Principles of Modern Grinding Technology
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Second Edition

W. Brian Rowe
I dedicate this book to my wife Margaret Ruth for her love and support throughout my work, the mother of my children Ivor and Ella and my constant companion.
Preface

*Principles of Modern Grinding Technology* explains in simple terms the principles that led to rapid improvements in modern grinding technology over recent decades. Removal rates and quality standards have increased a hundred-fold. Very fine tolerances are routine due to improved understanding of the process and the factors that need to be controlled.

Superb grinding machines now produce optical-quality finishes due to developments in process control and machine design. It is the same for extremely high removal rates. This book shows how best quality can be improved and costs can be brought down at the same time as output is increased.

The book is aimed at practitioners, engineers, researchers, students and teachers. The approach is direct, concise and authoritative. This edition introduces additional materials including data, photographs, updated references and design examples. There are additions in most chapters including abrasives, dressing, cooling, high-speed grinding, centreless grinding, materials, wear, temperatures and heat transfer. There are numerous worked examples. Progressing through each major element of a grinding system and then on to machine developments, the reader becomes aware of all aspects of operation and design. Trends are described demonstrating key features. Coverage includes abrasives and superabrasives, wheel design, dressing technology, machine accuracy and productivity, machine design, high-speed grinding technology, cost optimization, ultra-precision grinding, process control, vibration control, coolants and fluid delivery, thermal damage and grinding temperatures.

Advances in the field are supported with references to leading research. Analysis is presented in later chapters and appendices with new contributions to machine design, intelligent control, centreless grinding, fluid delivery, cost analysis and thermal analysis for prediction and control of grinding temperatures are provided. By selecting the right conditions, extremely high removal rates can be achieved accompanied by low temperatures. Techniques for measurement of grinding temperatures are also included.

This edition includes recent process developments and additional design examples.

- Trends in high precision and high-speed grinding are explored.
- Principles underlying improvements in machines and processes are explained.
- Numerical worked examples give scale to essential process parameters.
- Recent research findings and original contributions to knowledge are included.
- A number of ultra-precision grinding machine developments are included.
Acknowledgements

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W. Brian Rowe
About the Author

W. Brian Rowe is a research and consulting engineer, Emeritus Professor and previous Director of Advanced Manufacturing Technology and Tribology Research Laboratory (AMTTREL) at Liverpool John Moores University in the United Kingdom. A multiple recipient of prizes from The Institution of Mechanical Engineers (IMECHE), Dr Rowe has four decades of experience in academic and industrial positions concerned with machine tools, grinding processes and tribology. His accomplishments include over 250 published papers, several books, international visiting professorships and international consulting in industry.
List of Abbreviations

ACO  Adaptive control optimization
AE   Acoustic emission
ANSI American National Standards Institution
BN   Barkhausen Noise
CBN  Cubic boron nitride
CIRP International Academy of Production Engineering Research
CNC  Computer numerical control
CVD  Chemical vapour deposited
CW   Control wheel
ED   Electrical discharge
EDD  Electrical discharge dressing
ELID Electrolytic in-process dressing
EP   Electroplated
FEPA Federation of European Producers of Abrasives
FWM  Fluid wheel model of fluid convection
GW   Grinding wheel
HEDG High-efficiency deep grinding
HEG  High-efficiency grinding
HSS  High speed steel
ID   Impregnated diamond
ISO  International Standards Organization
JIS  Japanese Industrial Standards
LFM  Laminar flow model of fluid convection
MQL  Minimum quantity lubrication
MRR  Material removal rate
PCD  Poly-crystalline diamond
PLCs Programmable logic controls
PVD  Physical vapour deposition
RMS  Root mean square
SD   Single-point diamond
SEM  Scanning electron microscope
SG   Seeded gel (alumina composite abrasive) — trade name
SI   ISO international system (e.g. units)
SiC  Silicon carbide
UFM  Useful flow model
VHN  Vickers Hardness Number
WP   Workpiece
Notation for Grinding Parameters

Note: Symbols within a special context are explained in the relevant text.

- $a$: Depth of cut or hydrostatic bearing land width
- $a_d$: Dressing depth of cut
- $a_e$: Effective (real) depth of cut in grinding
- $a_p$: Programmed (set) depth of cut in grinding
- $b, b_r, b_w$: Width of grinding wheel contact with work
- $b_{cu}$: Width of uncut chip
- $b_d$: Dressing tool contact width
- $b_r$: Radial width of cut
- $c$: Machine damping
- $c, c_p$: Specific heat capacity
- $c_{d}, c_{v}, c_{a}$: Discharge, velocity and area coefficients in nozzle flow
- $d$: Diameter in pipe flow
- $d_c$: Control wheel diameter in centreless grinding
- $d_e$: Effective grinding wheel diameter
- $d_g$: Mean abrasive grain diameter
- $d_s$: Actual grinding wheel diameter
- $d_w$: Workpiece diameter
- $e$: Error
- $e_{c,u}$: Specific grinding energy (energy per unit volume removed)
- $e_{ch}$: Specific energy carried in chips
- $erf( )$: Error function given in math tables
- $f$: Frequency in cycles per second (Hz)
- $f$: Interface friction factor = $\tau/k$
- $f$: Grain force
- $h$: Thin film or chip thickness
- $h, h_f$: Convection factor and work-fluid convection factor
- $h_{cu}$: Uncut chip thickness
- $h_{eq}$: Equivalent chip thickness
- $h_g$: Convection factor into a grain
- $h_w$: Work height in centreless grinding
- $h_{wg}$: Convection factor into the workpiece at a grain contact
- $j$: Complex number operator
- $k$: Shear flow stress
- $k$: Thermal conductivity
- $k_w, k_g$: Thermal conductivity of work material and abrasive grain
- $l_c$: Contact length
- $l_t$: Contact length due to force and deflection of grinding wheel and workpiece
- $l_g$: Geometric contact length due to depth of cut
### Notation for Grinding Parameters

- **n**: Number of grinding passes
- **n**: Junction growth factor
- **n_d**: Number of dressing passes
- **n_s**: Grinding wheel rotational speed
- **n_w**: Work rotational speed
- **p**: Instantaneous power
- **p_p**: Fluid pumping pressure
- **q**: Speed ratio = $v_s/v_w$
- **q**: Flux value = heat per unit area in unit time
- **q_d**: Dressing roll speed ratio = $v_d/v_s$
- **q_{flash}**: Flux into the workpiece at a flash contact
- **r_{cu}**: Uncut chip width/chip thickness ratio = $b_{cu}/h_{cu}$
- **r_o**: Average effective grain contact radius
- **s**: Laplace operator in vibration theory
- **t**: Time
- **t_d**: Dressing time
- **t_p**: Point/flash contact time of grain and workpiece
- **t_s**: Grinding cycle time
- **t_t**: Grain contact time within contact length
- **t_t**: Total cycle time including grinding and dressing
- **u_i**: Input to a control system
- **u_o**: Output from a control system
- **v**: Mean velocity in pipe flow
- **v_d**: Dressing roll speed
- **v_f**: Work feed rate
- **v_{fd}**: Dressing feed rate
- **v_j**: Jet velocity
- **v_s**: Wheel speed
- **v_w**: Work speed
- **x**: Deflection
- **x, y, z**: Position coordinates
- **A**: Geometric stability parameter in centreless grinding
- **A**: Wear flat area on grinding wheel as fraction or percentage
- **A_c**: Apparent area of grinding contact zone = $l_c b$
- **A_{cu}**: Cross-section area of uncut chip
- **Al_2O_3**: Aluminium oxide, alumina
- **B**: Lateral grain spacing
- **C**: Number of active abrasive grains per unit area = cutting edge density
- **C**: C-factors giving temperature for particular grinding conditions
- **C_t**: Total cost per part
- **D**: Diameter as in journal diameter
- **E**: Young modulus of elasticity
- **F_{a, a}**: Axial force and specific value per unit width
- **F_{n, n}**: Normal force and specific value per unit width
- **F_{t, t}**: Tangential force and specific value per unit width
- **G**: G-ratio
- **H**: Feedback function in a control system
- **H_a**: Depth of cut function in vibrations
Notation for Grinding Parameters

\( H_f \) Fluid drag power
\( H_p \) Fluid pumping power
\( H_s \) Wheel wear function in vibrations
\( H_t \) Total fluid power
\( K \) Grinding stiffness factor = \( a_d/a_p \)
\( K \) Power ratio = \( H_t/H_p \)
\( K \) Archard wear constant
\( K_s \) Grinding stiffness = \( F_d/a_e \)
\( K_t \) Work-plate factor in centreless grinding
\( K_2 \) Control wheel factor in centreless grinding
\( L, B \) Grain spacing in grinding direction and in lateral direction
\( L \) Length as in bearing length or work length
\( L \) Peclet number related to thermal diffusivity
\( N_d \) Number of parts per dress
\( P, P' \) Grinding power and power per unit width
\( P_{NL} \) No-load power
\( P_s, P_p \) Supply pressure and pumped pressure
\( Q \) Dynamic magnifier of machine deflection
\( Q \) Bearing flow-rate
\( Q, Q_w \) Removal rate, workpiece removal rate
\( Q', Q_w' \) Removal rate per unit width
\( Q_t \) Nozzle fluid flow-rate
\( Q_u \) Useful fluid flow-rate
\( R_{a}, R_{t}, R_{z} \) ISO surface roughness parameters
\( R_e \) Reynolds number
\( R_{L} \) Contact length ratio = \( l_c/l_g \)
\( R_r \) Roughness factor = \( l_e/l_{fs} \)
\( R_w \) Fraction of heat going into workpiece
\( R_{ws} \) Work-wheel interface fraction of heat into workpiece
\( S_{cu} \) Surface area of the uncut chip
\( SiC \) Silicon carbide
\( SG \) Seeded gel (alumina composite abrasive) — trade name
\( T, \Delta T \) Temperature or temperature rise
\( U_d \) Dressing overlap ratio
\( V \) Volume removed
\( V_{cu} \) Chip volume removed
\( \alpha \) Thermal diffusivity = \( k/\rho c \)
\( \alpha \) Work-plate-wheel contact angle in centreless grinding
\( \beta \) Thermal property = \( \sqrt{k/\rho c} \)
\( \beta \) Tangent contact angle in centreless grinding
\( \beta \) Bearing pressure ratio = design value of recess pressure/supply pressure
\( \gamma \) Work-plate angle in centreless grinding
\( \gamma \) Friction angle = \( (\cos^{-1} f)/2 \)
\( \gamma_d \) Dressing sharpness ratio = \( a_d/b_d \)
\( \varphi \) Grinding contact angle = \( l_c/d_e \) radians
\( \Phi \) Wheel porosity
\( \Phi \) Through-feed angle in centreless grinding
\( \rho \) Density = mass per unit volume
\( \sigma \)  Direct stress  
\( \tau \)  Time constant of an exponential decay or growth  
\( \lambda \)  Static grinding system stiffness  
\( \lambda(j\omega) \)  Dynamic grinding system stiffness  
\( \mu \)  Grinding force ratio  
\( \nu \)  Poisson ratio  
\( \omega \)  Frequency (radians per second)  
\( \omega_n, \omega_o \)  Natural frequency, resonant frequency (radians per second)  
\( \Omega \)  Work angular speed (radians per second)  

**Commonly Used Suffixes and Affixes Which Modify a General Symbol Depending on the Context in Which It Is Used**

- **a**  Axial or ambient  
- **c**  Contact or cutting  
- **ch**  Chip  
- **cu**  Uncut chip  
- **d**  Dressing or discharge  
- **e**  Effective  
- **f**  Fluid or force  
- **g**  Geometric or grain  
- **i**  Instantaneous or input  
- **j**  Jet  
- **max**  Maximum  
- **n**  Normal or natural  
- **o**  Datum or zero or natural or output  
- **p**  Pressure or pumping or programmed or ploughing  
- **r**  Radius or roughness  
- **s**  Wheel or supply or sliding  
- **t**  Tangential or total  
- **u**  Useful  
- **v**  Velocity  
- **w**  Workpiece or width  
- **ws**  Workpiece-wheel  
- **L**  Length  
- **NL**  No-load
## Basic Units and Conversion Factors

<table>
<thead>
<tr>
<th>Category</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>1 metre = 39.37 inches</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>1 kilogram = 2.205 pounds mass</td>
</tr>
<tr>
<td><strong>Force</strong></td>
<td>1 newton = 0.2248 pounds</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td>1 joule = 0.7376 foot pounds</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>1 watt = 0.7376 foot pounds per second</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>1 kg/m$^3$ = 0.06243 pounds mass per cubic foot</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>1 pascal = 1 N/m$^2$ = 0.000145 pounds per square inch</td>
</tr>
<tr>
<td></td>
<td>1 bar = 14.5 pounds per square inch</td>
</tr>
<tr>
<td></td>
<td>1 atm ≈ 14.7 pounds per square inch</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>1 celsius degree rise = 1.8 fahrenheit degrees rise</td>
</tr>
<tr>
<td><strong>Gravitational acceleration in free fall</strong></td>
<td>9.807 m/s$^2$ = 32.175 ft/s$^2$</td>
</tr>
<tr>
<td><strong>Dynamic viscosity</strong></td>
<td>1 N s/m$^2$ = 0.000145 lbf s/in.$^2$ = 0.000145 reyns</td>
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</tbody>
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1 Introduction

1.1 The Role of Grinding in Manufacture  
Origins of Grinding  
What Is Grinding?  
A Strategic Process  
Cost, Quality and Speed of Production  
Machining Hard Materials and Ceramics  
Accuracy  
Surface Quality and Surface Texture  
Speed of Production  
The Value-Added Chain  
Reducing the Number of Operations  
Flexible Grinding Operations and Peel Grinding

1.2 Basic Grinding Processes  
Basic Surface and Cylindrical Grinding Processes  
Internal and External Variants  
The Range of Grinding Processes and Bibliography

1.3 Specification of the Grinding System Elements  
Basic Elements  
System Elements  
Element Characteristics  
The Tribological System  
The Grinding Machine  
The Grinding Fluid  
The Atmosphere

1.4 The Book and Its Contents  
The Emphasis  
Conventional and New Processes  
Worked Examples  
Book Outline

Basic Material Removal (Chapter 2)  
Grinding Wheels and Dressing (Chapters 3 and 4)  
Grinding Wheel Behaviour (Chapter 5)  
High-Speed Grinding (Chapter 6)  
Thermal Damage (Chapter 7)  
Fluid Delivery (Chapter 8)  
Grinding Costs (Chapter 9)  
Grinding Machine Developments (Chapter 10)  
Grinding Process Control (Chapter 11)
1.1 The Role of Grinding in Manufacture

Origins of Grinding

The use of abrasives for shaping goes back more than 2000 years. Abrasive stones were used for sharpening early knives, tools and weapons. From early times, abrasives have been used to cut and shape rocks and stones for construction of buildings and edifices, such as the pyramids. Abrasives were also used for cutting and polishing gems. Abrasives continue to be used in increasingly diverse applications today and much of modern technology relies on the abrasives industry for its existence. Even in the early days grinding was a finishing process applied to products approaching the most valuable stage in their production.

Grinding developed as a metal manufacturing process in the nineteenth century ([Woodbury, 1959](#)). Grinding played an important part in the development of tools and in the production of steam engines, internal combustion engines, bearings, transmissions and ultimately jet engines, astronomical instruments and microelectronic devices.

What Is Grinding?

Grinding is a term used in modern manufacturing practice to describe machining with high-speed abrasive wheels, pads and belts. Grinding wheels come in a wide variety of shapes, sizes and types of abrasive. Important types of wheels and abrasives are described in the following chapters. Grinding is an abrasive machining process. Abrasive machining technology also embraces polishing, lapping, honing and related superfinishing processes. Some areas of grinding technology overlap with this extended range of processes. A distinction between grinding and other processes may be purely kinematic, in some cases involving for example very low abrasive speeds as in lapping. In other cases, the extension of the grinding process into superfinishing is found in the application of chemical or electrochemical principles to assist the abrasive process. The techniques and principles described in this book are concerned mainly with the mechanical abrasion process and also extend into other aspects of superfinishing.

A Strategic Process

In the second half of the twentieth century, it was recognized that grinding is a strategic process for high-technology applications. It was realized, for example, by
manufacturers of aero-engines and missile guidance systems, that grinding was the key to achieving the necessary quality. This provided the motivation for rapid development in the latter part of the twentieth century. More recent still, grinding has become a strategic process for production of optical quality surfaces for communications and for electronic devices. Modern technology has also seen a trend towards hard ceramic materials that bring new challenges for economic manufacture.

Cost, Quality and Speed of Production

Industrial competitiveness is a balance between the competing requirements of cost, quality and speed of production. In recent decades, grinding has been transformed both for producing very high-quality parts and for fast economic production (Inasaki et al., 1993). This trend is illustrated in Figure 1.1 where grinding and cutting tools are seen as increasingly competitive both for machining accuracy and for production rate. Due to modern developments, grinding has a large role in efficient manufacturing industry both in terms of volume and in terms of value. For example, in a process known as planar grinding, many flat parts can be ground simultaneously on one worktable. This allows extremely high removal rates to be achieved and also high accuracy.

Machining Hard Materials and Ceramics

Abrasive processes are the natural choice for machining very hard materials. It is a general rule with few exceptions that the tool used for machining should be harder than the material being machined. Suitable abrasives to grind hardened steels and aerospace alloys include aluminium oxide, silicon carbide, sintered alumina and cubic boron nitride.

Diamond abrasive is used to grind hard ceramics and other highly abrasive materials. Hard ceramics are difficult to machine because they are not only very hard and very abrasive but also extremely brittle. Diamond grinding is well suited to coping with the challenges presented by new engineering structural materials, such as silicon nitride, silicon carbide and zirconia. Hard ceramics are employed in

![Figure 1.1 Trends in the application of grinding wheels and cutting tools.](image-url)
electronics, cutting tools, telecommunications, optical systems, bone replacements, heat exchangers, bearings, flow valves and heat engines (Marinescu et al., 2000).

Grinding is often the simplest and least expensive process for machining hard materials. Alternative processes such as hard turning may be feasible, but often it is grinding that is least expensive and achieves the quality and speed of production required together with process reliability (Klocke et al., 2005).

**Accuracy**

Grinding allows high accuracy to be achieved and close tolerances can be held for size, shape and surface texture. Grinding is used to machine large parts, such as machine tool slideways where straightness is important and tolerances are usually specified in microns. Grinding is also used to machine small parts including contact lenses, needles, electronic components, silicon wafers, and rolling bearings where all aspects of accuracy are important and tolerances extend from micron to submicron and even approach the nano range. Nanogrinding is where accuracies of less than 0.1 µm are required. Nanogrinding using the Electrolytic In-Process Dressing (ELID) process replaces polishing and achieves vastly improved removal rates for such applications as mirror-finish grinding and production of micro tools used in nanotechnology.

**Surface Quality and Surface Texture**

Quality is a term that includes all aspects required for parts to function correctly. Accuracy of dimensions, form and surface texture are obvious aspects of quality. Grinding carefully can ensure good quality where other processes may have difficulty meeting specifications. Another aspect is surface quality. The integrity of the material at the machined surface may not always be obvious but is vitally important in many situations. For example, the surface of a hardened part should not be softened or cracked. It may also be important to avoid tensile residual stresses that reduce strength and shorten service life. All these aspects of quality require careful design and control of the grinding process.

Roughness can be reduced down to mirror finishes and optical quality of flatness. The achievement of this quality depends on the roughness of the abrasive, the quality of the grinding machine and the removal rates employed.

**Speed of Production**

Speed of production depends on the material being machined and the accuracy and quality required. Grinding can be used to combine high removal rate with accuracy, for example, flute-grinding of hardened twist drills from a solid bar is accomplished in seconds. Alternatively, grinding can be employed with moderate removal rates to produce high-accuracy parts in large volumes. Examples are bearing rings and rolling elements for bearings. Nanogrinding can be considered as a high removal rate process because it replaces much slower processes, such as lapping and polishing.
**The Value-Added Chain**

Grinding usually comes towards the end of product manufacture when the value of the parts is already significant and when mistakes can be expensive. The buildup of costs in product manufacture is illustrated schematically in Figure 1.2.

As parts move from one operation to another, such as turning, hardening and tempering, and then grinding, the parts achieve greater value and the cost of holding stocks is increased. There are costs of moving parts and protecting them from damage. The cost of scrapping parts is greatly increased. The increase in cost and lead time with the number of operations is not linear but exponential.

**Reducing the Number of Operations**

If the number of operations and the lead time can be reduced, it is found that the overall cost of manufacture can be greatly reduced.

Manufacturers want either to eliminate the grinding process altogether if the required quality can be achieved through an earlier process or else to eliminate an earlier process if grinding can achieve the form and accuracy in one operation or even on one machine. Grinding tends to govern the accuracy of the parts produced and is often the key to the required quality. For example, the grinding of the flutes of hardened twist drills to full form in one operation is very efficient.

**Flexible Grinding Operations and Peel Grinding**

Flexible grinding operation suggests that a family of components or possibly several families can be produced flexibly on one automatically controlled machine tool. For example, it is possible that cylindrical components having several diameters and shoulders could be produced with a single machine setup.

Many grinding machine companies are now using the term peel grinding. Peel grinding combines high-speed grinding techniques with computer numerical control to allow the grinding wheel to be employed similarly to a hard-turning tool. Typically, a 5 mm wide grinding wheel follows a programmed path to produce a form or multiple diameters. The peel grinding machine introduces increased flexibility in the range of parts or operations that can be performed on a single machine.
1.2 Basic Grinding Processes

**Basic Surface and Cylindrical Grinding Processes**

Two main classes of grinding are flat surface grinding and cylindrical grinding. Photographs of typical machines appear in Chapters 10 and 11. These two classes of machine provide the four basic processes illustrated in Figure 1.3. The figure shows peripheral grinding of flat surfaces and cylindrical surfaces. Peripheral grinding employs the periphery of the grinding wheel. The figure also shows face grinding of nonrotational flat surfaces and face grinding of rotational flat surfaces. Face grinding employs the face of the grinding wheel. Face grinding of rotational flat surfaces can be carried out on a cylindrical grinding machine and is termed cylindrical face grinding. Basic cylindrical grinding processes include external, internal and centreless variants.

![Figure 1.3](image-url)  
**Figure 1.3** Four basic grinding processes.  
(a) Peripheral surface grinding, (b) peripheral cylindrical grinding, (c) face surface grinding and (d) face cylindrical grinding.
Internal and External Variants

Figure 1.4 shows important variants of the basic grinding process. The three examples include internal cylindrical grinding, external centreless grinding and external angle grinding. Internal grinding of bores is a cylindrical process where a small grinding wheel is mounted on a slender spindle known as a quill and the workpiece is held in a chuck or collet. In the internal centreless process, the workpieces may be held and rotated on a faceplate. External centreless grinding is a cylindrical process where the workpiece is supported at its external surface against a workrest and against a control wheel. Angle approach grinding may be employed for either internal or external cylindrical grinding and allows a face to be machined at the same time as a diameter. Angle grinding allows material removal to be spread across the face and periphery of the wheel thus prolonging wheel life between redress.

The Range of Grinding Processes and Bibliography

In practice, the complete range of grinding processes is very large including single-sided or double-sided face grinding of multiple components mounted on a plane surface. The range also includes profile generating operations and profile copying operations. Profiling processes include grinding of spiral flutes, screw threads, spur gears and helical gears using methods similar to gear cutting, shaping, planing, or hobbing with cutting tools. There are other processes suitable for grinding cam plates, rotary cams and ball joints.

Examples of a variety of these processes are illustrated in previous books (Marinescu et al., 2006, 2013). Other useful books for reference are Andrew et al. (1985),