the kinematics of both the abrasive tool and the workpiece).

In other words, $Aggr^*$ is the ratio of the component of velocity acting normal to the point of contact v_n to the component of velocity acting tangential to the point of contact v_t, which hence quantifies interaction between the abrasive tool and the workpiece in terms of geometry and kinematics at any given point on the abrasive-tool surface. This concept can be applied to any grinding process if the process geometry ($\vec{n}$) and kinematics (v_n, v_t) are mathematically described for an arbitrary contact point. The fundamental outcome of the Theory of Aggressiveness is derived from the general definition of the specific energy (Eq. (1)) obtained from the grinding power and the material removal rate. The specific energy depends on the process geometry and kinematics, which is bundled into the $Aggr^*$. According to Eq. (9), the shear at any point in the abrasive contact can be calculated as $\tau = u \cdot Aggr^*$. This is consistent with the model of Backer and Merchant [1] for tangential force, which is proportional to specific energy and instantaneous undeformed cross-sectional area of mean chip A, measured in a plane normal to the cutting velocity (where $A = Aggr^* / C$).

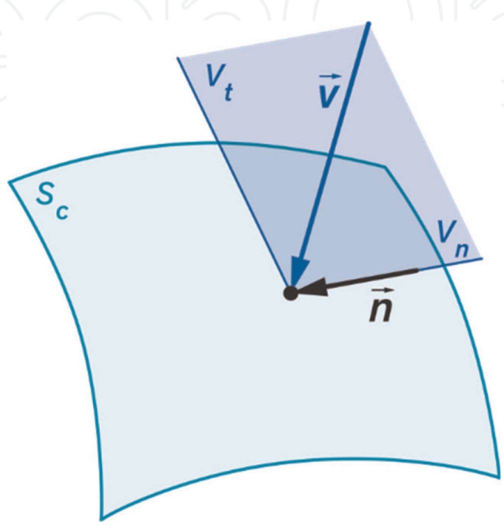

Figure 3.
Surface normal and relative-velocity vector with its components [3].

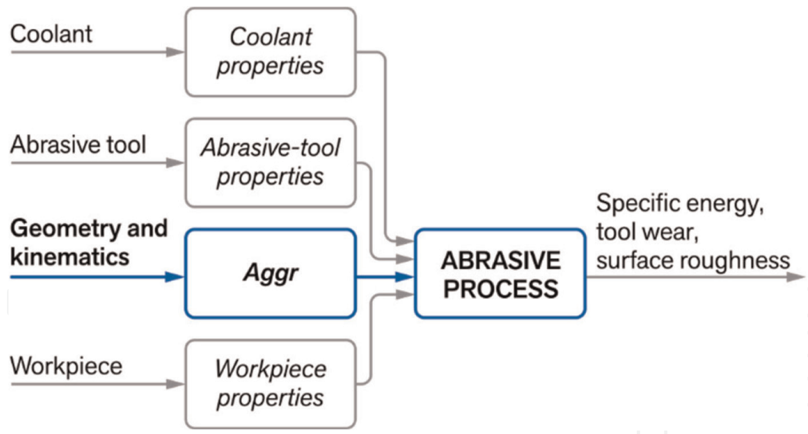

Figure 4.
Role of aggressiveness number in abrasive-process modeling [3].

The simplified quantity needed for optimization of grinding operations is the aggressiveness number, $Aggr = (v_w/v_s)\sqrt{a/d_e}$ (Eq. (5)), which is the average point aggressiveness ($Aggr^*$) in each abrasive contact. In operations with a trochoidal cutting path (such as surface, external, and internal cylindrical grinding), the point aggressiveness increases from zero to its maximum value, as in undeformed chip thickness. Here, the maximum point aggressiveness is double the aggressiveness number, i.e., $2 \cdot Aggr$. In operations with a linear path (such as face grinding, cup-wheel grinding, and cutting-off grinding), the aggressiveness is constant throughout the cut, such that $Aggr^*_{max} = Aggr$. In summary, the aggressiveness number, $Aggr$, gives the overall geometrical-kinematical characteristic of the abrasive contact, quantifying the abrasive interaction.

The Theory of Aggressiveness does not incorporate wheel-topography parameters, and the focus is solely on geometry and kinematics as the application of the aggressiveness number fully captures the correlation to process outputs such as specific energy, tool wear, and surface roughness, as shown in **Figure 4**. In a case where abrasive-tool properties need to be accounted for, then $Aggr^*$ should be replaced with h_m, by simply adding the two parameters of a wheel topography, i.e., $h_m = \sqrt{4/(C \cdot r)Aggr^*}$.

The theory of aggressiveness is a unifying modeling framework that quantifies the fundamental mechanics of any abrasive interaction for any arbitrary process geometry and kinematics. The fundamental dimensionless parameter of the theory of aggressiveness is the point-aggressiveness, $Aggr^*$, which is defined as the ratio of the normal and the tangential component of the relative-velocity vector at a given point on the abrasive-tool surface. Geometrically, the point aggressiveness can be interpreted as the tangent of an angle at which a given point of the workpiece penetrates into the abrasive tool. The overall geometrical-kinematical characteristic of the abrasive contact is quantified by the aggressiveness number, $Aggr$, defined as the average point aggressiveness over the entire abrasive contact.

4. Applications of the aggressiveness number *Aggr*

The authors recently published a conference paper to demonstrate how the concept of dimensionless aggressiveness number applies to most common process geometries and how it can be used to achieve practical results in a variety of applications [23]. For this, numerous grinding and dressing data were taken from literature and from our own work in production facilities. In addition, formulas were provided to calculate *Aggr* using only the parameters that can be readily altered on a machine: for surface (straight) grinding, cylindrical-plunge grinding, cylindrical-traverse grinding, face grinding, cup-wheel grinding, cutting-off grinding, and vertical-spindle grinding. Nevertheless, the applications and impacts of using *Aggr* to optimize industrial grinding operations are not yet summarized. Therefore, the summary of major case studies is given in subsections below.

4.1 Camshaft grinding

In camshaft grinding, an OD cylindrical grinding machine moves up and down during a single revolution of the workpiece to create the non-round cam shape. This is a complex grinding process that is characterized by transient geometry and kinematics [25], as shown in **Figure 5a**.

For example, the surge in material-removal rate on the cam-lobe flank causes a surge in workpiece temperature, which can result in localized grinding burn. Moreover, this surge produces higher normal forces, causing the machine to deflect,

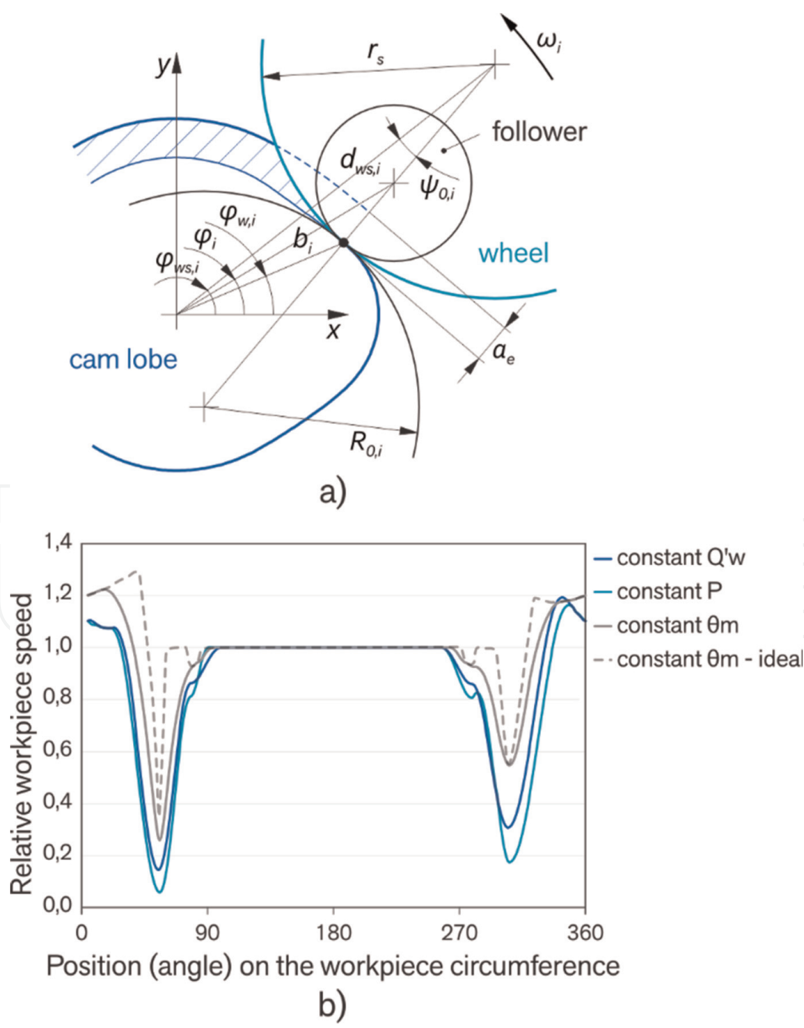

Figure 5.
(a) Geometry and kinematics of cam-lobe grinding and (b) output workpiece rotational speed for different process-control strategies, including the constant-temperature [26].

resulting in form errors on the ground cam lobes [26]. These surge issues drove the machine builders to develop and implement various cycle-optimization methods such as (i) grinding with constant speed [27]; (ii) grinding with constant specific material-removal rate, Q'_w [28]; and (iii) grinding with constant power, P [29]. The last two cycle-optimization algorithms are commonly provided with machine tools and embedded in their computer numerical control programs. Unfortunately, they do not fully solve the issue of grinding burn as they do not consider grinding temperature as the input to optimization. Research into non-round cylindrical grinding demonstrated that the incorporation of thermal modeling to run the process at a temperature just below the burn threshold leads to a much shorter grinding time compared to other optimization strategies [30]. The concept of constant temperature – based on analytical thermal models (initially developed for non-round cylindrical grinding [31]) and using the Theory of Aggressiveness – has been adopted to cam-lobe-grinding geometry and kinematics [26]. It was assessed against the constant-Q'_w and the constant-P methods in industrial production. **Figure 5b** shows how the workpiece rotational speed decreases during the surge region and increases during the cylindrical region, speeding up and slowing down during each workpiece revolution. It can also be seen that the previous control algorithms decreased the workpiece speed more than necessary, which led to longer cycle times and greater time in the high-temperature zone, increasing the risk of grinding burn.

The experiments confirmed that the constant-θ_m process provides the shortest cycle time and the lowest risk of grinding burn. The measured cycle time decrease was 18% compared to the constant-Q'_w process and 36% compared to the constant-P process. The end result was a significant increase in production capacity. In a representative production case in the automotive industry, the constant-θ_m process gave an approximate 50% increase in the production capacity, measured as the number of camshafts produced per day. The process underwent a rigorous Production Part-Approval Process (PPAP), followed by patenting [32] and then implementation in Scania's production lines in Sweden and Brazil.

4.2 Crankshaft grinding

Unlike camshaft grinding, limited research is available about the fundamental process mechanics in crankshaft grinding. Grinding of crankshafts (**Figure 6a**) with vitrified cBN wheels has been the industrial state of the art for the past 15–20 years. The challenge in crankshaft grinding is the changing process conditions across the wheel profile. The contact length increases significantly when grinding the sidewall, while the aggressiveness varies across the grinding-wheel profile. This can lead to grinding burn on the sidewall and excessive wheel wear within the radius. To address this challenge, machine builders developed and patented several methods for determining the feed increments. The two most common methods – implemented on Junker and Fives Landis machines, respectively – include: (i) radial-plunge grinding for roughing [35], where the grinding wheel plunges radially into the crankpin sidewall; and (ii) angle-plunge grinding, where the wheel plunges simultaneously into the crankpin both radially and axially, with increments that can be varied between roughing and finishing [36].

Our research into the fundamental aspects of crankpin grinding was based on analytical modeling and analysis of process geometry, kinematics, and temperatures [33]. The kinematics of crankshaft grinding are similar to non-round cylindrical

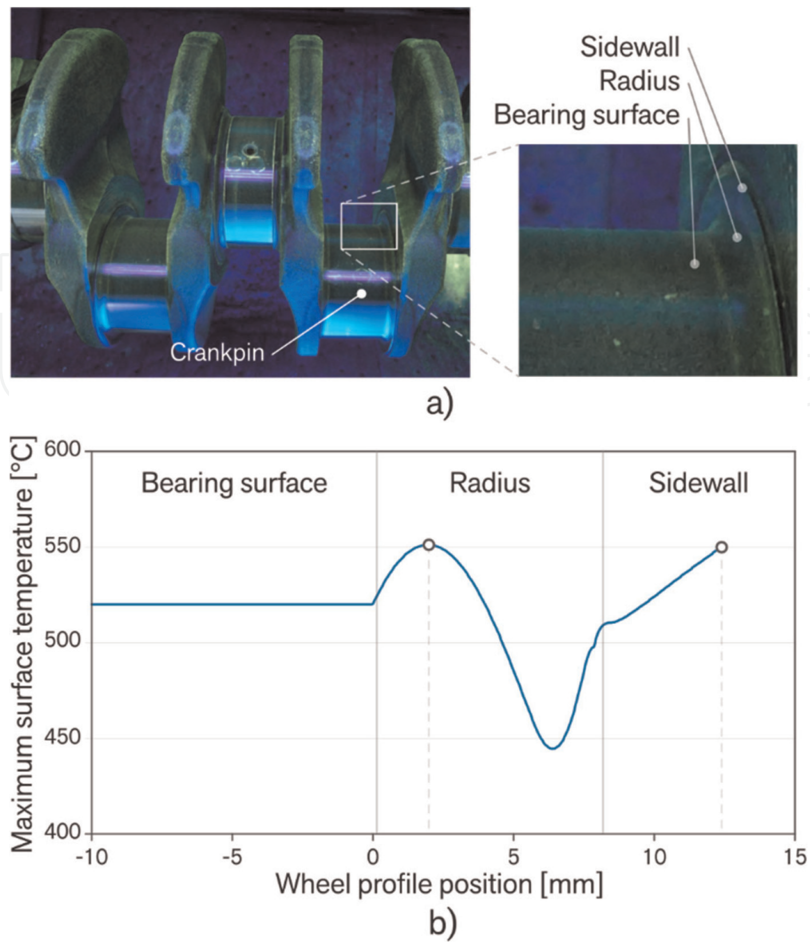

Figure 6.
(a) Crankshaft [33, 34] and (b) maximum surface temperature along the crankpin profile [33].

grinding [25] because of the crankpin's eccentricity. In contrast to camshaft grinding, however, the rotational frequency of the workpiece is constant. The implementation of a constant-temperature process [26, 30] was demonstrated in crankshaft grinding as well. Here, the thermal modeling requires the experimental determination of the specific energy in the workpiece [25]. This characteristic curve captures the effects of the workpiece material, grinding wheel, dressing, cooling, etc. The predicted maximum surface temperature along the wheel profile (**Figure 6b**) shows that the maximum temperature (set at 550°C) is reached at two critical contact points: on the radius and on the sidewall [33]. In summary, the temperature-controlled crankshaft-grinding algorithm determines the grinding increments so that a predetermined burn threshold is matched in these two critical points [37].

The grinding cycle analysis revealed that the temperature-based method is superior to the reference radial-plunge grinding method in terms of (i) productivity (minimum 25% improvement), (ii) the ability to avoid grinding burn [33], and (iii) increased the dressing intervals. The constant-temperature method was patented by Scania and subsequently implemented in production lines [37].

4.3 Grinding of cutting tools

Cutting tools such as sawblade tips and cutting inserts are often ground with cup wheels. Cup-wheel grinding can be divided into two types: (i) plunge grinding and (ii) traverse grinding. In plunge grinding, the workpiece is plunged either radially into the wheel on the outer-diameter face or axially on the bottom face. In addition, the workpiece may be oscillated back and forth. This is a form of face grinding, and the primary input is the feed rate. In traverse grinding, a fixed depth of cut is taken, and the workpiece is traversed across the bottom face of the wheel. Here, the primary inputs are the depth of cut and the feed rate. In addition, the infeed will be either on one side of the wheel or on both sides. The Theory of Aggressiveness was first applied to the traverse grinding operation of sawblade tips, which was implemented on a machine by VOLLMER WERKE Maschinenfabrik. During traverse grinding, the diamond wheel is trued with a silicon-carbide or aluminum-oxide truing wheel. Typically, this truing action is performed perpendicular to the axis of rotation. This is shown in **Figure 7a**. As a result, when grinding commences, all of the grinding action occurs on the leading outer-diameter edge of the wheel. During this time, the *Aggr* is enormously high, and the wheel soon wears away to develop a taper, as shown in **Figure 7b**. The grinding action then occurs on this taper, and the *Aggr* decreases drastically. This taper eventually encroaches on the trailing edge of the wheel. At this point, the surface finish becomes poor, and the wheel is sent for truing, where the cycle begins again. If the infeed is set to occur on both sides of the wheel, two tapers develop, meeting in the middle of the wheel. This is shown in **Figure 7d**. A taper, along with flat, can also be trued into the wheel, as show in **Figure 7c**.

After the taper breaks in, the grinding action shifts from the front face to the taper. Here, the aggressiveness number on the taper is $Aggr = (v_w/v_s)\sin\alpha_{taper}$. To gain a better understanding of the process, specific energy was plotted vs. the aggressiveness number. This is shown in **Figure 8**. Because the specific energy was transient – due to grit dulling and/or loading – the range of values is plotted with an arrow indicating whether they increased or decreased throughout the test. The results show that specific energies were higher at lower *Aggr*. More importantly, when the transient condition is considered, the differences in specific energy are drastic, with very high values of 1900 J/mm^3. In addition, self-sharpening of the wheel was very poor at the low

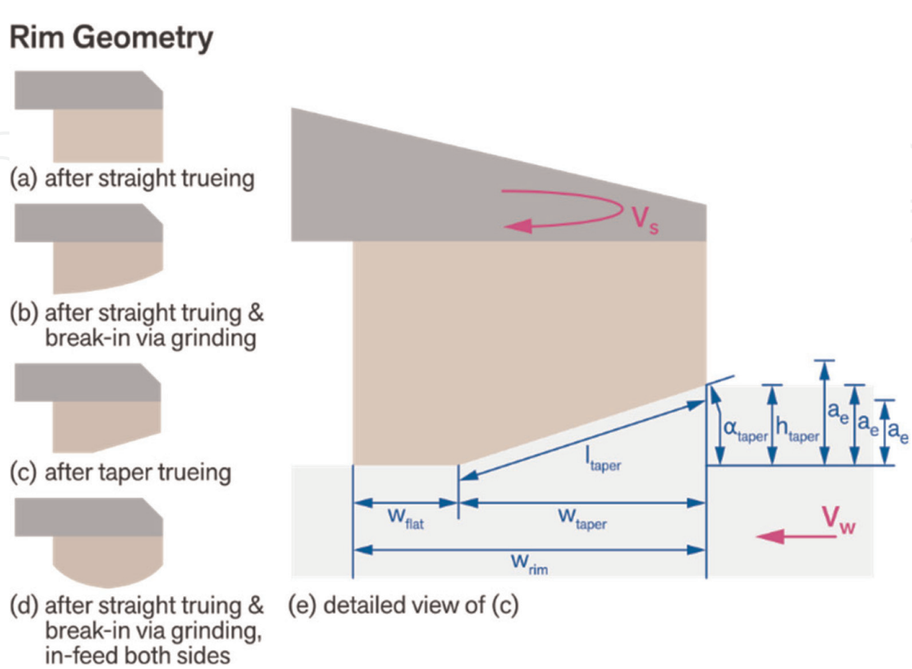

Figure 7.
Taper geometry in traverse cup-wheel grinding [38].

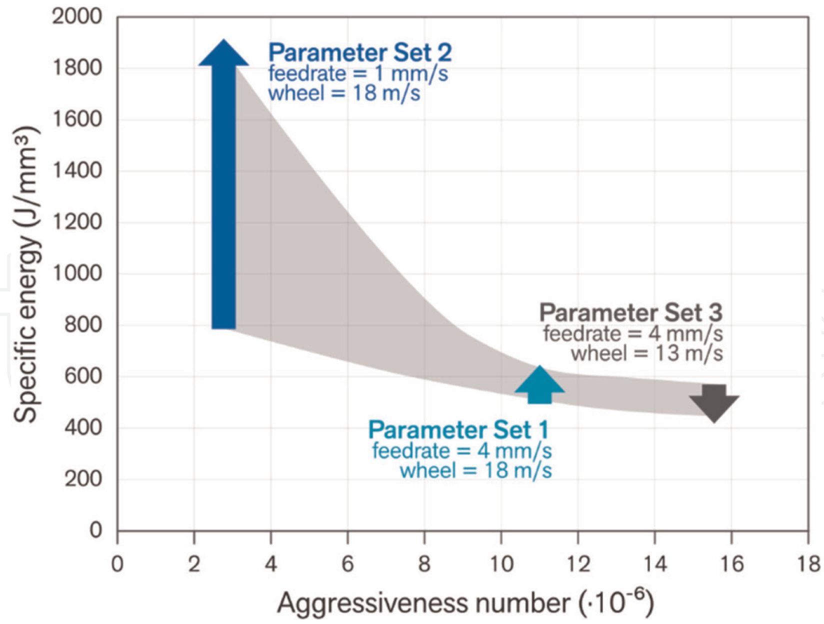

Figure 8.
Specific energy versus aggressiveness number in grinding of cermets with diamond [38].

Aggr. This has important implications in terms of the operator's choice of speeds and feeds. Typically, when an operator experiences a problem – for example, burn – his first reaction is to decrease the feed rate (parameter set 2). This may initially help the situation. However, the poor self-sharpening means that specific energies will rise drastically and eventually exacerbate the problem. On the other hand, a higher *Aggr* (parameter set 3) can lead to larger wheel wear and smaller G-ratios. Therefore, it seems optimal to run the process in the "sweet spot", associated with the initial (parameter set 1) grinding conditions. The grinding sweet spot, hence, refers to grinding conditions where the specific-energy curve straightens out [39]. This approach can be used to optimize any grinding operations, with a common need to experimentally determine the specific energy vs. *Aggr* curve.

The concepts learned from grinding of sawblade tips can be easily translated to the grinding of cutting inserts with diamond cup wheels. In this case, one could implement a constant-*Aggr* grinding process, which might help solve dissimilar wheel loading and wear. For this, the geometry and kinematics need to be determined for any given contact point around the insert circumference, similar to the case of modeling contact conditions in cam-lobe grinding.

4.4 Wheel lift-off in flute grinding

Another successful application of the Theory of Aggressiveness refers to optimizing wheel lift-off in flute grinding [40], as shown in **Figure 9**. During grinding, when the wheel lifts away from the workpiece (or vice versa) before coming to the end of the workpiece, it is referred to as lift-off in grinding. The most common workpieces that experience lift-off are drills and endmills. In this work, we investigated the phenomenon of end-of-cut power surge in flute grinding, a phenomenon that causes thermal damage and long cycle times.

To solve the issue, a geometric and kinematic model was developed to analyze the lift-off phenomenon. The theory was further upgraded with a thermal-model-based

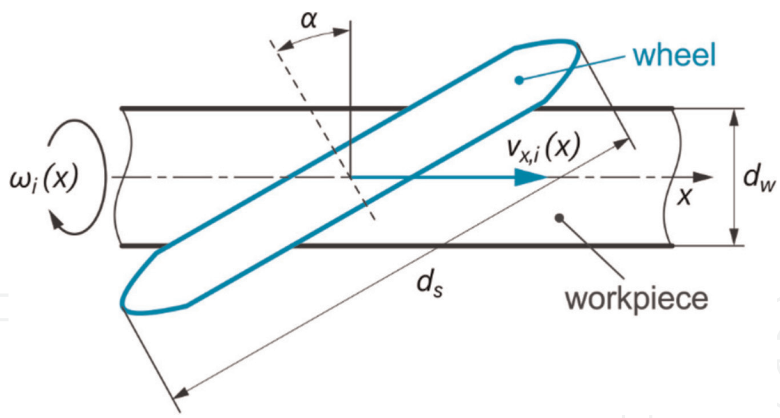

Figure 9.
Illustration of flute grinding [40].

optimization method for achieving a constant maximum surface temperature, resulting in shorter cycle times and lower risk of thermal damage. Thermal modeling is especially challenging in this case as the curved surface in flute grinding means that heat will flow to either side of the flute. Therefore, an investigation was made into the effect of side conduction on grinding temperatures. The Theory of Aggressiveness can be applied to determine the optimum strategy and parameters for lift-off, namely the infeed velocity, with the goal of (i) preventing thermal damage; (ii) minimizing an increase in *Aggr* and, consequently, wheel wear; and/or (iii) reducing grinding time. The constant-temperature method is one example of flute-grinding optimization and is conceptually the same as in camshaft and crankshaft grinding, where the approach is to hold the maximum surface temperature constant. This resulted in reducing the cycle time by 18.5%. Another optimization goal was to choose the velocity profile during the slowdown to give a constant *Aggr* (as exemplified in insert grinding). This means the forces on the individual grits would not vary drastically, resulting in more uniform wheel wear and surface finish. The cycle-time reduction in this case was 17.5%. To summarize, the application of the Theory of Aggressiveness in flute grinding involved describing the analytics behind the increasing depth of cut and the accompanying power surge and then successfully modeling the power surge with measured power profiles in a production environment. Machine builders can now implement this in their machines to choose the correct slowdown positions and slowdown rates, leading to a lower risk of grinding burn and shorter cycle times.

4.5 Double-disc grinding of bearings

The Theory of Aggressiveness was recently implemented in collaboration with SKF, a Swedish bearing manufacturer [41]. The objective was to model free-rotation double-disc grinding of bearing components with the goal of avoiding (i) workpiece rotational speed, and (ii) thermal damage, which occurs at high free-rotation workpiece rotational speed. While double-disc face grinding is widely used in the industry, limited research has been published on it. In double-disc grinding, the workpiece rotation can be driven externally, as in a process with planetary kinematics. In the case of a self-rotating process, the sleeve/bushing is used to hold the workpiece, and the workpiece rotation is caused by grinding forces from the two grinding wheels. Here, both workpiece faces are ground with a fixed infeed.

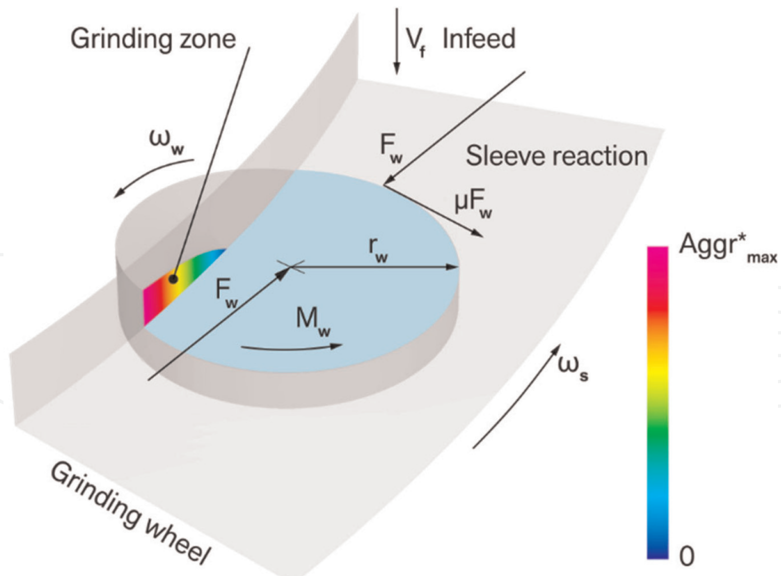

Figure 10.
Illustration of aggressiveness distribution and corresponding mechanics of self-rotating double-disc grinding [34].

The self-rotating process is challenging to control as one of the process parameters defining the grinding mechanics (i.e., workpiece rotational speed) is also one of the process outputs.

Advanced modeling was required to obtain a fundamental insight into the process mechanics. This was based on the distribution of the point-aggressiveness, $Aggr^*$ in the grinding zone, defined as a scalar field that incorporates the process geometry and kinematics at every point in an abrasive contact. **Figure 10** illustrates a (cylindrically) symmetric grinding situation with a workpiece "beneath" the grinding wheel. The Theory of Aggressiveness was used to predict the resultant grinding force, F_w, and the resultant workpiece moment, M_w. The workpiece rotational speed, ω_w, which is an unknown parameter depending on the grinding force and the grinding moment, can be calculated by solving the moment-equilibrium equation – as detailed in [41].

4.6 Truing of diamond wheels

The Theory of Aggressiveness was used to develop a truing editor for Rush Machinery [42], an American diamond-wheel truing machine builder. The end result was an HTML5-based online program to help users choose the optimal truing wheel and truing parameters to reduce cycle times and truing-wheel consumption [2]. In truing of diamond wheels, one typically uses a silicon-carbide or aluminum-oxide wheel to "grind" a diamond wheel in order to make it round (i.e., true). Since diamonds are enormously hard, truing is a painfully inefficient process. For every cubic millimeter of diamond wheel, trued away, somewhere between 6 and 100 cubic millimeters of truing wheel are consumed. This is a slow, tedious process. Unfortunately, very little research has been reported about the fundamentals of truing. Some general guidelines on truing-grit size and abrasive type have been given in handbooks and in catalogs by grinding-wheel manufacturers. However, these reports do not give any information on how these recommendations were arrived upon, nor on the fundamental mechanisms of material removal when the truing-wheel abrasive contacts the diamond. This work was hence undertaken to advance the state of knowledge of the truing geometry, kinematics, and removal mechanisms.

Truing is performed by traversing a truing wheel at a specified truing depth, a_T, truing overlap ratio, U_T, and truing traverse velocity, $v_{fa,T}$, with infeed before both the forward and the reverse stroke. The aggressiveness number for truing is calculated as:

$$Aggr = \frac{1}{|1 - q_T|}\sqrt{\frac{a_T}{d_e \cdot U_T}} \quad (10)$$

where q_T is the truing speed ratio (i.e., ratio between the diamond wheel speed and truing wheel speed), which has $0 < q_T < 1$ values in uni-directional truing and $q_T < 0$ in anti-directional truing; and d_e is the equivalent diameter (as in grinding). Since (i) truing efficiency depends on *Aggr*, (ii) specific truing energy increases with truing-grit size, and (iii) truing shear appears to be the dominant indicator of truing efficiency η_T, the authors were able to incorporate both *Aggr* and grit sizes into a unifying equation of truing efficiency, encompassing all the process inputs into a single relationship – the dimensionless truing compliance number $\Gamma_T = Aggr \cdot (d_{g,T}/d_{g,D})^2$, where $d_{g,T}$ is the truing-grit diameter and $d_{g,D}$ is the diamond-grit diameter. Based on this, a strong linear relationship can be observed for an enormously wide range of truing-grit sizes and truing parameters, as shown in **Figure 11**. In this way, a novel fundamental characteristic is obtained, which correlates the geometrical and kinematical inputs (i.e., *Aggr*) with the truing efficiency.

Finally, all mathematical models of the applied Theory of Aggressiveness were embedded in a software tool for optimizing the needs of the end-user, be it shorter cycle times, less truing-wheel consumption, lower truing forces, or all the above. The authors also took into consideration the hardness of the truing wheels. Software that uses HTML5 code can run in a web browser anywhere on any device. Web apps may also be “packaged”, meaning they can be bundled with the app and thus can be distributed to a mobile device through app stores. A screenshot of a developed web-based truing editor is shown in **Figure 12**.

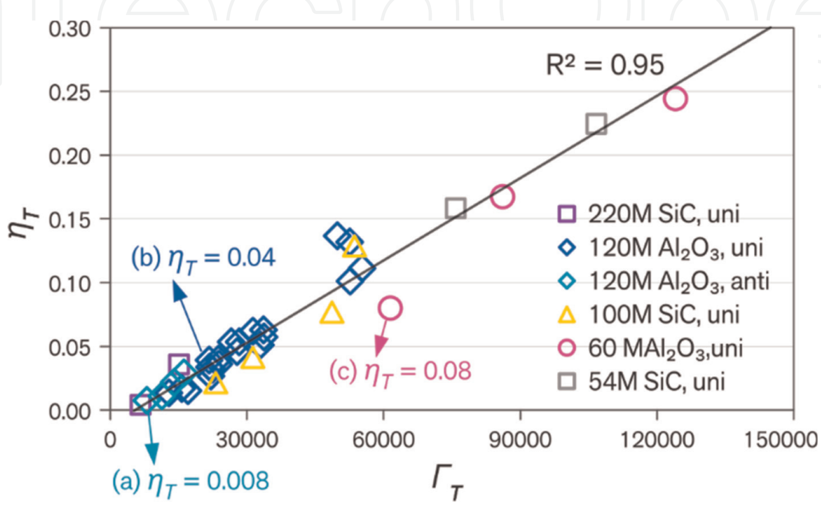

Figure 11.
Truing efficiency versus truing compliance number [2].

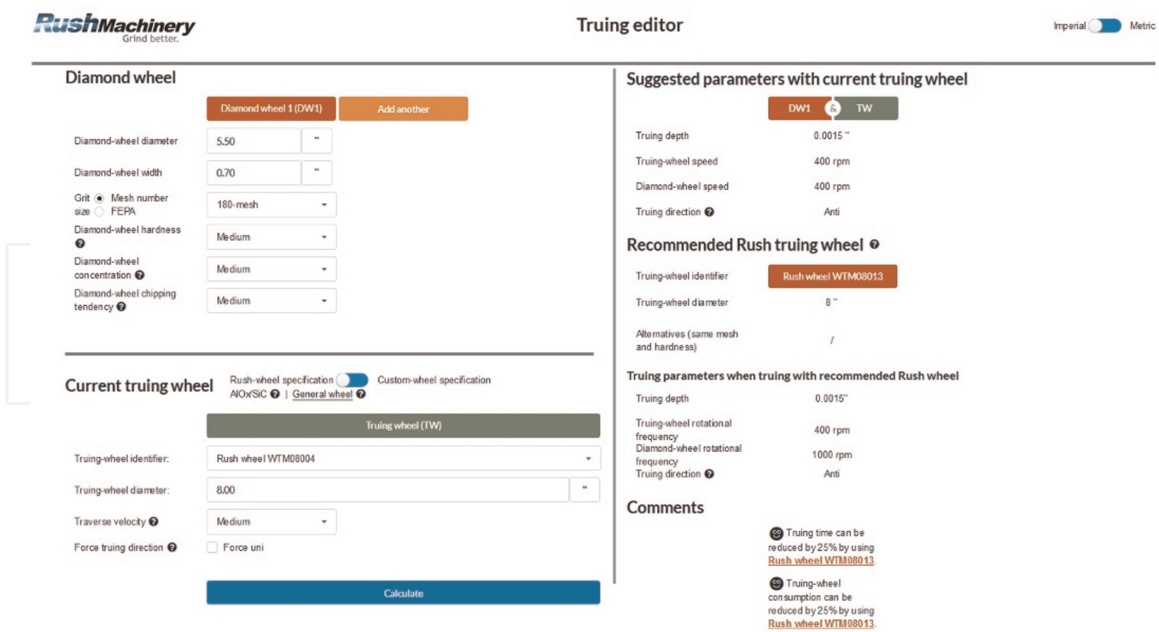

Figure 12.
Truing editor for online optimization of a truing process [42].

5. Conclusions

Various aspects of grinding theory have been reviewed with the overall objective of improving and optimizing grinding operations. The emphasis has been on presenting applications of a recently developed Theory of Aggressiveness, next to providing a comprehensive evaluation and comparison to the classical models developed mainly in the United States and Germany. The point aggressiveness $Aggr^*$ is shown to be the "first-principle" parameter that comprehensively accounts for any process geometry and kinematics and fundamentally relates them to specific energy and shear required for material removal (cutting). Its mean value, quantified by a dimensionless aggressiveness number $Aggr$, is then used to optimize diverse abrasive processes ranging camshaft and crankshaft grinding, saw-tip grinding, flute grinding, double-disc grinding, and diamond-wheel truing – without the need to measure/quantify the wheel topography or other wide-ranging empirical relationships. The application of $Aggr$ has also been proven to be an effective aid for machine operators in making quick calculations on the shop floor when optimizing grinding operations and troubleshooting problems. The optimization concept based on the Theory of Aggressiveness has hence been used in the high-end industry for several years, while some of the models (e.g., truing editor) have recently been translated into HTML5 language to enable the software-based process optimization via the World Wide Web.

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