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Shaping of engineering ceramics by electro, chemical and physical processes

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ABSTRACT

Thanks to the favourable combination of outstanding mechanical, thermal and chemical properties, engineering ceramics find widespread applications in the modern industry. Nevertheless, their extensive use is still hindered by the implementation of a labour and cost intensive manufacturing chain. Electro, chemical and physical shaping techniques, like electrical discharge machining, additive manufacturing and laser beam machining, have recently been investigated to offer efficient alternatives. This work provides a comprehensive overview of the current technological trends and main perspectives on electro, chemical and physical shaping of engineering ceramics with a focus on experimental works. The literature data trace back to the 80s.

1. Introduction

Engineering, advanced or technical ceramics have attracted increasing attention in the last thirty years. Advanced ceramics, such as nitrides, oxides, borides and carbides offer superior hardness combined with high strength to density ratio and excellent thermal and chemical stability. As an example, silicon nitride (Si_3N_4) has a very low density of 3.2 g/cm^3, combined with high flexural strength vs temperature (up to 700 MPa at 800 °C) and excellent chemical resistance in harsh environments (e.g. sulphuric and nitric acid and caustic soda). Aluminium oxide (Al_2O_3) and silicon carbide (SiC) display the most favourable wear rate, high hardness (Vickers hardness, HV_{10}, up to 20 and 26 GPa, respectively) and maximal operating temperatures up to 1000 and 1600 °C, respectively. Last but not least, zirconia ceramics (ZrO_2) have the highest fracture toughness (K_{IC} between 4 and 12 MPa/m$^{1/2}$) and flexural strength (up to 2 GPa for specific grades, @4pt bending test), combined with ionic conductivity and excellent thermal insulating properties. Biocompatibility is also a feature of alumina and zirconia ceramics.

Thanks to the very good combination of favourable mechanical, thermal, chemical and physical properties, engineering ceramics can be used in a wide range of applications. Stamping dies, extrusion tools, combustion engine parts, seal rings, welding nozzles, hip joints and orthodontic implants are just a few of the numerous examples. Despite the huge potential, the use of ceramic materials in modern industry is still limited to particular applications. Nowadays, ceramic components are commonly made in near net shapes and successively machined into the final parts. The traditional production chain from powder preparation, shaping, green machining, de-binding, sintering and finishing, is labour and cost intensive, and only economically advantageous for medium and large production runs. Moreover, technological challenges arise when complex shapes and microsized features are required.

Electrical, chemical and physical shaping techniques have been investigated in recent years in response to the increasing demand of advanced ceramics components and niche applications. Research actions particularly refer to the use of electrical discharge machining (EDM), direct and indirect additive manufacturing (AM), and laser beam machining (LBM). Additional effort is made in the area of electrochemical hybrid processes, ultrasonic machining (USM), and (abrasive) waterjet machining (AWJ). The main ambition is to offer valid alternatives, especially to

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Abbreviations: AM, additive manufacturing; AWJ, abrasive waterjet machining; CAGR, compound annual growth rate; CLF, ceramic laser fusion; CLS, ceramic laser sintering; CMC, ceramic matrix composites; CNT, carbon nanotube; CW, continuous wave; DLP, digital light printing; EAM, electrode assisted method; ECDM, electrochemical discharge machining; EDM, electrical discharge machining; FDC, fused deposition of ceramics; GNP, graphene nanoplatelet; HAZ, heat affected zone; HIP, hot isostatic pressing; LBM, laser beam machining; LCM, lithography-based ceramic manufacturing; LENS, laser engineered net shaping; LOM, laminated object manufacturing; MRM, material removal mechanism; PVA, polyvinyl alcohol; RBSC, reaction bonded silicon carbide; SISC, silicon infiltrated silicon carbide; SLA, stereolithography; SLM, selective laser melting; SLRS, selective laser reaction sintering; SLS, selective laser sintering; SPS, spark plasma sintering; T3DP, thermoplastic 3D printing; USM, ultrasonic machining.

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respond to the demand of complex shaping and miniaturisation as well as prototyping, small production runs, and customised solutions, meanwhile simplifying the entire production chain and reducing the cost of ceramic products.

Having established that electrical, chemical and physical shaping of ceramics is an emerging and industrially promising technological area, this keynote paper aims at comprehensively reviewing the main trends and perspectives thereof. The focus is on experimental work with evidence of the effect of the process and its parameters on the final material performance. Moreover, the industrial perspective is highlighted. The focus is given to engineering ceramics, such as Al_2O_3, ZrO_2, Si_3N_4, SiC and related ceramic matrix composites (CMC). Reaction bonded silicon carbide (RBSC or silicon infiltrated silicon carbide (SiSiC)) is also considered since it behaves like an engineering ceramic and because of its commercial relevance. Finally, attention is paid to those techniques in which material removal or material addition is based on electrical and/or chemical and/or physical principles. Research on (assisted) cutting, as for ultrasonic assisted grinding, laser beam assisted machining and ELID grinding is not included in the present work, and the interested readers are invited to refer to specialised literature. Collected data are going back to the early 80s. Previous surveys on the machining of advanced ceramics can be found in [101,250].

The paper follows the following strategy: Section 2 reviews the material properties and applications of the most commonly used commercial grade engineering compositions. The section also highlights the importance of material integrity and probability of fracture according to Weibull statistics. The most recently available market data are also reported. Section 3 outlines traditional ceramic processing technologies from powder synthesis to post-processing. The conventional manufacturing chain of ceramic components is reviewed against the emerging technologies. Literature statements on EDM, AM and LBM are then reviewed in Sections 4-6, each in a dedicated section according to their relevance. Significant breakthroughs and experimental methods are accounted for. AWJ, UAM and miscellaneous processes are summarised in Section 7. The main applications and conclusions are drawn in the final sections.

2. Ceramic materials

The earliest ceramics were pottery objects, made from clay, then glazed and fired to create a hard surface. Pottery and porcelains are classified as traditional ceramics and are still used as domestic and art products. In the 20th century, advanced ceramic materials have been developed. According to [202], they can be classified as engineering ceramics (also known as structural or technical ceramics) and functional ceramics (generally employed in the electronic industry due to their inherent physical features (e.g. electric, magnetic, dielectric, optical and piezo electric)).

The family of engineering ceramics includes oxides, carbides, nitrides, borides, silicates and glass ceramics as well as composites, i.e. ceramic matrix composites (CMC) [133]. The most widely used engineering ceramics are: aluminium oxide (Al_2O_3), zirconium oxide (ZrO_2), silicon nitride (Si_3N_4), silicon carbide (SiC) and boron carbide (B_4C). The shaping of those materials is the subject of this work; SiSiC and electrically conductive CMCs are also considered.

Compared to metals and engineering polymers, engineering ceramics offer numerous enhancements in durability, chemical stability, hardness, mechanical strength at elevated temperatures, wear resistance and thermal stability, that make them desirable for a wide range of industrial applications in mechanical, aerospace, automotive, electrical, biological and chemical engineering. Even though metals are strong, cheap and tough, they are chemically reactive and heavy and have limitations on the maximum operating temperature. Polymers are easy to fabricate and light, but they can only be used at temperatures below 300 °C. Ceramics are mainly applied at elevated temperature in corrosive and abrasive environments, where they easily outperform all other material classes, providing an exclusive solution. Tables 1 and 2 list material properties and applications of many commonly employed structural ceramics.

Table 1
Material properties of commonly employed technical ceramics for structural applications: indicative values across different commercially available grades (inspired by [62]).

Material properties	Al_2O_3	Si_3N_4	ZrO_2	SiC
Density (g/cm^3)	3.8–4.0	3.2	5.0–6.0	3.1
Vickers hardness (kg/mm^2)	1800–2000	1500–1600	1100–1300	2600
Fracture toughness (MPam$^{1/2}$)	3–4	4–8	4–12	3–5
Flexural strength (MPa)	300–500	700–850	500–1800	400–600
Weibull modulus	8–12	18	10	10–18
Young's modulus (GPa)	300–400	310	200	400–450
Thermal expansion 10^{-6} K^{-1}	7–8	3.2	10	4.5–8
Thermal conductivity (W/m K) @RT	25–35	30–40	1.5–2	80–120
Electrical conductivity (S/cm) @20 °C	$<10^{-14}$	$<10^{-14}$	$<10^{-10}$	0.2–1

Table 2
Typical engineering applications of commonly employed structural ceramics and performance advantage (inspired by [133]).

Applications	Performance advantages	Ceramics
Wear parts, seals, bearings, valves, nozzles	High hardness, low friction	SiC, Al_2O_3
Cutting tools	High strength, hardness	Si_3N_4, Al_2O_3
Heat engines: diesel engine components, gas turbines	Thermal insulation, high temperature strength, fuel economy	ZrO_2, SiC, Si_3N_4
Medical implants: hip, shoulder, knee, dental, joints	Biocompatibility, surface bond to tissue, corrosion resistance	Hydroxyapatite, bioactive glass, Al_2O_3, ZrO_2

2.1. Reliability of ceramics

Ceramics are intrinsically brittle due to the nature of the ionic and covalent bonding. Fracture strength is assessed using 3pt or 4pt bending tests [8] and strongly depends on the presence of defects and flaws (or cracks and voids), whose size and shape are statistically variant. Accordingly, the strength of a ceramic component is determined by the weakest link, i.e. the largest flaw in the component loaded in tension, which is commonly dealt with Weibull statistics [263]. More specifically, the probability of failure (*P*; cumulative probability of fracture) of a component can be related to the tensile failure stress (σ_f) as follows (1) [240]:

$$\ln\left[\ln\left(\frac{1}{1-P}\right)\right] = m\ln\sigma_f + (\ln V - m\ln\sigma_0) \quad (1)$$

where *m* indicates the Weibull modulus, *V* the workpiece volume and σ_0 the characteristic strength. High Weibull moduli are desirable, as these result in a narrow range of stress over which most parts will fail, i.e. a higher reliability. Bulk and surface integrity is therefore crucial for a high performance in service, which strongly depends on the processing strategy. As an example, Fig. 1 shows a Weibull plot for various ceramics before and after EDM.

2.2. Economic impact and perspectives

The performance of engineering ceramics is regarded to be crucial for growth, prosperity, and sustained profitability in the industry. A report from BCC Research in 2008 reports the North American market for structural ceramics to be \$2.7 billion in 2007.