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Background and Overview

1.1 INTRODUCTION

Most books on making ceramic bodies focus on the dominant technology of consolidating and densification of (primarily chemically derived) powders, mainly via sintering [1-3]. These books provide valuable insight into the underlying scientific principles that control such processing, as well as provide useful information on many of the process parameters, but their perspective on choice of fabrication method(s) is a basic one rather than an engineering one. Thus, such books generally have limited or no information on many of the important engineering or cost aspects of producing ceramic components. Further, even within their more basic scope, they are generally focused on the most common methods, e.g., of liquid chemical preparations of powders and their die pressing and sintering. Generally, they provide limited or no information on other methods of producing ceramic components, e.g., of chemical vapor deposition (CVD) or various melt processing routes, and typically no information on the property and engineering trade-offs between different basic production methods or within variations of a given approach, such as sintering of bodies from different forming methods. Thus, while existing books address the use of additives in densification, they do so only in broad terms of liquid-phase sintering, not by discussing specific additive uses for sintering, and they do not address a number of other additive uses. Further, there is limited discussion of the shape, especially

of component size, capabilities of the processing and fabrication technologies addressed, nor their cost aspects.

At the other extreme there are books that focus more on specific engineering aspects, for instance, specific formulations, including uses of both additives and of binders, but mainly for more traditional ceramics [4], for which such information is generally known, but is often proprietary for many newer ceramic materials. There are also some books that focus on specific powder fabrication/forming techniques [5-8], as well as on some other fabrication techniques, mainly CVD [9,10].

This book is intended to complement and supplement previous books by providing a much broader perspective on ceramic fabrication, which is defined as the combination of various process technologies to produce monolithic or composite ceramic pieces/components within given shape, size, and microstructure property bounds for a given composition. The focus is on higher performance monolithic ceramics, but with considerable attention to ceramic composites, especially particulate composites, as well as attention to some specialized bodies, e.g., those of designed porosity. This book is not intended to be an engineering fabrication "cookbook" since many of the technologies are not in production, and many that are may have various proprietary aspects. Instead, it is meant as a guide to the technological alternatives for practical application for those concerned with development of practical fabrication technologies beyond laboratory preparation of specimens for research purposes. Thus, while a broad range of topics is addressed for completeness, emphasis is given to technologies that are addressed less or not at all in previous books, but have known or potential practicality. Hence, while, both conventional and alternative powder-based fabrication are addressed, considerable attention is given to both CVD and melt processes, as well as to reaction processing. Further, the use of additives in all of these processes is reviewed, and specific attention is given to the issue of size and shape capabilities of different fabrication methods. Also, to the extent feasible, cost aspects are addressed, and examples of specific engineering extension of limits of given fabrication technologies are given. Finally, some overall trends and opportunities are discussed.

Before proceeding to the discussion of the various processing/fabrication technologies of subsequent chapters, four basic topics are addressed in the following three sections, the first being rational—why ceramics and opportunities and challenges to selecting candidate ceramics. Then, broad issues impacting ceramic development and application are discussed, followed by discussion and illustration of costs and trade-offs. Finally, some overall engineering factors are discussed, particularly sizes and shapes achievable, as well as possibilities of joining, and their associated costs and ramifications. These topics are treated in this chapter from a wide perspective, while some of these factors are discussed in more detail where specific fabrication technologies are addressed. These are

large subjects that can only be illustrated and summarized here (especially production costs) to provide guidance and awareness of their parameters, variations, and importance.

1.2 WHY CERAMICS AND WHICH ONES

The first decision to be made in selecting material candidates for an application is to determine which types of materials to consider. This commonly entails both fabrication and cost issues discussed below, especially where ready availability is desired or required, and significant development is not realistic. However, a basic question for many needs, especially longer term ones, is, What material candidates have the best intrinsic property potential to meet the requirements of the application, especially if they are demanding? This is especially true for ceramics and ceramic composites, since there is such a diversity of materials and properties, with much of their potential partially or substantially demonstrated, but often untapped. This potential arises from both the extremes and the unique combinations of properties that are obtainable from the diversity of ceramic materials.

Perspective on diversity can be obtained by remembering that solid materials can be divided into nominally single-phase materials that are polymeric (mainly plastics or rubbers), metallic, or ceramic, or into two- or multiphase composites of constituents from any one of the three basic single-phase materials, or combinations of two or three of the single-phase materials. Ceramics, or more specifically *monolithic ceramics*, are thus defined as nominally single-phase bodies that are not composites nor metals or polymers. While this includes a few elemental materials such as sulfur, or much more importantly, the various forms of carbon, the great bulk and diversity of ceramics are chemical compounds of atoms of one or more metallic elements with one or more metalloid or nonmetallic elements.

The more developed ceramics are mostly compounds of two types of atoms, that is, binary compounds, which are typically classified by the nonmetallic or metalloid anion element they contain—for example, compounds of metals with nonmetals, such as oxides and nonoxides, the latter including borides, carbides, halides, nitrides, silicides, and sulfides. Key examples are listed in Table 1.1. However, there are a variety of known ternary ceramic compounds formed with a third atom constituent. Those that contain either two metallic and one metalloid or nonmetallic types of atom continue to be classified as carbides, oxides, etc., as for binary ceramics. However those containing one type of metallic atom with two types of atoms of either metalloid or nonmetallic designation or a combination of one of each, are named by their latter atoms, e.g., as carbonitrides and oxysilicides, for compounds containing carbon and nitrogen or oxygen and silicon atoms, respectively. There are also higher-order ceramic

TABLE 1.1 Some Properties of More Common Refractory Metals and Binary Ceramics^a

Material		Density (g/cc)	MP (°C)	CTE (ppm/°C)	E (GPa)	Other
A) Refractory metals	Nb	8.4	2470	9	100	Ductile
	Ta	16.6	3000	8	190	Ductile
	Mo	10.2	2620	8	320	
	W	19.3	3400	7	420	
	Re	22	3180	7	480	Expensive
B) Borides	HfB ₂	11.2	3250	6–7		Decomposes
	NbB ₂	7.2	2900	9		
	TaB ₂	12.6	3000	6–7	260	
	TiB ₂	4.5	2900	7	500	
	WB ₂		2900			
	ZrB ₂	6.1	3000	8	450	
C) Carbides	HfC	12.7	3880	7	430	Sublimes
	SiC	3.2	2600	6	450	
	NbC	7.8	3700	7	450	
	TaC	14.5	3700	9	450	
	TiC	4.9	3140	9	450	
	ZrC	6.7	3450	8	420	
D) Nitrides	BN	2.2	3000	High crystalline anisotropy		Sublimes
	HfN	13.9	3300	7		α-emitter
	TaN	14.1	3200	5		
	ThN	11.6	2800			
	TiN	5.4	2950	10	260	
	ZrN	7.4	2980	8		
E) Oxides	BeO	3	2500	8	400	Toxic
	HfO ₂	9.7	2750	11		
	MgO	3.6	2800	16	350	Hydrates
	ThO ₂	9.8	3200	11	240	α-emitter
	ZrO ₂	5.7	2715	12	230	

^aMP = melting point, CTE = coefficient of thermal expansion, and E = Young's modulus.

compounds, that is, ceramic compounds consisting of four or more atomic constituents that are generally much less known. Such higher-order compounds offer opportunity for extending ceramic technology via more diverse properties.

The diversity of ceramics and their properties is significantly extended by the fact that the properties of a given ceramic compound can be varied, often substantially, by changing microstructure via differences in fabrication/processing, which is extensively discussed elsewhere [11,12]. The diversity is also significantly extended by addition of one or more other ceramic compounds that form a solid solution with the base ceramic compound. The limitations of such solid solution extension of properties are the limits of solubility due either to precipitation or reaction, or both. However, these limits on solubility also provide more specialized ways of extending the range of ceramic properties via ceramic composites, i.e., ceramic bodies consisting of two or more ceramic phases that have limited or no mutual solubility and a considerable range of chemical compatibility. More extensively, ceramic composites are made by consolidating mixtures of composite phases, which are classified by the character of the additional, usually second, phase, that is, particulate, whisker, platelet, or fiber composites, which are addressed in this book, generally in decreasing extent in the order listed.

The resultant diversity of ceramic properties from all of the ceramic compounds, their solid solutions, and composites is illustrated in part by a very abbreviated listing of some properties of the more refractory members of the more common and more extensively developed binary ceramic materials in Table 1.1. Note that other binary systems have refractory compounds, for example, sulfides and phosphides with melting points of 2000 to 2500–2700°C, and many systems with compounds having melting points of 1500–2200°C or above. Also note that, while ternary and higher-order compounds typically have lower melting temperatures than the more refractory binary compounds, this is not always true.

The property diversity of ceramics is further shown by the following observations addressing the six categories of functional properties: (1) thermal-chemical, (2) mechanical, (3) thermal conduction, (4) electrical, (5) magnetic, and (6) electromagnetic. Thus, there are a number of ceramics that have among the highest potential operating temperatures, approaching their melting points at and above those of their only other competitors, the refractory metals (Table 1.1), and have the highest energies for ablation, especially in the absence of melting, as is the case for important ceramics that commonly sublime without melting. Further, the diversity of ceramic compositions provides candidates for a diversity of environments, for example, halides for halide environments and sulfides for sulfur environments, as well as the formation or application of at least partially protective coatings that are chemically compatible with the ceramic substrate.

Considering mechanical performance, many ceramics have high stiffness and high melting points, reflecting the strong atomic bonding. While stiffness generally decreases with increasing temperature, as for other materials, it is typically an important attribute of many ceramics across the temperature spectrum. High bond strengths of many refractory ceramics also correlates with their high hardnesses, which tends to correlate some with armor performance and especially with much wear and erosion resistance, as well as with compressive strengths that can also be of importance at high temperatures, but are typically more important at modest temperatures [2,11,12]. Tensile strengths, though being particularly sensitive to microstructural and thus to fabrication process parameters, also correlate in part with elastic moduli, and can be quite substantial over a broad range of temperatures. Also note that some ternary compounds (such as mullite and perhaps higher-order compounds) can have much higher creep resistance than their more refractory binary constituents. At the extreme of mechanical precision, many ceramics offer the highest degrees of precision elastic stability, i.e., dimensional stability under mechanical and thermal loading, which is typically most pronounced and important at modest temperatures [12].

Different ceramics have among the lowest intrinsic thermal conductivities and others the highest ranges of thermal conductivities, with even more extremes shown for electrical conductivity or resistivity. This includes both highest-temperature superconductors (TiN and TiC) prior to the discovery of much higher-temperature ternary and higher-oxide superconductors of extensive interest for about the past 10 years. Some ceramics also have the highest resistance to dielectric breakdown, hence the ability to be good insulators even under very high electrical fields, as well as other important electrical properties [2,11,12]. These include high-temperature semiconductors for a variety of applications and ionic conductors for diverse applications, such as advanced fuel cells and batteries, as well as sensors. Of particular importance for many technological applications are ferroelectric and related electrical properties, especially in some ternary ceramics, which like many other properties are most often of particular importance at or near room and moderate temperatures. This is commonly also the case for their important magnetic and electromagnetic properties, but elevated temperature performance of such functions can also be important.

While a single property may drive applications, unique combinations of properties are commonly an important factor. Thus, for example, good magnetic properties in nonconductive, i.e., dielectric, ceramics is an important factor in their magnetic applications, while application of the transparency of dielectric ceramics to ultraviolet (UV), visible, infrared (IR), microwave, and other electromagnetic waves is often made due in part to the temperature capabilities of many ceramics. These and other applications are also often partly driven by the substantial hardnesses of many ceramics as reflected in their resistance to wear, erosion, and ballistic impact, for example, for transparent armor windows.

The challenge of fabricating ceramic components for various applications requires that the properties and performance sought be obtained in a reliable and cost-effective fashion. However, both these goals of suitable reliability and cost are dependent on the impacts of component composition as well as size, shape, and dimensional-surface finish requirements on fabrication routes, and the parameters of the processing techniques within these routes.

The properties sought are usually determined by the composition of the body, mainly by the compound selected. However, there may be uniform, heterogeneous, or both variations in either the composition of the ceramic compound sought, other constituents or impurities in solid solution or as second phases, or combinations of these. Thus, some compounds are very stable in composition during use, but others are less so, while fabrication processing parameters may often present greater problems of composition stability. For example, some oxides such as Al_2O_3 , BeO , and SiO_2 are quite stable, while others such as oxides of Ce, Ti, and Zr are less so, such that they may be reduced from their normal oxygen stoichiometry in varying degrees, depending on the extent of reducing conditions, temperatures, and times of exposure. Component sizes and shapes are key factors in resultant composition gradients and their effects. Such reduction can be very detrimental to some uses, especially electrical and electromagnetic and sometimes mechanical properties, as well as some possible use in special cases. Similar, though often less extreme effects of stoichiometry deviations may occur with useful nonoxide ceramics. Both the presence of impurities and use of additives can be important issues, since increased purification typically means increased costs and may have other ramifications on fabrication, as additives may be important in fabrication but present limitations in use. Chapter 3 addresses the use of additives in preparation of ceramic raw materials that, while having some desirable effect, may retain some impurities, variations in composition, or both. Chapter 5 extensively addresses use of additives in fabrication.

Another basic impact of fabrication on properties is its effects on microstructure, which arise for both intrinsic and extrinsic reasons, the latter often reflecting effects of chemical or physical heterogeneities in the body. The reason for this is that microstructure plays an important role in many properties, with the most critical microstructural factor being porosity. While porosity is critical to some important applications such as catalysis or filtration, and can also aid some other properties and applications, it commonly significantly reduces many important properties, such as mechanical and optical ones [11]. Thus, a fraction of a percent of porosity that scatters visible light may render a potentially transparent ceramic window ineffective for its purpose, while the $\sim 5\%$ porosity left from much sintering can reduce many mechanical properties by 10–25%. Next most significant is grain size (G), with many mechanical properties increasing as G decreases, by $\sim 50\%$ or more as G goes from ~ 100 to $\sim 1\ \mu\text{m}$, but other properties may be unaffected by G or increase with increasing G [12]. In composites

the dispersed particle size plays a similar role as G in monolithic ceramics, but the matrix grain size also still has similar effects in composites as in monolithic ceramics, though it may be more restrained in grain growth by the dispersed particles. Heterogeneities of grain and particle structure and porosity, as well as impurities or additives, can also be important in limiting levels and reliability of properties. All of these microstructural effects are impacted by the ceramic, the fabrication route, and processing parameters selected for a given application.

The above diversity of ceramic performance based on both the diversity of ceramic materials and on impacts of fabrication via effects on microstructure is a double-edged sword. On the one hand, performance diversity provides wider opportunity for application. On the other hand, it can dilute resources between possible competing candidates, which may jeopardize success of any candidate. It can also mean that the candidate that may be implemented is not the best one overall, but the one that required less development; however, once established, it is harder to replace with a potentially superior candidate. Such trade-offs are impacted by specific economic factors (see Sec. 1.4), as well as by larger political and economic factors. (see Sec. 1.3).

1.3 POLITICAL AND ECONOMIC FACTORS IMPACTING DEVELOPMENT AND APPLICATION OF ADVANCED CERAMICS

A major change reducing opportunities for development and application of ceramics (and other advanced materials) was the end of the cold war's reduction of military-aerospace funding. It probably also reduced opportunities for advanced processing and materials development, such as of ceramics with potential for extremes of performance, by shifting the balance from more impetus on performance to more on availability/affordability. This made such funding decisions driven even less by technology push, which is rare in general industry, where market pull dominates as the driving force for new technology. Thus, for example, implementation of some military systems, such as phased-array radar, was paced by the commercial development of cost-effective applicable technology developed in volume for home microwave ovens. Also, for perspective, it should be noted that the primary justification for one of the earlier major ceramic turbine engine programs was driven primarily by geopolitical concerns of the cold war for the availability of elements such as Cr, Co, and Mn critical for super-alloys in hot sections of metal turbine engines, to potentially be replaced by Si from sand and N from the air. Improved fuel efficiency was also cited as a benefit, but was not a major driving force, especially when oil costs were not high. Such efficiency provides much less driving force in the consumer market as shown by poor sales of fuel-efficient cars in the past, except when gas was scarce. The high sales of higher-fuel-consuming sport utility vehicles in recent

years in part resulted from low fuel costs. More recent justifications for ceramics in turbines have focused on reduced erosion, hence less maintenance and longer life for ground-based turbine auxiliary power units, (APUs) i.e., turbine-driven electrical auxiliary power units, and also possibly lighter weight for airborne APUs.

Two other related changes have been the revolutionary changes in medical and biological technology and electronics, especially in telecommunications and personal computers. While both offer opportunities for ceramic applications, for example, of bio- and electronic ceramics respectively, these are generally modest and also have some negative effects. The ceramic opportunities in these areas are limited on the one hand by distribution and liability issues for bioceramics (especially in the United States which has less use of bioceramics than Europe), and on the other hand by the short, rapid product development cycles of many electronic systems, which make it very difficult to implement newer technologies such as use of ceramics often represent. Further, these areas are absorbing large amounts of government and industrial funding, which leaves less money for other technologies. Additionally, the broad and growing availability of computer design technology has made design changes using existing materials, such as metals, much more rapid and cost-effective, thus allowing significant product improvements via new or improved design rather than new materials implementation, the latter typically being a much longer and more costly process. Thus, the addition of an additional set of valves in each cylinder of many automobile engines and the aerodynamic designs of cars, especially truck tractors, reduced driving forces for more fuel-efficient ceramic engine technology.

Another important factor is regulation, along with other public policy factors. Government engine emission controls generated the market of at least \$300 million per year for ceramic exhaust catalyst supports. Other existing and pending emission controls also provide further opportunity for ceramics (e.g., for burners), as well as for some competition from metallic burners and catalyst supports. Taxes can also be a factor, for example, an earlier tax on larger auto engines in Japan provided a financial impetus for development and sales of Si_3N_4 turbocharger rotors, and elimination of the tax greatly reduced the ceramic turbocharger market—which, if it does grow in the future could experience competition from other materials, such as metals, allowing variable pitch or carbon-carbon for lower mass. The high petroleum fuel taxes in most other developed countries were a major factor in the development of better fuel-efficient cars, which allowed other countries to expand their market share in the United States. Subsequent U.S. auto fleet fuel-efficiency standards helped provide a more uniform incentive for improvement of U.S. automobile efficiency in the face of fluctuating fuel costs.

Two other important and related factors that are commonly not adequately recognized are that there is always competition for any material application, and

that the competition is not static. Thus, many ceramic applications must compete with application of other materials, such as plastics or metals, as well as lower cost ceramics in bulk form by themselves or via coating technology, alternative designs, or both. Thus, various ceramic, intermetallic, or metallic coatings can compete with bulk ceramic components for a variety of wear and other (e.g., biomedical) applications. Low costs for many traditional ceramics due to use of low-cost mineral constituents and especially of processed materials, in particular, Al_2O_3 due to the economies of scale that are a result of the aluminum industry and generally lower processing costs for oxide ceramics, provide competition for higher performance ceramics, especially nonoxides. Metals are clearly the major competition for ceramics in engines, where air-cooling designs allow metals to be used beyond their normal temperature limits, but will most likely be replaced by ceramics (possibly also air-cooled) in some applications. In other cases it is strict cost competition—ceramic cam followers were considered for a number of years by Chrysler to replace metallic needle bearings in some of their auto engines. Ceramic cam followers have not been implemented in Chrysler auto engines due to reduced costs of the metal bearings stimulated by the potential of ceramic competition. (*Note:* The ceramic followers had to be lower cost than the metal bearings to be considered for automotive implementation; ceramic cam followers have been implemented in some diesel engines where cost-performance trade-offs are different.)

The above example of ceramic cam followers in auto engines also illustrates the fact that it is difficult to displace an established technology that can still be improved. This is also shown by other examples, such as solar cell panels for power in space, which have repeatedly been extended to larger sizes and higher powers beyond previously projected limits. However, changing of the balances between competing technologies over time is important, but can be complex. Thus, radomes used on missiles and aircraft used to be polymeric based composites below Mach 1, and ceramic above it, but the former have been improved over time for use to Mach 2–3, thus potentially reducing the market for ceramic radomes. However, the upper missile velocities for which ceramic radomes are used have also been substantially extended, thus maintaining considerable use of ceramic radomes. Similarly, plastic electronic packages have increased in their temperature-environmental and other capabilities allowing them to replace some ceramic packages, but application of ceramic packages in more demanding environments has also increased, leaving ceramic packages still a large and growing business. However, commercial AlN electronic substrates and packages for higher heat dissipation, though present as items of commerce, are well short of earlier expectations due to AlN's higher cost, competition from other heat dissipating materials and methods, as well as reductions in power to operate some semiconductor devices, and hence reduced needs for high heat dissipation. The

higher cost of AlN, especially versus that of Al_2O_3 , can be reduced with increased volume, as for most material. However, important questions for all materials are whether costs can be reduced enough to attract high-volume use, and are there intermediate cost/volume applications to bridge the gap(s) between lower and higher volume applications. Note that this issue of progressively expanding markets to provide an opportunity to progressively increase production volume and thus reduce costs can be particularly problematical for new technologies as discussed by Christenson [13]. Thus, major technological developments often start as niche markets, which may not be of interest to the business discovering them but may ultimately replace them. For example, buggy makers were generally not interested in automobiles, which were considerably developed by others before they started to replace the horse-drawn buggy.

It is useful to briefly take a long-term and broad perspective on ceramic engine programs. These actually began around the end of World War II with Allied intelligence indicating possible work in Germany to use ceramics to enhance performance of their jet fighter aircraft introduced late in the war [14], leading to a U.S. program following the war. The U.S. turbine blade candidates were a sillimanite ($-\text{Al}_2\text{O}_3-\text{SiO}_2$) and a BeO "porcelain" ($\sim 85\% \text{ BeO}$), then later MoSi_2 , and especially, an $\sim 80\% \text{ TiC}-20\% \text{ Co}$ cermet. All were unsuccessful (the latter giving cermets their reputation for often giving the brittleness of ceramics at lower and the poor deformation resistance of metals at high temperatures, rather than the hoped for combination of higher toughness of metals at lower and ceramic creep resistance at higher temperatures). This earlier turbine program apparently lead to industrial investigation of ceramics for piston engines, for example, cylinder liners, apparently focused on alumina-based ceramics. Thus, one could say that these types of ceramic programs have been investigated for ~ 50 and ~ 40 years, respectively, without success, and one could add that ceramic ball or roller bearings have been investigated for nearly 40 years and have only begun recently to achieve moderate commercial success. These earlier programs showed the need for better ceramic materials, development of which, especially silicon nitrides and related materials, stimulated subsequent programs and were further improved by them.

Thus, viewed in a broader perspective, the above programs are interrelated and moderate successes, and both bearing and piston engine cam applications of silicon nitride are, in part, derivatives of turbine engine programs, as was the temporary success of silicon nitride turbocharger rotors. This is also at least partially true of the increasing use of other ceramics (e.g., ZrO_2), in other diesel engine fuel-wear applications, which took fewer years from investigation to application and are growing with progression to newer engine models. Vehicles using hybrid combustion-battery or fuel-cell propulsion offer important opportunities for ceramics that benefit from past ceramic engine efforts. (A hybrid turbine-electric drive was proposed by this author as a follow-up to ceramic engine

programs, but was withdrawn based on advice that it was too expensive to have two power sources, an assumption that will be tested by the hybrid vehicles in production and development.) Overall, some possible stalls of uses, such as silicon nitride turbocharger rotors or thermal shock-resistant oxides as exhaust port liners, may prove permanent or temporary. Expansion of the ongoing applications and other developing opportunities, however, indicate growing engine application of ceramics—for example, silicon nitride or carbon-carbon valves or high-performance graphite pistons.

It is useful to note that electronic applications of ceramics are greater and have experienced much better growth than initially projected, especially in their earlier inception, (application forecasts were often short of actual results, while forecasts for engine applications of ceramics have typically been far above actual results). Thus, technology push can be successful, especially for new developments (but probably requires substantial government support), while market pull developments are typically faster and more likely to be successful, especially in modest time frames.

1.4 COST AND PROFIT FACTORS

While there are factors that impact the markets for ceramics on a broader, often long-term basis as outlined above, more fundamental to the success of any specific product is first its specific potential market and its producibility at acceptable costs. The market outlines the character of the product, such as its technical requirements, scale of potential production, product pricing, and possible interrelation of these, but much may be speculative and uncertain, especially for new applications. The producibility is directly related to fabrication (i.e., determining whether the perceived or known component performance, size, shape, dimensional, and other requirements can be met), as well as what its costs are likely to be and how they compare with potential prices and thus what the potential profitability may be. Again it must be emphasized that all of these factors may be quite uncertain for a new product but better defined for a manufacturer entering an existing market for an existing component. Many of the issues, especially those of marketing, are well beyond the scope of this book and are thus addressed little or not at all. The focus is on those issues most directly related to fabrication—focusing on costs—with some limited comments on prices and profitability.

Cost of technology development and especially of actual production implementation are critical to a product's successful introduction and success. Actual production costs for a given part are typically proprietary, so much of the information available comes from general production knowledge and especially from the increasing use of computer modeling of fabrication costs. Cost evaluations via modeling are a critical factor in successful development and implemen-

tation of ceramic component fabrication, both in the early stages of consideration as well as during development and implementation, since this indicates both possible fabrication routes and the more costly steps that need particular attention. However, such evaluations are quite dependent on key operational parameters (e.g., the specific fabrication route, processing parameters, and volumes of production), as well as factors such as excess material used, sharing of production resources, and especially yields achieved (the percent of components manufactured that are suitable for sale versus those that have to be scrapped). These factors are typically highly proprietary, and thus not available publicly, as is true for much data to verify cost models. However, there are some generally known cost aspects as well as specific cost modeling studies that provide useful guidelines, recognizing that there are exceptions to all trends that require specific evaluations of specific cases. Again, the purpose here is not a tutorial on modeling methods, which is a large subject in itself, but to give some sources of such information, and especially familiarize readers with factors, variations, and some basic guidelines.

First, consider overall trends, a major one being what technical market into which the specific component will fall, with a major differentiation being whether the component is an electronic one, especially a multilayer electronic package, or for some other use, such as for thermal-structural functions. Electronic packages (and to a lesser extent other electronic and some electrical components as well as ceramic cutting tools) sell at prices much higher per unit weight, reflecting both higher production costs and their small size, hence limited per part cost, and probable more value added. An overall assessment of the advanced ceramics industry in the United States outlined by Agarwal [15], that is apparently more focused on structural ceramics, noted that ceramic processing is typically batch and labor intensive. He attributed 40–50% of manufacturing costs of high-performance ceramics to inspection and rejection (basically to yield), versus 5–10% for high-performance metals, thus again emphasizing this as a major cost issue for ceramic production. Agarwal cited typical 15–20% of total costs for ceramic finishing, mainly for machining, and only 5–10% for metals. However, for precision parts (e.g., those in engines), machining costs can be substantially higher (e.g., machining costs were a major factor in projected high costs of toughened zirconia components for possible use in more efficient diesel engines (see Table 1.2). The potentially high costs of much machining of ceramic components is a major reason for emphasizing near net-shape fabrication, though an important exception has been ceramic ball manufacturing for bearings as discussed later.

While machining costs can be very high, and often the dominant single process cost if extensive machining is required, it is important to again emphasize another factor that often determines the viability of a product, namely its yield—the percentage of output that ends up in useable product. Resulting yields

TABLE 1.2 Estimated Manufacturing Costs for PSZ Diesel Engine Components^a

Component	Headface plate	Piston cap	Cylinder liner
Body costs (\$)	1.55 (1%)	1.36 (1%)	7.84 (3%)
Forming costs (\$)	2.88 (1%)	8.08 (3%)	38.09 (15%)
Firing costs (\$)	17.45 (9%)	12.97 (5%)	47.48 (19%)
Grinding costs (\$)	173.93 (89%)	259.03 (91%)	161.32 (63%)
Total costs (\$)	195.81	281.44	154.74

^aCosts of subsidiary operations [16] shown as a percent of the total component cost in parentheses. Note that in another related study modeling costs of some of the first two listed and other related components directed at design and manufacturing changes to reduce machining, showed overall costs substantially reduced to somewhat under \$100 each, with grinding costs reduced to 37–68% of total costs (but increasing the other fixed costs as a percent of other their total reduced costs [16,17]).

at each fabrication step vary in amount and cost impact, with the limited amount of recovery often being greater, hence somewhat less costly, in earlier processing stages, such as powder, and much greater in later stages, such as firing and machining. However, the cumulative product yield, which can be well < 50% in earlier stages of product production and possibly < 80% in later stages of production of complex components, is most critical, and is often the determining factor in product success and of constraints on costs of individual fabrication steps, especially more costly ones [18-23].

Turning to other specific fabrication costs, raw materials are a factor; Agarwal cites them as 5–10% of total costs (for structural ceramics, metals, and polymers), which is a common range, but subject to a variety of conditions, they are sometimes lower or higher (see Table 1.2). Thus, for example, Rothman and coworkers [18,19] report that higher cost SiC powder (\$22/kg, giving material costs at 22%) could be used for making small disk seals if a high overall yield (86%) was assumed, versus ~ \$3/kg powder (giving material costs at ~5%) with 40% overall yield. The impact of raw materials costs depends greatly on the amount used—expensive materials such as silver, gold, and platinum are used in electronic ceramics, but in small quantities, such that many packages can be sold for a few dollars each. More generally, consider a range of small, structural components, such as a Si₃N₄ balls for bearing applications: A 1/4-in. diameter ball requires a modest amount of Si₃N₄ powder, while a larger 1/2-in. diameter one requires eight times as much powder, so the sensitivity of such balls to raw material costs increases substantially as ball size increases. Thus, raw materials used for small balls may not be economically viable for larger ones. This issue of raw materials costs is important because many desirable powders have been developed, but their high costs severely limit their economical viability. For example, Schoenung, and coworkers [20-21] conducted substantial modeling of ceramic costs for a variety of advanced engine uses,

such as cam rollers, valves, and guides, showing that zirconia toughened components never or barely allowed the costs to get down to target component prices at substantial product volumes of 5–10 million/yr with \$13/kg powder, whereas \$4.50/kg powder cost allows component costs to reach target prices at production quantities of 2–4 million/yr. However, also note that many components, such as many in engine applications, have an approximately fixed physical volume, in which case zirconia suffers a disadvantage of requiring nearly twice the weight of powder per component relative to other candidate ceramics such as Si_3N_4 . On the other hand, other powders such as those of Si_3N_4 are commonly much more expensive than \$4.50/kg, thus not changing the raw material cost limitations much if at all favorably. Schoenung and coworkers' evaluations of similar Si_3N_4 components also showed similar material cost limitations—\$44/kg powder costs not even coming close to target prices even at production volumes of 10 million/yr, and even \$11/kg powder costs barely reaching the upper target price range at volumes of ~ 7 million/yr.

Das and Curlee [24] have also shown the importance of reducing Si_3N_4 powder costs (from ~ \$44/kg) along with machining costs making cam roller followers and turbocharger rotors more cost competitive with costs of metal components. However, their assertion that such higher cost ceramic engine components will be implemented where the improved benefits are adequately communicated must be viewed with considerable uncertainty. Morgan [25] correctly cites potential cost savings from broader use of advanced chemical preparation of ceramic raw powders and their processing, but does not address the key issue of how various production steps can be successfully made to go from the typical modest starting markets and common less-efficient batch processes used at such earlier levels of production to achieve potential large-scale lower costs.

Quadir et al. [26] corroborated that lower raw materials costs, including additives, are important in developing a lower cost Si_3N_4 (e.g., for wear, more modest temperature applications, and thermal shock resistance) and that comminution is an important powder cost factor where it must be used.

Tooling costs can vary from very modest to quite substantial depending on several factors, but particularly on the fabrication process selected. Thus, tooling costs for colloidal processing such as electrophoretic deposition and tape or slip casting, as well as isopressing, can be quite limited (though times for thicker deposits, tape lamination, drying times, die storage, and loading isopresses can be important cost factors). Pressure casting can entail more expensive tooling (and again deposition time issues). Die pressing and extrusion tooling costs can be modest (e.g., a few ten thousand dollars), since shapes are often simple, but even limited complexity and multiple cavity dies (for faster production and better use of presses) can substantially increase costs. Injection molding tooling can be substantially more expensive since it can form complex parts, a key virtue of injection molding, with tooling costs often reaching \$50,000 or more. Such die

cost are thus a factor in the choice of forming methods since modest levels of production, e.g., a few thousand components, often cannot cost effectively support more expensive tooling.

Some have assumed explicitly or implicitly that energy costs of sintering or other fabrication/densification processes are an important problem, avoiding some fabrication and seeking other approaches such as use of some highly exothermic reaction processes, such as self-propagating synthesis, to eliminate energy costs of densification. However, the energy costs (the “fuel bill” for most industrial ceramic processing), for example of sintering and hot pressing, are commonly < 5% of component costs (see Table 1.2). Thus, while savings on these costs are of value since these normally increase profits, they are not a major factor in determining process selection. (Further such energy savings can be greatly overshadowed by the high costs of the raw materials to yield the energy saving of such reaction processing [27,28]. Also, as discussed in later chapters, energy costs for other fabrication methods such as CVD and even melt processing are commonly similar.) Such energy savings would be of more impact if they also reduced the costs of heating facilities—their size, maintenance, and plant space used, (which are often factored into firing costs)—but these savings by such reaction processing also appear limited [27,28]. On the other hand, these or other reaction processes can give beneficial raw materials and (unexpected) comminution costs as discussed below and in subsequent chapters.

As noted above, there are other important factors in firing costs for ceramics, such as the furnace atmosphere, temperatures, volume, and more. Thus, oxide ceramics often have lower costs, since they can be fired in air, and at more moderate temperatures than nonoxides, the combination of which allows for both larger furnaces and especially continuous ones, such as tunnel kilns for oxides, both of which can increase cost effectiveness. While nonoxides are typically fired in batch kilns with significant lower through-capacity due to heat-up and cool-down times, some of the significant advantages of continuous firing of oxides can be realized by continuous firing of nonoxides. Thus, Wittmer and coworkers [29] showed substantial savings (e.g., 50–70% lower firing costs for silicon nitride fired in a (continuous) belt furnace than for firing in batch kilns). Though such belt furnaces typically do not have near the throughput of typical air fired tunnel kilns for firing oxides, they show substantial potential for continuous firing of nonoxides with sufficient production volume to justify higher belt furnace costs.

There has been a preliminary attempt at addressing cost aspects of hot forming of ceramics. Thus, Kellett and Wittenauer [30] discuss the possibilities of superplastic forming of nanograin ceramics such as $\text{Al}_2\text{O}_3\text{-ZrO}_2$ and Si_3N_4 as a means of lowering costs by producing components of near net shape, requiring less machining. Their focus was on effects of deformation rates on costs, reporting that strain rates of 10^{-3} to 10^{-5} sec^{-1} translate into forming times respectively of 4 min versus 6 hrs giving part costs of \$4 and \$400, respectively, for the case

chosen. They also noted steps to improve these, in particular grain growth inhibition. (*Note:* Large deformation at higher strain rates, e.g., $\sim 10^{-1} \text{ sec}^{-1}$, have recently been reported for a nanograin oxide composite; See Sec. 6.3.)

The impact of time required for individual process steps, as well as the overall cost factors and constraints in processing materials, can be seen by recognizing that there are just over 31.5 million seconds in a year, i.e., about 10.5 million for each 8-hr shift, with no days off, and about 7 million seconds for an 8-hr shift with typical days off. Thus, whatever the annual production expected, this time constraint is a fundamental factor in production costs since it defines how many parts must be produced per unit time and the impact of this on the productivity at each step to achieve the production goal. For example, if a million parts per year is the goal, then, depending on the shifts and days of production, a part must be produced every 7–31 sec (and even faster to allow for production losses, yields of $< 100\%$). Thus if a process consists of 10 steps, on average a part must take no more than 0.7–3.1 sec in each step. Most steps in a process take longer, often much longer per part, than the allowed average times, which means that many parts must be made simultaneously to achieve the targeted average time per part. For example if parts are formed in a press with a single cavity die, then the number of such presses needed will be the actual time for forming each part divided by the average time allowed for the forming step, which means that process steps that take longer times and have low or no multiplicity of simultaneous part formation from each press requires large numbers of presses and their associated costs.

Turning briefly to costs of producing ceramic powders (and whiskers), there are similarities to producing ceramic bodies, for example, impacts of starting materials. Thus, Schoenung [31] has modeled the costs of making Si_3N_4 powder by direct nitridation of Si versus by laser-stimulated CVD gas-phase nucleation of powder. For the assumed parameters, she showed nitridation yielding powder costs of \$17–230/kg, mainly \$25–50/kg, depending on seed powder costs, time of nitriding, and especially comminution costs; while the costs of the laser-CVD powder were more, $> \$100/\text{kg}$, driven heavily by the high cost of silane gas (assumed to be \$160/kg).

Schoenung [32] has also modeled costs of producing SiC whiskers via vapor solid (VS) reaction of SiO_2 and carbon, showing that costs could not be reduced to $< \$50/\text{kg}$ for the assumptions made, with raw materials cost and yields being important factors. Another indicator of the impact of precursor costs for ceramics is shown by the cost per kg of three common oxides in Table 1.3, which contrast with costs from other more conventional precursors of $< \$1$ to $< \$3/\text{kg}$. The costs of additives used in processing—commonly to aid densification and properties (see Chap. 5)—can also be significant. Thus, use of rare earth and other oxides for PSZ and TZP as well as Si_3N_4 often measurably increase raw materials costs, especially more expensive additives such as yttria versus others

TABLE 1.3 Costs of Common Oxide Ceramics from Commercial Sols^a

Ceramic/sol precursor	Colloidal	Alkoxide
SiO ₂	3.74	11.66
Al ₂ O ₃	8.80	9.02
ZrO ₂	27.50	27.50

^aCosts in \$/kg circa 1986 assuming 100% theoretical ceramic yield.

such as ceria, and especially magnesia or calcia. Another indicator of the frequent importance of comminution costs are commercial prices for abrasive grade SiC grits. The ratio of the costs of finer grits (400, 600, and 1000) to that of 240 grit material of two different purity grades from each of two major manufacturers were 1.6, 2.4., 4.2, and 1.1–1.2, 2, and 5.3–5.8. Since all were ground from the same SiC, the substantial increases in costs as grit size decreased is primarily due to comminution cost and secondarily to classification.

Finally, note that the typical model of decreasing costs per unit of production, e.g., per unit weight of powder or per component, progressively decreasing smoothly toward an approximately limiting cost at high volume (and hence also commonly with the passage of time), while a useful guideline, is often an oversimplification, as shown by costs of graphite fibers [23]. Thus, various perturbations of such smooth, continuous decreases occur, due to discrete changes in infrastructure, process technology, or both. Examples would be adding another or larger or more expensive piece of processing equipment such as a continuous furnace, the acquisition and installation of which require substantial levels of production before it can be justified. A specific example indicated in one ceramic study was that a relatively simple-shaped turbine vane could be hot pressed to net shape in modest quantities at lower cost than by injection molding and sintering, due to the much higher cost of the injection molding die versus the hot pressing tooling. Thus, the break-even level of production for both processes was several thousand per year, raising the dilemma of potentially starting with a more expensive process (injection molding) and hoping that volumes rose sufficiently to justify its cost, or of starting with hot pressing at low volume, then changing to injection molding if volume rose high enough, but with some cost penalty for switching processes (R. Palicka, Cercom, Vista, CA, personal communication, 2000). (Fig. 1.1).

Turning briefly to price and related profitability, it is essential to remember that price is determined by competition at one or more levels, which may change with different aspects of a given type of application. The most common and fundamental level is at the specific component material-fabrication level,

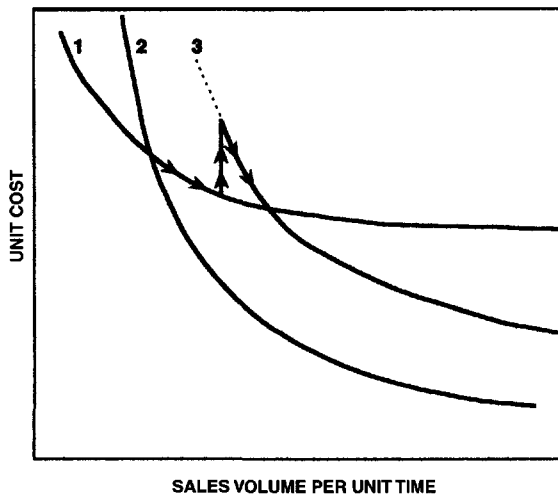


FIGURE 1.1 Schematic of cost impacts of changing manufacturing methods. Curves 1 and 2 reflect two different processes, e.g., hot pressing to net shape versus injection molding and sintering, respectively, with one reflecting a more efficient process at low volumes, but more inefficient at high volume. Thus, if process 2 is initially selected and production/sales volumes increase beyond the crossover point, this was a good selection, but not if the crossover point is not reached. On the other hand, if the process that is more efficient at lower volumes (curve 1) is chosen and volumes rise past the crossover volume, some added costs of changing the process would be required, shown schematically as a shift of curve 2 to curve 3 (probably with other changes in curve 3 not shown for simplicity).

but competition at the subsystem or complete system level can also be important, and may vary with the specific character of a given application. This is briefly illustrated for turbochargers, where at the fundamental level, ceramic (silicon nitride) turbocharger rotors compete with established use of metal rotors. This may be on a direct ceramic-metal rotor cost difference, or on the basis of overall turbocharger cost versus performance, but in either case the cost of metal components individually or collectively is a major factor in the competitive balance.

However, cost competition of different technologies may change as a function of component size, performance requirements, and market size, as well as other factors. As noted earlier, an important factor that drove use of ceramic turbocharger rotors for smaller auto engines was a Japanese tax on engine horsepower above a certain level, putting a premium on more performance from smaller engines. This shifted the balance in favor of ceramic rotors by putting a greater premium on faster response due to the lower ceramic versus metal density

(3.2 versus ~ 5.8 g/cc) until the tax was repealed. However, other circumstances could impact turbochargers—carbon-carbon rotors should be feasible with still faster response due to still lower density (e.g., 1.6–1.8 g/cc) and possibly less cost than silicon nitride rotors. On the other hand, variable pitch blades may be advantageous on some larger turbochargers, such as for diesel truck engines, again probably favoring metal rotors. Larger markets for turbochargers could also bring competition from other devices and related fabrication technologies, since a turbocharger is really only a way of temporarily increasing the volume of air delivered to the engine for faster acceleration; other devices to do this may be feasible, such as a small air compressor, storage tank, and valving to draw compressed air from the tank as needed, which could completely change the materials and fabrication technology picture.

Price constraints from existing technology can be seen in broad terms by considering resultant pricing of individual components or systems in which ceramics might be used. Thus, prices paid for major system purchases such as cars, tanks, and ships can provide some guidance. For example, the sales price of a 1200 kg car is \sim \$20,000, which translates to \sim \$17/kg, which, allowing for profit and assembly costs, means that the average purchase price for the individual components and basic materials (mainly steels) is generally $<$ \$10/kg. Thus, while small amounts of much more expensive materials, such as some ceramic components, can be tolerated, larger quantities of use rapidly become seriously price constrained by the existing technology. Such evaluation readily indicates cost constraints of substantial substitutions of ceramic for metal armor for tanks. While the competing technology is commonly that of metals, it can also be other materials, including other ceramics. A particular case in point is that the modest use and growth of AlN for electronic packages with higher heat dissipation than Al_2O_3 is, in part, due to the lower costs of Al_2O_3 packages, providing incentives for designs that reduce the thermal dissipation in packages or alternative ways of accomplishing the dissipation.

Finally, once the commitment to a product has been made, whether or not the uncertainties have been adequately addressed, the issue is whether suitable profitability, in both amount and timing, can be reached. This is a function of the development costs, which include research and development, especially production and market development, as well as interest costs, and of profits, that is volume and price-cost differential (Fig. 1.2) [23,33]. Interest is a factor since to be adequately profitable, a new product needs to not only pay back the costs of its development, but do so with a return of interest that makes the development a worthwhile investment by the company versus other possible investments. For a substantial new product the interest costs can be a significant factor, which can be easily estimated by the rule of 72, that is, the time in years to double an interest cost or return multiplied by the annual interest rate is 72. Thus for an annual interest of 10%, the amount of money to be returned by product sales to the com-

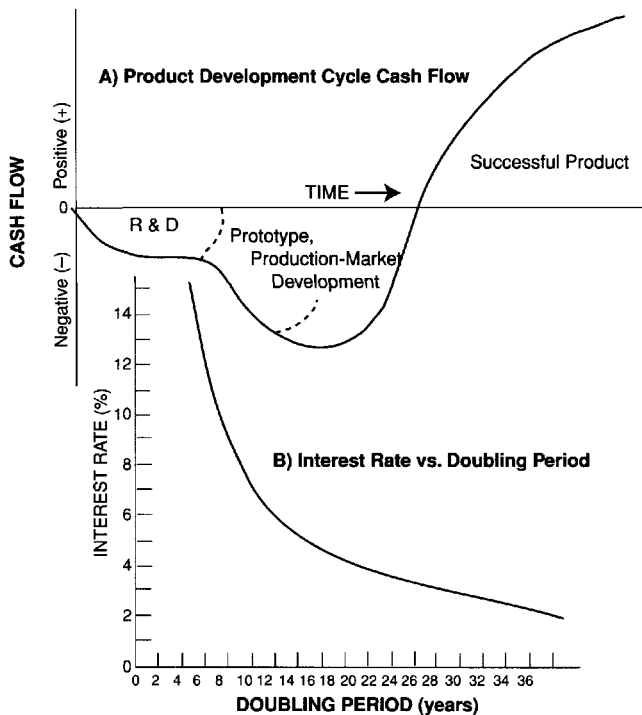


FIGURE 1.2 Cash flow factors for product development. (A) Schematic of the cash flow for a particular product development to be successful. Note that R & D costs are often much less than those for production and market development, and that positive cash flow only results after a substantial time with suitable profit from the product. (B) Interest rate versus the period (in yrs) to double the principle illustrating the rule of 72 and the significant impact that interest has on product payback. (From Ref. 23.)

pany would be doubled over a period of 7.2 years. Note that since such product investment costs are paid back only out of profits on sales of the product, pay-back times of a few to several years can be common.

1.5 OVERVIEW OF CERAMIC FABRICATION TECHNOLOGY

Ceramic fabrication technology consists of a diversity of processes that can be combined in various ways with varying material and microstructure (property), size and shape, and cost constraints and opportunities. The combinations of different processes to form a fabrication route to a component are determined

primarily by the process of producing a solid component of suitable character. The dominant process for fabrication of higher technology ceramics is sintering, mostly without pressure, of preformed bodies made by various powder consolidation techniques using powders from various preparation processes (see Chaps. 2 and 3). Typical powder consolidation-forming processes are die or isostatic pressing, extrusion, injection molding, and various colloidal processes, which along with sintering and its variations, are discussed in Chapter 4, emphasizing practical issues. Such sintering-based fabrication is very diverse with many variations as outlined in Fig. 1.3. While all of the above forming processes have considerable shape capability, their ranking in terms of decreasing shape complexity capability is approximately injection molding, colloidal forming, extrusion, and die- or isopressing.

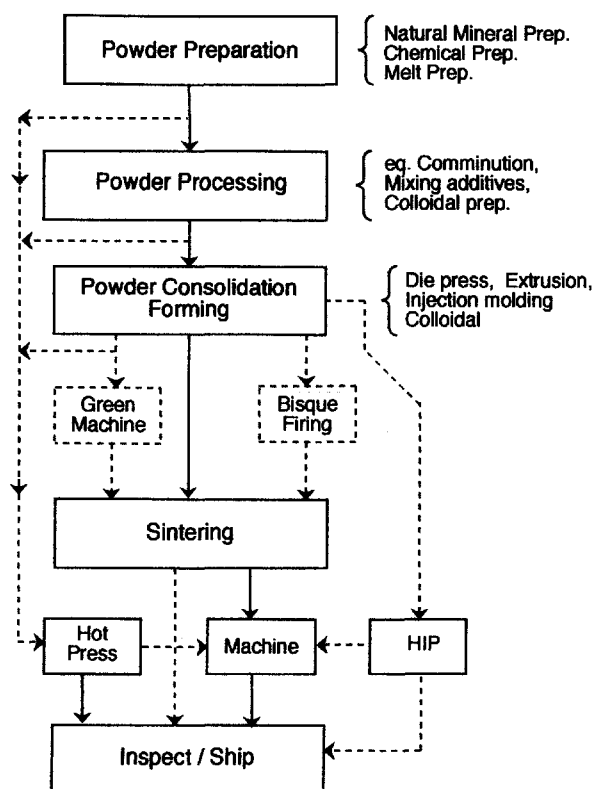


FIGURE 1.3 Schematic outline of sintering-based fabrication of ceramics and many of its variations, which are shown in boxes outlined by dashed lines and by dashed lines connecting various steps.

Variations in sintering-based fabrication include both newer methods of heating not shown in Fig. 1.3 that have been under investigation and can effect the sintering process, as well as many variations shown in Fig. 1.3. The latter include sintering under uniaxial pressure (i.e., hot pressing), which has seen considerable production use, and sintering under hydrostatic pressure (HIPing), done either following sintering or instead of sintering, which has seen some production use. Both of these pressure-sintering processes generally reflect higher costs, but have growing areas of application, and opportunities for further development as discussed in Chapter 6. There are also hot-forming processes, such as press forging, that have seen some investigation by starting with a sintered body or combining powder consolidation and hot forming of simple shapes. Such forming, though facing important time-cost issues (as discussed in Sec. 1.4), may have some specialized applications. Various reaction processes carried out in conjunction with either sintering without pressure or via various processes with pressure, especially for fabrication of ceramic composites are also addressed. Substantial discussion of this and other shifts in fabrication methods for monolithic versus composite ceramics is presented.

Other fabrication methods for producing ceramics without sintering, and may or may not entail use of powders (for example, polymer pyrolysis, deposition, and melting, as well as other reaction processes) are discussed in Chapter 6. There are also other fabrication methods for some speciality bodies, that is, fibers, balloons, beads, and bodies of designed porosity, including foams, which may entail various combinations of these methods (polymer pyrolysis), those entailing sintering, or both, which are discussed in Chapter 7. Deposition of coatings by various vapor processes is briefly discussed, while the use and significant potential of CVD for bulk monolithic and composite ceramics are more extensively discussed. Similarly, coating via various melt spray deposition techniques are noted, while making large bulk bodies by such methods are more extensively treated. Bulk melting and solidification are actually used to produce both some of the largest individual components as well as product volume of ceramics produced in view of its wide use for both the glasses and refractories, but has been more limited in its use for higher tech materials, mainly to single crystal growth. Earlier development of press forging of single crystals to produce shaped, polycrystalline optical (e.g., IR) windows, which has seen some use in production, is discussed along with other possible extensions of single crystal growth and melt casting.

Many issues discussed include effects of atmosphere on both calcining and sintering of powders as well as of adequate outgassing of anion impurities and adsorbed species, not only in various sintering processes but also other fabrication processes such as melting—for example, single crystal growth. Other methods of making powders and coarser particles, including melt forming, for fabrication of ceramic bodies for use by themselves or in nonceramic matrix

composites are discussed. Important shifts in fabrication methods for various types of ceramic composites are addressed, as is the array of various rapid prototyping-free form fabrication methods emerging. As noted earlier, preparation of raw materials, densification of powders, and control of microstructures via use of additives is extensively discussed. The size and shape potential and limitations of various fabrication routes are also addressed, including joining ceramics to themselves, as well as other materials. This shows some important advantages of hot pressing, CVD, and especially of melt processing. Some aspects of surface machining and other methods of surface finishing as well as joining are also discussed. Again, in all of these subjects the focus is on practical aspects including costs.

1.6 SUMMARY AND CONCLUSIONS

In summary, the large and growing families of ceramics have many known individual, as well as combinations of, properties of great technological importance. While the ending of the cold war substantially reduced the driving force for application of ceramics, especially more performance-driven development, and tax and regulation driving forces may come, change, and go, there is still substantial need and opportunity for ceramic applications, and this is likely to increase in the future. However, much of the development must be more focused and conscious of costs and economic constraints. There is even more limited opportunity for technology push applications, and competitive materials costs, such as for metals, will commonly be a limitation, except for the advantage that ceramics often have lower densities than common metal competitors, so less mass of ceramic is used in the many cases where component volume is dictated by the design.

These changes provide added needs for evaluating and modeling costs of various ceramics and their fabrication/processing. While detailed evaluation of these costs as a function of production methods and factors such as volume is the ultimate arbiter, some issues or flags for more attention were noted. Thus, yields are often a major factor, especially in earlier stages of manufacturing, but can be a sporadic problem in long term production. Machining costs can often be very high, being an important motivation for near net-shape fabrication, but details of methods and volumes are important. Direct energy costs are often modest, especially in comparison to many impressions (e.g., < 5% of total production costs) but must be considered, often with attention to broader factors such as throughput and duplication of firing facilities. Tooling costs for forming methods such as die pressing, extrusion, and injection molding can be substantial, with high tooling costs requiring high levels of production over which to spread those costs. Raw materials, commonly ~ 10% or less of total costs still must be considered, especially if their percentage of total costs is substantially higher, with additive costs often being a factor needing attention.

The key for successful production of ceramic is profitably producing components that perform with suitable reliability at cost-effective prices. This means that much change typically has to occur in transitioning from laboratory preparation to production, which commonly means changes in raw materials and fabrication and processing. Thus, for example typical laboratory use of many fine but expensive powders that are ideal for processing is often not cost-effective; the focus needs to be not on what is ideal—that is, the finest, most uniform, purest powder with the optimum ceramic phase content—but on what are the true needs to achieve the product goal. A great deal of development of the actual manufacturing steps, including evaluation of alternative approaches, is commonly necessary.

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