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Tailor-made ceramic-based components—Advantages by reactive processing and advanced shaping techniques

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Abstract

Affordable manufacturing of components with complex shapes is still the most essential shortcoming with respect to successful commercial use of advanced ceramics. This holds particularly for components with high demands of geometric precision and mechanical reliability at the same time. Two routes are considered here which offer a high potential for fast and cost-effective manufacturing of reliable components: (I) reactive-based processing exhibiting often low shrinkage and/or advanced shapability (and sometimes savings in raw material and processing costs) and (II) recently developed advanced shaping techniques suitable for CAD/CAM without labor intense tooling optimization. Recent developments in both areas are briefly highlighted.

Keywords: Reactive synthesis; Reaction bonding; Rapid prototyping; Green machining; Slip casting

1. Introduction

Modern structural ceramics and ceramic composites possess a number of unique properties that cannot be achieved by other materials. For example, ceramics combine high hardness, strength, and wear resistance with low density and the ability to withstand high temperatures and corrosive environments. Therefore, they have a potential for saving energy, reducing wear, and increasing the lifetime of components. However, regardless of their excellent properties, structural ceramics are not as widely used in industry as they should and could be. Among the reasons for the reluctance of industry to introduce structural ceramic components are

- high price of ceramic parts,
- insufficient knowledge in "traditional" metal-oriented engineering,
- low toughness,
- redesign components to meet specific ceramic requirements. As ceramic components should be designed in such a manner as to reduce stress concentrations and to avoid tensile stresses, a simple one-to-one substitution of an existing metal part is usually not possible. Other factors that can necessitate design changes are usually the high-elastic modulus and low thermal expansion of ceramics.

There is a number of examples where ceramic components have been designed and tested successfully, but, despite their superior properties, have not been put into production due to their high price. Particularly hard machining, which is usually inevitable for close tolerances in case of conventional manufacturing, plays a key hole here. As it is very time-consuming due to low material removal rates, hard machining increases the manufacturing costs for components drastically. Although the actual cost distribution varies, machining costs contribute a substantial fraction and can in some cases account for 80% of the overall manufacturing costs of a ceramic component.[1] In comparison to hard machining, other cost factors, such as shaping and sintering, are generally of minor importance.

Apart from the high costs associated with hard machining, conventional ceramic production processes have the disadvantage that they are usually suited for mass production, but not for fast and economical manufacturing of prototypes or small-scale series. Since a number of prototypes of the actual component will be required for evaluation in order to introduce a ceramic material into a certain application, the ability to deliver such prototypes in a reasonable time and at an acceptable price can be a decisive factor in a competitive market.

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The above remarks should show that it is of vital importance to reduce production costs and to make ceramic manufacturing more flexible. Ideally, a ceramic fabrication process suitable for prototypes or small numbers should make it possible to design a component at the computer, and to directly put the computer-aided design file to the processing line (CAD/CAM).

Challenging approaches are provided by synthesis routes which exhibit low to zero shrinkage, e.g., almost no dimensional change from the precursor to the final product. In this case, reactive processing routes like reaction bonding of silicon nitride or silicon carbide are well known examples, the latter one remerged recently as standard technology for the fabrication of commercial fiber-reinforced ceramic-matrix composite parts (e.g. Cf/C-SiC brake disc rotors). In the past decade, several other techniques have been developed offering low to zero shrinkage capability or – even more important in view of advanced manufacturing – readiness for precise manufacturing of complex shapes.

Shaping techniques like the recently developed rapid prototyping routes as well as advanced slip casting using solid dies, powder injection molding or even the well-known machining in the green state ("green machining") also fulfill the requirements to varying degrees and are therefore highlighted in the second part of the paper.

The present paper gives a brief overview on various approaches in both areas. Although reaction-based processes and shaping techniques are discussed separately, sometimes combinations will give particular advantage. However, all the techniques mentioned in the following offer various advantages and disadvantages in view of raw material costs, versatility, process stability, reproducibility of product performance in case of commercial production lines, etc., which cannot be discussed here in detail.

2. Reaction-based processes

In the following section, some reaction-based processes will be briefly discussed. For more detailed information, there are good general overviews available in the literature.[2–4] Although reaction processes are methods for synthesizing materials rather than shaping techniques for components, they are, in some cases, especially adaptable to certain shaping techniques, e.g., green machining or rapid prototyping, or they can be modified to combine synthesis with growing components directly into a desired shape (e.g. DIMOX), or make plastic forming techniques applicable (e.g. AFCOP). The classic reaction bonding processes (RBSC and RBSN) will be discussed in a very concise manner, as there is a great amount of literature covering these subjects.

2.1. Reaction bonded silicon carbide (RBSC)

In this process (also called reaction sintered silicon carbide) that dates back to the 1950s,[5–7] a preform consisting of SiC and C is infiltrated easily in vacuum at 1500–1600 °C by molten Si due to a good wettability,[8] followed by the reaction of C to form SiC:

$$\mathrm{SiC} + \mathrm{C} + \mathrm{Si} \rightarrow \mathrm{SiC} \qquad (1)$$

Fig. 1. RBSiC blower wheel made by milling of two semi-finished C–SiC green parts followed by green state joining and subsequent silicon infiltration (courtesy: Schunk Ceramics, Germany).

The process can be adjusted to yield either pure, but porous SiC, or dense Si/SiC composites as the final product. Normally, the latter one termed silicon-infiltrated silicon carbide (SiSiC) is chosen because of the higher strength. RBSC and SiSiC exhibit small dimensional changes and are suitable for all powder metallurgical (PM) shaping methods. The surface quality after the infiltration/reaction usually necessitates final machining. Fig. 1 shows a blower wheel made by "classical" reaction bonding. In the past decade, the silicon infiltration technique remerged for advanced fiber reinforced structures suitable for space applications and advanced friction systems.[9]

2.2. Reaction bonded silicon nitride (RBSN)

This process was developed in the 1970s.[10,11] Silicon powder compacts are reacted with nitrogen to form silicon nitride bodies at little dimensional change (<0.1%). Reaction bonding takes place at temperatures in the range of 1200–1450 °C:

$$3\mathrm{Si} + 2\mathrm{N}_2 \rightarrow \mathrm{Si}_3\mathrm{N}_4 \qquad (1200\text{–}1450\,^{\circ}\mathrm{C}) \qquad (2)$$

RBSN has normally a considerable residual porosity ($\gg$15%)[12] and, therefore, a relatively low strength. However, a large fraction of residual pores are small (<0.1 μm). The flexural strength of RBSN at a density of 2.55 g/cm^3 (i.e. ~80% T.D.) may reach ~360 MPa.[13]

2.3. Reaction bonded aluminum oxide (RBAO)

The RBAO process[14–23] starts from precursor mixtures consisting of Al and Al_2O_3. In practically all cases, ZrO_2 is added to enhance oxidation and to improve microstructure and mechanical properties of the final product. The precursor mixtures are intensively milled in order to reduce the particle size, mainly that of Al, and to achieve a high degree of homogenization. Green bodies for RBAO contain about 30–45 vol.% of aluminum