Grinding and Abrasive Machining of Composite Materials

Mark J. Jackson and Martin J. Toward

Abstract The grinding or abrasive machining of composite materials is a complex system that relies on the use of hard materials such as alumina and diamond to achieve precisely machined functional surfaces. This chapter focuses on the grinding of polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs) and explains how abrasive grain and bonding characteristics affect the grindability of fibrous materials surrounded by a binder. The chapter reviews the current literature surrounding the specification of abrasive products in use for shaping PMCs, MMCs and CMCs and provides an insight into the future specifications of abrasive grains and bonded products for grinding increasingly complex composite materials.

1 Introduction

Polymer-matrix composites (PMCs) are materials composed of a variety of short or continuous fibers bonded together to an organic polymer matrix. PMCs transfer loads between fibers through the matrix using an appropriate agent that provides stress paths within the composite structure. Some of the advantages of using PMCs include high stiffness and high strength along the direction of aligned fibers. PMCs are divided into two categories, reinforced and advanced composites. Reinforced plastic composite materials typically consist of polyester resins reinforced with low-stiffness glass fibers. Advanced composites consist of fiber and matrix combinations that have much higher strength and stiffness. The PMC is designed so that the mechanical loads that are being applied to the material are supported by the reinforcing agents. The function of the matrix is to bond the fibers together and to transfer loads between them. PMCs contain ~60% reinforcing fiber by volume. The fibers that are commonly

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found and used within PMCs include fiberglass, graphite and aramid. Fiberglass has a relatively low stiffness and at the same time exhibits a high tensile strength compared to other fibers. The reinforcing fibers focus their mechanical properties along their lengths rather than their widths and are arranged and oriented in different forms and directions to provide different physical properties and advantages based on their application. The properties of the matrix determine the resistance of the PMC to processes that includes impact damage, water absorption, chemical attack, and high-temperature creep. This PMC matrix is weak and easily ground away using conventional abrasive cutting tools composed of aluminum oxide or silicon carbide abrasive grains bonded together in a tight matrix usually vitrified with a large number of open pores.

Metal Matrix Composites (MMCs) are made by dispersing a reinforcing material into a metal matrix. The reinforced surface can be coated to prevent a chemical reaction with the matrix. Carbon fibers are commonly used in an aluminium matrix to synthesize composites having low density and high strength. However, carbon reacts with aluminum to create a brittle compound (Al_4C_3) on the surface of the fiber. The matrix is the monolithic material into which the reinforcement is embedded and is continuous. This means that there is a path through the matrix to any point in the material, unlike two separate materials that are sandwiched together. In structural applications, the matrix is usually a lighter metal such as aluminum, magnesium, or titanium, and provides a compliant support for the reinforcement. In high-temperature applications, cobalt and cobalt–nickel alloy matrices are common. The reinforcement material is embedded into a matrix and does not always reinforce the compound, but is used to change physical properties such as wear resistance, friction coefficient, and thermal properties. The reinforcement can be continuous, or discontinuous. Discontinuous MMCs can be isotropic, and can be worked with standard metalworking techniques, such as machining with polycrystalline diamond tools (PCD) or grinding with bonded diamond tools. Continuous reinforcement uses monofilament fibers such as carbon fiber or silicon carbide that are embedded into the matrix. Discontinuous reinforcement uses whiskers or very short fibers, or particles. The most common reinforcing materials are alumina and silicon carbide fibers. Again, resin bonded diamond tools are usually used to grind MMCs.

Ceramic matrix composites (CMCs) are a sub-group of composite materials as well as being a sub-group of monolithic ceramics (MC). They consist of ceramic fibers embedded in a ceramic matrix. The matrix and fibers consist of a ceramic material. The use of long length multi-strand fibers increases cracking resistance, elongation and thermal shock resistance. The most common reinforcement is the continuous-length ceramic fiber that has an elastic modulus that is higher than that of the matrix. The role of the fiber increases the energy expended during crack propagation and bridges cracks without fracturing providing the composite with a high ultimate tensile strength (UTS). Ceramic fiber reinforcements increase the composite's resistance to crack propagation and allow CMCs to avoid brittle failure. This behavior is different from the behavior of ceramic fibers in polymer matrix composites (PMCs) and metal matrix composites (MMCs), where the fibers typically fracture prior to the matrix owing to the higher strain capabilities of those matrices.

Carbon (C), silicon carbide (SiC), alumina (Al_2O_3) and mullite (Al_2O_3–SiO_2) fibers are commonly used in CMCs. The matrix materials are usually the same materials as the fibers used for reinforcement. CMCs include a combination of type of fiber/type of matrix such as carbon-fiber-reinforced carbon (C/C), or C/SiC for carbon-fiber-reinforced silicon carbide. Commercially available CMCs are C/C, C/SiC, SiC/SiC and Al_2O_3/Al_2O_3. Owing to the higher toughness of CMCs, diamond cutting and grinding wheels are predominantly used to shape parts made from CMCs.

The characteristic of abrasive grains and their placement in an appropriate bonding agent has a significant effect on the quality of ground components made from composite materials. The next sections describe the importance of such characteristics.

2 Characteristics of Grinding Grains and Grinding Tools for Composite Materials

2.1 Shape

The shape of an abrasive grain impacts the grain strength, grinding performance, and packing characteristics that affects grinding wheel formulation and manufacture. Shape will affect the *r* term in the undeformed chip thickness (t′) equation:

$$t' = \left\{[Vw/(Vs.C.r)].(d/De)^{1/2}\right\}^{1/2} \tag{1}$$

where r is the ratio of undeformed chip width-to-chip depth (~5–20 depending on grain size), V_w is the workpiece speed, V_s is the grinding wheel speed, C is the average grain density, d is depth of cut and D_e is the equivalent diameter. This equation controls grinding power, finish and force per grain. Shape and size are interlinked especially for particles of indeterminate shape, i.e. an imperfect sphere, cube, etc. For synthetic diamond particles, there exists an infinite combination of particle shapes derived from the transition between octahedral and cubic shapes. Crystal imperfections and polycrystalline particles further add to the wide variety of diamond shapes. Recent developments in engineered ceramic abrasives have led to the manufacture of extruded seeded gel alumina grains that increase the size of porosity creating the conditions for making large open porosity grinding wheels. These grains allow large depths of cut to be taken and also allow coolant to flood the contact zone. Their aspect ratios vary from 4:1 to 8:1 and are very effective when grinding PMCs (Fig. 1).

A blocky rounded grain shape will be far stronger than an angular, sharp-cornered grain. Quantifying blocky and angular shapes and defining the characteristics key to the performance of shape have been the sources of study both for grinding performance and batch-to-batch quality control during grinding wheel manufacture. A

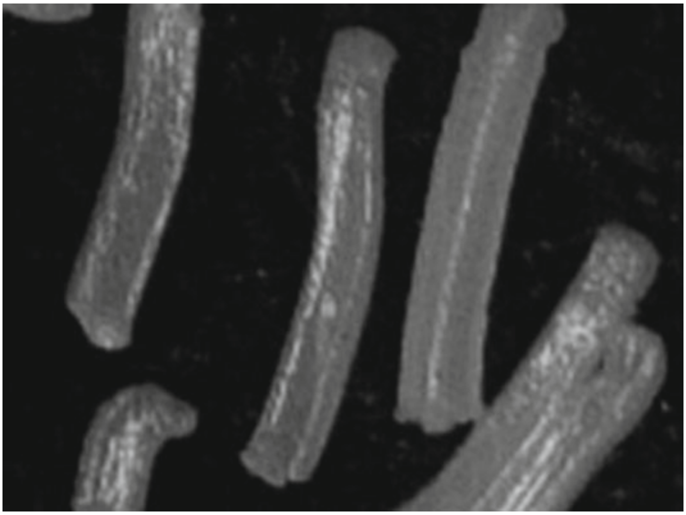

Fig. 1 Extruded seeded gel abrasive grains with high aspect ratio. (Courtesy of Philip Varghese of Norton-Saint Gobain)

variety of parameters describing the shape of particle projections, classified according to the feature of the measurement, are described by Jackson and Hitchiner [1].

Two key diametric dimensions are the major and minor diameters, d_a and d_b [1], which provide a fundamental measure of particle size (Fig. 2). Although size is an

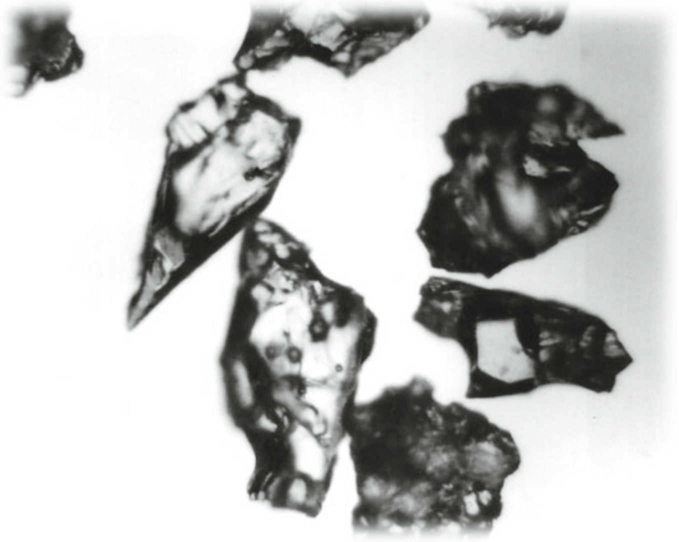

Fig. 2 A collection of defined shape abrasive grains

important feature, it is grain shape that governs the grain's abrasiveness. Algebraic combinations of linear dimensions provide measures of shape.

The calculated values from abrasive grain projections include:

(a) **Aspect ratio**, the ratio of the major-to-minor diameter d_a/d_b. A useful parameter to describe grain elongation and packing characteristics;

(b) **Projection area**, the area enclosed by the boundary of its projection. It is an indirect measure of size and bulk of the particle. It is an important component of the calculation of grain convexity; and

(c) **Convexity**, is a characteristic that strongly relates to the strength of the grain and its abrasive potential. A grain is convex if an idealized elastic membrane stretched across its projection leaves no space between itself and the grain's surface. The degree of convexity correlates with lower mechanical integrity but higher abrasive aggressiveness with the grain being, on average, less blocky. Convexity also correlates to the characteristic of grain irregularity. Convexity C as a parameter is defined as,

$$C = \left(A_f + A_p\right)/A_p. \tag{2}$$

where, A_p is the the projected area of the grain, A_f is the fill area between the grain projection and the idealized elastic membrane stretched across the projection [1].

(d) Grain '**sharpness**' is a parameter that has been developed specifically for the characterization of abrasive grains based on chip formation modeling where the rate of cutting is governed by the degree of penetration into the workpiece (Fig. 3).

The functional relationship between the two orthogonal areas, Ω and Λ, is known as the groove function and is shown in reference [1]. The function embodies the abrasive characteristics of an agglomeration of particles presented in a grinding wheel or on a coated abrasive product.

2.2 Abrasive Wear

Abrasive wear tends to occur progressively caused by interactions of the abrasive grain with the workpiece. These interactions are both physical and chemical, and are complex in nature. They can involve mechanical fracture (abrasion) and plastic deformation. Heat from friction and chip formation can lead to localized diffusion, chemical degradation and decomposition of the grain, and melting. The clean surfaces exposed by the creation of a chip are highly reactive and can drive chemical reactions that would normally occur at much higher temperatures. Even the presence of oxygen in the atmosphere has a profound effect by neutralizing the clean surface of the metal chip. Grinding in a vacuum will generally lead to high levels of loading from metal-to-metal contact and grain-to-metal adhesion.

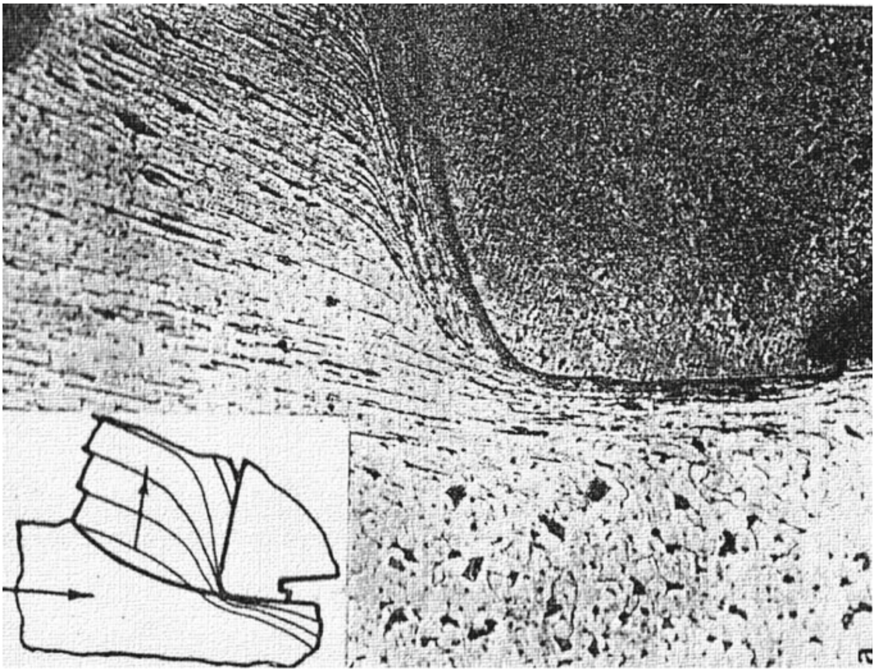

Fig. 3 Physical projection of the abrasive grain into workpiece showing penetration depth in relation to the abrasive grain

Hardness is the key factor in controlling abrasive wear characterized by mechanical micro-fracture and plastic deformation. In general a grain has to be at least 20% harder than the workpiece to be suitable as an abrasive. Temperature plays an important factor as localized temperatures can easily exceed several hundred centigrade and hardness of abrasives such as alumina decreases with temperature. The impact of hardness and other abrasive wear controlling factors can be seen by the comparison of typical G-Ratio values for the major abrasive type diamond and cubic boron nitride (cBN), alumina and silicon carbide grinding various industrial workpieces. When grinding polymer matrix composites (PMCs) with alumina the wear is essentially mechanical for each abrasive type especially at low wheel speeds where heat generation is minimal. The effect in this case of hardness is apparent. Diamond with its superior hardness provides a G-Ratio of typically 100 times greater than the second hardest abrasive, cBN, at slightly over half the hardness. Similarly, the G-Ratio for cBN is about 100 times higher than for silicon carbide with a similar proportional reduction in hardness. Alumina abrasive, with a hardness approaching that of the workpiece, gives a very poor G-Ratio and is in effect non-functional as an abrasive for MMCs and CMCs.

2.3 Abrasive Grain Fracture Toughness

Hardness provides a measure for the tendency of grain to wear by abrasive wear on the atomic scale, fracture toughness (or the inverse term known as friability) provides a measure for the loss of abrasive due to breakdown by fracturing or splintering of the grain typically at the micrometer level (micro-fracture) or macro and/or mesoscale (macro-fracture). The degree of fracture is in large degree dependent on grain properties such as crystal size and morphology, impurities, inclusions and pre-existing cracks, and shape. It is also dependent on the level and nature of the forces applied to the grain during grinding and from factors in the grinding environment such as rapid cooling from lubricant. Abrasive wear leads to the creation of wear flats that dramatically increases the force exerted on the grain and in turn leads to increased levels of fracture (Fig. 4).

Fracture toughness, particularly in diamond grains, is most commonly evaluated by a vibrating impact test. A grain sample of a known particle size distribution is placed in a tube with steel ball bearings and shaken with a fixed amplitude and frequency for a given length of time. The grain particle size distribution is then re-measured to assess the level of breakdown. The grain is either measured as received to give a Toughness Index (TI) value; or after processing at high temperatures, typical of those seen in wheel manufacturing process or use, to give a Thermal Toughness Index (TTI) value.

The high temperature processing can occur either in vacuum, or in the manufacturing atmosphere, or even after mixing with wheel bond that is dissolved with hydrofluoric acid subsequent to heat treatment. In general the TTI will be less than

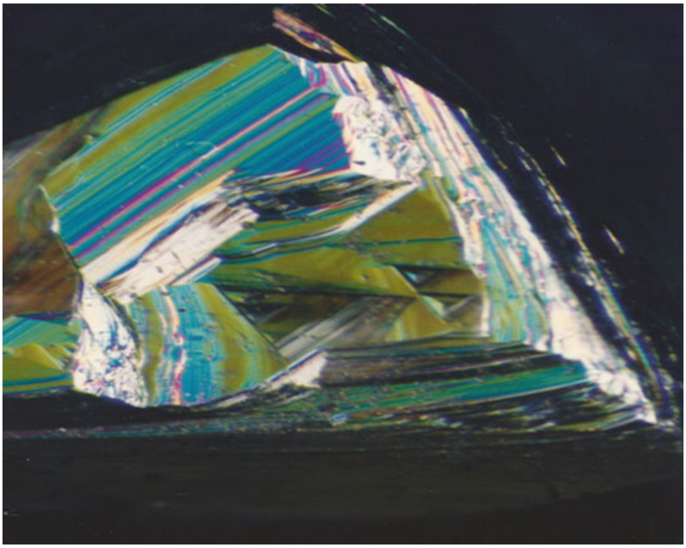

Fig. 4 Diamond grain showing wear flat and edge fracture

the TI as temperature causes the expansion of inclusions, reactions with the atmosphere, and infiltration of surface flaws with the bond. Where the grain has previously been through a significant degree of crush processing, especially for fused alumina grain, high temperature calcining can actually increase the TTI by annealing existing cracks. Crushing strength measurements are also made on single grains.

Methods of evaluating grain strength from fly cutting measurements using single grains have been developed. Evaluated grain strengths in terms of the onset of fracture for a given grain shape. Ten primary edge models for the morphology of fractured grains are typically used to characterize the fractured grains [1]. The probability of survival of an abrasive grain is given by the equation:

$$P_t = 1 - e^{-\gamma t} \tag{3}$$

where, γ is the fracture coefficient. Values for γ and primary fracture modes are shown in reference [1]. The technique distinguishes between alumina and SiC abrasive grains, showing the friable nature of the latter, as well as more subtle differences between various grades within a grain family. Grain toughness must be matched to both the wheel bond characteristics and the grinding conditions. Ideally the grain should fracture creating the loss of relatively fine particles typically at the micron or sub-micron level; a process termed micro-fracturing. The remaining portion of the grain should remain sharp and able to cut. If the grain is too tough relative to the bond holding it, or the grinding force per grain is extremely high, the grain is lost without doing any useful work. If the bond is strong enough to hold the grain but grinding forces per grain, and/or the grain crystallite size are large, then fracture is often caused by coarse loss of grain by macro-fracturing without the full amount of possible useful work being obtained.

If the abrasive grain is much weaker than the bond and/or prone to high abrasive wear due to mechanical, heat or chemical wear, then glazing occurs resulting in the creation of wear flats, high grinding forces and increased interface temperatures. Higher forces will lead to more fracture. The ideal stable state for wheel wear is a limited amount of abrasive wear controlled by micro-fracture. The maximum amount of wear flat area is set by the start of thermal damage. For ferrous materials this limit is about 1–2% of the wheel surface when using alumina or SiC abrasives, and about 4–5% when using cBN or diamond abrasives due to their higher thermal diffusivity or ability to remove heat from the grinding zone.

Fracture behavior is also important in terms of the abrasive grain's reaction to impact during dressing [1]. The application of micro-truing to grain structure is not limited to cBN and diamond. A growing awareness of the benefits of controlling fracture at the micro-level has led to the development of new family of engineered alumina abrasive grain structures. A description of conventional abrasives and bonding used used for those abrasive grains can be found in reference [1].

2.4 Medium Hardness Abrasive Grains

Properties of abrasive grains depend on the fusion process and its chemistry, but also on the comminution process. The cast ingot is initially split and sorted. Comminution is produced by passing the material through roll crushers. These processes create major fractures resulting in a grain that is sharp, flawed and anisotropic. Subsequent processing in steel- or rubber-lined ball mills reduces grain size by rounding the grain's edges to produce angular, or blocky, forms.

Fused aluminum oxide (brown): α-alumina containing 2–4% titanium dioxide that increases abrasive grain toughness. The most widely used abrasive in wheels to grind high-tensile-strength materials, and for rough grinding, deburring and snagging, low-alloy metals, ferrous materials. Brown, fused alumina is a tough, sharp but blocky abrasive. Depending on the processing regime, the grain is typically about 50% single crystal and can be provided in high, medium and low density configurations based on shape and packing characteristics. The grain may also be calcined after sizing to toughen it by annealing cracks generated in the crushing process. The material is sometimes termed blue fired (BFA) as the grain changes color due to surface oxidation of impurities. Specialty coatings such as silane (for resin-bonded wheels to resist coolant interactions) or red iron oxide (for resin- and rubber-bonded wheels to increase surface area) may also be applied to improve performance.

Low titanium dioxide content fused aluminum oxide: has 1–2% TiO_2 content, and is used in bonded or coated applications that require an abrasive that is slightly tougher than white aluminum oxide. Reducing TiO_2 content deteriorates the abrasive's toughness, but increases its friability. Light BFA is commonly used in depressed center wheels, cut-off wheels, and for surface and cylindrical grinding of heat sensitive metals and alloys, where fast cutting is required at lower temperatures.

Fused alumina (white): is standard multi-crystalline white, fused alumina (WFA) with sodium β-alumina contamination and is the most friable grain in the fused alumina family. It is considerably harder than BFA (Fig. 5a).

Single crystal fused alumina (white): is single crystal grain that has been produced in deep pour fusion pots and separated from any sodium β-alumina contamination. This is the hardest and most brittle of the alumina family of grains used most commonly for grinding tool and high alloy steels that are very sensitive to heat.

Pink alumina: is WFA to which less than 0.5% chromium oxide has been added during the fusion process to produce a grain that is slightly tougher than regular WFA. It is used for grinding unhardened high alloy steels (Fig. 5b).

Ruby alumina: is WFA to which 3% chromium oxide has been added to provide additional toughness over pink alumina (Fig. 5c). Used for grinding highly alloyed steels.

It can be inferred there is a steady increase in toughness but reduction in hardness in the following order: Single crystal WFA → WFA → pink WFA → ruby WFA → light BFA → BFA → Blue fire BFA. In general the wheel maker will blend various grain types and sizes to combine the properties of each. In addition to chromium, other metal oxide additions have been investigated including vanadium and beryllium.

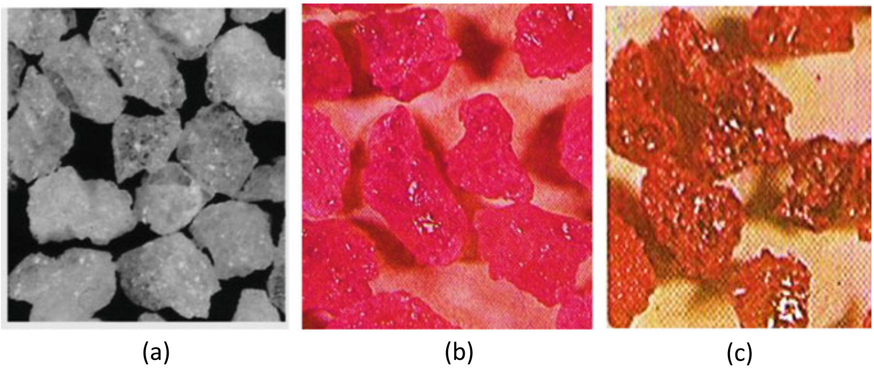

Fig. 5 Fused alumina: (a) white alumina; (b) pink alumina, and (c) ruby alumina (courtesy of Mike Hitchiner, Norton-Saint Gobain)

Sintered Alumina: is a family of grains developed in the 1950s produced from *unfused* alumina. Several processes exist based on both raw bauxite and Bayer processed alumina. The most common is to use a feed material of raw bauxite milled to <5 μm. The mix with binder is first extruded to produce rods which are cut into short cylinders, or cones, in the green state. They are then fired in rotary kilns at (1350–1500 °C) using natural impurities in the bauxite as sintering agents. The resulting grain is extremely tough especially at the relatively large sizes the technology allowed to be produced (8–20#) and the material found great success, until the advent of alumina–zirconia grain, in billet conditioning and other rough grinding operations. It is still used as a blend component with alumina–zirconia especially for the grinding of stainless steels (Fig. 6).

Engineered abrasive grains have microstructures that have been produced with controlled crystal sizes from the sub-micron to micron level by processes other than simple fusion and comminution. These include seeded-gel/sintering and agglomeration techniques. The result is a family of grain types that micro-fracture at controlled micron, or sub-micron, levels and have the ability to be trued, enhancing wheel life and process control compared with fused aluminum oxide grains.

Ceramic seeded-gel based abrasives—The development and commercial success of first sintered and extruded alumina family of grains followed by the development of rapidly chilled, fused alumina–zirconia grains had a major impact on the research programs of abrasive manufacturer regarding the importance controlling grain size. Furthermore, for alumina grains it was known that reducing the crystal size from the macro scale, common in fused material, to microscale grains (or ideally <0.5 micron sized crystalline grains) significantly enhanced grain properties such as hardness (Fig. 7).

Rather than using traditional fusing or sintering processes with the associated limitations on cooling and crystallization rates, it was possible to consolidate microstructures by sintering well dispersed sub-micron pre-cursors by the seeded gel route. This allowed the consolidation of α-alumina into a homogeneous and fully densified grain

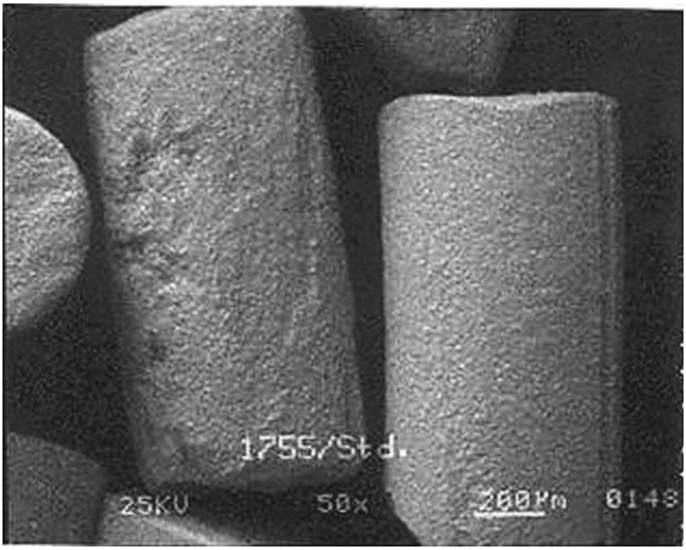

Fig. 6 Example of sintered extruded alumina grain (courtesy of Mike Hitchiner, Norton-Saint Gobain)

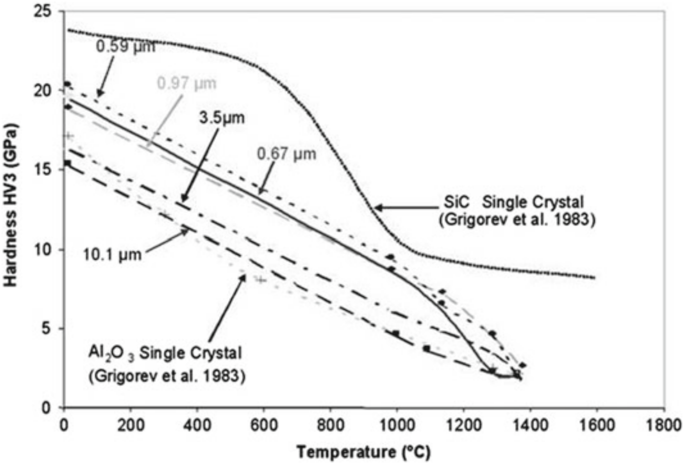

Fig. 7 Effect of crystal size and temperature on hardness of alumina grains (courtesy of Mike Hitchiner, Norton-Saint Gobain)

structure. The starting point of this new process is the manufacture of Boehmite, γ-aluminum oxide hydroxide (γ-AlO (OH)), from a modified version of the Ziegler process originally developed for the production of linear alcohols. The material is

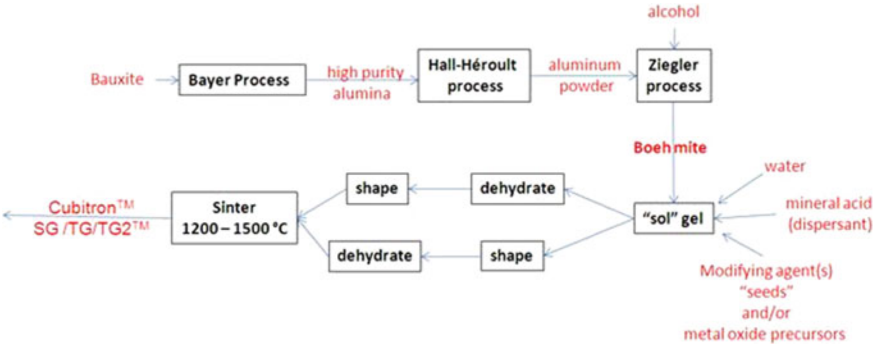

Fig. 8 Manufacturing route for production of "Ceramic" alumina grain (courtesy of Mike Hitchiner, Norton-Saint Gobain)

produced as a sub-micron powder which, mixed with water and a suitable acid dispersant, forms an agglomerate-free seeded-gel of aluminum hydrate ($Al_2O_{3.}$H2O) with a grain size ~100 nm. The seeded-gel is then dehydrated, shaped and sintered (Fig. 8).

Firing seeded-gel from Boehmite at 1400–1500 °C produces a large amount of porosity and relatively large grains of up >1 μm in size. This is due to high activation energy to convert from a transitional τ- to α-alumina phase resulting in infrequent nucleation with rapidly uncontrollable growth rates. Attempting to control growth rates with lower temperatures, e.g., 1200 °C, leads to larger crystals with higher porosity.

There are two routes that have been developed to reduce the activation energy and control crystal size and densification. The first is the creation of a bi- or multi-composite structure through the use of modifying agents, the second is the controlled creation of a single α-alumina structure through the use of seeding agents (Fig. 9).

Magnesium oxide (MgO) forms a bi-composite structure of α-alumina plus a spinel structure of magnesium aluminate ~25% by volume as shown in Fig. 9b. A fine acicular spinel structure within a relatively coarse α-alumina phase is apparent. This particular grain was used primarily used for low force coated abrasive applications. Multi-phase systems using various modifying agents including zirconia, manganese oxide, chromium oxide, nickel oxide and numerous rare earth oxides were developed over a period of time. One particularly effective material contains magnesia together with yttria and other rare earth oxides such as lanthana and neodymia to produce a dense and hard abrasive grain. In Fig. 9c, the microstructure shows a fine α-alumina phase with a sub-micron magnetoplumbite-type structure of needles and plates formed from adding modifiers to α-alumina. The structures created by the modifiers are believed to provide high strength and novel micro-fracturing properties.

The alternative route to control crystallization rates is by seeding the seeded gel with nano-sized (<100 nm) α-alumina particles, or other materials with a crystallographic match to α-alumina such as α-ferric oxide or various titanates. Additions of 1–5% of seeding agent creates a heterogeneous nucleation condition by increasing the number of nucleation sites from $10^{11}/cm^3$ to $10^{14}/cm^3$, and an average crystal

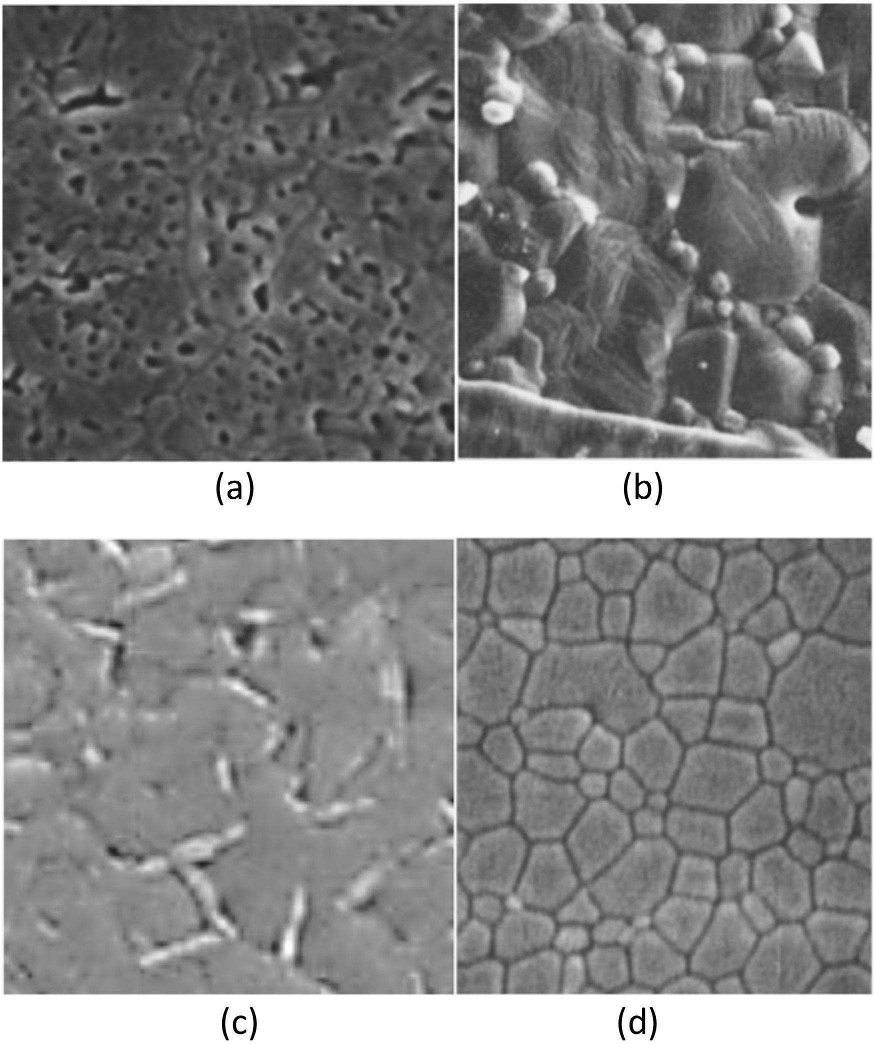

Fig. 9 **a** Sintered alumina microstructure from Boehmite with no modifying agent (image size: 3 μm × 3 μm); **b** Sintered alumina microstructure from Boehmite, with MgO modifying agent (image size: 3 μm × 3 μm); **c** Sintered alumina microstructure from Boehmite plus magnesia, yttria, lanthana and neodymia modifying agents (image size: 1.5 μm × 1.5 μm); and **d** Sintered alumina microstructure from Boehmite with seeding agent (image size: 1.5 μm × 1.5 μm) (courtesy of Mike Hitchiner, Norton-Saint Gobain)

size of about 400 nm (Fig. 9d). This type of grain is sold commercially under the name Norton SG™. One limitation of such a small crystal size is surface reactivity with vitrified bonds when making grinding wheels. Bonds had to be developed to be fired at <1000 °C rather than the 1200 °C of older bonds used for fused alumina abrasives. It is apparent that single-phase seeded microstructures are smaller than the multi-phase microstructures and would be expected to be harder and tougher than fused abrasives. It would also be expected to give longer life but require higher forces to micro-fracture when used as abrasive grain, or should be used at a lower concentration in a blended abrasive product. Further performance optimization can be obtained by bond formulation and grain shape. Seeded-gel manufacturing allows a much greater control of grain shape. Standard crushing and milling methods can produce a typically strong blocky or a weak angular shape. The angularity can be further increased by careful processing of soft, dried pre-sintered material (Fig. 10a–c). The grains are also weak but extremely successful if orientated correctly on a coated application with relatively low grinding forces.

Extruded rectangular prisms with extraordinary aspect ratios and having the appearance of smooth, surface defect free needles are shown in Fig. 10. Norton uses TG™ grains with an aspect ratio of 4–5, and TG2™ with an aspect ratio of 8 in their products (Fig. 10d). These grains maintain a high toughness but they also have a very low packing density. Typical blocky grains may pack to ~50% by volume; an extruded grain with an aspect ratio of 8 has a packing density closer to 30%. This provides for a very high level of permeability and excellent coolant access in the grinding wheel. Owing to the toughness, shape and ability to provide coolant, the stock removal capabilities can be enhanced to produce burn free surfaces on materials such as PMCs.

The most recent variant on the SG-type alumina abrasive is a grain called Norton Quantum™ (NQ™) which maintains the sub-micron crystallite size and associated hardness of the SG abrasive family of grains but has controlled levels of inclusions to promote micro-fracture the lower force levels (Fig. 11). This also allows the grain to be micro-trued with dress depths in the 5–15 μm range to generate sharp, fractured but durable cutting edges. Figure 11 shows the comparison between traditional seeded-gel abrasive grains (Norton SG™) and the submicron crystallite sized abrasive grains (Norton NQ™).

Agglomerated grains—The fusion process creates grains with crystallites comparable in size to the grain, i.e. 50–200 μm, while the seeded gel process creates crystallite sizes in 0.2–5 μm range. The latest edition to the engineered grain family is to produce agglomerated grains made by fusion, comminution, agglomeration, sintering, and re-communtion. The resulting grain has a controlled crystallite size that bridges the gap between SG™ and fused alumina. Since the size, shape and chemistry of the crystallites are controlled by the initial comminution process the possible variations in resulting grain grinding properties are enormous. Furthermore, the options for blending of SG™, NQ™ and Vortex™ grains in the same wheel offers an extraordinary range of complimentary grain properties.

As an example, it has been found that agglomerated grains pack to give a naturally high level of porosity in the resulting grinding wheel (Fig. 12). In addition to

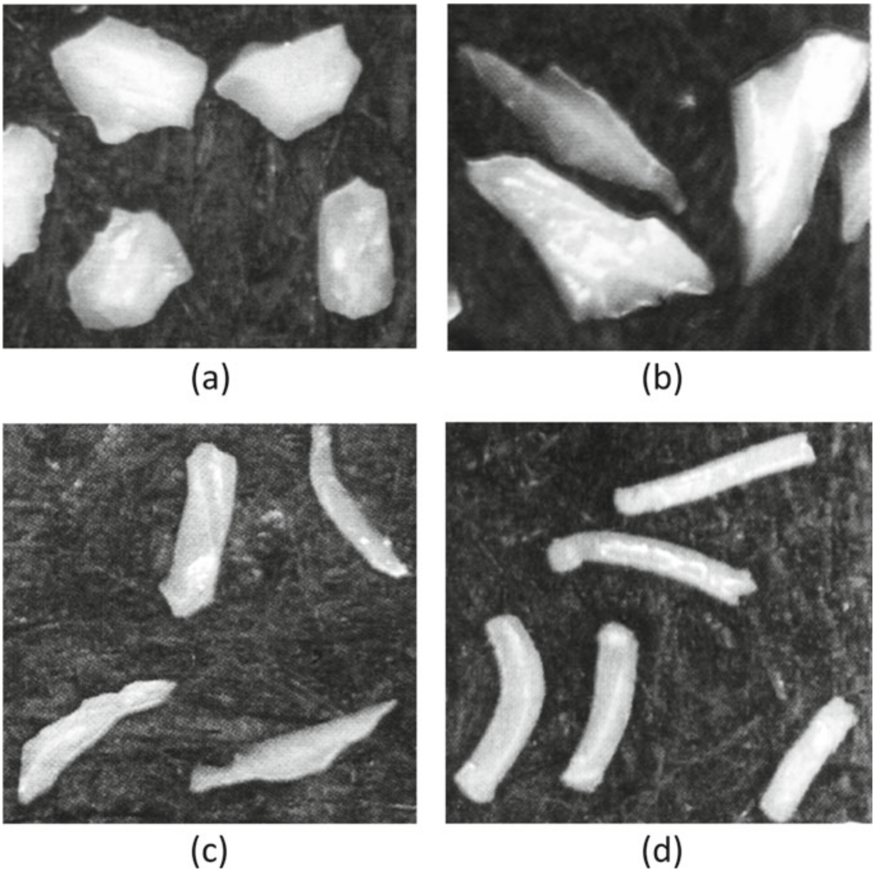

Fig. 10 **a** Tough blocky ceramic grain produced by milling; **b** Friable angular grain produced by crushing; **c** Weak extreme angular grain produced by crushing in green state; and **d** Extruded TG2$^{\text{TM}}$ ceramic grain (courtesy of Mike Hitchiner, Norton-Saint Gobain)

the creation of very sharp crushed crystallites in the initial comminution process combined with controlled strength, the agglomeration binder allows controlled crystals to break out to minimize the effects of wear flats, resulting in a very low temperature grinding zone on heat sensitive materials such as PMCs.

Conventional abrasives can be applied to the grinding of polymer matrix composites (PMCs) and applications of bonded abrasive products to the grinding of PMCs are described further in this chapter.

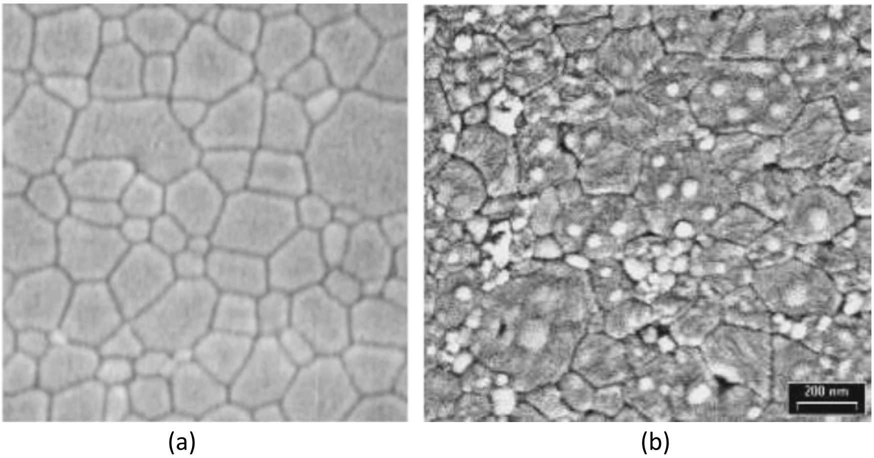

Fig. 11 **a** micro-structure of Norton SG™ seeded-gel alumina grain and **b** micro-structure of Norton Quantum™ NQ grain (courtesy of Mike Hitchiner, Norton-Saint Gobain)

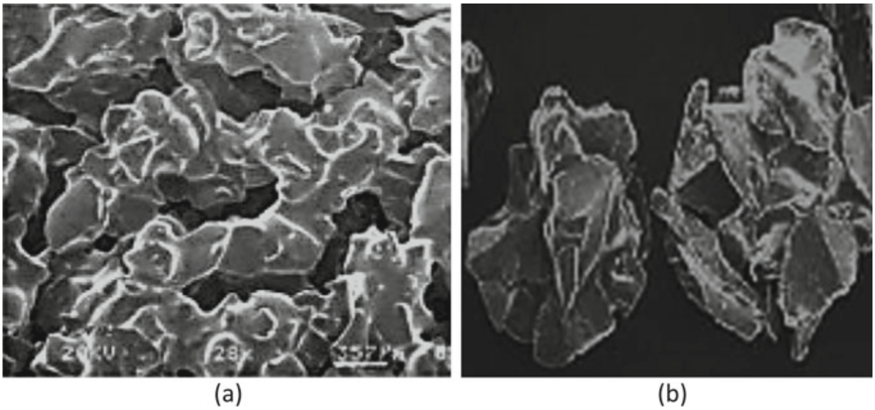

Fig. 12 Norton Vortex ™ agglomerated aluminum oxide grain **a** magnified image of open pores between grains and **b** Macro image showing agglomerated abrasive grains (courtesy of Mike Hitchiner, Norton-Saint Gobain)

2.5 High Hardness Abrasive Grains

Natural diamond, generally of a color, shape or inclusion level unpopular for the jewelry business, remains the standard for single point dressing tools and stones in rotary dressing form rolls. Crushed natural diamond is used in grinding wheels particularly in plated single layer products requiring abrasive grains with extreme sharpness and good convexity (Fig. 13).

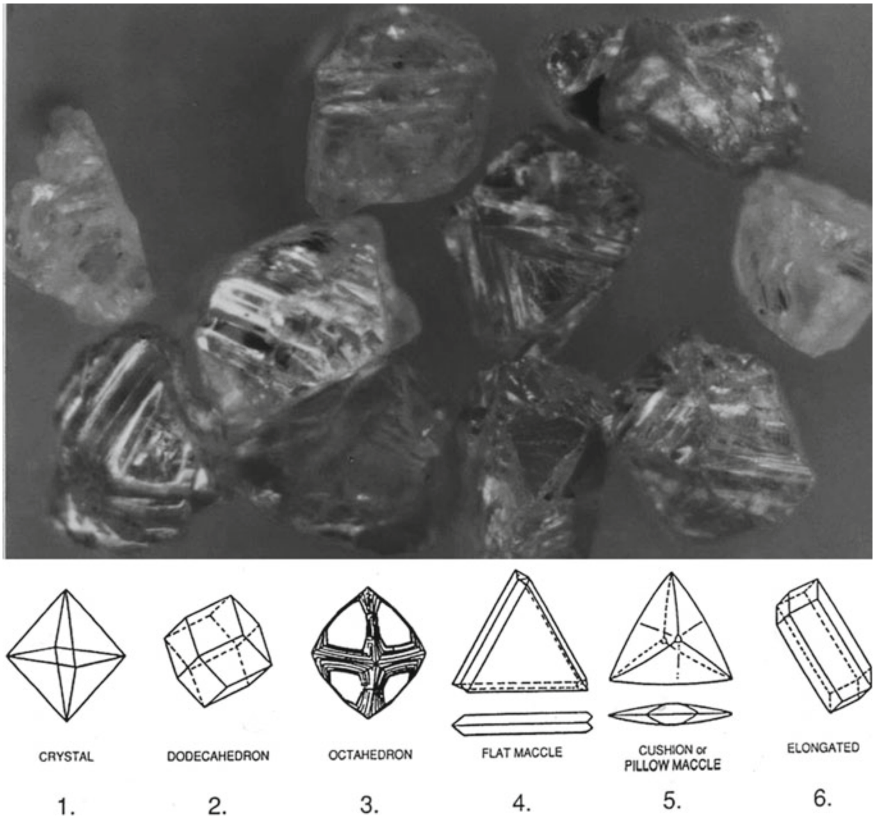

Fig. 13 Collection of natural diamonds of varying sharpness and convexity and their associated forms of habit

Natural diamond is formed at depths of 150–200m below the earth's surface under extreme temperature and pressure in the mantle. It may then be carried up in molten kimberlite and lamproite rocks where it is found at the earth's surface within alluvial deposits produced from erosion most commonly within old formations known as cratons. Large diamonds of the size used in dressing tools are believed to form and remain over great period of time in the mantle, but microdiamonds (<0.5 mm) are believed to form in kimberlite and lamproitic magma.

Some fields may contain predominantly micro-diamonds that were uneconomic due to the lack of traditional gem quality material. Furthermore, most of the major diamond deposits are in politically unstable areas of the world especially South and central Africa, although mines in Australia and Canada have recently become active while Russia has produced large quantities of both gem and industrial diamonds for many decades.

Synthetic diamond is created by the application of extreme high temperature and pressure to graphite precursors. The stable form of carbon at room temperature and pressure is graphite with its familiar layered hexagonal lattice structure. Although bonding within the lattice is sp^3 covalent, bonding between layers is Van de Waals bonding, resulting in low frictional resistance. Diamond, which is meta-stable at room temperature and pressure, has a cubic arrangement of atoms with sp^3 covalent bonding with each carbon atom bonded to 4 others. The direct conversion of graphite to diamond requires temperatures of 2500 K and pressures of >100 kbar. Diamonds produced by this route are termed high pressure, high temperature (HPHT). The severity of the growth conditions can be reduced significantly by the use of a metal solvent such as nickel or cobalt. Graphite has a higher solubility in these solvents than diamond; therefore at the high process temperatures and pressures the graphite dissolves in the molten solvent and diamond then precipitates out. The higher the temperatures, the faster is the precipitation rate and the greater the number of nucleation sites.

The earliest diamonds were grown fast at high temperatures and had weak, angular shapes with a mosaic structure. Also, the principal crystallographic planes of diamond are the cubic (100) plane, dodecahedron (011) plane and octahedron (111) plane. The relative rates of growth on these planes are governed by the temperature and pressure conditions and the metal solvent present. In general at low temperatures the primary growth plane is cubic, while at the highest temperatures is it octahedron.

Careful control of the growth conditions allows the shape to be engineered to specific applications. The blockiest and strongest form of diamond is the intermediate cubo-octahedral used in the strongest metal bonds for cutting or grinding composite materials (Fig. 14).

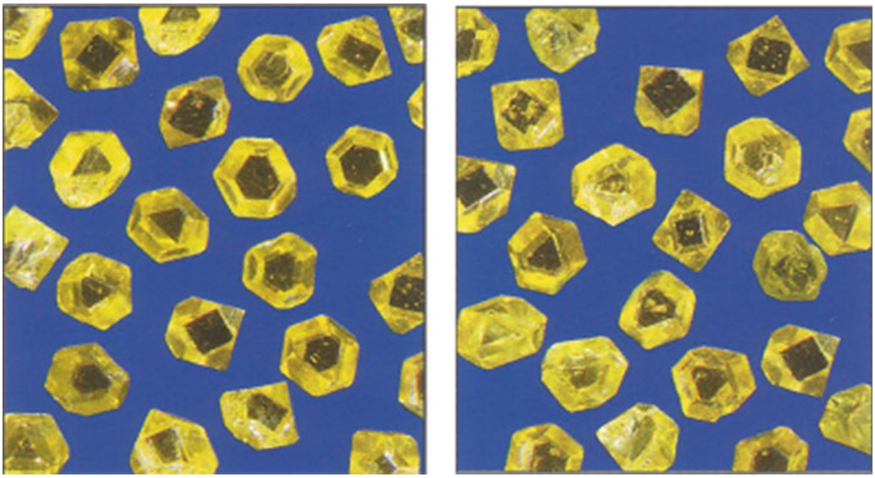

Fig. 14 Cubo-octahedral synthetic diamonds

High temperature and pressures are generated by three main press designs: the belt press, the cubic anvil press and the split-sphere (BARS) press. The belt press as developed for the first diamond synthesis consists of an upper and lower anvil applying pressure to a cylindrical inner cell or bombe. The pressure is confined radially by a steel belt. Belt presses with substantial bombe volumes have been developed in recent years for the growth of large single crystals. The bombe is doped with a seed crystal and a temperature gradient is created within such that diamonds are gradually and steadily deposited over a prolonged period of time. The resulting diamond crystal is then cut along specific crystallographic directions to produce needles and blocks suitable for diamond dressing tools. Owing to the superior hardness associated with diamond, MMCs and CMCs are typically ground with diamond embedded in resin, vitrified or a tough, or brittle, metal bond.

2.6 Grinding Products for Composite Materials

Abrasive grains are mixed with bonding agents in order to make products for grinding composite materials. A variety of products can be used with composite materials such as grinding wheels, coated abrasives, microfinishing tape, and diamond tools for correcting the truth of wheels. A selection of products is shown in Fig. 15. The products produced are optimized for use on composite materials and contain a careful selection of grain, bond and fillers to achieve the requirements specified by the user of those products.

A careful blend of both passive and active fillers are added to bonding systems based on the type of composite ground and the environment in which they are ground. For PMCs, conventional abrasives with both vitrified and resin bonds are typically used, while for MMCs and CMCs, diamond abrasive grains in resin, vitrified and metal bonds are used depending on the power developed by the machine tool, the specific metal removal rates and other operational factors associated with cross feed, linear feed, depths of cut and coolant application in order to minimize the melting of the matrix of the composite material and subsequent fiber pull-out.

3 Grinding of Composite Materials

The grinding of composite materials is becoming a significant part of industrial and academic research in recent years, especially with the advent of highly sophisticated aircraft components made with MMCs and CMCs. The following section describes some recent activities reported in the scientific literature [2–26].

Fig. 15 A selection of abrasive products commonly used for the processing of composite materials (courtesy of Mike Hitchiner, Norton-Saint Gobain)

3.1 Polymer Matrix Composites (PMCs)

El Wakil [2] describes the grinding of PMCs as being more difficult and complicated than the grinding of metals. He states that the direction of fiber ply is critical in achieving the right result and that conventional polymer matrices tend to melt if the grinding zone becomes too hot. A minimum bonding matrix of 30% by volume is required to prevent fibers from being pulled out due to the rotation of the grinding wheel. El Wakil suggests using a softer aluminum oxide grinding wheel such as WA46I8V, i.e., 46 grain size, I-hardness, 8-structure, vitrified bond. When compared to a harder wheel, the softer wheel gave better surface finish results and did not burn the polymer matrix [2]. Wang et al. [3] also ground PMCs and found that lower grinding forces are generated with high abrasive grain size and a lower concentration of abrasive. However, the opposite effect was noted for lower grain size and higher grain concentrations. Surface roughness was significantly improved using the latter specification [3]. From the research studies published so far, PMCs appear to be produce the best results when vitrified alumina grinding wheels are used at low cutting speeds.

3.2 *Metal Matrix Composites (MMCs)*

For the processing of Al/SiC/Graphite MMCs, electrical discharge abrasive grinding techniques are known to be very effective in producing good surface finishes [4]. A high metal removal rate and high wheel speed (~1300 rpm) are known to produce the best results [4–6]. Resin-bonded diamond wheels appear to be better at producing good surface finishes at high wheel speeds and depths of cut [6]. The resin bonded wheels were compared to electroplated wheels and it was found that electroplated grinding wheels tended to wear quickly probably due to the reduced amount of clearance between abrasive grains and the body of the wheel. The use of modelling techniques for the analysis of grinding MMCs was conducted by Di Ilio et al. [7] focusing on the relationship between cutting parameters and grindability. They concluded that the sliding component of grinding energy was negligible and that the normal and tangential components of grinding force were linear. They also showed that workpiece roughness decreased as the hardness of the MMC increased [7].

Wheel speed is slightly affected by metal removal rate [8, 9], whereas the removal rate is influenced strongly by electrolyte concentration and the magnitude of current in electrical discharge grinding of MMCs with peripheral wheels [10–12] and slotted grinding wheels [13]. In studies focusing on the mechanical properties of ground MMCs [14] and MMCs reinforced with alumina and SiC particles [14], resin-bonded diamond wheels produced no subsurface damage to the composite compared to vitrified SiC grinding wheels that produced significant amount of subsurface damage. It is expected that grinding with resin-bonded diamond wheels improves the fatigue life of ground MMCs compared to using conventional abrasives in a stiff bonding matrix [14]. A brief synthesis of the literature tends to suggest that resin-bonded diamond grinding wheels are best suited to grinding MMCs at reasonably high cutting speeds.

3.3 *Ceramic Matrix Composites (CMCs)*

Ceramic matrix composites are a new form of composite materials with enhanced properties owing to their hybrid construction. Their processing is described very well in a paper by Singh et al. [15] through methods such as solid state processing, seeded gel formation, laser synthesis, processing using the Pechini method, melt synthesis, co-precipitation and hydrothermal synthesis. New developments include spray and plasma drying, ball milling and mixing and final sintering of CMCs [15, 16]. C/SiC CMCs have been noted to fail by fibers being extruded from their matrix rather than being pulled out of the matrix [16]. This is thought to be caused by the direction in which grinding takes place rather than on operational parameters such as grinding wheel speed or metal removal rate. The authors also found that surface finish was dependent on fiber characteristics rather than the undeformed chip thickness [16]. Singh and Rao [17] found that improvements in grinding CMCs were achieved by cryogenically cooling the surface of the CMC to form brittle grinding conditions. Subsurface damage was also minimized according to their experimental study.

Wang and Lin [18] studied the grindability of CMCs using electron microscopy techniques. They discovered that the normal and tangential force components act differently to the grinding of metals and is a function of fiber orientation and direction. They also stated that the machine tool used needs to be stiff, powerful and have dynamic performance characteristics that produce a very good surface finish on CMCs. They also stated that wheel durability is also an issue that needs to be addressed in order to make the grinding of CMCs economically viable [18]. Tawakoli and Azarhoushang [19, 20] studied the use of a segmented wheel for grinding CMCs. They noticed that rubbing and plowing regimes were reduced due to intermittent cutting which improved surface finish and grinding force magnitude. An increase in grinding ratio was also observed [19]. A special ultrasonic-assisted grinding method was developed that improved G-ratio even further and reduced tangential and normal forces [20]. Surface waviness of ground CMCs was investigated by Cao et al. [21] to understand how waviness is affected by grinding.

Their studies implied that the work would further enhance the understanding of assembling, sealing and the lubricity of CMCs. Polymer concrete structures were the focus for Shamray et alia's [22] work associated with grindability. The purpose of the study was focused on finding ways to accurately grind polymer concrete structures and to use them for vibration dampening applications such as machine tools. They concluded that grinding forces are substantially less with polymer concrete compared to steel structures [22].

The development of CMCs in large part is due to increased use of these materials in the aerospace industry [23, 24]. Pratt and Whitney in the USA recently published their growth plan for geared turbofans and described the requirements for the development of new materials. As a result of the growth plan, engineers at Norton-Saint Gobain have already started characterizing the grinding characteristics of these materials [25].

Further studies on the grinding of CMCs for aerospace applications were published by Hitchiner et al. [25] and compared the grindability of other materials of interest such as γ-titanium aluminide [26]. Their studies showed that CMCs have better grindability than monolithic ceramics (MC) using standard resin-bonded diamond grinding wheels. The relationships between specific grinding energy, G-ratio and specific material removal rates are shown in Figs. 16 and 17 [26].

4 Conclusion

The expected growth in the use of composite materials can only be matched by the ability to process these materials in an economically feasible manner. As the complexity and difficulty in machining these materials become more prevalent due to the development of MMCs and CMCs and their hybrids, the more likely grinding will become the standard route for processing. The current published knowledge is

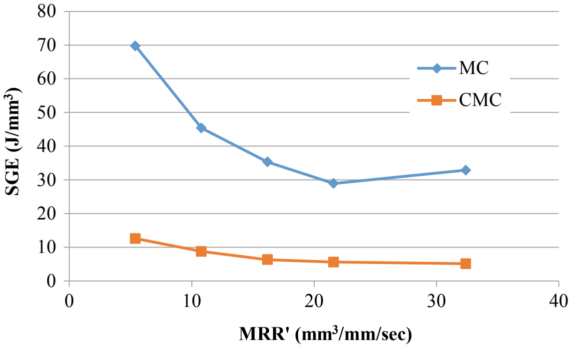

Fig. 16 Specific grinding energy (SGE) versus specific material removal rate (MRR') when grinding CMCs and monolithic ceramics (MC). (Courtesy of Philip Varghese of Norton-Saint Gobain)

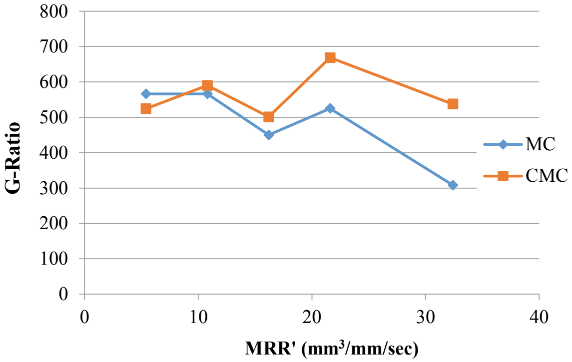

Fig. 17 Grinding ratio (G-ratio) versus specific material removal rate (MRR') when grinding CMCs and monolithic ceramics (MC). (Courtesy of Philip Varghese of Norton-Saint Gobain)

limited at this time but can be expected to grow as demand for these materials grows ever larger. It is expected that the material presented in this chapter will stimulate further investigations into the grindability of advanced composite materials. It is speculated that the effects of abrasive grain behavior and that of the bonding agent will further ignite the development of new abrasive products to grind composite materials and their hybrids. Indeed, fundamental understanding of tribological interactions between grain, bonding agent and workpiece material has already started and will further allow grinding to be transformed into a science rather than a practical art.

5 Review Questions

(1) Describe the differences between PMCs, MMCs and CMCs.
(2) Explain the mechanism of composite failure in CMCs and why they are different to the failure mechanisms exhibited in PMCs and MMCs?
(3) What are the essential characteristics of the undeformed chip thickness equation? What is r and how is the grain's aspect ratio defined?

(4) What effect does grain shape have on the magnitude of the undeformed chip thickness?
(5) If r is equal to 10, what is the size of the undeformed chip thickness compared to a value of 20?
(6) What is the concept of convexity applied to an abrasive grain?
(7) Describe the mechanisms of abrasive fracture.
(8) What is grain toughness and how would you define grain strength?
(9) Describe the differences between conventional abrasive grains.
(10) What are engineered abrasive grains and how does the microstructure of those grains significantly improve grinding performance of PMCs?
(11) How are MMCs and CMCs ground and what type of abrasive is used for those materials?
(12) Describe the mechanisms of fiber pull-out for PMCs and explain how failure mechanisms differ for CMCs compared to MMCs.
(13) What are monlithic ceramics and how do they compare with CMCs?
(14) Which is easier to grind, MCs or CMCs? Explain your answer in terms of grinding characteristics and the formulation of the grinding wheel used to grind these materials.
(15) Agglomerated abrasive grains offer a great deal of advantages in terms of improved grindability for composite materials. Justify this statement in terms of abrasive grain and grinding wheel formulation.

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